Representation of the seasonal hydrological cycle in climate and weather prediction models in west Europe.

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Introduction

The hydrological cycle over land is governed by complex interactions between surface evaporation, hydrology, precipitation, cloud formation and large scale circulation. The most important of these interactions are shown in Figure 1. For the purpose of this paper it is sufficient to identify the two major feedback loops: a diurnal one and a seasonal one. The diurnal loop represents feedback processes between the vegetation, planetary boundary layer and the atmosphere. The seasonal loop represents the longer term memory of the system through the soil water reservoir. Since many of these interactions are non-linear, accurate

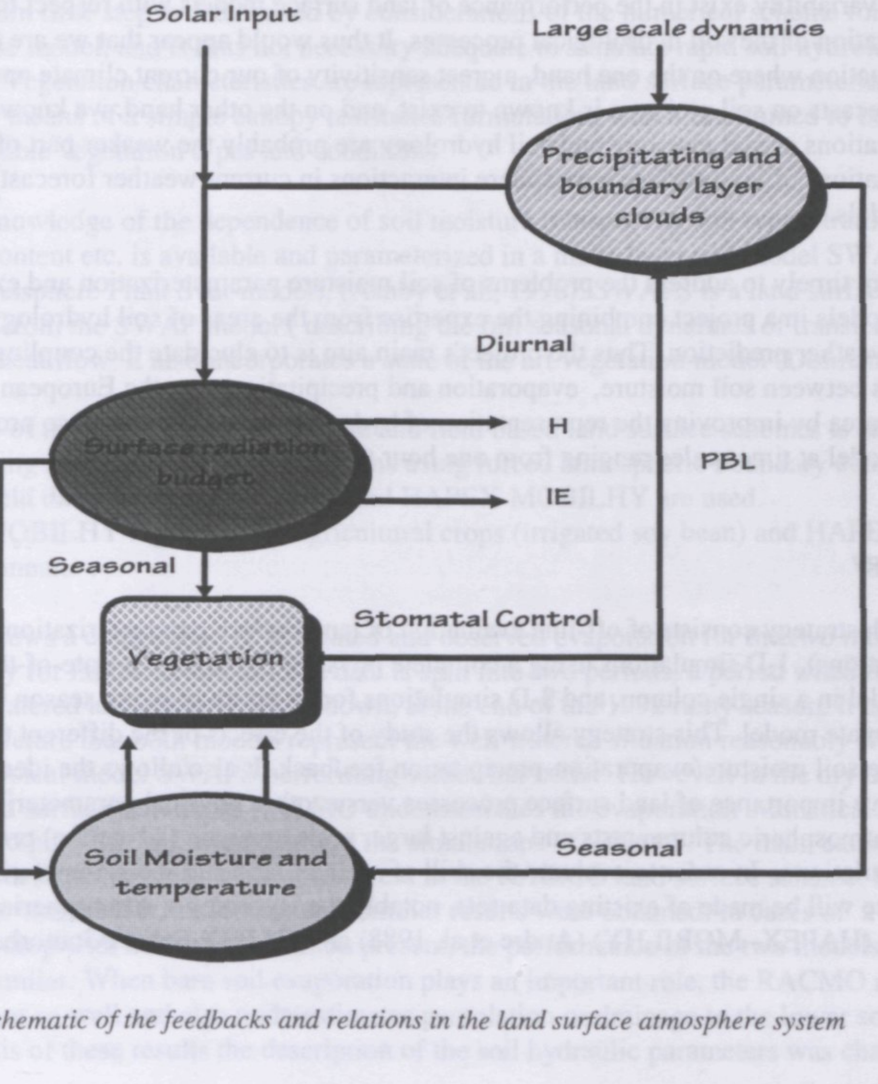

Figure 1. Schematic of the feedbacks and relations in the land surface atmosphere system

predictions of present and future weather and climate depend critically on the parameterizations of the hydrological cycle which affect both the diurnal and seasonal interactive feedback loops. (Milly and Dunne, 1994; Garratt, 1993). From this figure it is also clear that ultimately the effect of a possible change in a parameterization can only be assessed in a full 3-D climate of Numerical Weather Prediction models (NWPM's), as only here all feedback loops are present, from and surface to clouds, precipitation and large scale forcing.

Several studies with numerical weather prediction models (Betts et al., 1996) and climate models (Milly and Dunne, 1994) have shown that the initialization of soil moisture fields in NWPMs and General Circulation Models (GCM's) can have a large impact on the land surface hydrology and climate of the model. Recently, the need to realistically simulate anomalously dry or wet seasons has led to the replacement of climatological soil moisture fields by more sophisticated physical and prognostic treatments of soil hydrological parameters A new land surface parameterization scheme (Viterbo and Beljaars, 1995) was recently introduced in the global NWPM of the European Centre for Medium-range Weather Forecasts (ECMWF). The replacement of old soil moisture schemes takes place in parallel to the replacement of "old" vegetation models with increasingly complex descriptions of vegetation atmosphere interactions. However, the incorporation of more physically based soil parameterizations had also led models to drift towards very dry climates (Viterbo and Courtier, 1995).

Furthermore, studies in the context of the Project for Intercomparison of Land Surface Parameterization Schemes (PILPS), (Henderson-Sellers, 1996, Shao et al., 1996) have shown that a great variability exist in the performance of land surface models with respect to the parameterization of the soil hydrological processes. It thus would appear that we are faced with the situation where on the one hand, a great sensitivity of our current climate and weather forecasts on soil moisture is known to exist, and on the other hand, we know that the parameterizations of soil moisture and soil hydrology are probably the weaker part of the parameterizations of land surface atmosphere interactions in current weather forecast and climate models.

It is therefore timely to address the problems of soil moisture parameterization and excessive drying in models in a project combining the expertise from the areas of soil hydrology and numerical weather prediction. Thus the project's main aim is to elucidate the coupling mechanisms between soil moisture, evaporation and precipitation over the European continental area by improving the representation of hydrological and land surface processes in a climate model at time scales ranging from one hour to a full season.

Methodology

The research strategy consists of off-line evaluation of land surface parameterization schemes (0-D simulations), 1-D simulations using a complete physical package of a state-of-the-art climate model in a single column, and 3-D simulations for an entire growing season using a regional climate model. This strategy allows the study of the effects of the different time scales on the soil moisture/evaporation-precipitation feedback. It also allows the identification of the relative importance of land surface processes versus other physical parameterizations in 1-D single atmospheric column tests and against larger scale synoptic (advective) processes in the 3-D simulations. In order to evaluate the skill of current land surface parameterization schemes, use will be made of existing data sets, notably the Hydrologic Atmospheric Pilot Experiment (HAPEX--MOBILHY) (Andre et al, 1988) and HAPEX-Sahel (Goutorbe et al., 1997).

The approach is aimed at upgrading the soil moisture parameterization in a state of the art regional climate model, (Regional Atmospheric Climate Model, RACMO) and testing the effect of new implementations on the continental West-European Climate. RACMO is a regional weather prediction model with a physical package from the ECHAM4 climate model from the Max Planck Institute in Hamburg (Christensen and van Meijgaard,1992). We use the routinely used surface parameterization of the ECMWF model as a starting point for analysis and improvement. The research approach follows the complete trajectory from 0-D to full 3-D simulations; this allows assessment of various aspects of soil moisture parameterizations in NWPMs and GCMs.

1-Dimensional studies

The current land surface parameterization scheme of the ECMWF/RACMO models (Viterbo and Beljaars, 1995) contains a layered soil transport scheme with respect to both water and heat. The representation of the hydrological processes in the scheme is based on physical hydrological transport laws. It is designed to represent accurately the time scales involved with soil hydrological transport, varying from the model time step (typically 5 minutes) to the seasonal time scale. It treats soil moisture in a prognostic mode. As such, it is capable of adding predictability to the weather forecast owing to the intrinsic memory captured in the simulated development of the soil moisture reservoir. The scheme may be regarded as a state-of-the-art implementation of soil hydrology in weather prediction and climate models. However, the scheme is necessarily confined to a relatively coarse vertical resolution (4 layers), and does not include any horizontal differentiation of soil types or layer depths. Also, the minimum time step is determined by considerations of the numerical scheme for the atmospheric model, and is thus not necessary adequate to simulate rapid soil hydrological processes. Vegetation characteristics are represented in the land surface parameterization scheme by means of a simple canopy resistance formulation, which is assumed to be uniform for all possible vegetation types and conditions.

Detailed knowledge of the dependence of soil moisture transport on soil type, stratification, moisture content etc. is available and parameterized in a multi-layer soil model SWAPS (Soil Water Atmosphere Plant Svat-model), (Ashby et al., 1996). SWAPS is a land surface model developed from the SWAP model (describing the full seasonal dynamics of transient soil water and heat flow. It also incorporates a state of the art vegetation model (Dolman, 1993).

Evaluation of the skill of both the climate and field based land surface schemes is carried out by comparing model results to observations using forced atmospheric boundary conditions. For this, field data from HAPEX-Sahel and HAPEX-MOBILHY are used. HAPEX-MOBILHY represents an agricultural crops (irrigated soy bean) and HAPEX-Sahel a fallow savannah.

Figure 2 shows a comparison of simulated and observed evaporation for the two models used in this study for fallow savannah. The data is split into two periods: a period when the soil was well watered and a period of dry down, at the end of the 1992 rainy season. It is clear from this picture that both models represent the well watered situation reasonably well, with the full physical model SWAPS performing somewhat better. However, in the dry down the current land surface scheme of RACMO underestimates the evaporation dramatically compared to both the measurements and the simulations of SWAPS. The main cause for this is the parameterization of soil moisture stress in the RACMO land surface scheme. In a comparison with HAPEX-Mobilhy data similar results were obtained: in cases of a fully developed crop with no water limitation present, the performance of the two models is good and very similar. When bare soil evaporation plays an important role, the RACMO model performs not so well and also underestimates percolation or drainage to the lower soil layers. On the basis of these results the description of the soil hydraulic parameters was changed from the original Clapp and Hornberger to the more physically realistic Mualem-van Genuchten description (van Genuchten, 1980).

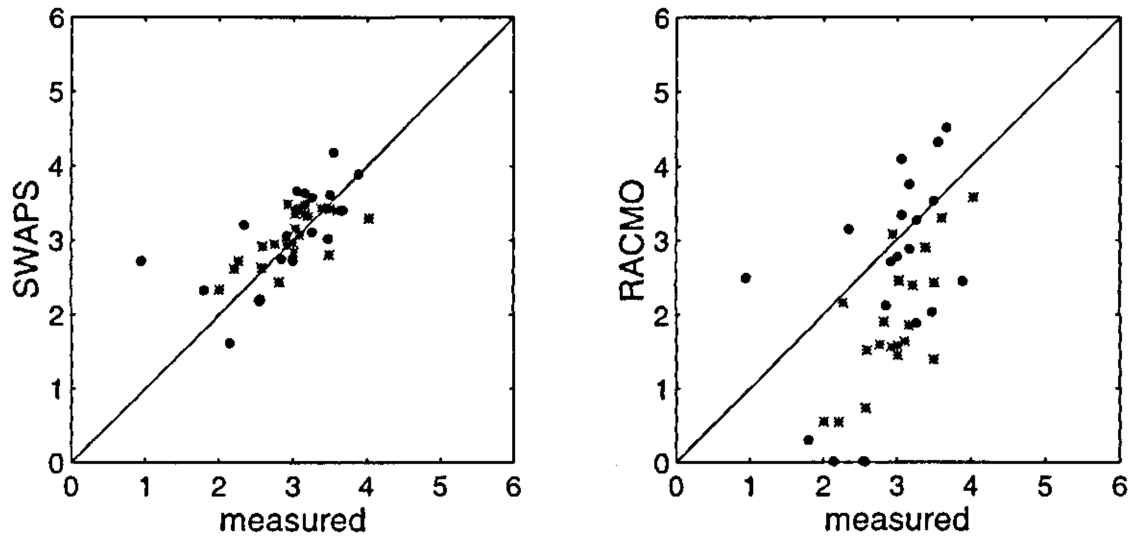

Figure 2. Comparison of estimated evaporation of RACMO and SWAPS with measured evaporation for a fallow savannah for well watered (closed circles) and dry conditions (asterisks).

3-Dimensional studies

A series of 48-hour runs has been executed with RACMO for the period of 1 March till 15 November 1995 for Europe. Figure 3 shows the temperature bias (modelled-observed) of three runs with differing boundary conditions. The daily restart run is a simulation where the boundary conditions of the model are updated daily from the large scale weather analysis of ECMWF, sea surface temperatures are also updated daily in this run. The climate run is a run where the model is let free with boundary conditions updated only at the ten most exterior grid points of the domain and the sea surface temperatures follow a climatological field. The run called analysed sst is similar to the climate run, except that the seas surface temperatures are now also updated daily.

The figure shows that in the climate run the model predicts too low temperatures, by almost 3.5^0 in October. The two other cases show a positive bias, indicating that the model is too warm. In these two cases positive biases start around spring and point to the drying phenomena as observed by Viterbo and Coutier (1995). Soil moisture dries out too quickly in spring and leads to a change in energy partitioning and increases in surface air temperatures.

There are similar changes in specific humidity with the model underestimating the surface humidity.
In Europe the weather is dominated strongly by advection from the Ocean and the results obtained by changing the forcing of the sea surface temperature underline this point dramatically. However, the sign and strength of the bias in the climate run with climatological sst's suggests that a feedback may be occurring in the model which tends to enhance the cooling trend initiated in the spring of 1995 in this simulation. The physical processes responsible for this need to be investigated more closely.

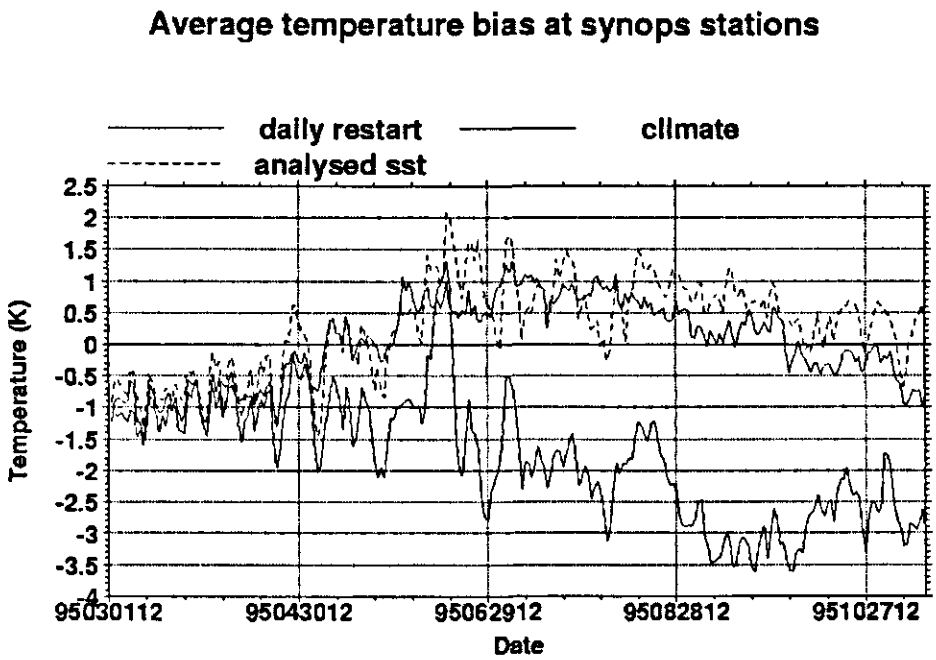

Figure 3. Temperature bias (simulated-observed) for all land point in RACMO simulation of Europe in 1995. Detail of the runs are explained in the text

Discussion and conclusions

The single soil and surface type currently used in the ECMWF model probably does not adequately represent the spatial variability in both soil and land use parameters in Europe. There is thus a need to introduce horizontal variability in soil and vegetation properties in the scheme. Information on the horizontal variability of soil types on the resolution of the RACMO model (50 km) is available for the European area (van Dam et al, 1995). This information will be used to represent horizontal variability of land cover in Europe, by extracting relevant parameters for the land surface scheme for appropriate land use and soil types. This will be done for the Mualem-van Genuchten parameter set and will involve scaling high resolution soil type information to the size of the RACMO gridboxes with existing or newly developed aggregation rules (Kabat et al., 1997).

Similar studies to investigate the effect of two contrasting land surface types in a single grid box are underway and use a slab model for the atmospheric boundary layer. Such situations where existing aggregation rules (Dolman and Blyth, 1997) fail, are lakes in a vegetated environment or melting snow in patches of rock and vegetation. In these cases effective parameters cannot be defined because they would yield negative diffusion coefficients as a result of the apparent counter gradient fluxes occurring at the scale of the boundary layer. The use of a tile or mosaic approach is currently investigated to solve this problem.

Furthermore, the impact of these modifications on the simulated interaction between the land surface and the overlying atmosphere is evaluated by incorporating and testing the newly derived parameterizations in a 1-D model atmospheric model. The emphasis in this study is on the diurnal time scale. An improved understanding of this interaction for different land surface types is an essential link between the implementation of sophisticated parameterizations and the operational use of these in a full 3D climate model context. For this, a one-dimensional version of the regional climate model RACMO is used (Christensen and van Meijgaard, 1995).

The results obtained in the RACMO modelling suggest that further analysis is needed to determine the relative strength of oceanic versus land surface forcing. However with improvements in the surface scheme and the incorporation of spatial heterogeneity, some of the dry bias may be removed.

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