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WIND PROFILES IN AN URBAN AREA

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Abstract: Wind speed profiles measuredduring one year by means of a SODAR-RASS system located within a large park were examined for the Urban Boundary Layer (UBL) over Rome, Italy. These data, combined with ultrasonic anemometer and temperature measurement performed near the ground were used to analyze the vertical structure of the boundary layer. About 52000 vertical profiles of wind speed and temperature were used for the analysis, allowing investigation for a large variety of stability conditions. The applicability of the Monin-Obukhov (MO) similarity theory – developed over rural terrain – was tested up to 200 m above ground level. The results show a gradual, continuous worsening with height of the MO similarity performance for all stability conditions, reaching maximum errors of the order of 300% at 200 m.

Key words: *SODAR-RASS, Urban environment, Vertical profile, Similarity theory.*

INTRODUCTION

Knowledge of the vertical profiles of wind speed and temperature is in use in studying the atmospheric boundary layer and related dispersive phenomena. The measurement of vertical profiles, however, involves a series of complications and costs that makes it still a little-used procedure. Therefore, of particular relevance is the definition of simple and efficient similarity laws, making it possible to obtain theoretical vertical profiles of the main meteorological variables, starting from ground level measurements carried out using standard monitoring stations. The MO similarity theory is the most common class of similarity scaling (Nieuwstadt, F.T.M. and P.G. Duynkerke, 1996). It is usually applied in homogeneous and stationary conditions, but is sometimes used also in complex terrain and urban environment (Roth, M., 2000). The similarity theory is of great importance also in atmospheric flows modeling in that numerical codes adopt empirical formulations to relate surface fluxes of momentum and thermal energy to the nodes of the numerical grid adjoining the ground level. This issue is particularly relevant in urban sites and associated UBL (Fernando, H.J.S., 2010).Studies reported in the literature clearly show that the classical similarity theory often provides poor results when applied to the urban case.

The main objective of this work is to gain insight into the salient features of the vertical structure of the atmosphere above the urban area of Rome and to understand whether the MO similarity is adequate or not in the description of the vertical profiles of wind speed and temperature. Rome is one of the most extensive and populous city in southern Europe. It has the typical characteristics of Mediterranean cities such as moderate ventilation, high levels of pollution and the sky mostly clear.The data set used in this study consists of vertical profiles of wind speed and temperature collected from June 2005 to June 2006 by a SODAR-RASS system located within Villa Pamphili Park, in Rome.

MEASUREMENT SITE AND EXPERIMENTAL APPARATUS

The observation site is located on a grassy area within Villa Pamphili urban Park (Figure 1). This large feature, situated in the west part of the city (41° 53’ N, 12° 26’ E, 70 m above the mean sea level), interrupts built-up zones. Since the measurements are made away from buildings and trees (at a distance of at least eight times the height of the obstacles), the data can be considered as free from the immediate effects of obstacle wakes.

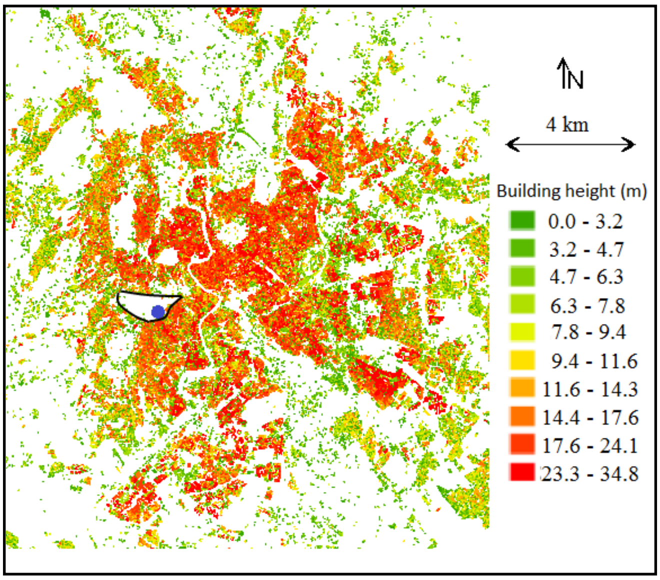

Figure 1. Rome area. Colors are building heights. The blue circle and the black line indicate the site and Villa Pamphili, respectively.

The meteorological instruments included a 10 m mast equipped with two ultrasonic anemometers (resolution ±0.1 m s^{-1}) mounted at 5.5 m and 10 m above ground level (agl) in order to measure the three velocity components u, v and w, respectively positive along east, north and the vertical, with a sampling rate of 4 Hz. In addition, two thermistors placed at 1.6 m and 10 m agl provided measurements of the air temperature T (accuracy ±0.2 K). Also, measurements of relative humidity, pressure, global solar radiation, net solar radiation, soil temperature and rain were continuously made during the campaign using a surface meteorological station. A data logger provided computation and storage of 10 min averages of the meteorological variables.In order to analyse the vertical structure of the boundary layer, a SODAR/RASS system (Metek, model DSPA90) was used to acquire the three components of the wind velocity and the virtual air temperature up to height of ~400 m. The vertical resolution is 20 m and the first range gate is centred at 40 m agl, and the system provided the vertical profiles of velocity and temperature averaged every 10 min.

Data were validated according to a number of test parameters such as signal to noise and plausibility values. Only data with passed tests were then used for further analysis. This choice is a reasonable compromise between the necessity of obtaining as many reliable profiles as possible, and to have profiles that are as much height coverage as possible. Based on the previous assumptions, nearly the 80% of the profiles were assumed valid below z=200 m agl, for a total number of nearly 52000 profiles considered for the analysis.

COMPARISON BETWEEN THEORETICAL AND OBSERVED VERTICAL PROFILES

One of the challenges in boundary layer meteorology is the assessment of accurate theoretical laws which permit the evaluation of both surface turbulent fluxes as well as vertical velocity and temperature profiles to be used in conventional mesoscale numerical models. This aspect is particularly true in urban fluid mechanics. Similarity theory provides an efficient method to determine non-dimensional parameters based on the variables of the governing differential equations of motion, and the MO similarity is the most common class of similarity scaling applied to the surface layer (Foken, T., 2006). In what follows, only a brief description of the surface layer relationships is given. More details can be found in Stull, R.B. (1988).The vertical profile of the wind speed $U = \sqrt{u^2 + v^2}$ can be obtained according to the following equation:

$$U(z)=\frac{u_*}{\kappa}\cdot\left[\ln\left(\frac{z}{z_0}\right)+\psi_m\left(\frac{z}{L}\right)\right] \tag{1}$$

where κ=0.4 is the von Karman constant,ψ_m is a universal dimensionless function depending on the atmospheric stability,$L = -u_*^3(\kappa q_0)^{-1}$ is the Obukhov length, q_0 is the surface buoyancy flux and z_0 is the roughness length. Here, the friction velocity $u_* = \left[\left(\overline{u'w'}\right)^2 + \left(\overline{v'w'}\right)^2\right]^{\frac{1}{4}}$is calculated using the ultrasonic anemometer (primes are fluctuations around the mean, the latter indicated by overbar). For the neutral case results ψ_m=0, while one possible choice for stable conditions is:

$$\psi_m = \beta_m \frac{z}{L} \tag{2}$$

while for the unstable(Paulson, C.A., 1970):

$$\psi_m = -2\ln\left(\frac{1+x}{2}\right) - \ln\left(\frac{1+x^2}{2}\right) + 2tg^{-1}(x) - \frac{\pi}{2} \tag{3}$$

where:

$$x = \left(1 - \gamma_m \frac{z}{L}\right)^{1/4} \tag{4}$$

while β_m and γ_m are empirical parameters. Businger, J.A.et al. (1971) proposed β_m=4.7 and γ_m=15.0.

In what follows, the performance of the theory will be analysed with the only condition to classify the data based on the atmospheric stability. The boundary layer will be assumed as neutral when |L|>1000 m. This condition, very stringent, reduces very much the number of neutral profiles; however, the wealth of availability of the data set allows a considerable amount of data on which to obtain meaningful statistics and to base comparisons.

RESULTS

In the urban case, the wind speed profile is no longer described by (1). In fact, even in the simplest situation of neutral boundary layer, the classical log-law:

$$U(z) = \frac{u_*}{k}\ln\left(\frac{z}{z_0}\right) \tag{5}$$

valid for flat terrain is regarded as inadequate. In that case the problem is usually overcome extending (5) by defining a suitable displacement height d_0(Panofsky, H.A. and J.A. Dutton, 1984):

$$U(z) = \frac{u_*}{k}\ln\left(\frac{z-d_0}{z_0}\right) \tag{6}$$

where U=0 at z=(z_0+d_0). A practical question to address concerns the values of z_0 and d_0 characterizing the site. From a theoretical point of view d_0 assumes the meaning of depth scale of the roughness layer, i.e. the region close to the ground where the wind speed does not follow the log-law (for a discussion on this issuesee Zilitinkevich, S.S. et al., 2008), while z_0 is the corresponding roughness height.

A question arises regarding the applicability of (6) in our case, since the meteorological site is not located above the urban canopy, but rather at a grassy meadow behind the blocks (see Figure 1). If we assume $d_0 = k_b H_b$, where H_b is the building height (12÷14 m in our case), k_b=0.7 (Zannetti, P., 1990) and z_0=0.05÷0.1 m (grassy area), equation (6) gives vertical profiles which are completely different from the measured ones (not shown). By changing d_0 and z_0 the results do not improve significantly. This suggests that our site is certainly influenced by the presence of the urban features but, at the same time, the flow pattern does not reflect the configuration of the buildings forming the lower boundary of the flow field. In other words, when the canopy becomes sparse a transition between the fully developed urban boundary layer and a wake layer exists. The characteristics of this transition are not yet well understood (Pietri, L., et al, 2009).

In this study, an alternative approach was therefore used. In particular, it was extended the range of applicability of (5) to non-flat terrain case by introducing a suitable length scale, z_e, which assumes the role of "equivalent" roughness length, viz.:

$$U(z) = \frac{u_*}{k} \ln\left(\frac{z}{z_e}\right) \tag{7}$$

Based on the available vertical profiles of the wind speed in neutral conditions in the height interval 10÷200 m, the best fit of the data to (7) is obtained with $z_e \cong 3$ m. In some ways, this is not an unexpected result in that the equivalent roughness length plays the role of both z_0 and d_0. It is important to underline that neither (5) nor (6) used by assuming canonical values of z_0 and d_0 give acceptable results. The comparison between the performances of the MO similarity theory compared with observations have been conducted by considering the height range 10÷200 m. In addition to both simulated and measured wind speed, the percentage errors calculated at each range gate, defined as:

$$Err_U(z) = \frac{U_M(z) - U_T(z)}{U_M(z)} \cdot 100 \tag{8}$$

where $U_M(z)$ and $U_T(z)$ are the measured and the theoretical wind speed at height z, respectively, will be shown. Regarding the theoretical wind speed for non-neutral conditions, equation (1) has been used by directly substituting z_e for z_0.The number of vertical profiles considered in the analysis is nearly 1400, 10000 and 8100 for the neutral, unstable and stable case, respectively. The lower number of neutral profiles is consistent with what has already been noted above with respect to the little cases classified as strictly neutral. Nevertheless, the results are indicative and generalizable.The results are presented according to atmospheric stability (Figure 2). One can readily note that: (i) the best performance is obtained in the unstable case; (ii) both in neutral and in stable cases there is a systematic overestimation of the wind velocity; (iii) in stable condition the trend of the error with altitude differs substantially from the other two in that there is a monotonic degradation in performance with height, with overestimation of 300% near the ground level up to 500÷600% at higher elevations. However, for stable atmosphere the results are completely unreliable.

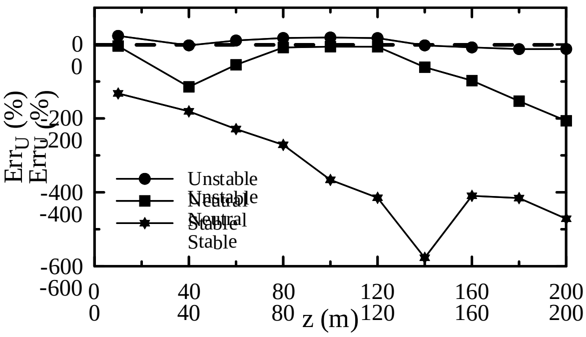

Figure 2. Vertical profile of the error (8) as a function of the boundary layer stability.

A question arises regarding the influence of the rotation of the velocity vector along the vertical. In fact, a careful inspection of the data shows a clear dependence of the results on the degree of homogeneity of the wind direction with height. To better clarify this point, in what follows the performance of the theory will be investigated by taking into consideration the wind direction. In particular, the vertical profile is discarded if the variation of wind direction in the range 10<z<200 m is greater than 22.5°, a value larger than the rotation angle commonly observed in neutral conditions (Holton, J.R., 2004). In other words, situations in which layers of different direction flow stacked one above the other are not considered in the analysis.

The first test regards the neutral case, and a total of 155 profiles (~11% of those classified as neutral without any additional restriction) satisfy the above condition. Figure 3a shows the measured (full circles) and the modeled (line with symbols) vertical profiles of the wind speed. The corresponding errors are reported in Figure3b. The comparison of the errors calculated using all data without restrictions (Figure 2) suggests that the condition of homogeneity of the wind direction along the vertical improves the results. It is also observed a clear degradation of the performance for z>60 m. It was for this reason that a second value of z_e was identified in order to improve the performance of the MO theory at higher levels. In particular, by imposing the error minimization at z=200 it was found $z_e \cong 1$ m. This fact seems to suggest that the optimum value of the roughness changes as a function of the layer of atmosphere to be modeled, i.e., lower z_e better simulate the high altitude, where wind speed is greater, while greater z_e are best suited near the ground, where the wind speed is lower. Same conclusions can be extracted for the unstable case. This result is consistent with that observed by Karlsson, S. (1986) in the study of the applicability of similarity theory to an urban-rural interface.

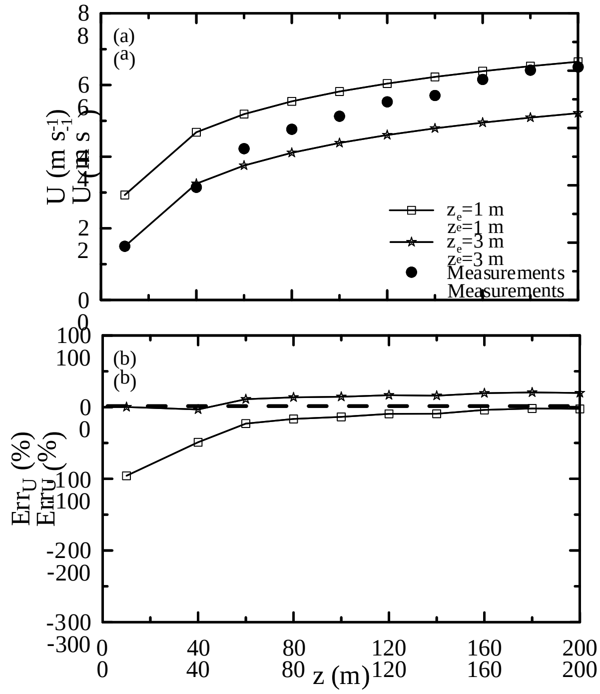

Figure 3. Vertical profiles of (a) wind speed and (b) error when the angle of rotation of the wind vector is less than 22.5° in the height range between 10 and 200 m agl (neutral atmosphere).

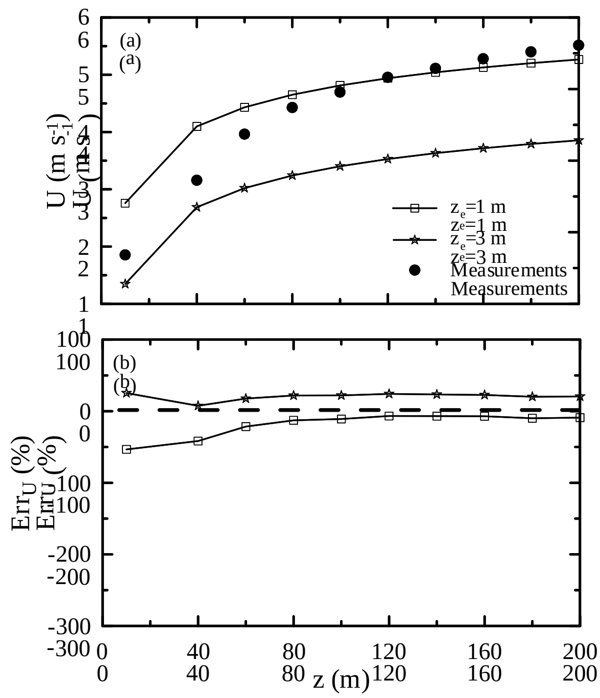

Figure4. As in Figure3, but for unstable atmosphere.

The previous result holds true even for unstable conditions (Figure4), when 2191 homogeneous profiles (22% of the data) were retained. Finally, Figure5 illustrates the poor performance of the theory in the stable case for both the equivalent heights considered here (1053 profiles, representing nearly 13% of the total number for the stable case, were considered in the analysis). Despite the improvement of the results with respect to those obtained without restrictions (Figure 2), the errors remain totally unacceptable.

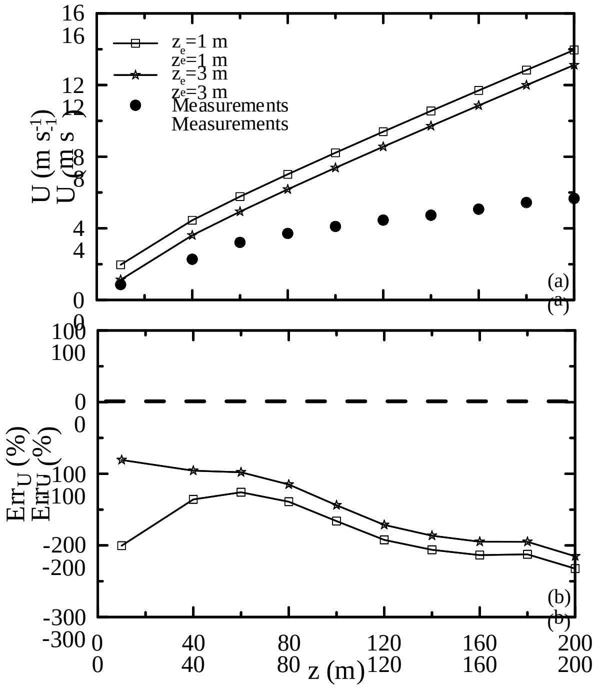

Figure5. As in Figure3, but for stable atmosphere.

SUMMARY AND CONCLUSIONS

Atmospheric boundary layer data taken in the city of Rome during the period June 2005 – June 2006, are used to study the nature of the urban boundary layer. A meteorological station instrumented with sonic anemometers, thermistors as well as a SODAR/RASS system are used for measurements. The observational location is a large park, covered with grass away from the direct influences of buildings and trees.

MO similarity, which is generally applied for rural case, is used in parameterization of wind speed for the first 200 m from the ground. An equivalent roughness length which plays the role of both the roughness length and the displacement height is used in the similarity laws. The better results occur for neutral and unstable atmosphere. In particular, during the latter condition error remains acceptable for all the depth of boundary layer investigated in the present paper, while in neutral condition the performance of the theory worse for z>100 m. In contrast, in stable condition error is ~400% at z=100 m and ~600% at z=200 m.

Finally, an overall improvement in the performance of the theory is obtained using profiles characterized by certain homogeneity of the wind direction along the vertical. The results, however, remain quite unsatisfactory and further studies are needed to obtain significant improvements in MO theory to be applied in urban areas.

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