

PROFILES OF TURBULENCE STATISTICS IN THE URBAN ROUGHNESS SUBLAYER WITH SPECIAL EMPHASIS TO DISPERSION MODELING

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Abstract

Turbulence observations from the BUBBLE project (Basel UrBan Boundary Layer Experiment) are analysed specifically in the context of urban pollutant dispersion modelling. These simulations are motivated by tracer release experiments that were performed in connection with BUBBLE. At the urban site in the vicinity of the tracer release point, turbulence observations included 6 levels of sonic and 2 levels of fast humidity sensors from 3.6m above street level up to about twice the local building height. In addition, full meteorological observations were available. It is shown that the actual observations of relevant turbulence statistics (e.g., velocity variances) can substantially differ from what is available to be employed in pollutant dispersion models. It is then demonstrated that the effect of inaccurate (i.e., parameterised) turbulence input variables leads to substantial departures between observed and simulated surface concentrations.

Key words: urban pollutant dispersion, roughness sublayer, velocity variances

1 INTRODUCTION

Dispersion models – if they do not employ detailed prognostic 3d meteorological fields as input – often rely on parameterisations for the relevant turbulence statistics. For ideal boundary layers (flat, horizontally homogeneous) such parameterisations are usually based on similarity theory and may be found, e.g., in Stull (1988). For vegetated surfaces, so-called ‘family portraits’ have been devised for turbulence and flow statistics within the roughness sublayer based on ample information from wind tunnel and full-scale studies over various types of vegetation (e.g., Kaimal and Finnigan, 1994). No similar compilation exists to the knowledge of the authors for urban surfaces. Wind tunnel investigations of turbulence characteristics near urban surfaces usually use regular arrays of ‘buildings’ (identical blocks) and these allow for a systematic investigation of building density and arrangement and their influence on the characteristic profiles. Kastner-Klein et al. (2000) have compared results from three different wind tunnel studies (two using ‘idealized’ street canyons, one based on a real urban model) and reported – not surprisingly – a pronounced influence from canyon geometry. Kastner-Klein et al. (2001) have compared observations from an idealized wind tunnel street canyon with the full-scale data of Rotach (1995) and Louka (1998) and found at least some qualitative similarity between full-scale and wind tunnel data. In this study, data from a recent detailed urban boundary layer study, BUBBLE (Basel UrBan Boundary Layer Experiment) are compared to a simple parameterisation that is based on the full-scale data of Rotach (1995) and has been developed for use in a Lagrangian Particle Dispersion Model (LPDM) over urban areas (Rotach 2001).



Fig. 1 Instrument tower at site ‘Sperrstrasse’ (left) and city structure around that site (right).

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2 THE BUBBLE DATA SET

The BUBBLE data set has been described in some detail in Rotach et al. (2002) and BUBBLE data have been presented in some preliminary studies (Christen et al. 2002, 2003). In this study, we only use a small fraction of this data set, namely from the site 'Sperrstrasse', which is situated within the region of the city where a tracer experiment was performed (Gryning et al. 2003). At this urban site, a 30m tower was placed in a street canyon without vegetation (aspect ratio about one) hosting (among many other instruments) 6 levels of turbulence instrumentation (Fig. 1). The local city structure may be characterized as relatively compact with a plan area density of 0.54. The local building height is 14.6m and the turbulence instruments were at 31.7, 22.4, 17.9, 14.7, 11.2 and 3.6m above street level, respectively.

3 PARAMETERIZATION OF TURBULENCE VARIABLES

The parameterisation that we examine here is the one used in the LPDM of Rotach (2001 – and references therein) and is essentially based on two ingredients:

- Reynolds stress is observed to be non-constant with height within the roughness sublayer (cf. the connotation of the surface layer as the constant stress layer) and a parameterisation for its profile has been devised by Rotach (2001) based on full-scale data from three urban sites. In this parameterisation (as in the observations) Reynolds stress increases (in magnitude) from zero at the zero plane displacement height to a maximum at a height z^* and then decreases towards the upper boundary layer. The height z^* is identified as the height of the roughness sublayer, and Reynolds stress at this level is used to obtain a characteristic velocity, $\hat{u}_* = \sqrt{-\hat{u}'w'(z^*)}$ where the hat has been introduced to distinguish from the traditional definition of a friction velocity using the *surface value* of Reynolds stress.
- Local scaling has been found to describe the observed data relatively well at many urban sites from all over the world (see Roth 2000 for an overview). However, this observation is primarily based on above-roof observations. Therefore, for the velocity variances a correction is made inside the street canyons. Observations of Rotach (1995) have shown that the *locally scaled* velocity variances do not fall below a certain threshold value (which is specific for the velocity component considered). This is taken into account close to the street canyons.

Based on these considerations near the surface, profiles for the entire boundary layer are constructed from the required input variables, \hat{u}_* , w_* , z_* and h (where w_* is the convective velocity scale, z_* is the mixed layer height and h the average building height) as follows

- Determine the height z^* , either as a multiple of h or, if available, from observations.
- Determine a local scaling velocity, u_{loc} for each height $z < z^*$ using the above parameterisation and \hat{u}_* .
- Use the model's boundary layer parameterisations for the velocity variances etc. throughout the entire domain but substitute the local scaling velocity u_{loc} for \hat{u}_* below z^* .

The boundary layer parameterisations are based on suggestions of Gryning et al. (1987) who combined similarity profiles for neutral and convective stratification to yield (e.g., for the vertical velocity variance):

$$\overline{w'^2} = 1.5 \left(\frac{z}{z_*}\right)^{2/3} \exp\{-2z/z_*\} w_*^2 + (1.7 - z/z_*) u_*^2 \quad (1)$$

where we have used u_* without hat to denote the 'generic' mechanical scaling velocity. Note that for $w_*=0$ and close to the surface (1) reduces to the well-known neutral limit $\sigma_w/u_* \approx 1.3$. For a complete list of the parameterisations see Rotach et al (1996).

For the profile of mean wind speed the procedure is slightly different. Rather than evaluating an explicit relation similar to (1), the mean wind speed is first determined at z^* using surface layer relationships and \hat{u}_* as a scaling velocity. From there the non-dimensional wind-shear function $\phi_m(z/L)$ is *numerically* integrated downward and upward, respectively, with L being the Obukhov length (also local below $z=z^*$).

It might be worthwhile to note that the type of near-surface parameterisation as presented above has been found by Rotach (2001), DeHaan et al (2001) and Leone et al. (2002) to be crucial in order to successfully simulate urban dispersion.

4 RESULTS

In this contribution we focus on the periods of the tracer release experiments (four 3 hour periods during afternoons in summer 2002) due to the possibility to substantiate the results by investigating the impact on modelled surface concentration fields. In the simulations the parameterised profiles are first calculated and then scaled to optimally match available observations. In the present case only the observations at the topmost level have been employed for the velocity variances while for the mean wind speed observations at 17.9 and 31.7m have been used. These scaling factors, determined at a height larger than two times the average building height (and hence most likely at or above the top of the roughness sublayer), may be used as an indication to what extent the parameterised *boundary layer profiles* (i.e., their lowest portion) are in agreement with the observations. A discrepancy at the lower levels indicates a specific urban roughness sublayer feature.

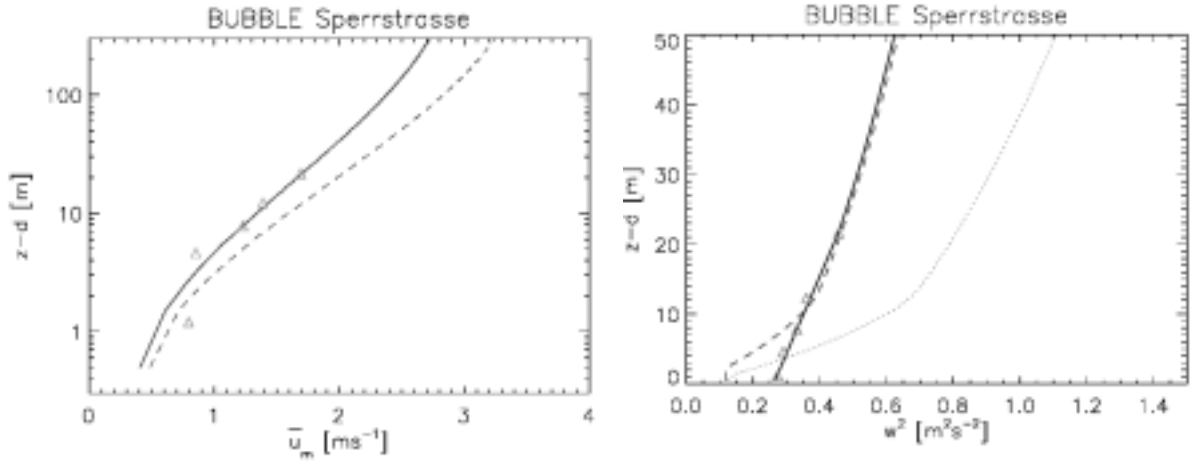


Fig. 2 Left: profile of mean wind speed during the tracer experiment #1 (June 26 2002), 15-16.00 (CET). The dashed line depicts the original and the solid line the scaled parameterisation, Triangles: observations. Right: the same for the vertical velocity variance. Here the dotted line is the original parameterisation, the dashed line the 'scaled' parameterisation (see text), and the full line a best fit through the data, Triangles: observations.

Fig. 2 shows profiles of mean wind and vertical velocity variance for one particular one-hour period during tracer experiment #1. This example shows that the parameterisation for mean wind speed is quite successful, except maybe in the lowest part where too strong a gradient is often modelled. Nevertheless, on average for all observations during the four tracer experiments relatively 'weak' scaling (i.e. a scaling factor close to one) is required in order to match the parameterisation with observations (Table 1). The situation is quite different for the velocity variances. As Fig. 2 demonstrates, the parameterisation (eq. 1) severely overestimates at the uppermost level of observation (see also Table 1). This indicates that the employed *boundary layer* parameterisation in general might not be appropriate for an *urban boundary layer* (note that parameterisations like eq. (1) were not devised for urban boundary layers). Alternatively, the parameterisation may become unrealistic for simultaneously large values of w_* and \bar{u}_* as it was typical during the tracer experiments (for the period displayed in Fig. 2 $w_* = 2.26 \text{ m/s}$ and $\bar{u}_* = 0.47 \text{ m/s}$). Clearly, such a value of the convective velocity scale would 'normally' imply the friction velocity to be very small, and hence the concurrently large values of both scaling velocities may also be regarded as an urban effect. Table 1 indicates that at least for the periods of concurrently large w_* and \bar{u}_* the velocity variances are severely overestimated. It will have to be investigated in more detail whether this also is true for more moderate combinations of the scaling velocities.

Variable	$\overline{w^2}$	$\overline{v^2}$	$\overline{u^2}$	\bar{u}
Scaling factor	0.61 ± 0.18	0.63 ± 0.23	0.49 ± 0.17	0.91 ± 0.11

Table 1 Scaling factors for the uppermost level of observation (two levels for mean wind, see text) at site 'Sperrstrasse' (31.7m) for the indicated turbulence variables. Based on 1/2-hourly observations for the periods of the four tracer experiments (total of $4 \times 6 = 24$ data points).

Within the roughness sublayer the velocity variances are found to exhibit an essentially linear decrease with height (Fig. 2 as an example). Comparison to the parameterised profiles shows that the parameterisation (local scaling with prescribed profiles of the scaling velocity, see section 3) also leads to a near-linear variation for the velocity variances close to the surface – however with a distinctly different gradient. First attempts to organize the data in a similar fashion as the 'family portrait' for vegetative surfaces, i.e. a representation of $\overline{u^2} / \bar{u}^2$ vs. z/h failed so far. More efforts will be necessary, in particular also in including data from periods of different stability.

4.1 Effect on dispersion modelling

Tracer experiment #1, which was in many respects the 'golden day' of the BUBBLE tracer releases, was used to investigate the impact of the turbulence parameterisation in a Lagrangian Particle Dispersion Model on its ability to predict near roof-level observed concentrations from a near-roof level source. The most striking result of this exercise was the fact that runs with purely parameterised turbulence (e.g., dotted line in the right panel of Fig. 2)

performed better (on average, based on some standard statistical measures) than those with 'optimal turbulence' (full lines in Fig. 2). This result will be analysed in detail elsewhere. In the following we will summarize a few of the more detailed results:

- 'Correct' mean wind speed by linearly interpolating the observations: very small impact on the fractional bias (FB), normalized mean square error (NMSE) and correlation coefficient.
- No correction (i.e. parameterised profile) for longitudinal velocity variance. This is interesting because usually in dispersion experiments the longitudinal velocity variance is considered insignificant and often not even provided. Including the scaling for the longitudinal velocity variance reduces the FB by about 7% and the NMSE by 16%. At the same time the correlation coefficient slightly increases and the 'Factor of 2' as well. The results of Tables 1 and 2 show that in an urban environment longitudinal velocity variance can be substantially different from more ideal boundary layers and that this has quite some relevance for accurately predicting dispersion of pollutants.

	FB	NMSE	Correlation coef.	F2
No scaling for u^2	-0.254	0.615	0.74	0.538
All variances scaled	-0.223	0.523	0.753	0.590

Table 2 Statistical measures for the performance of a LPDM as compared to near-roof level observations for the BUBBLE tracer releases (experiment #1, 26 June 2002, 1-hour periods, 13 data points for each 1-hour period. Shown are averages over 12 experiments, i.e. 1-hour periods).

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