REGIONAL SHEAR STRESS OF BROKEN FOREST FROM RADIOSONDE WIND PROFILES IN THE UNSTABLE SURFACE LAYER

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Abstract. Mean wind speed profiles were measured by tracking radiosondes in the unstable atmospheric boundary layer (ABL) over the forested Landes region in southwestern France. New Monin-Obukhov stability correction functions, recently proposed following an analysis by Kader and Yaglom, as well as the Businger-Dyer stability formulation were tested, with wind speeds in the surface sublayer to calculate the regional shear stress. These profile-derived shear stresses were compared with eddy correlation measurements gathered above a mature forest stand at a location roughly 4.5 km from the radiosonde launch site. The shear stress values obtained by means of the newly proposed stability function were in slightly better agreement with the eddy correlation values than those obtained by means of a Businger-Dyer type stability function. The general robustness of the profile method can be attributed in part to prior knowledge of the regional surface roughness ($z_0 = 1.2$ m) and the momentum displacement height ($d_0 = 6.0$ m), which were determined from neutral wind profile analysis. The 100 m drag coefficient for the unstable conditions above this broken forest surface was found to be $u_*^2/V_{100}^2 = 0.0173$.

1. Introduction

The surface shear stress τ_0, usually expressed as a velocity scale, called the friction velocity $u_*[\equiv(\tau_0/\rho)^{1/2}]$, is one of the essential variables in Monin–Obukhov similarity theory to describe turbulence in the surface sublayer or inner region of the atmospheric boundary layer (ABL). It is ubiquitous in all flux-profile relationships, but it appears probably most naturally in the wind speed gradient

$$\frac{\mathrm{d}V}{\mathrm{d}z} = \frac{u_*}{k(z - d_0)}\varphi_m(y) \tag{1}$$

where V is the wind speed, z the height above the ground, k von Karman's constant herein taken as 0.4, and d_0 the (zero-plane) displacement height; $\varphi_m = \varphi_m(y)$ is the Monin–Obukhov stability function, in which $y = [(z - d_0)/L]$ and

$$L = \frac{-u_*^3}{kg[H_v/\rho c T_a]} \tag{2}$$

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is the Obukhov length; $H_v = (H + 0.61\, T_a c_p E)$ is the specific flux of virtual sensible heat at the surface, H the specific flux of sensible heat, E the evaporation rate, g the acceleration of gravity, ρ the density of the air, c_p the specific heat at constant pressure and T_a the air temperature near the ground. For unstable conditions, which are of interest here, the stability function φ_m has been the subject of numerous experimental studies. Until a few years ago, the consensus based on the field observations was that the Businger-Dyer formulation (e.g., Dyer, 1974; Businger, 1988; Högström, 1988), viz., in a general form

$$\varphi_m = (1 - Cy)^{-1/4} \tag{3}$$

where C is a constant, gives a good description of the available data. However, almost all of the field studies on which (3) was based produced data for $(-y)$ smaller than 2.0; thus little was known about the behavior of φ_m for large values of $(-y)$, which represent strongly unstable conditions or measurements at higher elevations in the surface layer. More recently, following a theoretical analysis by Kader and Yaglom (1990) with a data collection with values of $(-y)$ up to 20, Brutsaert (1992) suggested as an interpolation function

$$\varphi_m = [(a + bx^n)/(a + x^n)] + cx^{1/3} \tag{4}$$

where $x = -y$, and a, b, c and n are constants, to be specified below.

In practical applications, the wind speed profile, which is the integral of (1), is often written in the form

$$V = \frac{u_*}{k}\left[\ln\left(\frac{z - d_0}{z_0}\right) - \Psi_m(y)\right] \tag{5}$$

in which z_0 is the roughness length and Ψ_m is the stability correction function, defined by

$$\Psi_m(y) = \int_{z_0/L}^{y} [1 - \varphi_m(z)]\, \mathrm{d}z/z\ . \tag{6}$$

This can be readily integrated using the two φ_m-functions. Thus the correction function derived from the Businger-Dyer formulation (3) is

$$\Psi_m(y) = \ln\left[\frac{(1 + u)^2(1 + u^2)}{(1 + u_0)^2(1 + u_0^2)}\right] - 2\arctan(u) + 2\arctan(u_0) \tag{7}$$

where $u = (1 - Cy)^{1/4}$ and $u_0 = (1 - Cz_0/L)^{1/4}$; in this paper the value $C = 16$ is used, which is typical for $k = 0.4$. In the integration of (6) with (4), two sets of constants were used. In the first implementation, the constants in (4) were chosen to produce a close fit with the data of Kader and Yaglom (1990). The result was (Brutsaert, 1992) the following (for $k = 0.4$)

$$\Psi_m(y) = 0 \quad \text{for } y > -0.0093$$

$$\Psi_m(y) = 1.72 \ln\left[\frac{(0.37 + x^{0.72})}{0.37 + (0.0093 + x_0)^{0.72}}\right] - 1.50[x^{1/3} - (0.0093 + x_0)^{1/3}] \quad \text{for } y \leqslant -0.0093 \tag{8}$$

where, again, $x = -y$ and $x_0 = -z_0/L$. In the second implementation of (4), the constants were selected as a compromise between the data set of Kader and Yaglom (1990) and the several earlier data sets for small $(-y)$, as exemplified by Högström (see Brutsaert, 1992). The proposed form was

$$\Psi_m(y) = 0 \quad \text{for } y > -0.00059$$

$$\Psi_m(y) = 1.47 \ln\left[\frac{(0.28 + x^{0.75})}{0.28 + (0.0059 + x_0)^{0.75}}\right] - 1.29[x^{1/3} - (0.0059 + x_0)^{1/3}] \quad \text{for } -0.0059 \geqslant y \geqslant -15.025$$

$$\Psi_m(y) = \Psi_m(-15.025) \quad \text{for } y < -15.025\,. \tag{9}$$

As an illustration, the three forms of Ψ_m, namely (7), (8), and (9) ($y_0 = 0$), are plotted for $z_0 = 0$ in Figure 1.

The surface-layer similarity scheme (1) has been developed and tested primarily for relatively smooth and homogeneous terrain; moreover, most experiments on which (3) and (4) are based, were conducted at the field scale with measurements at a few meters above the ground and effective fetches of the order of a few hundred meters, at most. Very few studies have dealt with rough surfaces such as forest or hilly terrain at more regional scales. Thom *et al.* (1975) were among the first to point out the difficulties encountered in the application of standard flux-profile relationships above forests. Many subsequent studies (e.g., Garratt, 1978, 1979, 1980; Raupach, 1979; Denmead and Bradley, 1985; Cellier, 1986; Chen and Schwerdtfeger, 1989) have confirmed that profiles measured near a forest canopy are not well described by the standard surface-layer similarity functions.

In this paper, an analysis is presented of wind speed profiles measured with radiosondes under unstable atmospheric conditions over the Landes Forest in southwestern France, as part of the 1986 HAPEX-MOBILHY field campaign. The present study is a sequel to two earlier analyses (Parlange and Brutsaert; 1989, 1990) of wind profiles under neutral conditions during the same experiment. The main objective of the present paper is to explore the usefulness of the Monin–Obukhov similarity formulation with the measured profiles in order to estimate the friction velocity u_* at the regional scale. The function (7), as well as (8) and (9), are considered in the process. The quality of the u_* estimates from the wind speed profiles is assessed by comparing them with independent eddy correlation measurements of the shear stress made above the forest.

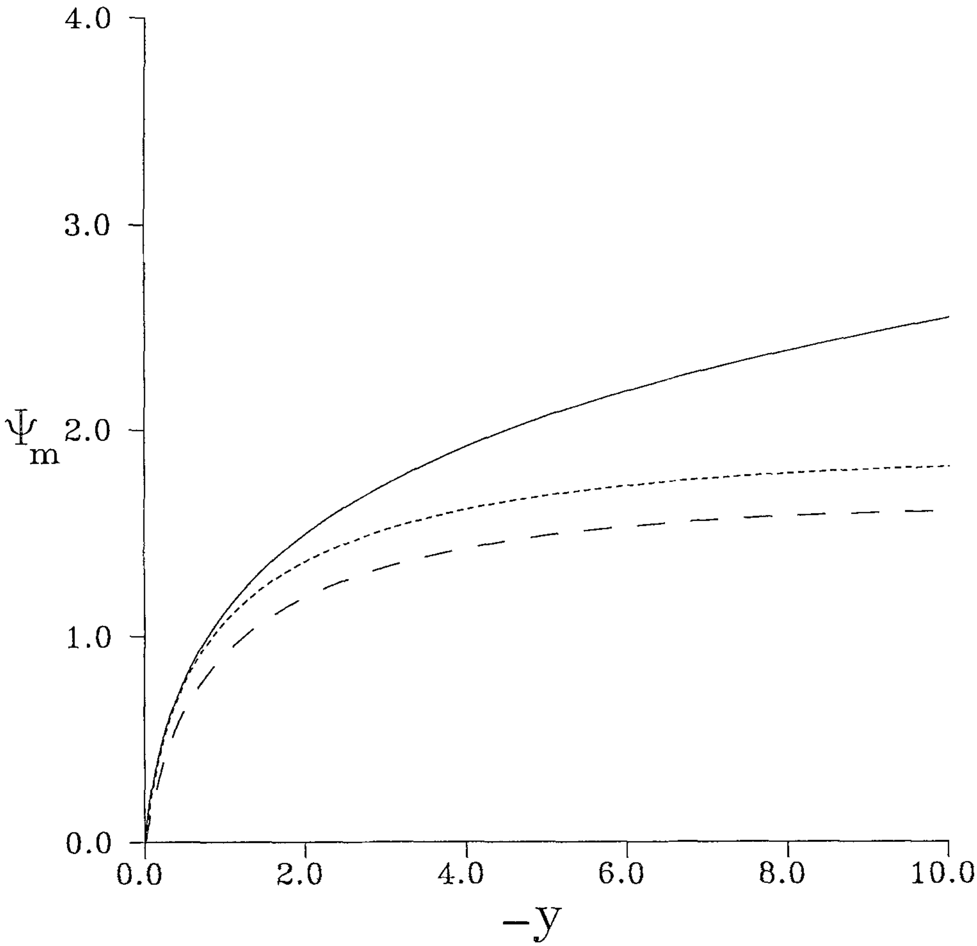

Fig. 1. The momentum stability correction functions Ψ_m ($z_0 = 0$); (7), solid line; (8), long dashed line; (9), fine dashed line.

2. Experiment

The radiosonde wind speed profiles were collected during the HAPEX-MOBILHY (Hydrologic Atmospheric Pilot Experiment-Modelisation du Bilan Hydrique). The scope and general objectives of this experiment have been described by André *et al.* (1986, 1988). The launch site was situated near Lubbon (00°03′ W, 44° 08′ N) within the predominantly flat Landes Forest region. Approximately 65% of the area surrounding the launch site, within a radius of 5 to 10 km, is covered by pine forest; the remaining land cover consists of agricultural clearings, remnants of logging operations and a few small villages. Further information on the experimental area and the radiosounding system have been presented by Parlange and Brutsaert (1989; 1990) and Brutsaert *et al.* (1989).

From May 6 through July 14, 1986, some 405 soundings were made. The time interval sampled for the mean velocity profile was taken as 10 s, which corresponded to a vertical resolution of approximately 50 m. The velocity profiles were derived by automatic radar tracking of the radiosonde position. From among the available soundings for the present analysis 62 unstable ones were selected on the basis of two additional criteria: (1) All three variables of the radiosounding (wind velocity, temperature and specific humidity) were measured; (2) eddy correlation measurements of shear stress, and of the sensible and latent heat fluxes are available at the time of the radiosonde flight. It was assumed that the surface was statistically uniform in all directions, and the profiles were not discriminated according to wind direction. The ABL was fairly well developed for all the profiles studied; the height of the capping inversion h_i for all soundings was more than 300 m above the ground.

The eddy correlation shear stress measurements were used to assess the quality of u_* estimates from the wind speed profiles. The eddy correlation measurements of the fluxes H and E were needed to determine the Obukhov length by means of (2). The eddy correlation flux station was located atop a mast above 29 m above the ground and about 9 m above the tree tops, in an area of mature forest, some 4.5 km southwest of the release site. This flux station was operated by a research team from the Institute of Hydrology, Wallingford, Great Britain. The system measured hourly flux averages (see Shuttleworth *et al.*, 1984; 1988; Gash *et al.*, 1989); for the present study, these were interpolated to the release times of the sondes. The earlier studies (Parlange and Brutsaert, 1989; 1990; Brutsaert *et al.*, 1989) of the neutral wind speed and humidity profiles have already provided a strong indication that the flux measurements made at the mast represent good estimates at the regional scale.

3. Wind Speed Profile Analysis

3.1. The Surface Sublayer

In order to apply (1) or (5), it is necessary to know the height range of the surface sublayer. In the analysis of the neutral wind speed profiles (Parlange and Brutsaert, 1989) the mean range of this inner region was found to be $86 \pm 22\ \mathrm{m} \leq z \leq 160 \pm 38\ \mathrm{m}$. It was noted in the study of neutral wind profiles that once the typical inner region range was known and z_0 and d_0 had been established, the omission or addition of a rawinsonde wind speed measurement at the upper or lower end of this range did not change the estimate of shear stress appreciably. This was an important result since a reliable estimate of the regional shear stress could be obtained from the wind profile once the zero velocity intercept was set and some average range of the inner region of the ABL was specified.

In the present study, an analysis of the unstable wind profiles was first carried out to establish "optimal" height ranges for application of (5) using the stability correction functions given by (7)–(9). For each individual profile, the optimal range of wind speed measurements above the land surface may be defined as the range for which the profile-derived u_* matches best the eddy correlation value. The objective was to check if the different stability correction formulations (7)–(9) in the Monin–Obukhov similarity model result in optimal ranges which differ from one another and from the range obtained earlier in the neutral wind study. The Obukhov length was calculated from the eddy correlation measurements taken at the Institute of Hydrology mast and for each wind profile the range was selected such that the u_* obtained with (5) was closest to the surface measurement. With the parameters $z_0 = 1.2$ m and $d_0 = 6.0$ m, known from the analyses of the neutral profiles, the mean height ranges (±standard deviations) for all 62 profiles analyzed were found to be:

$$\begin{aligned} &89\ (\pm 41)\ \text{m} \leqslant z \leqslant 183\ (\pm 50)\ \text{m for (7)} \\ &84\ (\pm 39)\ \text{m} \leqslant z \leqslant 177\ (\pm 46)\ \text{m for (8)} \\ &76\ (\pm 38)\ \text{m} \leqslant z \leqslant 181\ (\pm 39)\ \text{m for (9).} \end{aligned} \tag{10}$$

These results show that the extent of the unstable surface sublayer as determined by the fit of (5) to obtain the best u_* value for each individual profile does not depend strongly on the stability correction function used; indeed, the mean limits cannot be considered different at the 0.05 level of significance. The average lower surface sublayer limit is comparable with the average neutral profile lower limit (86 m) though the standard deviation of the limits found above are about twice the standard deviation of the neutral range lower limit. The average upper limit extends some 20 m above the neutral range. In general, the neutral profile analysis appears to give a reasonable estimate of the surface-layer range under unstable conditions which is useful for applications at other sites over heterogeneous terrain. The ranges are also very similar to those obtained for the temperature and humidity profiles of the same unstable soundings (see Brutsaert and Parlange, 1992). The overall regression comparison of the "optimal" u_*'s found above, obtained by matching the closest profile-derived flux against the friction velocities measured with the eddy correlation system, is presented in Table I. The slope of the regression lines forced through the origin are not different from unity at the 95% confidence level and the coefficients of determination (R^2) are about 0.90 for all three stability functions tested.

When the surface parameters (z_0 and d_0) and the average ABL surface sublayer range are known for a given region, the question is: how robust is the Monin–Obukhov similarity analysis for the determination of u_*, with the different stability correction functions, if the wind speed measurements between some prespecified limits are used? This is addressed below in a wind profile analysis where the mean inner region height ranges obtained from the neutral analysis (86 m $\leqslant z \leqslant$ 160 m) (Parlange and Brutsaert, 1989) and from the unstable analysis (80 m $\leqslant z \leqslant$ 180 m) are used. An additional check on the robustness of the profile analysis was carried

TABLE I

Overall regressions results for u_* obtained from profile analysis versus eddy correlation measurements (u_{*s}). $u_* = Au_{*s} + B$; $u_* = Cu_{*s}$, ($N = 62$) (units of B are m s^{-1})

Stability function	Height range: 86–160 m				Height range: 80–180 m				Height range: 40–220 m				Optimal results:			
	A	B	R	C	A	B	R	C	A	B	R	C	A	B	R	C
(7)	0.71	0.129	0.82	0.95	0.75	0.112	0.85	0.95	0.78	0.112	0.86	0.98	0.87	0.064	0.94	0.99
(8)	0.79	0.049	0.86	0.88	0.85	0.025	0.89	0.89	0.85	0.035	0.90	0.91	0.91	0.018	0.94	0.95
(9)	0.80	0.069	0.85	0.92	0.83	0.053	0.88	0.93	0.85	0.057	0.89	0.95	0.93	0.028	0.95	0.98

out using the wind speed measurements between 40 and 220 m. These limits represent the average optimal unstable range extended out one standard deviation (40 m) at the lower and upper limits.

3.2 Application of flux-profile functions

For each wind speed profile, (5) was fitted to all the measured wind speed values measured in the height ranges (86–160 m), (80–180 m) and (40–220 m). The wind speed profile analysis was done by linear regression of $\ln[(z - d_0)/\exp(\Psi_m(y))] - \ln(z_0)$ versus V, through the origin. The Obukhov length in y was calculated from the eddy flux measurements above the forest and each of (7), (8) and (9) was used to calculate the stability correction function $\Psi_m(y)$.

The overall regression analysis of the profile-derived friction velocities versus the eddy correlation measurements is presented in Table I. None of the correlation coefficients are significantly different at the 0.05 level of significance regardless of what stability function or inner layer region is used. In general, the correlation coefficient increases as a larger interval is used to define the surface sublayer. The slope of the regression line forced through the origin is not different from unity at the 0.05 level for all stability correction functions used and ranges tested. However, use of (8) appears on average to underpredict the measured friction velocities. That all the regression slopes approach unity when a larger range is used, is attributed in part to the somewhat coarse vertical resolution of the rawinsonde profiles. The inclusion of more wind speed measurements allows for a better realization of the mean wind speed profile in the ABL surface sublayer. That the statistical results do no differ significantly for the different ranges tested, for each of (7), (8) and (9), demonstrates that the profile analysis is robust with respect to the inner range selected. This finding is similar to what was observed in the neutral wind speed profile analysis (see Parlange and Brutsaert, 1989).

The u_* values derived by the procedure with Ψ_m functions (7), (8) and (9) are compared in Figures 2, 3 and 4, respectively, with the eddy correlation measurements denoted by u_{*s} with measurements made between 80 and 180 m above the land surface. The correlation coefficients for u_* versus u_{*s} are 0.85, 0.89 and 0.88 and the slopes of the regression line set through the origin are 0.95, 0.89 and 0.93, for functions (7), (8) and (9), respectively. The results shown in Table I demonstrate that on average there is no clear difference in the values of u_* obtained using either (7) or either of (8) or (9). None of the slopes forced through the origin are significantly different from unity at the 95% confidence level.

To test if there is any change in the results using the new stability correction functions, all the wind speed profiles were separated into two groups based on whether $-180/L$ was greater or smaller than 3; $z = 180$ m corresponds to the optimal mean upper limit of the ABL surface sublayer range. For the 62 profiles analyzed, 30 releases occurred when $-180/L$ was smaller than 3 and the remaining 32 releases took place when $-180/L$ was greater than 3. This demonstrates that in the calculation of regional-scale surface fluxes with measurements at around

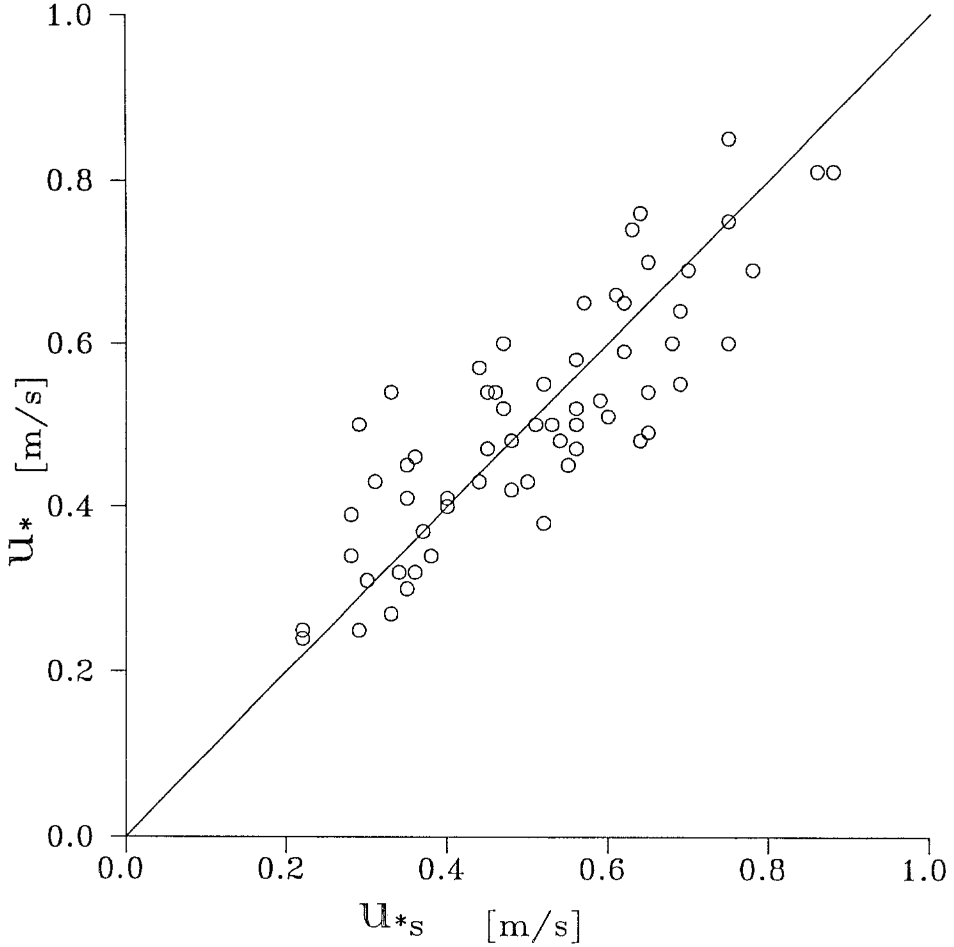

Fig. 2. Comparison between the u_* values derived from wind profiles (80–180 m) analyzed in the context of Monin–Obukhov similarity with the BD stability correction function (7), and the u_{*s} values measured some 4.5 km away by means of the eddy correlation method 9 m above the tree tops. The correlation coefficient is $R = 0.85$.

100 to 200 m, large values of $(-y)$ are not unusual and it is important to know the stability correction function for such values of y. The regression analysis presented above for all 62 profiles was repeated for the two groups of 30 and 32 profiles. The regression results are presented in Table II. It can be seen that all the correlation coefficients are similar for the three different stability correction functions (95% level of significance). In addition, none of the slopes of the regression lines forced through the origin is significantly different from 1.0. Nevertheless, it is clear in the u_* comparison for $-180/L < 3$ that the slopes through the origin using functions (7) or (9) are closer to 1.0 than the regression slope

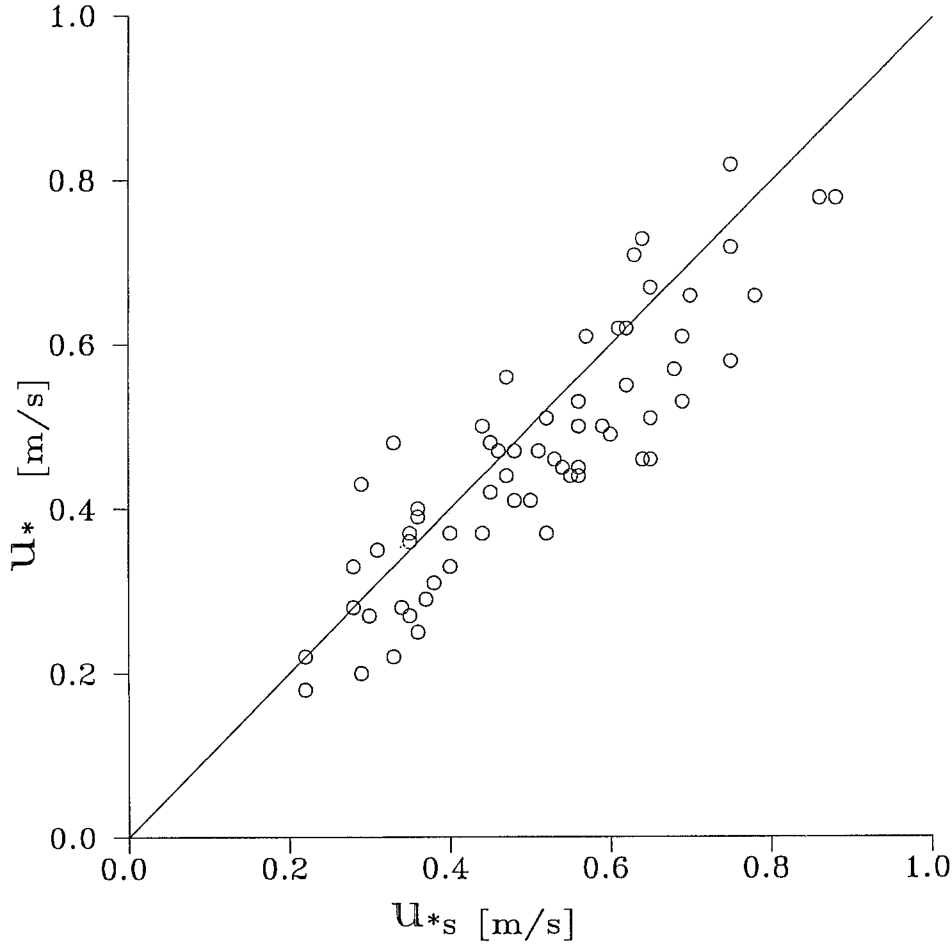

Fig. 3. Same as Figure 2 but with the stability correction function (8). The correlation coefficient is $R = 0.89$.

TABLE II

Overall regression results for $-180/L < 3$ ($N = 30$) and $-180/L > 3$ ($N = 32$), using profile height range 80–180 m to calculate u_*. $u_* = Au_{*s} + B$; $u_* = Cu_{*s}$ (units of B are m s^{-1})

Stabililty function	$-180/L < 3$				$-180/L > 3$			
	A	B	R	C	A	B	R	C
(7)	0.90	0.0074	0.74	0.91	0.90	0.064	0.77	1.06
(8)	0.92	−0.028	0.77	0.88	0.91	0.0047	0.79	0.92
(9)	0.90	0.0054	0.74	0.91	0.95	0.015	0.79	0.99

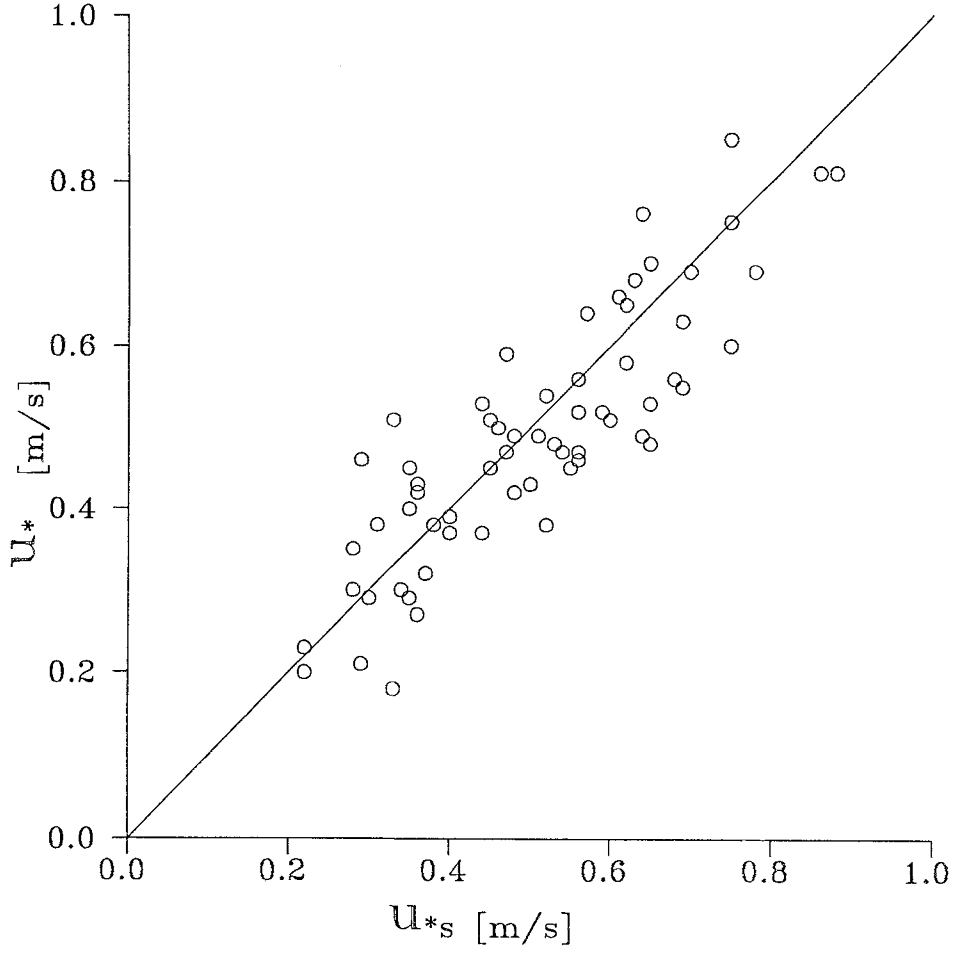

Fig. 4. Same as Figure 2 but with the stability correction function (9). The correlation coefficient is $R = 0.88$.

using (8), which is based on the Kader–Yaglom data set. On the other hand, for $-180/L > 3$, the u_* values obtained using (9) are closer to unity than those using (7) and (8). Hence, the present results show that on average, (9) represents a small but useful improvement, combining advantages of both (7) and (8) for situations where y may vary over a broad range.

3.3. Drag Coefficient (100 m)

In many applied situations, a useful stress estimate can be obtained by means of a simple drag coefficient. This is defined by

$$Cd_r = \frac{u_*^2}{V_r^2} \tag{11}$$

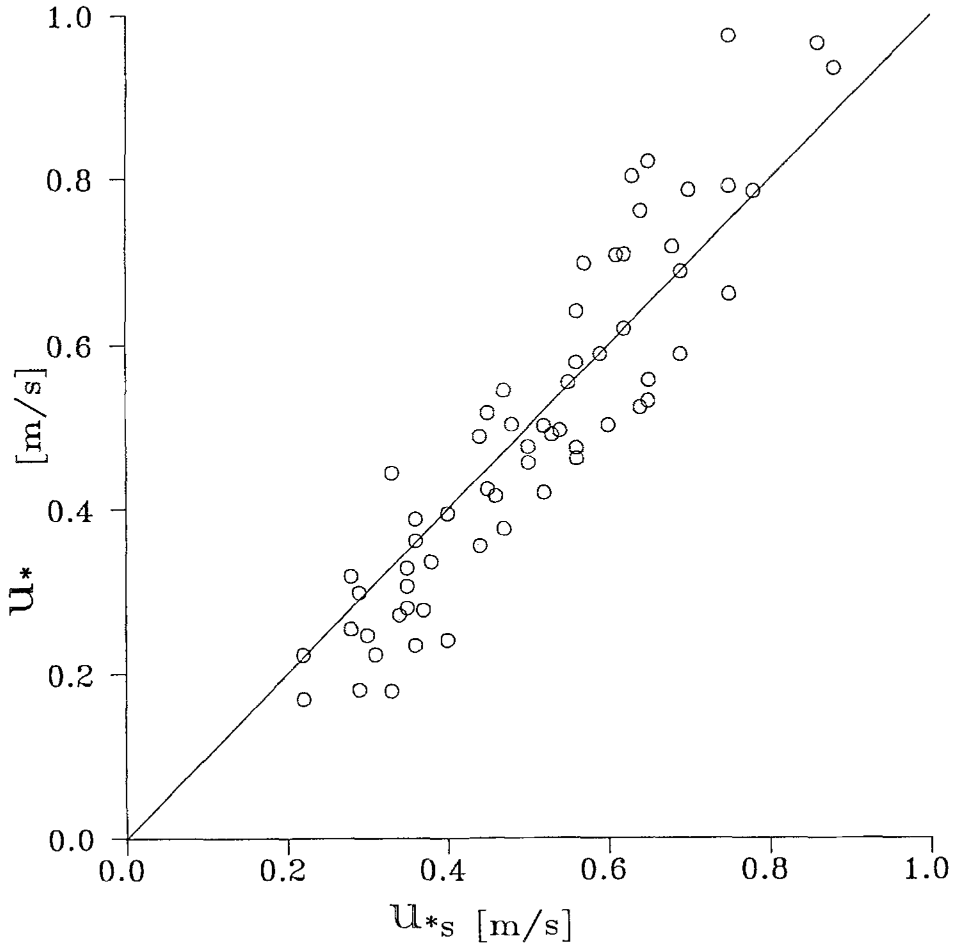

Fig. 5. Comparison between the u_* values derived from the 100 m wind speed by means of the unstable drag coefficient Cd_{100} versus the u_{*s} values. The correlation coefficient is $R = 0.92$.

in which the subscript r indicates the reference height $(z_r - d_0)$ at which V_r is measured; for simplicity, this reference height was taken as 100 m. To determine Cd_{100}, for each profile the wind speed at $(z - d_0) = 100$ m was obtained from the regression by means of (5) with (9) through the wind profile measurements (80–180 m) used in the analysis in Section 3.2. The value of Cd_{100} was determined by increasing Cd_{100} step-wise until the slope of the regression through the origin of u_{*s} versus u_* calculated with (11) became unity. The result of this exercise was $Cd_{100} = 0.0173$. The comparison plot of u_* versus u_{*s} from (11) is given in Figure 5. The coefficient of correlation is $R = 0.92$. The least-square linear regression that was obtained, $u_* = 1.18u_{*s} - 0.1$, is comparable to the results obtained using (5) and any of (7), (8) or (9).

4. Conclusions

The calculation of shear stress for complex or heterogeneous surfaces over length scales of tens of kilometers has particular significance for the linkage of land surface and atmospheric processes. Parameterizations of land-atmosphere interactions based upon surface-layer similarity typically require knowledge of the shear stress. This study of surface layer wind profiles measured with radiosondes demonstrates the value of Monin-Obukhov similarity analysis to obtain regional shear stress under unstable conditions. An advantage of Monin–Obukhov formulations, to describe wind speed measurements, is the general robustness of the approach. Once the inner-region range and the regional scale surface roughness (and displacement height) are established, all the wind profiles could be analyzed. All three stability correction functions tested produced about the same optimal ranges for the inner region, namely, $60 \leqslant (z - d_0)/z_0 \leqslant 145$. The Monin–Obukhov model implemented with the stability function based in accordance with (9) agreed slightly better with eddy correlation measurements on average, than when implemented with (7) or (8). More experiments over different land surfaces need to be carried out to test the reliability of (9). The 100 m unstable drag coefficient over this forested region was $Cd_{100} = 0.0173$.

The measurements used in the analysis were taken at heights between 80 to 180 m above the ground. At those elevations, the atmospheric turbulence is the result of surface conditions over upwind distances of the order of 10^4 m and perhaps more. Therefore, the surface shear stress values obtained in the analysis can be considered to be regional values at the same scale.

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