DETERMINATION OF THE ZERO PLANE DISPLACEMENT IN AN URBAN ENVIRONMENT

(Research Note)

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Abstract. A method to estimate the zero plane displacement is presented that is based on *in situ* turbulence measurements. As it does not depend on flux-gradient relations, it can be applied over non-homogeneous surfaces if they are dynamically but not thermally distorted. The zero plane displacement at an urban site is found to vary considerably with wind direction. The results compare well with estimates from conventional methods using the heights and distribution of the upwind roughness elements.

1. Introduction

The surface layer over a very rough surface has to be considered in two parts: a roughness sublayer (RS), where flow and the turbulence field are distorted by individual roughness elements and, higher up, an inertial sublayer (IS), where equilibrium theories may be expected to hold (e.g., Rotach, 1993). In the present study, the problem of estimating the zero plane displacement from measurements that are taken within the RS is addressed. Interpreting the zero plane displacement d as the level of mean momentum absorption (Thom, 1971), i.e., looking at d in terms of the flux-gradient relation for momentum, will not necessarily be possible in such an environment. On the other hand, it is clear that in complex terrain (e.g., in an urban RS) some 'zero plane' or reference level is required, since the height above the surface remains an important variable for the RS flow. For convenience, we shall also call the reference level in the urban RS the zero plane displacement.

Since it is common in surface-layer meteorology to describe fluxes in terms of profiles of mean quantities, the zero plane displacement is often determined from the mean wind profile. The measurements at different levels are forced to the inertial sublayer prediction by applying a minimizing procedure and thereby using a set of estimates for u_*, z_o and d. Thus this method is only useful if measurements from the IS are available. For the present purpose, a new method has been developed that is based on measurements of the scaled temperature variance and is thus called Temperature-Variance-Method (TVM).

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2. The Temperature Variance Method

The general idea of the method is that for certain types of dynamically rough surfaces (de Bruin *et al.*, 1988), the temperature variance distribution is affected very little and is well described by its ideal-site formulation. The height dependence of σ_Θ/Θ_* through its variation with stability z'/L, where $z' = z - d$, can therefore be used to determine the height above the reference level that the temperature variance field 'sees' in different directions. Under the assumption that this reference level is equal for other properties of the flow, such as momentum and water vapour, the height of this reference level can be identified with the zero plane displacement (as it will be termed in the following).

Clarke *et al.* (1982) and Roth (1991) show that the functional dependence of σ_Θ/Θ_* on stability in an urban or suburban area is in good agreement with the 'ideal' formulation from the Kansas data (Wyngaard *et al.*, 1971; Tillman, 1972). Similarly, de Bruin *et al.* (1988) find the Kansas formulation to be a valid representation of their data in the case of a modestly rough terrain (Cabau region, The Netherlands) without distinct temperature inhomogeneities. These results show that under certain conditions (see below), the surface of an urban area can be considered 'thermally homogeneous' even if it is dynamically very rough. Using the results of Schmid (1988) one can put this in a more precise way: for a suburban area in Vancouver, BC (Canada), a spectral analysis of the surface temperature showed that the dominant wavelengths of the spatial temperature variance spectrum correspond roughly to the distribution of roughness features (such as street width, block size, etc.). If the source area (Schmid and Oke, 1990) of a temperature measurement is much larger in diameter than the dominant wave length of the surface temperature distribution (or more generally: spatial features), the thermal regime can be considered 'homogeneous'. In this case, the height dependence of σ_Θ/Θ_* through its variation with the stability z'/L can be used to derive a value for the zero plane displacement d.

Similarity theory predicts for σ_Θ/Θ_* in the unstable SL (or better inertial sublayer) a $-1/3$ dependence on z/L only. This prediction has been experimentally verified, e.g., by Tillman (1972), who suggests

$$\frac{\sigma_\Theta}{\Theta_*} = -C_1\left(C_2 - \frac{z}{L}\right)^{-1/3} .$$

For the parameter C_1 a value of 0.95 (after Wyngaard *et al.*, 1971) is suggested and C_2 is determined by the neutral limit ($=C_3$) of the function. Tillman (1972) finds a value 'larger than 2.5' for C_3, while Beljaars *et al.*(1983) suggest a value of 3.5, and data from de Bruin *et al.* (1988) indicate $C_3 \approx 3$.

If instead of the height z in Equation (1), the modified height z' is introduced, it is possible to vary d in order to find the closest correspondence to Equation (1). For each estimate of d, the root-mean-square (rms) difference between predicted (Equation (1)) and observed values of σ_Θ/Θ_* for the ensemble of all available runs can be computed. The zero plane displacement can then be identified as the value for d, at which the function rms(d) exhibits its minimum.

For near-neutral stability, two problems arise. First, the measurements become quite inaccurate. This is due to the very small energy fluxes in general, and due to the correction procedure that has to be applied to the temperature data because of water vapour effects. According to Schotanus *et al.* (1983), these corrections (especially for σ_Θ) become doubtful in the near neutral limit. Second, the available data on urban σ_Θ/Θ_* in the literature show a wide spread in the neutral limit while following closely the relation (1) in the unstable regime (Clarke et al., 1982; Roth, 1991). This might be due to the uncertainty in the measurements mentioned above, but could also be a characteristic of an urban environment. Near-neutral measurements are therefore to be excluded from the analysis. As the height dependence of σ_Θ/Θ_* enters through the stability measure z'/L, care must be taken when selecting the data for analysis. In order to find the minimum of the function rms(d), the number of runs contributing to an estimate of d should be the same so that the rms differences become comparable with each other. Thus it is important to vary d from the largest possible value (most 'neutral' case, since $z'/L = (z - d)/L$) towards smaller ones, and to exclude those measurements from further analysis that fall into the 'neutral range' for the largest d.

For the present purpose, σ_Θ/Θ_* was calculated using data from a study conducted in the city of Zürich (Switzerland). Turbulence measurements were taken 5 and 10 m above the local roof level (18.3 m), i.e., fully within the roughness sublayer. Details on the site and the environment can be found in Rotach (1993). An averaging time of 15 minutes was used in order to maximize the number of data points. Considering the nature of turbulence over this very rough surface, this is very short. However, the effect of the short averaging time on the σ_Θ/Θ_* data was found to be small when compared to an averaging time of 50 min. Optimal d values were then calculated for eight wind direction sectors of 45° separately. The parameters are $C_1 = 0.95$ (Wyngaard *et al.*, 1971) and $C_3 = 3.5$ (Beljaars *et al.*, 1983). The zero plane displacement was allowed to vary between 0 m and the local roof height (18 m) in discrete intervals of 0.5 m; a finer resolution does not seem appropriate. The function rms(d) exihibited a clear minimum for all wind direction sectors (Figure 1 as an example). From the resulting d values (Figure 2), it can be seen that there is a large difference between the wind direction sectors, with d ranging from 9 to 16 m. This corresponds to d/h from 0.5 to 0.88 if we take the local roof level (18.3 m) as h. For the sector 91°–135°, it was not possible to determine a value for d, since for this wind direction the sonic anemometer was situated in the lee of the tower and thus the measurements were distorted. Sectors 181°–225° and 271°–315° are calculated in fact from too few data points (7 and 9 runs, respectively). In the next section the results from the TVM are compared to estimates of the zero plane displacement from information on size and distribution of the roughness elements in the surface area influencing a measurement.

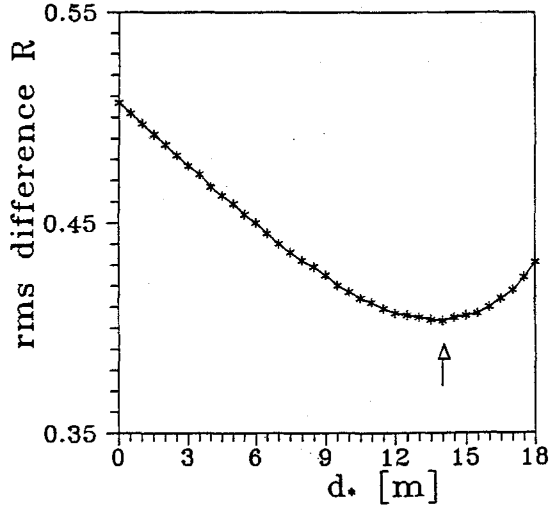

Fig. 1. Example for the variation of the root-mean-square difference (rms difference R) between predicted (Equation (1)) and measured σ_Θ/Θ_* for varying estimates of the zero plane displacement d_*. Example for the wind direction sector 0–45°.

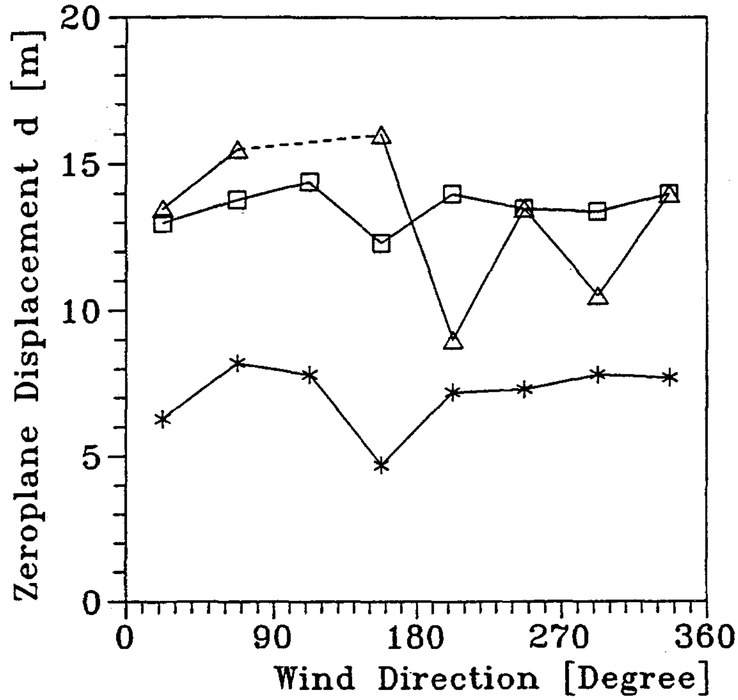

Fig. 2 Comparison of the zero plane displacements d_i from the TVM (triangles) and the two 'geometrical' approaches after Kutzbach (1961) (squares) and Counihan (1971) (stars).

TABLE I

Land use categories and the respective heights and area fractions that were attributed to them. The notation h_b and A_b indicates values that are available directly from the land use inventory.

Land use category	Average height	Fraction covered by roughness elements
Buildings	h_b	A_b
Gardens, courts	2 m	0.1
Streets, corners	2 m	0.1
Playgrounds, parks and sport areas	7 m	0.3
Agricultural ground and grass land	2 m	0.2
Forest	15 m	~ 1
Railway area	2 m	0.2
Miscellaneous	2 m	0.2
Open water	0 m	0

3. Land Use and Zero Plane Displacement

The zero plane displacement can be determined using empirical relations between d/h (h being the average roughness element height in the fetch) and A_r/A, the fraction ot the total fetch or source area A that is covered by roughness elements. Thus the method requires the source area, the average height of roughness elements and the fraction of area they occupy, to be specified. For comparison with the results from the TVM, the same data set was used. For each run (i.e., 15 min averaging period), the area influencing the observation (source area) was calculated using the so-called mini-SAM (a statistical version of the source area model, SAM, as described by Schmid and Oke, 1990). As an estimate of the total area of influence, the dimensions of the '90%-effect level' were calculated. For the average building height within the source area, the contributions from the various effect levels were weighed with the figures given in Schmid and Oke (1990), where details on the model and terminology can also be found.

The average height of roughness elements, and the area fraction covered with them within the source area, were then determined using a land use inventory for the city of Zürich with a resolution of 100 × 100 m. The data available for each square were the number of buildings, their average height, the fraction of built-up area and, if no buildings were present, a code for a land use category. For the area not covered with buildings, characteristic average heights and area fractions A_r were attributed to each land use category (Table I). If there are buildings on the square considered, i.e., if the land use category is 'built up area', it is assumed (from visual inspection) that half of the area not covered by buildings is covered by trees of mean height $h_t = 10$ m. The average height for that square is then calculated according to

$$\bar{h} = h_b A_b + 0.5 h_t (1 - A_b).$$

The Cartesian grid of surface data was first converted into polar coordinates for convenience. The individual estimate of d for the source area of each run was then calculated using the empirical relations $d/h = f(A_r/A)$ after Kutzbach (1961) and Counihan (1971), as given in Clarke *et al.* (1982). Finally, the zero plane displacement heights were again averaged separately for the eight wind direction sectors.

Figure 2 shows that the results from the TVM are in reasonable overall agreement with the zero plane displacements d_i (for the eight wind direction sectors) as estimated using the empirical curve of Kutzbach (1961). However, the results obtained by the TVM exhibit a larger variation from sector to sector. As the surface characteristics vary little with wind direction in the close neighbourhood of the site, this indicates that the TVM accounts for a larger upwind area than does the chosen procedure for the determination of A_r/A. On the other hand, the parameterization after Counihan (1971) yields d_i values that are much smaller (usually about half as large) than those from the other two methods and would correspond to d/h ranging from 0.26 to 0.44. It is, therefore, concluded that both the TVM and the empirical method after Kutzbach (1961) yield reasonable results for the wind direction dependent zero plane displacement at the present urban site, while the results after Counihan (1971) seem to be rather too small.

4. Conclusions

A method (Temperature Variance Method) to estimate the zero plane displacement is presented that is applicable in the non-homogeneous part of the surface layer (roughness sublayer) over rough (but thermally homogeneous) surfaces. The results compare reasonably well with estimates from an approach using size and distribution of the roughness elements in the upwind source area. As the TVM is based entirely on *in situ* measurements, it might be advantageous if no surface inventory is available.

Acknowledgements

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