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The relative merits of surface layer and bulk similarity formulations for surface shear stress

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Abstract. Application of the bulk similarity formulation to the atmospheric boundary layer (ABL) requires the adoption of an external wind velocity and temperature scale. Recent versions of this approach have made use of the average wind speed and average temperature over the outer region or mixed layer of the ABL. The method is applied herein with wind profile data measured over the Landes forest in southwestern France to estimate the regional surface shear stress under unstable conditions. It is found that these estimates can be as reliable as those obtainable with Monin-Obukhov similarity of the atmospheric surface layer.

1. Introduction

Monin-Obukhov similarity theory, applied in the inner region of the atmospheric boundary layer (ABL), i.e., the atmospheric surface layer (ASL), has proven to be a reliable way to obtain regional scale fluxes over rugged terrain. For instance, the mean wind speed profile $V = V(z)$ in the ASL can be described by the well-known Monin-Obukhov model

$$V = \frac{u_*}{k}\left[\ln\left(\frac{z-d_0}{z_0}\right) - \Psi_m\left(\frac{z-d_0}{L}\right)\right] \tag{1}$$

where $u_*(=(\tau/\rho)^{1/2})$ is the friction velocity, τ is the surface shear stress, ρ is the density of the air, $k(=0.4)$ is von Kármán's constant, z is the height above the land surface, z_0 is the surface roughness length, d_0 is the momentum displacement length, Ψ_m is the stability correction function which depends on $(z - d_0)/L$, and

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

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 is the specific flux of sensible heat, E is the evaporation rate, g is the acceleration of gravity, ρ is the density of the air, c_p is the specific heat at constant pressure, and T_a is the air temperature near the ground. In the ABL the characteristic horizontal length scales tend to be 10 to 100 times larger than the vertical scales. Therefore application of (1) with ASL wind speed measurements at heights around 100 m above the surface may produce u_* values that are representative for upwind distances (or surface length scales) of the order of 1 to 10 km. By the same token, formulations that make use of V measurements at higher elevations, namely, in the outer region of the ABL, may be capable of producing u_* values that are representative over even larger upwind fetches. At present, the ABL bulk similarity approach is the main practical formulation available for relating surface fluxes with outer layer profile measurements; however, this approach is still less known than (1), and its reliability has not been tested very widely. A recent version of the bulk similarity approach for the wind speed, which is an extension of (1) for larger z, is

$$V_a = \frac{u_*}{k}\left[\ln\left(\frac{h_i-d_0}{z_0}\right) - B_w\left(\frac{h_i-d_0}{L}\right)\right] \tag{3}$$

where V_a is the average wind speed in the outer region of the ABL (the mixed layer under unstable conditions) and $z = h_i$ is the height of this layer. This version with the average wind speed treated as a scalar and with a simple correction function B_w for stability was presented by *Brutsaert and Sugita* [1991]. The dependence of B_w on $(h_i - d)/L$ has been considered most recently by *Sugita and Brutsaert* [1992]; the u_* values needed in this inverse problem were obtained by application of (1) with ASL profile data.

In this paper the performance of (3) is compared with that of (1) using ABL wind speed measurements obtained during the Hydrologic Atmospheric Pilot Experiment–Modélisation du Bilan Hydrique (HAPEX-MOBILHY) field campaign over the Landes forest in southwestern France. One advantage of this data set for studying the relative performance of (1) and (3) to estimate u_* is the availability of independent eddy correlation measurements of the surface shear stress u_{*ec} $(=(-\langle u'w'\rangle)^{1/2})$. These near-surface measurements have been found to be representative for the Landes Forest region in several previous studies [e.g., *Parlange and Brutsaert*, 1989, 1990; *Brutsaert et al.*, 1989; *Brutsaert and Parlange*, 1992]. *Parlange and Brutsaert* [1993] compared friction velocity values (u_{*sl}) obtained with (1), using wind profile data in the ASL (80–180 m), with the u_{*ec} measurements. Herein, the test of the relative merits of (1) and (3) is carried out by comparing u_* estimates from (3) in which B_w is based on suggestions of *Sugita and Brutsaert* [1992] with the u_{*ec} measurements and by contrasting these results with the comparison between the u_{*sl} values and the u_{*ec} measurements.

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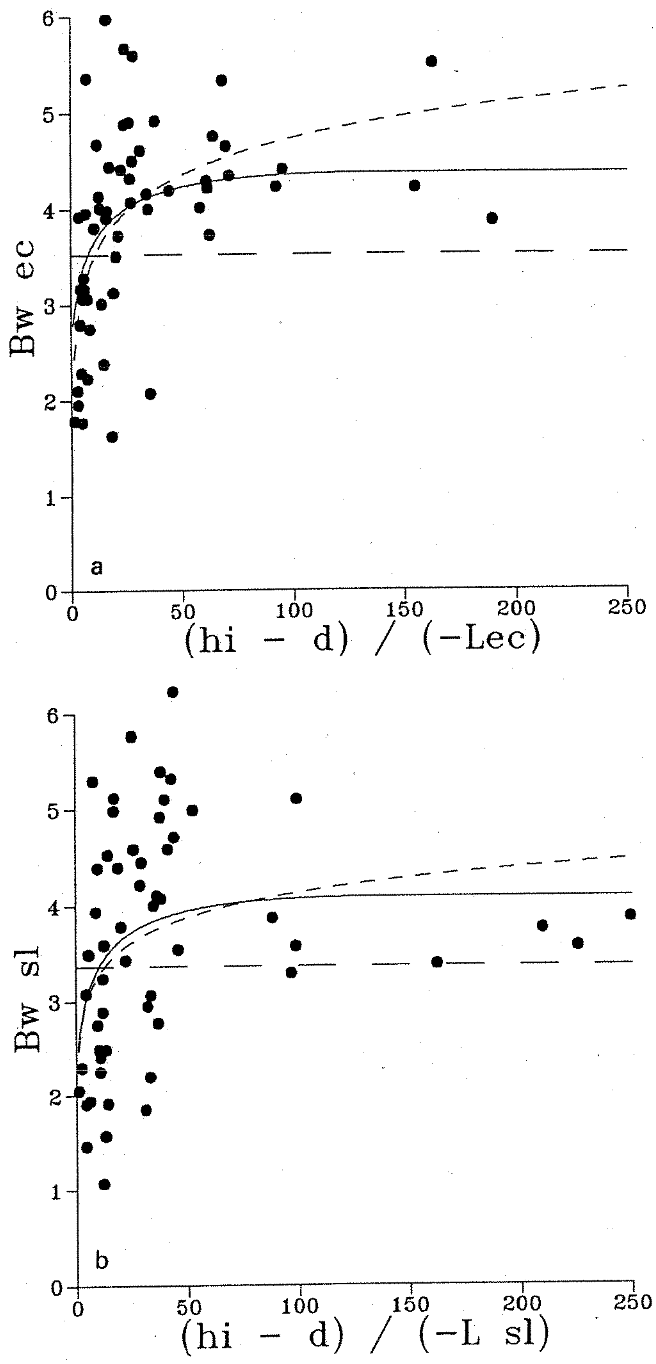

Figure 1. The values of the bulk stability correction function B_w (a) derived from eddy correlation measured surface fluxes and fitted functions (see Table 1) and (b) derived from surface fluxes obtained with ASL profiles. B_w = const, long-dashed line; (7), short-dashed line; (8), solid line.

2. Experiment

The topography of the Landes pine forest region in southwestern France is flat, with typical gradients smaller than 3 m/km. Even though the Landes forest is set in flat terrain, the surface physical characteristics are complex owing to the irregular break up of the pine tree stands by agricultural and logging operations. The agricultural sections, which typically range from 1 km to 10 km on a side, are predominantly planted with grain crops or left fallow. Because of year-round logging operations there are also clear-cut sites and other clearings recently planted with pine tree seedlings. The Landes forest area is operated under a system of tree harvesting and replanting so that the tree heights vary from 1 m to 20 m. The more mature sections have a thick undergrowth of bracken fern. The stands of trees (patched together at varying heights) may extend up to 20 km in one direction uninterrupted by agricultural clearings or small villages. Further details of the HAPEX-MOBILHY experiment and the Landes forest field site have been presented by *André et al.* [1986, 1988].

The wind speed profiles analyzed in this study were obtained by means of radiosondes released during the special observing field campaign from early May through mid-July 1986. The radiosondes were tracked with a small radar system, from which position coordinates of the balloon ascent could be obtained up to 100 hPa to derive the wind speed profiles. The surface roughness characteristics of the Landes forest region were obtained by *Parlange and Brutsaert* [1989] through an analysis of those radiosonde wind speed profiles in the ASL measured under neutral stability conditions. The roughness lengths were found to be z_0 = 1.2 m and d_0 = 6.0 m. Eddy correlation flux measurements of u_{*ec}, E_{ec}, and H_{ec} were obtained at a 29-m tower operated by a team from the Institute of Hydrology, Wallingford, England. As was already mentioned, these eddy correlation surface flux measurements may be considered to be representative of the Landes forest surface heat and momentum transfer. This assessment is based on the good agreement between the eddy correlation measurements and the surface fluxes estimated from Monin-Obukhov analysis of the ABL surface layer radiosonde measurements of specific humidity q, potential temperature θ [*Brutsaert and Parlange*, 1992], and wind speed V [*Parlange and Brutsaert*, 1993] under unstable stability. As further support of the eddy correlation measurements, a study was carried out using sodar-derived surface layer V measurements under near-neutral conditions to obtain u_*. The sodar-derived u_* values agreed well with both the eddy correlation (u_{*ec}) and radiosonde derived (u_{*sl}) values, and the same surface roughness characteristics (i.e., z_0 = 1.2 m and d_0 = 6.0 m) were obtained from the sodar wind speed profiles [*Parlange and Brutsaert*, 1990].

The 58 wind speed profiles analyzed here are taken from the set studied by *Parlange and Brutsaert* [1993]. Four soundings of the 62 previously analyzed in the surface layer are not included because their wind speed measurements were unreliable in the outer region owing to tracking problems of the radiosonde by the radar system. The height of the capping inversion h_i of the ABL (top of the outer region) for each individual sounding was identified from the potential temperature profile [*Brutsaert and Parlange*, 1992]. The mean wind speed V_a for each profile was simply obtained as the average of all the outer region wind speed measurements (i.e., without height interpolation scaling).

3. Analysis

3.1. The Bulk Stability Correction Function B_w

In this section, two separate sets of B_w versus $(h_i - d)/L$ formulations are calculated based upon (1) the eddy correlation measurements u_{*ec} and L_{ec} and (2) the ABL surface layer (ASL) profile-derived values u_{*sl} and L_{sl}. The subscripts ec and sl refer to the eddy correlation and the ASL profile-derived fluxes, respectively, used in the calculation of L. The integrated form of the Monin-Obukhov stability correction function applied to the ASL scalar profiles (θ and q) to obtain

H_{sl} and E_{sl} [*Brutsaert and Parlange*, 1992] was the usual Businger-Dyer equation

$$\Psi_c = 2 \ln [(1 + u^2)/2] \tag{4}$$

where the subscript c can represent either h for heat or v water vapor and

$$u = [1 - 16(z - d_0)/L]^{1/4} \tag{5}$$

The integrated form of the momentum stability correction Ψ_m to obtain u_{*sl} was taken as

$$\Psi_m(y) = 0 \qquad \text{for} \quad y > -0.00059 \tag{6a}$$

$$\Psi_m(y) = 1.47 \ln \left[\frac{0.28 + x^{0.75}}{0.28 + (0.0059 + x_0)^{0.75}} \right] - 1.29[x^{1/3} - (0.0059 + x_0)^{1/3}] \tag{6b}$$

$$\text{for} \quad -0.0059 \geq y \geq -15.025$$

$$\Psi_m(y) = \Psi_m(-15.025) \qquad \text{for} \quad y < -15.025 \tag{6c}$$

where $y = [(z - d_0)/L]$, $x = -y$, and $x_0 = -z_0/L$. Equations (6) were proposed by *Brutsaert* [1992] on the basis of the work of *Kader and Yaglom* [1990] and were found to be an improvement over the Businger-Dyer formulation of Ψ_m for x values greater than 3.0 [*Parlange and Brutsaert*, 1993; *Parlange and Katul*, 1995].

In Figure 1a the B_w values obtained using the eddy correlation surface flux measurements (B_{wec}) are plotted versus $(h_i - d)/L_{ec}$. A similar plot is shown in Figure 1b where the ASL derived heat and momentum fluxes were used to obtain B_{wsl} and $(h_i - d)/L_{sl}$.

Straightforward theoretical considerations [*Brutsaert and Sugita*, 1991] suggest that B_w should be taken as a function of stability. Two such formulations of B_w studied here, which depend on the dimensionless parameter $(h_i - d_0)/L$ are

$$B_w = a \ln [-(h_i - d_0)/L] + b \tag{7}$$

$$B_w = \Psi_m\left(\frac{cz_0}{L}\right) + \ln\left(\frac{h_i - d_0}{z_0}\right) - d \tag{8}$$

where a, b, c, and d are constants. The B_w function (7) is similar to earlier functions suggested by *Wyngaard et al.* [1974]. The function (8) was derived by *Sugita and Brutsaert* [1992] for a simple ABL in which the interface height between the ASL and the mixed layer can be scaled with surface roughness. With the FIFE data the values of the constants were found to be a = 0.500, b = 1.72, c = 69 and d = 4.79. The value c = 69 is based on the log-mean height of the ASL observed in the First ISLCSP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) [*Sugita and Brutsaert*, 1992]. With the same procedure for the heights observed over the Landes region for the present analysis this parameter was determined to be c = 93 [*Parlange and Brutsaert*, 1993]. In (8), (6) can be used to define Ψ_m. Note that upon substitution of (8) into (3), the explicit dependence upon the inversion height is removed, and the influence of the outer region is concentrated in the constant d.

Table 1. Best Fit Parameters for the Three Formulations of B_w Tested in This Study Applying Eddy Correlation Measured Fluxes and ABL Surface Layer Derived Fluxes

Formulation	Eddy Correlation	Surface Layer Profiles
B_w = const	3.523	3.362
(7)	a = 0.547; b = 2.215	a = 0.374; b = 2.408
(8)	d = 4.203 (for c = 93)	d = 4.490 (for c = 93)

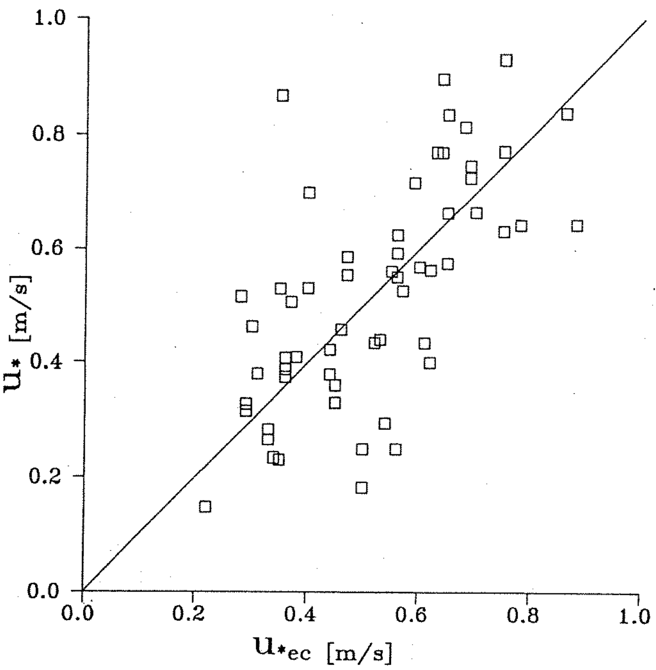

Figure 2. Comparison between the u_* values derived from V_a analyzed in the context of the bulk ABL similarity with the stability correction function (7), where a = 0.547 and b = 2.215, and the u_{*ec} values measured some 4.5 km away by means of the eddy correlation method 9 m above the tree tops. The correlation coefficient is 0.65.

In both Figure 1a and Figure 1b the plots of B_w versus $(h_i - d)/L$ display some scatter, and it could be argued that B_w demonstrates only a weak dependency upon $(h_i - d)/L$ and hence could be ignored in practice. Accordingly, a constant value of B_w will also be considered. An estimate of the constant B_w was made through an iterative solution designed such that the slope of the forced regression of u_{*s} (s represents ec or sl) versus u_* from (3) was equal to 1.0. In Table 1 the different fits of B_w versus $(h_i - d)/L$ based upon the data plotted in Figures 1a and 1b are summarized. The B_w functions using the two different sets of u_{*s} values are similar. The three B_w functions, namely $\langle B_w \rangle$ = const and equations (7) and (8), are compared in Figures 1a and 1b.

3.2. Flux Comparisons

Figures 2, 3, and 4 compare the bulk ABL predictions of u_* with measurements from the eddy correlation system. In Figures 2 and 3 the predictions are based on B_w values from (7) and (8), respectively, while in Figure 4 the predictions are based on the use of a constant B_w. These results are presented here as the test of relative merit of the u_* values derived using (3), versus those u_* values obtained with (1), compared to the u_{*ec} values. The results obtained with the Monin-Obukhov surface layer similarity model, (1) with (5), are presented in detail by *Parlange and Brutsaert* [1993].

The bulk ABL based estimates of u_* in Figure 2 were cal-

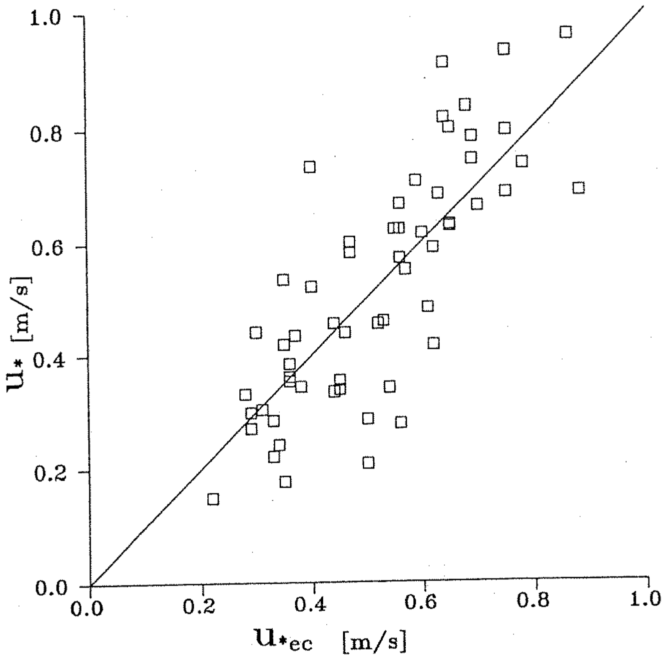

Figure 3. Same as Figure 2 but with the stability correction function (8), where $c = 93$ and $d = 4.203$. The correlation coefficient is 0.79.

culated with (3) using (7) in the form $B_w = 0.547 \ln [(h_i - d)/L] + 2.215$. The correlation coefficient for the predictions against the measurements is $r = 0.65$ and linear regression yields $u_* = 0.81u_{*ec} + 0.11$; the slope of the regression line forced through the origin is 0.99. The u_* data in Figure 2 appear on average to be closely scattered about the one to one line with minimal bias. However, the best overall agreement between the u_* data determined with the bulk ABL wind profile model and the eddy correlation measurements u_{*ec} can be seen in Figure 3, where the predictions are from (3) using (8) in the form $B_w = \psi_m(93z_0/L) + \ln [(h_i - d)/z_0] - 4.203$. Linear regression of the data shown in Figure 3 produces $u_* = 1.038u_{*ec} - 0.018$ with $r = 0.79$. Regression forced through a zero intercept has a slope of 1.01. *Parlange and Brutsaert* [1993] found the quality of the u_* estimates obtained from Monin-Obukhov similarity theory analysis of the ASL wind speed measurements, in comparison with u_{*ec}, to be similar with a regression model of $u_* = 0.83u_{*ec} + 0.053$ and $r = 0.88$. The regression slope of the model forced through the origin was 0.93 [*Parlange and Brutsaert*, 1993]. We note that the bulk ABL model performance depicted in Figure 3 compares quite favorably with those derived from surface layer similarity [*Parlange and Brutsaert*, 1993]. This result supports the use of bulk ABL modeling for the estimation of surface fluxes over larger regions, where ASL formulations do not necessarily apply. In fact, the correlation coefficient $r = 0.79$ (Figure 3) is typical of those found in regional-scale land-atmosphere studies. The results might be expected since the bulk transfer law is an extension of surface layer similarity into the mixed layer.

The comparison of u_* values obtained with (3) with the constant correction $\langle B_w \rangle = 3.523$ versus u_{*ec} measurements is presented in Figure 4. A marked bias is evident in this figure. The linear regression fit from Figure 4 is $u_* = 1.28u_{*ec} - 0.16$ with a correlation coefficient $r = 0.74$. In particular, the lower (<0.6 m/s) u_* values are underestimated. This is not surprising since the actual B_w values tended to be greater than $\langle B_w \rangle = 3.523$ for large $(h_i - d)/L$ (see Figure 1), which corresponds to small u_* estimates.

Finally, as an additional check on the universality of the similarity function and their sensitivity to the values of the constants, the constants given by *Sugita and Brutsaert* [1992] were also tested with the present data. It should be recalled that these constants ($a = 0.5$, $b = 1.72$, $c = 69$, $d = 4.79$) were obtained over tall-grass prairie terrain in the Flint Hills in northeastern Kansas. Linear regression of the present data with B_w given by (7), $a = 0.5$, and $b = 1.72$ yields $u_* = 0.79u_{ec} + 0.02$ with $r = 0.73$. Similarly, regression with B_w given by (8), $c = 69$, and $d = 4.79$ yields $u_* = 0.99u_{*ec} - 0.0135$ with $r = 0.79$. The friction velocity estimates using the coefficients of Sugita and Brutsaert, in particular for B_w given by (8), are similar to those obtained using the coefficients fitted to the data from the present paper in Figure 1a.

4. Conclusions

The simple bulk ABL formulation (3), with the stability correction function B_w defined by (8), performed nearly as well as the Monin-Obukhov surface layer similarity model for the determination of u_*. This result is certainly encouraging for the further application of this bulk ABL approach for estimating surface fluxes over regions larger than those represented by surface layer formulations using Monin-Obukhov surface layer similarity. Note that the bulk transfer equation is an extension of surface layer similarity into the mixed layer. The coefficient values used to define B_w for the ABL over the Landes forest in the present study produce u_* values very similar to those obtainable with the coefficients given by *Sugita and Brutsaert* [1992] for the considerably different prairie terrain of the Flint Hills in northeastern Kansas. However, additional field tests to check and strengthen the general validity of the formulation of B_w, and the values of the constants, are desirable.

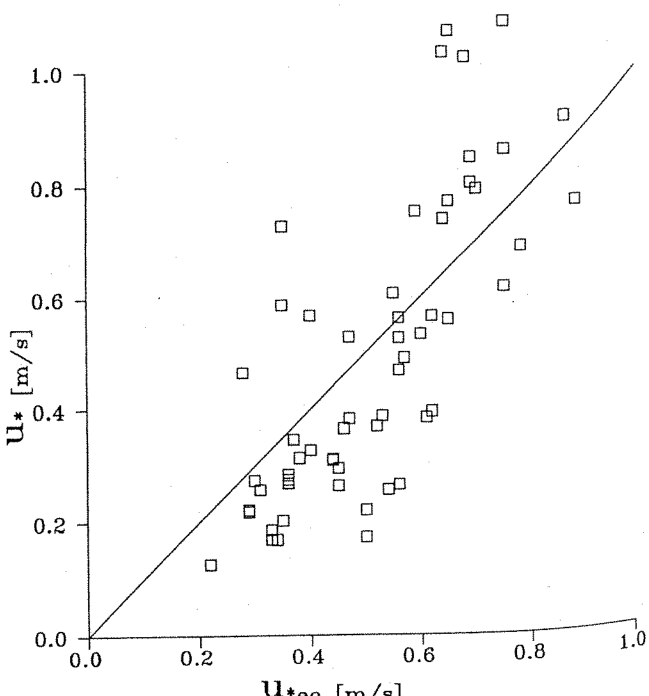

Figure 4. Same as Figure 2 but with the stability correction function $B_w = 3.523$. The correlation coefficient is 0.74.

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