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Wind speed and aerodynamic conductance variation in air layer affected by spruce forest stand

T. Hurtalová, F. Matejka
Geophysical Institute of the Slovak Academy of Sciences[1]

D. Janouš
Institute of Landscape Ecology, Academy of Sciences of the Czech Republic[2]

J. Rožnovský, I. Marková
Department of Agrosystems and Bioclimatology, Mendel University of Agriculture and Forestry[3]

Abstract: The results of the vertical wind speed profile analysis have been evaluated with the aim to determine the aerodynamic conductance in an air layer affected by a young spruce forest stand and to investigate the wind speed and aerodynamic conductance variation in this air layer. The simple method of the aerodynamic conductance calculation on the basis of the vertical wind speed profile analysis is presented. The experimental data were obtained at the Bílý Kříž Experimental Ecological Study Site in Moravian-Silesian Beskydy Mts, the Czech Republic (49°30′17″N, 18°32′28″E, 908 m a.s.l.). The analysed wind speed profiles were measured in and above the investigated spruce forest stand during growing season of 2004 (from July to October) on the plot with area of 2500 m^2 and with density 1880 trees/ha. This site represents the Norway spruce monoculture of a mean height (h) of about 10.4 m and with age of 23 years. The mean displacement height (d) during the investigated period was found to be 7.0 m and the roughness length (z_0) 0.9 m. The g_a values were determined for the layer from $(d + z_0)$ to z, in this case from 7.9 m to 18.0 m. It was shown that aerodynamic conductance values (g_a) increase with increasing wind speed exponentially. This dependence is more closed with the wind speed measured at the mean height of the forest stand than the wind speed measured at the level of 26 m.

Key words: spruce forest stand, wind speed profiles, aerodynamic conductance, zero-plane displacement, roughness length

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[1] Dúbravská cesta 9, 845 28 Bratislava, Slovak Republic; e-mail: geoftahu@savba.sk; geofmate@savba.sk

[2] Na sádkách 7, 370 05 České Budějovice, Czech Republic; e-mail: ejanous@brno.cas.cz

[3] Zemědělská 1, 613 00 Brno, Czech Republic; e-mail: roznovsky@chmi.cz; markova@mendelu.cz

1. Introduction

During the past decades, increasing attention has been paid to transpiration from forest stands as a key component of the water cycle, forest productivity, and particularly also the interaction of vegetation with the atmosphere from the aspect of global climate change (*Grelle et al., 1999*). To estimate transpiration rates, values for two parameters are required. These are r_a [s m^{-1}], the aerodynamic resistance for heat and for water vapour, or the aerodynamic conductance $g_a = 1/r_a$, and r_{s} [s m^{-1}], the bulk stomatal resistance for water vapour. The aerodynamic resistance governs the vertical aerial transport processes. It is known, that for most tree species the transpiration rate is limited by r_{s}, which is much greater than r_a. However, most species of trees have small r_{s}, i.e. large stomatal conductance g_{s}. As a result r_{s} is small, of similar magnitude to r_a, and both significantly affect the evaporation rate. It is therefore more important that r_a or g_a is known accurately (*Hall, 2002*). Many authors analysed aerodynamic conductance and its variation in the dependence on the airflow. *Daudet et al. (1999)* analysed the relationship between local boundary layer conductance and local wind speed measured nearby the crown of 20 year old walnut trees. *Lindroth (1993)* determined r_a for willow forest as a function of the leaf area index and wind speed. His results are not applicable to different forests because the significant differences between willow and other forests in stand structure will be reflected in differences in the aerodynamic resistances.

The majority of forest ecosystems in the Czech Republic are composed of Norway spruce stands which have more than 80% share. Therefore the extensive research of the climate of the Norway spruce monoculture is carried out at the Bílý Kříž Experimental Ecological Study Site in Moravian-Silesian Beskydy Mts, the Czech Republic (*Kratochvílová et al., 1989*).

It is the purpose of this paper to provide the determination of the aerodynamic conductance by the simple method on the basis of the vertical wind speed profile analysis. Further the dependence of the aerodynamic conductance on the wind speed and the roughness length in an air layer affected by a young spruce forest stand was investigated. The experimental data needed for this study were obtained from the research programme at Bílý Kříž.

2. Theoretical estimate of aerodynamic conductance

Within the framework of Monin-Obukhov similarity theory the eddy diffusivities for momentum, K_M, heat, K_H, and water vapour K_V [m^2 s^{-1}] are written:

$$K_M = u^* \kappa \left(z - d\right) \left(\phi_M \left(\frac{z}{L}\right)\right)^{-1}, \tag{1}$$

$$K_V = K_H = u^* \kappa \left(z - d\right) \left(\phi_{V.H} \left(\frac{z}{L}\right)\right)^{-1}, \tag{2}$$

where κ is the von Karman constant, z [m] the height above the ground, d [m] the zero-plane displacement height and ϕ_M, $\phi_{V.H}$ the stability corrections (e.g. *Dyer and Hicks, 1970*) that allow for departures from adiabatic conditions quantified by L [m], the Monin-Obukhov length (*Thom, 1975*). The friction velocity, $u*$ [m s^{-1}], can be calculated as (*Hall, 2002*)

$$u^* = \frac{\kappa u\left(z\right)}{\ln\left(\frac{\mathrm{z-d}}{\mathrm{z_0}}\right) - \Psi_M\left(\frac{z}{L}\right)} \quad , \tag{3}$$

where $u(z)$ [m s^{-1}] is the wind speed at z level, z_0 [m] the roughness length for momentum for the underlying vegetation, and $\Psi_M\left(\frac{z}{L}\right)$ the momentum stability correction integrated between $(d+z_0)$, the height at which the wind speed extrapolates to zero, and z level. If $\left|\frac{z}{L}\right| > 1$, then

$$\Psi_M\left(\frac{z}{L}\right) = 1 + \beta\frac{z}{L}, \tag{4}$$

where β is the universal semiempiric constant (*Monin and Obukhov, 1954*).

Then integrating the K_M between the same limits gives the aerodynamic conductance for momentum g_a [m s^{-1}] as

$$g_a = \frac{\kappa u^*}{\ln\left(\frac{z-d}{z_0}\right) + \frac{\beta}{L}\left[\left(z-d\right) - z_0\right]}. \tag{5}$$

The values of z_0, u^*, and parameter $\frac{\beta}{L}$ can be obtained from the analysis of the vertical wind speed profiles measured over an active surface under different atmosphere thermal stratification. Following from the Monin-Obukhov similarity theory, each vertical wind speed profile $\bar{u}_k(z_i)$ can be approximated by the relation (*Monin and Obukhov, 1954*)

$$u_k(z_i) = A_k(\gamma + \log z_i) + C_k z_i, \tag{6}$$

where k is the profile number. The values of A_k, γ, and C_k parameters are calculated by the least squares method for every profile. Then the values of z_0, u^*, and $\frac{\beta}{L}$ are obtained from the following relationships (*Monin and Obukhov, 1954*)

$$z_0 = 10^{-\gamma}, \tag{7}$$

$$u^* = \frac{\kappa A_k}{\ln(10)}, \tag{8}$$

$$\frac{\beta}{L} = \frac{C_k}{A_k}\ln(10). \tag{9}$$

The value of the zero-plane displacement (d) was determined by processing the vertical wind speed profiles measured at the neutral thermal stratification of the atmosphere (*Brutsaert, 1982*).

3. Site description and experimental data

The experimental data needed for this study were obtained at the Bílý Kříž Experimental Ecological Study Site in Moravian-Silesian Beskydy Mts, the Czech Republic (lat. 49°30′17″N, long. 18°32′28″ E, 898–908 m a.s.l.) which is situated on a mild slope with SW orientation. The investigated forest is created by the Norway spruce monoculture *(Picea abies* L., Karst) with age of 17 years in 1998 (age of the trees was 21 years) when the automatic measurements of vertical wind profiles in and above the forest stand started. These measurements are part of extensive research of the climate of the Norway spruce monoculture on this experimental site (*Havránková and Janouš, 1999; Kratochvílová et al., 1989*).

By climatic classification the locality Bílý Kříž is a cool and humid region with abundance of precipitation. The mean annual air temperature is 4.9°C, the mean annual precipitation total is 1100 mm, the mean relative air humidity is 80%, and the vegetation period length is 120–140 days (*Rožnovský, 1998*).

The experimental site was established within a homogeneous spruce stand with an area of 6.15 ha, which was part of an extended spruce forest, so that the distance of this experimental plot from the nearest forest edge was at least 370 m. It means that the peripheral effects can be neglected (*Hailman and Brittin, 1989*).

The prevailing wind direction above this experimental site is south, in spite of this, generally in this part of the Beskydy Mts a north and west airflow predominates. It is a result of the orographically broken terrain (*Havránková et al. 2001*).

The analysed wind speed profiles were measured in and above the investigated spruce forest stand during growing season of 2004 on the plot with area of 2500 m^2 and with density 1880 trees/ha. Profile measurements were realized by automatic measuring equipment from Delta-T Devices, LTD (UK) on the 26 m height tower continuously during 24 hours with 30 minute records of data average.

4. Results and discussion

The analysed wind speed values were measured at levels of 7, 9, 10, 13, 18, and 26 m from July to October 2004. In this time the mean forest stand height h was 10.4 m. For the analysis of the vertical wind speed profiles a selected set was used. The analysed wind speed profiles fulfilled the condition $\bar{u}\,(h-1) > 1.0\ \mathrm{m\,s^{-1}}$. In this case the conditions of turbulent development can be supposed. During this investigated period 557 profiles, mean hourly wind speed values, which fulfilled this condition were analysed. These profiles were divided into six ranges:

$$\begin{array}{rlcccr}
\text{I} & 1.0\ \mathrm{m\,s^{-1}} & < & \bar{u}(h) & < & 2.0\ \mathrm{m\,s^{-1}} & 10\% \\
\text{II} & 2.0\ \mathrm{m\,s^{-1}} & \leq & \bar{u}(h) & < & 3.0\ \mathrm{m\,s^{-1}} & 37\% \\
\text{III} & 3.0\ \mathrm{m\,s^{-1}} & \leq & \bar{u}(h) & < & 4.0\ \mathrm{m\,s^{-1}} & 35\% \\
\text{IV} & 4.0\ \mathrm{m\,s^{-1}} & \leq & \bar{u}(h) & < & 5.0\ \mathrm{m\,s^{-1}} & 14\% \\
\text{V} & 5.0\ \mathrm{m\,s^{-1}} & \leq & \bar{u}(h) & < & 6.0\ \mathrm{m\,s^{-1}} & 3\% \\
\text{VI} & 6.0\ \mathrm{m\,s^{-1}} & \leq & \bar{u}(h) & & & 1\%
\end{array} \tag{10}$$

The mean vertical wind speed profiles in the range of I–VI are graphically presented in Fig. 1. Most of these profiles were in the range II (37%) and III (35%).

The mean forest height (h) was from 10.3 m in July to 10.4 m in October, the mean zero-plane displacement value (d) was found to be 7.0 m and then $d/h = 0.67\ h$. The mean roughness length value was 0.91 m.

Further the aerodynamic conductance values (g_a) were determined by the simple method on the basis of the wind speed profile analysis. The g_a values were determined for the layer from $(d + z_0)$ to z, in this case from 7.9 m to 18 m. Daily means of g_a values from July to October 2004 are graphically presented in Fig. 2. From the analysed set, 16% of wind speed profiles were measured in July, 11% in August, 20% in September, and 53% in October. Dispersion of g_a values can be explained by the dependence of g_a values on the wind speed, roughness length, and atmosphere thermal stratification. The atmosphere stratification in Eq. (5) is characterized by parameter $\frac{\beta}{L}$. As it is written before the analysed wind speed profiles were measured in and above investigated forest stand under different atmosphere thermal stratification.

The dependence of the g_a values on the friction velocity is linear, cf. Eq. (5). This dependence is graphically presented in Fig. 3. In this case the experimental points can be approximated by the relationship in the form of $g_a = 0.208\ u^* - 0.0125$ with a correlation coefficient $r_{xy} = 0.80$. So, the g_a values increase with increasing values of u^*. It implies that stronger airflow creates better conditions for the turbulent exchange between vegetation and the lower atmosphere layers.

It is evident from Eq. (5) that aerodynamic conductance depends also on the roughness length. This dependence is in Fig. 4 and in this case experimental points can be fitted by a relation in the form of $g_a = 0.245(z_0)^{0.744}$. The correlation coefficient between experimental g_a values and their values

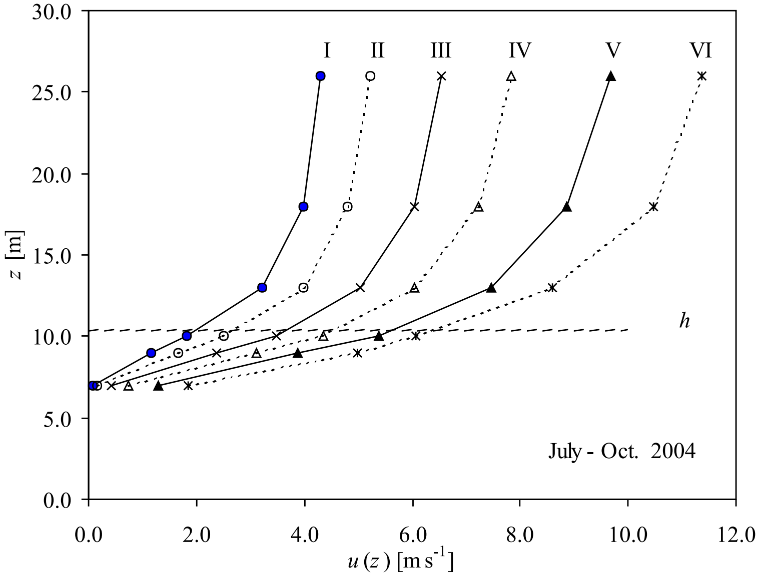

Fig. 1. Mean vertical wind speed profiles in the range of I-VI (Eqs 10), symbol h means the mean stand height.

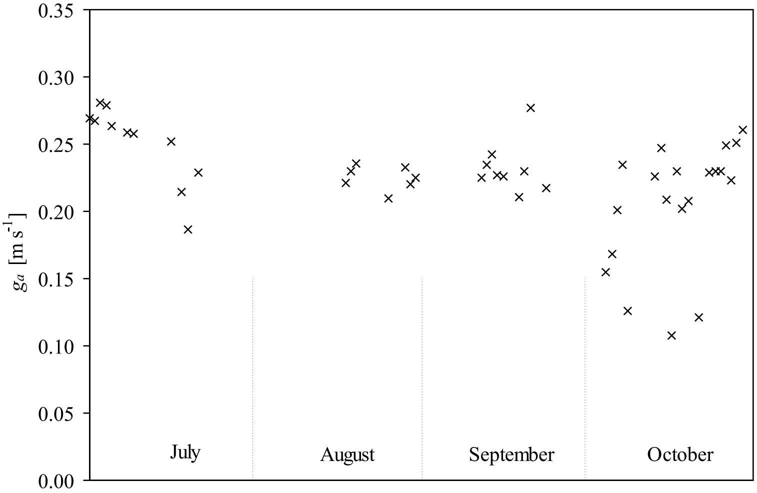

Fig. 2. Daily means of aerodynamic conductance (g_a) during investigated period of growing season 2004.

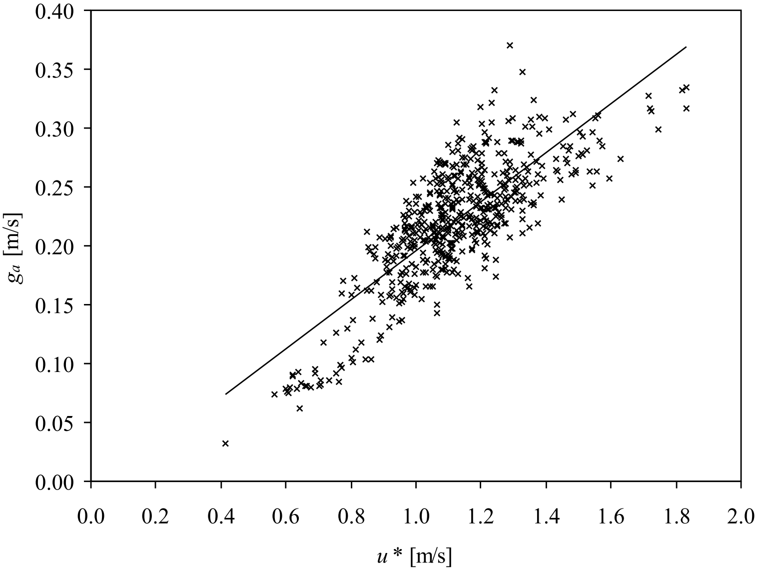

Fig. 3. Dependence of the aerodynamic conductance (g_a) on the friction velocity (u^*).

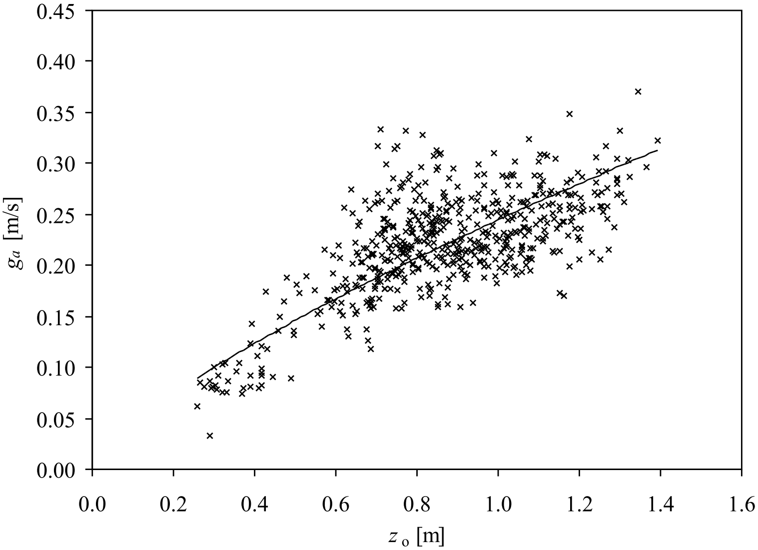

Fig. 4. Dependence of the aerodynamic conductance (g_a) on the roughness length (z_0).

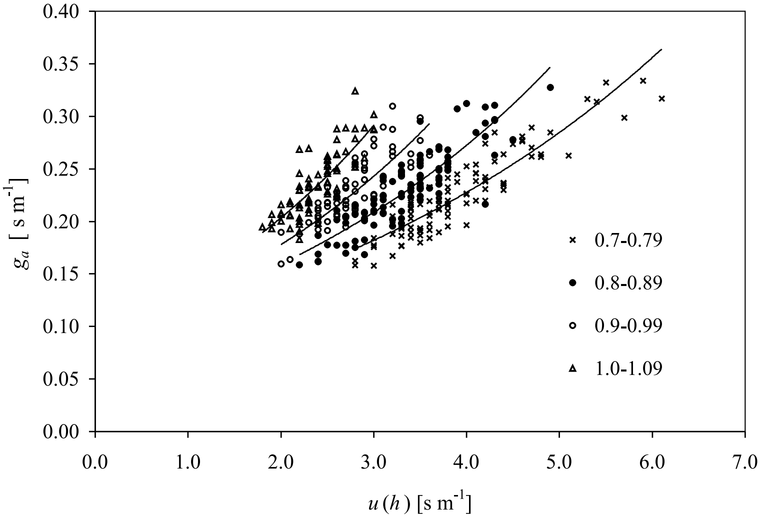

Fig. 5. Dependence of the aerodynamic conductance (g_a) on the wind speed ($u(h)$) measured at the mean height of the forest stand (h) for 4 ranges of z_0 values.

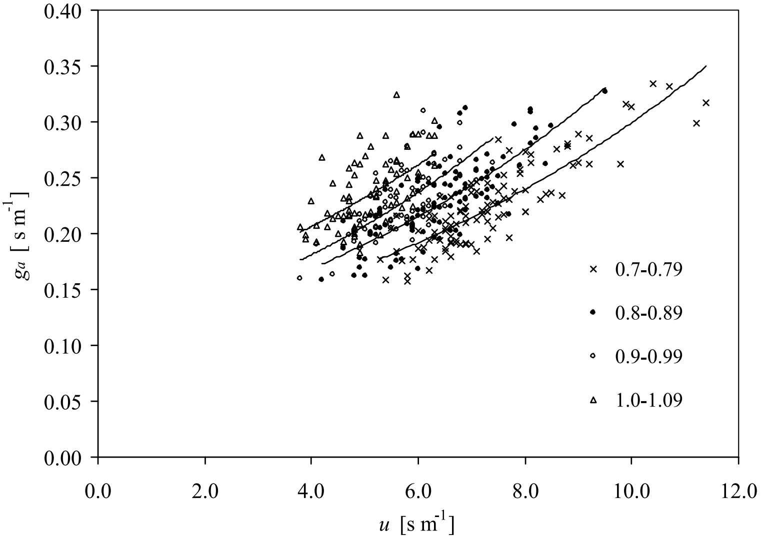

Fig. 6. Dependence of the aerodynamic conductance (g_a) on the wind speed (u) measured at the level of 26 m for 4 ranges of z_0 values.

calculated from this relationship is 0.78.

The dependence $g_a = f(u(z))$ is more difficult. Because the g_a values are dependent on the roughness length, the analysed set of g_a values was divided into the ranges on the basis of the z_0 values. The dependence $g_a = f(u(z))$ was analysed for the z_0 [m] from the interval values: $< 0.7, 0.8), < 0.8, 0.9), < 0.9, 1.0), < 1.0, 1.1)$, and for the wind speed measured at the level of the mean height of the forest stand, $z = h$ and the wind speed measured at the level of 26 m, so $z = 3.7d$, Figs 5, 6. It was found, that the dependence $g_a = f(u(h))$ has correlation coefficient r_{xy} from 0.89 for range $z_0 \in< 0.7, 0.8)$ m, to 0.80 for range $z_0 \in< 1.0, 1.1)$ m, Fig. 5. The r_{xy} values of the dependence $g_a = f(u(z))$, where $z = 3.7d = 26$ m, were from 0.84 for $z_0 \in< 0.7, 0.8)$ m, to 0.58 for range $z_0 \in< 1.0, 1.1)$ m, Fig. 6. From this it follows, that the analysed values of the aerodynamic conductance were dependent more on the airflow measured nearby the tree crown than on the airflow measured higher. Notice that the g_a values were determined for the layer from $(d+z_0)$ to z, in this case from 7.9 m to 18.0 m for the analysed spruce forest stand of a mean height of about 10.4 m. The aerodynamic conductance values within and above the investigated forest stand were highly variable, and only partially explained by average wind speed measurements.

5. Conclusions

The wind speed profile analysis was made with the aim to determine the aerodynamic conductance (g_a) and to investigate the wind speed and aerodynamic conductance variation in the air layer affected by young spruce forest stand. The analysed profile measurements were carried out in and above a young spruce forest stand from July to October 2004. The mean forest height (h) was 10.4, the mean zero-plane displacement value (d) was found to be 7.0 m, so $d/h = 0.67\ h$. The mean roughness length value (z_0) was 0.9 m. The set of 557 wind speed profiles was analysed, which fulfilled the condition $\bar{u}(h - 1) > 1.0$ m s^{-1}. In this case the conditions of turbulent development can be supposed. The g_a values were determined for the layer from $(d + z_0)$ to z, in this case from 7.9 m to 18.0 m. The hourly means of g_a values were found from 0.033 m s^{-1} to 0.370 m s^{-1}. The aerodynamic conductance values within and above the investigated forest stand were highly variable. The g_a value is largely dependent upon the aerodynamic and thermal conditions of the air column.

As stated before, the aerodynamic resistance or aerodynamic conductance governs the vertical aerial transport processes. It was shown, that the g_a values increase with increasing values of the roughness length and also with increasing wind speed. Further the g_a values were dependent more on the wind speed measured nearby the tree crown than on those measured higher. From this it follows, that a rougher surface and a stronger airflow create better conditions for the development of the turbulent exchange between the vegetation and the lower atmosphere layers.

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