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Land surface scheme conceptualisation and parameter values for three sites with contrasting soils and climate

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Abstract

The objective of the present study is to test the performance of the ECMWF land surface module (LSM) developed by Viterbo and Beljaars (1995) and to identify primary future adjustments, focusing on the hydrological components. This was achieved by comparing off-line simulations against observations and a detailed state-of-the-art model over a range of experimental conditions. Results showed that the standard LSM, which uses fixed vegetation and soil parameter values, systematically underestimated evapotranspiration, partly due to underestimating bare soil evaporation, which appeared to be a conceptual problem. In dry summer conditions, transpiration was seriously underestimated. The bias in surface runoff and percolation was not of the same sign for all three locations. A sensitivity analysis, set up to explore the impact of using standard parameter values, found that implementing site specific soil hydraulic properties had a significant effect on runoff and percolation at all three sites. Evapotranspiration, however, was affected only slightly at the temperate humid climate sites. Under semi-arid conditions, introducing site specific soil hydraulic properties plus a realistic rooting depth improved simulation results considerably. Future adjustments to the standard LSM should focus on parameter values of soil hydraulic functions and rooting depths and, conceptually, on the bare soil evaporation parameterisation and the soil bottom boundary condition. Implications of changing soil hydraulic properties for future large-scale simulations were explored briefly. For Europe, soil data requirements can be fulfilled partly by the recent data base HYPRES. Sandy and loamy sand soils will then cover about 65% of Europe, whereas in the present model 100% of the area is loam. © 2000 European Geophysical Society

Keywords: land surface model; soil hydraulic properties; water balance simulation

Introduction

At the land surface–atmosphere interface complex interactions and feedbacks determine the exchanges of water and energy. On a seasonal time scale, this includes the ability of land surfaces to store and transmit precipitation and to release water to the atmosphere at a later stage via evapotranspiration. As reviewed by Mintz (1984) and Garratt (1993) amongst others, these land–atmosphere processes have a significant impact on climates simulated by General Circulation Models (GCMs). The sensitivity to water storage capacity of the land and consequent feedback mechanisms can affect simulations of future climate, for instance the summer dryness predicted for increasing levels of atmospheric greenhouse gases may be counteracted by an increase of available water through deeper plant rooting systems (Milly, 1997).

Present-day GCMs apply a wide variety of land surface modules (LSMs) (see e.g. Rowntree, 1988, Avissar, 1995 and Shao and Henderson-Sellers, 1996). In the past decades increasingly detailed physically based approaches were introduced in LSMs to improve long term predictions. These detailed LSMs explicitly specify vegetation and soil layers where transpiration is mostly parameterised by the concept of a canopy resistance as a measure of moisture transfer efficiency. Moisture fluxes between soil layers are often computed by a diffusion type approach. The majority of these schemes consider the soil and the land surface to cover a grid element of the atmospheric model homogeneously. Both, therefore, should effectively represent the subgrid scale variability of land surface processes.

Off-line comparisons of different LSMs were performed within the framework of the Project for Intercomparison of Land surface Parameterization Schemes PILPS (Shao and Henderson-Sellers, 1996). Results showed that under identical meteorological forcing simulated annual runoff, drainage and evapotranspiration may differ significantly. In a further analysis of these results, Koster and Milly (1997) inferred that the soil moisture control is a critical LSM feature. Dooge *et al.* (1994) also found significant differences between annual water budget terms simulated by different LSMs; their preliminary conclusion was that the most critical factors responsible for these differences were soil column depth and treatment of the lower boundary condition.

This paper analyses one particular LSM which was developed for the ECMWF (European Centre for Medium-Range Weather Forecasts) atmospheric model (Viterbo and Beljaars, 1995). This scheme is also implemented in the Regional Atmospheric Climate Model (RACMO) used at the Royal Netherlands Meteorological Institute KNMI. After the implementation of this LSM, longer term precipitation forecasts with the ECMWF model improved significantly for a heavy rain period over the USA (Betts *et al.*, 1996). However, both atmospheric models produce a systematic dry warm bias in spring over the European continent. Recent studies for the Baltic Sea basin using RACMO showed additionally that runoff is seriously underestimated (pers. comm. Van den Hurk, KNMI). Presumably LSM behaviour and consequent land surface–atmosphere interactions play a significant role in both the dry bias and runoff underestimation. Therefore, a framework was developed to assess the realism of the current land surface and hydrology parameterisation in a sequence from 1-dimensional off-line to 3-dimensional coupled LSM–atmospheric model simulations. Here the off-line 1-D study is presented i.e. vertical fluxes of energy and water near the surface and in the soil are modelled but not the atmosphere. The objective is to analyse LSM performance for different conditions, to identify primary research items for 3-D modelling experiments. Since results indicate that soil hydraulic properties are such items, the impact of introducing multiple soil types for Europe was explored briefly.

Model and data sets description

STANDARD RACMO LAND SURFACE MODULE

Land surface processes in RACMO are parameterised according to the ECMWF scheme (Viterbo and Beljaars, 1995), the main concepts of which are common to several atmospheric model land surface parameterisations. In each grid cell of the atmospheric model, the land surface is characterized by a skin layer which represents vegetation, an interception reservoir and bare soil, overlying a 2.9 m deep soil column. Soil and vegetation characteristics are identical for all grid cells; hence fixed standard parameter values are used. The typical horizontal resolution of the atmospheric model is 50 km.

The LSM applies the 'big leaf' concept, solving the energy balance at the surface for a homogeneous isothermal cover:

$$(1-a)SW_{\downarrow} + LW_{\downarrow} - LW_{\uparrow} - G = H + \lambda E \qquad (1)$$

with SW and LW (Wm^{-2}) short and long wave radiation ($\downarrow$ and $\uparrow$ incoming and outgoing), a albedo and H, λE and G (Wm^{-2}) sensible, latent and soil heat flux densities. For evaporation calculations, vegetation, bare soil and an interception reservoir are distinguished. The total latent heat flux density for a grid cell λE is calculated as the weighted sum of evaporation from these different cover types. The latent heat flux density from dry vegetation λE_v is specified using a canopy resistance r_c (s m^{-1}) (Fig. 1a). This resistance is defined by the minimum stomatal resistance for a single leaf $r_{s\min}$ (s m^{-1}), leaf area index LAI (m^2 m^{-2}) and bio-physical stress functions for averaged root zone soil moisture $\overline{\theta}$ (m^{3}m^{-3}) and photosynthetic active radiation PAR (Wm^{-2}):

$$r_c = \frac{r_{s\min}}{LAI} f(\overline{\theta})^{-1} f(PAR)^{-1} \qquad (2a)$$

$$f(\overline{\theta})^{-1} = \frac{\overline{\theta} - \theta_{wp}}{\theta_{fc} - \theta_{wp}} \qquad (2b)$$

with θ_{fc} and θ_{wp} (m^3 m^{-3}) soil moisture content at field capacity and wilting point. The average moisture content in the root zone is calculated as $\overline{\theta} = \sum_{i=1}^{4} R_i \theta_i$ with R the fraction of roots in soil compartment i. Bare soil evaporation λE_s is parameterised as a bulk transfer of water vapour between the roughness length for moisture transfer z_{0q} (m) and the atmospheric reference level z_{ref}. The relative humidity α at z_{0q} is a function of θ_1/θ_{fc} where θ_1 is top soil layer moisture content. In Fig. 1, λE_i is interception reservoir evaporation, z_{0m} (m) and d_m (m) are roughness length and displacement height for momentum, h (m) is vegetation height and q (kg kg^{-1}) and e (hPa) are specific humidity and vapour pressure at different levels, with subscript sat indicating saturation value.

Soil water flow is described by the diffusivity form of the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D(\theta)\frac{\partial \theta}{\partial z} + k(\theta)\right) - U(z) \qquad (3)$$

where sink term U (s^{-1}) represents root water uptake, t (s) is time and z (m) is positive upwards. Hydraulic conductivity $k(\theta)$ (m s^{-1}) and soil water diffusivity $D(\theta)$ (m^2 s^{-1}) are specified by the Clapp and Hornberger (1978) relationships with parameter values for a standard loam soil. Surface runoff is generated when the maximum infiltration capacity is exceeded or when the soil becomes saturated. The flow rate at the lower boundary is calculated as free drainage. The model specifies four soil compartments of 7, 21, 72 and 189 cm depth with an equal percentage of roots in the upper 3 layers.

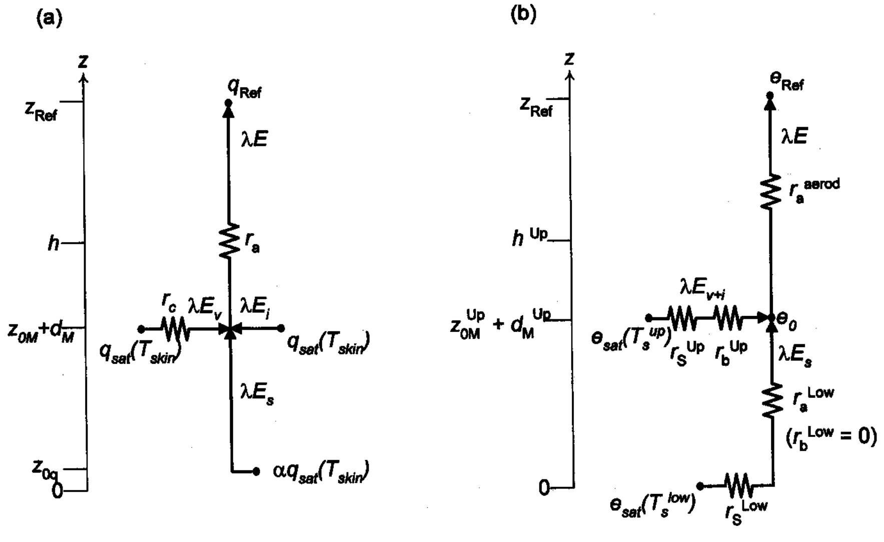

Fig. 1. *Schematic resistance schemes for latent heat flux calculations. (a) RACMO applies a bulk transfer scheme based on skin layer* q_{sat} *and reference level q-value. (b) SWAPS explicitly uses in-canopy vapour pressure* e_0 *and surface temperatures* T_s^{up} *and* T_s^{low} *for upper and lower layer.*

DETAILED SOIL-VEGETATION MODEL SWAPS

In addition to the data sets, results generated by a complex multi-layered LSM were used in the analysis. This model SWAPS (Fig. 1b) was described in detail by Ashby (1999). The surface energy balance is modelled by two separate surface layers, in this study an upper vegetation layer and a lower bare soil layer were used.

The energy balance (1) is solved for each surface layer using meteorological forcing data at a single reference height z_{ref} located above both surfaces. The latent heat flux density for each layer is specified by the Penman-Monteith equation:

$$\lambda E = \frac{\Delta A + \rho c_p \delta e/(r_a + r_b)}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a + r_b}\right)} \qquad (4)$$

with Δ (hPa K^{-1}) gradient of saturation vapour pressure versus temperature, A (W m^{-2}) available energy, ρ (kg m^{-3}) dry air density, c_p (J kg^{-1} K^{-1}) specific heat of air, δe (hPa) vapour pressure deficit, γ (hPa K^{-1}) psychrometric 'constant' and r_a, r_b and r_s (s m^{-1}) aerodynamic, viscous boundary layer and surface resistance. For dry vegetation, the surface resistance is specified in terms of a minimum resistance and bio-physical stress functions $f(X)$:

$$r_s = r_{s\min} f(LAI)^{-1} f(SW_{\downarrow})^{-1} f(\theta)^{-1} f(\delta e)^{-1} \qquad (5)$$

For partially wet vegetation, the actual evapotranspiration rate is a weighted sum of the flux densities for a 'wet' ($r_s = 0$) and 'dry' layer (r_s according to (5)). Bare soil evaporation is parameterised using an explicit soil surface resistance r_{slow}, calculated from the resistances to liquid and vapour transport through the soil.

Soil moisture flow is described by the 1-D Richards equation in its capacity form, where differential moisture capacity $C(h) = d\theta/dh$ (m^{-1}) and h (m) is pressure head. The retention and conductivity curves $\theta(h)$ and $k(h)$ may be specified for multiple horizons and are described according to the Mualem-Van Genuchten relationships (Van Genuchten, 1984). The numerical scheme comprises 25 compartments, gradually increasing from 0.01 to 0.35 m with a total soil depth of 2.9 m. At the lower boundary either free drainage or a time dependent groundwater level was specified. Root density distribution and rooting depth may vary in time.

DESCRIPTION OF DATA SETS

Three data sets covering different climate regimes, vegetation and soil types were used (Table 1). These sets provide high resolution meteorological forcing data, daily values of evapotranspiration and regular measurements of soil moisture profiles at field scale. Additional requirements for selection of the sets were: 1) easy availability; 2) model parameter values available from field measurements or literature; 3) long term measurements. The HAPEX Sahel data set covers only 2 months, but it includes the hydrologically interesting transition from wet to dry conditions at the end of the rainy season.

HAPEX Mobilhy

The HAPEX Mobilhy experiment was a large scale land surface–atmosphere experiment in South-Western France, 1986. For an agricultural site near Caumont, high resolution atmospheric forcing data, daily evapotranspiration rate for the entire year and soil moisture profiles at weekly intervals were available from a previous PILPS experiment (Shao and Henderson-Sellers, 1996). The soya crop started to grow in May and was harvested at the end of September. Vegetation

Table 1. Specifics of the selected data sets.

experiment	region	period	climate	vegetation	soil
HAPEX Mobilhy	Caumont, France	1986	semi-humid	soybean	loam
HAPEX Sahel	Sahel, Niger	Aug-Oct 1992	semi-arid	savannah	sand
Hupselse Beek	Netherlands	March '81–Dec '82	semi-humid	pasture	sand

cover fraction, *LAI* and root development during the growing season were set according to PILPS experiment 13 (Shao and Henderson-Sellers, 1996). Values of r_{smin} and stress functions $f(X)$ in (5) were estimated from data in the literature (Bailey and Davies, 1981; Kelliher *et al.*, 1995).

The soil type at the Caumont site is classified as loam and soil physical properties were based on measurements at another loam site in the Mobilhy area. Assuming zero soil water storage change over the year, the sum of runoff and percolation was estimated from the water balance data. Limitations inherent in the data set were summarized by Wetzel *et al.* (1996).

HAPEX Sahel

The large scale HAPEX Sahel experiment in Niger lasted from Aug 15 to Oct 10, 1992, including part of the rainy season and a 3 weeks dry-down. The total rainfall amount in the wet season was 425 mm with 247 mm during the HAPEX Sahel observation period. Atmospheric forcing data for a fallow savannah site was obtained from the data set described by Verhoef (1995). Data gaps were completed by measurements from an additional flux tower at the same site (Kabat *et al.*, 1997) or from a nearby savannah site. The total evapotranspiration amount was estimated by interpolating daily evapotranspiration measured at this specific site.

The savannah vegetation consisted of bushes with an understory of annual grasses and herb species with *LAI* increasing from 0.35 to 1.25 (Hanan and Prince, 1997). The bare soil cover fraction was estimated at 0.32. Detailed root length measurements yielded an exponential root density distribution continuing to over 2 m depth. Values of r_{smin} and stress functions $f(X)$ in (5) were based on the analysis by Verhoef (1995) and Hanan and Prince (1997). Soil moisture profiles to 1.8 m depth were measured every other day. Hydraulic properties were determined from laboratory measurements and single $\theta(h)$ points measured in the field. Field observations indicated surface crusting during rainfall; this was included in the SWAPS simulations by introducing a 1 cm top layer with saturated hydraulic conductivity $k_{s,top} = 0.1k_s$.

Hupselse Beek

The Hupselse Beek catchment is situated in the eastern part of The Netherlands. Data used for this study cover the period from March 1981 to December 1982. Meteorological forcing data, daily evapotranspiration and biweekly soil moisture to 2.05 m depth are available for the entire period. The second year was fairly dry with 577 mm precipitation where long term average precipitation is about 770 mm a^{-1}.

The site had a grass cover with an estimated *LAI* of 1.1. Values of r_{smin} and stress functions $f(X)$ in (5) were estimated from data in the literature (Kelliher *et al.*, 1995). Roots were uniformly distributed in the upper 25 cm of soil. In the soil profile 2 distinct pedological horizons were present. Both layers were classified as sandy but with different hydraulic characteristics (Hopmans and Stricker, 1989). A specific feature of the Hupselse Beek site is the influence of a high groundwater table; it reached its deepest level at 168 cm below surface in the dry summer period of 1982.

Performance of standard land surface module

The standard RACMO LSM was run with its fixed parameter values (Table 2) for the 3 data sets. For SWAPS, measured or literature parameter values as described for the different sites were input; for some of the parameters of SWAPS limited tuning within the range of available values was allowed to improve performance. In practice it affected simulated water balance terms only slightly and SWAPS simulated available measurements adequately. It is acceptable, therefore, to use SWAPS' results to estimate missing data, e.g. percolation. Measured soil moisture profiles were used to initialise the models. Simulation runs were not repeated until equilibrium for stored soil water was reached.

Cumulative evapotranspiration *ET* (mm) for HAPEX

Table 2. Standard parameter values of the RACMO LSM.

parameter	standard
soil type	loamy
θ_s	0.472
$\theta_{fc}(h = -337\text{ cm})$	0.323
$\theta_{wp}(h = -15300\text{ cm})$	0.171
k_s (cm d^{-1})	39.5
r_{smin} (s m^{-1})	240
LAI ($m^2\,m^{-2}$)	4
root depth (m)	1.0
root density	exponential

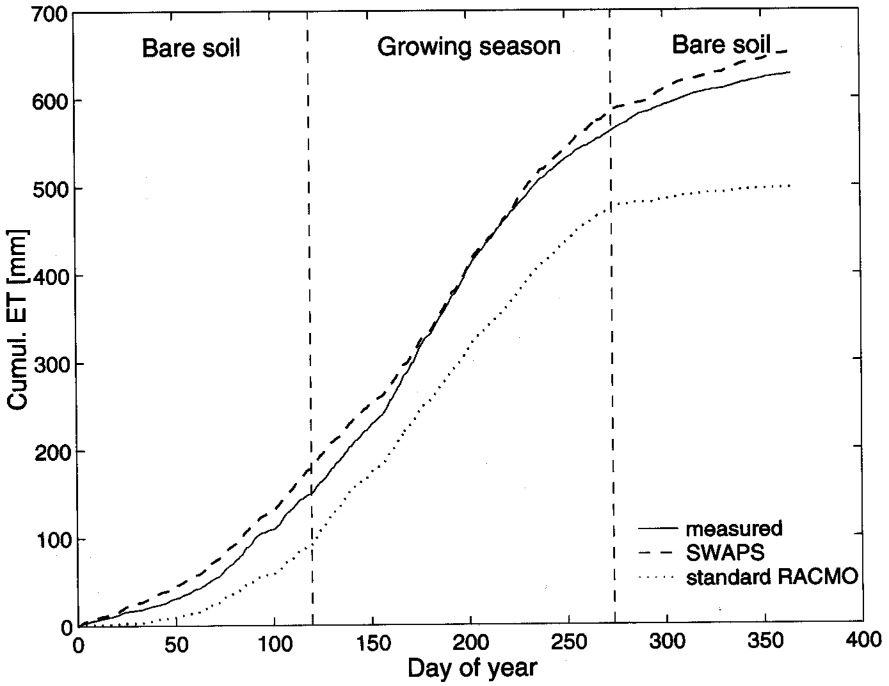

Fig. 2. *Course of measured and simulated cumulative evapotranspiration in time for the HAPEX Mobilhy site.*

Mobilhy is shown in Fig. 2. Annual *ET* simulated by RACMO is 130 mm (21%) below the measured value which is due mainly to an underestimation of bare soil evaporation E_s. On the other hand, RACMO overestimates percolation Q_{bot} by about 120 mm, especially in the bare soil period before the growing season.

Daily *ET* for the HAPEX Sahel site is presented in Fig. 3. RACMO seriously underestimates *ET* especially during the dry-down period (Fig. 3b). Additionally, zero percolation is calculated whereas SWAPS yields a total value of 213 mm which corresponds to qualitative field observations. Both discrepancies can be explained easily because the standard soil hydraulic properties that were used were very unrealistic for this site (see Fig. 7). Initialising the model using measured soil moisture in combination with its standard soil hydraulic properties obviously leads to inaccurate results at the Sahelian site as shown in Fig. 4. Firstly, storage builds up due to the standard soil hydraulic properties. To explore the impact of the initial conditions, an additional run (Fig. 4, R2) was performed, initialising at standard model field capacity ($\theta_{fc} = 0.32$) which is a reasonable assumption in the midst of the rainy season. Daily *ET* is now overestimated considerably especially in the dry-down period (Fig. 3c). Also root zone water storage is overestimated whereas Q_{bot} is still underestimated by about 100 mm.

Measured and simulated *ET* for the Hupselse Beek site are shown in Fig. 5. RACMO underestimates *ET* by 86 mm (18%) in 1981 and by 139 mm (27%) in 1982. The difference between the two years is due mainly to the period

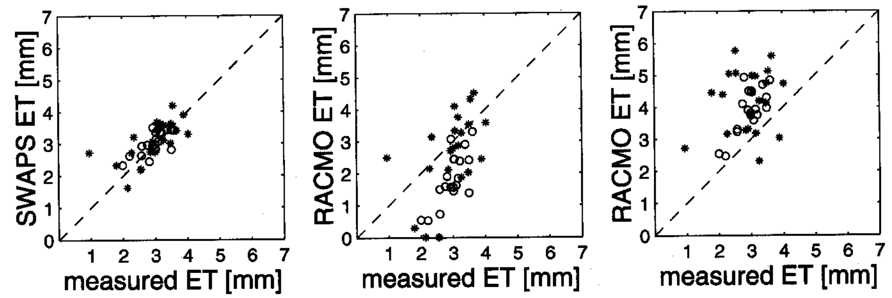

Fig. 3. *Simulated daily evapotranspiration versus measured values for the HAPEX Sahel savannah site during rainy season (∗) and dry-down period (○). Results were generated by (a) SWAPS or (b) standard RACMO LSM initialised using measured soil moisture or (c) model field capacity. The dashed line represents the 1:1 line.*

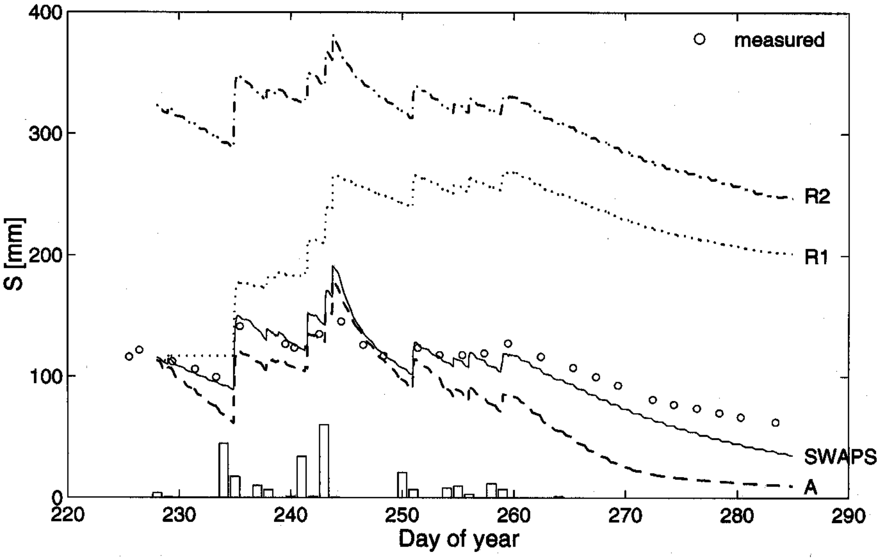

Fig. 4. *Course of measured and simulated moisture storage for HAPEX Sahel in 0–1 m standard RACMO root zone. Simulation results were generated by SWAPS, standard RACMO LSM initialised using measured θ-values (R1) or model θ_{fc} (R2) and case A of the sensitivity analysis (see Table 3). Bars represent daily values of precipitation in mm.*

following the relatively dry growing season of 1982. The lower boundary in RACMO is free drainage whereas the groundwater table at the Hupselse Beek site lies within the model soil column. Despite this discrepancy, soil water storage for the upper 1 m layer corresponds reasonably well with measured values (Fig. 6). Due to its thickness, the lowest soil compartment apparently acts like a 'groundwater' reservoir in this case.

Sensitivity to vegetation and soil parameters

SETUP OF SENSITIVITY ANALYSIS

Inadequate simulation results by the standard RACMO LSM may be the consequence of i) inaccurate model concepts like choice of soil evaporation parameterisation or

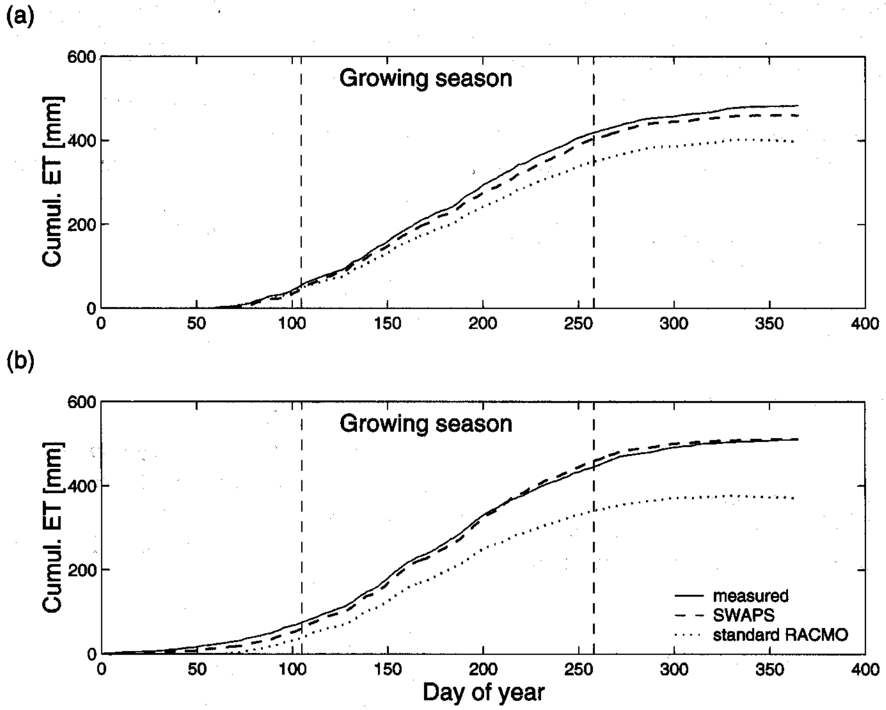

Fig. 5. *Course of measured and simulated cumulative evapotranspiration at Hupselse Beek site (a) over 1981, starting from day number 60 and (b) over 1982.*

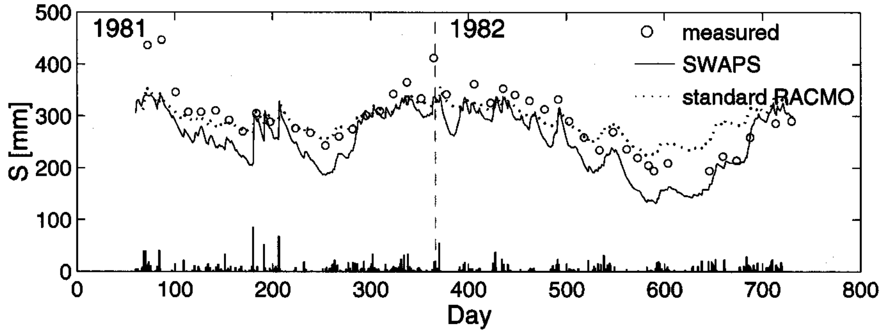

Fig. 6. *Course of measured and simulated moisture storage in standard RACMO root zone (0–1 m depth) for the Hupselse Beek site. The plotted SWAPS run used a groundwater level boundary condition. Bars represent daily values of precipitation in mm.*

'big leaf' model type; ii) standard soil and vegetation parameter values; iii) numerical schematisation. Based on the analysis in the previous section, deviations from measured data can hardly be attributed to any of these features directly. To separate the impacts of using standard parameter values and inaccurate model concepts, a sensitivity analysis was set up. In this analysis, site specific parameter values are introduced stepwise in the RACMO LSM to allocate the effects of the different parameters on the hydrological balance. Different numerical schematisations for soil models were studied by Blyth and Daamen (1997). According to their results, a four layer soil model can reproduce water budget terms fairly accurately whereas a finite difference method as used in RACMO may lead to errors of 0 to 14%.

The cases that are considered are summarized in Table 3; case ESM is discussed later. In option A the soil hydraulic properties are modified, for which RACMO needed to be adjusted to incorporate the Mualem-Van Genuchten relations directly. By changing the retention curve, $\theta(h)$, θ_{fc} and θ_{wp} change automatically since these depend on the pressure head (Fig. 7). Option B specifies the vegetation through r_{smin} and LAI which interact in determining the canopy surface resistance (see (2)). In option C, site specific rooting depth and distribution are used which was somewhat limited by the fixed soil compartments. A summary of site specific parameters is given in Table 4. The θ_{fc}-value for the Sahelian site is still unrealistic since field data show that the pressure head at field capacity is about −100 cm corresponding with $\theta = 0.11$.

Table 3. RACMO model cases with site specific parameter values used in the sensitivity analysis.

case	site specific parameters
A	soil hydraulic properties, specified by MVG relations
B	r_{smin} and LAI
C	rooting depth and distribution
AB	soil hydraulic properties + r_{smin} and LAI
AC	soil hydraulic properties + rooting depth and distribution
BC	r_{smin} and LAI + rooting depth and distribution
ABC	soil hydraulic properties + r_{smin} and LAI + rooting depth and distribution
ESM	soil hydraulic properties from HYPRES data base

RESULTS OF SENSITIVITY ANALYSIS

The annual water balance for the different cases at the HAPEX Mobilhy site is shown in Fig. 8. Case A has a significant effect on surface runoff due to the now lower values of saturated moisture content θ_s and maximum infiltration capacity. Furthermore, case A shows an increase of soil evaporation E_s which is apparently caused by changing θ_{fc} because the other variables involved (θ_l and skin temperature) are almost identical to the standard run. The effects of case B are minimal. As in the standard model run, total ET remains too low for all cases which is still due to an underestimation of E_s.

Figure 9 shows the resulting water budget terms for HAPEX Sahel. Case A yields a considerable improvement; the most distinctive change is the increase of Q_{bot} from 0 to 200 mm. The transpiration term E_v also increases by 35%, which appears to be composed of an increase over the rainy period but a decrease in the dry-down (Fig. 10). The latter is a consequence of stronger soil moisture depletion in the wet season (see Fig. 4). In case B, transpiration E_v also increases due to the lower r_{smin}. Despite the deeper rooting system, E_v decreases in case C. This is caused by the low value of θ_4 which leads to a decrease of root zone moisture $\overline{\theta}$ in (2). In case AC, however, water uptake can easily occur from the deepest layer due to the change in soil hydraulic properties, leading to an increase of E_v during both the rainy season and the dry-down period. The final effect of including all site specific parameters in case ABC is an overestimation of ET by about 140 mm. This results in an

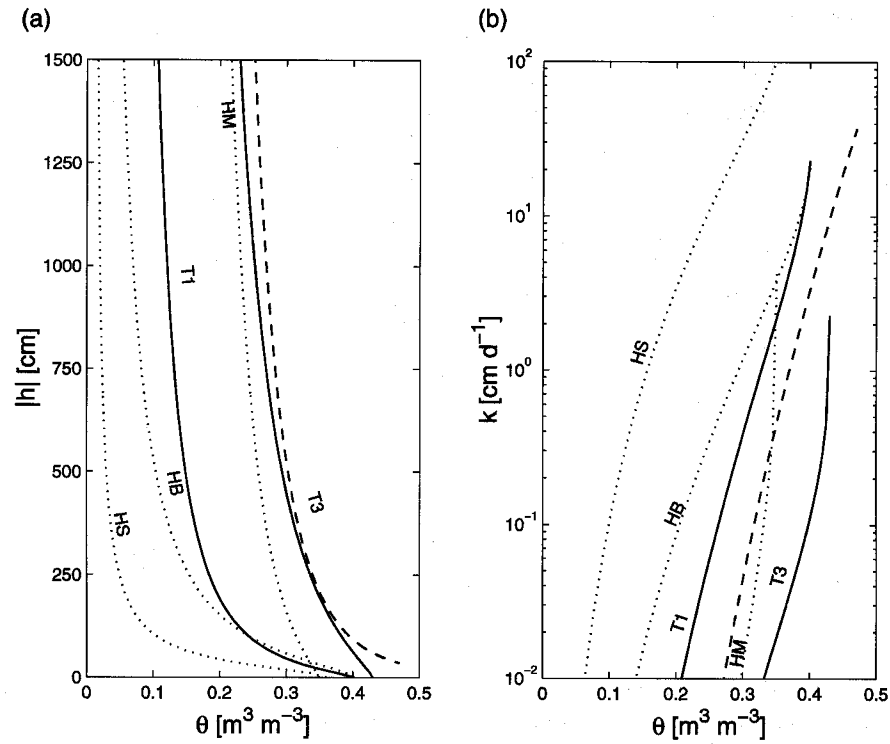

Fig. 7. *(a) Soil water pressure head and (b) hydraulic conductivity as functions of soil moisture θ using site specific MVG parameters (dotted), European soils data base HYPRES (solid) or standard RACMO curve (dashed). Sites are: HAPEX Mobilhy (HM), HAPEX Sahel (HS) and Hupselse Beek (HB); HYPRES texture classes are coarse (T1) and medium fine topsoil (T3).*

over-depletion of the soil moisture reservoir during the dry-down period.

Simulated water budgets for the Hupselse Beek site are shown in Fig. 11. Introducing the site specific soil has a dramatic effect for the year 1981. Lower θ_{fc} and higher k-values compared to the standard model cause fast drainage in the first months of the simulation period whereas in the field situation soil moisture stays at a high level due to groundwater influence. After this drainage of 'excess' water, however, relative changes in soil moisture are similar for case A and the standard model run. To illustrate the effect of the lower boundary condition, two SWAPS model runs are shown in Fig. 11 using either daily measured groundwater levels or free drainage. For the latter, the effect of 'excess' drainage in the starting period of the simulation is even more pronounced than for case A. Apparently, the Q_{bot} overestimation for case A can be attributed mainly to an improperly defined lower boundary condition. The shallower rooting depth (28 cm) in case C hardly affects soil moisture stress since E_v for the 1982 dry summer period is only 5% lower. Combining site specific soil and root distribution in case AC yields an additional decrease of E_v

Table 4. Site specific parameter values used in the sensitivity analysis of RACMO LSM.

parameter	HAPEX Mobilhy	HAPEX Sahel	Hupselse Beek
soil type	loam	sand	sand
θ_s ($h = 0$)	0.350	0.360	0.402
θ_{fc} ($h = -337$ cm)	0.273	0.039	0.130
θ_{wp} ($h = 15300$ cm)	0.147	0.011	0.014
k_s (cm d^{-1})	4.3	181.7	33.7
r_{smin} (s m^{-1})	125	45	66
LAI (m^2 m^{-2})	0.5–4	0.39–1.21	1.1
root depth (m)	1.0	2.9	0.28
root density	exponential	exponential	uniform

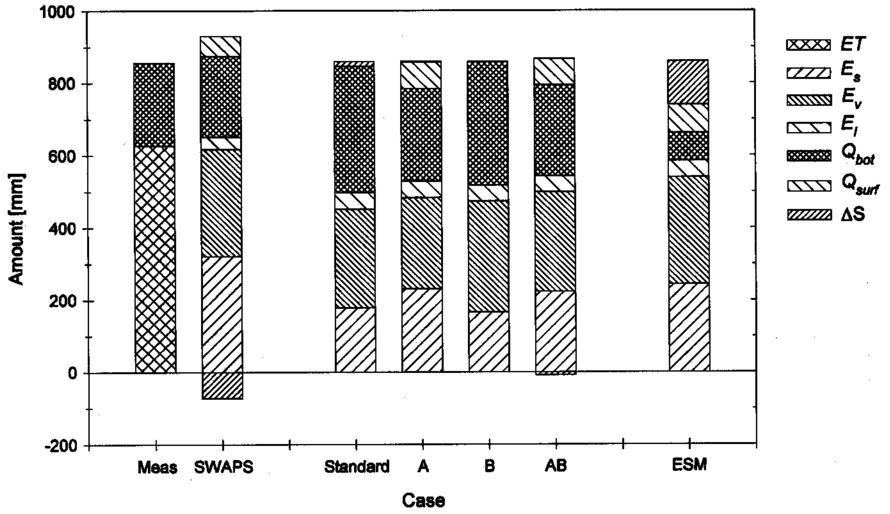

Fig. 8. *Annual water budget terms for different RACMO case studies (see Table 3) at HAPEX Mobilhy site. Rooting depth and distribution are identical to the standard model, therefore cases including C are not shown.*

for the 1982 growing season, which is caused by lower θ-levels in the upper soil layers. In the final case ABC, total *ET* is comparable to the standard model run due to the counteracting effects of B and AC.

European soils

The sensitivity of off-line RACMO LSM results to soil type implies a need to supply more specific information on soil hydraulic properties to the model. As mentioned in the introduction, the larger framework of this study aims at improving simulations with the 3-D atmospheric model for the European continent. The bulk division of soil types over that region, using standard FAO textural classes, is about 25% coarse, 40% medium and 12% medium fine textured soils, the remaining areas are (very) fine textures and histosols. This leads apparently to an increase in surface area with sandy soil types (coarse + medium) compared to the current model's standard loam soil (medium fine). The impact of this shift on 3-D atmospheric model results depends on complicated land surface–atmosphere feedbacks and, thus, needs to be analysed in a coupled mode, which is the objective of a forthcoming study.

Explicit $\theta(h)$ and $k(\theta)$ data are generally not available for the grid cell sizes used in RACMO. To fulfil data requirements, hydraulic properties can be derived indirectly from textural data provided by soil maps. Recently, Wösten

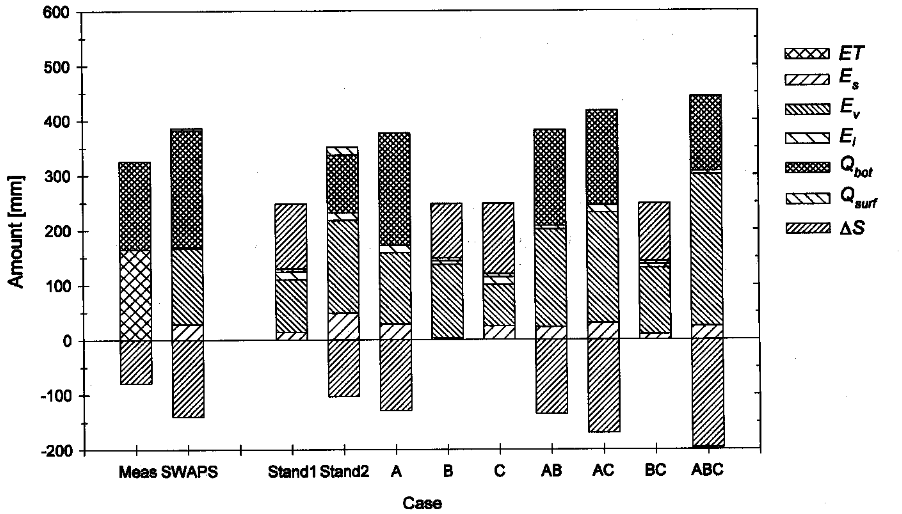

Fig. 9. *Water budget terms for different RACMO case studies (see Table 3) at HAPEX Sahel site. The standard RACMO LSM was initialised using measured θ-values (Stand1) or model field capacity (Stand2).*

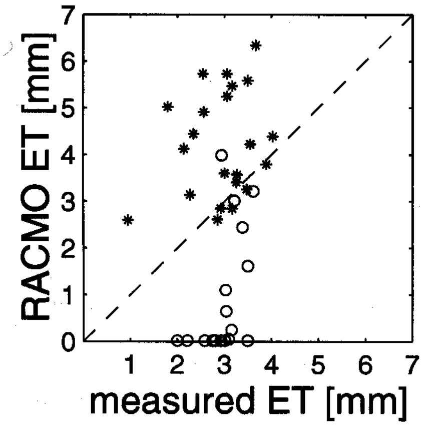

Fig. 10. *Simulated daily evapotranspiration by RACMO, case A, for HAPEX Sahel during rainy season (*) and dry-down period (○). The dashed line represents the 1:1 line.*

et al. (1999) presented the HYdraulic PRoperties of European Soils (HYPRES) data base which supplies MVG-parameters for the standard FAO soil texture classes. The applicability of this data base was explored briefly for the HAPEX Mobilhy and Hupselse Beek sites. Based on the European soil map (scale 1:10^6), the texture classes are medium fine and coarse respectively. As shown in Fig. 7, the HYPRES curves resemble site specific curves whereas the standard RACMO $k(\theta)$ curve is quite different.

The RACMO LSM was run with these HYPRES properties, keeping vegetation parameters and rooting depth at the standard value (case ESM in Table 3). Hence, results should be directly comparable to case A. For HAPEX Mobilhy there is a remarkable difference between annual Q_{bot} for cases A and ESM (Fig. 8). This is caused by differences in saturated moisture content θ_s, in combination with the steepness of $k(\theta)$ near saturation. The model with

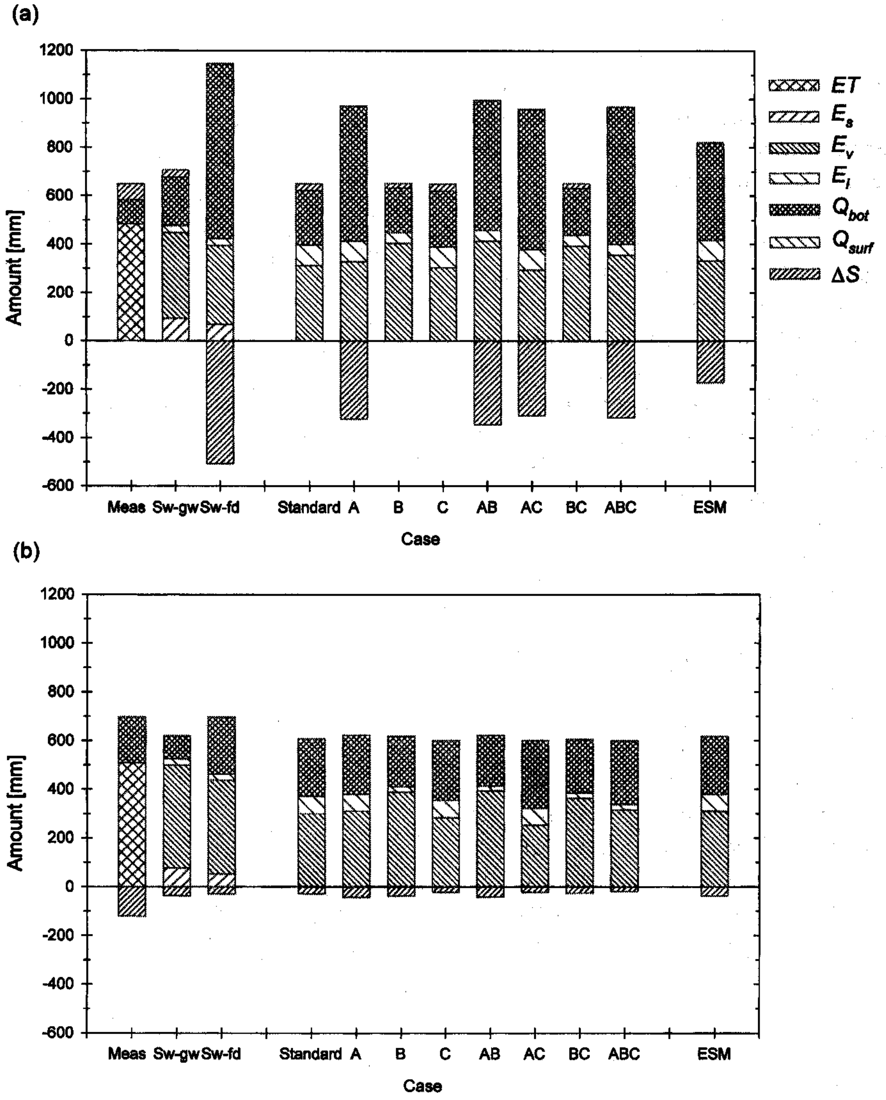

Fig. 11. *Water budget terms over (a) 1981 and (b) 1982 for different RACMO case studies (see Table 3) at Hupselse Beek site. The SWAPS bottom boundary condition was daily measured groundwater level (Sw-gw) or free drainage (Sw-fd).*

site specific soil produces more percolation in winter, when θ-values for the deepest compartment are close to saturation. Results for the Hupselse Beek site compare well with case A (Fig. 11).

Discussion

The analysis of the standard RACMO LSM reveals that longer term *ET* is systematically underestimated which can be attributed partly to the bare soil evaporation parameterisation. This is in accordance with results by Mihailović *et al.* (1995). Presumably this is caused by the relative humidity at the surface α (see Fig. 1) dropping too sharply when top soil moisture content θ_1 decreases. Transpiration is simulated fairly accurately when moisture stress plays a minor role and standard vegetation parameters are close to site specific values (HAPEX Mobilhy). Under more extreme conditions as in the Sahelian dry-down period, the standard LSM seriously underestimates E_v. Results improve when both soil type and rooting depth are changed to site specific values. For the HAPEX Sahel site, E_v is then overestimated while soil moisture levels compare fairly well with measurements. The model response to moisture stress therefore seems inadequate, which may be caused partly by the unrealistic value of θ_{fc} (Table 4).

The deviation of surface runoff and percolation compared to SWAPS or field estimates is not of the same sign for all 3 sites. Changing soil hydraulic properties lead to significant improvements in both Q-terms. The Hupselse Beek site, however, is a very specific case which cannot be analyzed for Q_{bot} easily since the model bottom boundary and the field situation with shallow groundwater tables are not comparable. The inappropriate settings for the bottom boundary condition are highlighted only after introduction of site specific soil properties.

Initial soil moisture conditions had a pronounced effect on simulation results. Koster and Milly (1997) showed that different LSMs can produce a similar partitioning of rainfall over evapotranspiration and runoff and similar seasonal cycles of soil moisture, even when absolute soil moisture levels are quite different. One could, therefore, argue that only changes in soil moisture as a component of the land water budget are important. Any LSM should then be initialised in accordance with its interior properties. This approach was attempted at the Sahelian site by initialising at the interior model θ_{fc}-value which led, however, to an overestimation of *ET*. At the Hupselse Beek site, however, the low θ-values after initial drainage of 'excess' water (case A) had no serious effect on the simulated water budget in the second year. These examples indicate that, unfortunately, the choice of initial conditions depends on the simulated period and objective of any modelling study. However, when large scale aggregated soil moisture values become available from model-independent sources like remote sensing, realistic simulation of absolute soil moisture levels gains importance for both initialisation and validation. In that case, properly scaled parameterisation of the components of the terrestrial hydrological balance becomes unavoidable.

Conclusions

In general, this evaluation of the ECMWF/RACMO LSM indicates that using simple standard parameter values has a significant effect on simulated water budgets in 1-D off-line mode. Also, implementation of all site specific information (cases ABC) does not lead automatically to the best performance. Thus, the interaction between different aspects of the LSM stresses the need for careful analysis of future model adjustments. Simulations with the LSM coupled to the 3-D atmospheric model must reveal the sensitivity of long term weather and climate predictions to changes in the LSM.

Finally, the main items for further analysis with the 3-D atmospheric model and adjustments to the standard LSM to improve the simulation of hydrological components are:

1. Introduction of distinct soil types. Recent initiatives like the HYPRES data base may aid this topic. Since RACMO applies a horizontal spatial resolution of about 50 km, a grid cell will cover multiple soil types with different properties. Therefore, the representation of horizontal spatial variability or determination of effective soil hydraulic parameters needs to be addressed.
2. Variable rooting depth and root density distribution. This adjustment is currently being implemented in a new version of the ECMWF LSM (pers. comm. Beljaars, ECMWF).
3. Bare soil evaporation parameterisation. For the current model setup, this includes the functional dependency of the relative humidity α on top soil moisture content as well as the effect of soil type and upper layer depth.
4. Soil column bottom boundary condition. Currently, the thick lower layer apparently provides the possibility of some capillary rise to the root zone in dry periods. The effect of prolonged dry periods and the impact of changing soil hydraulic properties should be investigated.

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