

Fluxes over non-uniform vegetation: a numerical study

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Abstract

A detailed, two-dimensional, second-order closure model for the Planetary Boundary Layer is used to study theoretically the fluxes and the state of the PBL over non-uniform terrain. Simulations are performed for a number of hypothetical surfaces, consisting of alternating patches of idealized forest and grassland. Inhomogeneities are chosen at different length scales, L_x , with $L_x=2, 8$ and 32 km. The results suggest that, in the absence of meso-scale circulations, the average fluxes are almost independent of L_x . The simulations confirm that, in order to compute an effective roughness length, the concept of blending height leads to satisfactory results.

1. INTRODUCTION

The exchange of momentum, heat and mass (e.g., water vapour) between the surface and the atmosphere is rather well understood for homogeneous areas. However, large parts of the Earth's surface are inhomogeneous. The grid scale in large-scale models, such as climate models, often does not allow to resolve these inhomogeneities. Thus, an important question is as to how the processes in the Planetary Boundary Layer (PBL) are integrated, that is, how can the relevant fluxes or the surface characteristics be averaged so that correct boundary conditions for large-scale models are obtained ?

The present study is performed in the framework of the Surface Layer Integration Measurement and Modelling project (SLIMM; [1-2]). Its major goal is to study the vegetation-atmosphere exchange for inhomogeneous terrain theoretically at the landscape scale (~ 10 km).

2. MODEL AND METHOD

The detailed, two-dimensional (2-D), second-order closure model of Rao and co-workers [3-6] is used to simulate fluxes and the state of the PBL. We extended the model

with the Penman-Monteith big-leaf model [7] to include a description of the surface fluxes. The surface layer part includes stability corrections [8] and a distinction between the roughness length for momentum, z_0 , and that for scalars, z_{0s} [9]. The reader is referred to the cited literature for a detailed description of the model.

The model consists of a 1-D part and a 2-D part. The 1-D part simulates the diurnal evolution of the PBL over homogeneous terrain, with a time step of 2.5 s. The vertical grid is logarithmic between 10 and 421 m, and linear between 421 and 2000 m, with a maximum grid spacing of 79 m in the linear part. Initial profiles of temperature, humidity and windspeed must be provided, along with boundary conditions like geostrophic windspeed and solar radiation. The 1-D part generates the initial profiles and boundary conditions for the 2-D part. In its turn, the 2-D model describes a stationary situation for a terrain with horizontal extension x , using a step size of 1 m and with the same vertical grid as in the 1-D part.

The simulations presented here were performed for fair-weather summer conditions in the mid-latitudes (45°N; initial potential temperature, θ , and specific humidity, q , at 6 LT: 20°C and 9 g/kg, respectively; geostrophic windspeed: 10 m/s; solar radiation at noon: 855 W/m²). In the initial profiles, a strong inversion was assumed at a height of 875 m ($d\theta/dz=6$ K/km; $dq/dz=0.5$ (g/kg)/km). The 1-D model was run for idealized grassland (roughness length, $z_0=0.05$ m; albedo, $a=0.2$; surface resistance to evapotranspiration, $r_s=50$ s/m) and the 2-D model was initialized with the 1-D output for 12 LT. In the 2-D simulation air was advected over 30 km of homogeneous grassland in order to certify that the fluxes had become independent of position before the air reached the first inhomogeneity. Next, the air enters the inhomogeneous part assumed to consist of alternating patches of forest ($z_0=1$ m; $a=0.1$; $r_s=100$ s/m) and grassland (characteristics as before). The horizontal length scale of the inhomogeneities, L_x , was taken 2, 8 and 32 km, respectively (Fig. 1).

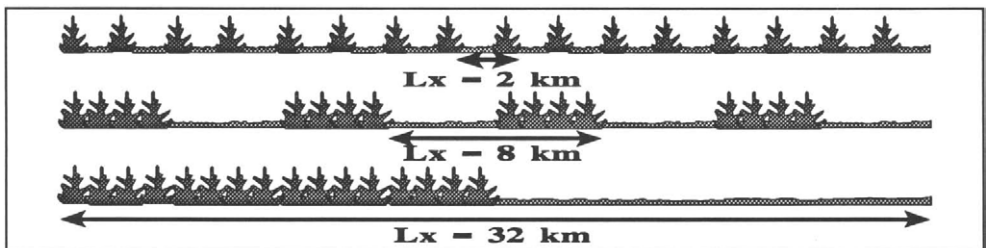


Figure 1. Arrangement of surface patches in the hypothetical inhomogeneous terrain, assumed in the simulations. Trees denote forest (50% of total), flat parts denote grass (50% of total). The total distance of the inhomogeneous part is 32 km.

3. RESULTS AND DISCUSSION

Simulated fluxes of momentum and sensible heat in the heterogeneous part are depicted in Figs. 2 and 3, respectively, for the various values of L_x . The influence of changes in the surface characteristics can clearly be seen. Above forest, the momentum flux is higher than above grass, because of the higher roughness length of forest. Due to

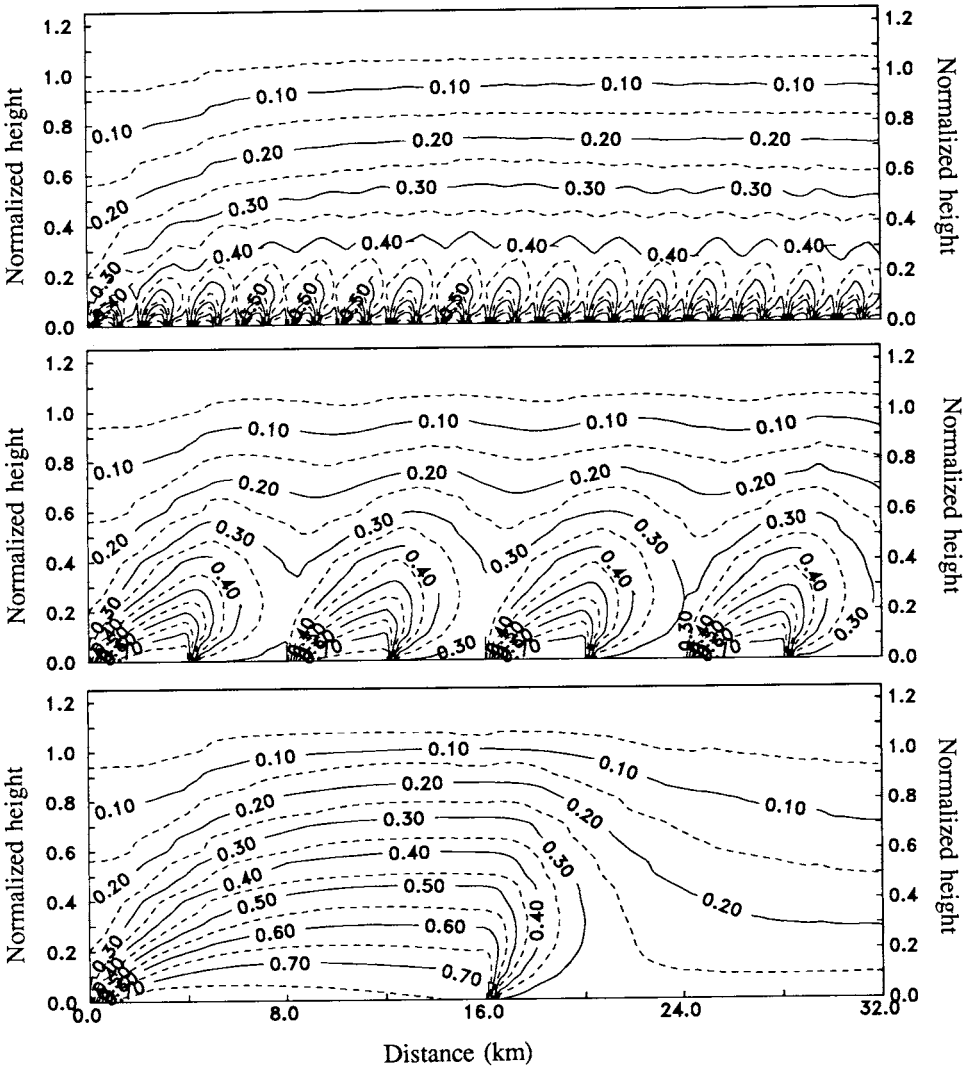


Figure 2. Contour plots of simulated momentum flux over the surfaces depicted in Fig. 1. Upper panel: $L_x = 2$ km; middle panel: $L_x = 8$ km; lower panel: $L_x = 32$ km.

the lower albedo and the higher surface resistance of forest the sensible heat flux is higher as well. Lower albedo implies less reflection of solar radiation. Thus, more energy is available to the sensible and latent heat fluxes. In addition, the higher surface resistance leads to less evapotranspiration (not shown here), so that more energy is used for the sensible heat flux.

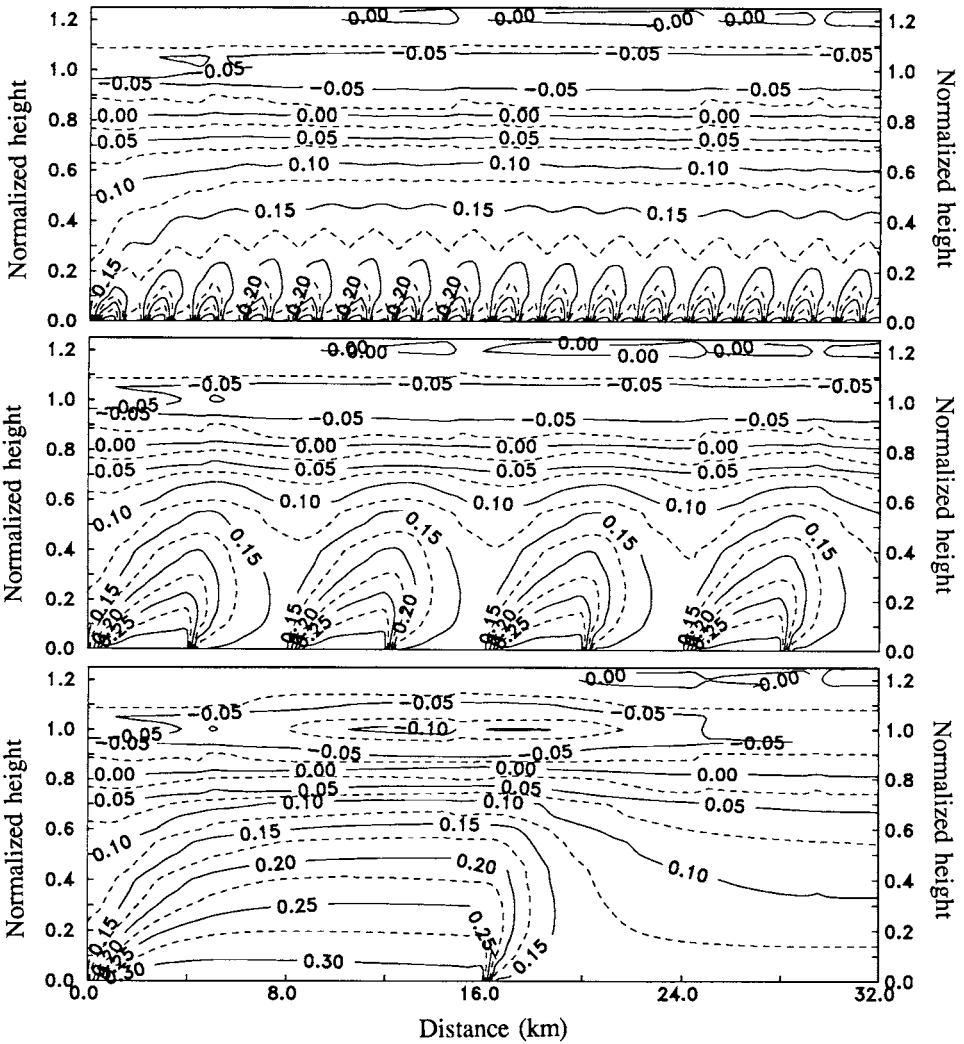


Figure 3. Contour plots of simulated sensible heat flux over the surfaces depicted in Fig. 1. Upper panel: $L_x = 2$ km; middle panel: $L_x = 8$ km; lower panel: $L_x = 32$ km.

Isolines are tilted in the direction of the horizontal wind (from the left to the right) indicating the influence of one surface on the other. Furthermore, a larger part of the PBL is directly affected by a new surface if the patch size becomes larger, that is, if L_x increases. For $L_x = 2$ km the influence of the inhomogeneities is felt in the lower 40% (300-400 m) of the PBL only. Above this level, the PBL is able to average out the effects of the individual patches. If L_x is 8 km, the influence of the inhomogeneities extends almost to the top of the PBL. For $L_x = 32$ km the entire PBL is affected. This scale is in fact the regional scale at which feedback between the PBL and the surface becomes significant [10]. Furthermore, meso-scale circulations around inhomogeneities may become important at this scale [11]. The present model is not able to simulate such features and therefore, results for $L_x = 32$ km should be interpreted with caution.

Average fluxes over the inhomogeneous region are shown in Fig. 4. L_x has hardly any influence on the averages. This suggests that, in the absence of meso-scale circulations, the flux profiles can be calculated using a single set of surface characteristics, independent of the scale of the inhomogeneities. Such an approach has been tested here. An average surface was created by taking $a=0.5*0.1+0.5*0.2=0.15$ and $r_s=1./(0.5/100 + 0.5/50)=67$ s/m. An effective roughness length, $z_{0,e}$, was calculated using the concept of blending height [12-14], by taking [13]:

$$\left(\frac{1}{\ln(l_b/z_{0,e})} \right)^2 = \left(\frac{0.5}{\ln(l_b/z_{01})} \right)^2 + \left(\frac{0.5}{\ln(l_b/z_{02})} \right)^2 \quad (1)$$

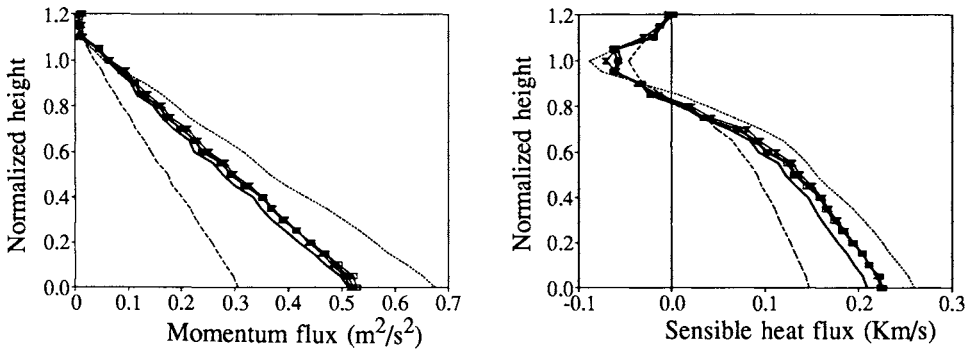


Figure 4. Profiles of momentum flux (left) and heat flux (right), averaged over the inhomogeneous part, over homogeneous forest and grassland, and over the surface with "average" characteristics (see text). Lines with squares: $L_x=2$ km; Lines with crosses: $L_x=8$ km; Lines with hourglasses: $L_x=32$ km; Solid line: average surface; Dotted lines: homogeneous forest; Dashed lines: grassland.

where z_{01} and z_{02} denote the roughness length of forest and grassland, and l_b is the blending height. According to (1), $z_{0,e}$ depends rather strongly on l_b for $l_b < 10$ m, but is rather insensitive to l_b for $l_b > 100$ m. Thus, the results given above suggest $l_b > 100$ m. Therefore, we used the parameterization for l_b suggested by Claussen [14], according to which $l_b = 0.7z_0(Lx/z_0)^{4/5}$, leading to $l_b = 249$ m and 746 m for $Lx = 2$ and 8 km, respectively. Note that these values are in reasonable agreement with the results presented in Figs. 2 and 3. For $Lx = 32$ we obtain $l_b = 2240$ m, which would suggest that the entire PBL is strongly affected by the inhomogeneity. However, this value of Lx may be associated with the occurrence of meso-scale circulations, in which case the concept of blending height breaks down [14]. Using the values of l_b given above leads to $z_{0,e} = 0.35$ m.

An additional run was made with the inhomogeneous area replaced by a homogeneous area with $a=0.15$, $r_s=67$ s/m and $z_0=0.35$ m. Results are also shown in Fig. 4. A satisfactory representation of the average momentum flux is obtained, but the average heat flux is somewhat underestimated. The latter feature corresponds to a slight overestimation of the latent heat flux (not shown here). This result can perhaps be improved if an alternative way to calculate average surface resistance and perhaps albedo would be used. Also, the calculation of roughness length for scalars might have to be adjusted.

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