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Coupled modeling of the hydrological and carbon cycles in the soil–vegetation–atmosphere system

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Abstract

A coupled model of the hydrological and carbon cycles in the soil–vegetation–atmosphere system is suggested. The model describes the interception and evaporation of precipitation by canopy, transpiration, vertical transfer of soil moisture, photosynthesis, the interaction between transpiration and photosynthesis, and plant and soil respiration. The validation of this model was carried out using the FIFE measurements from a grassland site in Kansas, the BOREAS measurements from a jack pine forest site in Saskatchewan, and the observations conducted within a deciduous forest in the southeastern United States. The model results show a good agreement with experimental data. The model was shown to adequately describe the influence of soil moisture and atmospheric CO_2 concentration on transpiration and net ecosystem CO_2 exchange.

Keywords: Hydrological processes; Carbon cycle; Vegetation ecosystems; Modeling; Stomatal resistance

1. Introduction

Despite a large progress in understanding the role of the terrestrial biosphere in regulating energy, water, and carbon dioxide fluxes in the climate system, simulation models of these processes have not been sufficiently developed yet to yield reliable estimates of water and carbon dioxide fluxes for different types of terrestrial ecosystems. There are considerable uncertainties in calculating carbon sinks and sources in an ecosystem and variations of carbon dioxide and transpiration fluxes in space and time. At the same time, these calculations are extremely important for determining possible changes in the climate system and the sensitivity of terrestrial ecosystems to climate change.

The complicated interactions between hydrological and biogeochemical processes and the diversity of these interactions in various vegetation ecosystems makes constructing mathematical models of water and carbon exchanges in the soil–vegetation–atmosphere system very difficult. Moisture content of the soil, vegetation, and atmosphere, as well as water evaporation and transpiration affect both directly and indirectly the photosynthesis and respiration of vegetation and microbiological processes in the soil. At the same time, vegetation controls transpiration through its internal physiology related to

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photosynthesis and respiration and through its albedo, geometric structure, and leaf area. The geometric structure of plants and the characteristics of their leaves also influence the energy and water exchange of the ecosystems. The most important interaction mechanism in the water and carbon exchange of plants is expressed in variation of the stomatal resistance to air fluxes. The stomatal openings respond very quickly to changes in the environment, and the stomatal resistance has a well-expressed diurnal cycle, as well as seasonal and inter-annual variations caused by hydrometeorological conditions or biological processes in plants.

Most studies in the investigation and simulation of the dependence of transpiration and photosynthesis on hydrometeorological variables were aimed at solving agricultural problems (first of all, irrigation and programming of harvest) (e.g. Monteith and Unsworth, 1990; Bihele et al., 1980; Hillel, 1982; Brutsaert, 1981). On the other hand, numerous studies have addressed the biophysical aspects of respiration and photosynthesis (e.g. Thornley, 1976; Farquhar, 1980; Kobak, 1988; Amthor, 1989). However, these studies did not pay proper attention to the interaction between hydrological and biogeochemical processes as parts of the climatic system. The coupling of models of the hydrological and carbon cycle provides an instrument for improving descriptions of both cycles for predicting the effects which could not be accounted for by independent hydrological or carbon models.

Large-scale international field experiments (FIFE, HAPEX-Sahel, BOREAS, NOPEX) significantly extended the possibility to integrate the descriptions of the hydrological and carbon cycles into coupled models. These experiments produced unique data collected by simultaneous short-term measurements of energy, water, and carbon dioxide fluxes in the atmosphere, vegetation, and soil for various ecosystems and created a totally new base for the development of complicated models, testing assumptions, and estimation of sensitivity of ecological systems to different environmental and human impacts. Numerous studies have been devoted to analysis of these data and their use for the development and evaluation of biophysical models of CO_2 exchange and evapotranspiration. The results of model evaluations and model comparisons for different elaboration levels of the description of processes have been reported by Baldocchi et al. (1997); Lloyd et al. (1997); Cox et al. (1998); Baldocchi et al. (2001) and in other publications.

In this paper, we present a coupled model of heat, water, and carbon exchange in the soil–vegetation–atmosphere system, which has been constructed and evaluated on the basis of measurements carried out during FIFE and Boreas, as well as observations in a forest site, located in the southeastern United States and included in the international FLUXNET project of study of long-term carbon dioxide fluxes. The main distinction of this model from previous ones is a more detailed description of the vertical heat and water transfer in the soil–vegetation–atmosphere system. At the same time, we tried to reduce, as much as possible, the number of parameters to be calibrated.

2. Model description

It is assumed that a fraction U_k of the precipitation rate P_f is intercepted by the canopy and can be temporarily stored, evaporated, or drained to the soil surface; the remaining part $(1-U_k)$ reaches the soil surface directly. It is supposed also that the canopy storage capacity is exponentially distributed over the canopy area with the maximum value W_{cm} and the evaporation from the wet part of canopy is equal to the water surface evaporation E_w. In this case, the precipitation rate P_s reaching the soil at the moment t can be calculated as

$$P_S = P_f(1-U_k) + (P_f - E_w)\eta U_k, \qquad (1)$$

where $\eta = 1 - \exp(-S/W_{cm})$ is the proportion of canopy area from which the stored water drains to the soil surface, $S = \int (P_f - E_w)dt$ and $W_{cm} = \mu \times \mathrm{LAI}$, where LAI is the leaf area index and μ is an empirical coefficient (according to Dickinson (1983) μ varies from 0.05 to 0.20 mm).

Evaporation from the wet part of canopy is given by

$$E_w = \rho_a \frac{q^*(T_f) - q_a}{r_a} \eta U_k \qquad (2)$$

where ρ_a is the air density, q_a is the specific air humidity, $q^*(T_f)$ is the saturated specific air humidity