NOTES AND CORRESPONDENCE

Global Datasets of Rooting Zone Depth Inferred from Inverse Methods

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ABSTRACT

Two inverse methods are applied to a land surface model to infer global patterns of the hydrologically active depth of the vegetation’s rooting zone. The first method is based on the assumption that vegetation is optimally adapted to its environment, resulting in a maximization of net carbon uptake [net primary production (NPP)]. This method is implemented by adjusting the depth such that the simulated NPP of the model is at a maximum.

The second method assumes that water availability directly affects the leaf area of the vegetation, and therefore the amount of absorbed photosynthetically active radiation (APAR). Rooting depth in the model is adjusted such that the mismatch between simulated and satellite-derived APAR is at a minimum. The inferred patterns of rooting zone depth from both methods correspond well and reproduce the broad patterns of rooting depth derived from observations. Comparison to rooting depth estimates from root biomass distributions point out that these may underestimate the hydrological significance of deep rooted vegetation in the Tropics with potential consequences for large-scale land surface and climate model simulations.

1. Introduction

The depth of the rooting zone of the vegetative cover, or rooting depth, determines the extent to which soil moisture can be extracted by the vegetation for transpiration. During dry episodes, the access to soil moisture through roots determines the capacity of the vegetation to maintain transpiration, thereby affecting the surface energy and water balance with consequences for the atmosphere. Observations show that deep reaching roots of more than 2-m depth is a common phenomena for many ecosystems across the world (Stone and Kalicz 1991; Canadell et al. 1996). It has also been observed that these deep roots contribute significantly to transpiration during dry periods (e.g., Nepstad et al. 1994). Sensitivity simulations with climate models have demonstrated that land surface and climate system functioning are sensitive to the size of the soil water storage capacity (Milly and Dunne 1994; Kleidon and Heimann 1998a), which is determined by the depth of the rooting zone and how roots are distributed in the soil (Desborough 1997; Zeng et al. 1998). This is particularly the case in regions exposed to extended dry periods, such as the tropical transition regions from humid to arid. Climate model simulations have also emphasized the importance of rooting aspects for global change studies, for instance, with respect to summer dryness under enhanced atmospheric carbon dioxide concentrations (Milly 1997), the climatic impacts of Amazonian deforestation (Kleidon and Heimann 2000), or the continental aridity during the last ice age (Kleidon and Lorenz 2001).

The need to adequately describe below ground aspects was identified by the Terrestrial Observation Panel for Climate (1997) of the Global Climate Observation System (GCOS), in particular the depth that includes 95% of the root biomass as a key variable needed to quantify interactions among climate, soil, and plants. This led to efforts to assemble global root-related datasets suitable for modeling of the climate system and the terrestrial biosphere (Jackson et al. 2000; Feddes et al. 2001). Examples of available datasets are the ones of Dunne and Willmott (1996), Jackson et al. (1996), Cairns et al. (1997), and Schenk and Jackson (2002). For instance, Jackson et al. (1996) and Schenk and Jackson (2002) assembled observations of root profiles to yield a global dataset of root biomass with depth for different biomes of the world (see also the modification by Zeng 2001). While root biomass is important to estimate aspects such as carbon storage and can give some indication of the depth of the rooting zone, it gives little information about how active roots are in terms of soil water uptake, which is needed for land surface and climate models. For instance, the maintenance of transpi-
ration during an extended dry episode in eastern Amazonia was achieved by less than 2% of the total root biomass in the deep soil (Nepstad et al. 1994). What this clearly reflects is that roots serve multiple purposes in addition to water uptake (such as nutrient uptake, anchoring, etc.), and that there are processes associated with roots, which are not fully understood, that may significantly enhance water uptake efficiency of deep roots (such as hydraulic lift; Caldwell et al. 1998). On the other hand, desert vegetation, which has rooting depths reported up to 68-m depth (Stone and Kalicz 1991) would seem unnecessary to be included in a land surface scheme of a climate model. The lack of rooting information for vast regions (in particular in the Tropics) and the variation of rooting patterns with soil texture within biomes (e.g., Hacke et al. 2000) pose potential limitations to the suitability of these datasets for the use in large-scale climate modeling studies.

An alternative way to estimate the hydrologically “active” depth of the rooting zone can be done by inverse methods (Fig. 1). One method, which will be referred to as “maximization,” is based on the assumption that vegetation has adapted to its environment in an optimum way, therefore maximizing the long-term uptake of carbon [e.g., measured by mean net primary productivity (NPP)]. Kleidon and Heimann (1998b) implemented this method to derive a global map of “optimum” rooting depth by using a coupled land surface–vegetation simulation model. This model simulates NPP from atmospheric forcing. Rooting depth was subsequently adjusted such that simulated, long-term NPP was maximized. By using a global climatology, this approach resulted in a global pattern of optimum rooting depth. Another way to indirectly infer rooting depth patterns is based on the assumption that green vegetation indicates the presence of sufficient soil moisture. By assimilating satellite-derived vegetation greenness into a simulation model of the terrestrial biosphere, Knorr (1997) derived a distribution of rooting depth that minimizes the misfit between satellite-derived and model-simulated greenness. Rather than an actual depth of the rooting zone, both of these methods derive a hydrologically “effective” rooting depth; that is, they estimate how much soil moisture is depleted during dry episodes. Therefore, these indirect means of deriving rooting depth patterns complements the sparse coverage of field observations, particularly in water-limited environments.

The objective of this note is to extend Kleidon and Heimann’s (1998b) work by (i) using more realistic climatic forcing, (ii) comparing the simulated global patterns of active rooting depth between the two inverse
methods, and (iii) comparing these to other datasets of rooting zone depth to Canadell et al. (1996) and from root biomass distributions (Zeng 2001; Schenk and Jackson 2002). This will provide us with valuable insights into whether rooting depth can be viewed as a property that has optimally adapted to the environment. This comparison will also point out whether the 95% depths derived from observed rooting biomass profiles adequately capture the “hydrologically active” depths, which may have important consequences for land surface functioning in climate models.

2. Methods

   a. Model description

   This study uses the simple vegetation–land surface model of Kleidon and Heimann (1998b) in order to simulate the seasonal to annual variations of soil moisture dynamics. Their model consists of a “bucket” formulation of soil hydrology. Actual evapotranspiration is calculated as the minimum of supply and demand (Federer 1982). Evaporative demand is described by the equilibrium evaporation rate, based on the approach by McNaughton and Jarvis (1983). Runoff and/or drainage only occurs when the rooting zone reaches field capacity and this water is not available for subsequent evapotranspiration. The value of soil albedo is prescribed in the model. Lateral transport of water among grid points is not considered. Net primary productivity (NPP) is calculated following the approach by Monteith (1977), which expresses NPP as the product of limiting factors and photosynthetically active radiation (PAR). Here, only water limitations will be considered. Comparison of model simulations to river basin discharge and sensitivity simulations are described in Kleidon and Heimann (1998b).

   b. Model setup

   The model runs at a 1° latitude–longitude spatial resolution. It uses a 6-h time step, using atmospheric forcing for two years (1987 and 1988) of solar radiation, thermal radiation, precipitation, and near-surface temperature, which is taken from the International Satellite Land Surface Climatology Project (ISLSCP) 1 dataset [Sellers et al. (1996), based on the the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis]. In its standard version, the model uses a standard rooting depth equivalent of a bucket size of 150 mm of water. The model runs for several years, repeating the atmospheric forcing, with the first two years excluded from the analysis in order to remove spinup effects.
Fig. 2. (Continued)
c. Inverse methods

The two inverse methods are summarized in Fig. 1. The optimization method is based on the assumption that vegetation has adapted to its environment, thus making optimum use of available resources. This approach is implemented by maximization of long-term simulated NPP, or, approximately, the amount of absorbed photosynthetically active radiation (APAR) with respect to rooting depth. This is done iteratively, using golden section search (Press et al. 1992). During each iteration, the model is run for a prescribed value of rooting depth for the entire simulation. The maximization process is constrained to values between 5 and 1000 mm of available water. Note that, since there is no trade-off for increasingly deeper roots, the smallest rooting depth is used at which the maximum of NPP is achieved.

The assimilation method minimizes the discrepancy between simulated absorbed PAR (i.e., APAR) and that derived from remote sensing (Sellers et al. 1994). However, since there is some artificial variations in APAR in tropical rainforest areas, presumably due to cloud contamination, I minimized the variations from the mean (following Knorr 1997), that is, I minimized the cost function $C$ given by

$$C = \sum_{\text{all months}} \left( \frac{\text{APAR}_{\text{OBS}} - \overline{\text{APAR}_{\text{OBS}}}}{\text{APAR}_{\text{SIM}}(W_{\text{MAX}}) - \overline{\text{APAR}_{\text{SIM}}(W_{\text{MAX}})} \right)^2.$$

Again, golden section search was used to iteratively minimize the cost function.

d. Deriving rooting depths

From the simulated seasonal dynamics of soil moisture the minimum and maximum value of soil water content ($W_{\text{MIN}}$ and $W_{\text{MAX}}$, respectively) in the rooting zone is extracted. This magnitude of soil moisture variation is then used as an approximation for the amount of total plant-available water within the rooting zone. This is done in order to exclude the effects of the water stress formulation on the estimate of rooting depth (Kleidon 1998). In order to convert the magnitude of soil moisture variation $W_{\text{MAX}} - W_{\text{MIN}}$ into an actual depth $D$, soil texture information of plant available water (PAW) per meter of soil depth of Batjes (1996) is used:

$$D = \frac{W_{\text{MAX}} - W_{\text{MIN}}}{\text{PAW}}.$$

These depths are averaged over biomes, using the land cover classification of Wilson and Henderson-Sellers (1985) and then compared to biome averages of observed rooting depth (Canadell et al. 1996). The biome averages of rooting depth by Zeng (2001) and Schenk and Jackson (2002) are matched to the biomes used by Canadell et al. (1996).

3. Results and discussion

The mean distribution of APAR, or, directly related, NPP, of the standard simulation is shown in Fig. 2a as a reference. The increase of APAR due to the maximization method is shown in Fig. 2b. The largest increases can be found in regions with a pronounced dry season, in particular in the seasonal Tropics, Mediterranean climates, and some parts of the humid midlatitudes. As one would expect, the variation of rooting depth in arid regions and in the high latitudes does not increase APAR substantially. In arid regions, precipitation is so limited that no substantial soil storage capacity is needed to retain it. In high latitudes, evaporative demand is low so that no large storage sizes are required. The reduction of mismatch between simulated and satellite-derived APAR due to the assimilation method is shown in Fig. 2c. Areas in which the mismatch was substantially reduced roughly correspond to the areas in which APAR was substantially increased by the optimization method (Fig. 2b). These patterns most noticeably deviate in tropical Africa, where the reduction of error is confined to a much smaller region. The fact that the errors cannot be reduced in the adjacent regions means that, by adjusting rooting depth, the seasonal course of seasonal APAR cannot be improved by changing the water storage capacity. Therefore, other factors would need to be considered for these particular regions. Both patterns are consistent with previously reported results (Kleidon and Heimann 1998b; Knorr 1997).

a. Comparison of methods

The active rooting depths derived by these methods are shown in Fig. 3 in terms of a “hydrological” depth, that is, the amplitude of soil water storage $W_{\text{MAX}} - W_{\text{MIN}}$. Both methods lead to very similar patterns, leading to a correlation coefficient of $r = 0.83$ when compared on a point-by-point basis. The optimization method tends to show larger active rooting depth values compared to the assimilation method, which is also reflected in the biome averages shown in Fig. 4. This difference is most pronounced in the semiarid regions of tropical Africa and may be attributed to land use changes or vegetation types that have alternative drought avoidance strategies (dry-deciduous forest and savanna).

b. Comparison to Canadell et al. (1996)

Also shown in Fig. 4 are the biome averages of maximum rooting depth $D_{\text{MAX}}$ from observations. In general, the trend of observed depths is well reproduced by both methods. In most biomes, the rooting depths derived here are smaller, which may be attributed to the fact that observed rooting depths do not necessarily reflect actual size of the water storage capacity while the two methods used here simulate hydrologically active, or
FIG. 3. Depth of the rooting zone (in mm H$_2$O of plant-available water) inferred from (a) maximization and (b) assimilation.
Fig. 4. Comparison of biome averages of inferred rooting zone depths from maximization $D_{\text{OPTI}}$ and assimilation $D_{\text{ASSI}}$ from this study: observations of maximum rooting depth $D_{\text{MAX}}$ (Canadell et al. 1996), rooting depths $D_{\text{OPTI}}$ inferred from maximization in a previous study (Kleidon and Heimann 1998b), and derived from root profiles by taking the depth that contains 99% of the root biomass (Zeng 2001) and 95% of the root biomass (Schenk and Jackson 2002).

c. Comparison to Kleidon and Heimann (1998b)

The rooting depths derived here are generally smaller than those from an earlier study (Kleidon and Heimann 1998b). This is most likely attributable to differences in climate variability in the atmospheric forcing used. The previous study made use of a weather generator to generate climatic variability. This likely led to artificially high variability in dry regions, especially in deserts, thus overestimating the importance of soil water storage. However, an important difference is that the rooting depth for the tropical evergreen forest biome is notably higher in this study. This again can be attributed to a more realistic representation of climatic variability in the forcing (e.g., for the Amazonian basin where pronounced effects of El Niño are documented).

d. Comparison to Zeng (2001) and Schenk and Jackson (2002)

The other two estimates for rooting depth in Fig. 4 are both derived from biomass rooting profiles. While Zeng (2001) defined rooting zone depth by using the functional, rooting depth. Notably, this functional rooting depth is overestimated by both methods for the dry deciduous forest biome. This can be explained by the fact that dry deciduous vegetation avoids water stress by senescence. Predicted rooting depths for tundra are also overestimated, which may be attributable to physical restrictions of root development, such as a short growing season and permafrost.
depth $D_{99}$ at which 99% of the total root biomass is contained, Schenk and Jackson (2002) used a depth $D_{95}$ corresponding to 95% of the root biomass. The $D_{95}$ depth is generally lower for all biomes than the estimates derived here, which indicates that $D_{95}$ may not adequately describe the depth that captures the full seasonal soil moisture dynamics, particularly in the humid Tropics. There is closer agreement between the estimates of this study with $D_{95}$ in temperate regions while in tropical biomes, $D_{99}$ is generally smaller. Considering that the hydrological significance of deep roots has been documented for some of the biomes (e.g., Nepstad et al. 1994) and that these roots represent less than 2% of the total root biomass (i.e., these roots are below the 98% depth), what this comparison indicates is that rooting depths derived from root biomass profiles may systematically underestimate the depth of seasonal soil moisture dynamics, particularly in tropical regions.

e. Limitations

The inverse methods as well as the simple model used in this study naturally carry some inherent limitations, which are discussed in detail in Kleidon and Heimann (1998b). As pointed out above, alternative drought avoidance strategies like dry deciduous vegetation have not been considered here and can explain the overestimation for this biome. Not considered here are physical limitations by bedrock or permafrost, which can explain the overestimation of estimates for the tundra biome. Also, other sources of water, for instance ground water, lateral flow, or from irrigation, has not been considered here. The use of a bucket-type model may underestimate the amount of surface runoff, which is likely to have the largest consequences in semiarid regions.

4. Summary and conclusions

Two different inverse approaches have been used to infer the hydrologically active depth of the rooting zone. Both approaches lead to similar results for many regions of the world and produce patterns consistent with biome averages of observations. The fact that both inverse approaches lead to similar patterns also suggests that natural vegetation may indeed operate close to maximizing productivity and/or land surface evapotranspiration. The resulting patterns also indicate that rooting zone depths derived from root biomass profiles may not be sufficient in capturing the seasonal soil moisture dynamics in tropical areas. The estimates given here should provide guidance on defining the hydrologically active rooting zone depth for land surface and climate modeling studies.

The general methodology used here could be extended and be applied to multilayer land surface models. Such an extension would possibly allow for the determination of root biomass profiles by these inverse methods and a comparison to observed root biomass profiles could help to identify the relationship of rooting biomass and water uptake characteristics. This would be an interesting direction of future research (see also van Wijk and Boutsen 2001).

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