ON THE PROFILES OF WIND VELOCITY IN THE ROUGHNESS SUBLAYER ABOVE A CONIFEROUS FOREST

A. WENZEL, N. KALTHOFF and V. HORLACHER
Institut für Meteorologie und Klimaforschung (IMK), Universität Karlsruhe/Forschungszentrum Karlsruhe, Germany

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Abstract. Wind velocity and temperature measurements from a 200 m tower, located in a forest near Karlsruhe were used to investigate the modified profile function of the wind velocity in the roughness sublayer.

To avoid determination of the friction velocity we introduced an alternative analysis with the expression

$$F_m^* = z\frac{\partial}{\partial z}\ln\left(\frac{\kappa z}{u_*}\frac{\partial u}{\partial z}\right)$$

instead of

$$\Phi_m^* = \frac{\kappa z}{u_*}\frac{\partial u}{\partial z}.$$

From the observed F_m^* profiles we evaluated the profile function Φ_m^*. The wind profiles observed under neutral conditions were well represented by a modified non-dimensional profile function with physically based boundary values at the top and at the bottom of the roughness sublayer.

The results of our analysis can be used to take into consideration the momentum exchange between the atmosphere and a forest in mesoscale atmospheric models in a refined way.

Key words: Roughness sublayer, Wind profile, Profile function, Coniferous forest, Large roughness

1. Introduction

Measurements above surfaces with large roughness, e.g., forests or large crops showed (e.g., Raupach, 1980) that the momentum flux calculated with the Monin–Obukhov function $\Phi_m\left(\frac{z}{L}\right)$ (Monin and Obukhov, 1954)

$$\frac{\kappa z}{u_*}\frac{\partial u(z)}{\partial z} = \Phi_m\left(\frac{z}{L}\right) \tag{1}$$

differs from flux values calculated with the covariance method. Here L defines the Obukhov length, κ the von Karman constant, u the horizontal wind velocity, u_* the friction velocity, and z the height above the displacement height d. The height range up to which the Monin–Obukhov function is not valid is defined as the roughness sublayer. The height of the roughness sublayer is roughly three times the height of the roughness elements h_v (e.g., Brutsaert, 1982) which gives values of about 90 m if the height of the trees is 30 m. This means, the roughness-layer depth is of the same order as the height of the surface layer s_l. For example, according to Stull (1988) $s_l \approx 0.1 z_i$ which gives $s_l = 100$ m for a typical mixed-layer height of $z_i = 1000$ m. According to Wyngaard (1973) the surface-layer height $s_l \approx 100 z_0$, where z_0 defines the aerodynamic roughness length. Assuming $z_0 \approx 0.1 h_v$ (Tanner and Pelton, 1960) results in a surface-layer height of $s_l = 300$ m. As in most cases a tower within a forest does not exceed the top of the roughness sublayer, for practical applications profile functions are necessary which are valid within the roughness sublayer itself.

For such surface layers it was proposed by Raupach (1979a) to include the influence of the roughness elements on the profiles by a second length scale z_*, the roughness-layer depth which defines the top of the roughness sublayer. This leads to the modified Monin–Obukhov function for momentum

$$\frac{\kappa z}{u_*}\frac{\partial u(z)}{\partial z} = \Phi_m^*\left(\frac{z}{L}, \frac{z}{z_*}\right). \tag{2}$$

From measurements it was found that the quotient $\frac{\Phi_m^*}{\Phi_m}$ is independent of stability. So it was proposed by Raupach (1979a) that

$$\Phi_m^*\left(\frac{z}{L}, \frac{z}{z_*}\right) = \frac{\Phi_m\left(\frac{z}{L}\right)}{\gamma_m\left(\frac{z}{z_*}\right)}. \tag{3}$$

In this equation the function $\gamma_m\left(\frac{z}{z_*}\right)$ is independent of stability and the influence of the surface roughness elements is characterized by the length scale z_*. Raupach (1979a) found from measurements that

$$\gamma_m\left(\frac{z}{z_*}\right) = 1. \tag{4}$$

above a mature scot pine forest, i.e. there is no difference with respect to the Monin–Obukhov function for momentum (Equation (1)). The function

$$\gamma_m\left(\frac{z}{z_*}\right) = \begin{cases} \left(\frac{z}{z_*}\right)^{-\nu} & z \le z_* \\ 1 & z > z_* \end{cases} \tag{5}$$

with ν varying between 1 for sparse vegetation and 0 for dense vegetation was proposed by Cellier and Brunet (1991). From this point of view, Equation (4) is only valid for dense vegetation. The introduction of ν in Equation (5) indicates that it is not possible to take into account the influence of the roughness elements with different spacings δ and different heights h_v by only one length scale z_*. Another empirical relation

$$\gamma_m\left(\frac{z}{z_*}\right) = \begin{cases} \exp\left(\alpha\left(1 - \frac{z}{z_*}\right)\right) & z \le z_* \\ 1 & z > z_* \end{cases} \tag{6}$$

was found by Garratt (1980) with α on the order of 0.7. Thus, γ_m ranges from 2 at $z = 0$ to 1 at $z = z_*$. As emphasized by Garratt (1992) the main failure of this formula is the implied discontinuity in $\frac{\partial \gamma_m}{\partial z}$ at $z = z_*$. The same applies to the formula of Cellier and Brunet (1991). As a result of an analysis of tower wind profile measurements over a coniferous forest, a new γ_m formula is proposed. The main advantage of this formula is that $\gamma_m(z)$ has no jump of the first derivative at the roughness-layer depth and also a physically based boundary value at the bottom.

2. Measurement Site

For the analysis of wind velocity and temperature, data measured at the 200 m tower of Forschungszentrum Karlsruhe were used. The tower is located in a coniferous forest with an extension of 10 km in a southerly direction. The east–west extension is about 8 km. The trees are 30 m high and roughly 10 m apart.

The data set consists of 10-min mean values. Wind velocity data were available at heights of 30 m, 40 m, 50 m, 60 m, 80 m, 100 m, 130 m, 160 m and 200 m, whereas temperatures were measured at heights of 30 m, 60 m, 100 m, 130 m, 160 m and 200 m. A detailed description of the site and the instrumentation of the tower is given in Kalthoff and Vogel (1992).

To satisfy the fetch requirements, i.e., to use only data from the fully adjusted layer $\delta \approx 0.01x$, where the fetch x defines the distance downwind from the change in surface features, only data which had been measured when the wind came from south, i.e., the sector between 155° and 205°, were selected.

To reduce scattering of the data the 10-min mean values were averaged over 30 min. For further calculations it is necessary to build the first and the second derivatives of wind speed and temperature. An approximation with a differential quotient produces great errors in these values. To minimise the errors in the derivatives a cubic function in $\ln(z)$

$$\left.\begin{array}{r} u(z) \\ \Theta(z) \end{array}\right| = a_1 + a_2 \ln(z) + a_3 \ln^2(z) + a_4 \ln^3(z). \tag{7}$$

was fitted through the measured wind speed u and potential temperature Θ profiles using a least square fit before calculating the first and the second derivatives.

One of the main conditions is that the gradients of velocity and temperature are not too small. Otherwise, measuring errors dominate the results. To filter out such cases, we use the criterion that the wind velocity at 100 m height must be greater than 5 m s^{-1}. Additionally the analysis is restricted to the neutrally stratified surface layer, as explained in Section 4. This reduces the number of profiles available for our analysis to 103 for the years 1991–1994.

The significance of the interpolated values with respect to their derivatives is dependent on stochastic and systematic errors of the measured values. The

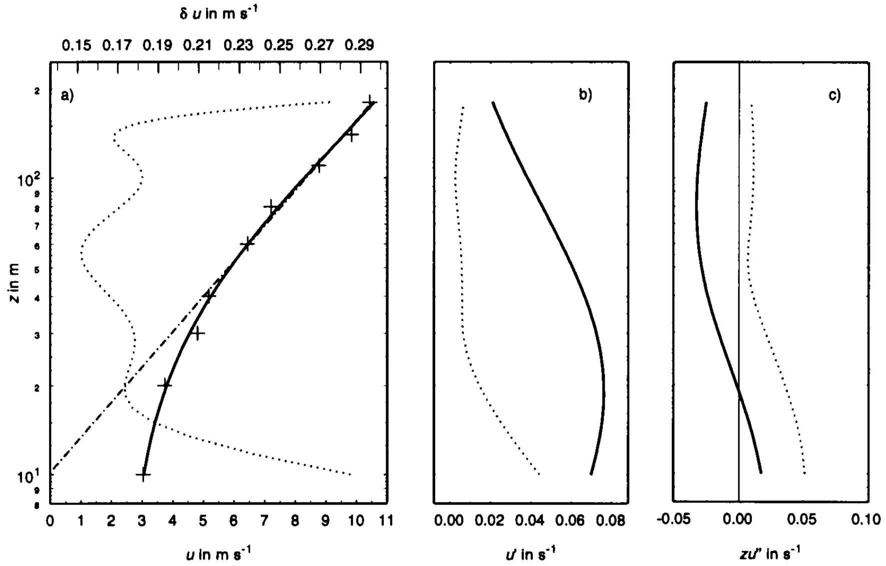

Figure 1. Profiles of the wind velocity, derivatives of the wind velocity and the estimated systematic errors on September 12, 1994, 1730 hrs. a) measured wind velocities u_i (+), interpolated values (solid line), estimated error (dotted line) and logarithmic wind profile (dashed dotted line). b) first derivative $\mathcal{L}(u) = u'(z)$ (solid line) and estimated error (dotted line). c) second derivative multiplied by z, i.e., $\mathcal{L}(u) = zu''(z)$ (solid line) and estimated error (dotted line).

influence of stochastic errors can be estimated from the standard deviation of the values evaluated from the interpolated wind velocity and potential temperature profiles.

The impact of systematic errors in the wind velocity values, u_j ($j = 1..M$) or potential temperature values, Θ_j measured at the j-th height, z_j on the fitted profiles and on the profiles of the first and second derivatives necessary for our analysis can be estimated by the following considerations.

Using a least squares fit to estimate the coefficients a_k in Equation (7) the coefficients a_k, $k = 1 \ldots N$ are linear functionals (see e.g., Bronstein and Semendjajew, 1996)

$$a_k = \sum_{j=1}^{M} B_k^j u_j \tag{8}$$

of the measured wind velocity values u_j (the same holds for the potential temperature). The matrix B_k^j can be found by setting successive $u_j = \delta_{j,l}, l = 1 \ldots M$ (see Equation (8)) and evaluating the coefficients $a_k^{(l)}$ with least squares fit techniques. From this the matrix B_k^j is given by $B_k^l = a_k^{(l)}$.

Now the influence of incorrect wind velocity or potential temperature measurements on interpolated profiles can be estimated. Substituting Equation (8) in (7) gives

$$u(z) = \sum_{j=1}^{M} C_j(z) u_j \tag{9}$$

with the vector

$$C_j(z) = \sum_{k=1}^{N} B_k^j \ln^{k-1}(z). \tag{10}$$

Assuming the measured values for u_j are disturbed by δu_j results in the disturbance of the wind profile

$$\delta u(z) = \sum_{j=1}^{M} C_j(z) \delta u_j . \tag{11}$$

An estimation for $|\delta u(z)|$ using the Schwartz inequality gives

$$|\delta u(z)| \leq \|C_j(z)\| \, \|\delta u_j\| . \tag{12}$$

If $\mathcal{L}$ is a linear operator for $u(z)$, from Equation (11) it can be found that

$$|\delta \mathcal{L}\left(u(z)\right)| \leq \|\mathcal{L}\left(C_j(z)\right)\| \, \|\delta u_j\| . \tag{13}$$

The value of the norm $\|\delta u_j\|$ depends on the problem under consideration. Here we will assume that every anemometer used for the measurements has the same systematic error δu. In that case $\|\delta u_j\| = \sqrt{M}\delta u$.

Inequality (13) was applied to estimate the influence of the systematic errors on the fitted curves and on their first and second derivatives. In Figure 1 a typical wind velocity profile used for our analysis and the corresponding systematic error estimated from the inequality (12) are shown. Assuming a systematic error $\delta u \approx$ 0.1 m s^{-1} for the measured wind velocity values results in a systematic error for the fitted wind profile of about 0.3 m s^{-1} at the edges of the profile and about 0.2 m s^{-1} in the middle (see Figure 1).

The error of the wind velocity gradient ($\mathcal{L} = \frac{\partial}{\partial z}$), also shown in Figure 1, is about 15% of the gradient evaluated from the fitted wind profile. Only at the edges of the profile measurements does the error reach 50%.

For our analysis we also need zu'' ($\mathcal{L} = z\frac{\partial^2}{z^2}$) values (see Equation (14)). In Figure 1 a profile of these values together with an error estimate is shown. It can be seen that near the edges of the profile the error in the second derivative is of the same order of the derivative itself. This information has to be considered in the interpretation of the results shown in Section 4.

Here potential temperature profiles were only used to calculate the gradient Richardson number to find out the nearly neutral cases. So an error estimate is not given.

3. Determination of the γ_m Function

The modified Monin–Obukhov function for momentum can be determined directly from Equation (2) if the wind profile $u(z)$ and the friction velocity u_* are given. If there are no eddy–correlation measurements for u_* available, u_* can be calculated from the wind profile of the upper part of the surface layer. The method fails if the upper part of the profile is still in the roughness sublayer. In our case, the roughness element height is $h_v \approx 30$ m and thus the roughness sublayer is assumed to cover the main part of the surface layer. Hence, if no logarithmic wind profile exists we have to propose an alternative analysis, for which u_* is not needed. For such an analysis a variable independent of u_* is necessary from which we can calculate the unknown Φ_m^*–function. The variable

$$F_m^* = 1 + z\frac{\partial^2 u}{\partial z^2}\left(\frac{\partial u}{\partial z}\right)^{-1} = z\frac{\partial \ln\left(\frac{\kappa z}{u_*}\frac{\partial u(z)}{\partial z}\right)}{\partial z} \tag{14}$$

is independent of u_* and is a universal function if $\frac{\kappa z}{u_*}\frac{\partial u(z)}{\partial z}$ is a universal function, as

$$z\frac{\partial \ln\left(\frac{\kappa z}{u_*}\frac{\partial u(z)}{\partial z}\right)}{\partial z} = z\frac{\partial \ln\left(\Phi_m^*\left(\frac{z}{L},\frac{z}{z_*}\right)\right)}{\partial z}. \tag{15}$$

For $\frac{z}{z_*} \to \infty$, $\Phi_m^* \to \Phi_m$ and the function F_m^* depends only on $\frac{z}{L}$. So

$$\lim_{\frac{z}{z^*}\to\infty} F_m^* = F_m = z\frac{\partial \ln\left(\Phi_m\left(\frac{z}{L}\right)\right)}{\partial z}.$$

In order to derive a relation between the γ_m–function and the Φ_m^*–function, Equations (3), (14) and (15) were used. Substituting of Equations (3) and (14) in Equation (15), dividing the resulting equation by z and integrating yields

$$\gamma_m = e^{\int_z^\infty \frac{F_m^* - F_m}{z'}dz'} \tag{16}$$

and for the modified Φ_m^*–function

$$\Phi_m^*\left(\frac{z}{L},\frac{z}{z_*}\right) = \Phi_m\left(\frac{z}{L}\right)e^{-\int_z^\infty \frac{F_m^* - F_m}{z'}dz'} \tag{17}$$

Under neutrally stratified conditions the F_m^* function defined by Equation (14) is proportial to the ratio between z and the length scale of changes in Φ_m^* resulting from the wake–shear interaction in the roughness sublayer (Garratt, 1980). Near the vegetation top, the changes in Φ_m^* with height are most pronounced whereas for $z \gg h_v$, $\Phi_m^* \to 1$ and the changes in Φ_m^* have to vanish. This means the length scale of change in Φ_m^* $(= z/F_m^*)$ must be a function of height. Taking into account measured profiles for F_m^* (or z/F_m^*) for evaluating γ_m seems to be more adequate than assuming a constant value for this length scale inside the whole roughness sublayer as has been done by Garratt (1980).

4. Results

The term F_m in Equations (16) and (17) is zero for a neutrally stratified surface layer so that γ_m can be calculated from Equation (16). Here only cases with neutral or near-neutral conditions $(-0.01 < Ri < 0.01)$ were selected. First F_m^* is calculated from Equation (14) and then γ_m from Equation (16). The displacement height d was taken as $0.67h_v$ which gives a height of $d = 20$ m. Figure 2 shows the profile of measured F_m^*–values averaged over all data available for neutral stability. It can be shown from this diagram that the F_m^*–function is approximately 1 at the vegetation height h_v and decreases to 0 if $z \to \infty$. Outside the roughness sublayer we have $F_m^* \approx F_m = 0$ for neutral stratification and so we will use the roughness sublayer depth defined as $F_m^*(z_*) = 0.1$ at neutral stratification for the calculation of the length scale z_*. The measurements support a value of about 80 m for z_*. As the spacing of the trees δ is approximately 10 m, the ratio $\frac{z_*}{\delta} = 8$ is higher than the value $3 - 5$ found by other investigators. For instance, Cellier and Brunet (1991) obtained values on the order of $3 - 4$ for crops, Cellier (1986) found 3.1 for sugar beets, Garratt (1980) found 3.0 for savanna, and Chen and Schwertfeger (1989) got 4.6 for a coniferous forest. On the other hand, $z_* + d \approx 3h_v$, i.e., the z_* value from our analysis is equal to the lower limit of height range where the Monin–Obukhov theory is valid (Brutsaert, 1982). This supports the assumption that the roughness-layer depth is related primarily to the roughness element height rather than to the spacing of the roughness elements.

Using the proposed γ_m function of Cellier and Brunet (1991) (Equation (5)) to evaluate the F_m^*–function for neutral stratification, we get

$$F_m^* = \begin{cases} \nu, & z \leq z_* \\ 0, & z > z_* \end{cases} . \tag{18}$$

In Figure 2 this F_m^*–function is also displayed. As the function is constant with height, good agreement can only be found in the height range of $\frac{z}{z_*} \approx \frac{1}{2}$. Even a change of the parameter ν does not give better approximation for the whole F_m^* profile than the value $\nu = 0.45$.

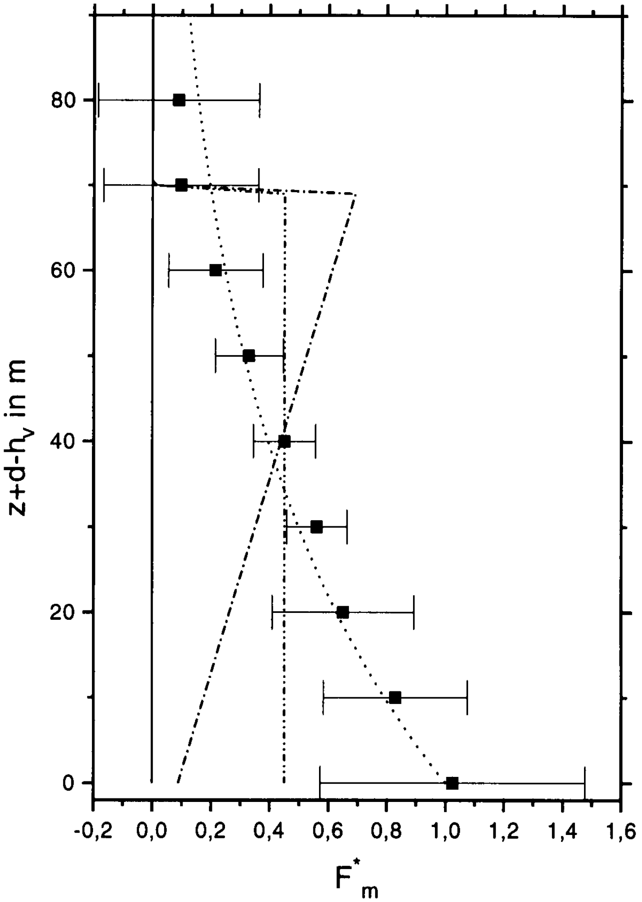

Figure 2. Black squares: Measured F_m^* values according to Equation (14) plus standard deviation as a function of $z + d - h_v$ for neutral stability $(-0.01 < Ri < 0.01)$; dotted line: F_m^*–values according to Equation (20); dashed–double dotted line: F_m^*–function with $z_* = 80$ m evaluated from the γ_m function after Brunet and Cellier (1991); dashed–dotted line: F_m^*–function with $z_* = 80$ m evaluated from the γ_m–function after Garratt (1980).

From the γ_m–Equation (6) proposed by Garratt (1980) we get for the F_m^*–function:

$$F_m^* = \begin{cases} \alpha \frac{z}{z_*}, & z \le z_* \\ 0, & z > z_* \end{cases} . \tag{19}$$

This F_m^*–profile exhibits a behaviour similar to that of the profile evaluated with the γ_m–formula proposed by Cellier and Brunet (1991), i.e., there is agreement between the measured and the evaluated profiles only in the middle of the roughness sublayer.

It is evident from Figure 2 that an exponential function of the form

$$F_m^* = \exp\left(-\frac{(z+d)-h_v}{l_*}\right) \tag{20}$$

with $l_* = 42.3$ m fits our measured F_m^*–values well. l_* is a length scale which includes the influence of the spacing of the trees, δ, with $l_* = 4\delta$. For dense vegetation l_* becomes zero, i.e., $\lim_{l_* \to 0} F_m^* = 0$ and the influence of the roughness elements disappears, while for sparse vegetation $\lim_{l_* \to \infty} F_m^* = 1$. This is in agreement with results from other investigations (Cellier and Brunet, 1991). For the roughness-layer depth defined from $F_m^*(z_*) = 0.1$ we get $z_* = 100$ m.

The upper limit of this expression

$$\lim_{z \to \infty} F_m^* = 0 \tag{21}$$

results from the assumption that for $z \gg z_*$ and neutral stratification $\Phi_m = 1$ and so $F_m^* = F_m = 0$.

Of more interest is the lower limit

$$\lim_{z \to h_v - d} F_m^* = 1 \tag{22}$$

which is confirmed by the measured F_m^*–values in Figure 2. Evaluation of the term on the right–hand side of Equation (14) shows that $F_m^* = 1$ is equivalent to

$$\left.\frac{\partial^2 u}{\partial z^2}\right|_{z=h_v-d} = 0$$

if $\frac{\partial u}{\partial z} \neq 0$ at $z = h_v - d$. The wind profile in the vegetation layer is well described by the exponential law $u = u_h \exp\left(-a\left(1 - \frac{z+d}{h_v}\right)\right)$ (e.g., Brutsaert, 1979), i.e., $\frac{\partial^2 u}{\partial z^2} > 0$ inside the vegetation layer. Above the vegetation layer, the fluxes are constant with height and so $\frac{\partial^2 u}{\partial z^2} = -\frac{1}{K_m}\frac{\partial K_m}{\partial z} u_*^2 < 0$. If the profiles of the second derivative are steady within the transition zone between both regimes, there must be a height very near the vegetation top where $\frac{\partial^2 u}{\partial z^2} = 0$. From these considerations it can be postulated that

$$\lim_{z \to h_v - d} F_m^* = \lim_{z \to h_v - d} \frac{z}{\Phi_m^*}\frac{\partial \Phi_m^*}{\partial z} = 1 \tag{23}$$

must be a boundary condition for every Φ_m^* formula, which takes the influence of the roughness sublayer into account.

Applying Equation (20) to calculate the γ_m–function from Equation (17) gives

$$\gamma_m = \exp(g(z)) \tag{24}$$

with

$$g(z) = -\exp\left(\frac{h_v - d}{l_*}\right) \mathrm{Ei}\left(-\frac{z}{l_*}\right),$$

where $\mathrm{Ei}(x)$ is the exponential integral function (e.g., Bronstein and Semendjajew, 1996) defined by

$$\mathrm{Ei}(x) = \int_{-\infty}^{x} \frac{e^{x'}}{x'} dx' \tag{25}$$

or

$$\mathrm{Ei}(x) = C + \ln|x| + \sum_{k=1}^{\infty} \frac{x^k}{k!k}, \tag{26}$$

where the Euler–constant $C = .57721567$.

In the upper part of the roughness sublayer the different γ_m formulations are quite similar (see Figure 3) whereas for lower levels the γ_m function (24) gives much greater values than other formulations. In terms of mixing length l, $\gamma_m = l/(\kappa z)$ (Garratt, 1980) and so γ_m values greater 1 found in the roughness sublayer indicate that the length scale of energy containing eddies is larger than one would expect from a surface layer with a logaritmic wind profile. At the vegetation top, γ_m found from Equation (24) is about 4, so $l \approx 16$ m. This means the mixing length l is nearly half of the vegetation height h_v.

The γ_m function proposed here (Figure 3) has two advantages: (i) the function of Equation (20) fits well the measurements, and (ii) the function satisfies the upper and lower boundary conditions defined in Equations (21) and (22). In the upper part of the roughness sublayer the γ_m–profile from Equation (24) is very similar to the γ_m functions of Equations (5) and (6) found by other investigators. However, there is only one free parameter, l_*, in the formula. Another advantage of the formula is that there is no jump of $\frac{\partial \gamma_m}{\partial z}$ at $z = z_*$.

5. Conclusions

Above very rough surfaces such as forests the depth of the roughness sublayer, z_*, is on the order of 100 m. In this case, it is impossible to calculate the roughness length, z_0, and the friction velocity, u_*, from profile data, because there is no well defined logarithmic wind velocity profile within the lower half of the surface layer at neutral stratification. Usualy, measurements above surfaces with large roughnesses are limited to the roughness sublayer, so it is necessary to take into account the influence of a rough surface for the calculation of the momentum exchange between the surface and the surface layer using an equation resembling in Equation (2).

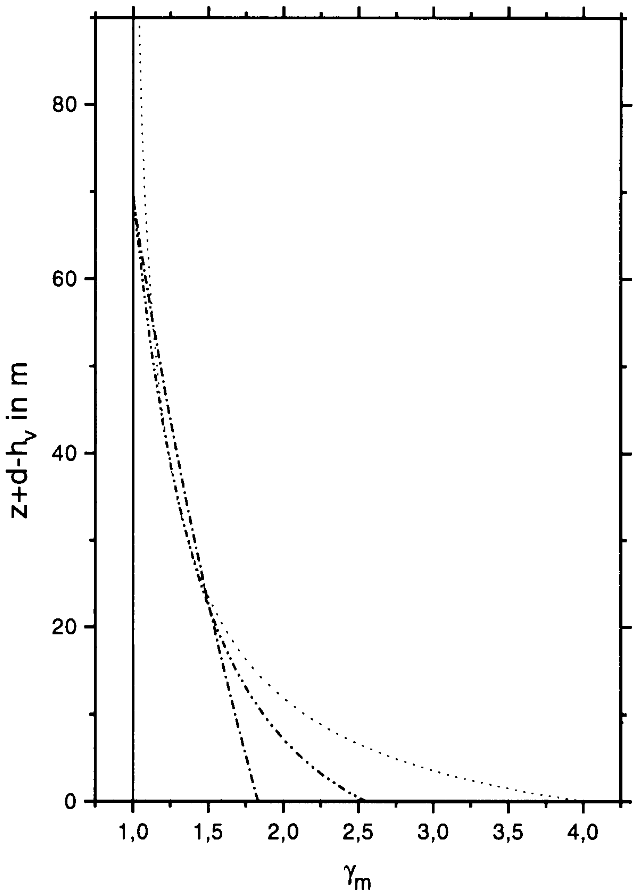

Figure 3. Comparison of different γ_m functions; dotted line: γ_m values according to Equation (24); dashed–double dotted line: γ_m function with $z_* = 80$ m after Brunet and Cellier (1991); dashed–dotted line: γ_m function with $z_* = 80$ m after Garratt (1980).

To find the modified Monin–Obukhov function for momentum over a coniferous forest an expression derived from the dimensionless gradient of the wind velocity was used. This expression is independent of the friction velocity. From this, the modified Monin–Obukhov function for momentum was derived from the wind profile only.

It was shown that the modified Monin–Obukhov function Φ_m^* for neutral stratification is represented by a function of the type

$$\Phi_m^* = \exp(-g(z))$$

with

$$g(z) = -\exp\left(\frac{h_v - d}{l_*}\right) \mathrm{Ei}\left(-\frac{z}{l_*}\right). \tag{27}$$

The proposed γ_m function has physically based boundary conditions at the top, $z = \infty$, and at the bottom, $z = h_v$, of the roughness sublayer. Additionally, in comparison to other formulae, there is only one free parameter, l_*.

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