Modeling Root Water Uptake in Hydrological and Climate Models

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ABSTRACT

From 30 September to 2 October 1999 a workshop was held in Gif-sur-Yvette, France, with the central objective to develop a research strategy for the next 3–5 years, aiming at a systematic description of root functioning, rooting depth, and root distribution for modeling root water uptake from local and regional to global scales. The goal was to link more closely the weather prediction and climate and hydrological models with ecological and plant physiological information in order to improve the understanding of the impact that root functioning has on the hydrological cycle at various scales. The major outcome of the workshop was a number of recommendations, detailed at the end of this paper, on root water uptake parameterization and modeling and on collection of root and soil hydraulic data.

1. Introduction

Within atmospheric modeling there is still only limited confidence that the land surface matters in weather and climate. Work from the Anglo-Brazilian Amazonian Climate Observation Study (see Gash and Nobre 1997) and intercomparison of different land surface parameterization schemes (Pitman et al. 1999), however, provide evidence that the vegetation and other land surface properties may directly affect the atmospheric boundary layer. Deforestation experiments showed that the regional climate is affected, with regional-scale perturbations leading to geographically remote changes in temperature and precipitation via atmospheric teleconnections (see also Kleidon and Heimann 2000). Climate system models also demonstrate that land cover changes during the last 7000 years amplified climate variations regionally and globally (e.g., Claussen et al. 1999; Ganopolski et al. 1998).

In land surface modeling, treatment of, for example, vegetation canopy structure, spatial vegetation variability and associated length scales, boundary layer formulation, runoff generation, and groundwa-

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ter flow play an important role. This paper focuses on the role of below-ground vegetation and the importance of root zone structure in land surface effects. Roots perform a variety of functions that are critical to the survival of all plants. One key function of plant roots is their ability to link the soil, where water and nutrients reside, to the organs and tissues of the plant, where these resources are used. Hence roots serve to connect the soil environment to the atmosphere by providing a link in the pathway for fluxes of water and other materials through the plant canopy to the atmosphere (Dawson et al. 1998). Fluxes along the soil–plant–atmospheric continuum are regulated by above-ground plant properties, like the leaf stomata, which can regulate plant transpiration when interacting with the atmosphere and below-ground plant properties like depth, distribution, and activity of roots as well as soil properties like water potential, water content, and hydraulic conductivity (Jackson et al. 2000a,b).

Water for evapotranspiration from land is supplied mainly by the soil, and in relatively mesic systems most water leaves the soil through plant roots and out of plant canopies, rather than by direct evaporation at the soil surface (Chahine 1992). The soil water reservoir balances the episodic excesses of water supply from rainfall against the more smoothly varying atmospheric demand for evapotranspiration. The role of soil moisture within the soil–plant–atmosphere system depends on the soil moisture reservoir size and the availability of water in that reservoir, which in turns depends, in part, on the texture and structure of soil and the characteristics of the root system.

Plant root systems show a remarkable ability to adapt to soil depth and to changes in availability of water and nutrients and the chemical properties (e.g., salinity) in soils. Root response to soil properties in turn affects the uptake of soil water and nutrients and the storage of carbon below ground. Root distribution may change when ecosystems respond to greenhouse warming and carbon dioxide fertilization. For example, at higher atmospheric CO_2 concentration, stomata of the plants can contract somewhat for a given influx of CO_2. Transpiration thus decreases, and coupled with generally higher photosynthesis in higher CO_2 water-use efficiency can increase dramatically (Field et al. 1995). Increased water-use efficiency will potentially feed back to changes in root characteristics, with the possibility of further, substantial changes in the water (and energy) balances. Exploration of such feedbacks has only begun.

This paper explores how information about plant root characteristics such as rooting depth, distribution, and functioning has been and could be used in land surface modeling from the perspective of the hydrological cycle and climate. Within this context, one objective is to explore the level of detail that needs to be included to parameterize properly models of water and energy flux on local, regional, and global scales. Toward this goal we examine the existing databases on plant rooting depth, distribution, dynamic water uptake behavior, and some of the key models that use these data.

Existing models use different levels of detail and, consequently, different types of plant root information in their parameterizations. These differences influence estimates of simulated water fluxes from land surfaces and their feedbacks with climate and therefore have important implications for other biogeochemical cycles (Zeng et al. 1998). These models often do not include information on root functioning. Yet the incorporation of information about root responses to soil water availability and/or stress and the redistribution of soil water by root systems into a modeling framework has the potential to affect model outputs dramatically (Mahfouf et al. 1996). We discuss how future parameterization schemes might include such information to improve model predictions relative to observations. We also acknowledge some trade-offs with the greater below ground detail and input requirements.

The second objective of this paper is to discuss the interpretation of root data by different modeling communities and the implications this has for refining predictions and determining future research directions. For example, there are two broad classes of modeling approaches that use root data in different ways:

- bottom-up or microscopic models that contain detailed descriptions of the plant, its root and soil systems, and the physical interaction among these components;
- top-down or macroscopic models based on first principles of energy and mass transfer that tend to parameterize root properties more simply, that is, through specification of a plant-available water capacity of the root zone.

We argue here that the functioning of roots, whether they are represented microscopically or macroscopically, needs to receive more attention in land surface and climate modeling and we highlight evidence of their importance in climate models.

2. How is root water uptake currently modeled in ecological, hydrological, and atmospheric communities?

a. Local point-/field-scale ecological and hydrological modeling

Bottom-up point-/field-scale models that are constructed around the plant, its root system, and how plant roots work consider multiple vertical soil layers and specify details of the root distribution and the soil hydraulic characteristics that determine water availability to roots. In principle two alternative approaches can then be taken (for reviews see Feddes 1981; Molz 1981).

The first plant-based approach is to consider the convergent radial flow of soil water toward and into a representative individual root, taken to be a line or narrow-tube sink uniform along its length, that is, of constant and definable thickness and absorptive properties. The root system as a whole can then be described as a set of such individual roots, assumed to be regularly spaced in the soil at definable distances that may vary within the soil profile. This microscopic approach that is commonly used in ecological communities (e.g., van Noordwijk and van de Geijn 1996; Sperry et al. 1998; Jackson et al. 2000b) casts the flow equation in cylindrical coordinates and solves it for the distribution of soil water pressure heads, water contents, and fluxes from the root outward. The problem with this approach is that often only steady-state conditions are considered and that the required rather detailed plant information is often not available.

The second more hydrologically oriented approach is to regard the root system as a diffuse sink that penetrates each depth layer of soil uniformly, though not necessarily with a constant strength throughout the root zone. Root water uptake can then be represented as a sink term that is added to the vertical water flow equation through the soil. One has to realize, however, that one-dimensional root system models may fail when lateral transport of water by subsurface or overland flow occurs. In case of catchments with complex sloping terrain and groundwater tables, a vertical domain model has to be coupled with either a process or a statistically based scheme that incorporates lateral water transfer. This macroscopic way of solving the root water uptake problem is to combine the continuity equation of water flow with a sink term representing water extraction by plant roots:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} - S, \tag{1}$$

where θ is the soil water content (cm^3 cm^{-3}), t is time (days), z is the vertical coordinate (cm) taken positively upward, q is the Darcian soil water flux density (cm day^{-1}) taken positively upward, and S is the actual root water uptake rate (cm^3 cm^{-3} day^{-1}).

Darcy's equation can be written as

$$q = -K(h)\frac{\partial (h+z)}{\partial z}, \tag{2}$$

where K is hydraulic conductivity (cm day^{-1}) and h is soil water pressure head (cm). Combination of Eqs. (1) and (2) results in Richards' equation:

$$\frac{\partial \theta}{\partial t} = C(h)\frac{\partial h}{\partial t} = \frac{\partial\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]}{\partial z} - S(z), \tag{3}$$

where C is the differential water capacity ($d\theta/dh$) (cm^{-1}), that is, the slope of the soil water characteristic. Ven Genuchten (1980) has provided analytical expressions for the strongly non-linearly behaving soil hydraulic characteristics $\theta(h)$ and $K(h)$.

Under optimal moisture conditions the maximum possible root water extraction rate $S_p(z)$, integrated over the rooting depth, is equal to the potential transpiration rate, T_p (cm day^{-1}), which is governed by atmospheric conditions. Here, $S_p(z)$ (day^{-1}) may be determined by the root length density, $\pi_{\text{root}}(z)$ (cm cm^{-3}), at this depth as the fraction of the total root length density over the rooting depth D_{root}(cm):

$$S_p(z) = \frac{\pi_{\text{root}}(z)}{\int_{-D_{\text{root}}}^{0} \pi_{\text{root}}(z)\partial z} T_p. \tag{4}$$

Stresses due to dry or wet conditions and/or high salinity concentrations may reduce $S_{\text{p}}(z)$. The water stress may be described by the function proposed by Feddes et al. (1978), which is depicted in Fig. 1. For salinity stress the response function of Maas and Hoffman (1977) may be used (Fig. 2), as this function has been calibrated for many crops (Maas 1990).

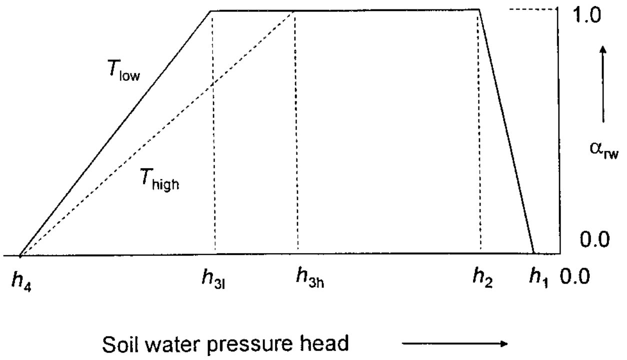

FIG. 1. Reduction coefficient for root water uptake, α_{rw}, as function of soil water pressure head h (cm) and potential transpiration rate T_p (cm/day^{-1}) (after Feddes et al. 1978). Water uptake above h_1 (oxygen deficiency) and below h_4 (wilting point) is set to zero. Between h_2 and h_3 (reduction point) water uptake is maximal. The value of h_3 varies with the potential transpiration rate T_p.

For the conversion of solute concentration C into soil water electrical conductivity, EC, one may use C(mg L^{-1}) = EC (dS m^{-1})640.

In order to simplify parameter calibration and use of existing experimental data, one may assume the water and salinity stress to be multiplicative. This means that the actual root water flux density, $S(z)$ (day^{-1}), can be calculated from

$$S(z) = \alpha_{rw}\alpha_{rs}S_p(z), \qquad (5)$$

where α_{rw} (–) and α_{rs} (–) are the reduction factors due to water and salinity stresses, respectively. Integration of $S_a(z)$ over the rooting depth yields the actual transpiration rate T_a.

To obtain a solution of Eq. (3) one has to supplement it with conditions for the initial situation and for the top and bottom boundary of the flow system. At the top the vegetation plays a dominant role in the partitioning of the various fluxes. Hence one needs in principal a coupling of the soil water balance model with a daily vegetation growth model. Only in this way can a proper prediction of vegetation development and growth in dependency of the actual prevailing soil water conditions be obtained, thus assuring the proper feedback.

One example of the integration of Eqs. (1)–(5) into a numerical simulation model is the agro- and ecohydrological model SWAP (Soil–Water–Atmosphere–Plant) as developed by van Dam and Feddes (2000). For application of the SWAP model for multiyear growing seasons of agricultural crops under different irrigation regimes and drainage conditions, see van Dam (2000) (and http://www.alterra.wageningen-ur.nl/onderzoek/afdelingen/water/producten/swap/swap.htm).

A potentially important effect that happens in the real world but that models overlook is the marked influence plant roots can have on the distribution and redistribution of soil water via the processes of "hydraulic lift" (see Fig. 3; Dawson 1996; Caldwell et al. 1998; Jackson et al. 2000b), that is, that deep rooted herbs, grasses, shrubs, and trees take in water from deeper moist soil layers, for example, from being close to the groundwater table, and exude that water during the night into the drier, upper soil layers (during the day, water is absorbed at all depths and passes into the main transpiration stream).

For example, sugar maple trees can hydraulically lift 100 L of water through their roots systems and into the upper soil layer each night. This water is then absorbed the next day and transpired. But also neighboring plants may utilize this source of water. The result of hydraulic lift is usually a decline in groundwater table depth as well as stream discharge, compared with vegetation systems where hydraulic lift is absent.

b. *Large-scale atmospheric modeling*

In general circulation models (GCMs) land surface parameterizations are often based on the concept of a big leaf (Deardorff 1978), implying that the land represented in each grid element of the model is homogeneously covered by a big leaf. However at the resolvable scale of GCMs land surfaces are very heterogeneous. Avissar and Chen (1993) have therefore developed a set of prognostic equations for momentum, heat, moisture, and other gaseous material quantifying mesoscale circulations generated by landscape discontinuities and turbulent fluxes.

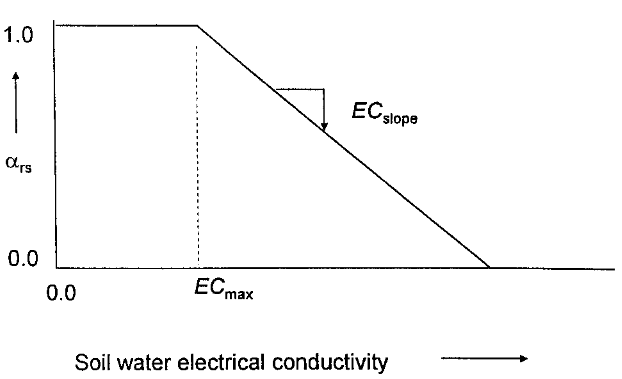

FIG. 2. Reduction coefficient for root water uptake, α_{rs}, as function of soil water electrical conductivity EC (dS m^{-1}) (after Maas and Hoffman 1977).

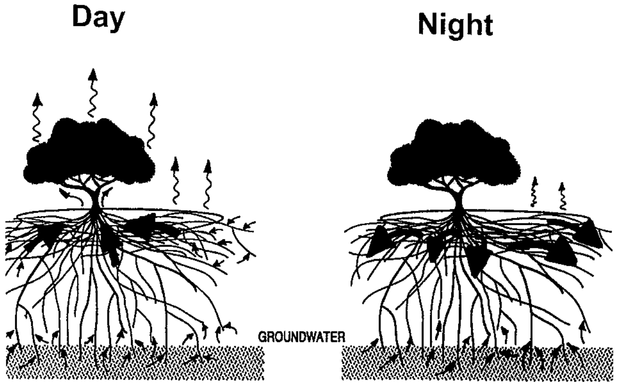

FIG. 3. Hydraulic lift in plants (after Dawson 1996).

On the other hand various soil–vegetation–atmosphere Transfer (SVAT) schemes have been developed for use in GCMs and numerical weather prediction models. Their weakest component however remains their link with the lower boundary. SVAT models face various difficulties, which include (Kalma et al. 1999) comparable complexity between system components; scaling incongruities between atmospheric, hydrological, and terrestrial components; and validation of SVATs at appropriate time- and space scales. SVATs, which sometimes may be overparameterized, use a variety of different methods to represent the relationship between roots, soil moisture and transpiration. Moreover SVAT parameters are generally highly variable in space and difficult to measure. Because of all these reasons it was not a surprise that the Project for Intercomparison of Landsurface Parameterization Schemes showed that different SVATs/Land Surface Schemes (LSSs) driven by the same meteorological forcing of air temperature, humidity, wind speed, incoming solar radiation, longwave radiation, and rainfall can produce remarkably different surface energy and water balances (Chen et al. 1997; Koster and Milly 1997; Pitman et al. 1999). The question in this context was therefore raised: what is the role of roots?

3. Are land surface models and climate models sensitive to the representation of roots?

Using the SWAP model approach described above, one can evaluate the effect of root distribution on the course of actual transpiration in time. We take as an example a grass vegetation (covering the soil completely) with a rooting depth of 80 cm growing on a loamy sand of 2-m depth containing 10% clay (< 2 μm). At the bottom free drainage prevails. As initial condition throughout the profile the soil water pressure head $h = -200$ cm, implying a rather wet soil. Then at the soil surface a potential transpiration rate $T_p = 4$ mm day^{-1} is applied for two different relative root density distributions: Root1, where most of the roots are located in the topsoil, and Root2, where most of the roots are in the lower soil (Fig. 4a).

The result of the simulation is shown in Fig. 4b. Transpiration is more sensitive to the moisture content θ of the densely rooted soil layer than to that in the remainder of the root zone. Hence Root1 produces an earlier onset of moisture stress than Root2, after 30 days showing an actual transpiration rate that is about half that of Root2. Similar results were reported by Desborough (1997). This is a clear demonstration that *roots can influence the behavior of a land surface model, the role of roots being particularly important when soil moisture limits evapotranspiration.*

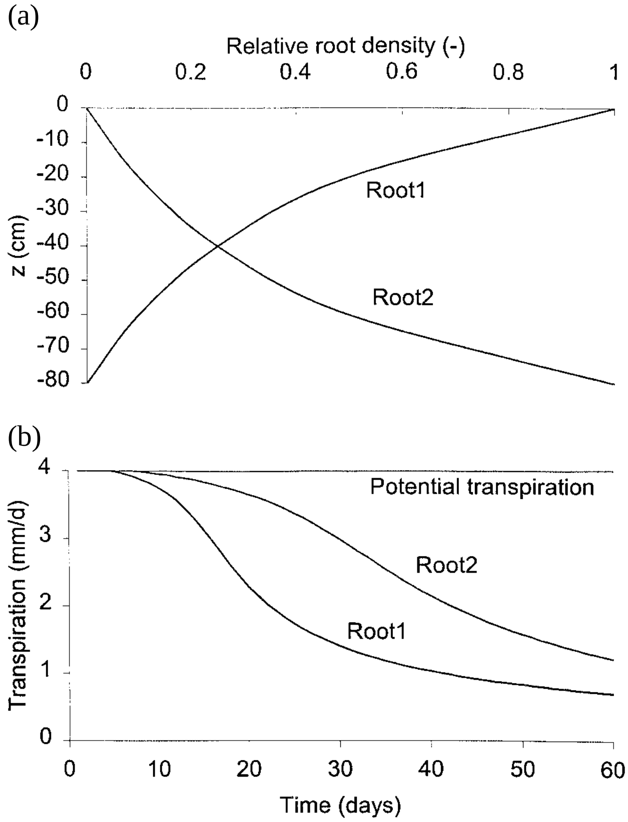

FIG. 4. (a) Two different relative root density distribution functions adopted for grass, with a rooting depth of 80 cm, growing on 2-m-deep loamy sand. (b) Simulating with SWAP the effect of these two different root distribution functions on the actual transpiration rate in time, taking $T_p = 4$ mm day^{-1} as upper boundary condition.

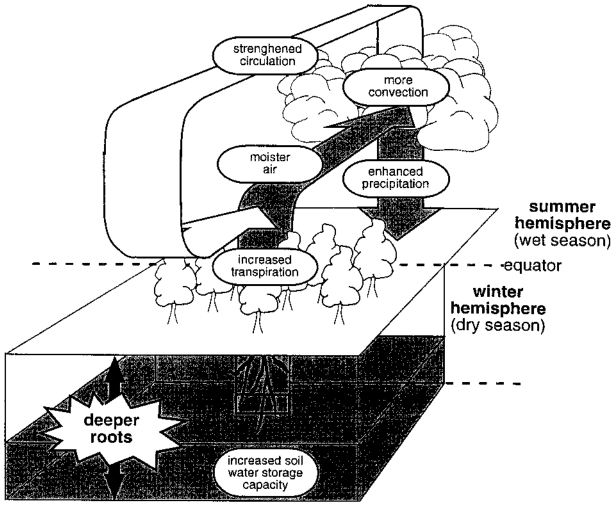

FIG. 5. Illustration of the effects of the incorporation of deeper roots on atmospheric changes as computed by the ECHAM-4 GCM; the shaded areas denote water (after Kleidon and Heimann 2000).

In some LSSs a large portion of root parameterization sensitivity may be caused by the use of inappropriately large surface root fractions that may be inconsistent with observations (Jackson et al. 2000b).

The sensitivity of the water balance to plant-available water capacity (and, by implication, to plant root characteristics in general) has been addressed by several investigators. Milly (1994) formulated a simple supply–demand–storage model of the water balance that allows explicit quantification of the sensitivity of mean water balance to plant-available water capacity. The sensitivity is a function of the capacity itself such that if capacity is so large as to equalize all temporal variability of water supply and demand, then further increase in capacity has no effect. If capacity is small enough to be fully utilized, then the long-term evaporation/runoff partitioning is sensitive to capacity. For the United States east of 105°W, results of Milly (1994) suggest that a doubling or halving of the available water capacity produces about a 25% decrease or increase of runoff (with compensating changes in evapotranspiration). This was taken as an indication that actual rooting depths reflect ecologically optimized responses to weather and climate variability. A near maximization of evaporation, on the global scale, was noted by Milly and Dunne (1994), in connection with GCM-based studies of the sensitivity of a climate model to plant-available water capacity. They found that the annual, global-mean evapotranspiration from land changed by about 70 mm for a factor of 2 change in available water capacity. Resultant changes in precipitation, runoff, energy balance, and atmospheric circulation were also identified. On a global basis, a capacity-induced reduction of evapotranspiration was balanced about equally by decreases in land precipitation and increases in runoff (and, equivalently, ocean–land convergence of atmospheric water vapor). The results of Milly and Dunne (1994) suggest a strong sensitivity of continental evaporation to water capacity, hence closer root modeling in GCMs might improve soil–vegetation control instead of uncontrolled continental evaporation that extracts water from a deep soil moisture reservoir.

GCMs typically use shallow rooting depths around 2 m. However, deep rooted vegetation (of up to 68 m) has been found in the Tropics. Therefore Kleidon and Heimann (2000) investigated the effects of larger rooting depths, associated with the incorporation of deep roots on the surface energy balance and the atmosphere using a GCM. They derived a global dataset of deep rooted vegetation assuming that vegetation adapts to its environment in an optimum way, that is, maximizing net primary productivity. The incorporation of deep rooted vegetation into the GCM leads to large-scale differences in the simulated surface climate and the atmospheric circulation, mostly in the seasonal humid Tropics (Fig. 5).

The increased water availability during the dry season that is associated with deep roots leads to enhanced evapotranspiration, which affects the local surface energy balance leading to lower and more realistic simulated air temperatures. This enhanced evapotranspiration leads to a wetter atmosphere, causing large-scale differences in the atmospheric moisture and heat transport. More moisture is transported toward the intertropical convergence zone causing enhanced precipitation and an overall strengthened atmospheric circulation. Hence deep rooted vegetation forms an important part of the tropical climate system. This conclusion appears to be true for some temperate forest ecosystems as well (Dawson 1996).

Dirmeyer et al. (2000) found that most of the sensitivity of surface evaporative fluxes to soil moisture exists when soil wetness is low, and roots greatly constrain transpiration by conveying soil moisture stress to the plants. This was found to be true in three different LSSs: SSiB (Xue et al. 1991; Dirmeyer and Zeng 1997), Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson et al. 1986, 1993), and Mosaic (Koster and Suarez 1992). The parameterized roots in these LSSs appear to be quite efficient at extracting moisture from the soil and maintaining steady transpiration rates for moderately wet and wet soils, but restricting water fluxes when soil wetness is low.

De Rosnay and Polcher (1998) have presented root water uptake in the LSS Sechiba that receives climatic forcing from the GCM and explicitly takes into account subgrid-scale variability of vegetation and root profiles. Normalized [compare with Eq. (4)] root length density R (varying between 0 at the bottom of the rooting zone and 1 at the soil surface where $z = 0$) is here assumed to depend exponentially on (positive) soil depth z as

$$R = e^{-cz}, \tag{6}$$

where c is a fitting constant depending on the biome considered. In a somewhat alternative way to the earlier approach described in Eqs. (4) and (5) de Rosnay and Polcher (1998) integrate root water uptake from the soil surface through a bottomless soil column to include the entire root system and to obtain a function that is independent of total soil depth. Root water uptake U, being defined as the integral of the water stress exercised by the roots and normalized over the soil depth is then expressed as

$$U = e^{-cd}, \tag{7}$$

where U varies between 0 and 1 and d is the (positive) dry soil depth corresponding to the dry fraction of the first soil moisture layer (Fig. 6). From this figure it is clear (U as large as 0.2 at 2-m depth) that a soil depth greater than 2 m should be considered.

The use of a relatively easily observable parameter such as c makes the development of a global dataset for root water uptake parameterization feasible. The authors conclude that taking into account root profiles (and not only root depth) improves the representation of the seasonal cycle of transpiration, and increases the control of the continental evaporation by the soil–plant system. In a new version of the Sechiba model (de Rosnay et al. 2000), physical soil water flow modeling (Eqs. (1)–(3)] is combined with the macroscopic root modeling approach of Eqs. (4) and (5) and a subgrid-scale variability of the surface, which is new for a GCM. This opens a wide range of possibilities for future applications in large-scale modeling, including simulating groundwater flow and soil–plant–atmosphere interactions at various scales. It also allows representation of the root water uptake at different soil depths depending on the seasons.

Experiments of Zeng et al. (1998) applying the LSS BATS based on both observed global rooting depths and distributions, showed that evapotranspiration as well as soil wetness are affected over tropical as well as over midlatitude land.

Finally, Hallgren and Pitman (2000) performed a sensitivity assessment of the BIOME3 model that selects the plant functional type (PFT), which may potentially be present at any particular location based on ecophysiological constraints, resource availability, and competition. These authors found that if root distribution in the model was varied within observational uncertainty, BIOME3 predicted significantly different distributions of PFTs and that root distribution was one of the most important single parameters within the model.

Overall, there is significant evidence that roots play an important role in the simulations by land surface models. They also appear to be significant in the simulation of the current climate and may play a signifi-

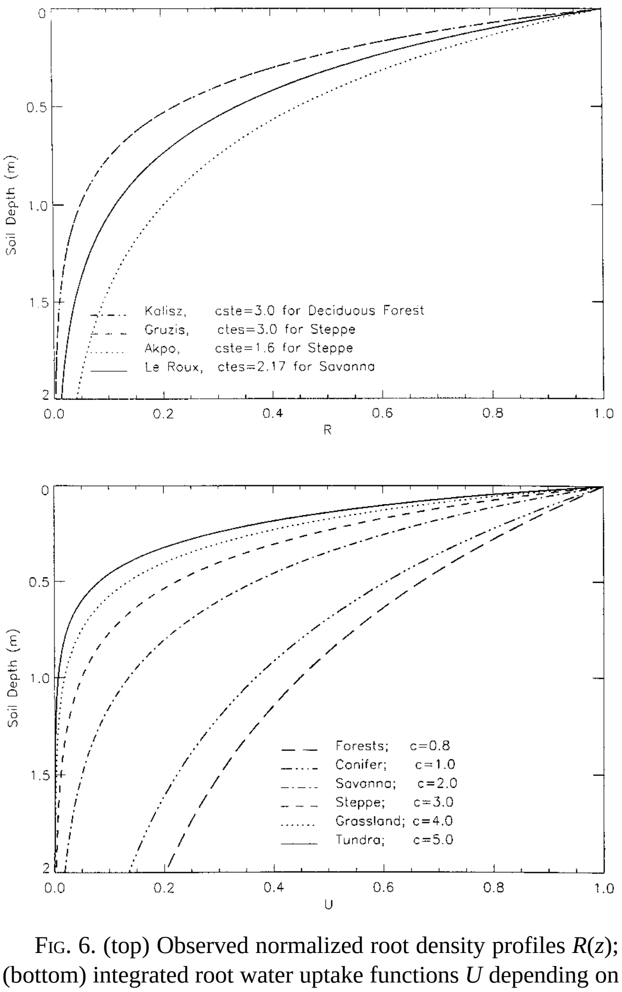

FIG. 6. (top) Observed normalized root density profiles $R(z)$; (bottom) integrated root water uptake functions U depending on soil depth z and the biome-dependent constant c (after de Rosnay and Polcher 1998).

cant role in our ability to simulate both future and past climate. Understanding the interactions of root distributions with water use, as well as potential feedbacks with climate, is important for climate simulations as we determine which systems in nature actually rely on relatively deep soil water (Greenwood 1992; Nepstad et al. 1994; Jackson et al. 2000a).

4. What root and soil information exists?

a. Root information

Because of the sensitivity of simulated transpiration in climate models, global datasets of root and soil properties are increasingly needed. Cumulative root distribution Y from the soil surface down to rooting depth d, here defined as the depth where Y reaches an arbitrary value, for example, 99%, can for various biomes be fitted with a vegetation-dependent coefficient β to the following asymptotic equation (Gale and Grigal 1987; Jackson et al. 1996, 1997; Zeng 2001):

$$Y = 1 - \beta^d. \tag{8}$$

Values for β, and properties like fine/total root biomass, root length, maximum rooting depth, root/shoot ratio, and nutrient content of different terrestrial biomes, can be found in the above cited references.

To date a root database (Jackson et al. 2000a,b) of more than 1000 profiles exists that covers various combinations of maximum rooting depth of fine and coarse roots, root length densities, root biomass (and surface area in a small subset of the data), as well as root nutrient concentrations by biome and plant life form (e.g., Jackson et al. 1996, 1997; Canadell et al. 1996; Gill and Jackson 2000). There is, however, a lack of information on annual crops within the database.

This root database currently has no spatial expression. Work is however underway to implement the data in a spatially explicit manner at 0.5° × 0.5° grid scales for use in climate models. This will be done by using the information within the root database to characterize the root profiles of the 12 major biomes identified within the global International Satellite Land Surface Climatology Project (ISLSCP) spatial dataset and with a continuous vegetation classification scheme in ISLSCP (de Fries and Townshend 1999; de Fries et al. 1999). The root parameters will include global estimates of 50% and 95% rooting depths and maximum rooting depth. Such data represent a first step in providing spatial root profile data at a global scale, but it was also recognized that further field observations of root profiles within undersampled vegetation types may be necessary to improve the overall predictions of the root profile.

b. Soil information

Global-scale spatial datasets of soil types and their allied soil hydrological properties have existed for many years. A number of regional and global soil databases relevant to global change research are currently available (Table 1).

The largest is the National Soil Characterization Database (NSCD) of the U.S. Department of Agriculture (USDA 1994). It contains analytical data for more than 20 000 pedons of U.S. soils (standard morphological descriptions are available for about 15 000 of these) and about 1100 pedons from other countries. A second useful resource is the World Inventory of Soil Emission potentials (WISE) database compiled by the International Soil Reference and Information Centre (Batjes and Bridges 1994; Batjes 1995). This database has a bias toward tropical regions, but its primary purpose is estimating in a spatially explicit fashion the soil factors that control global change processes. The WISE database has information on the type and relative extent of the component soil units of each 0.5° latitude by 0.5° longitude grid cell of the world (derived from the revised 1:5 M-scale Food and Agriculture Organization of the United Nations (FAO) Soil Map of the World) with selected morphological, physical, and chemical data for more than 4350 soil profiles. A subset of 1125 WISE profiles along with some form the NSCD is used in the Global Pedon Database of the International Geosphere–Biosphere Programme Data and Information System (IGBP-DIS) (Tempel et al. 1996). Existing soil maps and soil classification systems need to be translated into physical and hydrological properties for many IGBP activities, including global estimates of water-holding capacity needed by the IGBP Core Project on Biospheric Aspects of the Hydrological Cycle and data for predicting trace gas fluxes and global carbon cycling in the IGBP Core Project on Global Change and Terrestrial Ecosystems. To date in the DIS soils activity, a pedon database has been produced, pedotransfer functions have been developed for soil thermal properties, a procedure for making the data spatially explicit has been implemented, and among others, global fields of C, N, and thermal properties for surface and subsoil ho-

TABLE 1. Database names, soil pedon numbers (where available), contact, and Web site information for eight regional and global soil databases.

Database	Institution	No. of pedons	Contact	Web site information
AMAZONIA	EMBRAPA/WHRC	1153	D. Nepstad	http://www.whrc.org/science/tropfor/LBA/WHRCsoilpr01.htm
CANADA	Canadian Forest Service	1462	M. J. Apps	None available
IGBP-DIS	IGBP-DIS	Variable		http://www.pik-potsdam.de/igbp-dis/igbp-site
NSCD	USDA	>21 000	E. Benham	http://www.statlab.iastate.edu/soils/ss1/natch_data.html
WISE	ISRIC	4350	N. H. Batjes	http://www.isric.nl/WISE.htm
HYPRES	Alterra/MLURI	5521	J. H. M. Wösten/ A. Lilly	http://www.mluri.sari.ac.uk/hypres.htm
Global Plant-Extractable Water Capacity			K. A. Dunne et al	http://www.daac.ornl.gov/daacpages/soils_collections.html
Global Soil Types			Modified L. Zobler	http://www.daac.ornl.gov/daacpages/soils_collections.html
Global Soil Texture and Water-Holding Capacities			R. W. Webb et al.	http://www.daac.ornl.gov/daacpages/soils_collections.html

rizons are available. Windows-compatible software allows users to select the location and spatial resolution for each variable of interest. Various pedotransfer functions to predict soil hydrological properties have also been tested using the IGBP-DIS dataset (Bisher et al. 1999).

Third, the UNSODA database (Database of Unsaturated Hydrolic Properties; Leij et al. 1994; Nemes et al. 1999) contains nongeoreferenced soil hydrological data for approximately 800 soil profiles from around the world and, from which, a suite of pedotransfer functions have been derived (Schaap 1999).

A number of regional soil databases are also relevant to global change studies.

A database of 1153 soil profiles from Amazonia was developed as an input to a rooting depth model for producing a regional map of Amazonian plant available water (de Negreiros and Nepstad 1994).

Another relatively new database from the Canadian Forest Service emphasizes soils data for Canadian forest and tundra sites (Siltanen et al. 1997). It has been used in analyses of carbon storage in boreal systems.

A third regional soil database is Hydraulic Properties of European Soils (HYPRES) established by 20 institutions from 12 European countries (Wösten et al. 1998, 1999). This database holds a wide range of both soil pedological and hydrological data and has a flexible relational structure that allows interrogation by a number of attributes or by a combination of attributes. Almost all records are georeferenced and can be linked to soil profile descriptions. A common problem with many of these databases is that they are often not internally consistent particularly where they have been developed over a number of years or from a variety of sources. This issue was addressed within HYPRES by standardizing both the particle-size fractions according to FAO definitions, and mean hydraulic properties in the form of the easily applicable Mualem–van Genuchten parameters for 11 FAO texture classes. Apart from these mean hydraulic properties, HYPRES has been used to develop regression-type pedotransfer functions that predict the hydraulic properties based on actually measured soil texture data.

Within the modeling community, however, there seems to be currently an overreliance on the empirical correlation between soil texture and soil hydrological properties for the derivation of model parameters. Although such relationships can be demonstrated and used (e.g., Wösten et al. 1999) they generally lack a high degree of statistical confidence. The use of only soil texture inevitably leads to a high degree of variability in soil hydrological properties within each textural class. This variability can be reduced by considering other basic soil factors such as organic matter content, soil type, and pedogenesis in determining soil porosity, which in turn should lead to improvements in model parameterization.

It is also important to note that as soil type (taxonomic unit) and soil characteristics (e.g., waterlogging or the presence of mechanically impeding layers) often modify the form of the plant root profile, there is a need to maintain referential integrity between the biome-type and the soil taxonomic unit. There is a substantial risk of providing inappropriate or highly unlikely combinations of soil type and biome type as a consequence of overlaying these as two independent spatial datasets. Thus prior to providing global-scale rooting parameters and soil hydrological data, there must be a process of validation to ensure the dataset provides realistic estimates.

Last, aggregation that takes into account subgrid variability of roots and soil, requires improved root and soil data in combination with better knowledge of the interaction of these two systems.

5. Conclusions and recommendations on improving root water uptake models

IGBP and the World Climate Research Programme as well as other research programs have a number of activities that focus on below-ground processes. The workshop in October 1999 in Gif-sur-Yvette, France, was a welcomed opportunity to bring together the different communities of hydrological, weather prediction and climate modelers with ecologists and plant physiologists. In addition to root water uptake and transport through the plant to the atmosphere other plant physiological processes were also discussed, including biogeochemical feedbacks, such as water–carbon interactions, that is, carbon investments in developing the root system sufficiently deep for securing water uptake. Putting roots in a wider global change context poses questions as to predictions of changes in roots and root water uptake due to land use and climate change. The workshop developed a research strategy for modeling root water uptake and the consolidation of root datasets through a combination of approaches.

a. *Research strategy—Part 1: How to parameterize and model root water uptake in hydrological, climate, and weather prediction models*

A systematic evaluation of the role of roots and root dynamics in water fluxes between the land surface and the atmosphere is required. A first priority is to firmly establish relationships between root biomass, rooting depth, root distribution, and root functions with vegetation type, soil type, soil texture, topography, and climate. Synergies are to be gained from a combination of this information.

Two different modeling approaches should be pursued to improve root water uptake descriptions:

- Increased detail/complexity of existing physically based models. For this approach it was hypothesized that root water uptake can be modeled better when more complete information on vertical distribution of roots and a physical description of root functioning is available.
- Keeping root water uptake models as simple as possible, with an implicit description of roots that assumes that water in the root zone is available to the plants.

At first glance the two recommended modeling approaches seem at odds—one says complexity, the other says simplify. Two points should, however, be emphasized here. First both perpendicular approaches are needed to ensure that relevant processes are considered and understood, but that appropriate computational weight is paid to each, depending on its importance. Second, complexity really means completeness, both in terms of data (complete sets of parameters, requiring more observations and data mining), and in terms of the relevant processes modeled. The goal here is accuracy and a proper scientific understanding of the physical processes.

An "optimizing systems" perspective could guide the modeling of the vegetation/soil system, in particular with respect to the use of available resources. This may also help to determine the degree of detail required.

Deep roots play a major role in ecosystems such as forests and need to be studied globally in more detail. They are likely to have somewhat more effect in the Tropics than in midlatitudes. On the other hand, the role of shallow roots seems to be overestimated in many land surface schemes.

It should be investigated how one can deal with hydraulic lift, that is, vertical water transfer from deep below toward dryer upper soil layers, resulting from root water transport and efflux to the soil. This mechanism can lead to increased transpiration under water stress conditions and can account for enhanced water loss via plant canopies and hence can change the proportional importance of runoff, drainage and evapotranspiration.

Beyond issues of water uptake and transport there is a need to study all biogeochemical cycles and feedbacks, and whether (and how) to include these in GCMs. An important link to the biogeochemical modeling community could be the issue of above-/belowground partitioning of carbon.

b. Research strategy—Part 2: Consolidation of root and soil data and observations

With respect to the above modeling strategies, data needs from the communities of global climate modeling, numerical weather prediction and mesoscale modeling need to be specified clearly. Potentially relevant root data are rooting depth (maximum and 90% value), root distribution over depth, root surface area or “active roots,” proportion of fine/coarse roots, proportion of live/dead roots, root biomass, and possibly also nutrient content (N, P, K, Ca, Mg) of roots.

This “wish list” needs to be matched with an inventory of existing root data on regional and global scales, including levels of uncertainty in data. Regional priorities for root data are to be established from the climate perspective, like in Monsoon regions such as India, or regions of strong climatic gradients or transition zones.

Synergies in determining root functionality could be gained by linking existing datasets functionally, for example, rooting depth and soil texture with vegetation/biome information. Root data collection should include existing field studies. One important initiative that provides data from a network of harmonized measurements is FLUXNET. In addition to measurements of water and carbon fluxes, site information is available for FLUXNET stations. Currently more than 80 stations in various biomes and climates provide additional site information, for example, on water use and net primary production relationships for certain plant types (see http://daac.ornl.Gov/FLUXNET).

Coregistration and uniform gridding at 0.5° of spatially explicit data would be desirable. Statistical distributions of values within a grid cell should be preserved throughout the aggregation processes. If several land cover types coexist, single root distribution data have to be aggregated to a kind of “effective root distribution function.”

In order to develop gridded root datasets, existing root data should be linked with remote sensing information on vegetation types and leaf area index and correlated with soil data. To obtain effective, mesoscale soil hydraulic parameters there is a considerable potential in combining large-scale inverse modeling of unsaturated flow in combination with remotely sensed areal evapotranspiration and areal surface soil moisture (e.g., Feddes et al. 1993a,b).

A number of regional and global soil databases that are currently available are listed in Table 1. Prior to providing soil hydrological and root datasets there must be a process of validation. A number of well-documented systems should be included in any strategy, in particular crop and deciduous forest systems in North America and Europe.

Two approaches were recommended in combination for the production of a global root database:

- a fast-track product using existing datasets with some “added value” procedures as described above—timeline 6 months;
- a slower-track more systematic product that will link to other relevant initiatives, for example, FLUXNET and future land surface experiments—timeline 3–5 years.

Finally, metadata that explain measured values and methods used to derive information for data-sparse regions, as well as error estimates and confidence levels, should supplement root data.

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