On wind velocity profiles over urban area

Klara Bezpalcova

Department of Meteorology and Environmental Protection,
Charles University, V Holesovickach 2, 180 00 Prague 8, CR

Zbynek Janour

Institute of Thermomechanics,
Dolejskova 5, 182 00 Prague 8, CR
Fax: +4202858495 E-mail: janour@it.cas.cz

Viktor M.M. Prior

Instituto de Meteorologia, Rua C, Aeroporto,
P-1700 Lisboan, Portugal
Fax: +351218402370 E-mail: victor.prior@meteo.pt

Cecilia Soriano

Departament de Matemàtica Aplicada I,
Universitat Politècnica de Catalunya (UPC),
Av. Diagonal 647. 08028 Barcelona, Spain
Fax: +34934011713 E-mail: cecilia.soriano@upc.es

Michal Strizik

LIDAR s. r. o. V Holesovickach 2, 180 00 Prague 8, CR
E-mail: lidarsro@volny.cz

Abstract: The horizontally homogeneous atmospheric boundary layer over rough surface with a large roughness length z_0 is introduced to model the simplest cases of the Urban Planetary Boundary Layer (UABL) over the flat plain. The system of the equations of motion was non-dimensionalised and it has been demonstrated that the Rossby number similarity exists for the core of the UABL. That means that the non-dimensional profiles of the horizontal Reynolds stresses, eddy viscosity and velocity defect components are universal and independent of surface characteristics, contrary to the non-dimensional components of the velocity which are not universal. Radiosounding launched in Barcelona (ES), Lisboa, Èvora and Neves Corvo (PT) and sodar measurements for wind above Prague (CR) are compared with the universal profiles determined by numerical simulation.

Keywords: atmospheric boundary layer; urban area; wind velocity; roughness length; stratification; surface Rossby number independence; universal profile; blending height; radiosounding; sodar measurement.

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Biographical Notes: Klara Bezpalcova received her MS degree in Meteorology and Climatology from Charles University, Prague, the Czech Republic, in 2002, and nowadays she is a student of PhD study program meteorology and climatology at Charles University. In 2000, she joined the Department of Environmental Aerodynamics, Institute of Thermomechanics, Academy of Sciences of the Czech Republic, where she has been focused on micro-scale physical modelling of atmospheric pollution dispersion within urban atmospheric boundary layer using low-speed wind tunnel.

Zbynek Janour received his BSc in Theoretical Physics from the Charles University, Prague (1967), PhD in Theoretical Physics from Charles University, Prague (1972) and Associate Professor in meteorology from Charles University, Prague (2003). In 1967, joined Department of Boundary layer meteorology, Institute of Physics of the Atmosphere of the Czechoslovak Academy of Sciences and since 1982 the Institute of Thermomechanics, Academy of Sciences of the Czech Republic. He holds the Head of the Department of Environmental Aerodynamics and Chairman of Scientific board positions. He is specialised in mathematical modelling of the turbulent shear flows, of the transitional boundary layer, of the Atmospheric Boundary Layer and in physical modelling of the Atmospheric Boundary Layer. He is national representative in Management Committee of the COST Action 715 and member of EUROMECH Society.

Victor M.M. Soares Prior has a BSc in Physics from the University of Aveiro (1989) and MSc in Geophysical Sciences/Meteorology from the University of Lisboa (1998). PhD student in the Aveiro University. Adviser Meteorologist in the Portuguese Meteorological Institute from October 2000. Her research interest are oriented on surface and upper-air observations and lightning detection; data processing and quality control.

Cecilia Soriano has a BSc in Physics from the University of Barcelona (1992), and completed her PhD in 1997 in Environmental Engineering at the Technical University of Catalunya (UPC) in Barcelona. She holds a tenure-track position as a full professor at UPC. Made a stage at Los Alamos National Laboratory (New Mexico, USA) working in lidar and atmospheric modelling issues. Participant in several national and international scientific projects and author of several papers and conference communications. Her research interests are oriented towards meteorological and pollution modelling on complex terrain, and remote sensing of the atmosphere with lidar. She also has experience in environmental impact assessment studies, waste treatment and management, and pollution prevention.

Michal Strizik received his BS degree in chemistry, MS, and PhD degrees in analytical chemistry from Charles University, Prague, the Czech Republic, in 1993, 1995, and 2003, respectively. In 1999, he joined the Department of Environmental Aerodynamics, Institute of Thermomechanics, Academy of Sciences of the Czech Republic, where he has been engaged in micro-scale physical modelling of atmospheric pollution dispersion using low-speed wind tunnel and laser photo-acoustic detection. Since 2000 he has had a job with private company LIDAR, s.r.o., Prague (CZ), focusing its effort to investigation of dispersion of gaseous pollutants in the ABL by combined differential absorption LIDAR / SODAR technique

1 Introduction

The basic parameters that should be concerned for air pollution studies are wind and temperature profiles and main turbulence structures. There have been numerous investigations into atmospheric boundary layer carried out, but relatively few of them were carried out in urban areas in contrast to the fact that the most direct impacts of air pollution are felt in cities. The continuous increase of vehicular traffic within densely populated cities adds further pressure on a deteriorating urban air quality in many towns. Therefore, in recent years, boundary-layer meteorologists' attention has been directed towards problems of Roughness and Internal Sublayers. Velocity and temperature profiles over urban areas above this layer are of interest to designers of structures, buildings in towns, meteorologists and are studied in the framework of COST 715 – Working Group 1.

This topic is still considered very complex. Only a few engineering or micrometeorological rules are general enough to be exported from one city to another. The aim of this contribution is to find a simple 'universal' mean velocity profile for the core of the urban atmospheric boundary layer (UABL). Obviously the horizontally homogeneous atmospheric boundary layer belongs to the simplest cases. This layer is a theoretical case of the atmospheric boundary layer (ABL) with conditions, which in reality are never satisfied simultaneously. In analogy to [1] UABL can be defined as a *Urban Planetary Boundary Layer (UPBL)*, if:

- the boundary-layer flow over urban area is turbulent
- the mean flow and the turbulence properties are stationary
- the mean flow and the turbulence properties are horizontally homogeneous.

2 Rossby number similarity

The simplest model of the UABL is based on considering that the flow over an urban area is similar to the flow over a rough surface, with a given, large, roughness length z_0 and defined surface heat flux. In this way we shall model the UABL as the UPBL over a rough surface.

The equations of motion for an inviscid fluid in tangent-plane coordinates reduce to

$$f(U-U_g)=\frac{\mathrm{d}(\tau_y/\rho)}{\mathrm{d}z} \tag{1}$$

$$-f(V-V_g)=\frac{\mathrm{d}(\tau_x/\rho)}{\mathrm{d}z} \tag{2}$$

where U and V are components of mean velocity in its direction and perpendicular of the surface stress, respectively, U_g and V_g are the components of the geostrophic wind, τ_x, τ_y are components of the horizontal Reynolds stress and f is the Coriolis parameter. The boundary conditions at the lower boundary are:

$$z=z_0: \quad \begin{aligned} &U=V=0 \\ &\tau_x=\tau_{x_0},\ \tau_y=\tau_{y_0} \end{aligned} \tag{3}$$

and at the upper boundary

$$z=H: \quad \begin{aligned} &U=U_g,\ V=V_g \\ &\tau_x=\tau_{y'}=0 \end{aligned} \tag{4}$$

where H is a boundary layer thickness. The Boussinesq assumption on eddy viscosity is introduced to close the system of equation

$$\begin{aligned} \tau_x &= \rho K \frac{\mathrm{d}U}{\mathrm{d}z} \\ \tau_y &= \rho K \frac{\mathrm{d}V}{\mathrm{d}z} \end{aligned} \tag{5}$$

and the assumption of a constant thermal wind:

$$\begin{aligned} U_g &= U_{g_0} + \left(\frac{\mathrm{d}U_g}{\mathrm{d}z}\right)_c (z-z_0) \\ V_g &= V_{g_0} + \left(\frac{\mathrm{d}V_g}{\mathrm{d}z}\right)_c (z-z_0) \end{aligned} \tag{6}$$

is taken into account, where index '0' denotes at the lower boundary.

Let us non-dimensionalise the variables by using the friction velocity $u*$ and the internal scale height of the PBL $H = \kappa u*/f$, where κ is von Kárman in the following manner:

$$\begin{aligned} Z &= z/H \\ U &= U/u* \\ V &= V/u* \\ X &= \tau_x/(\rho u*^2) \\ Y &= \tau_y/(\rho u*^2) \\ \lambda_x &= \mathrm{d}U_g/\mathrm{d}z \\ \lambda_y &= \mathrm{d}V_g/\mathrm{d}z \end{aligned} \tag{7}$$

Mixing length hypothesis is non-dimensionalised by following relations:

$$\begin{aligned} K_m &= (L/\kappa)(X^2 + Y^2)^{1/4} \\ L &= L(X, Y, L_\infty) \end{aligned} \tag{8}$$

Then the system of equations of motion and boundary conditions under the very idealized assumptions mentioned above become following form:

$$\frac{\mathrm{d}^2 X}{\mathrm{d}Z^2} + \frac{Y}{K_m} - \lambda_x = 0 \tag{9}$$

$$\frac{\mathrm{d}^2 Y}{\mathrm{d}Z^2} - \frac{X}{K_m} + \lambda_y = 0 \tag{10}$$

$$K_m = K_m(Z, \mu) \tag{11}$$

With following boundary conditions:

$Z \rightarrow \infty$:

$$X \rightarrow K_{m\infty}\,\lambda_x \tag{12}$$

$$Y \rightarrow K_{m\infty}\,\lambda_{yy} \tag{13}$$

$$K_m \rightarrow K_{m\infty} \tag{14}$$

$Z = Z_0$:

$$X = X_0 = 1 \tag{15}$$

$$Y = Y_0 = 0 \tag{16}$$

$$K_m = K_{m_0} = Z_0 \tag{17}$$

μ stands for stability parameter.

The set of equations (9)–(11) and boundary conditions (12)–(14) depends on three internal parameters – λ_x, λ_y, μ. The lower boundary conditions depend on non-dimensional roughens length:

$$Z_0 = 1/(\kappa c_g\, Ro_0) \tag{18}$$

with

$$Ro_0 = \frac{|V_{g_0}|}{f z_0} \quad \text{and} \quad c_g = \frac{u^*}{|V_{g0}|} \tag{19}$$

Here the surface Rossby number depends on a non-dimensional combination of the external parameters $|V_{g0}|$, f and z_0. If Z_0 would be zero ($Ro_0 \rightarrow \infty$) and eddy viscosity should satisfy the condition

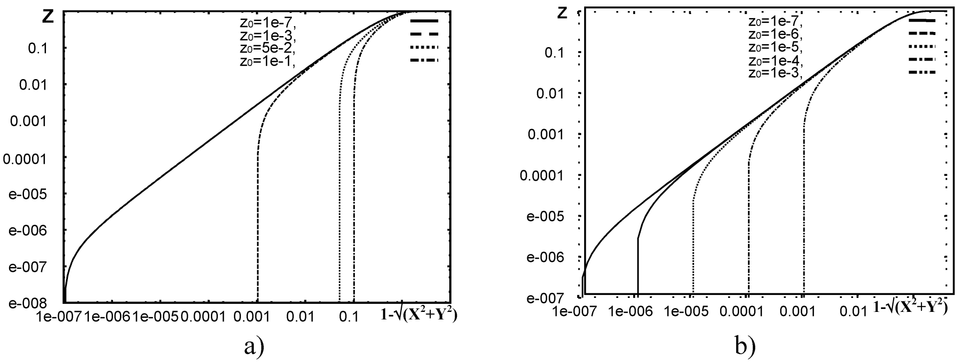
$$\frac{\partial K_m}{\partial (Ro_0)} = 0 \tag{20}$$

the system would be independent of Ro_0, i.e. the profiles X(Z), Y(Z) and $K_m(Z)$ must be independent on Ro_0 . This is called Rossby number similarity and the profiles X(Z, λ_x, λ_y, μ), Y(Z, λ_x, λ_y, μ), K_m(Z, λ_x, λ_y, μ) and the dimensionless velocity defect components $\kappa(U - U_{g_0})/u^*$, $\kappa(V - V_{g_0})/u^*$ are universal. However, the non-dimensional roughness length Z_0 is different from zero and the Rossby number similarity does not apply in a layer adjacent to the surface. This layer has depth Z_b on the order of the roughness length and its depth may be identified with the blending height. The blending height can be e.g. defined as the height over the ground at which the ground inhomogeneity is not perceived, above which the various Internal Boundary Layers merge into a layer having an horizontally homogeneous structure.

3 Blending height assessment

To assess this depth, a mixing length hypothesis according to Wipermann [2] has been used and numerical solution for varying roughness length Z_0 and for different thermal stratification has been performed – see [3]. The example of the nondimensional Reynolds stress profiles for different roughness length Z_0 is shown on Figure 1 to demonstrate dependence upon roughness length Z_0. The used values of the roughness length are from the interval: $z_0 \approx 10^{-4}$ m corresponding to a rural flat snowfield; $z_0 \approx 100$ m corresponding to an extremely high (unrealistic) city centre.

Figure 1 Plot of function $1 - \sqrt{(X^2 + Y^2)}$ for different roughness lengths Z_0 – a) unstable, b) extremely stable stratification

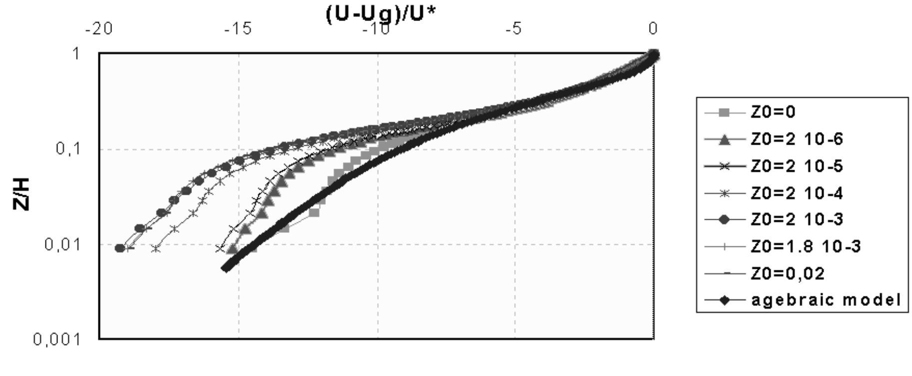


All determined profiles coincide in the upper part, which means that the Rossby number similarity exists there under the very idealized assumptions made here. The profiles are splitted in the lower part – the Rossby number similarity is not existent. It can be assessed that the height Z_b, where the Rossby number similarity exists, is roughly

$$Z_b \approx 10 Z_{0,\max} \tag{21}$$

The results of the CFD code Fluent [4] with 'k-ε' model of turbulence were used for more exact assessment of the blending height. The nondimensional velocity defect for different roughness length Z_0 (indifferent stratification) are plotted on Figure 2 demonstrating the qualitative similarity to the above-mentioned results.

Figure 2 Wind defect profiles for different roughness lengths Z_0



Let us define the depth Z_b in analogy to the boundary layer thickness δ as the distance for which difference of velocity defect for rough surface with Z_0 and for smooth surface is less than n%, i.e. for n = 1, 5 and 10 by following definitions:

$$(f(Z_{b1\%}, Z_0) - f(Z_{b1\%}, 0)) / f(Z_{b1\%}, 0) = 0.01 \quad (22)$$

$$(f(Z_{b5\%}, Z_0) - f(Z_{b5\%}, 0)) / f(Z_{b5\%}, 0) = 0.05 \quad (23)$$

$$(f(Z_{b10\%}, Z_0) - f(Z_{b10\%}, 0)) / f(Z_{b10\%}, 0) = 0.1 \quad (24)$$

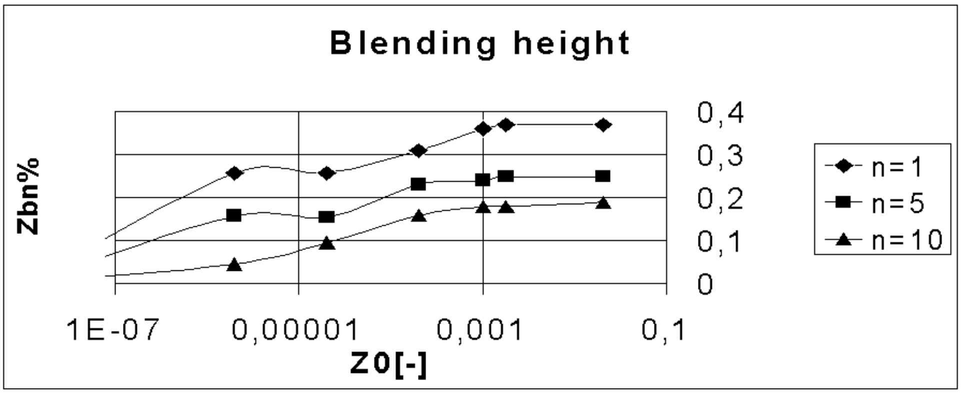
where

$$f(Z, Z_0) = \sqrt{[(\kappa(U - U_{g_0})/u^*)^2 + (\kappa(V - V_{g_0})/u^*)^2]} \quad (25)$$

is absolute value of the nondimensional velocity defect. The estimation of the blending height from CFD data is plotted in Figure 3. From results in Figure 3 following estimation can be concluded:

$$Z_{b1\%} \to 0.35,$$
$$Z_{b5\%} \to 0.25, \quad (26)$$
$$Z_{b10\%} \to 0.19.$$

Figure 3 Blending height Z_b assessment



The result can be interpret that the blending height z_b (in full scale) for urban area under the simplified assumptions made here with roughness length z_0 more than 1 m is of the order 200 m, i.e. double of the surface boundary layer height – see. e.g. Rotach et al. [5].

4 Comparison with experiments

There have been relatively few available experiments performed in urban areas to test the above-introduced results:

Jones et al. [6] used a captive balloon to carry measurement instruments for wind and other meteorological magnitudes above Liverpool urban area. The boundary layer depth and the dependence of power-law index on stratification had been assessed;

Dobbins [7] selected data from low-level soundings over Cambridge, USA. and determined the data on the basis of an 'Ekman-like' variation of the wind vector with altitude; radiosounding launched from roof of building of Polytechnic University by SERVEI DE METEOROLOGIA DE CATALUNYA (Catalan Meteorological Service) in downtown of Barcelona; radiosounding launched by INSTITUTO de METEOROLOGIA (Portugal hydrometeorological institute) in Lisbon (suburb), Èvora and Neves Corvo (small towns); SODAR measurements for wind (and concentrations) above city centre of Prague for COST 715 project by LIDAR s. r. o., CR (more details in [8]).

Much information concerning the experimental data sets is missing. e.g. detailed topography, urban surface and upwind characteristics. Therefore only a qualitative comparison has been performed. Indifferent stratification (determined from mean velocity profile) has been taken into account for this reason.

Examples of comparisons of our simulation with above-mentioned results and with Jones et al. [6] power-law profiles are presented on Figures 4–8:

Figure 4 Comparison of velocity defect profiles inside the UABL simulation with radiosounding launched in Lisboan (Date and time of the observation is in the form yy/mm/dd/hh, NN, NE wind directions on the top of the UABL)

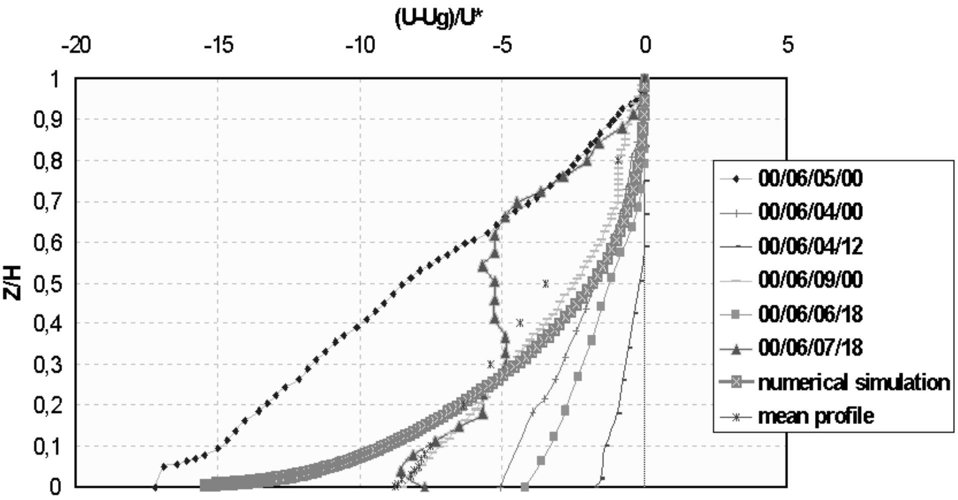


Figure 5 Comparison of velocity defect profiles inside the UABL simulation with radiosounding launched in Barcelona (Date and time of the observation is in the form yy/mm/dd/hh, SE wind direction on the top of the UABL)

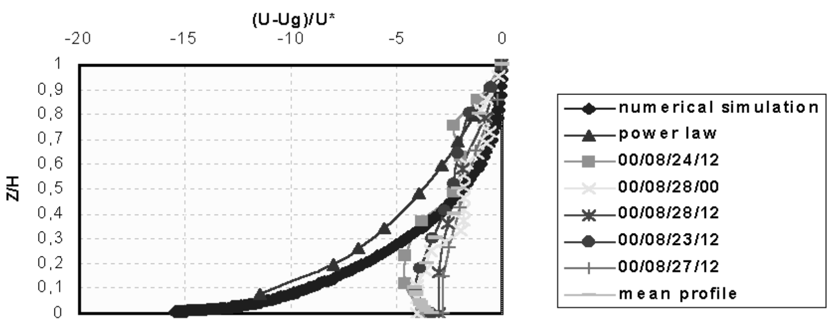


Figure 6 Comparison of velocity defect profiles inside the UABL simulation with radiosounding launched in Évora (Date and time of the observation is in the form yy/mm/dd/hh, NE wind direction on the top of the UABL)

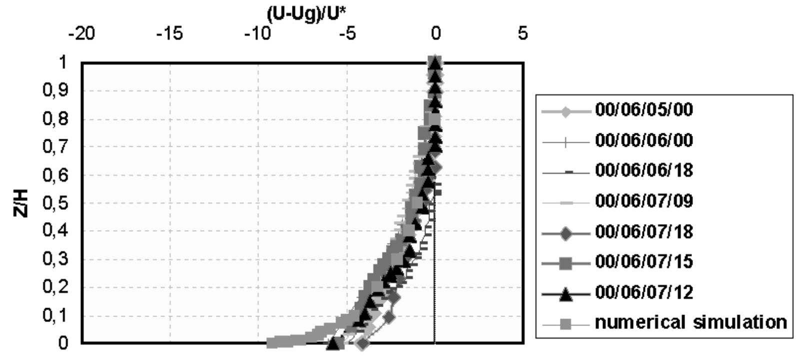


Figure 7 Comparison of velocity defect profiles inside the UABL simulation with radiosounding launched in Neves Corvo (Date and time of the observation is in the form yy/mm/dd/hh, NW wind direction on the top of the UABL)

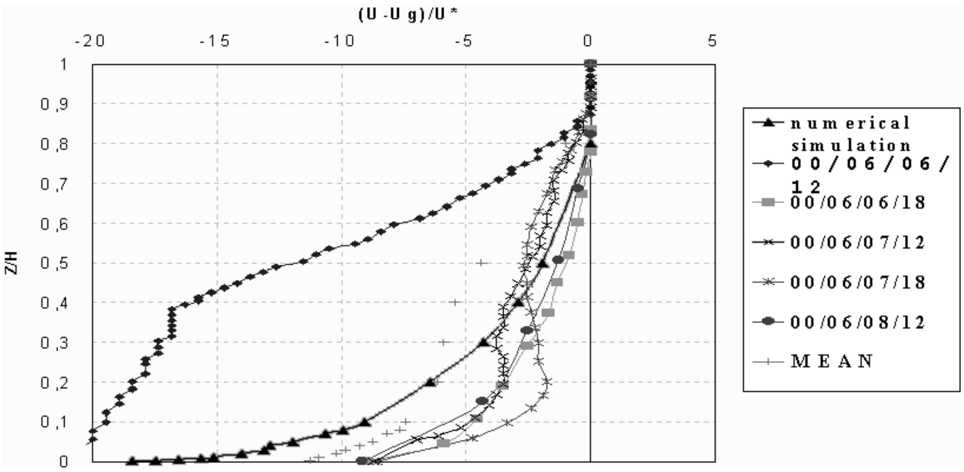
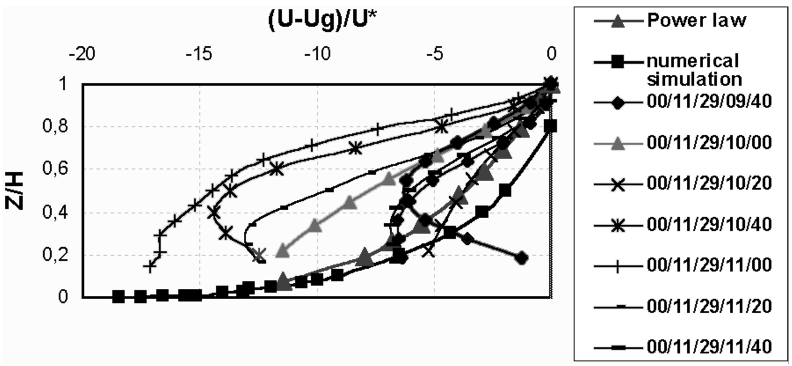


Figure 8 Comparison of velocity defect profiles inside the UABL simulation with sodar measurement in Prague (Date and time of the observation is in the form yy/mm/dd/hh/mm, *W* wind direction on the top of the UABL)



Scattering of the velocity defect profiles determined from radiosounding measurements is evident from the figures. It is consequence of the fact that the radiosounding velocities with averaging time $T \sim 1$ minute are compared with the simulated mean values with $T \sim 15$ minutes averaging time. Therefore we tried to assess 'mean velocity profiles' from these results for each area. This 'virtual' mean velocity defect profiles are comparable with the simulated ones. The averaging time of sodar measurements is of the order 20 minutes and therefore it can be compared to simulated mean values.

A minimum in the wind defect at about $Z \approx 0.3$ in Figure 8 can be explained by an influence of the upwind topography (river Vltava valley).

5 Conclusions

The horizontally homogeneous atmospheric boundary layer over rough surface with a large, roughness length z_0 has been investigated to model the simplest cases of the UABL over flat plain. The Rossby number similarity has been demonstrated for the core of the urban atmospheric boundary layer (UABL). It means that the profiles $X(Z, \lambda_x, \lambda_y, \mu)$, $Y(Z, \lambda_x, \lambda_y, \mu)$, $K_m(Z, \lambda_x, \lambda_y, \mu)$ and velocity defect components $\kappa(U - U_{g0})/u^*$, $\kappa(V - V_{g0})/u^*$ are universal and independent on surface characteristics for $Z > Z_B$. The Rossby number similarity cannot be used for non-dimensional components of the velocity. The conclusion differs to Rafailidis [9] deductions from wind tunnel simulations according to his paper; the mean wind profile above an urban fetch is influenced by the presence of the buildings only within three building heights above ground. The altitude of the Rossby number similarity lower limit corresponding to the blending height was estimated. Because of lack of additional information about experiment data sets only the qualitative comparison of our simulation with experimental results has been performed.

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References

1 Wippermann, F. (1972) 'Empirical formulae for the universal functions $M_m(\mu)$ and $N(\mu)$ in the resistance law for barotropic and diabatic planetary boundary layer', *Beitrage zur Physik der Atmosphere*, Vol. 45, pp.305–311.

2 Wippermann, F. (1973) *The Planetary Boundary Layer of the Atmosphere*, Deutscher Wetterdienst, p.346.

3 Janour, Z. and Benes, M. (2001) *Numerical Simulation of the Planetary-Boundary-Layer Equations*, Workshop on Urban Boundary Layer Parametrisations, Zűrich.

4 Kozubkova, M. and Drabkova, S. (2002) 'Influence of the wall roughness on the wind profile and concentration of pollutants in the atmosphere', *Seminar Topical problems of fluid mechanics 2002*, pp.49–52.

5 Rotach M. *et al*. (1997) 'Wind input data for urban dispersion modelling', in Schatzmann, M. *et al*. (ed.): *Preparation of Meteorological Input Data for Urban Site Studies, Proceedings of the Workshop 15 June 2000*, Prague, Czech Republic, Directorate-General for Research, 2001, pp.77–86.

6 Jones, P.M., de Larringa, M.A.B. and Wilson, C.B. (1971) 'The urban wind velocity profile', *Atmospheric Environment*, Vol. 5, pp.89–102.

7 Dobbins, R.A. (1977) 'Observations of the Barotropic Ekman layer over an urban terrain', *Boundary-layer Meteorology*, Vol. 11, pp.39–54.

8 Zelinger, Z. *et al*. (2003) *Comparison of Model and in-situ Measurements of Distribution of Atmospheric Pollutants* (accepted for Physmode 2003, 3–5 SEPTEMBER 2003 PRATO – ITALY).

9 Rafailidis, S. (1997) 'Influence of building areal density and roof shape on the wind characteristics above a town', *Boundary-Layer Meteorology*, Vol. 85, pp.255–271.