Environmental Fluid Mechanics **2:** 315–337, 2002.
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An Approach for the Aggregation of Aerodynamic Surface Parameters in Calculating the Turbulent Fluxes over Heterogeneous Surfaces in Atmospheric Models

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Received 21 August 2001; accepted in revised form 8 June 2002

Abstract. Experimental evidence indicates that there is a significant departure of the wind profile above the underlying surface consisting of patches of solid and liquid parts, and plant communities with different morphological from that predicted by the logarithmic relationship, which gives the values larger than those observed. This situation can seriously affect the transfer of momentum, heat and water vapor from the surface fluxes into the atmosphere.
The object of this paper is to generalize the calculation of the exchange of momentum between the atmosphere and a very heterogeneous surface, find a general equation for the wind speed profile in a roughness sublayer under neutral conditions, and, then, derive aggregated roughness length and displacement height over the grid cell. The suggested expression for the wind profile is compared with some earlier approaches, using a common parameterization of aerodynamic parameters over the grid cell, and the observations obtained at an experimental site in Philadelphia, PA.

Key words: aggregation of aerodynamic parameters, land-surface parameterization, mixing-length theory, momentum transfer coefficient, roughness sublayer, urban modeling, wind profile

1. Introduction

It is well known that turbulent transfer models can sometimes produce results that cannot be realized in nature. This situation is particularly important in the parameterization of land-surface turbulent transfer over heterogeneous surfaces. An improper parameterization of land-surface processes leads to uncertainties in calculating the boundary layer variables and further in predicting the temperature and wind fields in air quality models. For example, a detailed overview of the literature related to the problems faced when determining momentum and energy fluxes over heterogeneous surfaces is comprehensively given in Burke *et al.* [1]. In the numerical modeling of surface layer processes, three approaches are commonly

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taken for calculating the transfer of momentum, heat and moisture from a grid cell comprised of heterogeneous surfaces. According to Hess and McAvaney [2, 3] they are: (a) 'Parameter aggregation', where grid-cell mean parameters such as roughness length, albedo, leaf area index, stomatal resistance, soil conductivity, etc., are derived in a manner which attempts to best incorporate the combined nonlinear effects of each of different relatively homogeneous subregions ('tiles') over grid-cell; (b) 'flux aggregation', where the fluxes are averaged over the grid cell, using a weighted average with the weights determined by the area covered by each tile; and (c) a combination of the flux aggregation and parameter aggregation methods [4, 5].

In atmospheric models, in numerical modeling of surface layer processes meteorologists usually either use the dominant type over the grid cell or simple linear average to determine grid cell averages of parameters such as roughness length or some other surface parameters [6, 7]. Both methods have problems in parameterizing the surface layer processes when large differences exist in the heterogeneity of the surfaces over the grid cell. A number of papers have appeared in the literature dealing with the problem of aggregation of surface fluxes and surface parameters in atmospheric and other models including also papers that have been done by groups of different national weather services and agencies [2, 3, 7–15]. These problems are particularly pronounced in models dealing with the urban areas. Recently published papers offer a detailed overview of aerodynamic properties of urban areas derived from analysis of surface form [16–18].

It is possible to make aggregation of some surface parameters over the grid cell in a more physical way than those suggested in previous studies. It means that assumption in parameter aggregation should be done to follow the non-linearity of the relationship between turbulent fluxes and vertical mean profiles as much as possible closely. To this end, we suggest approaches to: (a) Calculate the exchange of momentum between the atmosphere and heterogeneous surface; (b) derive an equation for the wind speed profile in a roughness sublayer under neutral conditions; and (c) derive aggregated roughness length and displacement height over the grid cell.

2. Exchange of Momentum above a Heterogeneous Surface under Neutral Conditions

2.1. MIXING LENGTH AND MOMENTUM TRANSFER COEFFICIENT

In this section, we derive an expression for the momentum transfer coefficient K_m and the wind profile, under neutral conditions, above a heterogeneous grid cell consisting of patches of vegetation, solid part (bare soil, rock, urban part) and water. The non-uniformity of the vegetative part is expressed with the surface vegetation fractional cover σ_i representing the i type of vegetation cover filling the grid cell. Their sum takes values from 0 (when only solid surface or water are present) to 1 (when the ground surface is totally covered by plants). The non-uniformity of

solid (solid parts of urban area, rock solid and bare soil) and liquid portions (sea, river, lake, water catchments) of the grid cell will be denoted by symbols δ_i and ν_i, representing the surface solid and water fractional cover, respectively; the total sum of all these fractional covers must be equal 1. A realistic surface of the grid cell is rather porous, with patches of solid material, vegetative portions and free air spaces inside or around it, which can produce quite different modes of turbulence in comparison with a uniform underlying surface, which is either solid and water, or surface covered with vegetation. Also, such designed underlying surface in the grid cell is a mosaic of patches of various size and different aerodynamic characteristics. Presumably, this mosaic will produce microcirculation with possible flow separations at leading and trailing edges, setting up a highly complex dynamic flow. In this paper, we will not address the consequences of such non-uniformity of the vegetation part of the underlying surface. Instead, following calculations are based on the assumption that the underlying surface is a combination of the only three portions consisting of vegetative portion, characterized with total fractional cover σ, the solid portion, characterized with total δ and the liquid portion having total fractional cover $\nu = 1 - \sigma - \delta$.

As suggested by Mihailovic *et al.* [19], who introduced an expression for the mixing length over a grid cell consisting of vegetated and non-vegetated surface, the aggregated mixing length l_m^a at level z above a grid cell consisting of the heterogeneous surface defined above, might be represented by some combination of their single mixing lengths. If, as a working hypothesis, we assume a linear combination weighted by fractional cover, according to mixing-length theory we can define l_m^a as

$$l_m^a = k\left[\sum_{i=1}^{K}\sigma_i\alpha_i(z-d_i) + \sum_{i=1}^{L}\delta_i z + \sum_{i=1}^{M}\nu_i z\right], \tag{1}$$

where: k is the von Karman's constant taken to be 0.41; σ_i, δ_i and ν_i are partial fractional covers for vegetation, solid part and water surface, respectively, while d_i is zero displacement height for the ith vegetative part in the grid cell. Parameter α_i is the dimensionless constant introduced by Mihailovic *et al.* [19], that depends on morphological and aerodynamic characteristics of the vegetative cover whose values vary according to the type of vegetative cover. Let us note that in the expression (1) the zero displacement height of urban area is not considered [17]. The functional form of the parameter α, considered as a function of leaf drag coefficient C_d and leaf area index LAI, was derived empirically by Lalic [20, 21] who analyzed the wind profiles measured above a broad range of vegetation, i.e., short grass [22], tall grass [23] and forest [24]. This was done by analyzing the wind profiles in the sublayer above the vegetation using the maximum and minimum values of LAI for 20 types of vegetation listed in [25]. Comparison of model simulations with observations showed a good agreement with the expression $\alpha^2 = \sqrt{2}\,(C_d LAI)^{1/10}$ for short grass, $\alpha^2 = 2\,(C_d LAI)^{1/5}$ for tall grass and $\alpha^2 = 4\,(C_d LAI)^{1/2}$ for forest [20, 21].

The momentum transfer coefficient K_m for the non-homogenous vegetative cover is

$$K_m = l_m^a u_*^a, \tag{2}$$

here u_*^a is a friction velocity above non-homogeneously covered grid cell. Replacing l_m^a, in Equation (2), by the expression (1), we get

$$K_m = k\left[\sum_{i=1}^{K}\sigma_i\alpha_i(z-\mathrm{d}_i) + \sum_{i=1}^{L}\delta_i z + \sum_{i=1}^{M}\nu_i z\right]u_*^a \quad . \tag{3}$$

2.2. WIND PROFILE

Using the foregoing assumption that the friction velocity u_*^a is equal $l_m^a \mathrm{d}u/\mathrm{d}z$ yields

$$u_*^a = k\left[(\sum_{i=1}^{K}\sigma_i\alpha_i + \sum_{i=1}^{L}\delta_i + \sum_{i=1}^{M}\nu_i)z - \sum_{i=1}^{K}\sigma_i\alpha_i\mathrm{d}_i\right]\frac{\mathrm{d}u}{\mathrm{d}z}. \tag{4}$$

This equation can be integrated to

$$u(z) = \frac{u_*^a}{k}\frac{1}{\sum_{i=1}^{K}\sigma_i\alpha_i + \sum_{i=1}^{L}\delta_i + \sum_{i=1}^{M}\nu_i}\ln\left[(\sum_{i=1}^{K}\sigma_i\alpha_i + \sum_{i=1}^{L}\delta_i + \sum_{i=1}^{M}\nu_i)z - \sum_{i=1}^{K}\sigma_i\alpha_i\mathrm{d}_i\right] + C_i \tag{5}$$

where C_i is an integration constant. If we introduce the following notations

$$\Lambda = \sum_{i=1}^{K}\sigma_i\alpha_i + \sum_{i=1}^{L}\delta_i + \sum_{i=1}^{M}\nu_i \tag{6}$$

and

$$\Gamma = \sum_{i=1}^{K}\sigma_i\alpha_i\mathrm{d}_i, \tag{7}$$

then Equation (5) can be written in a concise form

$$u(z) = \frac{u_*^a}{k}\frac{1}{\Lambda}\ln(\Lambda z - \Gamma) + C_i. \tag{8}$$

The constant C_i can be found if we introduce the assumption that the extrapolation of the wind profile given by Equation (8) gives zero wind velocity at some height z_k defined as

$$z_k = Z_0 + D, \tag{9}$$

where

$$Z_0 = \frac{z_0}{\Lambda} \tag{10}$$

and

$$D = \frac{\Gamma}{\Lambda}. \tag{11}$$

where z_0 is the roughness length in the classical logarithmic expression for the wind profile. The last two expressions can be considered as aggregated roughness length and displacement height over a non-homogenous surface in the grid cell as in Mihailovic *et al.* [19], but in the case of a surface consisting only of bare soil and vegetation patches.

The above condition can then be written as

$$0 = \frac{u_*^a}{k}\frac{1}{\Lambda}\ln(\Lambda z_k - \Gamma) + C_i. \tag{12}$$

After replacing the expressions (9), (10) and (11) in Equation (12), we find that the constant C_i is given by

$$C_i = -\frac{u_*^a}{k\Lambda}\ln z_0. \tag{13}$$

Finally, combining the expressions (8) and (12), we derive a wind profile in the roughness sublayer above the non-uniform surface in the grid cell under neutral conditions (hereafter referred as the 'proposed' or 'P'), which can be written in the form

$$u(z) = \frac{u_*^a}{k\Lambda}\ln\frac{z - D}{Z_0}. \tag{14}$$

In this wind profile, Z_0 and D, defined by Equations (10) and (11), represent the aggregated roughness length and displacement height above the grid cell, respectively. Note that the aerodynamic properties of different types of vegetation, expressed through the vegetation-type dependent parameter α, are incorporated into the expressions for Λ and Γ and, thus, Z_0, D and $u(z)$.

3. Parameterization of Roughness Length and Displacement Height

3.1. GENERAL DERIVATION

In the parameterization of the aggregated roughness length given by the Equation (10), it seems that a suitable choice to make it is separately for vegetative, z_{0v}, and non-vegetative, z_{0n}, part of the grid cell. Bearing in mind that the non-vegetative part includes solid and liquid fraction with roughness lengths z_{0s} and z_{0l}, respectively, the aggregated roughness length may be written in the form

$$Z_0 = \frac{1}{\Lambda}\frac{\sigma z_{0v} + \delta z_{0s} + \nu z_{0l}}{\sigma + \delta + \nu}. \tag{15}$$

Since the sum of total fractional covers is equal 1, the last expression can be simplified

$$Z_0 = \frac{\sigma z_{0v} + \delta z_{0s} + \nu z_{0l}}{\Lambda}. \tag{16}$$

For roughness length of solid and water fraction, we use a simple average having the form

$$z_{0s} = \frac{\sum_{i=1}^{L} \delta_i z_{os,i}}{\sum_{i=1}^{L} \delta_i} \tag{17}$$

and

$$z_{0l} = \frac{\sum_{i=1}^{M} \nu_i z_{ol,i}}{\sum_{i=1}^{M} \nu_i}. \tag{18}$$

However, for the roughness length of the vegetative part, we will use also a simple average in combination with the expression for the generalized roughness length [19]. In that case, we obtain

$$z_{0v} = \frac{\sum_{i=1}^{K} \frac{\sigma_i \alpha_i^m}{\sigma_i(\alpha_i - 1) + 1} z_{ov,i}}{\sum_{i=1}^{K} \sigma_i}, \tag{19}$$

where α_i is a parameter for i part of a vegetative cover in the grid cell that is described in Section 2, while m is a parameter set to be 2 according to Mihailovic

Table I. CAMx [17] land-use categories and the default surface roughness length values $\mathbf{z}_0$ displacement height d and leaf area index LAI [26, 27] used for calculating the α parameter according to Lalic [20], as described in Section 2.

Category number	Land cover category	z_0 (m)	d (m)	LAI	α
1	Urban	3.00			
2	Agricultural land	0.25	0.75	4.2	1.38
3	Rangeland	0.05	0.32	3.3	1.18
4	Deciduous	1.00	6.3	2.1	1.61
5	Coniferous including wetland	1.00	6.3	3	1.76
6	Mixed forest	1.00	6.3	6.4	2.12
7	Water	0.0001			
8	Barren land	0.002			
9	Non-forested wetlands	0.15	0.95	2.5	1.23
10	Mixed agricultural and range	0.10	0.63	3.5	1.20
11	Rocky	0.10	–	–	

et al. [19]. The calculated values of α parameter for the different land-use categories considered in this study are listed in Table I, using $C_d = 0.2$ for all plant communities [6]. The land-use categories listed in Table I are identical to those introduced by EPA [28] and are currently used in two-regional scale air photochemical models, namely, UAM-V (SAI, 1995) and CAMx (Environ, 2000). The use of this parameter in the expression for the wind profile in the roughness layer gives systematically better results above the broad range of plant communities than if the classical logarithmic wind profile [10].

Replacing (17), (18) and (19) in Equation (16), we obtain the expression for the roughness length Z_0 as

$$Z_0 = \frac{1}{\Lambda}\left[\sum_{i=1}^{K} \frac{\sigma_i \alpha_i^m}{\sigma_i(\alpha_i - 1) + 1} z_{0v,i} + \sum_{i=1}^{L} \delta_i z_{0s,i} + \sum_{i=1}^{M} \nu_i z_{0l,i}\right]. \tag{20}$$

According to Equations (6), (7) and (11), the aggregated displacement height D has the form

$$D = \frac{\sum_{i=1}^{L} \sigma_i \alpha_i d_i}{\sum_{i=1}^{K} \sigma_i \alpha_i + \sum_{i=1}^{L} \delta_i + \sum_{i=1}^{M} \nu_i}. \tag{21}$$

3.2. A NUMERICAL EXPERIMENT

To examine how well the proposed expressions for the aggregated values of roughness length and displacement height over a grid cell represent the influence of the non-homogenous surface on above air layer, we have performed a numerical experiment. We assume that single grid cell consists of five different covers commonly appearing as land-use categories in grid cells in and around urban areas, i.e. urban part, forest, barren land, agricultural land and water. Calculations have been performed for Λ parameter, roughness length and displacement height by Equations (6), (20) and (21), respectively, as a function of fractional covers of different patches, whose impact as a whole is considered in the following manner. When a single fractional cover σ_i of i patch of a grid cell is chosen to be independent variable, increasing in the range from 0 to 1, the fractional covers of the four other land-uses automatically have taken equal values set to be $(1-\sigma_i)/4$. In these calculations, the corresponding values of d, z_0 and α parameter were taken from Table I.

Figure 1 depicts changes of Λ parameter depending on the variation of fractional covers in the grid cell. From Figure 1a, it is seen that increasing of the forest part determines fast growth of this parameter, resulting in the decrease of the values for Z_0 and wind speed that is given by Equation (14). However, if σ_i of agricultural land goes up, this parameter decreases tending to 1.1, which is the value of α parameter for tall vegetation and crop (Table I). Figure 1b indicates that Λ parameter always decreases when any of non-vegetative parts in the grid cell increases tending to 1. According to Equation (14), the wind speed over a grid cell that is considered as a uniform urban, barren land or water surface, takes the form derived from the classical logarithmic approach.

The proposed method for the aggregation of the roughness length and displacement height (P method) is not a simple averaging of their single values. Rather, it is an attempt to take into account the non-linearity of the processes over a non-homogeneous surface. Consequently, it is useful to make comparison of this method with methods commonly being used in mesoscale and urban-scale numerical models. To this end, we have chosen two methods. One proposed by Kondo and Yamazawa [10] that will be referred as the K method, and the second one the so called 'blending height' method [3] (hereafter referred to as the B method).

Kondo and Yamazawa [10] suggested a practical method for estimating the roughness length over an extensive area with different types of inhomogeneities. They established the table with fifteen division numbers and four categories (A, B, C and D) describing possible patches in the grid cell of an area. Using that classification, on the basis the multi-linear regression of roughness length z_{0K}, they obtained an expression of the form

$$z_{0K} = 0.40a + 1.25b + 2.00c + 1.10d - 0.30, \tag{22}$$

where $a = S_a/S$, $b = S_b/S$, $c = S_c/S$ and $\mathrm{d} = s_\mathrm{d}/S$, while S_a, S_b, S_c and S_d are areas of categories A, B, C and D. In case where the whole area is classified

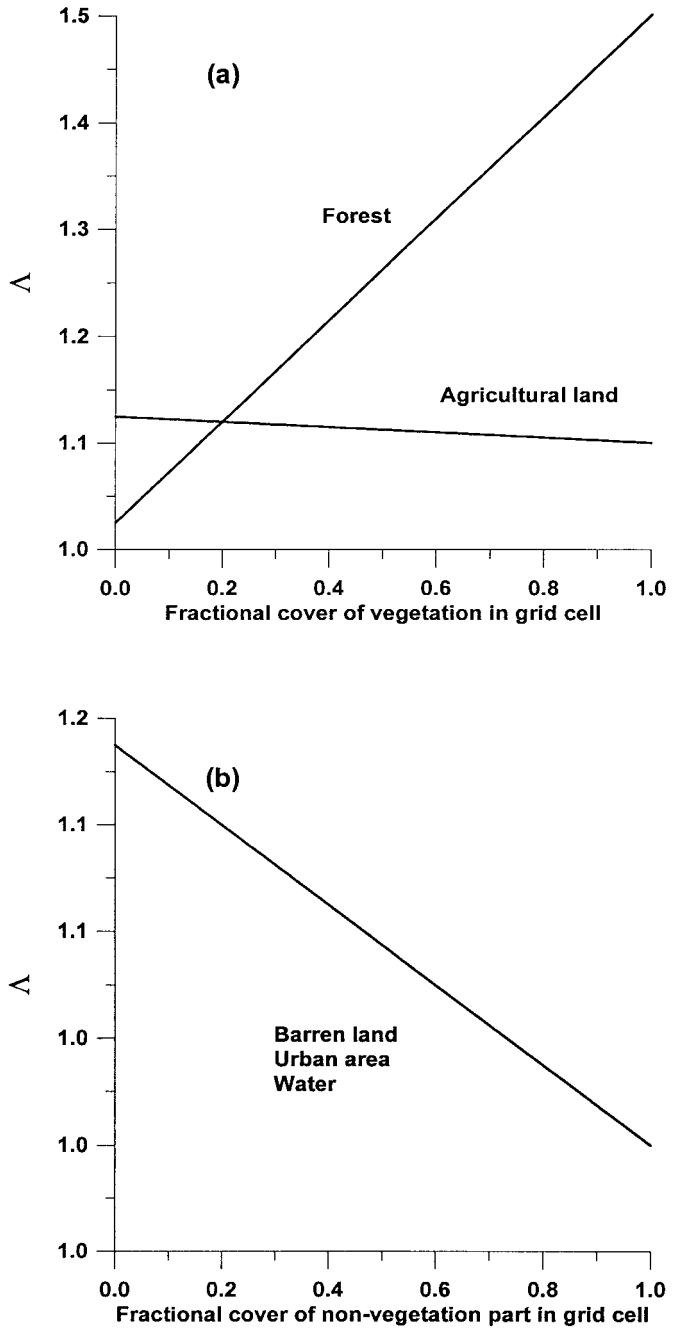


Figure 1. Λ parameter (Equation (6)) as a function of fractional covers in grid cell.

as water surface Equation (22) is no longer valid. In that case, we can take $z_{0K} = 0.0002$ m following Kondo [29]. In order to apply expression (22) correctly, we had to make the correspondence between Kondo and Yamazawa's [10] categories and land-use categories listed in Table I in this study.

Following Hess and McAvaney [3], we have obtained z_{0b}, i.e., the effective roughness length for momentum, in the form

$$z_{0b} = \frac{h_b}{\exp\left[\sum_{i=1}^{K} \sigma_i \ln^{-2}\left(\frac{h_b}{z_{0v}}\right) + \sum_{i=1}^{L} \delta_i \ln^{-2}\left(\frac{h_b}{z_{0s}}\right) + \sum_{i=1}^{M} \nu_i \ln^{-2}\left(\frac{h_b}{z_{0l}}\right)\right]^{-0.5}}, \tag{23}$$

where h_b is the 'blending height', that is, the height at which the air flow senses the blended influence from the whole grid cell [3, 4, 7]. Following Claussen [5] and Hess and McAvaney [3], a value of 75 m can be used for h_b.

4. Results and Discussion

The functional dependence of the roughness length, calculated by three methods, on the fractional amount of five different covers filling the grid cell are presented in Figures 2a–e. Parameters needed for these calculations are taken from Table I. It is seen from Figure 2a, that the P method, gives higher values of roughness length aggregated over the grid cell for the whole range of forest fractional cover changes. The K method gives lower values than the P method. In contrast to them, the B method gives systematically much smaller values for z_{0b}, even for values of the forest fractional cover reaching 0.8. However, after this value, z_{0b} rapidly goes up, as expected for a rough surface like forest. These conclusions can be also made for the case when the fractional cover of urban area varies (Figure 2b). Apparently, the method proposed in this study considers the urban area as a rougher surface than the K method does. In all other cases (Figures 2c–e), the P method still gives higher values than the other two methods. Note that the unrealistically high value for the water roughness length (Figure 2d) occurs because of constraints in Equation (22), when water completely fills the grid cell that as discussed before [10].

Figure 3 shows the comparison of the displacement heights, calculated by the proposed method (P) as a function of fractional covers in the grid cell. Figure 3a indicates that the aggregated displacement height according to Equation (11) has higher values for higher fractional covers of forest and close to forest plant communities, while it decreases for agricultural fields and lower vegetation. Higher amount of non-vegetative patches in the grid cell over urban area (barren land, urban area, and water) significantly reduces the displacement height (Figure 3b). Usually, in the numerical atmospheric, hydrological, air quality or urban models, displacement height is either used as corresponding value of dominant vegetative cover or calculated by a simple averaging of single displacement heights in the grid cell. Undoubtedly, sometimes these procedures yield results that are far away

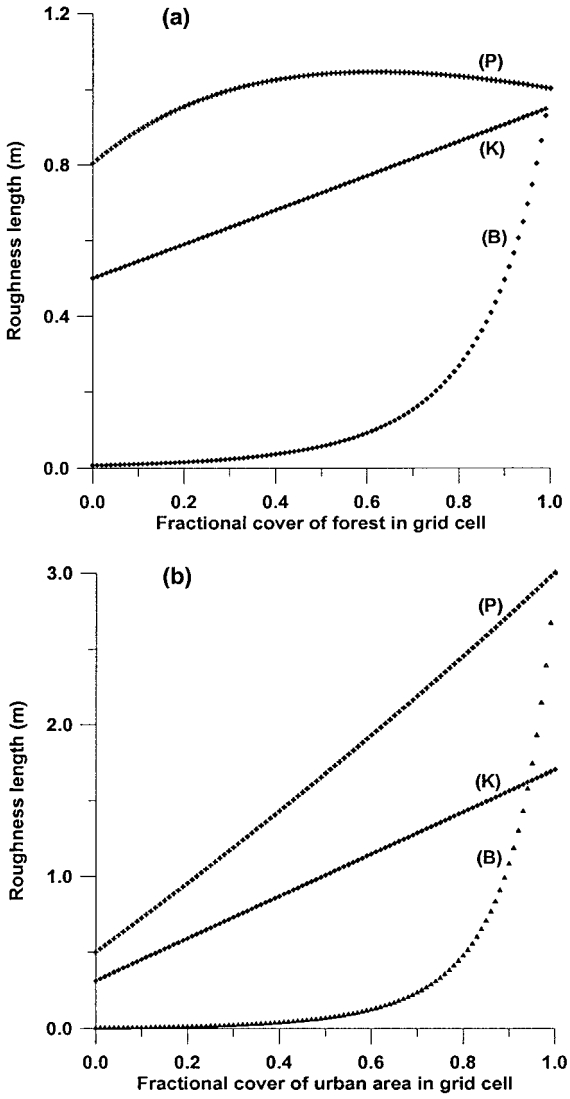


Figure 2. Comparison of the roughness lengths, calculated by different, methods as a function of fractional covers in grid cell. The calculations were performed using: Kondo and Yamazawa's [10] method (K), 'blending height' method (B) and proposed method (P).

from the real-world situations as well documented by Fernando *et al.* [16] and Grimmond *et al.* [17] . However, the proposed method for the aggregation of the displacement height takes into account each single vegetative fractional cover in the grid box, depending on its amount and corresponding displacement height.

To illustrate the differences among different methods for aggregating the aerodynamic characteristics over non-homogenous surfaces, we calculated the roughness length as well as the displacement height over the area centered in the New

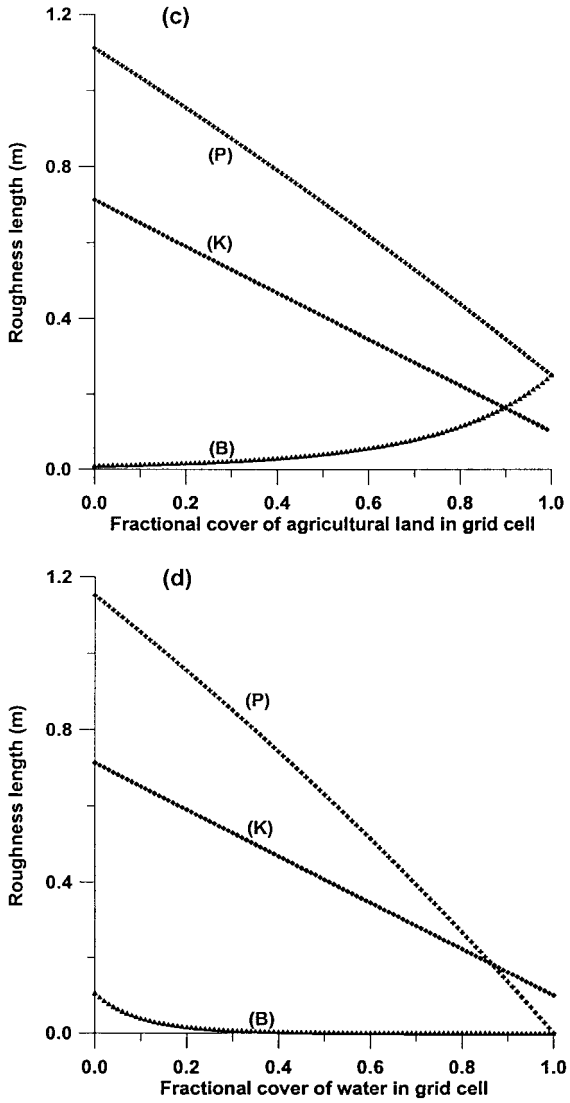
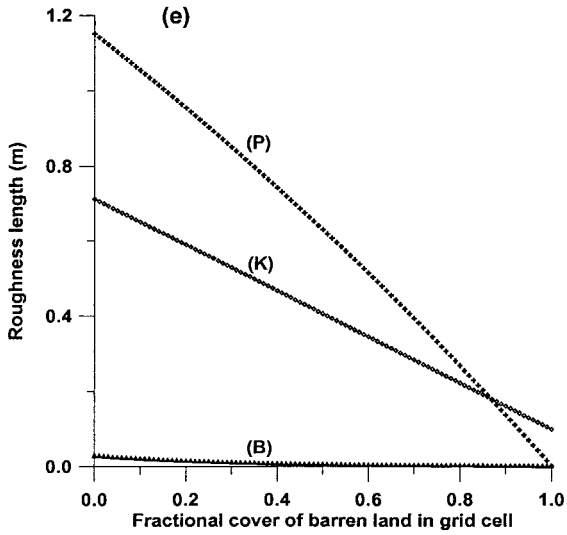


Figure 2. Continued.

York City, since it mostly consists of land covers considered in above numerical experiment (Figure 4). In Figure 4, we displayed the dominant land-use category (according to Table I) on a 6 min $\times$ 6 min grid. The results of the roughness length calculations for this domain are presented in Figure 5. The P and B methods were applied at the whole domain having 1089 grid cells. However, the K method was used for calculating the roughness length only over grid cells where the urban area had dominant fractional cover (category number 1 in Table I) because it is mostly applicable for this type of land-use. The B method has given lower values in all grid cells, than those obtained by the P method. Also, the values of the roughness length



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calculated by the B method were systematically lower comparing with the values coming from the K method. These results support the analysis of the numerical experiment outputs in Figures 2a–e. Similarly, the K method over urban area (gray light shadowed cells in Figure 5a), where it was applied, has given lower values than the P method (indicated by the letter P in Figure 5a). The RMSE (root mean square error) of their difference is 0.89 m for 31 grid cell. At some cells the letter P is omitted because the Kondo and Yamazawa's [10] method was not applied since the fractional cover of urban area was less than 0.50. However, the fractional cover of urban area in those grid cells was still the dominant land-use category over other categories so they were considered as the urban area (39 grid cells).

In meteorological modeling, there is still a tendency for using the dominant type of land-use category in land surface interface schemes, even in cases where a very detailed documentation of land-use categories is available. This kind of simplification is not acceptable when the meteorological model is an interface, either for air quality models or if it is to be used in urban climate. The differences between the roughness length prescribed (Table I) for the dominant type and roughness length calculated by the P method are seen in Figure 5a. The dominant type has higher values over the P method everywhere where numbers fill the grid cell. In non-shadowed grid cells (162), only two dominant land-use categories are present according to Table I, i.e., deciduous forest and mixed woodland with the category numbers 4 and 6, respectively. The RMSE of roughness length differences in them is 0.14 m. However, in the shadowed grid cells, i.e., urban areas the RMSE is 1.01 m. This implies that the P method considers urban area and a surface with patches of forest as a less rough surface than the dominant type method. Presumably, it comes from the fact that the P method more physically takes into account

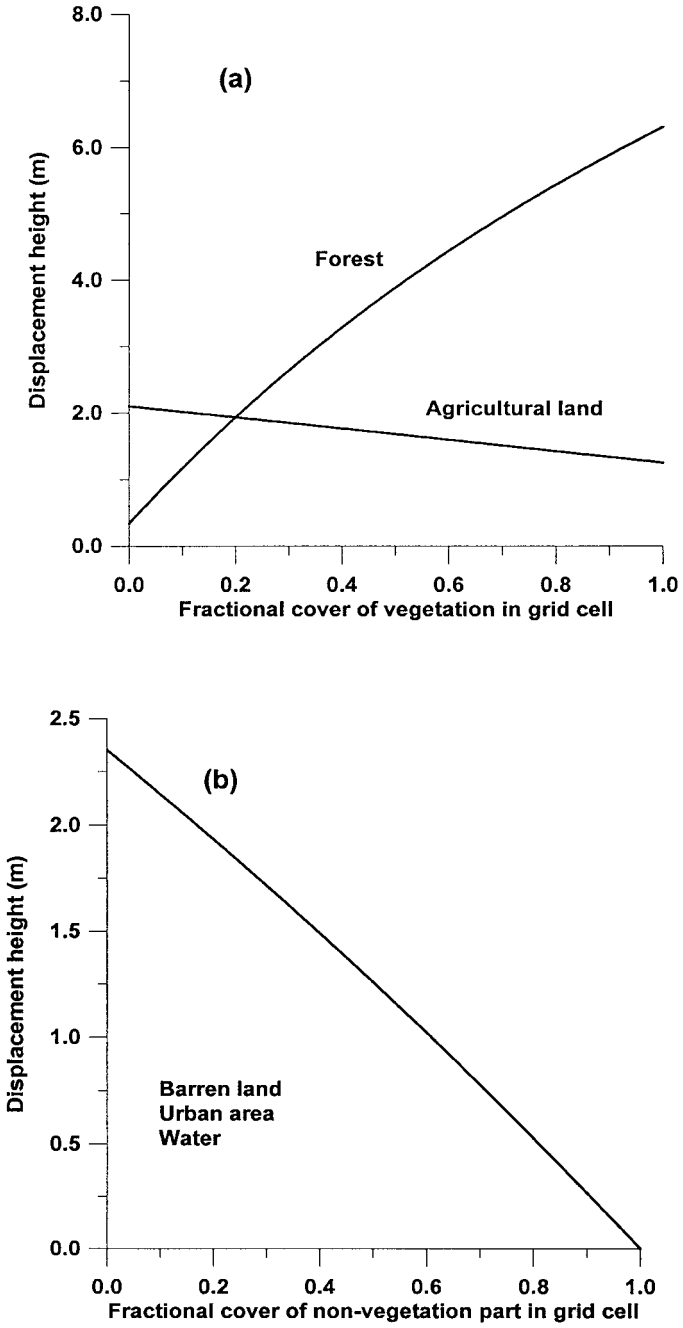

Figure 3. Comparison of the displacement heights, calculated by the proposed method (P) as a function of fractional covers in grid cell.

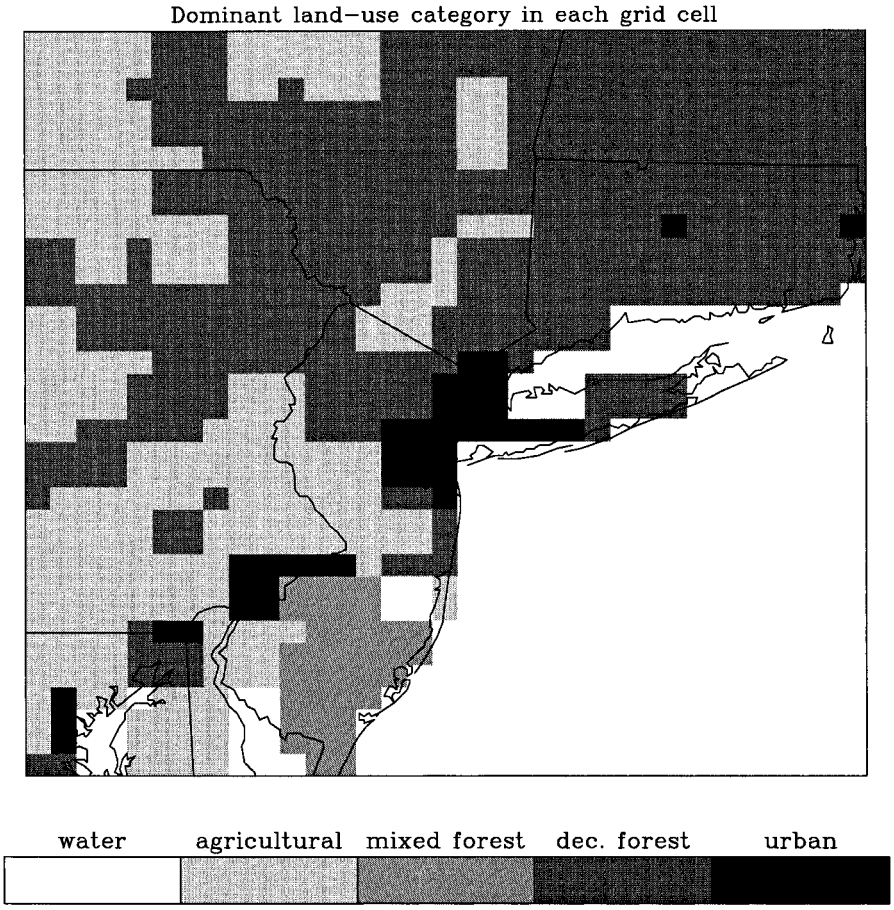

Figure 4. Geographic distribution of dominant land-use categories (Table I) used in calculations of aerodynamic characteristics. The grid cells are plotted on a $6' \times 6'$ resolution.

the whole spectrum of the roughness lengths in the grid cells than the other methods. Finally, Figure 6 depicts the distribution of the aggregated displacement height over the considered domain. It takes values up to 3 m over a huge area where the forest prevails while its value rapidly goes down in agricultural and urban areas.

Equation (14) can be used in numerical modeling of processes above built-in urban areas and forest canopy since the dynamics in urban and forest canopies has many similarities as well as dissimilarities. This wind profile also can be successfully applied instead of the formulas commonly used in above urban modeling which are summarized by Fernando *et al.* [16]. For a comparison of wind profiles using the aerodynamic characteristics obtained by the B, K and P methods over the urban area, all available observations for the wind profiles for July 15, 1999 measured over the Baxter site (40.0357 N, 75.0047 W) in Philadelphia, PA obtained by the thetersonde have been assembled. From these profiles, we randomly

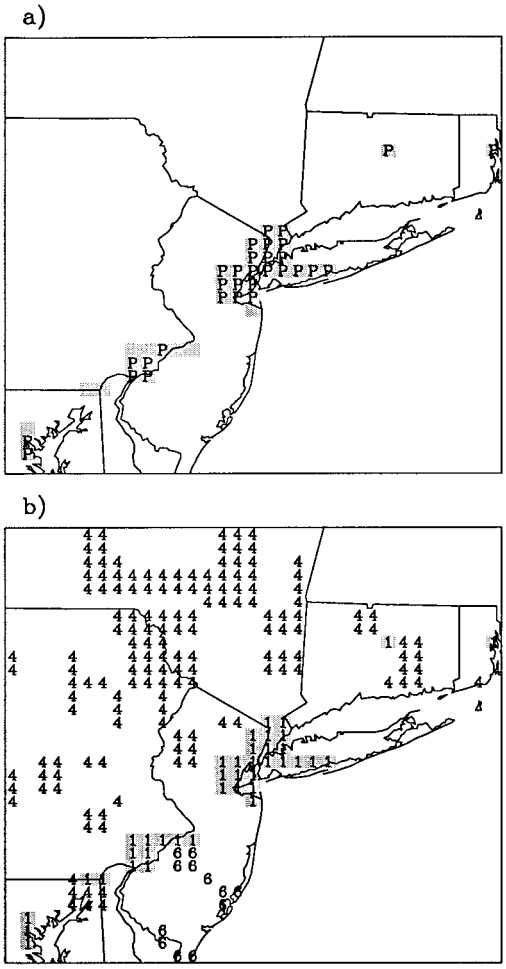

Figure 5. Differences of roughness length for the domain in Figure 4: (a) Between the proposed method (P) and the Kondo and Yamazawa's [10]. method (K); (b) between their values derived from the dominant type (the fourth column in Table I) and the P method. The numbers (number categories from Table I) and letter P indicate that the first method gives greater value.

selected the four wind profiles at: 1000 UTC, 1415 UTC, 1615 UTC and 1755 UTC, which will be denoted as B1000, B1415, B1615 and B1755, respectively. More details about these measurements are available in Philbrick [30]. The grid cell, where the Baxter site was situated, consists of urban area (0.85), agricultural field (0.10) and deciduous forest (0.05) that categorized by numbers 1, 2 and 4, respectively, according to Table I. All parameters needed for calculating the wind profiles were taken also from the same table.

We calculated the wind profiles from the B, K and P methods. The calculations were performed according to the classical logarithmic wind profile (B and K) while the P profile was calculated according to Equation (14). The calculated values of

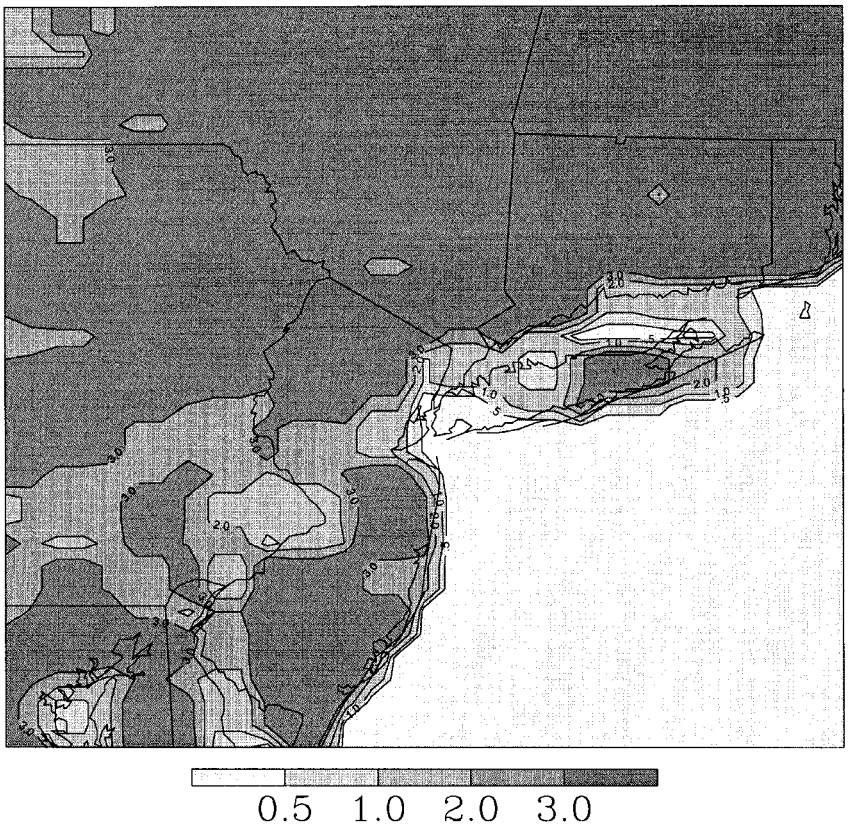

Figure 6. Displacement height for the domain in Figure 4 obtained by the proposed method (P).

roughness length were $z_{0b} = 2.04$ m, $z_{0K} = 1.86$ m and $Z_0 = 2.60$ m for the B, K and P profiles, respectively, and the displacement height used for calculating the P profile was $D = 0.63$ m. Let us note that the z_{0b} is greater than z_{0K} since the fractional cover of urban area is 0.85, i.e. in the region when the values of the roughness length calculated by the 'blending height' method quickly go up (Figures 2a and 2b). Additionally, it is seen that the value of the displacement height D is very small; it means that urban surface prevails in the grid cell. However, the presence of a small vegetative part (deciduous forest and agricultural field) still have influence on the aggregated displacement height. The simulated wind profiles at the Baxter site together with the observations are presented in Figure 7. From this figure, we see different levels of agreement between computed results and observations. The P profile more correctly simulates the wind speed than the two other schemes. The B and K profiles yield systematically higher values than those by the P profile. The results of the comparison between the calculated and observed values of the wind speed may be clearer if they are visualized as in Figure 8, which shows the calculated values of wind speed plotted against the observations using different

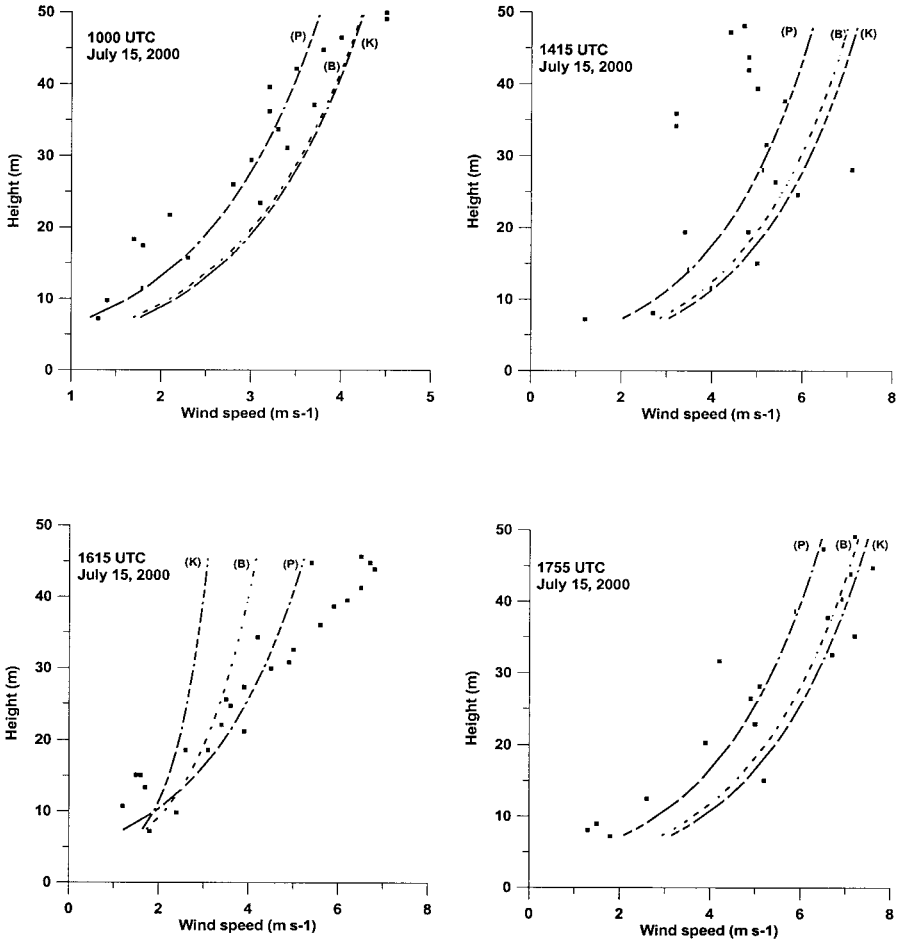

Figure 7. Comparison of the calculated wind profiles with the profile observed above the Baxter site, Philadelphia, PA. The calculations were performed using roughness length obtained by: 'blending height method' (B), Kondo's and Yamazawa [10] suggestion (K) and proposed method (P).

approaches for the wind profile over the mostly urban surface. From Figure 8 it is evident that the B and K profiles overestimate the observed wind speeds, but better represented by the P profile.

If we intend to use show an advantage of the proposed aggregation of aerodynamic parameters due to the commonly used approaches it is very useful to compare corresponding momentum fluxes. In that sense we have compared the B, K and P methods using the outputs obtained by the land surface scheme LAPS (Land Air Parameterization Scheme) that is comprehensively described in Mihailovic and Kallos [26]. For the comparison, we used a data set which is a part of micrometeorological measurements just above and inside a maize canopy during its growing season in De Sinderhoeve (The Netherlands) in 1988. The experimental

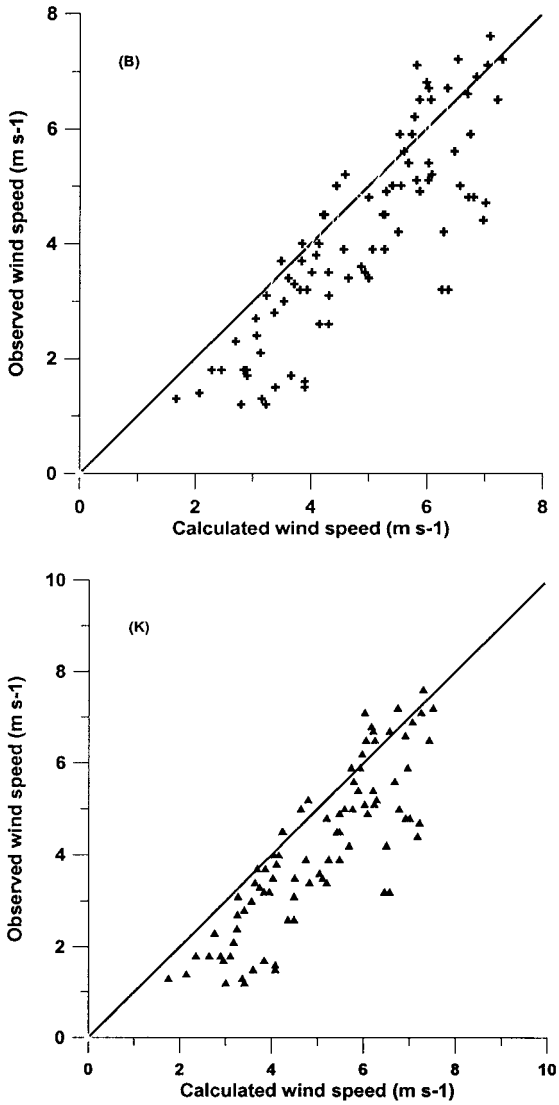

Figure 8. The values of the wind speed profiles calculated by the P, K and B profile methods, plotted against the observations.

site was located in the centre of the Netherlands (52° N, 5.75° E). The site was sized 250 m × 300 m, surrounded by other agricultural fields where maize was dominant. The maize was planted in north-northeast/south-southwest rows with a row spacing of 0.75 m and with 0.11 m spacing in the row (12 plants per m^2). We selected September 9, because it represents the underlying surface consisting of bare soil and maize with fractional covers of 0.35 and 0.65, respectively. Parameters, such as the plant height, the roughness length and the displacement height were measured [29]. The minimum stomatal resistance was not measured and was assumed to be equal

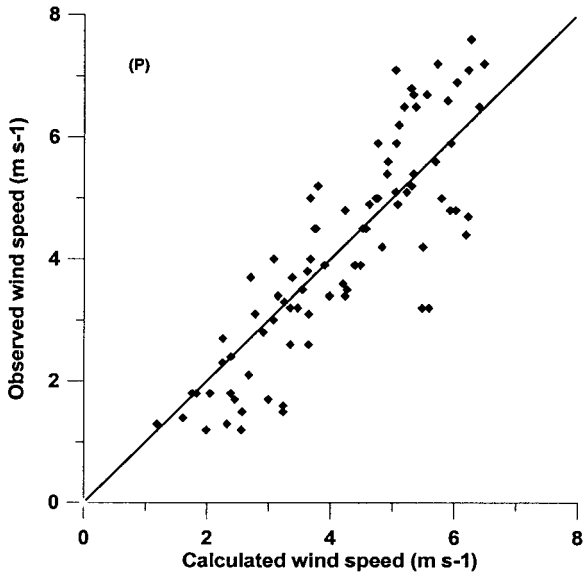

Figure 8. Continued.

to 200 s m^{-1}. The texture of soil at the experimental site was very similar to the soil texture indicated in the paper by van Pul [31]. Soil parameters at test site have the following values: volumetric soil water content at field capacity (0.15 m^3 m^{-3}), volumetric soil water content at saturation (0.41 m^3 m^{-3}), wilting point volumetric soil water content (0.075 m^3 m^{-3}), Clapp–Hornberger constant (4.38), Heat capacity of solid soil faction (820 J kg^{-1} K^{-1}), saturated hydraulic conductivity (0.95×10^{-12} m s^{-1}), soil density (1410 kg m^{-3}) and soil moisture potential at saturation (0.1717 hPa). Maize parameters used in the runs are described in detail by and Mihailovic and Kallos [26]. The atmospheric boundary conditions at the reference level, $z_r = 4.5$ m, were derived from measurements of global radiation, cloudiness, precipitation, specific humidity, temperature and average wind speed for 24 h from 0000 UCT at 15-min intervals. These values were interpolated at the beginning of each time step ($\Delta t = 600$ s). The time integration was started at 0000 UCT with the initial values of atmospheric pressure of 1024 hPa. The initial value of volumetric soil moisture content and soil surface temperature were derived from Mihailovic and Kallos [26]. The comparison of the methods was made by analysing the one-day time integration of outputs of aggregated momentum fluxes calculated over the maize canopy. The observed values of the momentum fluxes over the maize canopy were used from van Pul [31]. Figure 9 depicts the results of the B, K and P methods in computing the momentum fluxes over the sparse maize canopy by plotting them against the observations. Looking at this figure it is seen that the best agreement with the observations is achieved by the proposed method. In contrast to that, the K and B method significantly overestimates and underestimates the observed values, respectively.

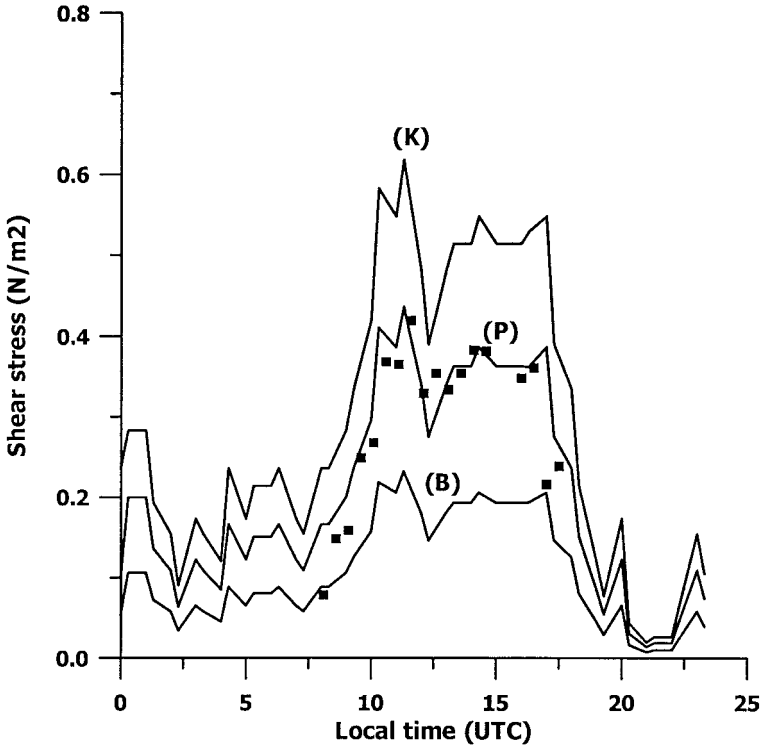

Figure 9. Comparison of the momentum fluxes, calculated by the LAPS surface scheme, with the observations above De Sinderhoeve (The Netherlands) for September 9, 1988. The calculations were performed using roughness length obtained by: 'Blending height method' (B), Kondo and Yamazawa's [10] suggestion (K) and proposed method (P).

5. Summary

In this paper we have attempted to generalize: (a) The calculation of exchange of momentum between the atmosphere and heterogeneous surface and (b) equation for the wind speed profile in a roughness sublayer under neutral conditions. This was done assuming a linear aggregation of a mixing length from relative distribution between different fractions in the grid cell; then, we derive the aggregated roughness length and displacement height over the grid cell.

In order to check the validity of the assumptions introduced, we have performed: (a) Numerical tests, and (b) a comparison of the suggested expression for the wind profile with some earlier approaches, using the observations obtained in an urban area. The major results derived from them may be summarized as follows:

- The aggregated aerodynamic characteristics are derived more physically than in the case when aggregation is made by a simple averaging method.

- In numerical experiments with different fractions of grid cell components the aggregated aerodynamic parameters show more realistic behavior reproduction of observed features.
- The wind profiles above the urban area obtained by the P profile more correctly simulate the wind speed than the two other methods.

Although the comparison of the proposed model with the observations gives acceptable results, we have to keep in mind some potential limitations due to assumptions made, and the representativeness of the validation data used here.

6. Acknowledgements

This research was supported by the U.S. Environmental Protection Agency STAR grants R826-3731476 and R828-73301 awarded to Dr. S.T. Rao of the University at Albany.

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