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A note to the simulation of the annual and inter-annual variability of the water budget over the Baltic Sea drainage basin

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With 11 Figures

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Summary

The annual and inter-annual variability of the water budget over the Baltic Sea area has been studied using the global climate model ECHAM4/T106 and the regional climate model REMO for three experiments covering a time period of 10 years each. To address the capability of REMO to simulate realistically the water budget over the Baltic Sea re-analyses data (so-called *perfect boundaries*) were applied as lateral boundary conditions. The validation against observations shows that the results agree rather well. However not all components of the hydrological cycle are observed, therefore only some of them could be compared to the simulation results. A clear dependence of the annual cycle of precipitation from the horizontal resolution was found in the experiments. Until now it is still unclear which processes are responsible for this. Further research will help to identify the sensitive physical processes involved in the water budget and their interactions.

1. Introduction

The climate of the Baltic Sea ranges from mild and humid mid-latitude conditions to a sub-arctic winter climate. Traditionally temperature and precipitation – the most important elements of the climate system – are used as basic quantities to classify climate. According to this, the understanding of the mechanisms and physical processes of the energy and water cycles on global and regional scales is essential.

The hydrological cycle has two major compartments: the terrestrial one – consisting of the inflow, outflow and storage of water in and on the land surfaces and the oceans – and the atmospheric one, which mainly consists of the atmospheric transport of water in various phases. Both parts are strongly connected to each other through evaporation (a loss of water for the earth's surface and a source for water in the atmosphere) and precipitation (a loss for the atmospheric water content and a gain for the terrestrial branch).

The Baltic Sea and its drainage basin can be subdivided into the Baltic Sea area with a size of 0.45 million km^2 (a little more than 0.1 percent of the world oceans) and the land area of about 1.9 million km^2. In the centre of the area under investigation is a semi-closed sea with a narrow connection to the world oceans. It separates large parts of Scandinavia from central and eastern Europe. The Baltic Sea and its drainage basin are dominated by frequent synoptic-scale depressions with maritime air masses from north-west or west, for which the Scandinavian mountains form a barrier. However, no mountain ranges form obstacles for Atlantic air coming from the south-west over Denmark and Northern Germany. Speth and Skade (1977), and Behr and Speth (1977) discussed the climate character of the Baltic area, which seems to be more continental than maritime. However the coastal areas are strongly influenced by the Baltic Sea. They also studied the influence of the Baltic Sea on the atmosphere, which is largest during the cold season.

An increasing amount of research has been carried out to understand and describe the climate of the Baltic Sea, as well as the components of the water and energy budgets. A few examples are given in: Graham and Bergström, 2000; Heise, 1996; Henning, 1988; Mietus, 1998; Omstedt et al., 2000, and Van den Hurk et al., 2000.

During the BALtic Sea EXperiment (BALTEX), a continental scale experiment of the Global Energy and Water Cycle EXperiment (GEWEX), major activities are carried out to explore and quantify the energy and water cycles of the Baltic region (Bengtsson, 1995), thus leading to a better understanding of the various processes involved. This includes the quantification of the variety of processes which determine the spatial and temporal variability of the water and energy cycles of the BALTEX region and their relation to the large scale flow.

Within the European Union founded projects NEWBALTIC I and II (Numerical Studies of the Energy and Water Cycle of the Baltic Region; Bengtsson, 1998, 2000) model simulations of atmospheric phenomena on time scales from days to decades have been carried out and validated against observations.

In this paper we present first results from three experiments with a global and a regional climate model. They have been performed to investigate the annual and inter-annual variability of the water budget for today's climate on a time scale of 10 years. Major emphasis lays on exploring the ability of the models to describe and simulate the hydrological cycle.

The following two questions will be discussed:

- Is the high resolution regional climate model capable of describing the water cycle of the Baltic area realistically?
- Does the horizontal resolution of the model influence the water balance in the Baltic Sea area?

A first validation of some components of the hydrological cycle against observations is shown pointing to sensitive variables in the model, where improvement seems necessary.

2. Models and experiments

Two climate models are involved in this work: the regional climate model REMO and the global climate model ECHAM4/T106.

The regional climate model REMO is based on the *Europamodell*, the former numerical weather prediction model of the German Weather Service (Majewski, 1991). Further development of the model took place at the Max-Planck-Institute for Meteorology, where the physical parameterisations from ECHAM4/T106 were implemented into the *Europamodell* code in addition to the ones which already existed (Jacob and Podzun, 1997). Now one dynamical core model with two physical parameterisation packages exists under the new name REMO. Details and references about the physical parameterisations can be found in Jacob et al., in this issue.

REMO can be used in the *forecast mode* (e.g., consecutive 30 h forecasts without assimilation cycle) or in the *climate mode*. This means, continuous runs for long time periods up to decades with updates of the lateral boundaries every 6 hours. Here, the limited area model is nested into the driving fields using a sponge zone of 8 grid points to harmonise the fields. It can not be expected that in simulations using REMO in climate mode every single weather event is calculated realistically in time and space, only the climate will be represented. Using the nesting technique in climate mode has the advantage that mesoscale phenomena, which are not present in the driving fields due to the coarse horizontal resolution and which are for example initiated through a more detailed land surface representation in the regional model, can develop within the simulation domain and without strong constraints from outside. Using the forecast mode with restarts for example every 24 hours restricts the lifetime of these mesoscale phenomena and looses the advantage of the high horizontal resolution in long simulations.

REMO has been used to study the climate of 1979 to 1988, for which it was driven at the lateral boundaries by re-analyses from ECMWF. They can be considered as *perfect boundaries* describing the state of the atmosphere close to reality. The simulation results are validated against observations.

To investigate the influence of horizontal resolution REMO with a grid spacing of 0.5° was driven by ECHAM4/T106 data (horizontal resolution about 1°). The driving fields from the spectral global climate model ECHAM4/T106 for the atmosphere, which was developed at the Max-Planck-Institute for Meteorology (Roeckner et al., 1996), were taken from an already existing climate simulation using ECHAM4 on T106 horizontal resolution (Stendel and Roeckner, 1998). This simulation is part of the atmospheric model inter-comparison project AMIP (Gates et al., 1999), in which several global atmospheric climate models participated simulating a climate similar to the years 1979 to 1988. This time period was prescribed through the observed sea surface temperatures of the world's oceans.

All REMO experiments presented here were carried out in *climate mode* on a horizontal resolution of 0.5° using the physical parameterisation packages from ECHAM4/T106. This guarantees that the description of the physical processes in the driving model ECHAM4/T106 and the driven model REMO are the same for the experiment concerning the horizontal resolution and similar for the experiment using ECMWF re-analyses (the ECHAM model is partly based on the ECMWF model). Therefore changes in the water budget can be related to the horizontal resolution.

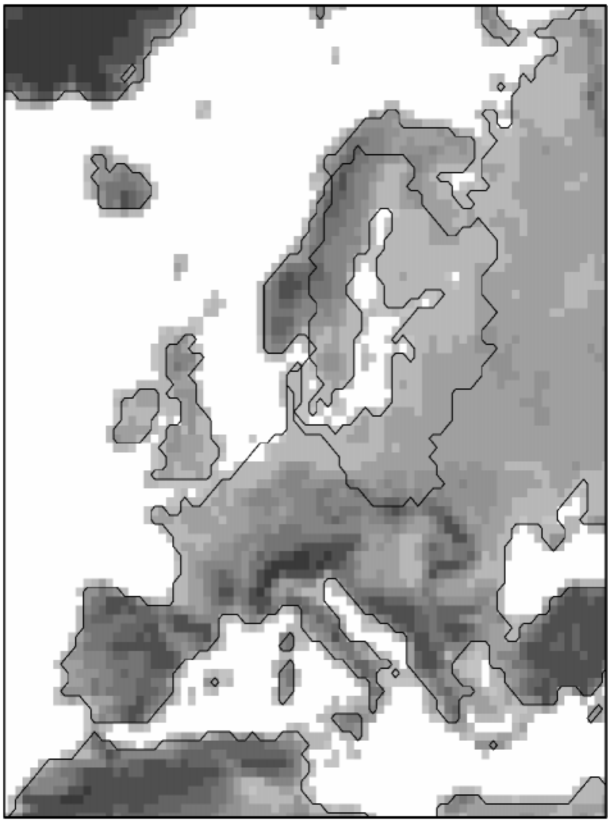


Fig. 1. Simulation domain including relaxation zone using the 0.5° grid. The grey shading represents the orographical structure. The black line shows the coastlines as well as the drainage basin of the Baltic Sea for clarification

The simulation domain including the relaxation zone is shown in Fig. 1.

3. Results

Is the high resolution regional climate model capable of describing the water cycle of the Baltic area realistically?

We will explore the quality of the REMO simulation using *perfect boundaries*, which are considered as reality and which are partly used for validation. In addition, independent observations of parameters of the hydrological cycle such as total precipitation (uncorrected gridded data on 1° × 1° interpolated from synoptic stations) and runoff on a monthly basis are used. These data are part of The BALTEX Hydrological Data Centre (BALTEX-HDC) at the Swedish Meteorological and Hydrological Institute (SMHI).

The hydrological cycle in the Baltic region is virtually controlled by the large scale circulation. Therefore a comparison of the large scale fields has been carried out first. It shows that the large scale fields simulated by REMO are in general similar to the re-analyses. The comparison of the mean sea-level pressure over 10 years shows almost no differences. The same is true for the geopotential height. However the calculated mean summer temperature in 850 hPa differs from the re-analyses fields in the south-east of the Baltic Sea drainage basin and leads to warmer temperatures. A difference of about 1 °C can also be found in the mean winter temperature.

The time series of uncorrected observed and calculated total precipitation over the Baltic Sea drainage basin (land only) are shown in Fig. 2 for the period 1981 to 1988, for which observations are available. The good agreement especially during autumn and winter shows that REMO driven by *perfect boundaries* is in principle able to simulate an annual cycle close to observations. It also shows that there is no systematic artificial trend in the long term precipitation simulation. However there are still deviations in spring and early summer resulting in an overestimation of

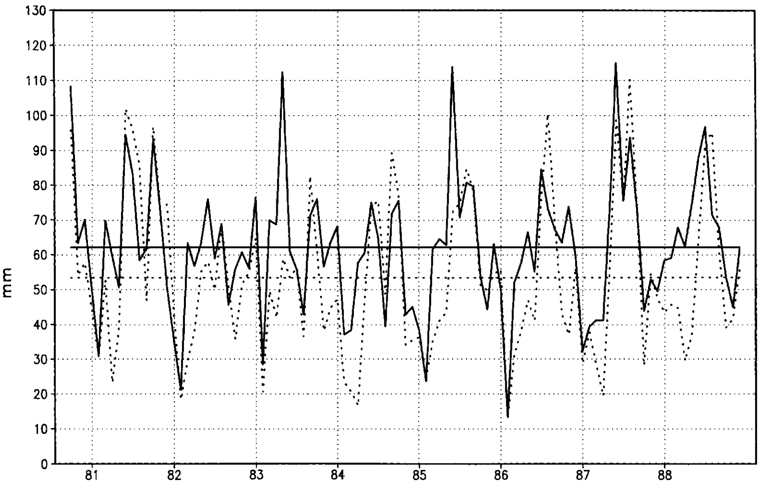


Fig. 2. Time series of observed (uncorrected, dashed) and simulated (solid) mean and monthly total precipitation (mm/month) for 1981 to 1988 over land surfaces within the Baltic Sea drainage basin

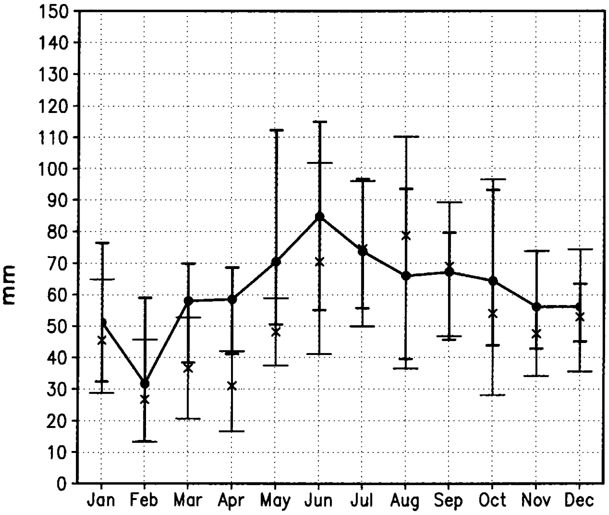


Fig. 3. 8 year mean annual cycle of monthly precipitation in mm/month over land surfaces within the Baltic Sea drainage basin. Observations: single crosses and thin bars, REMO results: bold line. The bars indicate the minimum and maximum

precipitation, which might be due to deficiencies in the soil parameterisation. Comparing the means, REMO overestimates the long term mean by roughly 10%, assuming the correction of precipitation for undercatch is about 5%.

Figure 3 shows ten years mean annual cycles of simulated and observed total precipitation over land. Simulated annually averaged precipitation amounts to 738 mm over land with a maximum in summer and 612 mm over sea with a maximum in winter (not shown). The observed value over land derived from the SMHI data base is 636 mm, whereas the GPCP data set delivers 802 mm as average for the Baltic region. Table 1 also shows the ratio between GPCP and SMHI (1,27 in average) as well as REMO and SMHI data (1,17 in average). Compared to the SMHI data the other two data sets are systematically higher. As mentioned above the SMHI data set is based on uncorrected precipitation measurements and an annually underestimation of at least 5% can be expected for undercatch.

Table 1. Annual total precipitation in mm/year for 1981 to 1988 derived from GPCP products (left column), from SMHI data base (middle column) and from REMO driven by ECWMF re-analyses (right column)

Year	GPCP	SMHI	REMO	G/S	R/S
1981	919	766	776	120%	101%
1982	746	554	662	134%	120%
1983	827	609	783	136%	129%
1984	766	590	676	130%	115%
1985	812	647	757	126%	117%
1986	765	609	716	126%	118%
1987	780	660	731	118%	111%
1988	803	650	805	123%	124%
Mean	**802**	**636**	**738**	**127%**	**117%**

An independent comparison of GPCP data against 4000 rain gauge observations collected by the BALTEX Meteorological Data Centre has been carried out by Rubel and Hantel, 2001 (in this issue) for the years 1996 to 1998. They found an annual average overestimation of the GPCP products during the years 1996 to 1998 of 4.5%. Unfortunately these values can not directly be compared to the simulation experiments, but it can clearly be seen that REMO is able to give reliable estimates.

The mean annual cycle and the annual variability are similar to the observed ones, however the simulated inter-annual variability especially for May months is much larger than observed. It can be seen that the model generates too much precipitation in spring and early summer. The reason to this is unclear but as mentioned above may be related to an overly wet ground in late spring and early summer. This in turn is presumably also leading to an increased evaporation over land.

Precipitation over sea cannot be validated due to the lack of observed data but validation against SSM/I data and measurements on ships (ferries) during the PIDCAP campaign (3 months in autumn 1995) suggests that the model calculated data are slightly too high (Bengtsson, 2000).

The latent heat fluxes for land and sea respectively, are practically reversed (not shown). They have a pronounced annual cycle reaching $-100\,\mathrm{W/m^2}$ over land (maximum in summer) and $-70\,\mathrm{W/m^2}$ (maximum in winter) over the sea. There is a strong inter-annual variability over the sea in late autumn and winter. The annually averaged latent heat fluxes for land and sea are practically the same. Modelled data are in good agreements with other studies. For example, Omstedt and Rutgersson (2000) found that the annual means of the net heat loss and the solar radiation in the open water area are in close balance, but large inter-annual variations of the latent heat flux can be noticed, which illustrate the reduced evaporation rates during cold winters.

The simulated annual sums for precipitation (P), evaporation (E) and P−E are given in Table 2. The calculations show a positive balance P−E over land of 250 mm and also a positive water balance over the Baltic Sea amounting to 176 mm annually or ca. 15 mm in monthly average. Modelling results are in good agreement with the estimates provided by Omstedt and Rutgersson (2000). A more detailed investigation of the water balance over the Baltic Sea has been carried out in the EU- project PEP in BALTEX (*Pilot Study of Precipitation and Evaporation in the Baltic Sea*). Here P−E is achieved through different interpolation methods including interpolation from ship measurements and sums up to about 150 ± 50 mm for the period September 1998 to August 1999 (Smedman, 2001). The discussion on these findings and the relation to the long term mean is still ongoing. Further investigations of the amount of precipitation and evaporation over sea are important to find the truth. Observations are insufficient, which makes it particularly problematic.

Table 2. 8 years of total precipitation (P), evaporation (E) and P−E, all in mm/year, simulated with REMO driven by ECWMF re-analyses; (a) Land points only, (b) over the Baltic Sea

a)

Year	Total precipitation	Evaporation	P−E
81	776	487	289
82	662	470	193
83	783	495	288
84	676	464	212
85	757	500	257
86	716	477	239
87	731	487	244
88	805	529	276
Mean	**738**	**488**	**250**

b)

Year	Total precipitation	Evaporation	P−E
81	681	436	245
82	516	433	83
83	640	526	114
84	599	426	173
85	602	395	207
86	591	434	157
87	612	367	245
88	660	467	193
Mean	**612**	**436**	**176**

Table 3 shows the simulated seasonal sum of P−E over land and sea for the full simulation period of 10 years (1979 to 1988). It can be seen that the balance over sea is always positive, with a minimum in summer and autumn and a destinct maximum in spring. Over land P−E has its maximum in autumn and winter with a clear minimum in summer, where the balance is negative. This means that the water release from the land surfaces through evaporation exceeds the precipitation.

The simulated water budget for the period 1981 to 1988 is given in Fig. 4. The mean annual runoff amounts to 439 $\mathrm{km^3}$/year with a maximum of 519 $\mathrm{km^3}$/year and a minimum of 306 $\mathrm{km^3}$/year. This is an underestimation compared to the observations from 1981 to 1990 (10 year mean instead

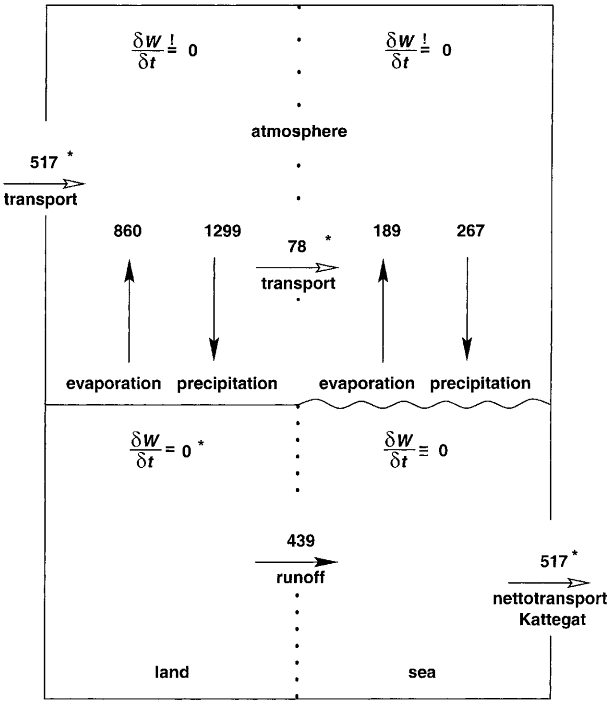
Table 3. 8 year mean seasonal total precipitation (P), evaporation (E) and P–E, all in mm/3 months, simulated with REMO driven by ECWMF re-analyses; (a) Land points only, (b) over the Baltic Sea

a)

	Total precipitation	Evaporation	P–E
Spring			
mean	184	160	24
max (y)	251 (83)	172 (83)	78 (83)
min (y)	155 (80)	148 (87)	−9 (84)
Summer			
mean	229	250	−21
max (y)	284 (87)	271 (85)	20 (80)
min (y)	160 (83)	229 (84)	−83 (83)
Autumn			
mean	194	63	131
max (y)	228 (81)	67 (80)	164 (81)
min (y)	162 (82)	55 (84)	104 (87)
Winter			
mean	139	10	129
max (y)	169 (83)	16 (82)	153 (83)
min (y)	107 (81)	4 (85)	100 (81)

b)

	Total precipitation	Evaporation	P–E
Spring			
mean	131	21	110
max (y)	188 (83)	40 (80)	170 (83)
min (y)	96 (80)	3 (86)	56 (80)
Summer			
mean	114	95	19
max (y)	183 (87)	127 (82)	103 (87)
min (y)	52 (83)	68 (85)	−70 (83)
Autumn			
mean	207	190	17
max (y)	265 (81)	240 (83)	90 (81)
min (y)	167 (82)	160 (87)	−28 (85)
Winter			
mean	174	127.4	46.6
max (y)	206 (83)	159 (82)	92 (87)
min (y)	139 (81)	111 (87)	20 (84)



* residual values

Fig. 4. Water budget for the Baltic Sea drainage basin calculated using REMO with ECMWF re-analyses for the period of 1981 to 1988 in units km^3/year

of the simulated 8 year mean), which gives a fresh water input to the Baltic Sea of about 526 km^3/year. Bergstrøm and Carlsson (1994) presented a long term climatic mean of about 443 km^3/year for a period from 1920 to 1999.

It can be stated that the limited area model REMO is capable to simulate the water budget over the Baltic Sea and its drainage basin. The comparison against different observations shows in general a good agreement. However the results point to some deficiencies in the physical parameterisations, especially at the surface. The onset of snow melt seems to be too early, so that in spring the soil is too wet. This leads to enhanced evaporation and precipitation. Over land both precipitation and evaporation seem to be overestimated compared to observations, however the calculated total runoff is less than in observed climate data. Further research will show whether compensation effects are involved.

Earlier investigations showed that the coupling of the atmospheric model with a hydrological model is a very powerful tool to study the effects influencing the runoff (Graham and Jacob, 2000; Graham, 1999; Graham and Bergstrøm, 2000). The runoff is not only determined by the vertical water fluxes in the soil, which are calculated in a very simple way in most regional climate models, but also through the routing of water to the rivers. This is usually not included in atmospheric models. Figure 5 shows the difference between the simulated runoff generation without routing and the observed runoff. The strong routing, lakes

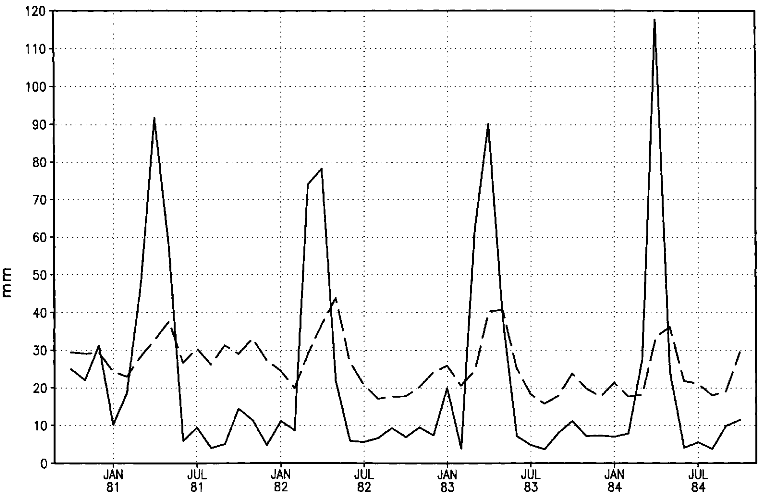


Fig. 5. Time series of observed monthly runoff (mm, dashed line) and simulated runoff generation without routing (mm, solid line)

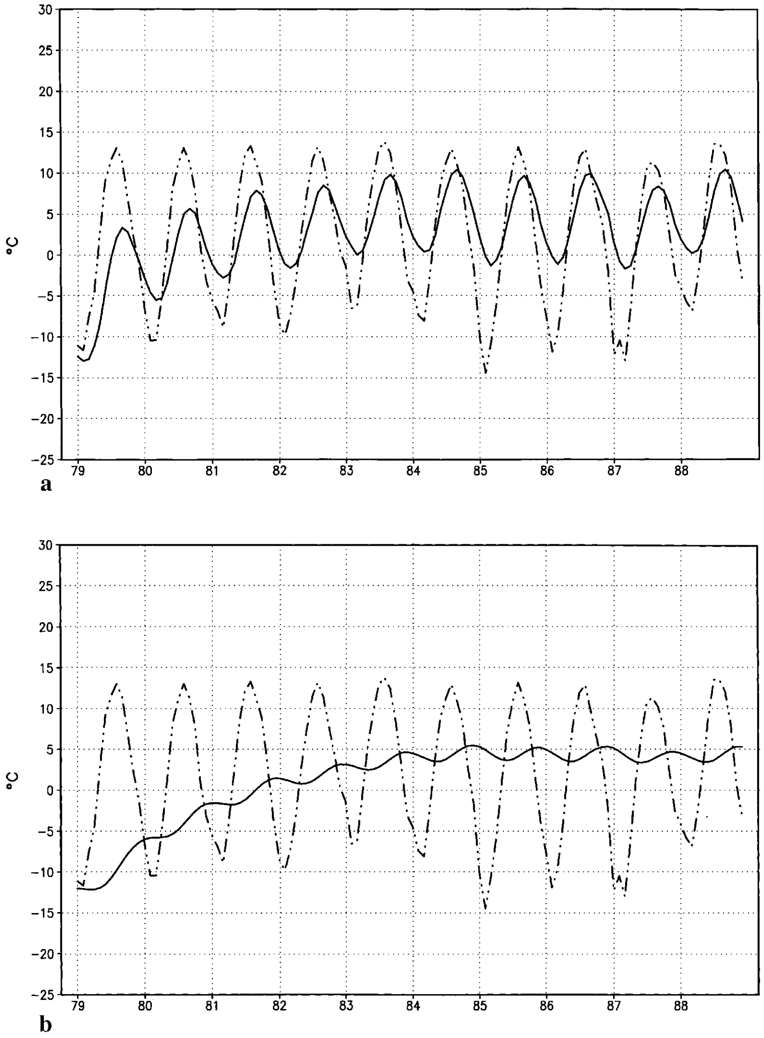


Fig. 6. Time series of deep soil temperatures in °C. **a** In about 3.5 m depth, **b** in about 7.5 m depth. Dashed: ECWMF re-analyses data, solid: REMO results

and river regulations are damping the runoff in spring and increasing it in the second half year. This must be taken into account when comparing runoff data, which in general is very helpful to detect compensating effects in the soil parameterisation.

A very important issue is the simulation length, which is related to the representation of physical processes in the soil. Initialising the soil temperature using data from re-analyses connected with the slow spin-up of the deep soil layers leads to deficiencies in the simulation if only 10 years are under investigation. The upper layers follow mainly the radiation budget. Figure 6 shows the time series of monthly mean soil temperatures for ECMWF re-analyses interpolated to the REMO grid and the calculated REMO values. There is a major difference in the annual cycle of the deep soil layers (Fig. 6a, this soil layer is 2.9 m thick and the centre lies ~3.5 m deep. Fig. 6b, this soil layer is 5.7 m thick with the centre in about 7.5 m) due to the different parameterisation of the soil. The ECMWF soil temperature values are only used for initialisation, but this leads to an unrealistically cold initialisation of the deep soil, which needs about 5 years to come to equilibrium.

Does the horizontal resolution of the model influence the water balance in the Baltic Sea area?

The influence of the horizontal resolution will be investigated using REMO on 0.5° horizontal resolution driven by ECHAM4/T106 data and a comparison to the driving ECHAM4/T106 fields.

The water budget for a global climate similar to the years 1979 to 1988 is shown in Fig. 7. It is important to note that the simulated decade can only be seen as an example. It is not representative for the quality of the global model results. Only an ensemble of decades will give reliable statements. However up to now only one realisation of the regional climate model run using the global model data as input has been finished. Therefore we will investigate in the following analyse the influence

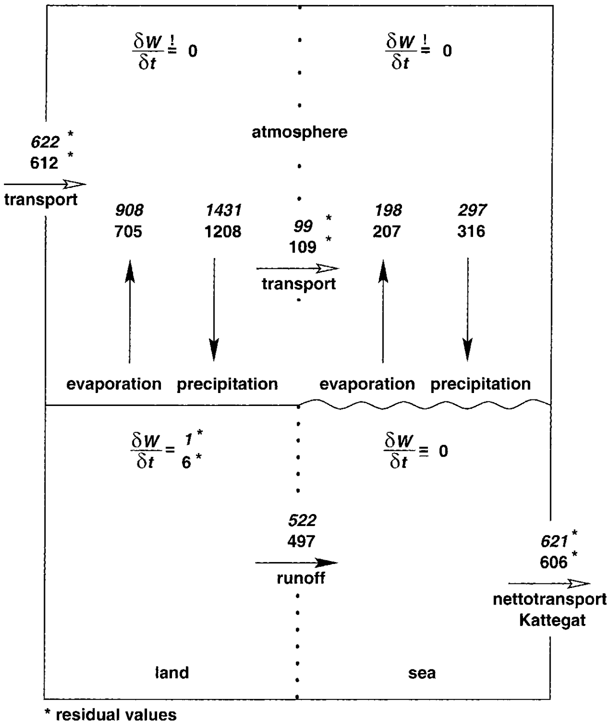


Fig. 7. Water budget for the Baltic Sea drainage basin for a period of 10 years. Upper value REMO driven by ECHAM4/T106 data, lower value ECHAM4/T106 in units km^3/year

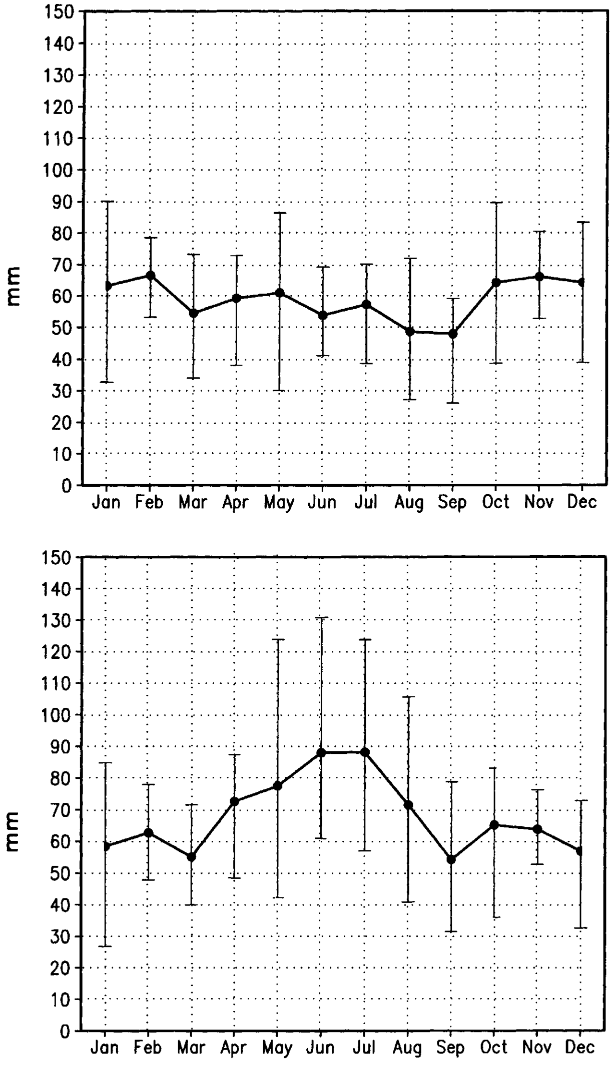


Fig. 8. 10 year mean annual cycle of monthly precipitation in mm/month over land surfaces within the Baltic Sea drainage basin. Upper panel: ECHAM4/T106, lower panel: REMO driven by ECHAM4/T106. The bars indicate the minimum and maximum

of horizontal resolution on the results without relating them directly to observed data.

A comparison of the water budgets calculated by ECHAM4-T106 and REMO driven by ECHAM4-T106 data (Fig. 7) shows that the higher resolution leads to a much more intense hydrological cycle over the land areas, but over the sea it is slightly less than calculated within T106.

The simulated annual mean precipitation over land, which is about 700 mm per year for the ECHAM4/T106 experiment and 910 mm/year for the REMO simulation using ECHAM4/T106 fields at the lateral boundaries shows that REMO overestimates the precipitation, while the global model gives for this example a mean value closer to observations. Although the mean value is well simulated by the global model, the annual cycle is missing (Fig. 8) and the annual and inter-annual variabilities are very small compared to the high resolution run. The high resolution experiment shows a distinct annual cycle with a strong maximum in June and July. This is similar to the climatic mean annual cycle, but the actual amount of rain is overestimated.

Several reasons can be related to this:

- the hydrological cycle is partly controlled by the large scale flow. Although the large scale flow in the regional model is strongly dominated by the prescribed large scale flow through

Table 4. 10 years total precipitation (P), evaporation (E) and P−E, all in mm/year, simulated with REMO driven by ECHAM4/T106; (a) Land points only, (b) over the Baltic Sea

a)

Year	Total precipitation	Evaporation	P−E
79	745	481	264
80	783	509	274
81	834	528	306
82	840	528	312
83	894	563	331
84	883	537	346
85	708	479	229
86	835	516	319
87	928	544	384
88	686	474	212
Mean	**814**	**516**	**298**

b)

Year	Total precipitation	Evaporation	P−E
79	560	307	253
80	676	418	258
81	761	565	196
82	699	465	234
83	731	519	212
84	730	513	217
85	594	373	221
86	767	467	300
87	721	364	357
88	584	552	32
Mean	**682**	**454**	**228**

Table 5. 10 year mean seasonal total precipitation (P), evaporation (E) and P−E, all in mm/3 months, simulated with REMO driven by ECHAM4/T106; (a) Land points only, (b) over the Baltic Sea

a)

	Total precipitation	Evaporation	P−E
Spring			
mean	210	168	42
max (y)	243 (87)	180 (84)	82 (87)
min (y)	179 (85)	157 (82)	15 (85)
Summer			
mean	256	268	−12
max (y)	342 (83)	303 (83)	39 (83)
min (y)	165 (79)	235 (85)	−72 (79)
Autumn			
mean	184	66	118
max (y)	216 (85)	78 (87)	148 (84)
min (y)	154 (86)	52 (85)	101 (83)
Winter			
mean	175	19	156
max (y)	210 (83)	23 (83)	187 (83)
min (y)	142 (79)	14 (79)	128 (79)

b)

	Total precipitation	Evaporation	P−E
Spring			
mean	151	33	118
max (y)	213 (81)	64 (83)	173 (81)
min (y)	117 (82)	13 (80)	76 (83)
Summer			
mean	124	64	60
max (y)	168 (83)	88 (84)	139 (87)
min (y)	55 (79)	25 (87)	−2 (79)
Autumn			
mean	201	199	2
max (y)	239 (81)	264.8 (81)	49 (79)
min (y)	167 (87)	138.9 (79)	−26 (81)
Winter			
mean	214	154	60
max (y)	273 (83)	183 (80)	115 (83)
min (y)	155 (84)	123 (79)	28 (87)

the lateral boundaries mesoscale circulations can develop inside the simulation domain due to a more detailed representation of the surface. These features can modulate the large scale flow inside the simulation domain and thus influences the hydrological cycle.

- the total amount of precipitation is strongly influenced by the moisture transport into the simulation domain. If the driving fields (here ECHAM4/T106) provide a continuous unrealistically high value of atmospheric moisture at the lateral boundaries, then the precipitation in the driven model will also be influenced.
- stronger vertical motion can be initiated by a more detailed orography and land surface representation and through the smaller grid sizes. This might trigger more precipitation.
- the applicability of the physical parameterisation package coming from the global model for a horizontal resolution of about 1° has to be questioned. The above mentioned results point to the need of scale dependent adjustment of the physical parameterisations for higher resolutions.

Table 4 shows the annual sums of precipitation (P), evaporation (E) and P−E for the high resolution experiment using REMO with ECHAM4/T106 data at the lateral boundaries. The driest year is 1988 with a total of 686 mm over land and the wettest one is 1987 with 928 mm. The 10 year mean water balance over land and sea is positive and sums up to 299 mm and 228 mm per year, respectively.

The seasonal variability of P−E is shown in Table 5. Over land P−E is positive in all seasons except summer, where evaporation excesses precipitation. The maximum is in winter. Over the Baltic Sea P−E is positive throughout the year, with a minimum in autumn and the maximum in spring. Figure 9 displays the mean annual cycle of P−E over land and water for ECHAM4/T106 and

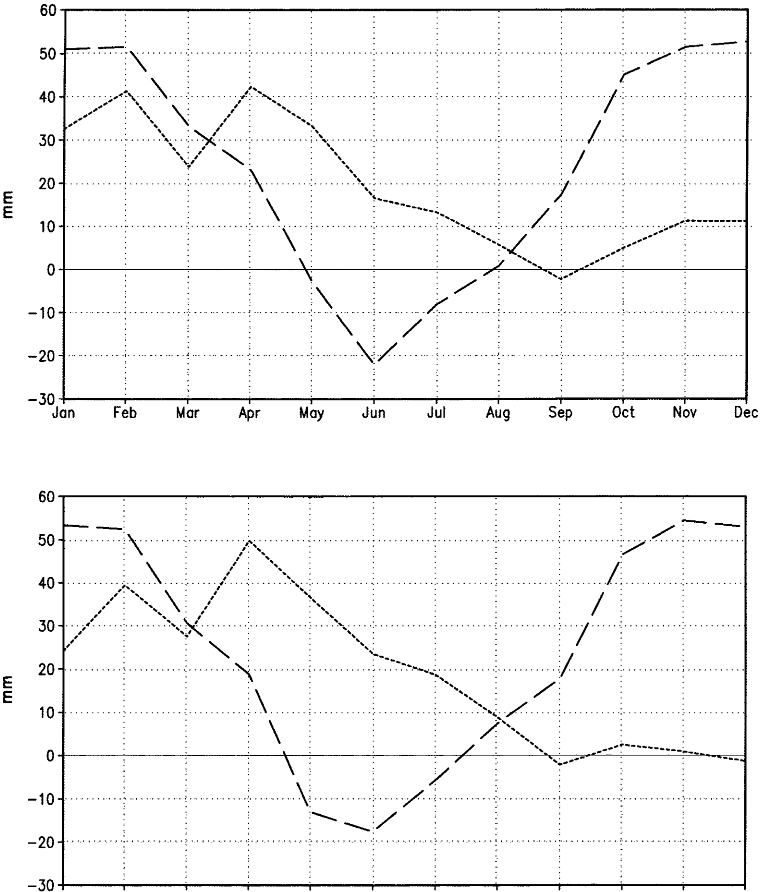


Fig. 9. 10 year mean annual cycle of P−E. Upper panel: ECHAM4/T106, lower panel: REMO driven by ECHAM4/T106. Short dashed: sea, long dashed: over land

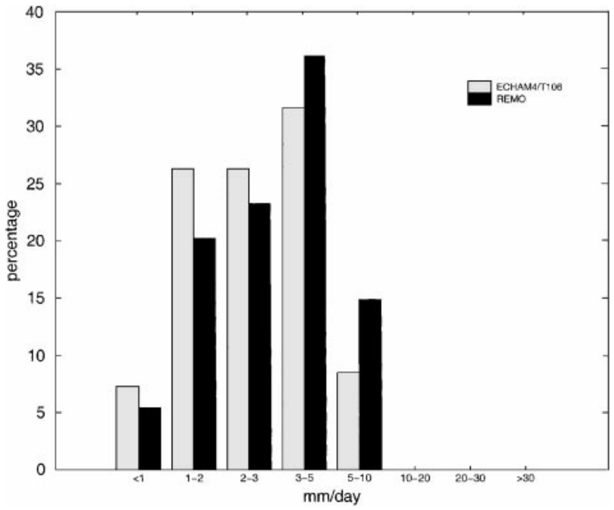


Fig. 10. Precipitation intensity in mm/d

REMO 0.5° resolution. The annual cycles are similar to each other, but REMO gives a wider range.

Another interesting aspect of the higher resolution is the difference in precipitation intensity. Fig. 10 shows the percentage of precipitation intensity classes of the annual sum of all land points in the Baltic Sea drainage basin. It can be seen that the lower resolution favours small precipitation intensities, while REMO contributes more in the classes of 3–5 mm/day and 5–10 mm/day due to stronger vertical motion initiated by more detailed surface information. This of course is a very coarse information due to the averaging over all land areas, but the same pattern is expected in subdomains.

It could be shown that the horizontal resolution of the simulating model has a major impact on the

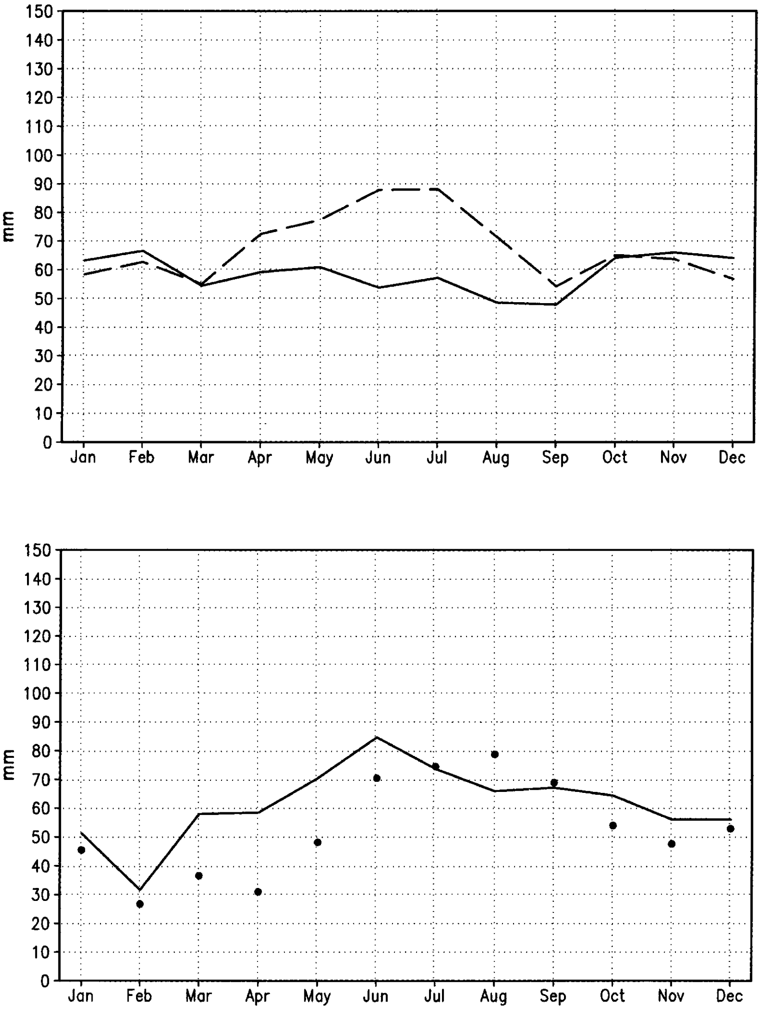


Fig. 11. Monthly mean precipitation in mm/month over land surfaces within the Baltic Sea drainage basin. Upper panel: ECHAM4/T106 (solid line) and REMO driven by ECHAM4/T106 (dashed line). Lower panel: Uncorrected observations (dots) and REMO driven by ECWMF re-analyses (solid line)

annual cycle of the water balance in the BALTEX area. However the results must be seen as preliminary. Further investigations concerning the physical parameterisations and more experiments are necessary to support the findings.

4. Conclusions

The annual and inter-annual variability of the water cycle over the Baltic Sea area has been studied using observations and climate models on different scales. It could be shown that the regional model REMO is able to reproduce the annual cycle and the inter-annual variability similar to observations. It can also be stated that the calculated water budgets are influenced by the horizontal resolution of the applied model. It is still unclear which physical processes are responsible. Further investigations focussing on special aspects of the physical parameterisation like convection, snowmelt and runoff generation are needed.

Looking again at the mean annual cycles of simulated and observed total precipitation over land areas in the Baltic Sea drainage basin for all experiments (Fig. 11) summarizes the major findings:

- the global model ECHAM4/T106 simulates the mean annual value satisfactory, but shows no annual cycle;
- REMO driven with ECHAM4/T106 data shows an annual cycle similar to observations, but overestimates the precipitation generally;
- REMO driven by ECMWF re-analyses gives realistic results for September to February, but overestimates the precipitation in spring and early summer.

Finally, it has to be mentioned that the discussed suite of climate simulations is not sufficient to give reliable answers. Ensemble studies to investigate the variability and coupled model simulations including atmospheric, oceanographical and hydrological modules are needed. They will provide a more complete picture of the total water budget over the Baltic Sea and its drainage basin. In addition to the model development more observational data are required. In order to identify compensating effects it is not sufficient to compare only some components of the hydrological cycle (e.g., precipitation and runoff). A long time series of the three-dimensional atmospheric moisture field could help identifying, whether the overestimation of precipitation is caused by too much available moisture or insufficient parameterisation of the micro-physical processes in clouds.

Note added in proof

Very recently an inconsistency between the fields of cloud liquid water, total cloud cover and radiation has been detected. First tests indicate that the correction of this inconsistency will lead to less warming in the summer months. A decrease in precipitation is also very likely. In general a small shift in all mean fields towards observations is expected.

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