An Improved Blending-Height Concept for Aggregating Fluxes of Sensible and Latent Heat, Momentum, and Carbon Dioxide over Heterogeneous Landscapes

Gerhard Kramm[1], Ralph Dlugi[2], and Nicole Mölders[1]
[1]Geophysical Institute
University of Alaska Fairbanks
Fairbanks, Alaska, USA
[2]Working Group Atmospheric Processes
Munich, Germany

1. INTRODUCTION

Natural surfaces of a landscape are often heterogeneous over virtually all scales, i.e., also over the resolvable scales considered in weather and climate models (e.g., Mölders and Raabe, 1996; Giorgi and Avissar, 1997; Kramm et al., 2004). Thus, the exchange of sensible and latent heat, momentum, and long-lived trace constituents like carbon dioxide (CO_2) at the interface land surface-atmosphere of any grid element of such models cannot be treated by assuming homogeneous or dominant land-use types. To address this heterogeneity of a landscape in weather and climate models it is indispensable to aggregate the fluxes mentioned before over the patchy fields of any grid element.

Different strategies have been developed to consider subgrid-scale surface heterogeneity of the patchy surface of a grid element, for instance, by averaging surface properties (e.g., Lhomme, 1992; Dolman, 1992) or by *statistic-dynamic* approaches (e.g., Wetzel and Chang, 1988; Entekhabi and Eagleson, 1989; Avissar, 1992). Computationally more expensive concepts to consider the properties of a heterogeneous surface are flux-related strategies like the *mosaic approach* (Avissar and Pielke, 1989), the conventional *blending-height concept* (e.g., Wieringa, 1986; Mason, 1988; Claussen, 1995), the *explicit-subgrid scheme* (Seth et al., 1994; Mölders et al., 1996), the *vertically extended explicit-subgrid scheme* (Tetzlaff et al., 2002), or the *mixture approach*, wherein for the different surface types tightly coupled energy balance equations are solved (e.g., Deardorff, 1978; Sellers et al., 1986; Kramm et al., 1996).

In our contribution we will present and discuss an improved version of the *blending-height concept*. In contrast to its conventional form, our version of the blending height concept is based on a consistent formulation of the *mosaic approach* by including the thermal stratification of air in the atmospheric boundary layer (ABL), where not only forced-convective conditions, but also free-convective conditions are considered. Since the prediction of the blending height is related to thermal stratification of air in the ABL, it can be varied during the diurnal cycle.

2. THEORETICAL BACKGROUND

2.1 The conventional blending-height concept

The conventional blending-height concept can be considered as a mosaic approach for momentum. This mosaic approach is related to

$$F_j^{\ k} = \sum_{i=1}^{N} \alpha_{i,j}\, F_{i,j}^{\ k} \qquad (1)$$

Here, F_j^k is the representative of a flux of the jth grid cell, where $k = 1$ stands for momentum, $k = 2$ for water vapor, $k = 3$ for sensible heat, and $k = 4$ for long-lived trace species like CO_2, and $\alpha_{i,j}$ is the fractional area of the j^{th} grid cell covered by the i^{th} patch. The quantity F_j^k is considered as an area-weighted one, where $F_{i,j}^k$ is the corresponding flux provided by the i^{th} patch with a given land-use type from the N patches that compose the j^{th} grid cell. Note that in the following the subscripts have always the same meaning. The mosaic approach was introduced into the literature by Avissar and Pielke (1989). Mölders et al. (1996) evaluated it by comparison with the *explicit-subgrid strategy* of Seth et al. (1994).

The conventional blending-height concept is based on the following set of equations:

$$F_{i,j}^{\;1} = \frac{\overline{\rho_j}\,\kappa^2\,\left\{\hat{u}_j\left(h_{b,j}\right)\right\}^2}{\left\{\ln\left(\frac{h_{b,j}}{z_{0,i,j}}\right)\right\}^2} \tag{2}$$

$$F_j^{\;1} = \overline{\rho_j}\,\kappa^2\,\left\{\hat{u}_j\left(h_{b,j}\right)\right\}^2 \sum_{i=1}^{N} \frac{\alpha_{i,j}}{\left\{\ln\left(\frac{h_{b,j}}{z_{0,i,j}}\right)\right\}^2} \tag{3}$$

where the blending height $h_{b,j}$ is related to the horizontal length scale, $L_{c,j}$, of the aerodynamic roughness variation by (Mason, 1988)

$$\frac{h_{b,j}}{L_{c,j}}\left\{\ln\left(\frac{h_{b,j}}{z_{0,j}}\right)\right\}^2 \cong 2\,\kappa^2 \tag{4}$$

Here, $\hat{u}_j$ is the mean horizontal wind speed, $\overline{\rho_j}$ is the mean air density, $z_{0,i,j}$ is the roughness length, and $z_{0,j}$ is the aggregated one. The friction velocity, $u_{*,j}$, derived from the area-weighted friction stress, F_j^1, is then used as a scale quantity in the Monin-Obukhov similarity laws to calculate the fluxes of sensible and latent heat, and long-lived trace constituents.

Taking this set of equations into account, one can inferred from this conventional blending-height concept mean vertical velocities, $\hat{w}$ (Figs. 1 and 2), so that close to the ground the constant flux approximation, on which the Monin-Obukhov similarity laws are based, may notably be violated. Another shortcoming of this concept is that thermal stratification of air in the ABL is ignored.

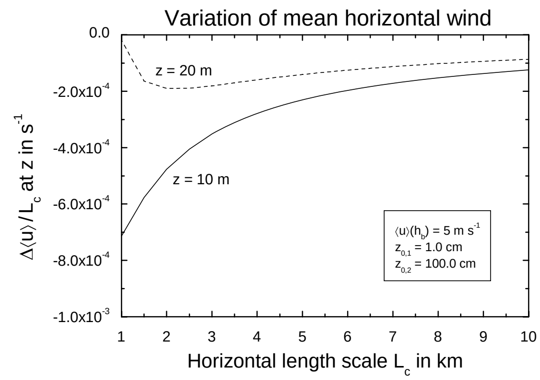

Fig. 1. Variation of the mean horizontal wind speed, $\langle u \rangle = \hat{u}$, versus horizontal length scale, L_c, for two different levels below the blending height, h_b.

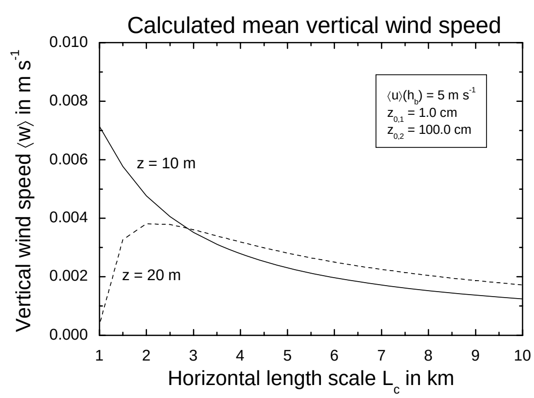

Fig. 2. Calculated mean vertical wind speed, $\langle w \rangle = \hat{w}$, versus horizontal length scale, L_c, for two different levels below the blending height, h_b.

2.2 An improved blending-height concept

To guarantee that the blending-height concept is entirely self-consistent, it is indispensable (a) to include diabatic effects, (b) to calculate the corresponding area-weighted fluxes of sensible and latent heat, momentum and long-lived trace constituents in accord with the principles of the mosaic approach defined by Eq. (1), and (c) to guarantee that the effects of the inferred mean vertical velocity, $\hat{w}$, can be ignored. The first two requirements can be satisfied by the following set of equations:

$$F_{i,j}^{1} = \frac{\overline{\rho_j}\,\kappa^2 \left\{\hat{u}_j\left(h_{b,j}\right)\right\}^2}{\left\{\ln\left(\frac{h_{b,j}}{z_{0,i,j}}\right) - \Psi_m\left(\zeta_{b,i,j}, \zeta_{0,i,j}\right)\right\}^2} \tag{5}$$

$$F_{j}^{1} = \overline{\rho_j}\,\kappa^2 \left\{\hat{u}_j\left(h_{b,j}\right)\right\}^2 \sum_{i=1}^{N} \frac{\alpha_{i,j}}{\left\{\ln\left(\frac{h_{b,j}}{z_{0,i,j}}\right) - \Psi_m\left(\zeta_{b,i,j}, \zeta_{0,i,j}\right)\right\}^2} \tag{6}$$

$$F_j^2 = -\overline{\rho_j}\,\hat{u}_j\left(h_{b,j}\right)\sum_{i=1}^{N}\alpha_{i,j}\,C_{q,i,j}\left\{\hat{q}\left(h_{b,j}\right) - \hat{q}_{s,i,j}\right\} \tag{7}$$

$$F_j^3 = -c_{p,0}\,\overline{\rho_j}\,\hat{u}_j\left(h_{b,j}\right)\sum_{i=1}^{N}\alpha_{i,j}\,C_{h,i,j}\left\{\hat{\Theta}\left(h_{b,j}\right) - \hat{T}_{s,i,j}\right\} \tag{8}$$

$$F_j^4 = -\overline{\rho_j}\,\hat{u}_j\left(h_{b,j}\right)\sum_{i=1}^{N}\alpha_{i,j}\,C_{c,i,j}\left\{\hat{c}\left(h_{b,j}\right) - \hat{c}_{s,i,j}\right\} \tag{9}$$

$$C_{X,j} = \sum_{i=1}^{N}\alpha_{i,j}\,C_{X,i,j} \tag{10}$$

$$X_{s,j} = \frac{1}{C_{x,j}}\sum_{i=1}^{N}\alpha_{i,j}\,C_{X,i,j}\,X_{s,i,j} \tag{11}$$

$$C_{X,i,j} = \frac{u_{*i,j}\,\kappa}{\hat{u}_j\left(h_{b,j}\right)\left(\kappa\,B_{X,i,j}^{-1} + \ln\frac{h_{b,j}}{z_{0,i,j}} - \Psi_h\left(\zeta_{b,i,j}, \zeta_{0,i,j}\right)\right)} \tag{12}$$

$$\frac{h_{b,j}}{L_{c,j}}\left\{\ln\left(\frac{h_{b,j}}{z_{0,j}}\right) - \Psi_m\left(\zeta_{b,j}, \zeta_{0,j}\right)\right\}^2 \cong 2\,\kappa^2 \tag{13}$$

Here, $\Psi_m\left(\zeta_{b,i,j}, \zeta_{0,i,j}\right)$ and $\Psi_h\left(\zeta_{b,i,j}, \zeta_{0,i,j}\right)$ are the integral stability functions of momentum and sensible heat, respectively, where the latter is used for all passive scalars. These integral stability functions are given by

$$\Psi_{m,h}\left(\zeta_{b,i,j}, \zeta_{0,i,j}\right) = \int_{\zeta_{0,i,j}}^{\zeta_{b,i,j}} \frac{1 - \Phi_{m,h}\left(\zeta\right)}{\zeta}\,d\zeta \tag{14}$$

i.e., they depend on the Obukhov numbers at the lower and the upper boundaries of this integral, $\zeta_{b,i,j} = h_{b,j}/L_{i,j}$ and $\zeta_{0,i,j} = z_{0,i,j}/L_{i,j}$, where $L_{i,j}$ is the Obukhov stability length. Note that the Obukhov numbers $\zeta_{b,j}$ and $\zeta_{0,j}$ are the aggregated ones. Furthermore, $C_{X,i,j}$ is the bulk transfer coefficient, where X stands for water vapor, sensible heat, and long-lived trace species, and $X_{s,i,j}$ represents the surface values of these quantities. Equation (11) mirrors that averaging the surface properties, as suggested by Lhomme (1992) and Dolman (1992), requires that $C_{x,i,j} = C_{x,j}$ is valid for all patches of the grid cell so that $X_{s,j} = \sum_{i=1}^{N}\alpha_{i,j}\,X_{s,i,j}$. It is unlikely that over a patchy surface of a grid element this requirement is fulfilled.

For unstable stratification these integral stability functions are usually determined on the basis of the Businger-Dyer-Pandolfo-type local stability function

$$\Phi_m\left(\zeta\right) = \left(1 - 16\,\zeta\right)^{-1/4} \tag{15}$$

where the Businger-Pandolfo relationship

$$\Phi_h\left(\zeta\right) = \Phi_m^{\,2}\left(\zeta\right) \tag{16}$$

is considered. The subscripts m and h stand for momentum and sensible heat. Unfortunately, the relationship (15) is not valid for free convective conditions. Therefore, the Carl-Tarbell-Panofsky-type local stability function

$$\Phi_m\left(\zeta\right) = \left(1 - 15\,\zeta\right)^{-1/3} \tag{17}$$

is taken into account. As shown by Kramm (2004), the integral stability function of momentum based on Eq. (17) closely follows that deduced from O'KEYPS formula

$$\Phi_m^{\,4}\left(\zeta\right) - 15\,\zeta\,\Phi_m^{\,3}\left(\zeta\right) = 1 \tag{18}$$

that serves as an interpolation formula between neutral and free convective conditions; whereas the integral stability function based on Eq. (15) differs more and more from the two others when ζ_R tend to large negative numbers, representing free-convective conditions. By considering Eq. (16) as entirely valid for the stability range from neutral to free-convective conditions and taking relationship (17) into account, one can also derive a modified version of the integral stability function of sensible heat. This modified version differs from the conventional one, based on Eqs. (15) and (16), in a similar manner like in the case of momentum.

To guarantee that the constant flux approximation is valid, the ratio $h_{b,j}/L_{c,j}$ has to be related to criterion $|\hat{w}| << |v_e^k|$. Here, $\hat{w}$ is, again, the mean vertical velocity, and v_e^k is the exchange velocity (for more details, see Kramm et al., 2004).

Currently, the improved blending-height concept is thoroughly tested.

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