

Short Communication

Modeling of influence of hydrological processes on the carbon cycle of a forest ecosystem

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Abstract

A coupled model of the hydrological and carbon cycles in a forest ecosystem is suggested. The model includes interception, vertical moisture transfer in the system “soil–forest vegetation–atmosphere”, heat balance and temperature variation of canopy, photosynthesis and its relation to the leaf temperature and stomatal conductivity, plant and soil respiration. The model was tested with data for a pine forest plot in central Canada carried out during the international experiment BOREAS. Most model parameters have been assigned on the basis of field measurements, several parameters were taken from publications; four parameters have been calibrated using the latent heat and CO₂ measurements. Model results were in good agreement with the observed values for evapotranspiration, soil moisture, and net CO₂ ecosystem exchange.

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Software availability

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Availability: expected to be distributed as soon as
licensing issues are solved

1. Introduction

The boreal forest occupies about 11% of land, mainly in Russia and Canada. Interaction between water and carbon fluxes in boreal forest ecosystems may play

a significant role in existence of this biome and its impact on the regional and global climate. Photosynthetic capacity of the boreal ecosystems and carbon exchange with the atmosphere depend on complicated biophysical and hydrological processes in forest plants and soils, and a small change in energy and water fluxes may destroy the existing equilibrium. Shortage of detailed measurements of moisture and carbon fluxes in forest ecosystems for a long time was the main barrier in constructing reliable models of coupled hydrological and carbon cycles. A unique opportunity to improve these models has appeared after continuous monitoring has started in the framework of international field experiments including the Boreal Ecosystem-Atmosphere Study (BOREAS). This paper is based on the observations gathered by the BOREAS team at the tower flux site in a boreal jack pine forest in central Canada during the 1994 growing season (Newcomer et al., 2000). We developed and validated a coupled model of the hydrological and carbon cycles for a forest

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ecosystem that describes the interaction between main hydrological and biogeochemical processes and can be commonly provided by the information needed for calibration of unmeasured parameters.

2. Model description

It is assumed that a fraction U_k of the precipitation P_f reaches the forest floor directly; the remaining part $(1 - U_k)$ is intercepted by canopy and may be temporarily stored, evaporated or drained to the forest floor. 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 canopy E_w equals the evaporation from water surface. In this case, the precipitation P_s reaching the forest floor at the moment t can be calculated as

$$P_s = P_f U_k + (P_f - E_w) \eta (1 - U_k) \quad (1)$$

where $\eta = 1 - \exp(-S/W_{cm})$ is the relative portion of canopy area from which stored water drains to the forest flow and $S = \int_0^t (P_f - E_w) dt$. The evaporation from the wet part of canopy is given by

$$E_w = \rho_a \frac{q^*(T_f) - q_a}{r_a} \eta (1 - U_k) \quad (2)$$

where ρ_a is the air density, q_a is the specific air humidity, $q^*(T_f)$ is the saturated specific air humidity at leaf temperature T_f , r_a is the aerodynamic resistance for water vapor at the leaf surface.

Transpiration from dry leaves can be calculated as

$$E_f = \rho_a \frac{q^*(T_f) - q_a}{r_a + r_s} \text{LAI} \quad (3)$$

where LAI is the leaf area index, r_s is the stomatal resistance calculated by the modified formula of Jarvis (1976):

$$r_s = r_0 \frac{\theta_{fc} - \theta_r}{\theta - \theta_r} \left(1 + \frac{\gamma}{\text{PAR}} \right) \quad (4)$$

where r_0 is the stomatal resistance at fully opened stomata, θ is the volumetric soil moisture content, θ_{fc} is the moisture content at the field capacity, θ_r is the residual moisture content, PAR is the photosynthetically active radiation, γ is an empirical coefficient.

The evaporation from bare soil E_g can be found using

$$E_g = \rho_a \frac{r q^*(T_g) - q_a}{r_{ag}} \quad (5)$$

where r_{ag} is the resistance of the soil to evaporation, T_g is the soil temperature, r is the relative air humidity at the soil surface. The value r is found from assumption that $r = \exp[Mg\psi(\theta)/R(T_g + 273)]$, where M is the

molecular weight of water, R is the universal gas constant, $\psi(\theta)$ is the soil water potential.

To describe vertical transfer soil moisture, the Richards equation in the diffusion form is used:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[D(\theta) \frac{\partial \theta}{\partial z} - K(\theta) \right] - S_k(\theta, z) \quad (6)$$

where $K(\theta)$ is the soil hydraulic conductivity, $D(\theta)$ is the soil diffusivity, z is the soil depth, $S_k(\theta, z)$ is the uptake of water by plant roots which is defined from:

$$S_k(\theta, z) = -K(\theta) [\psi_e(\theta) - \psi(\theta)] b \rho_k(z) \quad (7)$$

where $\psi_k(\theta)$ is the water potential of root system, $\rho_k(z)$ is the root density. It is assumed that $\rho_k(z) = \rho_0 \exp(-k_1 z)$ where ρ_0 is the root density at the soil surface, k_1 is an empirical constant.

The functions $K(\theta)$, $\psi(\theta)$ and $D(\theta)$ are expressed through the soil moisture content and the soil constants (the saturated hydraulic conductivity K_s , the soil porosity θ_s , the residual moisture content θ_r) using relationships suggested by van Genuchten (1980). It is assumed that $E_f = \int_0^{z_{max}} S_k(\theta, z) dz$ where z_{max} is the depth of root distribution.

The soil surface temperature T_g is given from measurements; the leaf temperature T_f is calculated from the heat balance equation for canopy using the measured values of the soil temperature, short-wave radiation absorbed by the canopy and atmosphere long-wave radiation. The system (Eqs. (1)–(7)) was solved numerically with an implicit finite difference scheme and a procedure described by Kuchment and Startseva (1991).

The carbon dioxide flux through the leaf stomatal openings (the net leaf photosynthesis rate) can be found as $A = (C_a - C_i) / (1.6r_s + 1.4r_a)$ where C_a and C_i are the CO_2 concentration at measurement level in atmosphere and within the leaf, respectively (Cox et al., 1998). To assign C_a , the measurements of CO_2 at the upper boundary of canopy were used. To calculate internal concentration C_i , the model of leaf photosynthesis and carbon exchange taken from Farquhar et al. (1980) and Collatz et al. (1991) was used. In this model the leaf photosynthesis $P = A + R_d$ (R_d is the leaf dark respiration) is a function of C_i and the rate of carboxylation V_T that depend on the leaf temperature and the photosynthetically active radiation. The model has two adjustable parameters: the maximum carboxylation rate of leaves, V_{max} , and the quantum efficiency, α . The leaf dark respiration was estimated as $R_d = 0.025 V_T$.

The following relationships were used to transfer from the leaf model to the canopy model: $P_c = P \cdot \text{LAI}$, $R_p = R_d \cdot \text{LAI}_c$ where P_c and R_p are the gross canopy photosynthesis rate and the plant respiration, LAI_c is the plant area index which includes except the leaf area, the area of canopy branches and stems. The difference

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