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Application of a two-dimensional model to describe the CO_2 exchange between a spatially non-uniform forest stand and the atmosphere

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Within the framework of the study a two dimensional hydrodynamic high-resolution model of the energy, H_2O, CO_2 turbulent exchange was developed and applied to describe effect of the horizontal and vertical heterogeneity of a forest canopy on CO_2exchange between soil surface, forest stand and the atmosphere under different weather conditions. Most attention in the study was paid to analyze the influence of forest clearing, windthrow of different sizes, forest edges, etc. on turbulent exchange rate and CO_2 flux partitioning between forest overstorey, understorey and soil surface. The modeling experiments were provided under different wind conditions, thermal stratification of the atmospheric boundary layer, incoming solar radiation, etc. To quantify effect of spatial heterogeneity on total ecosystem fluxes the modeling results were compared with CO_2 fluxes modeled for a spatially uniform forest canopy under similar ambient conditions.

The averaged system of hydrodynamic equations is used for calculating the components of the mean velocity $\vec{V} = \{V_1,\ V_2\}$:

$$\frac{\partial V_i}{\partial t} + V_j \frac{\partial V_i}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial \delta P}{\partial x_i} - \frac{\partial}{\partial x_j}\left(\delta_{ij}E - K\left(\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i}\right)\right) + F_i, \qquad \frac{\partial V_i}{\partial x_i} = 0,$$

where E is the turbulent kinetic energy (TKE), K is the turbulent diffusivity, δP is the deviation of pressure from the hydrostatic distribution and $\rho_0 \vec{F}$ is the averaged force of air flow interaction with vegetation. $\vec{F}$ was parameterized as $\vec{F} = -c_d \cdot LAD \cdot \left|\vec{V}\right| \cdot \vec{V}$, where c_d is the drag coefficient and *LAD* is the leaf area density. The turbulent diffusivity K can be expressed by means of TKE and the velocity of TKE dissipation ε as follows: $K = C_\mu E^2 \varepsilon^{-1}$, where C_μ is the proportionality coefficient.

One of the ways to obtain E and ε is to solve the additional system of two differential equations of diffusion-transport type:

$$\frac{\partial E}{\partial t} + V_j\frac{\partial E}{\partial x_j} = \frac{\partial}{\partial x_i}\left(\frac{K}{\sigma_E}\frac{\partial E}{\partial x_i}\right) + P_E - \varepsilon, \qquad \frac{\partial \varphi}{\partial t} + V_j\frac{\partial \varphi}{\partial x_j} = \frac{\partial}{\partial x_i}\left(\frac{K}{\sigma_\varphi}\frac{\partial \varphi}{\partial x_i}\right) + \frac{\varphi}{E}\left(C_\varphi^1 P_E - C_\varphi^2 \varepsilon\right) - \Delta_\varphi,$$

where σ_E and σ_φ are the Prandtl numbers, P_E is the TKE production by shear, C_φ^1 and C_φ^2 are the model constants. The term $\Delta_\varphi = \frac{\varphi}{E}\left(C_{\varphi 1} - C_{\varphi 2}\right) \cdot 12 C_\mu^{1/2} c_d LAD \left|\vec{V}\right| E$ describes the increase of TKE dissipation due to the interaction with vegetation elements.

The function φ can be any of the following variables: ε, ε/E, or El, where l is the mixing length. Detailed analysis of these equations performed by Sogachev (Sogachev, Panferov, 2006) showed that for $\varphi = \varepsilon/E$ the model is less sensible to the errors of the input data.

Transfer equation for CO_2 within and above a plant canopy can be written as:

$$\frac{\partial C}{\partial t} + V_j\frac{\partial C}{\partial x_j} = \frac{\partial}{\partial x_i}\left(\frac{K}{\sigma_C}\frac{\partial C}{\partial x_i}\right) + F_C,$$

where C is CO_2 concentration, σ_C is the Prandtl number, and the term F_C describes the sources/sinks of CO_2 in the vegetation and soil. For parameterization of the photosynthesis rate in the forest canopy the Monsi and Saeki approach (Monsi M., Saeki T., 1953) was applied. Stem respiration was ignored in the study. The CO_2 emission from the soil surface into the atmosphere was assumed to be constant for entire forest area.

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