MOMENTUM TRANSFER BY A MOUNTAIN MEADOW CANOPY: A SIMULATION ANALYSIS BASED ON MASSMAN'S (1997) MODEL

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Abstract. Using a mountain meadow as a case study it is the objective of the present paper to develop a simple parameterisation for the within-canopy variation of the phytoelement drag (C_d) and sheltering (P_m) coefficients required for Massman's model of momentum transfer by vegetation. A constant ratio between C_d and P_m is found to overestimate wind speed in the upper canopy and underestimate it in the lower canopy. Two simple parameterisations of C_d/P_m as a function of the plant area density and the cumulative plant area index are developed, using values optimised by least-squares regression between measured and predicted within-canopy wind speeds. A validation with independently measured data indicates that both parameterisations work reliably for simulating wind speed in the investigated meadow. Model predictions of the normalised zero-plane displacement height and the momentum roughness length fall only partly within the range of values given in literature, which may be explained by the accumulation of plant matter close to the soil surface specific for the investigated canopies. The seasonal course of the normalised zero-plane displacement height and the momentum roughness length are discussed in terms of the seasonal variation of the amount and density of plant matter.

Keywords: Canopy structure, Drag coefficient, Roughness length, Sheltering coefficient, Wind speed, Zero-plane displacement height.

1. Introduction

Wind is an important factor for the biosphere-atmosphere exchange of mass and energy, affecting the flux rates from/to the exchanging surfaces by modifying their boundary-layer resistances and the surface-to-air scalar gradients by the turbulent mixing of the atmosphere. Therefore, models concerned with the soil–vegetation–atmosphere-transfer of mass and energy (so called SVAT models), usually contain, in varying complexity, some formulation for the attenuation of wind speed within the canopy. The spectrum of these models ranges from simple, phenomenological ones, which simulate the attenuation of wind speed as a function of height within the canopy (e.g., Leuning et al., 1995; Wohlfahrt et al., 2001), to higher-order and non-local closure models (e.g., Wilson and Shaw, 1977; Li et al., 1985; Meyers and Paw U, 1986), which deal with the various components of the turbulent kinetic energy budget equation. As an alternative, Massman (1997; henceforth M97) proposed a model of momentum absorption by vegetation of arbitrary structure

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which Massman and Weil (1999) entitled as being ‘neither a first- nor a second-order closure, but rather a self-contained, semi-empirical model of momentum absorption by vegetation’. It is based on an approximate solution to a phenomenological second-order closure model by Albini (1981), and, by parameterisation of the surface drag coefficient, provides estimates of the mean horizontal wind speed and the turbulent shear stress within the canopy, the momentum roughness length and the zero-plane displacement height. The model is analytical, computationally simple, and ‘captures some, but not all (e.g., secondary wind speed maxima), of the observed features of the mean canopy flow field’ (Massman and Weil, 1999).

Yet up to now, M97’s model has been seldom applied (Massman, 1999; Massman and Weil, 1999; Su et al., 2001), which in part may be due to the fact, that the model, despite its general simplicity, requires parameterisations of the within-canopy variation of the phytoelement drag coefficient (C_d) and the momentum shelter factor (P_m). We note that the ratio C_d/P_m represents the effective phytoelement drag coefficient (C_{Deff}), which accounts for the combined effects of phytoelement drag and sheltering by neighbouring phytoelements (Thom, 1971). Reports on the within-canopy variation of C_{Deff} are controversial: Meyers and Paw U (1986), Watanabe and Kondo (1990) and Zeng and Takahashi (2000), amongst others, found good correspondence between observed and predicted within-canopy wind speed using a constant C_{Deff}; Amiro (1990), comparing three boreal forest canopies, found a constant C_{Deff} appropriate for pine and aspen, with a leaf area index (LAI) of 2 and 4, respectively, but not for spruce with a LAI of 10; Brunet et al. (1994) reported a characteristic height dependency of C_{Deff} for a model of a waving wheat crop. M97 accounted for this contrasting evidence by means of a sensitivity analysis, investigating both the effects of a constant and a variable C_{Deff} on the resulting model predictions.

Using a mountain meadow as a case study, it is the objective of the present paper to explore various options for the parameterisation of C_{Deff} in M97’s model of momentum absorption by vegetation. In particular, we aim (i) to assess whether a constant, as opposed to a variable, parameterisation of C_{Deff} is appropriate for the investigated canopy, and (ii) to search for a simple parameterisation of C_{Deff} in terms of readily measurable canopy characteristics. For this purpose, we conducted several field campaigns in a mountain meadow in the Eastern Alps, where concurrent measurements of the vertical plant area distribution and the within-canopy profile of mean horizontal wind speed were made.

2. Material and Methods

2.1. SITE DESCRIPTION

Investigations were carried out in June 1999 and throughout the vegetation period 2000 at a meadow in the vicinity of the village Neustift (47°07′ N, 11°19′ E) in the Stubai Valley, a valley typical for the Austrian part of the Eastern Alps. The study site, which is essentially flat, is situated at an elevation of 970 m a.s.l. and receives on average 850 mm of precipitation per year, the average annual temperature is 6.3 °C. The meadow is usually cut twice a year, in year 2000 on day-of-year (DOY) 166 and 223. The vegetation has been classified as Pastinaco-Arrhenatheretum, the soil as a Fluvisol (FAO classification).

2.2. EXPERIMENTAL METHODS

Canopy structure was assessed in a destructive fashion by stratified clipping (Monsi and Saeki, 1953) of square plots of 0.3 m lateral length at DOY 161 in 1999 and DOYs 108, 137, 165, 166, 189, 222, 223 and 270 in 2000. Thickness of the harvested layers ranged between 0.05 and 0.1 m, depending on plant area density. The harvested plant material was separated into leaves, stems, reproductive organs, dead plant matter and cryptogams. Plant areas were determined by the means of an area meter (LI-3100, Li-Cor, Lincoln, U.S.A).

Horizontal wind speed within the canopy was measured on DOY 161 in 1999 and DOYs 137, 147 and 189 in 2000 using three hot-wire anemometers (ThermoAir2, Schiltknecht, Gossau, Switzerland). One anemometer was installed just at the upper canopy height, one close to the soil surface and the remaining instrument was shifted periodically in height between the other two. Anemometer output was logged every 5 seconds by a data logger (DL2E, Delta-T devices, Cambridge, U.K.), from which 1 min averages were calculated.

2.3. STATISTICAL METHODS

Multiple non-linear regression analysis, using the root-square mean error as the objective value, was applied to estimate and/or optimise parameters using the Standard EXCEL SOLVER (Ragsdale, 2001). Model performance is assessed by linear regression analysis (slope and y-intercept), the root mean squared error (RMSE), the Pearson's correlation coefficient (r) and the F value.

3. Model

According to M97, the horizontal wind speed within the canopy, $u(z)$, and the turbulent shear stress, $-\overline{u'w'}(z)$, are modelled as exponential functions of the cumulative phytoelement drag area index, $\zeta(z)$, as

$$u(z)/u(h) = e^{-n[1-\zeta(z)/\zeta(h)]} \tag{1}$$

and

$$-\overline{u'w'}(z)/u_*^2 = e^{-2n[1-\zeta(z)/\zeta(h)]}, \tag{2}$$

where

$$\zeta(z) = \int_0^z [C_d(z')a(z')/P_m(z')]\,\mathrm{d}z \tag{3}$$

and

$$n = \frac{\zeta(h)}{2u_*^2/u(h)^2}. \tag{4}$$

Here u_* is the friction velocity (m s^{-1}), $C_d(z)$ is the phytoelement drag coefficient (dimensionless, $-$), $a(z)$ is the plant area density function ($\mathrm{m}^2\ \mathrm{m}^{-3}$) and $P_m(z)$ the phytoelement sheltering factor for momentum, all a function of height within the canopy. P_m is unity, if effects of sheltering are absent and increases beyond unity as neighbouring phytoelements reduce the exposure of other phytoelements to the turbulent wind. Following reasoning by M97, that 'C_d and P_m are not necessarily completely separable from each other', we denote the ratio C_d/P_m as the effective phytoelement drag coefficient (C_{Deff}), reflecting the combined effects of drag and sheltering.

This set of equations is closed by parameterising the surface drag coefficient, $C_{\mathrm{surf}} = 2u_*^2/u(h)^2$, using

$$u_*/u(h) = c_1 - c_2 e^{-c_3\zeta(h)}, \tag{5}$$

where $c_1 = 0.32$, $c_2 = 0.264$ and $c_3 = 15.1$ are constants (for a discussion of their numerical values see M97).

The zero-plane displacement height, d, and the momentum roughness length, z_0, are given as

$$d/h = 1 - \int_0^1 e^{-2n[1-\zeta(z)/\zeta(h)]}\,\mathrm{d}\xi \tag{6}$$

and

$$z_0/h = (1 - d/h)e^{(-ku(h)/u_* + \varphi)}, \tag{7}$$

where $\xi = z/h$ (−), k is the von Karman constant (0.4) and φ is the roughness sublayer influence function (Raupach, 1994). Equation (6) is integrated numerically using a five-point Gaussian integration (Goudriaan and Van Laar, 1994). Symbols and abbreviations are given in the Appendix.

4. Results and Discussion

4.1. CONSTANT VERSUS VARIABLE C_{Deff}

Least-squares regression was used to determine for each canopy a single C_{Deff} which maximised the correspondence between measured and simulated wind speed (constant C_{Deff}). The same procedure, except that C_{Deff} was allowed to vary with height, was applied to determine the optimal C_{Deff} for each canopy layer (optimised C_{Deff}). Using the optimised C_{Deff}, correspondence between predictions and measurements is almost perfect for DOY 189, but less so for DOYs 137 and 161 (Figure 1, Table I), where the model is not capable of capturing the existence of weak secondary wind speed maxima (cf. Shaw, 1977). This though should not come as a surprise, given the model's local closure assumptions (Massman and Weil, 1999). Values for the constant C_{Deff} are 0.31, 0.19 and 0.37 for DOYs 137, 161 and 189, respectively, which are at and slightly beyond the upper limit of the range of 0.03–0.30 reported in the literature (e.g., Meyers and Paw U, 1986; Massman, 1987; Zeng and Takahashi, 2000). Using the constant C_{Deff} values, predictions generally overestimate measured wind speeds in the upper canopy and underestimate them in the lower canopy (Figure 1). Underestimation in the lower canopy is most pronounced for DOYs 137 and 189, where plant area density (PAD) is low in the upper canopy and increases strongly between z/h = 0.3–0.4 (cf. Tappeiner and Cernusca, 1998), and least for DOY 161, where PAD is much more homogenous (Figure 2). Obviously, with a constant C_{Deff}, PAD is not able to account for the observed attenuation of wind speed. This finding contrasts studies by Meyers and Paw U (1986), Watanabe and Kondo (1990), Zeng and Takahashi (2000), amongst others, who found a constant C_{Deff} appropriate for modelling wind speed in plant canopies. Our study indicates that C_{Deff} should be larger in the upper canopy and decrease towards the ground surface, as will be discussed in more detail in the next section.

4.2. SIMPLE PARAMETERISATION OF C_{Deff}

Since evidence exists that C_d and P_m are functions of both PAD and wind speed (Landsberg and Thom, 1971; Thom, 1971; Landsberg and Powell, 1973; Grant 1984; Brunet et al., 1994), one reasonably might expect C_{Deff} to be so too. While parameterising C_{Deff} as a function of PAD is straightforward, making C_{Deff} a function of wind speed voids the analytical solution of the model (M97). Among

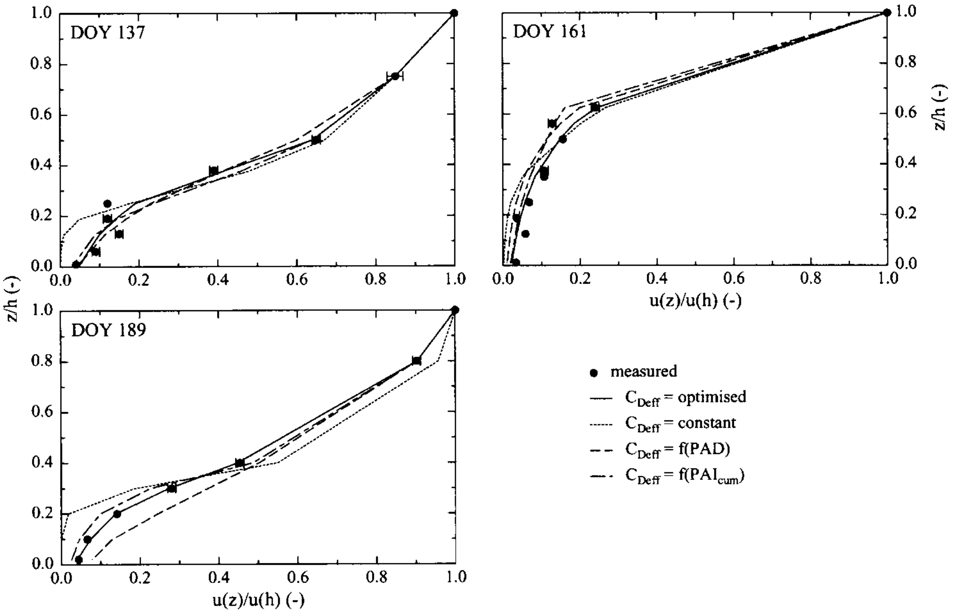

Figure 1. Observed (symbols) and predicted (lines) non-dimensional wind speeds ($u(z)/u(h)$) within a mountain meadow canopy at DOYs 137, 161 and 189. Simulations have been conducted (i) using optimised values of the effective drag area index (C_{Deff}), (ii) assuming C_{Deff} to be constant throughout the canopy depth, and using C_{Deff} determined as a simple function of (iii) plant area density (PAD) and (iii) the cumulative plant area index ($\mathrm{PAI}_{\mathrm{cum}}$).

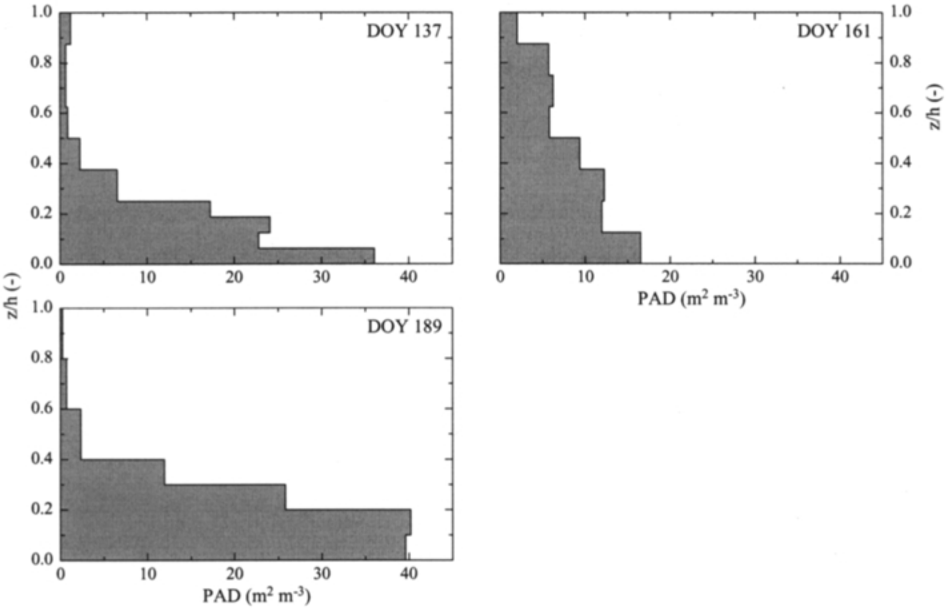

Figure 2. Vertical distribution of the plant area density (PAD) in a mountain meadow canopy at DOYs 137, 161 and 189 in year 2000.

TABLE I

Statistics for comparison between measured and predicted non-dimensional wind speeds $(u(z)/u(h))$ using four different parameterisation options for C_{Deff} (for details refer to text). Model performance is evaluated by the slope and y-intercept of a linear regression (mean ± standard deviation), the root mean squared error (RMSE), the Pearson's correlation coefficient (r) and the F-value.

DOY	Parameterisation	Slope	y-intercept	RMSE	r	F-value
137	C_{Deff} optimised	1.00 ± 0.03	0.00 ± 0.02	0.0320	1.00	920.1
	C_{Deff} constant	0.90 ± 0.06	0.06 ± 0.03	0.0748	0.99	254.1
	$C_{\mathrm{Deff}} = f(\mathrm{PAD})$	1.03 ± 0.05	−0.02 ± 0.02	0.0461	0.99	463.2
	$C_{\mathrm{Deff}} = f(\mathrm{PAI_{cum}})$	0.99 ± 0.05	−0.01 ± 0.03	0.0520	0.99	351.6
161	C_{Deff} optimised	0.99 ± 0.03	0.00 ± 0.01	0.0235	1.00	1260.9
	C_{Deff} constant	0.95 ± 0.04	0.03 ± 0.02	0.0446	0.99	451.7
	$C_{\mathrm{Deff}} = f(\mathrm{PAD})$	0.97 ± 0.03	0.03 ± 0.01	0.0366	1.00	1461.5
	$C_{\mathrm{Deff}} = f(\mathrm{PAI_{cum}})$	0.98 ± 0.03	0.03 ± 0.01	0.0360	1.00	1063.3
189	C_{Deff} optimised	1.00 ± 0.01	0.00 ± 0.00	0.0057	1.00	28477.2
	C_{Deff} constant	0.87 ± 0.06	0.07 ± 0.03	0.0846	0.99	244.5
	$C_{\mathrm{Deff}} = f(\mathrm{PAD})$	1.08 ± 0.04	−0.09 ± 0.02	0.0667	1.00	914.1
	$C_{\mathrm{Deff}} = f(\mathrm{PAI_{cum}})$	0.96 ± 0.03	0.03 ± 0.01	0.0335	1.00	1254.8

several possible indirect measures, we thus adopted the cumulative plant area index, $\mathrm{PAI_{cum}}$,[⋆] as a surrogate for the attenuation of wind speed within the canopy. $\mathrm{PAI_{cum}}$ was preferred over the normalised canopy height employed by M97 for parameterising C_d, because it is an absolute, rather than a relative measure, and because the normalised canopy height is not necessarily a good predictor for the decrease of wind speed (Wohlfahrt et al., 2000). However, using $\mathrm{PAI_{cum}}$ as a surrogate for the attenuation of wind speed ignores the existence of secondary wind speed maxima. Given that we aim for a simple parameterisation and that the model is anyhow not capable of capturing these (Massman and Weil, 1999), we consider this a reasonable approximation. Furthermore, in the present case the observed secondary wind speed maxima (Figure 1) are weak.

C_{Deff} values optimised as described in the previous section decrease exponentially with both increasing PAD and $\mathrm{PAI_{cum}}$ (Figure 3), to which a second-order exponential function of the form

$$C_{\mathrm{Deff}} = a_1^{-X/a_2} + a_3^{-X/a_4} + a_5 \tag{8}$$

was fitted, where X stands either for PAD or $\mathrm{PAI_{cum}}$. For economy in model parameters we tried several simpler equations, i.e., with less parameters, in the pre-

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[⋆] Counted from the canopy top downwards.

paration of the manuscript, but none resulted in equal quantitative and qualitative correspondence. Values for the constants a_1–a_5 are given in the Appendix.

A discussion on why C_{Deff} decreases both with $\mathrm{PAI}_{\mathrm{cum}}$ and PAD is somewhat complicated by the fact, that in the present situation $\mathrm{PAI}_{\mathrm{cum}}$, as a surrogate for the attenuation of wind speed, and PAD are positively (inversely for wind speed) correlated, the canopies generally becoming thicker towards the ground (Figure 2). This is likely to be the reason for the similar shapes in Figures 3A and B, since the two quantities are otherwise unrelated. Generally, as discussed in M97, it is reasonable to assume that C_d is much more strongly influenced by wind speed, whereas P_m appears to be more dependent on PAD. Based on Landsberg and Thom (1971), Landsberg and Powell (1977) and others, who showed that P_m increases with increasing PAD, the observed decrease in C_{Deff} with canopy depth may be interpreted as an effect of the increase in PAD, since $C_{\mathrm{Deff}} = C_d/P_m$. Thereby it should be noted, that the PADs of the investigated canopies (Figure 2) are up to twice as high as those investigated in similar studies (e.g., Zeng and Takahashi, 2000), where sheltering may thus be relatively less prominent. C_d has been shown to increase (i.e., increase in form drag due to increase in pressure deficit on the lee side of phytoelements; Grant, 1984) and decrease (i.e., streamlining of phytoelements; Thom, 1968) with increasing wind speed. In the former case C_d would act to enforce the decrease of C_{Deff} with canopy depth caused by the increase in P_m, while in the latter case C_d would counteract the influence of P_m.

Given that PAD and $\mathrm{PAI}_{\mathrm{cum}}$ are closely related in the present case, it is not surprising that both quantities are almost equally suitable to predict C_{Deff}, differences in quantitative and qualitative model statistics being subtle (Table II). Using C_{Deff} estimated by means Equation (8), predictions of within-canopy wind speed are both qualitatively and quantitatively superior to those assuming a constant C_{Deff} (Table I, Figure 1). Predictions are even similar to those obtained using the optimised C_{Deff} values, except for DOY 189, where a constant underestimation of C_{Deff} predicted on the basis of PAD (Figure 3A) causes an overestimation of non-dimensional wind speeds (Table I, Figure 1). Otherwise, differences between the two parameterisation options are again small (Table I, Figure 1).

4.3. VALIDATION

For validation of within-canopy wind speeds, independent measurements, i.e., data not used in the parameterisation of C_{Deff} in the previous section, were determined on DOY 147, as shown in Figure 4. The vertical plant area distribution for this date was not available and was thus derived from linear interpolation between DOYs 137 and 165. Given the crudeness of this linear interpolation, there is quite favourable correspondence between model predictions and measurements (Table III): The parameterisation of C_{Deff} as a function of PAD slightly underestimates wind speed, but mimics the shape of the wind speed profile below $z/h = 0.25$ fairly well. Due to the high sensitivity of C_{Deff} to changes in PAD at low PAD values

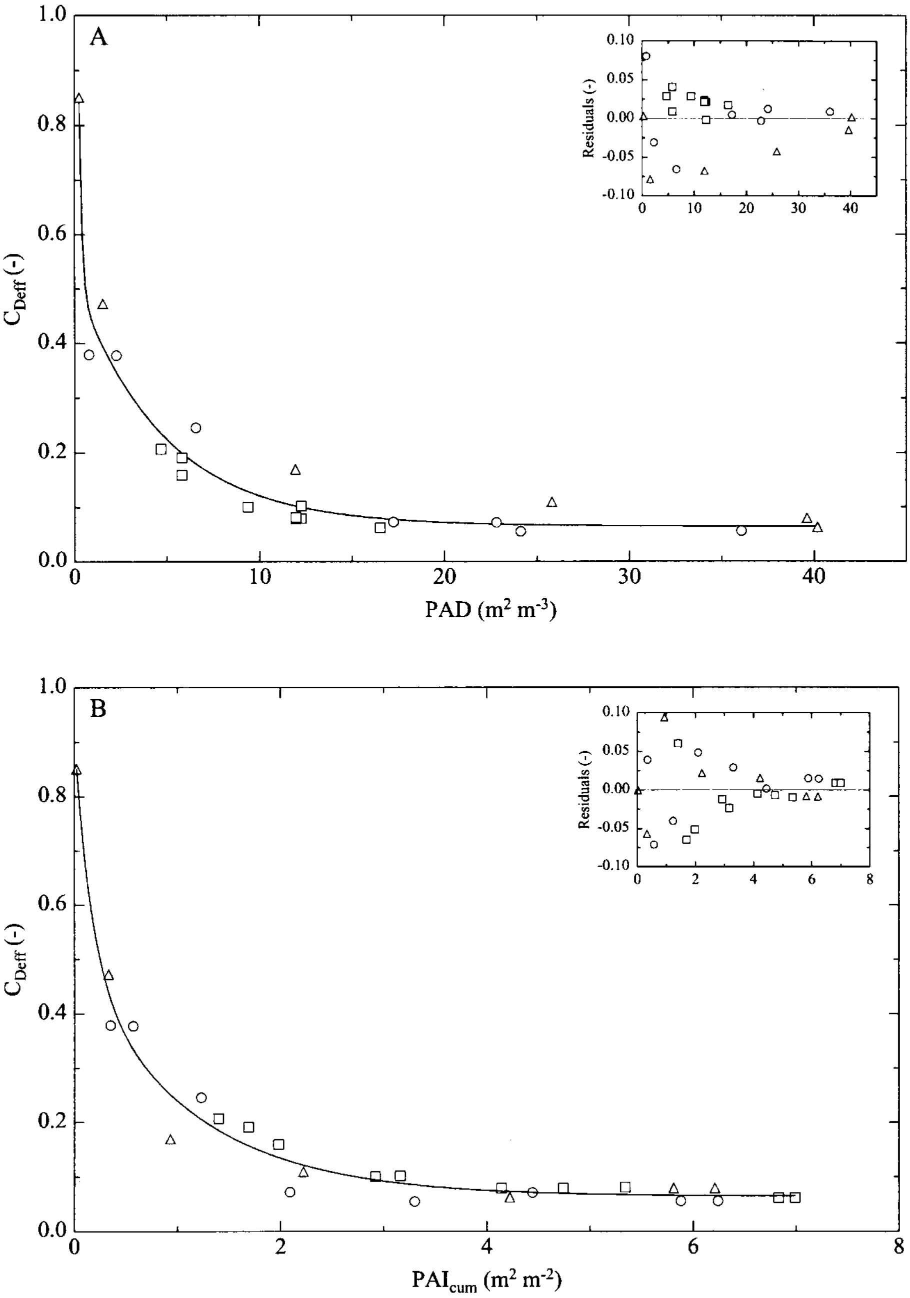

Figure 3. Dependence of the effective phytoelement drag coefficient (C_{Deff}) on the plant area density (PAD, Figure 3A) and the cumulative plant area index (PAI_{cum}, Figure 3B) for a mountain meadow on DOYs 137 (circles), 161 (squares) and 189 (triangles). The solid lines represent a fit to data using Equation (8). Values for the constants a_1–a_5 are given in Appendix A. Residuals are shown in the upper right corner.

TABLE II

Statistics for comparison between measured and predicted effective phytoelement drag coefficients C_{Deff}, parameterised as a function of the plant area density (PAD) and the cumulative plant area index ($\mathrm{PAI_{cum}}$). Model performance is evaluated by the slope and y-intercept of a linear regression (mean ± standard deviation), the root mean squared error (RMSE), the Pearson's correlation coefficient (r) and the F-value.

Parameterisation	Slope	y-intercept	RMSE	r	F-value
$C_{\mathrm{Deff}} = f(\mathrm{PAD})$	0.97 ± 0.01	0.04 ± 0.01	0.0356	0.98	579.7
$C_{\mathrm{Deff}} = f(\mathrm{PAI_{cum}})$	0.95 ± 0.04	0.01 ± 0.01	0.0388	0.98	483.2

TABLE III

Statistics for comparison between measured and predicted non-dimensional wind speeds ($u(z)/u(h)$) on DOY 147 using four different parameterisation options for C_{Deff} (for details refer to text). Model performance is evaluated by the slope and y-intercept of a linear regression (mean ± standard deviation), the root mean squared error (RMSE), the Pearson's correlation coefficient (r) and the F-value.

Parameterisation	Slope	y-intercept	RMSE	r	F-value
C_{Deff} optimised	1.00 ± 0.01	0.00 ± 0.01	0.0104	1.00	5792.8
C_{Deff} constant	0.96 ± 0.03	0.04 ± 0.01	0.0424	1.00	686.4
$C_{\mathrm{Deff}} = f(\mathrm{PAD})$	0.97 ± 0.01	0.03 ± 0.01	0.0281	1.00	5094.9
$C_{\mathrm{Deff}} = f(\mathrm{PAI_{cum}})$	1.00 ± 0.03	−0.01 ± 0.01	0.0276	1.00	982.8

(Figure 3A), simulated wind speeds would fit measurements virtually as good as with C_{Deff} optimised, if PAD was decreased by a mere 10% at $z/h > 0.25$ (data not shown). A 10% error is a fairly reasonable assumption in the present case, given that PAD in the upper canopy is comparably more heterogeneous as compared to the lower canopy strata, and that PAD was derived from linear interpolation in time. Wind speeds simulated on the basis of C_{Deff} parameterised as a function of $\mathrm{PAI_{cum}}$ decay too slowly with canopy height, underestimating the slope of the measured wind speed profile (Figure 4). While below $z/h = 0.1$ correspondence between model and measurements is good, this causes an overestimation of wind speeds between $z/h = 0.1$–0.25 (Figure 4). Both parameterisations are superior as compared to a constant C_{Deff} (Table III), but also, like the optimised C_{Deff} values, not capable of predicting the secondary wind speed maximum at approximately $z/h = 0.1$ (Figure 4), which again is due to the model's local closure assumptions (Massman and Weil, 1999).

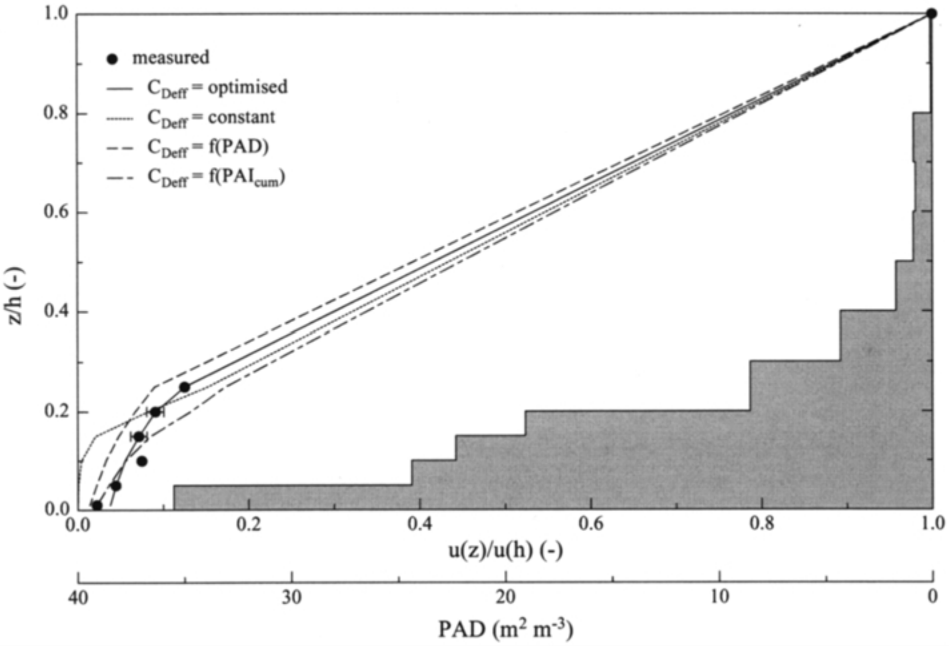

Figure 4. Validation of the non-dimensional wind speed $(u(z)/u(h))$ on DOY 147 using four different parameterisation options for C_{Deff} (cf. Figure 1). Plant area density (PAD), derived from linear interpolation between DOYs 137 and 165, is shown for convenience.

4.4. ZERO-PLANE DISPLACEMENT HEIGHT AND MOMENTUM ROUGHNESS LENGTH

Predictions of d/h and z_0/h (ignoring roughness sub-layer effects) using the simple parameterisation of C_{Deff} as a function of PAD, shown in Figures 5 and 6 respectively, coincident only partly with the range of values reported in M97, which covers the predictions of the models of Shaw and Pereira (1982) and Raupach (1994). Using the parameterisation of C_{Deff} based on $\mathrm{PAI}_{\mathrm{cum}}$, generally similar results were obtained (data not shown). This lack of correspondence is due to differences between the present study and M97 regarding the vertical distribution of PAD: M97 showed that d/h and z_0/h decrease and increase, respectively, if the foliage is concentrated in the lower canopy, as opposed to a uniform distribution. For the purpose of the sensitivity analysis of M97 the height of the maximum foliage density was though never below $z/h = 0.2$. The canopies investigated in the present study, in contrast, exhibit a marked accumulation of plant matter close to the ground surface (Figure 2), a typical feature of mountain meadows (Tappeiner and Cernusca, 1998). That this is indeed the cause for the discrepancy in Figures 5 and 6 can be seen from the fact that, d/h and z_0/h fit almost perfectly into the range given in M97, if a uniform vertical PAD distribution is assumed (open symbols in Figures 5 and 6). Results along this line have been reported in M97

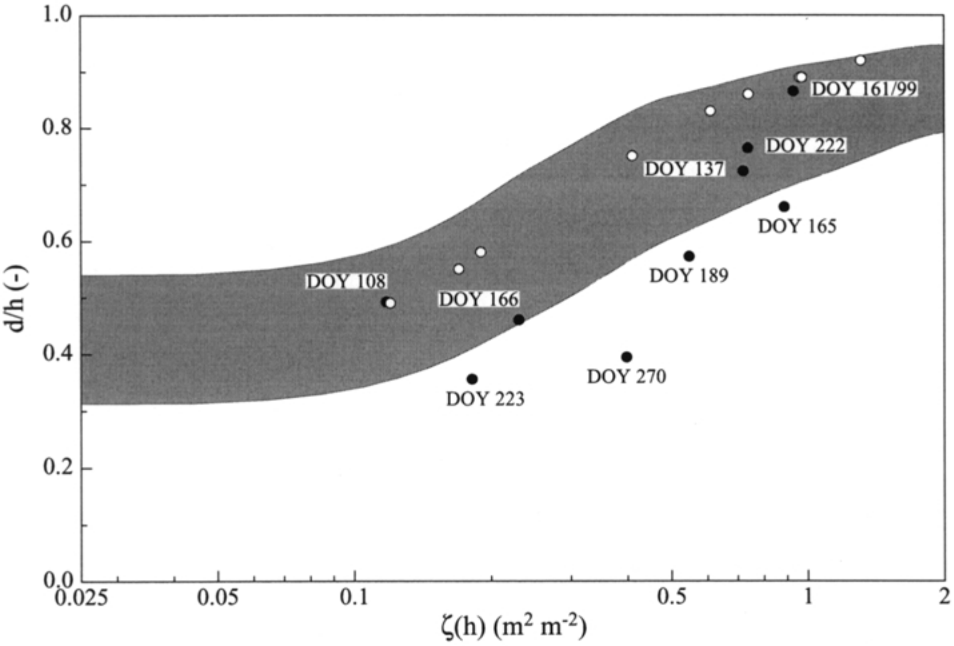

Figure 5. Variation of the normalised zero-plane displacement height (d/h) with the canopy drag area index $(\zeta(h))$. d/h and $\zeta(h)$ were calculated using the parameterisation of C_{Deff} as a function of PAD (Figure 3A). Closed symbols indicate simulations with the actual PAD distribution, open symbols simulations with an assumed uniform PAD distribution. Shaded areas refer to the range given in M97.

and for various types of grassland canopies in Massman (1999). These findings are in contrast to Raupach (1994), who argued that d/h and z_0/h may be simulated satisfactorily without any information on the vertical PAD distribution.

The seasonal course of d/h and z_0/h reflects the canopy development, d/h generally increasing and z_0/h decreasing with increasing PAI, as shown in Figure 7. Two exceptions are evident though: between DOY 137–165 d/h and z_0/h decrease and increase with increasing PAI, respectively, whereas d/h and z_0/h remain approximately constant despite an increase in PAI between DOY 222–270 (Figure 7). These exceptions are due to a decrease of the average plant area density (= PAI/h), which offsets (DOY 222–270) and reverses (DOY 137–165) the effects of the increase in PAI (Figure 7).

Predictions of z_0 so far ignored the effects of a roughness sub-layer, assuming that the logarithmic surface layer wind profile reaches down to the canopy top ($\varphi = 0$). This may uniformly increase all values of z_0/h by as much as 37% (M97). Future experimental work on the seasonal variation of d and z_0 should aim at addressing the appropriateness of this assumption.

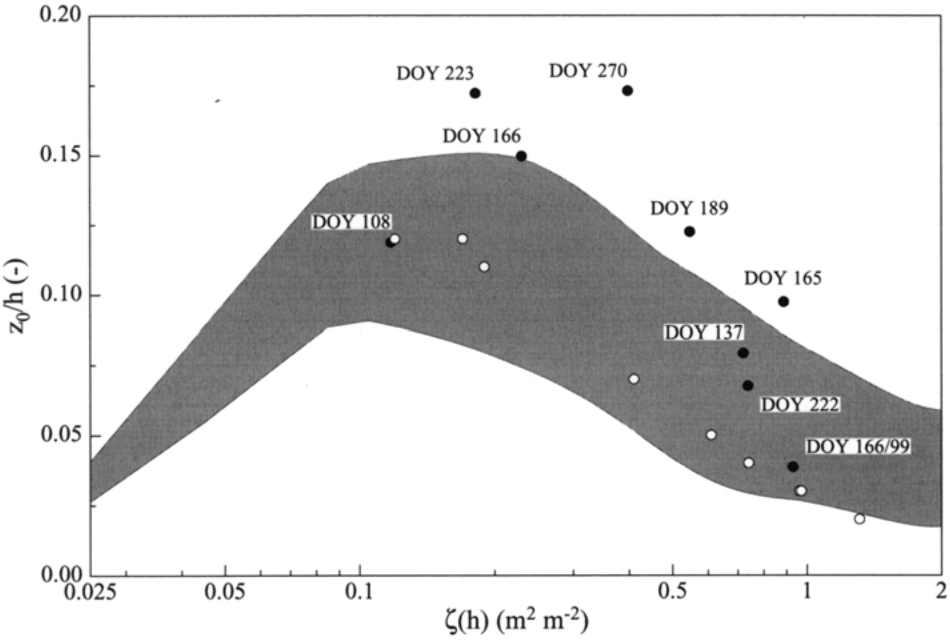

Figure 6. Variation of the normalised momentum roughness length (z_0/h) with the canopy drag area index ($\zeta(h)$). z_0 and $\zeta(h)$ were calculated using the parameterisation of C_{Deff} as a function of PAD (Figure 3A). Closed symbols indicate simulations with the actual PAD distribution, open symbols simulations with an assumed uniform PAD distribution. Shaded areas refer to the range given in M97.

5. Summary and Conclusion

The present paper uses a mountain meadow in the Eastern Alps as a case study to test Massman's (1997) model of momentum transfer by vegetation and several parameterisation options for the required within-canopy variation of the effective phytoelement drag coefficient (C_{Deff}). A constant C_{Deff} is found to overestimate and underestimate non-dimensional wind speed in the upper and lower canopy, respectively, the bias increasing with the extent to which the vertical plant area distribution deviates from uniform. Two simple parameterisations of C_{Deff} as a function of the plant area density and the cumulative plant area index are developed, using C_{Deff} values optimised by least-squares regression between measured and predicted within-canopy wind speeds. A validation with independently measured data indicates, that both parameterisations work reliably for simulating wind speeds in the investigated meadow. Model predictions of d/h and z_0/h fall only partly within the range of values given in literature, which may though be explained by the skewed plant area distribution, i.e., the accumulation of plant matter close to the soil surface.

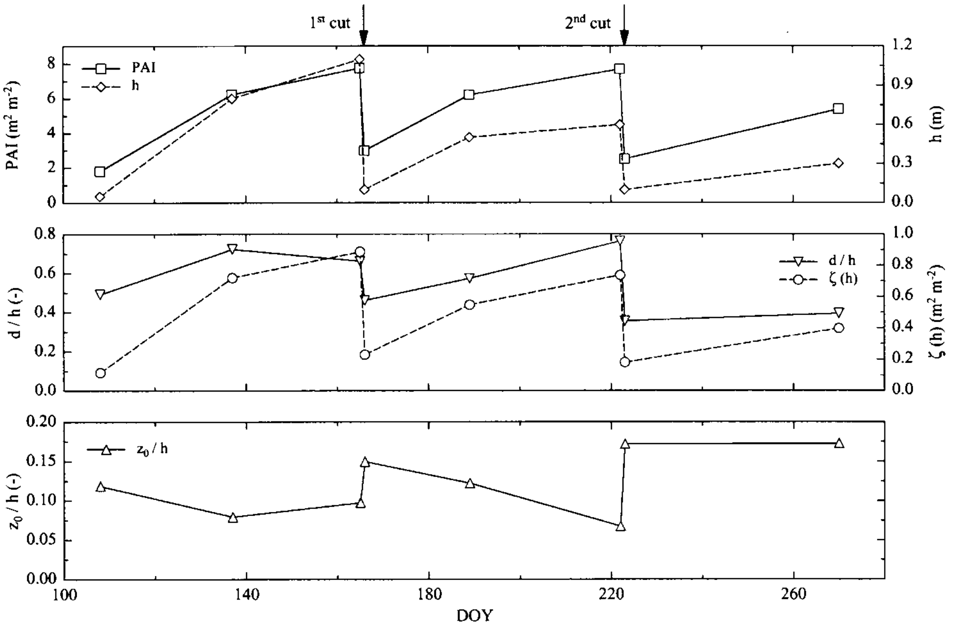

Figure 7. Seasonal variation (year 2000) of the plant area index, PAI, and the canopy height, h (upper panel), the normalised zero-plane displacement height, d/h, and the canopy drag area index, $\zeta(h)$ (central panel), and the normalised momentum roughness length, z_0 (lower panel). d/h, z_0 and $\zeta(h)$ were calculated using the parameterisation of C_{Deff} as a function of PAD (Figure 3A).

It is intuitively clear, that the parameterisations developed in the present paper are specific to the investigated canopies, given the close relation between PAD and $\mathrm{PAI}_{\mathrm{cum}}$. Future work should thus be directed towards assessing the validity of our parameterisations for canopies of different structure, and also for phytoelements of different aerodynamic properties, e.g., woody species. Finally, it should be pointed out, that the parameterisations developed within the present paper, have been developed within the frame of M97's model. Accordingly, they are affected by any theoretical weakness pertaining to this deliberately simple model (cf. M97, Massman and Weil, 1999) and thus do not necessarily reflect the C_{Deff} that would be measured directly in the field (e.g., Brunet et al., 1994).

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Appendix A: Symbols and Abbreviations

a	plant area density function ($m^2\ m^{-3}$)
a_1–a_5	constants: PAD: 0.452 (−), 4.809 ($m^2\ m^{-3}$), 1.876 (−), 0.149 ($m^2\ m^{-3}$), 0.065 (−); $\mathrm{PAI_{cum}}$: 6.140 (−), 0.001 ($m^2\ m^{-2}$), 0.434 (−), 0.751 ($m^2\ m^{-2}$), 0.071 (−)
c_1–c_3	constants (0.32, 0.264 and 15.1)
C_d	phytoelement drag coefficient (−)
C_{Deff}	effective phytoelement drag coefficient ($= C_d/P_m$) (−)
C_{surf}	surface drag coefficient (−)
d	zero-plane displacement height (m)
DOY	day of year (d)
h	canopy height (m)
k	von Karman constant (0.4)
LAI	leaf area index ($m^2\ m^{-2}$)
n	canopy profile exponent (−)
PAD	plant area density ($m^2\ m^{-3}$)
PAI	plant area index ($m^2\ m^{-2}$)
$\mathrm{PAI_{cum}}$	cumulative plant area index ($m^2\ m^{-2}$)
P_m	phytoelement sheltering coefficient (−)
r	Pearson's correlation coefficient (−)
RMSE	root mean squared error
u	mean horizontal wind speed ($m\ s^{-1}$)
u_*	friction velocity ($m\ s^{-1}$)
$\overline{u'w'}$	turbulent shear stress ($m^2\ s^{-2}$)
z	height above ground (m)
z_0	momentum roughness length (m)
ζ	phytoelement drag area index ($m^2\ m^{-2}$)
ξ	normalised canopy height (−)
φ	roughness sub-layer influence function (−)

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