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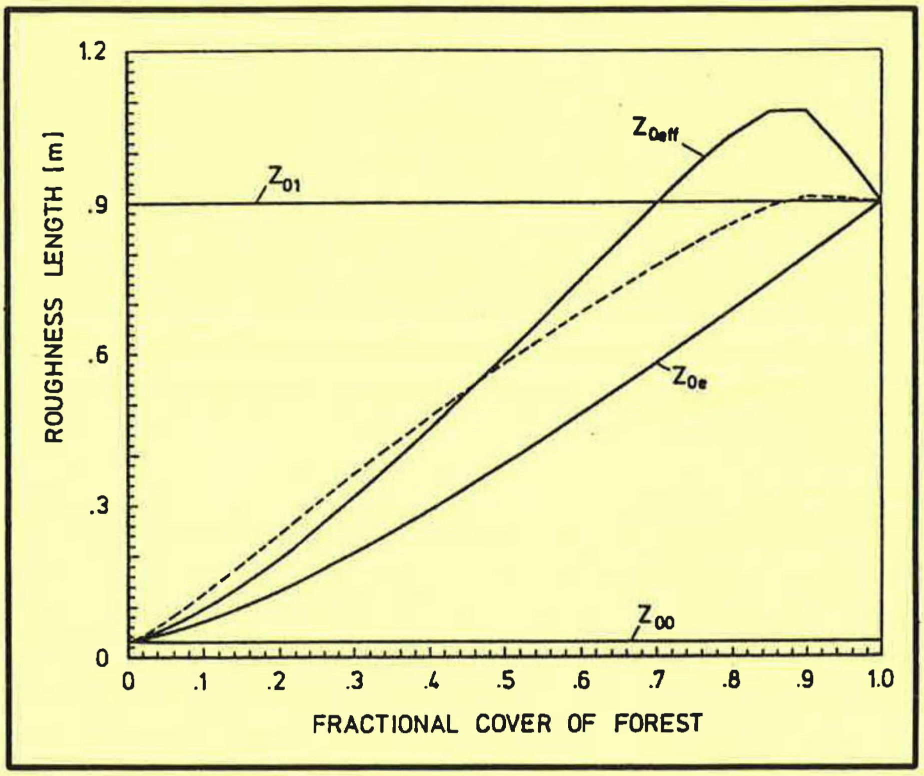

ON REGIONAL SURFACE FLUXES OVER PARTLY FORESTED AREAS

by

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On regional surface fluxes over partly forested areas

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Abstract

Neglection of air flow into and from the edges of tall vegetation appears to result in a severe underestimation of local advection. On a regional scale, this 'edge effect' leads to an increase of momentum flux, whereas the sign of change varies for the heat fluxes. 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.

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1. Introduction

In numerical models of atmospheric flow it is necessary to consider the properties of boundary-layer flow as well as the underlying surface characteristics as averaged over the grid size of the model. Often, local advection resulting from subgrid-scale variations in surface conditions is neglected. However, local advection leads to more momentum flux at the rough part and only a little bit less flux at the smooth part. As a consequence, ignoring local advection when estimating a "grid-averaged" roughness would result in too small a surface roughness (Wieringa, 1992).

Recently, the concept of blending height has become a useful tool in aggregating surface fluxes (e.g. Wieringa, 1986, Mason, 1988, Claussen, 1991). Implicit in this concept is the assumption that at sufficiently large heights, 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.

However, the concept of blending height yields an aggregated roughness length which is always smaller than the roughness length 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, 1991). In this study, it will be argued that this failure of the concept of blending height can be attributed to the neglection of form drag due to the edges of tall vegetation or to isolated obstacles.

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 model, which is two-dimensional and takes into account the air flow within the forest canopy.

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:

$$\tau = S_d + F_d \quad . \tag{1}$$

A detailed discussion of Schlichting's theory is found in Marshall (1971) as well as its testing in wind tunnel experiments, and in Arya (1975) and Hanssen-Bauer and Gjessing (1988). The latter computed the aerodynamic drag of pack ice and ice floes.

If it is assumed that wakes which originate at the forest edges blend at a height l_b in such a way that at heights $z << l_b$ the flow is in equilibrium with the local surface, whereas at $z >> l_b$ the individual wakes will not be recognizable individually, and the flow just'feels' a rougher surface, then the ratio of total drag τ and skin drag S_{d0} of the open field without any forest can be written as

$$\frac{\tau}{S_{d0}} = \left(\frac{ln \frac{l_b}{z_{00}}}{ln \frac{l_b}{Z_{0eff}}} \right)^2 \quad . \tag{2}$$

Hence, for the effective roughness length Z_{0eff}:

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

where z_{00} is the roughness length of the open field.

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:

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

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

$s = (1 - exp(-0.18 * d/h_c))$ is a factor that accounts for sheltering effects between forest strips.

The sheltering factor in Equation 4 has been designed for ice floes. It seems likely that the sheltering factor of a porous medium like forest deviates from ice floes. 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):

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

where z_{0e} is the "effective roughness length due to skin drag" defined by:

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

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

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

That $l_b = 2h_c$ 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 l_x of surface variations. Claussen (1990) found $l_b \sim 50\text{m} \pm 10\text{m}$ for various landscape configurations, whereas Mason (1988) derived $l_b \sim l_x/200$. Claussen's estimate is of the same order of magnitude as Wieringa's proposal $l_b = 2h_c$ =20m, whereas Mason's estimate yields a blending height of a few meters only. It will be shown later that Mason's estimate provides an effective roughness length which is too small in comparison with Klaassen's model results.

2.2 Regional 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_{00t}, z_{01t}. z_{0it} (i=0,1) is the roughness length of the temperature profiles over the open field and the forest, respectively. $z_{0i}/z_{0it} = 10$ is prescribed in keeping with measurements over dense vegetation (e.g. Hicks, 1985). Following the proposal by Claussen (1991), the local heat fluxes are computed for each surface type with respect to the blending height, and the average heat fluxes are obtained by the surface fluxes on the various surface types wheighted 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

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

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 computed which is used to evaluate the stability dependence of the regional momentum flux:

$$\rho U_{*eff}^2 = \rho C_m U_a^2 \quad , \tag{10}$$

where

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

and 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 the same as Klaassen's single-layer model, except that 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=200m)=10 m/s, Θ(z=200m)=293.16 K, relative humidity h(z=200m)=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.

Figure 1 gives the roughness lengths over the forested and partly forested area. The effective roughness length Z_{0eff} 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 dashed line in Figure 1 represents the effective roughness length when using a blending height of l_b =5m for computation of Z_{0eff}, S_d, and z_{0e} in Equations 3, 5, 6, respectively. The value l_b =5m is chosen according to Mason's (1988) proposal. Using such a small value of l_b, the calculated regional momentum flux only barely exceeds the momentum flux over the forest.

The "effective roughness length due to skin drag" 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_{0eff} - in qualitative agreement with Klaassen.

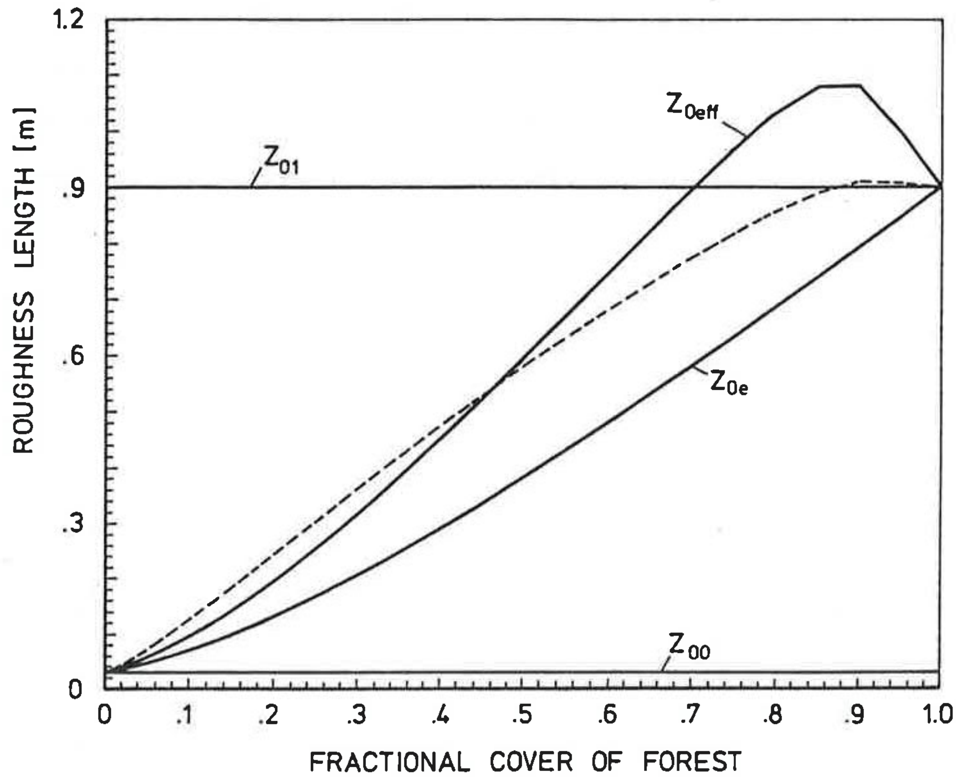

Figure 1: Roughness lengths as a function of fractional cover of forest. Z_{0eff}: effective roughness length reflecting form drag and total skin drag, z_{0e}: effective roughness length due to total skin drag, z_{01}, z_{00} roughness length of forest and open field. Dashed line: effective roughness length Z_{0eff} reflecting form drag and total skin drag, but computed with a blending height of l_b =5m in Equations 3, 5, 6.

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 $Z_{0eff} = z_{0e}$. 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.

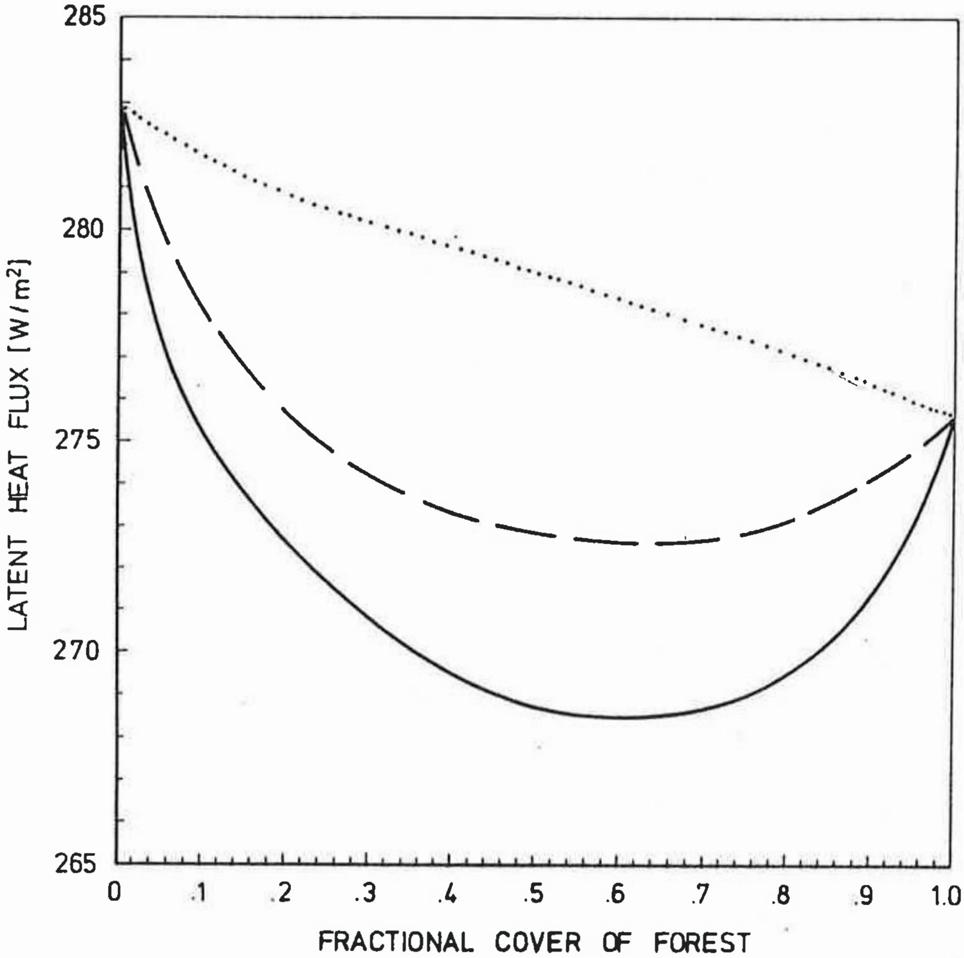

Figure 2: Regional latent heat flux as a function of fractional cover of forest. Full line: Klaassen's (1992) multi-layer model, dotted line: one-dimensional model neglecting edge effects, long-dashed line: one-dimensional model including form drag.

From the figures it can be judged that the inclusion of form drag may explain why the effective roughness length exceeds the roughness length of the roughest surface. The computation of form drag via Equation 4 (and, therefore, the computation of effective roughness length) should be considered as preliminary, particularly because it contains an empirical parameter c_d. 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, $c_d = 2f_f$ is chosen as a first guess.

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. Although it is assumed - based on observational evidence - that evaporation is not directly affected by the form drag at the forest edges, it appears that regional evaporation is smaller than one would expect from simple averaging, presumably because of strong wind reduction due to enhanced regional momentum flux.

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.

One problem, however, remains: 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. After all, both the simple model and Klaassen's model await experimental verification.

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