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On Regional Surface Fluxes over Partly Forested Areas

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Abstract

Neglect of air flow into and from the edges of tall vegetation appears to result in underestimation of local advection. On a regional scale, this 'edge effect' leads to an increase of momentum flux, but a decrease of latent heat flux. Here, a heuristic model is presented showing that the edge effect can be attributed to form drag at tall vegetation. It is hypothesized that the regional momentum flux should be evaluated from an effective roughness length which implicitly accounts for the form drag, whereas the regional heat fluxes should be determined from local surface parameters. The fair agreement of results from a one-dimensional model, which is based on the above reasoning, and a two-dimensional, multi-layer model of vegetation, supports the hypothesis.

Zusammenfassung

Zu regionalen Oberflächenflüssen über teilweise bewaldeten Flächen

Vernachlässigung des Ein- und Ausströmens bodennaher Luft an den Rändern hoher Pflanzenbestände führt zu einer Unterschätzung der lokalen Advektion. Auf der regionalen Skala ist dieser ‚Kanteneffekt' mit einer Zunahme des Impulsflusses und einer Abnahme des Flusses latenter Wärme verbunden. In diesem Aufsatz wird ein heuristisches Modell vorgestellt, das den Kanteneffekt auf den Formwiderstand hoher Pflanzenbestände zurückführt. Es wird angenommen, daß der regionale Impulsfluß aus einer effektiven Rauhigkeitslänge, die implizit den Formwiderstand berücksichtigt, berechnet werden muß, wohingegen die regionalen Wärmeflüsse mittels lokaler Oberflächenparameter bestimmt werden sollten. Die gute Übereinstimmung der Ergebnisse eines eindimensionalen Modells, das auf diesen Überlegungen beruht, mit denen eines zweidimensionalen Modells, in dem die Um- bzw. Durchströmung von Pflanzenbeständen simuliert wird, stützt diese Hypothese.

1 Introduction

In numerical models of atmospheric flow it is necessary to consider the properties of boundary-layer flow as averaged over the grid size of the model. In heterogeneous terrain this leads to the problem of estimating area averages of surface fluxes and associated roughness lengths, the latter being defined only for homogeneous conditions.

Recently, the so-called concept of blending height has become a useful approach to the parameterization of areally averaged surface fluxes over heterogeneous terrain (e.g. Wieringa, 1986, Mason, 1988, Claussen, 1990, 1991). Implicit in this concept is the assumption that at sufficiently large heights above a heterogeneous surface, the modification of air flow due to changes in surface conditions will not be recognizable individually, and an overall stress or heat flux profile will exist, representing the surface conditions of a large area. Consequtively, regional momentum and energy fluxes should be estimated at the blending height which, according to Mason (1988), is defined as a scale-height at which the flow changes from equilibrium with the local surface to independence of horizontal position.

However, the idea of forming averages from the knowledge of homogeneous surfaces yields an aggregated surface roughness which is always smaller than the surface roughness of the roughest surface within a grid domain. This conflicts with the results of Klaassen's (1992) study of average fluxes from heterogeneously vegetated regions. It also conflicts with observations above irregular forests with many clearings (Wieringa, 1992). In this study, it will be argued that this conflict can be attributed to the neglect of form drag due to isolated obstacles or edges of tall vegetation.

Therefore, a heuristic argument is presented here that the edge effect can simply be simulated by an effective roughness length which is a measure of form drag exerted by the forest edges on the air flow and skin drag of surface cover. Furthermore, it is hypothesized that only the momentum flux is directly affected by the form drag, whereas the regional heat fluxes are influenced by the dominant surface cover. Hence, only the momentum flux will be computed from the effective roughness length, whereas for the heat fluxes the local roughness lengths are used. In order to test this hypothesis, regional momentum flux and evaporation over a partly forested area is simulated using a one-dimensional model of the lower part of the planetary boundary-layer. Its results are compared with computations by Klaassen's (1992) model.

Klaassen's model is a two-dimensional model which takes into account the air flow within the forest canopy where the form drag due to pressure perturbations is parameterized in the usual way, i.e., being expressed in terms of an empirical drag coefficient and the square of mean velocity. Klaassen's model does not solve for the pressure distribution explicitly. Hence we do not expect this model to yield realistic wind fields right at a forest edges. On the other hand, Klaassen's model compares favourably with observed data a few canopy heights away from the edge. This is in keeping with Li et al. (1990) who demonstrate that the pressure gradient is an important contributor to the momentum balance only within a few tree heights from the edge. We assume that the shortcoming of Klaassen's model is not important for our present study, because we focus on the parameterization of averages of surface fluxes over a larger area with relatively wide forest strips and clearings in between them.

2 Heuristic Considerations

2.1 Form Drag at Forest Edges

It is suggested that Schlichting's drag partition theory can be used to express the total wind drag τ over a partly forested area as the sum of a skin drag S_d and a form drag F_d due to the forest edges:

$$\tau = S_d + F_d . \qquad (1)$$

A detailed discussion of Schlichting's theory is found in Marshall (1971) as well as its testing in wind tunnel experiments.

In turbulent flow over rough surfaces, the division between skin drag and form drag is somewhat arbitrary and depends on one's perspective. Here, 'skin drag', or better: surface shear stress, is considered as that portion of the drag associated with roughness elements, whose dimensions are of the order of a few centimeters or less. The effect of these small roughness elements on the surface-layer flow is represented by use of a roughness length z_0 in the usual way. The influence of larger roughness elements is parameterized in terms of an effective roughness length which will be constructed in the following manner.

Following Arya (1975), it is assumed that wakes which originate at the forest edges blend at a height l_b in such a way that at heights $z \ll l_b$ the flow is in equilibrium with the local surface, whereas at $z \gg l_b$ the individual wakes will not be recognizable individually, and the flow just 'feels' a rougher surface. If both conditions are met at $z = l_b$, then the ratio of total drag τ and skin drag S_{d0} of the open field without any forest can be written as

$$\frac{\tau}{S_{d0}} = \left(\frac{\ln \dfrac{l_b}{z_{00}}}{\ln \dfrac{l_b}{Z_{0\,\mathrm{eff}}}} \right)^2 , \qquad (2)$$

where z_{00} is the roughness length of the open field. Hence, for the effective roughness length $Z_{0\,\mathrm{eff}}$:

$$\ln \frac{Z_{0\,\mathrm{eff}}}{z_{00}} = \ln \frac{l_b}{z_{00}} \left(1 - \left(\frac{\tau}{S_{d0}} \right)^{-1/2} \right) . \qquad (3)$$

In order to compute the effective roughness length, the form drag F_d and the total skin drag S_d have to be known. The ratio of form drag F_d and skin drag S_{d0} is assumed to take the form:

$$\frac{F_d}{S_{d0}} = \frac{1}{2} c_d \frac{h_c}{l+d} \left(\frac{s}{\kappa} \ln \frac{h_c}{e\, z_{00}} \right)^2 \qquad (4)$$

as derived in Hanssen-Bauer and Gjessing (1988). c_d is the drag coefficient (to be determined empirically), κ is the von Kármán constant (here, $\kappa = 0.4$), h_c is the mean height of the forest, l is the horizontal extent of the forest strips – because a two-dimensional flow is considered – d is the distance between forest strips, $e = \exp(1)$, and $s = (1 - \exp(-0.18 \times$

d/h_c)) is a factor that accounts for sheltering effects between forest strips.

The sheltering factor in Eq. (4) has been derived from empirical data of wind reduction downstream of very dense, but porous obstacles. It has not been proven whether it also applies to forest strips. At the moment we cannot show to have selected the best model for form drag at forest edges. It will turn out, however, that it is necessary in partly forested regions to include some form drag relation.

The total skin drag S_d of the forest surface and the field between forest strips is estimated without taking into account the reduction of skin drag between forest strips at sufficiently small d. This effect is neglected, because the skin drag of the forest is supposed to be much larger than that of the open field. Thus, the skin drag is simply computed at the so-called blending height (e.g. Wieringa, 1986):

$$\frac{S_d}{S_{d0}} = \left(\frac{\ln \frac{l_b}{z_{00}}}{\ln \frac{l_b}{z_{0e}}} \right)^2 , \tag{5}$$

where z_{0e} is the aggregated roughness length defined by:

$$\frac{1}{\left(\ln \frac{l_b}{z_{0e}}\right)^2} = \frac{f_f}{\left(\ln \frac{l_b}{z_{0f}}\right)^2} + \frac{(1-f_f)}{\left(\ln \frac{l_b}{z_{00}}\right)^2} . \tag{6}$$

z_{0f} is the roughness length of the forest and f_f is the fractional area covered by forest strips.

The blending height is simply evaluated as

$$l_b = 2 h_c . \tag{7}$$

That $l_b = 2\,h_c$ was estimated for heterogeneous terrain by Wieringa (1976, 1992) in keeping with laboratory experiments. Other estimates of l_b by Mason (1988) and Claussen (1990, 1991) indicate that l_b should vary with the horizontal scale of surface variations. However, if $h_c \sim O$ (10 m) and $l + d \sim O$ (100 m), then Wieringa's and Claussen's proposal are of the same order of magnitude. In principle, it should be possible to determine l_b from measurements in the atmosphere, and their are experiments being proposed to address this problem, e.g. Klaassen et al. (1992).

2.2 Regional Heat and Momentum Fluxes

In the previous Section 2.1, representation of form drag by an effective roughness length has been outlined. In this section, it will be discussed how the concept of an effective roughness length should be implemented into a one-dimensional model.

As already mentioned, the regional momentum flux is supposed to be a function of the effective roughness length. We assume that this is not valid for turbulent heat fluxes: Empirical data discussed in Beljaars (1982) and Beljaars and Holtslag (1991) support the conjecture that the turbulent heat fluxes over a terrain with bluff roughness elements is not directly affected by the form drag of the roughness elements. Therefore, we suggest to evaluate the heat fluxes from local roughness lengths z_{00}, z_{01} and $z_{00\,t}$, $z_{01\,t}$. $z_{0\,it}$ ($i = 0,1$) is the roughness length of the temperature profiles over the open field and the forest, respectively. $z_{0\,i}/z_{0\,it} = 10$ is prescribed in keeping with measurements over dense vegetation (e.g. Hicks, 1985 – over smooth surfaces, the ratio $z_{0\,i}/z_{0\,it}$ can be smaller than unity, e.g. Brutsaert, 1975). Following the proposal by Claussen (1991), the local heat fluxes at the level of the blending height are computed for each surface type, and the average heat fluxes are obtained by the surface fluxes on the various surface types weighted by their fractional area. For the regional latent heat flux $[Q_{lat}]$:

$$[Q_{lat}] = f_f\, Q_{lat,\,1} + (1 - f_f)\, Q_{lat,\,0} \tag{8}$$

with

$$Q_{lat,\,i} = \rho\, l_v\, C_{q,\,i}\, U_a\, (q_{G,\,i} - q_a) . \tag{9}$$

ρ is the density of the air within the surface layer, l_v is the latent heat of vaporization, U_a and q_a are horizontal mean velocity and specific humidity at the first model level z_a above the surface, and $q_{G,\,i}$ is the specific humidity at the interface between forest and atmosphere ($i = 1$) and above the fields in between ($i = 0$). The transfer coefficients $C_{q,\,i}$ are computed taking into account the blending height (see Claussen, 1991).

In the same manner, the average of local momentum fluxes (just due to skin drag) are obtained. From these average surface fluxes, an average Richardson number [Ri] is estimated by approximation (see Byun, 1990). [Ri] is used to evaluate the stability dependence of the regional momentum flux τ_{eff} which can be written as

$$\tau_{eff} = \rho\, C_m\, U_a^2 \tag{10}$$

where the exchange coefficient C_m depends on the effective roughness length and [Ri]:

$$C_m = \left(\frac{\kappa}{\ln \frac{z_a}{Z_{0\,eff}}} \right)^2 F_m([Ri]) . \qquad (11)$$

F_m is the stability function according to Louis (1979).

3 Model Results

The one-dimensional model which is used to compute the regional surface fluxes over a partly forested area is – apart from implementation of the ideas outlined in the previous sections – the same as Klaassen's model in its one-dimensional version. Only the stability functions implicit in the turbulence closure differ. (Here Louis' (1979) functions are taken, whereas Klaassen computes Webb's functions (in Garratt and Pielke, 1989).) Hence, with the same boundary conditions as in Klaassen (1992) (i.e. U (z = 200 m) = 10 m/s, Θ (z = 200 m) = = 293.16 K, relative humidity h (z = 200 m) = 0.7) we had to adjust the stomatal resistance to r_s = 54.3 s/m for forest and r_s = 28 s/m for the open field in order to get the same evaporation over the homogeneous areas (i.e. cases f_f = 0,1). The original values are r_s = 58, 30.

The flow domain is, as in Klaassen (1992), l + d = 1000 m. The height of the canopy is h_c = 10 m.

Figure 1 gives the roughness lengths over the forested and partly forested area. The effective roughness length $Z_{0\,eff}$ exhibits a maximum value at f_f = 0.85, which is considerably larger than z_{01}. As a consequence, the regional momentum flux (not shown here) exceeds the momentum flux over a homogeneous forest by some 8 %. Klaassen predicts a maximum of the regional momentum flux at the same fractional cover of forest, but with an excess of 3 %.

The effective roughness length $Z_{0\,eff}$ depends implicitly on f_f. f_f appears in skin drag (Eq. (5)) via the aggregated roughness length (Eq. (6)) and in form drag (Eq. (4)) via the sheltering factor and via the empirical parameter c_d. The latter parameter has been chosen to depend on f_f, because form drag due to vegetation depends on a specific drag coefficient and the leaf area density (e.g. Klaassen, 1992). The parameter c_d used here is a product of both, hence, c_d should somehow depend on the horizontal size of a forest strip. Here, $c_d = 2 f_f$ is chosen as a first guess.

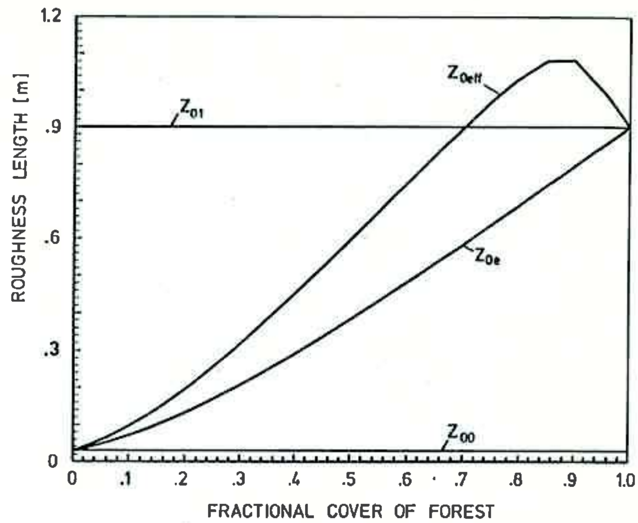

Figure 1 Roughness lengths as a function of fractional cover of forest. $Z_{0\,eff}$: effective roughness length reflecting form drag and total skin drag, z_{0e}: effective roughness length due to total skin drag, z_{01}, z_{00} roughness length of forest and open field.

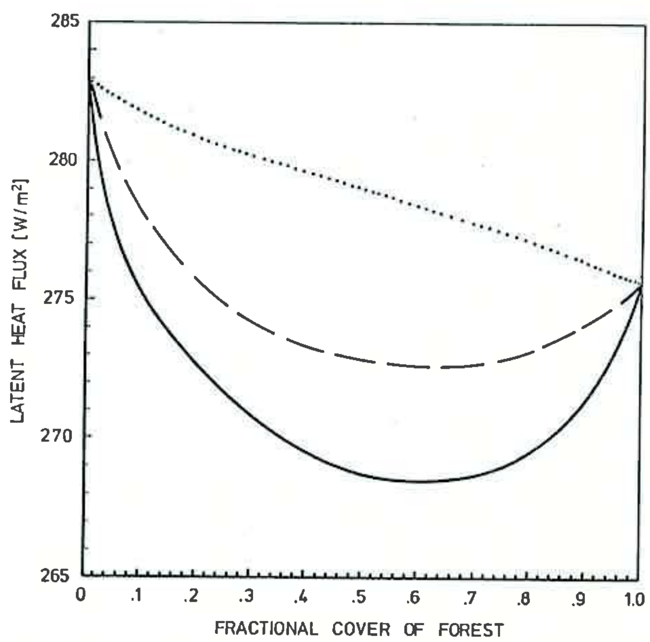

Figure 2 Regional latent heat flux as a function of fractional cover of forest. Full line: Klaassen's (1992) multi-layer model, dotted line: one-dimensional model neglecting edge effects, long-dashed line: one-dimensional model including form drag.

The aggregated z_{0e} falls in between z_{01} and z_{00}. It indicates that the regional momentum flux would be underestimated by approximately 20 % when using z_{0e} instead of $Z_{0\,eff}$ – in qualitative agreement with Klaassen.

Figure 2 shows the regional latent heat flux. The full line is copied from Klaassen (1992), the dotted line represents the regional latent heat flux computed by the one-dimensional model, but ignoring the edge effect, i.e. setting $Z_{0\,\mathrm{eff}} = z_{0e}$. Evidently, the regional latent heat flux is overestimated – as already presumed by Klaassen. The long-dashed line is the result of the one-dimensional model, but now the edge effect is taken into account. Although the regional latent heat flux estimated by using our simple approach overestimates Klaassen's by some 1.5 %, it can safely be stated that the results of our simple model and of Klaassen's two-dimensional, multi-layer vegetation model are at least in qualitative agreement. It is assumed – based on observational evidence – that evaporation is not directly affected by the form drag at the forest edges. Nevertheless it appears that regional evaporation is smaller than one would expect from simple averaging which presumably can be attributed to strong wind reduction due to enhanced regional momentum flux.

4 Conclusion

By comparing the results of the simple model presented here and Klaassen's two-dimensional, multi-layer vegetation model, it can be concluded that the so-called edge effect of tall vegetation can be attributed to the form drag at these edges. The form drag leads to a regional momentum flux which exceeds the equilibrium momentum flux over the roughest area within the region.

The heuristic model of form drag is simple enough to be easily implemented into larger scale models. Furthermore, it depends on simple geometrical parameters such as vegetation height, horizontal extent of forest patches and of clear cuts in between. These parameters could be obtained from high resolution satellite data or land-use maps.

It should be mentioned, however, that the ideas presented here apply only to small-scale variations of topography, say scales smaller than 10 km. For variations of surface conditions at scales larger than 10 km, the concept of blending height will fail in convective situations due to the onset of secondary meso-scale circulations.

Whether the concept, presented here, is applicable to hilly terrain remains to be investigated. Presumably only a few modifications will be necessary as indicated by a recent theoretical study of Raupach et al. (1992). Their linear analysis predicts that spatial averages of heat and water vapour fluxes are independent of low-terrain undulations, except for adiabatic elevation effects.

The following problems remain: Implicit in the model of form drag is a drag coefficient c_d, which has to be specified empirically. Here, just a first guess has been made, and we have not tried to look for an optimum $c_d(f_f)$ to tune our results to Klaassen's. The heuristic model has been formulated to isolate certain mechanisms, not to precisely fit model data. Furthermore, results of two models have been compared which are both not perfect. We have only shown that the parameterization used in a one-dimensional model is able to reproduce spatially averaged values of a two-dimensional model. This is still some progress as it could not be expected a priori that the one-dimensional model is able to do so, because horizontal gradients are not resolved there. Therefore, we had to assume that the form drag associated with horizontal gradients of wind and pressure occurs at scales smaller than the domain over which averages are performed, i.e. it is a subgrid-scale phenomenon which can be parameterized in terms of spatially averaged variables.

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