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DERIVATION OF THE AERODYNAMIC ROUGHNESS PARAMETERS FOR A SAHELIAN SAVANNAH SITE USING THE EDDY CORRELATION TECHNIQUE

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Abstract. Vertical exchange of heat, moisture and momentum above the earth's surface depends strongly on the turbulence generated by surface roughness. This roughness is best specified through the roughness length and the zero plane displacement. The ratio of windspeed to friction velocity was measured at four heights using the eddy correlation technique at a fallow savannah site in the Sahel. The change in this ratio with height was used to derive the zero plane displacement and the roughness length of the surface, together with an estimate of the error in each parameter. These were estimated as 0.93 ± 0.35 m and 0.17 ± 0.01 m, respectively. The method appears to be a more robust alternative to wind profile derivation.

1. Introduction

Roughness length and zero plane displacement are used in most models of the land surface energy balance. They determine the efficiency of the turbulent transport, or aerodynamic conductance, through the lower boundary layer. For uniform crops, these roughness parameters can probably be adequately estimated using empirical relationships in terms of the height or cross-sectional profile of the vegetation (e.g., Monteith and Unsworth, 1990). For incomplete canopies however, these relationships have been found to be invalid (Hatfield, 1989). For natural vegetation with a heterogeneous species composition and an irregular structure such as the savannah bushland, such relationships may also be inappropriate and the local roughness parameters will need to be measured as part of any micrometeorological study. In the past, the roughness parameters have usually been derived by fitting a straight line to a logarithmic profile of windspeed (see Thom, 1975). The disadvantages of this method have been discussed by Molion and Moore (1983), and De Bruin and Moore (1985). The method is subjective, and sensitive to errors – requiring accurate windspeed measurements. Although this technique can be improved using analytical techniques (Molion and Moore, 1983; De Bruin and Moore, 1985), use of the eddy correlation technique allows an alternative method

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of deriving the surface roughness based on the simple solution of the logarithmic profile equation.

Under neutral atmospheric stability, the wind profile can be described by

$$u = \frac{u_*}{k} \ln\left\{\frac{z - d}{z_0}\right\} \tag{1}$$

where u is the wind vector at height z, d is the zero plane displacement, z_0 is roughness length, u_* is friction velocity and k, von Kármán's constant, is 0.41. Using Equation (1), Shuttleworth *et al.* (1984) and later Gash *et al.* (1989) derived a parameterisation of the surface roughness for two forest sites in terms of the combination $\ln\{(z - d)/z_0\}$. This was determined from the slope of a regression of u and u_*, u_* being derived from eddy correlation measurements. Although the derived relationships were both used in subsequent analyses, the aerodynamic conductance can only be calculated for the original reference height when the two parameters are combined in this way. Gash (1986) applied a similar approach to measurements made over heather (*Calluna Vulgaris*), and he was able to obtain a separate value of z_0 using an assumed value of d because the measurement height was much greater than the height of the vegetation. The derived value of z_0 in that case was insensitive to the value of d chosen. By taking measurements at more than one height, this technique can be extended so that both d and z_0 can be derived. This technique is used to derive the roughness parameters for a savannah site in the Sahel.

2. Experimental Details

The measurements were made in a fenced area of fallow bushland on the ICRISAT experimental farm at Sadoré, 45 km south of Niamey, Niger (Lat. 13°15′ N, Long. 2°17′ E, altitude 240 m). The site was flat and situated in an area of bushland whose fetch was between 300 and 500 m in all directions. Some 500 m to the south of the site is a building complex, with a further large area of fallow savannah beyond: 300 m to the east is the experimental farm which, at the time of the measurements, mainly comprised fields of millet stubble. Beyond 500 m to the north and west, the land was under traditional agriculture, with areas of millet stubble interspersed with fallow grazing land. Measurements were made during the first six weeks of the 1988 dry season when 78% cent of the ground was covered by a mixture of leguminous and grass species, with an average height of 0.74 m. Almost all the remaining ground was covered by woody shrubs, *Guiera senegalensis*, with an average height of 2.3 m, but there were also occasional trees, between 5 and 10 m tall and with a density of approximately 1.5 per hectare. Further details of the vegetation at this site are given by Wallace *et al.* (1990) and Gash *et al.* (1991).

Measurements of hourly average evaporation, sensible heat flux and momentum flux were made with two MK 2 Hydra (Institute of Hydrology, Wallingford, UK) eddy correlation devices (Shuttleworth *et al.*, 1988). The Hydra uses a sonic anemometer to measure vertical windspeed and a sensitive cup anemometer (Vector Instruments, Rhyl, UK) to measure horizontal windspeed. Humidity and temperature fluctuations were measured with an infra-red absorption hygrometer and a fine-wire thermocouple, respectively. One instrument was mounted at an overall height of 12.8 m, on a mast at the top of a 10 m high tower; the second instrument was mounted on a pneumatic, telescopic mast. Figure 1 shows the site and vegetation cover together with the tower and mast-mounted Hydras from a position west of the tower while Figure 2 shows an aerial view of the site indicating the spatial distribution of the vegetation types. Over the six weeks of the experiment, the pneumatic mast was operated at heights of 3.5, 6.5 and 9.5 m. In addition, for an intercomparison period of five days, both instruments were mounted next to each other at a height of 12.8 m on top of the tower. The measurement heights used here refer to the height of the cup anemometer; this is 0.5 m above the normally quoted reference height for this instrument, which is to the centre of the path of the vertical sonic anemometer.

An automatic weather station mounted at the top of the 10 m tower made hourly average measurements, of which temperature, humidity and wind direction are relevant to the analysis reported here. Further details of the instrumentation are given by Gash *et al.* (1991).

3. Data Analysis

Although Equation (1) requires the horizontal wind vector, u, the horizontal windspeed, s, as measured by a cup anemometer, is commonly used in its place. This generates an overestimate of the wind vector because; (a) windspeed is a priori greater than the mean wind vector in turbulent conditions and (b) cup anemometers are prone to 'overspeeding' in fluctuating wind conditions. The Hydra uses the cross-correlation of instantaneous horizontal and vertical windspeed in its calculation of the friction velocity, u_*. Any overestimate of the wind vector using cup anemometers will propogate through into the evaluation of u_*. The magnitude of such an overestimate in the absence of independent horizontal wind vector measurements can only be gained from previous work on overspeeding of cup anemometers. The work of Businger *et al.* (1971) and Izumi and Barad (1970), later re-evaluated by Weiringa (1980), indicates overspeeding to be 5% for their 3-cup fast response anemometer. Their anemometer had a distance constant of 1.5 m, compared to 1 m for the Hydra 6-cup anemometer. Hyson (1972) in his wind tunnel and open grassland work reports 1% overspeeding. Such errors will be greatest at times of maximum instability, which leads us to assume a mean maximum difference of 3% between the true wind vector and the windspeed as measured by the cup anemometer. The effect of this upon the values of d and z_0 will be illustrated later.

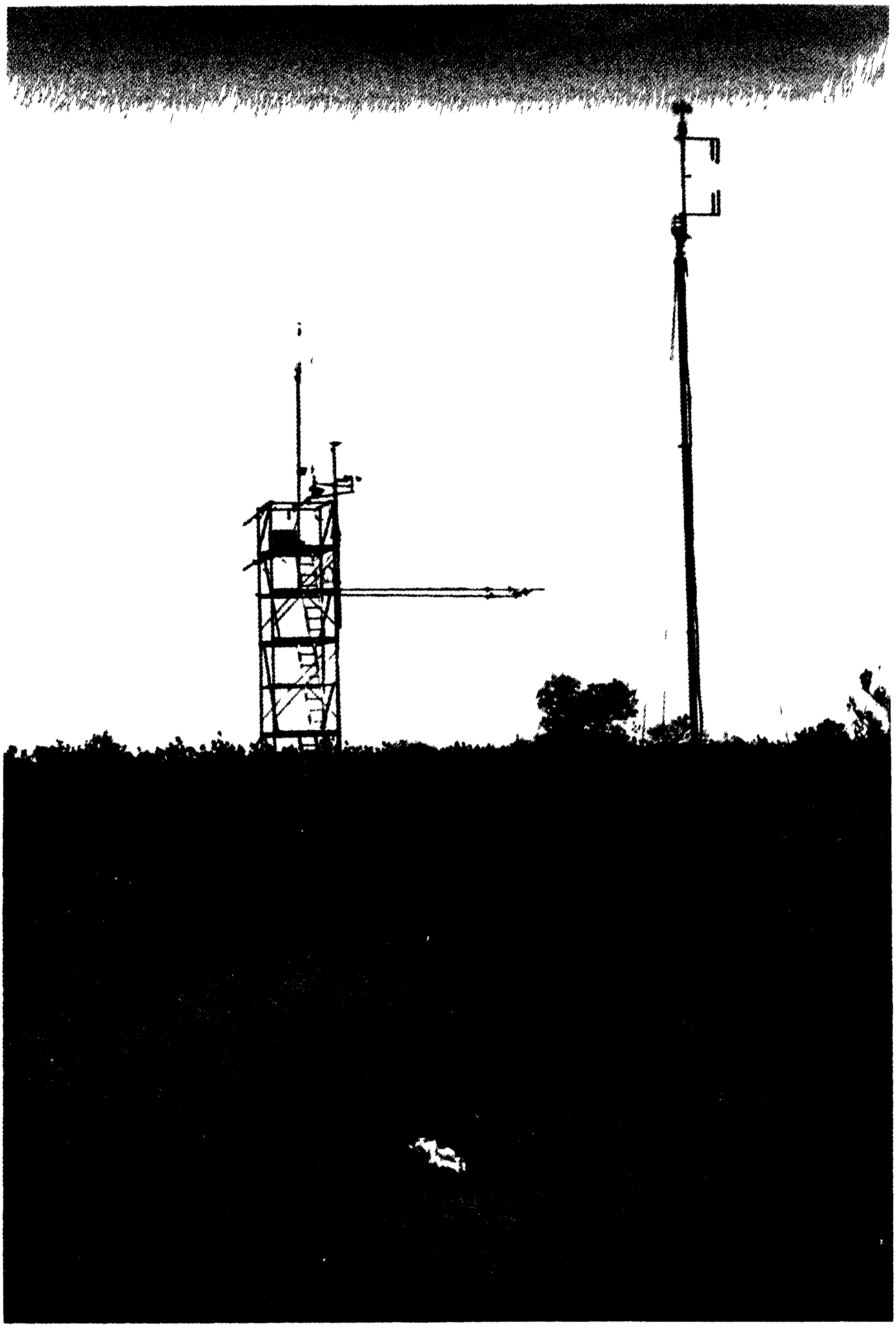

Fig 1 The fallow savannah site from a position west of the tower showing the typical vegetation cover and the tower and pneumatic mast Hydras

The eddy correlation method requires that the correlation of measurements between two entities, e.g., vertical and horizontal windspeed, take place at exactly the same time and point in space for the correct evaluation of, in this example, the friction velocity u_*. The failure to achieve this in practice results in a loss of flux through the combination of frequency- and stability-dependent losses due to sensor response time, path-length averaging, sensor separation and signal processing. The Mk.2 Hydra was physically designed to minimise the effect of this flux loss to typically 5 to 10% for sensible and latent heat flux but, due mainly to the cup anemometer response and the distance between the cup anemometer and the sonic anemometer (0.52 m), the flux loss in evaluating u_* can be much higher.

The Hydra software routinely computes the losses due to the above factors in both the flux and variance evaluations and corrects the estimates accordingly. A fuller and more detailed explanation of this procedure can be found in Moore (1986).

The data used in this analysis have been restricted to near-neutral conditions, which have been defined as being when $-0.02 < 1/L < 0.02$, where L is the Monin-Obukhov scale length. To avoid cup anemometer stalling errors, data were selected, following Shuttleworth (1988), when the average windspeed was greater than 1 m s^{-1} and u_* was greater than 0.1 m s^{-1}. Stringent upwind direction limits of ±50° of the frame orientation were applied to the intercomparison period at 12.8 m to exclude mutual interference of the sensors. Such limits reduced neutral data values during this period to 7 and 17 h of data from the two Hydra's, the discrepancy in the number of points reflecting the difference in the accuracy of the two Hydra's when measuring u and u_* close to the 1 m s^{-1} windspeed cutoff. Regressions of u versus u_* for the two Hydra's were not significantly different at the 90% confidence level. The gradient (and standard error of the coefficient) of these regressions were 0.087 (±0.006) and 0.090 (±0.005) with correlation coefficients of 0.69 and 0.77, respectively. We therefore conclude that there was no significant systematic instrumental bias between the two Hydra's.

For the periods when the Hydra's were operated at different heights, data for hours when the supporting frame of the instrument may have been upwind of the sonic anemometer, i.e., when the downwind direction was within ±30° of the frame orientation, have been excluded. The remaining data consisted of 85 h from 12.8 m, and 68, 34 and 34 h from 9.5, 6.5 and 3.5 m, respectively.

4. Results

Unconstrained regressions of u against u_* were statistically compared with regressions of u against u_* forced through the origin for each of the four measurement heights. The unconstrained regressions were not significantly different to the forced-origin regressions at the 95% level for all heights except 3.5 m. The data and forced-origin regression lines are shown in Figure 3 for each of the measurement heights.

Rearranging the differential of Equation (1) and taking the exponent, the slope of each regression can yield $(z - d)/z_0$ from

$$\frac{z - d}{z_0} = e^{k(\mathrm{d}u/\mathrm{d}u_*)} . \tag{2}$$

Fig 2 An aerial view looking southwest of the fallow savannah vegetation surrounding the tower

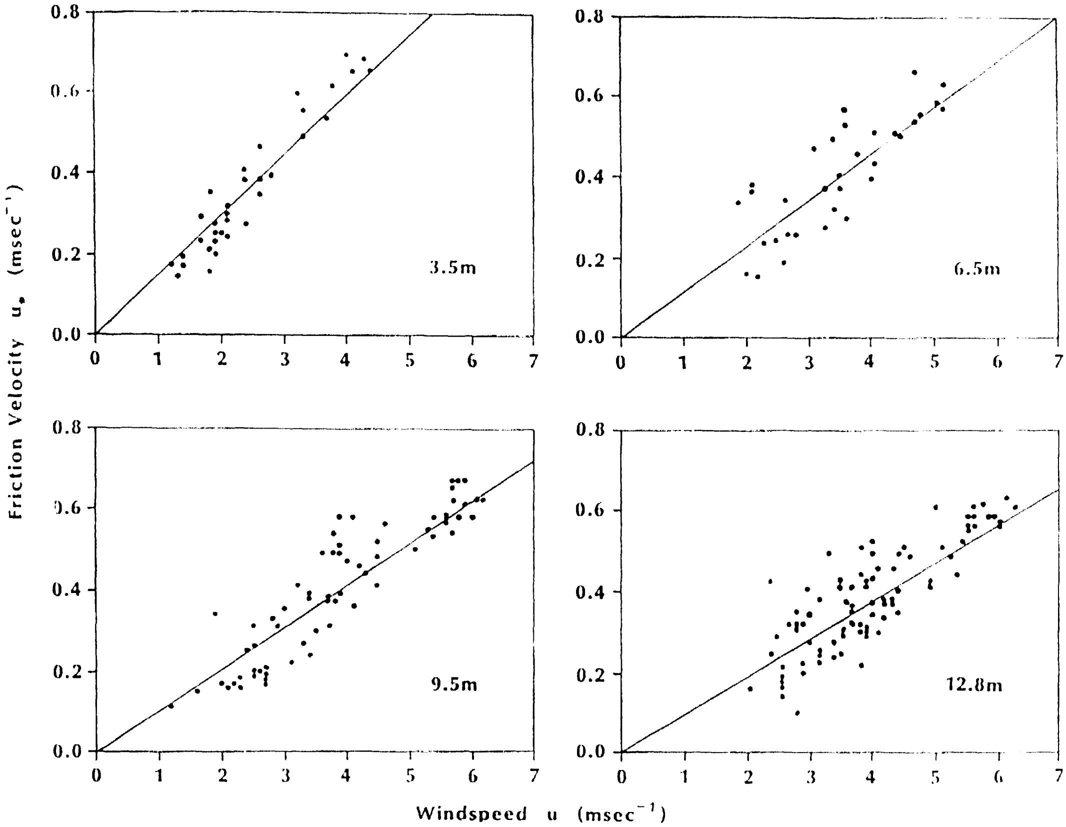

Fig. 3. Hourly average values of u_* plotted against windspeed for near-neutral conditions at heights of 3.5, 6.5, 9.5 and 12.8 m. The lines are regressions forced through the origin.

Figure 4 shows a plot of values of $(z - d)/z_0$ derived from the regressions, against height. A Chi-square maximum likelihood regression, with these four points weighted according to their standard errors, gives the zero plane displacement, d from the intercept with the vertical axis, and the roughness length, z_0 from the slope. Values of $d = 0.93 \pm 0.35$ m and $z_0 = 0.17 \pm 0.01$ m were obtained. The error limits refer to the 68% (one standard deviation) confidence limits.

Figure 4 also allows an assessment of the adequacy of the fetch. Any change in roughness should be apparent as a change in the slope of a line joining the points. As there is no statistically valid evidence from that figure of any systematic change in slope, it must be concluded that, at least from an aerodynamic point of view, the fetch is adequate. The results also imply that the sparse trees have little noticeable effect on the aerodynamic transfer of momentum to the surface. This apparently anomalous result will be discussed below.

Although in this case, measurements were taken at four heights, d and z_0 could also be obtained from solving Equation (1) simultaneously from measurements made at only two heights. The results of using the present data in this way are given in Table I, where the value of $(z - d)/z_0$ obtained from the slope of the regression through the data from 12.8 m is taken as a reference and Equation (1) solved simultaneously with the result obtained from each of the other levels. As would be expected from the error limits given above, the value of z_0 is insensitive

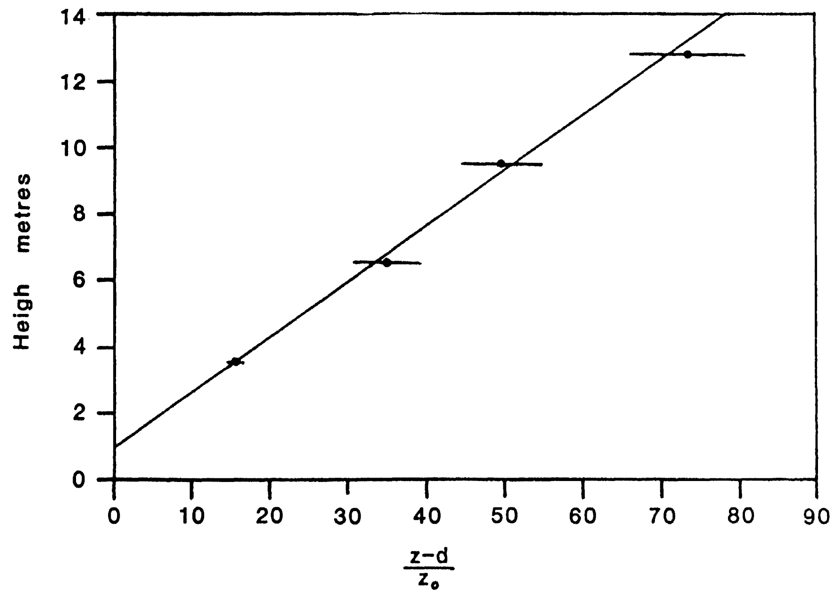

Fig. 4. The value of $(z - d)/z_0$, derived from the slope of regressions between u and u_*, plotted against height. The line is the result of a regression in which the points were weighted according to their standard error. The zero plane displacement is given by the intercept with the vertical axis; the roughness length by the slope of the regression line.

TABLE I

The slope of a regression, forced through the origin, between u and u_*, for four heights, and the values of d and z_0 derived by solving the logarithmic wind profile equation simultaneously at 12.8 m and at each of the other heights. The values in parentheses are derived by assuming a constant 3% overspeeding error when estimating windspeed from windspeed and its propagation into u_*.

Height (m)	du/du_*	d (m)	z_0 (m)
3.5	6.68 (6.58)	1.02 (0.94)	0.16 (0.17)
6.5	8.65 (8.52)	0.84 (0.71)	0.16 (0.18)
9.5	9.51 (9.56)	2.66 (2.58)	0.14 (0.15)
12.8	10.47 (10.55)	–	–

to the level chosen, but the data from 9.5 m yield a notably higher value of d = 2.66 m. Such a result, apparent from consideration of Figure 4, indicates that if the two-height estimate of d and z_0 is to be used effectively, the two heights should be as far apart as possible, consistent with limitations imposed by fetch and vegetation cover.

Table I also shows, in parentheses, the evaluation of du/du_*, d and z_0 for each of the heights assuming an overspeeding error of 3% in the windspeed measurement. For this exercise, it was assumed that in neutral conditions, the overspeeding error is constant with windspeed and height. The evaluations, which included propagation of such an error into the measurement of u_*, produced errors of the order of 5% in both d and z_0.

5. Discussion

The implication in the results above that the trees apparently have little discernible effect upon the evaluation of d and z_0 requires an explanation over and above the fact that they only covered 0.3% of the ground area. Such a result has important consequences for the measurement of surface fluxes in areas of similar inhomogeneous vegetation cover. Such areas, especially in the Sahel, are often of limited extent and would probably be viewed as unsuitable for experiments if the fetch requirements were based on the height of the tallest vegetation. An estimate of z_0 based solely on the sparse trees can be gained by using Equation 1 of Lettau (1969), viz,

$$z_0 = 0.5h^* \frac{s}{S}, \tag{3}$$

where h* is the average vertical extent (effective obstacle height), s is the silhouette area of the average obstacle (area seen by the wind in the approach towards one characteristic individual obstacle) and S is the specific area, which can be estimated as A/n, where A is the total horizontal area and n is the number of roughness elements (in this case, trees) in that area. Lettau explains the numerical factor 0.5 as the average drag coefficient of the characteristic individual obstacle of silhouette area s. Assuming the trees to have a maximum 5 m diameter spherical outline (ignoring the trunks), Equation (3) was evaluated with $h^* = 8$ m and a density of 1.5 trees per hectare and gave a value of $z_0 = 0.012$ m. This value is an upper estimate but is commensurate with the size of the error limits on z_0 presented in the results section of this paper. This may explain the apparent inability of the measurements to register the presence of the trees. By assuming an effective surface height to be commensurate with the height of the grass layer, a similar analysis for the bush cover using Equation (3) gave a value of $z_0 = 0.145$ m.

It is often convenient to describe the roughness parameters in terms of the height of the vegetation. Analysis of data, taken mainly from uniform crops, suggests that d and z_0 can often be taken as 65 and 13% of the vegetation height, respectively (see Brutsaert, 1982). Kondo and Yamazawa (1986) derived an average geometric roughness height for inhomogeneous surface cover by weighting the average height for each component surface cover type according to the proportion of the area that it covered. Such an exercise for this site gives a mean geometric roughness height of 1.04 m, the trees only contributing 0.01 m. The zero plane displacement is then 89%, and the roughness length 16%, of this height. Thus the roughness length is related to the weighted average height in the same way as would be expected for a uniform crop. However the windspeed profile is displaced above the generally accepted 65% of the mean vegetation height, being influenced more by the 2.3 m high bushes than the simple linear weighted average height allows. Such a result is not inconsistent with the measurements of Garratt (1978) in a heterogeneous sand, grass and tree surface cover where d and z_0 were found to be 192 and 15% of the mean geometric roughness height respectively. His larger zero displacement factor may be attributed to the increased effect of the trees at his site which were 8 m high and covered 25% of the surface.

6. Conclusions

A method has been described to derive the roughness parameters for a savannah bushland site. It gives an objective derivation and, provided that measurements are taken at least at four levels, a quantitative estimate of the errors involved can be deduced. It would appear to he a more robust method than the more traditional use of a simple windspeed profile, and should find increasing application with the more widespread use of eddy correlation instrumentation.

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