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Extended Abstract

Mathematical Modeling of Vegetation Heterogeneity and Complex Topography Effects on Turbulent Exchange of GHG within the Atmospheric Surface Layer †

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Abstract: The local-scale 2D and 3D models of greenhouse gases (GHG) exchange between a non-uniform land surface and the atmosphere were developed. They are based on solution of the system of averaged Navier-Stokes, continuity and diffusion-advection equations. For numerical solution of the differential equations the stable finite-difference schemes were suggested. The models were applied to derive effects of complex topography and vegetation heterogeneity on 2D-3D air flow patterns, as well as on CO_2 exchange within the atmospheric surface layer. Several numerical experiments were also provided to describe the air-flow re-establishing after its interaction with some obstacle (e.g., forest edge). Quantitative criteria for selection of the experimental sites for continuous eddy covariance flux measurements characterized by minimum effects of horizontal advection on measured fluxes were suggested.

Keywords: atmospheric surface layer; GHG turbulent transfer; 2D and 3D hydrodynamic models; 1.5-closere scheme

1. Introduction

Accurate projection of climate changes requires adequate parameterizations of the land surface-atmosphere interaction and fluxes of greenhouse gases (GHG) at the land surface—atmosphere interface. To derive fluxes of GHG between land surface and the atmosphere in the last decades the numerous models of different scales and levels of complexity were suggested and applied [1–3]. One of the key topics of the modern studies of land surface—atmosphere interaction is an estimation of effects of land surface heterogeneity (such as topography and vegetation) on atmospheric fluxes of GHG, including water vapor and carbon dioxide. Most of existed modeling approaches ignore usually the local scale heterogeneity of vegetation and surface topography and consider the land surface as horizontally uniform area [1,2]. To validate the different model parameterizations describing the GHG exchange between land surface and the atmosphere the experimental data from global observation networks (such as FLUXNET) are usually used. The eddy covariance method is the main measuring technique that is used in these monitoring stations [4]. These measurements are performed using common methodology, equipment and software that provide their good comparability. The eddy covariance method is based on numerous assumptions (e.g., negligible flow convergence and divergence, negligible density fluctuations, etc.) and assumes the horizontal terrain (vegetation and topography) homogeneity. It is obvious that any flux measurements performed using this method over non-uniform land surface can result in large uncertainties in flux estimations.

Within the framework of the study the local-scale 2D and 3D models of GHG exchange between a non-uniform land surface and the atmosphere were developed to derive effects of vegetation heterogeneity and complex topography on spatial air flow patterns, and on CO_2 exchange within the atmospheric surface layer. Stable finite-difference schemes for a numerical solution of the corresponding initial-boundary value problems were suggested and realized. Moreover the processes of the air-flow re-establishing after its interaction with some obstacle were numerically investigated and some quantitative criteria for selection of station location for continuous eddy covariance flux measurements, at which the horizontal advection in case of mosaic vegetation is insignificant and can be neglected, were suggested.

2. Materials and Methods

The developed 2D and 3D models are based on a system of averaged Navier-Stokes and continuity equations for the mean wind-speed components using a 1.5-order closure scheme [5–10]:

$$\frac{\partial V_i}{\partial t} + \left(\vec{V}, \nabla\right) V_i = -\frac{1}{\rho_0}\frac{\partial}{\partial x_i}\delta P - \sum_{j=1}^{n}\frac{\partial}{\partial x_j}\overline{\left\langle v_i' v_j' \right\rangle} + g\frac{\delta T_v}{T_0}\delta_{i,n} + F_i,$$

$$\operatorname{div}\vec{V} = 0,$$

where V_i and v_i' are averaged and fluctuating components of the wind speed, x_1 is the horizontal coordinate in the prevailed air flow direction, x_n is the vertical coordinate, ρ_0 is the density of dry air, δP is the deviation of the mean air pressure from the hydrostatic distribution, F_i is a component of the viscous drag force. The symbol $\overline{\langle \ \rangle}$ denotes the average over a certain time interval and space volume, g is the gravitational acceleration, δT_v is the deviation of the virtual temperature from the adiabatic temperature T_0 for dry air. The 1.5-order closure scheme assumes that the turbulent fluxes $\overline{\left\langle v_i' v_j' \right\rangle}$ can be expressed using the turbulent kinetic energy $\bar{e}$ (*TKE*) and space derivatives of the averaged wind speed components:

$$\overline{\left\langle v_i' v_j' \right\rangle} = \frac{2}{3}\delta_{ij}\bar{e} - K\left(\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i}\right),$$

$$\bar{e} = \frac{1}{2}\sum_{j=1}^{3}\overline{\left\langle \left(v_j'\right)^2 \right\rangle},$$

$$K = C_\mu \bar{e}^2 \varepsilon^{-1},$$

where ε is the dissipation rate for *TKE* and C_μ is the dimensionless model constant. The functions $\bar{e}$ and $\varphi = \varepsilon / \bar{e}$ can be found by solving the following equations [5,9]:

$$\frac{\partial \bar{e}}{\partial t} + \left(\vec{V}, \nabla\right)\bar{e} = \operatorname{div}\left(\frac{K}{\sigma_e}\nabla\bar{e}\right) + P_{\bar{e}} - \varepsilon - g\frac{\alpha_a K}{T_0}\frac{\partial}{\partial x_n}\delta T_v,$$

$$P_{\bar{e}} = -\sum_{i=1}^{n}\sum_{j=1}^{n}\left\langle \overline{v_i' v_j'} \right\rangle \frac{\partial V_i}{\partial x_j},$$

$$\frac{\partial \varphi}{\partial t} + \left(\vec{V}, \nabla\right)\varphi = \mathrm{div}\left(\frac{K}{\sigma_\varphi}\nabla\varphi\right) + \frac{\varphi}{\bar{e}}\left(C_{\varphi 1}P_{\bar{e}} - C_{\varphi 2}\,\varepsilon - C_{\varphi 3}\,g\frac{\alpha_a K}{T_0}\frac{\partial \delta T_v}{\partial x_n}\right) + 12\sqrt{C_\mu}\left(C_{\varphi 2} - C_{\varphi 1}\right)c_d LAD\left|\vec{V}\right|\varphi,$$

where σ_e , σ_φ are the Prandtl number and turbulence Schmidt number, α_a is the inverse-turbulent Prandtl number for the temperature, $C_{\varphi 1}$, $C_{\varphi 2}$, $C_{\varphi 3}$ are model constants. The initial and boundary conditions in the developed model were taken to be consistent with the classical 1D model, which is widely used for horizontally homogeneous surfaces [8,10]. The main system of equations also includes diffusion-advection equation for turbulent transfer of GHG:

$$\frac{\partial C_s}{\partial t} + \left(\vec{V}, \nabla\right)C_s = \mathrm{div}\left(K_C \cdot \nabla C_s\right) + F_C,$$

where C_s is the concentration of the tracer (e.g., CO_2), K_C is the turbulent exchange coefficient for GHG, F_C describes the sources/sinks of GHG.

3. Results

Using the models described above we investigated the air-flow re-establishing after its interaction with some obstacle in the case of neutral atmospheric stratification. The scenarios of numerical experiments assumed that the air flow crossed the boundary between some open area (e.g., bare soil) and some area covered by vegetation of different height (from 1 m to 20 m) and leaf area index, LAI (from 1 to 5 m^2 m^{-2}) in both directions. The results of our numerical experiments showed that the vegetation edge influences significantly on the spatial air flow pattern in downwind direction. Since mean vertical wind speed component must be negligible in the steady-state flow under neutral atmospheric conditions, we used the smallness of its derivative with respect to horizontal coordinate as criteria for the air flow re-establishing. Results showed that the air flow re-establishment distance from vegetation edge is strictly depended on the height and density (LAI) of vegetation cover (Figure 1). Higher vegetation results in increase of the air flow re-establishment distance at both modeling scenarios. On the other hand, the vegetation density influences on air flow re-establishing very differently. Whereas an increase of LAI in the first scenario (the air flow moves from open area to the land surface covered by vegetation) results basically in decrease of the air flow re-establishment distance, an increase of LAI in the second scenario (the air flow moves from the area covered by vegetation to open area) leads in turn to opposite effects. In case of high forest vegetation the air flow re-establishment is manifested at the distance of about 450 m from the forest edge. In case of lower vegetation the distance of the air flow re-establishment decreased to 60–80 m. These ranges can be considered as a minimum distance from vegetation edge at which the influence of air flow disturbances due to air flow interaction with vegetation edge is minimal and turbulent horizontal fluxes tend to zero, that allows to provide representative measurement of atmospheric fluxes using micrometeorological methods (e.g., eddy covariance) without large uncertainties.

The spatial patterns of CO_2 fluxes are mainly influenced by air flow heterogeneity at windward and leeward sides of vegetation edge as well as by difference in CO_2 emission and fixation rates at open area (e.g., bare soil) and at the area covered by photosynthesizing vegetation of different height and density. The modeled vertical and horizontal CO_2 fluxes under sunny weather conditions along profile crossing the forest edge (Figure 2) are characterized by significant heterogeneity and in contrast to momentum fluxes the horizontal CO_2 flux above the forest canopy has non-zero values even far away from the forest edge in downwind direction (>1000 m). In case of low vegetation the distance of CO_2 flux re-establishing is some lower.

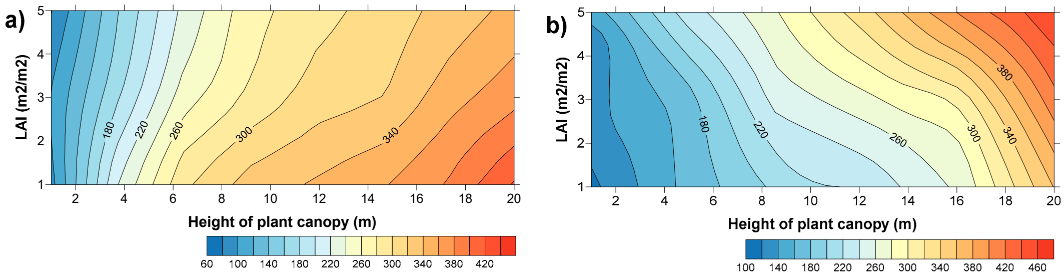

Figure 1. Dependence of the distance between the "point" of the air flow re-establishment and vegetation edge on the height and density of vegetation for the first (**a**) and second (**b**) scenario (for 30 m above the surface).

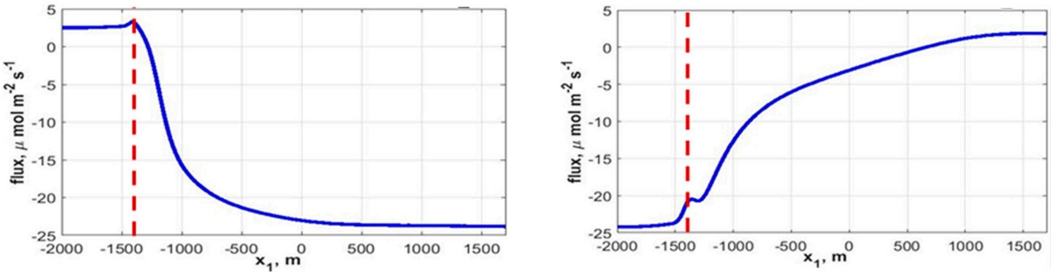

Figure 2. Vertical CO_2 fluxes at the height of 30 m above the ground surface (forest height is 15 m, LAI = 5 m^2 m^{-2}). The air flow moves from open area to the land surface covered by forest (**a**) and from the forested to open area (**b**) respectively. The dotted line shows the vegetation edge.

4. Conclusions

The results of modeling experiments showed a significant influence of vegetation heterogeneity and complex topography on spatial air flow patterns as well as on vertical and horizontal atmospheric fluxes of GHG. Effect of vegetation heterogeneity on vertical and horizontal momentum fluxes at some height above the ground surface is depended on numerous factors including the vegetation height and density of windward and leeward sides and can be manifested far away from the vegetation edge (up to 450 m). In case of CO_2 fluxes this distance due to various photosynthesizing and respiration rates of windward and leeward sides can increase to 1000–1500 m. Provided estimates of the air flow re-establishing distance can be very useful for selection of optimal location of the experimental sites for GHG flux measurements using various micrometeorological methods, including eddy covariance technique, in order to minimize disturbing effects of land surface heterogeneity on measuring equipment and to obtain representative atmospheric fluxes.

Author Contributions: I.M. and A.O. have formulated mathematical statement of the problem, A.O. has proposed the main idea of numerical experiments, I.M. has proposed the finite-difference scheme for numerical solution of the problem, I.M. and A.K. have realized and tested the algorithm and have calculated CO_2 fluxes over a selected profile with complex topography and mosaic vegetation, P.M. has tasted and analyzed the boundary conditions for choosing optimal set and has performed a series of numerical experiments to determine the re-establishing of the air flow, I.M. and A.O. have written the paper.

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