Soil–Vegetation–Atmosphere Transfer Schemes and Large-Scale Hydrological Models (Proceedings of a symposium held during the Sixth IAHS Scientific Assembly at Maastricht, The Netherlands, July 2001). IAHS Publ. no. 270. 2001.

The representation of the seasonal hydrological cycle in a regional climate model in west Europe

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Abstract Soil moisture is key to adequate prediction of near surface temperature and humidity in climate models. To improve the performance of the hydrological cycle in a regional climate model (RACMO) a series of experiments was performed with one-dimensional land surface models. The starting point for these experiments was the ECMWF land surface model. Detailed comparison with a multi-layer process-based SVAT model, SWAP, showed particular sensitivity to the parameterization of soil hydraulic properties and rooting depth when compared with data. A new gridded soil map was produced for inclusion in the regional climate model. This map was used in a 3-D regional climate model RACMO. Comparison with the old parameterization of the model showed changes in the water balance that differed by region and were primarily determined by changes in saturated conductivity.

Key words west Europe; RACMO; hydrological cycle; climate model; soil hydraulic properties

INTRODUCTION

The hydrological cycle over land is governed by complex interactions between surface evaporation, cloud formation and precipitation. Soil moisture plays a key role in this context (e.g. Dirmeyer *et al.*, 1999). Considerable improvement in climate predictions is expected when the land surface hydrology is parameterized more realistically. Development of land surface schemes has generally followed the line of (a) incorporating more heterogeneity through a tile (mosaic) approach; (b) incorporating more realistic and adequate land surface classifications; (c) increasing the complexity of the description of surface exchange; (d) incorporation of more realistic soil parameters; and (e) increasing realism in the parameterization of snow and frost.

In this paper we will use the European Centre for Medium Range Weather Forecasting (ECMWF) land surface scheme in a three-dimensional (3-D) land and climate model (RACMO: the Regional Atmospheric Climate Model) to study the impact of new parameterizations of soil moisture. First we will describe the models used in this study. To unravel the complex interactions between the land surface and the atmosphere, we follow an approach where one-dimensional sensitivity studies are used to highlight particular problems in the land surface model. We achieve this by comparing the performance of the land surface model against that of a more complex description and against experimental data (Soet *et al.*, 2000). We then describe the new parameterizations and the production of a geographically varying map of soil hydraulic properties. Finally we describe the impact of this new parameterization in a simulation of European weather for 1995–1996.

MODEL DESCRIPTIONS

Three models are used in this study. The RACMO (ECMWF) land surface scheme (Viterbo & Beljaars, 1995), a detailed unsaturated zone model SWAPS (Ashby, 1999) and the three-dimensional atmospheric climate model RACMO.

The basic features of the ECMWF model are described in Viterbo & Beljaars (1995). There are four basic soil layers for which the differential equations for heat and water transport are solved. The thickness of the layers is based on the possibility of representing the relevant time scales. Thus, the thin, upper layer is influenced by short-term, diurnal fluctuations, while the lowest, thickest layer controls, to a large extent, the seasonal processes. Important for the water balance is the interception reservoir. This represents a thin layer of intercepted water on vegetation and soil that can be subsequently evaporated. A (virtual) skin layer that represents vegetation and litter on bare soil improves the parameterization of the surface heat balance. The top boundary conditions for the soil system are the net heat flux for the surface energy balance and the infiltration (precipitation minus surface runoff and evaporation from the interception layer) for the water balance. The bottom boundary condition for the water balance is the deep drainage from the bottom layer and the evaporation. A later version of this model is described as TESSEL and is more fully described in van den Hurk *et al.* (2000b).

The SWAPS model is a complex model to simulate the flow of water through the vegetation and unsaturated zone (Ashby, 1999). It can deal with various configurations of the canopy and uses a two-layer solution of the Penman-Monteith equation to describe the partitioning of the surface energy balance (Dolman, 1993). Flow of moisture in the soil is described by the 1-D Richards equation. Soil evaporation is modelled using a resistance formulation. Soil retention and conductivity are based on Mualem-van Genuchten curves.

The Regional Atmospheric Climate Model, RACMO, is a full three-dimensional limited area model that is derived from the physics of the Hamburg (MPI) climate model and is nested in ECMWF boundaries (Christensen *et al.*, 1996). The model has 19 layers in the vertical; the grid size is roughly 50 km. For the current simulations, the domain extended from the northern part of Africa to somewhat north of Scandinavia and from the Urals in the east to the Atlantic below Greenland to the west (see also Fig. 2).

ONE-DIMENSIONAL SENSITIVITY EXPERIMENTS

The objective of the 1-D studies (Soet *et al.*, 2000) was to test the performance of the RACMO land surface model (LSM) for realistic field situations, to identify the main causes of disagreement of model results with observations and to point the way to further improvements. The focus hereby was on the soil hydrology of the model. Data against which to assess the model performance were selected from the 1986 HAPEX-Mobilhy experiment in southern France, the 1992 HAPEX-Sahel experiment in Niger and from the Hupselse Beek, The Netherlands from 1982. Land surface cover for these three experiments consisted of soybean on a loamy soil, savannah on sand and pasture on sand, respectively. These datasets were chosen to represent a wide range of climatic, soil and land cover conditions. We show here the results of the two HAPEX sites only.

In the ECMWF and RACMO models, single, globally applicable uniform parameters were used until recently to describe the soil and vegetation. The first test was to see how well (or badly) this represents the real situation. Long-term evaporation in the RACMO LSM was systematically underestimated when single, generally applicable parameters were used. At the HAPEX-Mobilhy site, the underestimation could be attributed to a poor representation of the bare soil evaporation, and at the HAPEX-Sahel site, the simulated transpiration decreased too rapidly after the rains had ceased to supply the soil with moisture (Soet *et al.*, 2000). Using site-specific parameters generally improved the simulation. This is shown in Fig. 1(a) and (b) for the cases of HAPEX-Mobilhy and HAPEX-Sahel, respectively.

The sign of the differences between the observations and the results from the complex model SWAPS for surface runoff, percolation and evaporation is not the same. For the HAPEX-Mobilhy site the percolation was too high compared with SWAPS and the surface runoff too low (Fig. 1(a)). At the HAPEX-Sahel site the percolation was too high (Fig. 1(b)). The situation at the Hupselse Beek was complicated because the site has a non-negligible impact of groundwater recharge. This is not simulated at all in the RACMO LSM.

To separate the effects of changes in parameters, a sensitivity test was performed where stepwise new parameters or parameterizations were introduced. These cases are described in Table 1. In the standard runs with RACMO the Clapp & Hornberger (1978) conductivities are used. A first step was to introduce the Mualem-van Genuchten (van Genuchten, 1980) relationships for retention and conductivity (case A). The other cases refer to evaporation and the partitioning between soil and canopy (case B) and to rooting depth, determining the availability of soil moisture (case C).

The results are shown in Fig. 1(a) and (b) for the HAPEX-Mobilhy and HAPEX-Sahel sites. Details can be found in Soet *et al.* (2000). Case A for HAPEX-Mobilhy significantly affects surface runoff and percolation. As expected, case B primarily

Table 1 RACMO model cases with site-specific parameters used in the sensitivity study.

Case	Site-specific parameters
A	Soil hydraulic properties (Mualem-van Genuchten)
B	*Rs*min and *LAI*
C	Rooting depth and distribution
AB	A and B
AC	A and C
BC	B and C
ABC	A, B and C
ESM	Soil hydraulic properties from HYPRES database

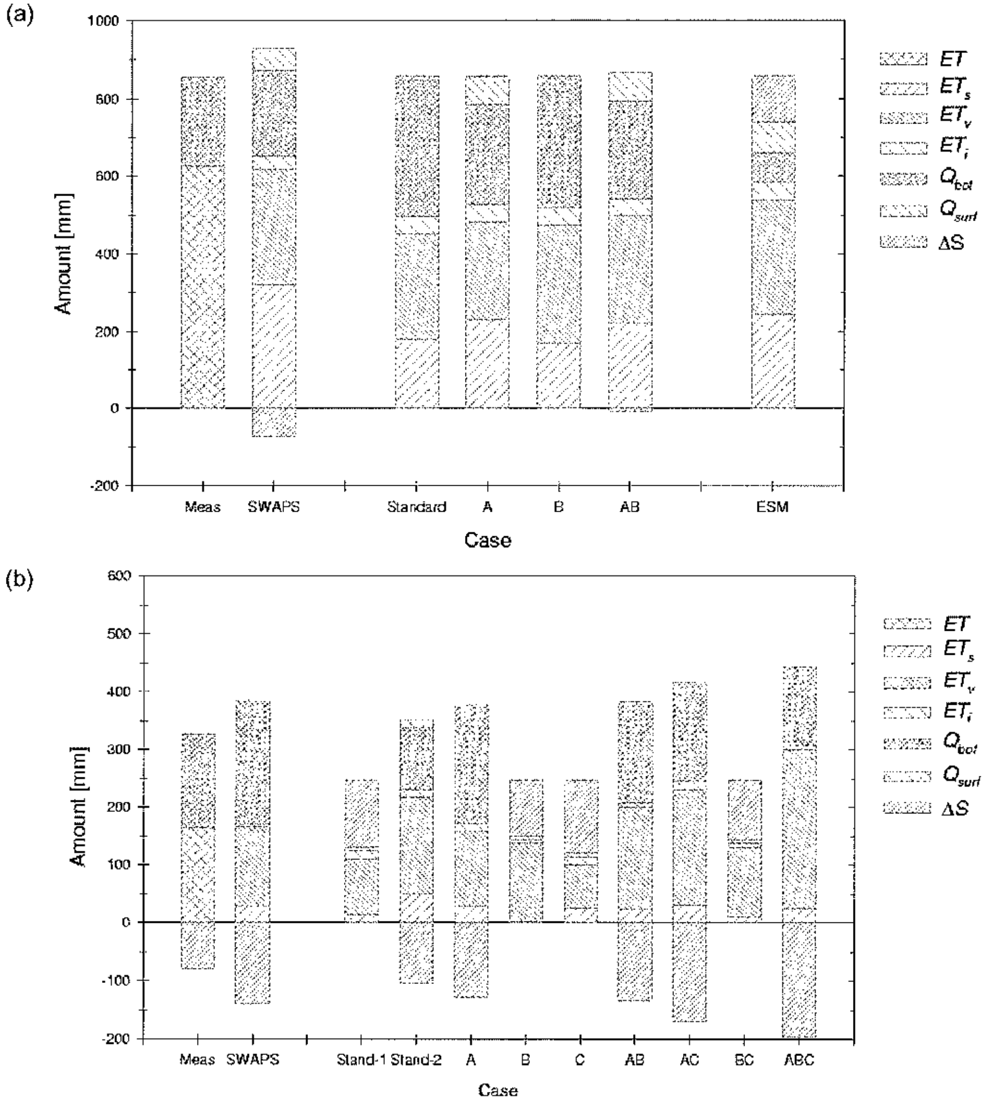

Fig. 1 Annual water budgets from the RACMO-LSM, SWAPS, and observations for (a) HAPEX-Mobilhy and (b) for a two month period during HAPEX-Sahel. Capital letters indicate sensitivity study results (Table 1). ET = total evaporation, ET_s = soil evaporation, ET_v = transpiration (evaporation from a dry canopy), Q_{bot} = drainage at bottom of profile, Q_{surf} = surface runoff, ΔS = change in soil moisture storage.

affects transpiration that increases. In the HAPEX-Sahel case A, the improvement in percolation is dramatic. The combined cases appear to be supplementary in the Sahel. This is not the case in HAPEX-Mobilhy (compare AB with A and B, respectively). The overall results of the sensitivity analysis indicate that the introduction of site-specific parameters has a considerable impact on the water budgets simulated by the RACMO LSM. Consequently there is a need to improve the representation of the soils in RACMO from a single representative value to a spatially varying one.

A NEW SOIL MAP

The Hydraulic Properties of European Soils (HYPRES) database allows the introduction into RACMO of the more physically realistic Mualem-van Genuchten parameters. HYPRES (Wösten *et al.*, 1999) supplies these parameters for five topsoil and subsoil classes of the FAO soil texture classification. In Fig. 1(a) and (b) the effects of using these curves is also indicated for the HAPEX-Sahel and HAPEX-Mobilhy sites (case ESM).

The HYPRES database was used with the FAO soil map to produce a map for five soil types: coarse, medium, medium fine, fine, very fine and histosol. These soil classes were assigned typical retention and conductivity curves based on the HYPRES database. Figure 2 shows the resulting soil map as it is projected on the RACMO model domain.

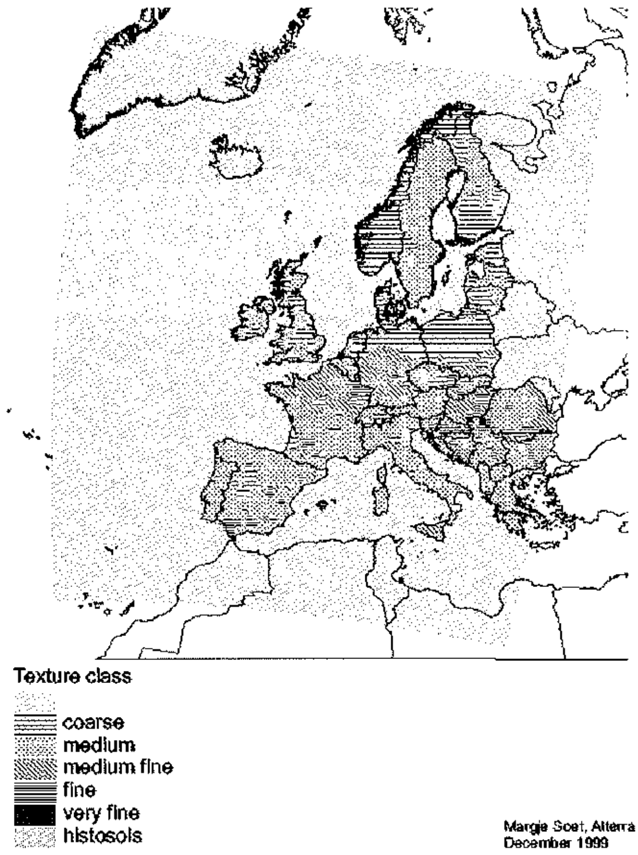

Fig. 2 Map of soil texture used in RACMO.

THREE-DIMENSIONAL SENSITIVITY STUDIES

With the new soil map, 3-D simulations were performed to assess the impact of the new soil parameterization in RACMO. For this the new ECMWF scheme, TESSEL (van den Hurk *et al.*, 2000b) was used. We expected that the improvement in the soil parameterizations and values for the parameters would affect precipitation, evaporation and soil moisture, in specific regions, where the new values would differ considerably from the old global values and might, as a result, improve the skill of the model in predicting temperature and relative humidity near the surface, because of a change in surface energy partitioning.

Table 2 summarizes the main conclusions from this study. Overall there appears to be little change in precipitation in Europe as compared with the old run where a non-variable soil map was used. The difference for Europe as whole is in the partitioning of rainfall into evaporation and runoff. There is less water available for runoff in the new run and consequently there is more water available for transpiration and soil evaporation.

When looking at specific regions, the effect of the incorporation of the new parameterization becomes more apparent (Table 2). For coarse soils, where the saturated conductivity of the new parameterization is larger than that of the old one, runoff

Table 2 The changes resulting from the implementation of the variable soil map, based on Mualem-van Genuchten parameterization, in comparison to the non-variable soil map based on Clapp & Hornberger parameterization.

	Area	Climate type	Soil water balance	General conclusions
Europe (total)	0	-	More precipitation and evapotranspiration in summer. More surface runoff and less deep runoff.	Small hydraulic conductivity (*k*) and large soil water storage leads to more continental evapotranspiration and precipitation in summer. *RH* and *T* confirm this.
Coarse	1 Norway	Oceanic/Sub-arctic (wet)	More deep runoff and less evapotranspiration in summer	In wet conditions, *k* is larger than the Clapp & Hornberger soil. This leads to less evapotranspiration and more runoff. Model error for *RH* and *T* does not decrease much however.
	2 Poland	Continental (dry)	More precipitation in summer, and little more evapotranspiration. More deep runoff in wet conditions.	
Medium	3 Sweden	Sub-arctic (wet)	No important changes in precipitation and evapotranspiration. More surface runoff in spring, less water storage in soil and thus less deep runoff in summer.	More soil water storage capacity and smaller *k* results in intensification of the mainland circulation of evapotranspiration and (particularly convective) precipitation.
	4 Spain	Mediterranean (dry)	Less deep runoff in winter and significantly more evapotranspiration in summer.	Annual amplitude of soil water content in the upper soil layers with highest plant root density has increased. Deep runoff decreases, but frequency of surface runoff increases. Enhanced *RH* and lowered *T* for area 5 support the increase of evapotranspiration.
Medium-Fine	5 France/ Germany	Altered Oceanic	More convective precipitation and evapotranspiration in summer. More deep runoff at field capacity, as hydraulic conductivity is relatively large.	
Fine + Very Fine	6 Hungary	Continental	Slightly increased summer evapotranspiration and surface runoff.	Too few data for reliable analysis. Lower hydraulic conductivity and increased storage cause probably more surface runoff and evapotranspiration.
Histosols	7 UK/ Ireland	Oceanic	Evidence for more evapotranspiration and less deep runoff in summer.	

increases and evaporation decreases. This effect is most pronounced in wet climates. Where the reverse is true and saturated conductivity reduced, the percolation decreases by a marginal amount, or stays the same; surface runoff decreases and evaporation and convective precipitation both increase. Relative humidity (*RH*) and near-surface temperature (*T*) were also used to assess the skill of the model, but the results were less conclusive than for the water budgets. Relative humidity increases and temperature decreases in summer as a result of the changes in the soil parameterizations. The average and random model error decreases slightly, particularly in summer.

DISCUSSION AND CONCLUSIONS

To elucidate the main mechanisms behind the interaction of the land surface and the atmosphere, we adopted a stepwise approach whereby improvements in 1-D models are first tested against observations and detailed models, and secondly incorporated in a 3-D atmospheric model. An important step in this is the production of regionally varying fields of parameters.

The variable soil map, based on Mualem-van Genuchten parameterization, caused shifts in the modelled precipitation, runoff and change of soil water storage, although they are small. This depended primarily on a simple division between coarse soil types and all other fine soil types. Coarse soils have relatively large hydraulic conductivity and low evaporation in summer, compared to the Clapp & Hornberger soil type. The other finer soil types have relatively small hydraulic conductivity and large soil water storage capacity, which leads to higher evaporation and precipitation on the European mainland in summer.

The overall effects of the incorporation of a new soil parameterization in Europe are small, but, in particular regions, more substantial. These effects were obtained using a limited area version of a climate model. Van den Hurk *et al.* (2000a) showed that the impact of the land surface on the atmosphere for such a model in Europe depends on the relative strength of the land surface *vs* the advective forcing. Hence improvement in precipitation estimates is likely to be obtained primarily for summer convective conditions and less for frontal precipitation. The present results are in rough agreement with this.

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