SELECTED CHARACTERISTICS OF THE ATMOSPHERIC TURBULENCE OVER A CENTRAL EUROPEAN CITY CENTRE – INTEGRAL STATISTICS

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Abstract

The contribution presents selected characteristics of turbulence calculated on the base of long term measurements in Łódź, central Poland (population ca 750,000). Turbulent characteristics were measured with the aid of fast respond sensors (sonic anemometers) at two points in the city centre. At the first point data were collected in years 2000-2003 and at the second point measurements are continued since 2005. At both stations sensors were mounted at thin masts at the level (37m and 42m above ground), significantly taller than mean building height (11m and 17m respectively). The study presents integral characteristics of turbulence at both stations. Typical integral characteristics (a drag coefficient and normalized standard deviations of wind component and temperature) are calculated as a function of stability parameter. Results show good agreement with functions predicted by Monin-Obukhov similarity theory.

Keywords: turbulence, drag coefficient, normalized standard deviation

1. INTRODUCTION

Knowledge of the structure of turbulence is essential for many practical applications including atmospheric dispersion. The spectral and integral properties of turbulence over homogenous surface are well established. In accordance of Monin-Obukhov (M-O) similarity theory, both spectra and normalized velocity standard deviations, σ_i/u_*, should depend on z/L where L is Obukhov length. In the urban atmosphere roughness sublayer where the flow is three-dimensional due to the influence of individual roughness elements can be relatively extended. As a consequence upper part of surface layer, the inertial sublayer where the Monin-Obukhov similarity is supposed to work, shrinks. It raises a question on the applicability of the M-O theory on the urban areas. Because of the absence of generally accepted alternative theory results of measurements on urban areas are analyzed with the M-O similarity framework. Review of turbulence over urban areas was done by Roth (2000). The objective of this study is to investigate integral turbulence statistics (drag coefficient and normalized standard deviations of wind component and temperature) at two urban measurement points located in Łódź, central Poland. Turbulence statistics are expressed as a function of local values of z/L to get functional relations.

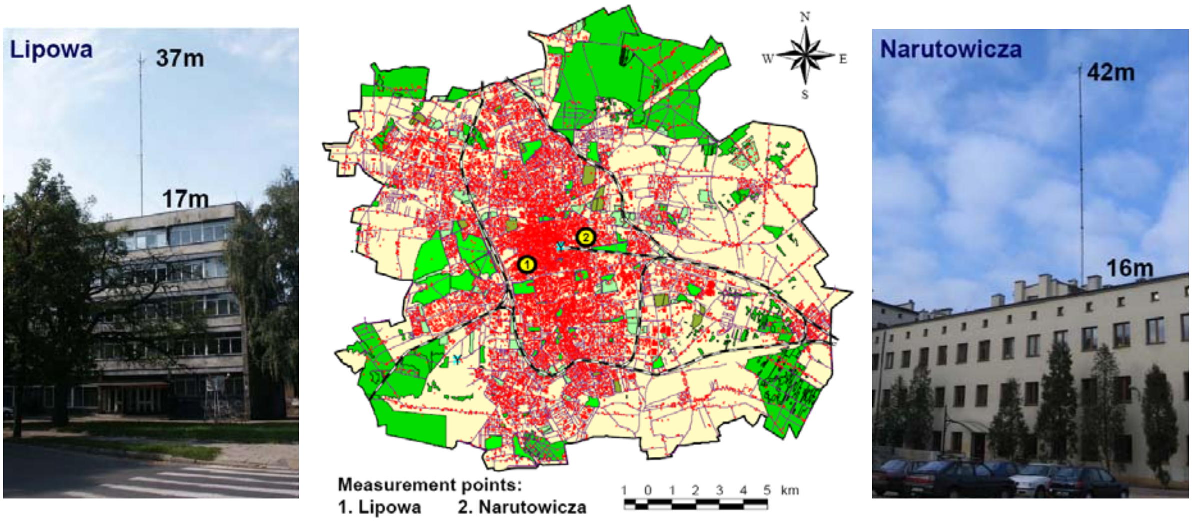

Fig. 1 Location of the measurement points in Łódź, central Poland.

2. MEASUREMENT SITE AND DATA USED

Łódź (51°47'N, 19°28'E) is the one of the largest Polish city with population ~750 000. It is placed in the centre of Poland on relatively flat area with lack of big rivers, lakes or other water reservoirs. The city center is

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characterized by a regular urban arrangement. Buildings reaching 15-20m in height were built in the end of 19th and at the beginning of 20th century and they compose a clear roof level. Roofs are mainly covered by black tar, pavements are concrete and roads are roofed by asphalt.

Measurement points are located in the core of old centre (Fig. 1). First point, Lipowa, was established in 2000 and data used in the present work cover the period 2000-2003. Eddy covariance system was constructed and installed by Prof. Sue Grimmond and Dr Brian Offerle (Offerle at al. 2005, 2006). Wind components and temperature fluctuations were measured by sonic anemometer (SWS-211/3K Applied Technologies, Inc.) and stored with 10Hz frequency. Anemometer was mounted on the top of 20m mast placed on the roof of the 17m in height building, so the measurement height is z_s=37m above the ground. Average building height in the nearest surrounding is about z_H=11m, which gives a displacement height z_d=7.7m according to empirical formula $z_d=0.7z_H$ (Grimmond, Oke 1999). Roughness length estimated on the base of relation, $z_0 = (z_s-z_d)\cdot\exp(-k\cdot U/u_*)$ for neutral stability is angularly dependent, but its average value is close to 2.0m. Data from the second point, Narutowicza, cover period May 2005 – January 2008. Measurements were made by sonic anemometer (RMYoung 81000) mounted at the 25m mast placed at 16m building. Measurement height is z_s=42m above the ground. Other characteristics at Narutowicza point are: z_H=16m, z_d =11.2m, z_0 =1.9m. At both stations turbulence statistics were calculated in 1 hour intervals.

3. RESULTS

Information on drag coefficient, $C_D=(u_*/U)^2$, is important for many practical purposes, especially for parameterization of surface stress in numerical models. For neural condition C_D depends on non-dimensional height (Roth 2000). In Łódź drag coefficient for neutral stratification ($-0.05<\zeta<0.05$) is equal C_D=0.0254 for Lipowa, and C_D =0.0214 for Narutowicza. These values are slightly higher than given by exponential relation between u_*/U and z_m/z_H given by Roth (2000). Dependence of C_D on $\zeta=(z_s-z_d)/L$ for non-neutral conditions is presented at Fig. 2.

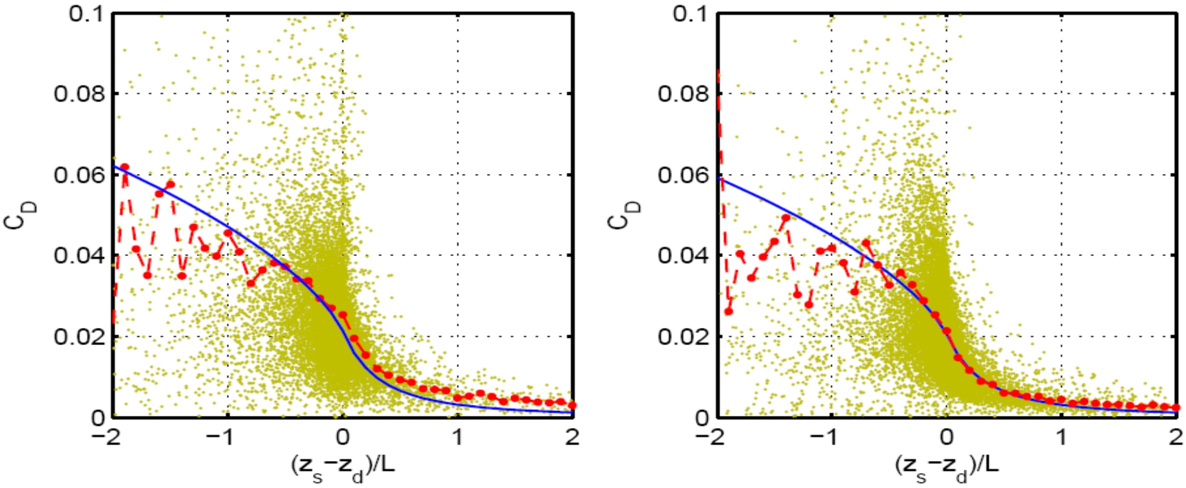

Fig. 2 Momentum drag coefficient $C_D=(u_*/U)^2$ as a function of stability for Lipowa (left) and Narutowicza (right) measurement points. Yellow points – measurements; red dashed line – box averages for 0.1 intervals; blue solid line – C_D calculated with M-O theory.

For unstable conditions results are very scattered and do not compose a clear pattern. To get more apparent picture results were box-averaged for intervals 0.1. Average data show good agreement with the drag coefficient given by Monin-Obukhov theory:

$$C_D = k^2\left[\ln\left(\frac{z_s - z_d}{z_0}\right) - \Psi_m(\zeta) + \Psi_m\left(\frac{z_0}{z_s - z_d}\zeta\right)\right]^{-2},$$

with k=0.4 and conventional integrated stability function for momentum Ψ_m given by:

$$\Psi_m(\zeta) = 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2\tan^{-1}(x) + \frac{\pi}{2}$$ with $x = (1 - 15\zeta)^{1/4}$, for unstable conditions ($\zeta < 0$) and

$$\Psi_m(\varsigma) = -4.7\cdot\zeta$$ for stable conditions ($\zeta > 0$).

Classical parameters of universal functions given by Businger at al. (1971) work in the case of Łódź better than presently used ones given by Högström (1988). Because of results scattering reliable comparison is possible only for $\zeta>-1$, but average values for more unstable conditions suggest that theoretical function overestimate real values in high unstable conditions. For $\zeta>-1$ the agreement is better for Narutowicza than for Lipowa where theoretical function systematically underestimate results of measurements.

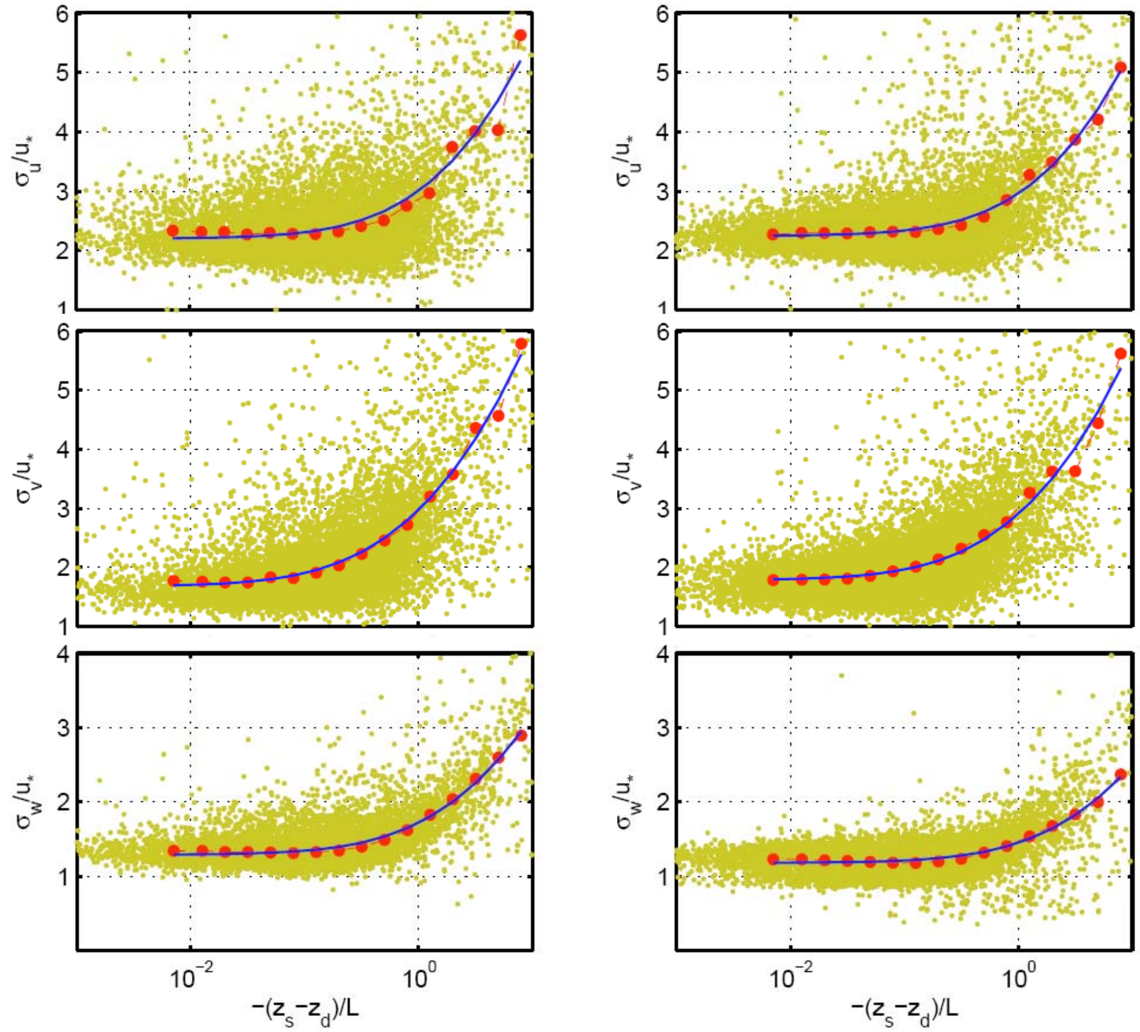

Fig. 3 Normalized standard deviations for u (top), v (middle) w (bottom) plotted against $\zeta=(z_s-z_d)/L$ for unstable conditions. Data from Lipowa (left) and Narutowicza (right) measurement points. Yellow points – measurements; red dashed line – box averaged data; blue solid line – fit to function $\sigma_i/u_*=a(1-b\cdot\zeta)^{1/3}$.

According to Monin-Obukhov similarity normalized velocity standard deviations, σ_i/u_*, within the surface layer are the functions of stability parameter, ζ. The vertical component standard deviation scales with observation by universal function $\sigma_i/u_*=\Phi_w(\zeta)$. Different formulations for $\Phi_w(\zeta)$ have been proposed, but one of the most common is 1/3 power function defined for unstable conditions:

$$\sigma_w/u_*=a_w\cdot(1-b_w\cdot\zeta)^{1/3}.$$

By analogy similar relation is proposed for horizontal velocity variances (Panofsky at al. 1977, Roth 2000) but some authors reports weak dependence of $\sigma_{u,v}/u_*$ on stability for urban areas because scatter of the results with larger $-\zeta$ (Rotach 1993). Data form the present measurement points are also scattered (Fig. 3). However, box averaged values show clear power scaling. In fitted functions power is fixed to 1/3 as this is suggested by M-O theory in the limit of free convection, but it should be stressed that it stays close to 0.33 even when it is estimated as a free parameter. Box averaged normalized velocity standard deviations are well scaled by relation $\sigma_i/u_*=a_i(1-b_i\cdot\zeta)^{1/3}$ not only in large instabilities but in general for unstable conditions. However, σ_i/u_* are found to be closed to $(-\zeta)^{1/3}$ for $-\zeta > 0.4$ only. Parameters a_i which determine σ_i/u_* values for neutral conditions are in the limits of urban average given by Roth (2000). Parameters b_i are higher for σ_w and σ_v but smaller for σ_W.

Table 1. Empirical constants for scaling $\sigma_i/u_* = a(1-b\cdot\zeta)^{1/3}$ in unstable conditions

i	Lipowa		Narutowicza	
	a	b	a	b
u	2.202	1.541	2.243	1.288
v	1.679	4.559	1.785	3.299
w	1.286	1.388	1.179	0.854

According to free convection similarity theory, Wyngaard et al. (1971) suggested $-\sigma_T/T_* = a_T(-\zeta)^{1/3}$ with $a_T=0.95$ for the normalized temperature standard deviations under unstable conditions. Other authors apply the same type of equation as for wind components (De Bruin at al. 1993). In the case of analyzed data first type of relationship fits well to the box-averaged data with parameter $a_T=1.547$ for Lipowa and $a_T=1.568$ for Narutowicza (Fig.4).

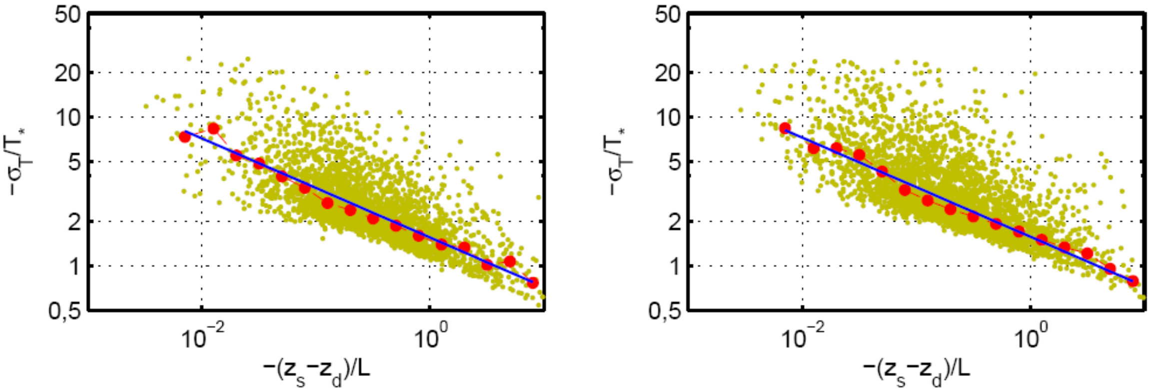

Fig. 4 Normalized standard deviations of T plotted against $\zeta=(z_s-z_d)/L$ for unstable conditions. Data from Lipowa (left) and Narutowicza (right) measurement points. Yellow points – measurements; red dashed line – box averaged data; blue solid line – fit to function $-\sigma_T/T_*=a(-\zeta)^{-1/3}$.

4. CONCLUSIONS

Results of the present study show high scatter of integral turbulent statistics as a function of ζ. Clear relationships are hardly detectable before box-averaging. Average values are very similar for both measurement points. Drag coefficients are well scaled with M-O universal functions, but even for average values clear relationship can be observed for $\zeta > -1$ only. Normalized standard deviations for wind components and for temperature fits to the typical scaling function with parameters within the range observed for other cities. Similar scaling laws at both stations and good agreement M-O theory give hope that sensors are placed close to the top or above roughness layer and results are representative for a relatively large area within the city.

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