Importance of root depth distribution for modeling of the interactions between water, soil, vegetation and atmosphere

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Abstract Large scale modeling as in GCM, commonly disregards much complexity to avoid high numerical demands. The simplifications affect model outcome and for a number of these, we assess the errors that may be involved. We consider first, how the root depth distribution affects the water and energy balances, by considering the effect on evapotranspiration for two common vegetation classification types. This effect is found to be significant. To assess whether this effect should be prioritized in water-vegetation research, we compared the impact choices for root depth distributions with commonly made simplifications for climatic, numerical, soil, and vegetation parameters. This assessment was done for all combinations of variates, with calculations that cover a time span of 44 years. This way it is feasible to rank the different factors with respect to the impact of simplifications on model result (soil dessication, transpiration, evaporation). It appears, that improvements on the root depth distribution have a much smaller priority than several other factors.
Keywords: root depth distribution; evapotranspiration; vegetation; soil water balance; natural vegetation; climate modeling

INTRODUCTION

Research on climate change is gradually shifting from observation, prediction, and mitigation, towards adaptation, i.e., on how to best deal with developments that cannot be fully controlled. The scientific questions change fundamentally, as they become redirected towards identifying gaps in different disciplines, interdisciplinary integration, and towards planning and design. To enable such practical and often detailed aims, higher quality requirements are set for climate models.

Large scale climate modeling, as is done with Global Circulation Models, GCM, is very demanding both computationally and regarding data requirements. As with all modeling, an optimum is sought between the simplifications made and technical limits. In finding this optimum, which continuously shifts, it is of primary importance to recognize which simplifications affect the model outcome most. Such simplifications should receive priority regarding model and parameterization fine-tuning.

The parameterization of the land surface was identified by Pitman (2003) as a priority candidate for GCM improvement. In such an improvement, many different factors and processes can be involved. One could think in this respect of e.g. land use and vegetation cover, and soil and groundwater characteristics. To vary these factors within GCM would be prohibitive in view of the numerical demands. Instead, an impression can be obtained using a simpler approach.

Scope of this research was to assess the influence of the parameterization of the root depth distribution (RDD) on the local water and energy balances. In particular, two issues are of concern, namely whether and how much the RDD of different vegetations affect the balances and whether or not this effect is important and should be prioritized in comparison with other common simplifications.

MODEL APPROACH

To determine the effect of root depth distribution (RDD) on the soil surface water and energy balances, attractive model output for comparison are the evaporation, transpiration, and soil water content. The latter has been recognized as the main single variate that affects these balances. In our approach, we choose for not varying vegetation (via RDD) in a GCM, but use climatic conditions as a forcing function on local balances. The weakness of this approach is that local climatic conditions are decoupled from the vegetation type. However, the advantage is that the numerical demands are in proportion for such a first order approach.

For our analysis, we use the numerical Soil-Water-Atmosphere-Plant model SWAP (van Dam, 2000), which solves the highly nonlinear flow equation subject to designated initial and boundary conditions, and implements state-of-the-art root-water extraction models. The upper boundary condition is the potential evapotranspiration (ETp). Water uptake by vegetation is calculated after first attributing ETp over evaporation from the soil surface and transpiration by plants. This is done on the basis of the leaf area index (LAI).

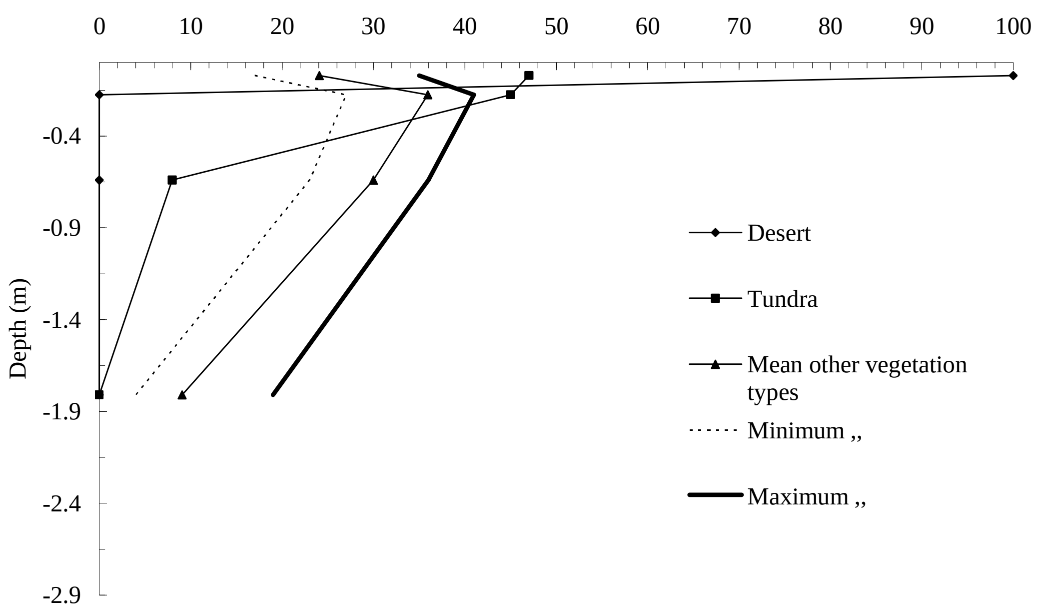

Figure 1: Root Density Distributions (RDD) used in modeling

The transpiration part, which is provided by soil, comes from different depths, and is for a wet soil assumed to be proportional with the fraction of roots in each soil segment according to RDD. The 16 different RDDs of ECMWF (2004) are grouped into three main groups and shown in Figure 1. For dry and for very wet soil, the transpiration part of each depth segment is reduced in dependency of the soil water potential (Van Dam, 2000).

Actual evaporation (Ea) compared with the potential evaporation, depends strongly nonlinearly on soil water content and is different for different soil types, because of differences in their capillary behaviour. These nonlinear relationships cause the actual evapotranspiration, ETa, and its contributions by evaporation and transpiration, to be dependent on the leaf area index, RDD, and the choice of reduction functions.

PARAMETERIZATION

We first consider the changes in the ratio ETa/ETp, for 16 natural vegetation types as distinguished by ECMWF (2004). We do so for constant conditions, such as ETp=6 mm.d^{-1}, LAI=3, and an initial uniform water potential of -200 cm. We simulate a long drought situation on a deep sandy soil (2.9 m deep, total available water equal to 544 mm) to determine how evapotranspiration and soil water content decrease as a function of time. A second series of simulations used the different and more simplified 7 vegetation classes of Masson et al. (2003) and for this purpose, the data of Schenk and Jackson (2002) were regrouped.

Secondly, we varied climate and weather, vegetation, soil, and lower boundary conditions, for one type of plant (maize) with a growing season extending from May 1 till October, 15. Aim was to assess the relative importance of the variation of these factors compared with varying RDD. For this purpose, two quite different climate zones were considered, i.e., Central Atlantic (England, 52.14 N, 0 E) and Pannonic (Great Hungarian Plain, 44.29 N, 21.09 E). These two zones are based on the analysis of Metzger et al. (2005), who distinguished 13 main climate zones within Europe. For these two climate zones, 44 year-periods were simulated, using weather data available from the ERA-40 archives (ECMWF, 2005).

Varied vegetation factors were LAI (constant or time dependent), root profile (constant, or time dependent according to average maize data), and root zone depth (0.74 m, or increasing to 1 m as a function of time). Soil properties were texture, stone fraction (0 or 40% by volume), soil profile thickness is 5 m, with two layers separated at 0.4 m depth. Soil physical parameters in dependency of texture were taken according to Wösten et al. (1994). The lower boundary was either free drainage or a constant matric head of -30 cm at the lower boundary. Vertical soil discretization comprised either 64 or 4 layers. Altogether, this resulted in a $3x2^6$ factorial design.

RESULTS

The calculations regarding drying out of the soil are illustrated in Figure 2 for the vegetation classification provided by ECMWF (2004). Shown is the ratio of actual over potential evapotranspiration as a function of time. For both classification systems, also the time required for decreasing the relative evapotranspiration by 50% was calculated.

As Figure 2 reveals, the evapotranspiration decreases gradually as a function of time. It is also apparent, that desert and tundra are poorly buffered extremes compared with the other vegetation types, and these two cases show a rapid decrease in transpiration. The other types are much closer together, as is shown by the band that spans their maximum and minimum curves, respectively. If only 7 vegetation types are distinguished (not shown), the extremes are averaged out. Therefore the two poorly buffered cases are absent as they were not distinguished in this classification. Moreover, we observed a small shift towards a faster decrease and a slightly larger band width between maximum and minimum curves, because more variation is averaged into only 7 vegetation classes. It is noteworthy, however, that the results for the 7 and 19 vegetation types are still well comparable for the range that they have in common (minimum – maximum range) if we disregard the desert and tundra cases in the latter classification.

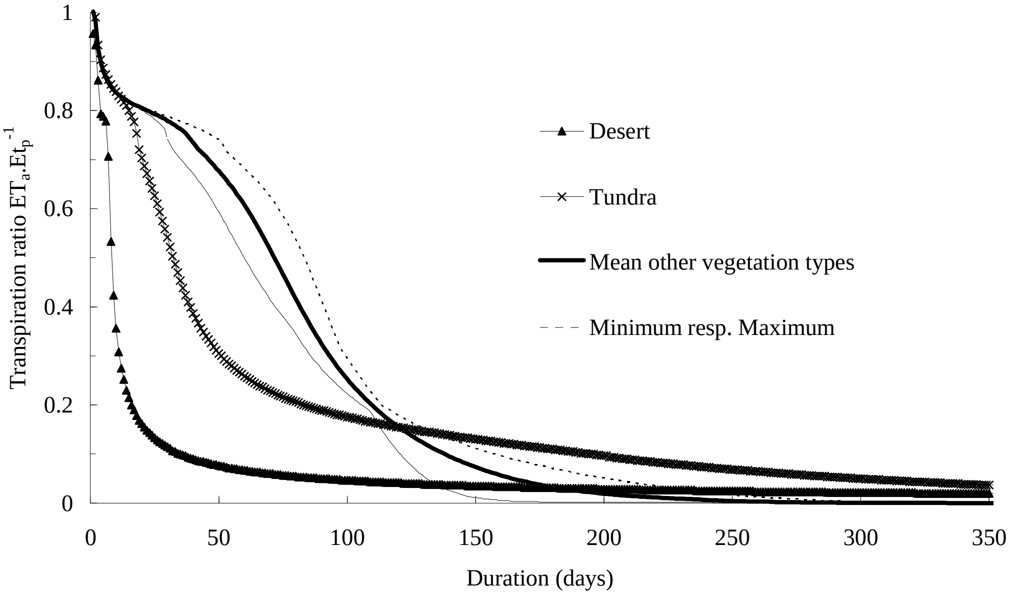

Figure 2: Time required to decrease relative evapotranspiration by 50% for 16 vegetation types

The period required for reaching a 50% transpiration reduction is shown in Figure 3 for both the 16 and the 7 vegetation classifications as a function of the average root density of the entire soil profile. This period again has a larger range for the ECMWF (2004) classification than for the other one, which is in agreement with the observations presented above. Furthermore, a distinct dependency of the dry out period with the average root density is found, which is equal for both classifications.

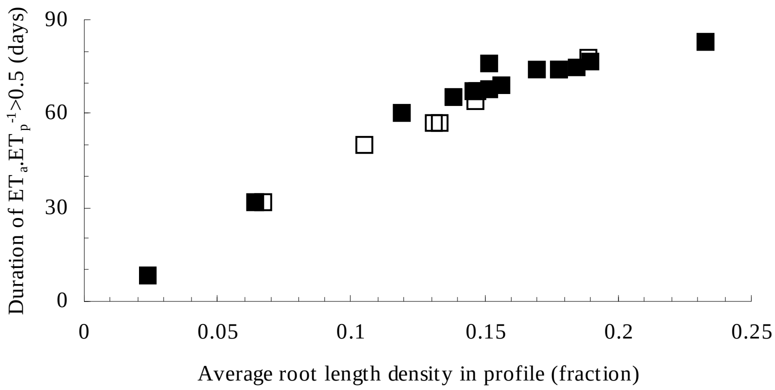

Figure 3: Period needed for a 50% reduction of the actual evapotranspiration divided by potential evapotranspiration, as a function of average root density in the entire profile

With Figures 2 and 3, we have established that the description of the rooting pattern is significant for soil dessication and evapotranspiration reduction. From these results, it can be inferred that choices made with regard to rooting pattern affect the water and energy balances in soil, water, vegetation, atmosphere modeling. This conclusion suggests that root density profiles, and their performance in water extraction require more attention in e.g. climate modeling, and that it may be necessary to investigate gaps in our knowledge on the dynamics of water uptake, and different water strategies of natural vegetations.

What has not yet been established is whether such research also has priority, over other research targets. For this purpose, the factorial design calculation scheme was treated with an ANOVA. The results are presented in Table 1, in terms of the variance ratio of the main effect with regard to the residual variance (of all interactions). The larger the variance ratio is, the more important is a particular factor. As the main effects are large compared with interactions, only these are shown, for the annual sums of actual transpiration, evaporation, change in profile storage, both for all calculations, and separated with regard to climatic zone.

Table 1 Variance ratios for all factors with regard to residual variance of all interactions

	Actual Transpiration	Actual Evaporation	Change in profile storage
Discretization	42793 (1.00)	412 (0.13)	6504 (0.58)
Climate	17282 (0.40)	3209 (1.00)	77 (0.01)
Stoniness	4408 (0.10)	414 (0.13)	2078 (0.18)
LAI	4242 (0.10)	850 (0.26)	609 (0.05)
Texture	2180 (0.05)	1937 (0.60)	2443 (0.22)
Root length density	1229 (0.03)	47 (0.01)	369 (0.03)
Lower boundary	980 (0.02)	0 (0.00)	11234 (1.00)
Year	106 (0.00)	316 (0.10)	118 (0.01)
Root depth	26 (0.00)	7 (0.00)	4 (0.00)

	Actual Transpiration T		Actual Evaporation		Change in profile storage	
	Atlantic	Panonic	Atlantic	Pannonic	Atlantic	Pannonic
Discretization	36046	35525	574	900	4740	4925
Stoniness	4063	3410	558	841	1806	1446
LAI	4252	3098	435	2900	576	380
Texture	2225	1580	2654	4118	2035	1744
Root length density	1369	825	73	91	312	252
Lower boundary	331	1261	3	0	9429	7792
Year	185	153	1273	823	192	172
Root depth	13	29	15	10	2	4

From these results, it is apparent that the present settings for discretization constitutes a major factor, in particular for transpiration, as has been observed previously by Martinez et al. (2001).

Also assumptions regarding stoniness and leaf area index effects affect results predominantly for transpiration. In comparison with the other factors, these preliminary results indicate that the assumptions that were varied for the root zone profile have less urgency in model revisions, than the other varied factors of this study. For some factors, the cause of their effect on evapotranspiration and soil water storage is relatively simple to identify. For example, the choice of the lower boundary affects the ease with which water is irreversibly lost to the system and whether capillary rise is feasible. For a factor such as discretization, such a cause-effect relationship is more difficult to give, as all aspects of the calculations are affected.

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