J6.7 AN EXAMINATION OF RELATIONSHIPS BETWEEN URBAN AND RURAL MICROMETEOROLOGY USING SEMI-EMPIRICAL AND COMPREHENSIVE MODELS

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1. INTRODUCTION

Recent studies (Venkatram et al, 2005) indicate that simple dispersion models can be used to estimate ground-level concentrations in an urban area if meteorological information at the site is used to construct model inputs. Because such information is usually not available, there is a need for methods that can estimate urban variables from more routinely available rural measurements. This paper examines two methods, one based on a two-dimensional internal boundary layer model, and the other on a 3-D prognostic meteorological model. The performance of these two methods is evaluated with data from a boundary layer field study conducted in Basel, Switzerland, in 2002. Data from Joint Urban 2003 (JU2003; Allwine et al, 2004) were used for the evaluation, as well. We first provide a brief description of the studies and present results from a preliminary analysis of the data using similarity methods.

2. EXPERIMENTAL DATA

We used data collected during a field campaign, BUBBLE (Basel UrBan Boundary Layer Experiment; Christen and Vogt, 2004a; Rotach et al, 2004) and JU2003. BUBBLE, conducted in Basel, Switzerland during the period of June 10th to July 10th, 2002, provides extensive measurements of mean and turbulence velocities and fluxes and radiation variables in a rural as well as in an urban built-up area. The main urban measurements tower, Basel-Sperrstrasse (or U1), was 32 m high and located inside a street canyon in an area with dense, fairly homogeneous, residential building blocks. The local roof-top level was 14 m above the ground level (AGL), the mean building height of the area was 14.6 m AGL, and the plan aspect ratio of the buildings was 0.54. The tower measured meteorological parameters using sonic anemometers at six levels, viz. 3.6, 11.3, 14.7, 17.9, 22.4 and 31.7 m AGL, to characterize the vertical structure of the mean flow and turbulence within the urban roughness sub-layer (i.e., the layer directly influenced by individual roughness elements). The rural site, Village Neuf (or R2), located about 6.5 km NNW of the U1 site, measured flow and turbulence at 3.3 m AGL over bare soil in an agricultural area.

JU2003 was conducted during the period June 28th to July 31st, 2003 in Oklahoma City, Oklahoma. The JU2003 measurements were made using a number of instruments at multiple sites. Among them, we focused on flow and turbulence measurements taken in typical industrial or warehouse urban areas, and in its upstream suburban and rural areas (Huynh et al, 2005). Measurements taken at towers #2 and #5 operated by U.S. Army Research Laboratory were considered as industrial and warehouse urban values and tower #3 was located in a rural area (Huynh et al, 2005).

The mean building height for the urban area of Oklahoma City is 5-15 m (Landquist et al, 2004), while the Central Business District (CBD) has an average building height of 50 m and an aspect ratio (the height-to-width ratio) of about 2 (Brown et al, 2004).

3. SIMILARITY RELATIONSHIPS

According to Monin-Obukhov (M-O) similarity, the mean wind profile $U(z)$ in the diabatic surface layer is given by (e.g. van Ulden and Holtslag, 1985)

$$U(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z-d}{z_0}\right) - \psi_m(\zeta_1) + \psi_m(\zeta_0)\right], \quad (1)$$

where z is the height above the surface, κ is the von-Karman constant (= 0.4), z_0 is the surface roughness length, d is the displacement height, u_* is the friction velocity, $\zeta_1 = (z-d)/L$, $\zeta_0 = z_0/L$ and the function ψ_m are

$$\psi_m = 2\ln\left(\frac{1+x'}{2}\right) + \ln\left(\frac{1+x'^2}{2}\right) - 2\tan^{-1}(x') + \frac{\pi}{2} \quad (2)$$

$$\psi_m = -17\left[1-\exp(-0.29\zeta)\right], \quad (3)$$

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for $L < 0$ and $L > 0$ respectively. *L* is the Obukhov length, and $x' = (1 - 16\zeta)^{1/4}$. The similarity relation (1) coupled with (2) in unstable conditions can be applied to heights greater than |*L*|, even though, strictly speaking, they are valid for smaller heights. Similarly, Expression (3) for stable conditions, in addition to being applicable for $z < L$, can also be used for $z > L$ with good accuracy (van Ulden and Holtslag, 1985).

Figure 1 compares the wind speeds estimated using the M-O similarity with the observed wind speed at six heights over the urban area. At heights of 31.7 m and 22.4 m, M-O surface similarity theory is able to describe the data satisfactorily, but for the lower levels there is an increasing overestimation of the observations. Such departure from the similarity behaviour is expected as these measurement levels lie very close or within the height of the roughness element for which similarity theory is not applicable. Even the levels 31.7 m and 22.4 m are influenced by the local roughness element and, therefore, probably lie within the roughness sublayer. Consequently, M-O similarity may only be valid approximately for these two levels, although similarity results are in reasonable agreement with the data.

4. 2-D URBAN INTERNAL BOUNDARY LAYER MODEL

4.1. Internal boundary layer height over urban area

There are a number of formulae of varying complexity to estimate the growth of the IBL (see Garratt, 1990; Savelyev and Taylor, 2005). One such formula based on Miyake's diffusion analogy and discussed by Savelyev and Taylor (2005) is

$$U(h)\frac{dh}{dx} = A\,\sigma_w, \tag{4}$$

where *h* is the height of the IBL, *x* is the downwind distance from the roughness change, *U*(*h*) is the wind speed at height *h*, and *A* (≈1) is a constant. We consider the values of *U*(*h*) and σ_w to be those of the modified flow (i.e. over the urban surface).

We assume that Monin-Obukhov surface similarity theory is valid within the IBL over an urban area, which is a reasonable assumption, given the comparisons presented earlier. We substitute for *U* from Equations (1), and σ_w from

$$\sigma_w = 1.25 u_* \left(1 - 3\frac{(z-d)}{L}\right)^{1/3}, \quad \text{for } L<0 \tag{5}$$

$$\sigma_w = 1.25 u_*, \quad \text{for } L \geq 0. \tag{6}$$

at $z = h$ into Equation (4). Note that u_* cancels out; however, *L* for the urban area needs to be specified. We assume that under unstable rural conditions, the urban *L* is the same as the rural value, and under stable rural conditions the urban stability is neutral. Equation (4) is solved numerically for the growth of *h* with *x* using a 4th order Runge-Kutta scheme with z_0 and *d* for the urban area as inputs coupled with the above assumption about *L*.

There may be significant mean vertical velocities caused by local horizontal gradients of the mean wind speed after a step change in surface conditions in order to satisfy continuity constraints. Such a velocity may need to be included in Equation (4) (Savelyev and Taylor, 2005), but we neglect such effects here.

4.2. Calculation of the urban friction velocity

We assume that the flow over the urban area above the height *h* is the same as that above the rural area. Therefore, by equating the rural and urban wind speeds at $z = h$, we obtain the following expression for the urban friction velocity

$$u_{*,U} = u_{*,R}\frac{\ln\left(\frac{h-d_R}{z_{0,R}}\right) - \psi_m\left(\frac{h-d_R}{L_R}\right) + \psi_m\left(\frac{z_{0,R}}{L_R}\right)}{\ln\left(\frac{h-d_U}{z_{0,U}}\right) - \psi_m\left(\frac{h-d_U}{L_U}\right) + \psi_m\left(\frac{z_{0,U}}{L_U}\right)}, \tag{7}$$

where the subscripts *R* and *U* represent rural and urban conditions. However, Equation (7) cannot be used as it is because L_U, which itself is a function of $u_{*,U}$ is not known.

We assume that under the daytime convective mixing (i.e. unstable) conditions, L_U is the same as L_R. This is a tentative assumption, but can be justified on the grounds that the sensible heat flux from an urban surface is usually greater than that from a rural area (not shown) due to the characteristics of the urban surface and the presence of an anthropogenic heat flux, and this increase in the sensible heat flux tends to compensate for the increase in the friction velocity over the urban surface in the calculation of L_U. Therefore, when $L_R < 0$

$$u_{*,U} = u_{*,R}\frac{\ln\left(\frac{h-d_R}{z_{0,R}}\right) - \psi_m\left(\frac{h-d_R}{L_R}\right) + \psi_m\left(\frac{z_{0,R}}{L_R}\right)}{\ln\left(\frac{h-d_U}{z_{0,U}}\right) - \psi_m\left(\frac{h-d_U}{L_R}\right) + \psi_m\left(\frac{z_{0,U}}{L_R}\right)}. \tag{8}$$

For typical rural conditions, the terms d_R and $\psi_m(z_{0,R}/L_R)$ in Equation (8) can be neglected.

When rural conditions are stable in the nighttime (i.e. $L_R > 0$), it is reasonable to assume that the boundary layer is neutral (e.g. Britter and Hanna, 2003) as the air mass travels from an area where the heat flux is negative to the center of the much rougher urban area where the heat flux can be slightly positive. Hence, Equation (7) can be written as:

$$u_{*,U} = u_{*,R} \frac{\ln\left(\frac{h-d_R}{z_{0,R}}\right) - \psi_m\left(\frac{h-d_R}{L_R}\right) + \psi_m\left(\frac{z_{0,R}}{L_R}\right)}{\ln\left(\frac{h-d_U}{z_{0,U}}\right)}, \quad (9)$$

Hence, we can now calculate the friction velocity and the wind speed profile within the IBL over the urban area given the rural meteorology (above the IBL, the wind profile is taken to be the same as the rural one). The IBL height at a distance of $x = 5$ km from the urban boundary was used in the above calculations for BUBBLE case. In the following, we compare urban values observed at 22.4 m with the estimated values. An analysis of the BUBBLE data by Christen and Rotach (2004b) shows that the data at 22.4 m AGL represent the overall surface measurement conditions better than the data at any other height.

4.3. Results from the analytical scheme

Figure 2a presents a scatter plot of the observed u_* values over the urban area from BUBBLE vs. the estimates from the analytical scheme for unstable conditions (i.e. when $L_R < 1$). Although there is a significant scatter, it is clear that the proposed scheme predicts urban friction velocities that are in reasonable agreement with the observations. 85% of the model estimates lie within a factor of two of the observations. Figure 2b is the same as Figure 2a, except for stable conditions. The sample size is only 40 compared to 204 for unstable conditions. There is some overestimation of the observed u_*: approximately 70% of the predictions are within a factor of 2.

5. 3-D MESOSCALE MODEL

The mesoscale model TAPM is a three-dimensional, prognostic meteorological and air pollution model, and is used here to study the flow transition from rural to urban areas. Details of the model are given in Hurley (2002) and Hurley et al. (2005). Hurley et al. (2003) and Luhar and Hurley (2003) describe model validation studies conducted using TAPM.

5.1. Model Configuration - BUBBLE

TAPM (version 3.0) was run for the period 10 June – 10 July 2002. We used four nested grid domains at 20, 7.5, 2, 0.5 km resolution (35 × 35 grid points), all centered at the location (7°36′ E, 47°34′ N), which is equivalent to 612.144 east and 268.452 km north in the CH1903 coordinate system, and is almost the location of the U1 (Bspr) urban monitoring site. The lowest ten of the 25 vertical levels were 10, 25, 50, 100, 150, 200, 250, 300, 400 and 500 m, with the highest model level at 8000 m.

In view the objective of the present study, i.e. to estimate surface-layer meteorology over an urban area given upwind rural meteorology, we assimilated wind speeds and wind directions observed at 3.3 m at the rural site R2 in TAPM while allowing the model to adjust these winds over the urban area, the latter can then be compared with the observations made at the urban site U1. In this way, the TAPM setup is also consistent with the analytical technique used earlier in which the observed rural meteorology is used.

5.2. Model Configuration – JU2003

The period of 2 July – 31 July 2003 was selected for TAPM simulations. Four nested domains of which horizontal grid spacings are 32, 8, 2, and 0.5 km. The numbers of horizontal grid of all the domains is 40 by 40 in easting and northing, respectively, and is centered at (633.860 km, 3923.945 km) of UTM zone 14. The selected vertical computational layers were identical to those of the BUBBLE case. Data assimilation was conducted with observed wind speeds and directions measured at 10 m AGL of Tower #3.

5.3. Modeling Results

The TAPM results were compared with measurements taken at 10 m AGL of Tower #5, which was located in a warehouse urban area. The predicted wind speeds are in reasonable agreement with observations (Figure 3). As evident from Figure 3b, the prevailing wind direction in the Oklahoma City during the field campaign was southerly, which was well simulated. The estimated friction velocities also compare well with observations.

The scatter plot in Figure 4a compares TAPM predicted u_* with the observations at the rural site R2 (the total number of observations is 245, dominated by unstable conditions). The model performance is very good, which is partly due to the fact that the observed winds at R2 have been assimilated in the model. Figure 4b shows that the model is able to simulate u_* at the urban site U1 ($r^2 = 0.48$), and that the model u_* values at U1 are higher than those at R2, which is consistent with observed behaviour.

6. CONCLUSIONS

This paper used two methods to estimate urban micrometeorology from rural surface measurements: the first based on a two-dimensional internal boundary layer model that uses Monin-Obukhov surface similarity theory and rural variables as upwind inputs, and the second uses a 3D prognostic model, CSIRO's TAPM, in which upwind rural observations are assimilated. Results from these methods were compared with high quality data collected from field campaigns. Urban surface friction velocities estimated from both methods compared well with corresponding observations. TAPM performance was slightly better than that of the internal boundary layer model. The results indicate that the internal boundary layer model might be suitable for routine dispersion applications involving models such as AERMOD.

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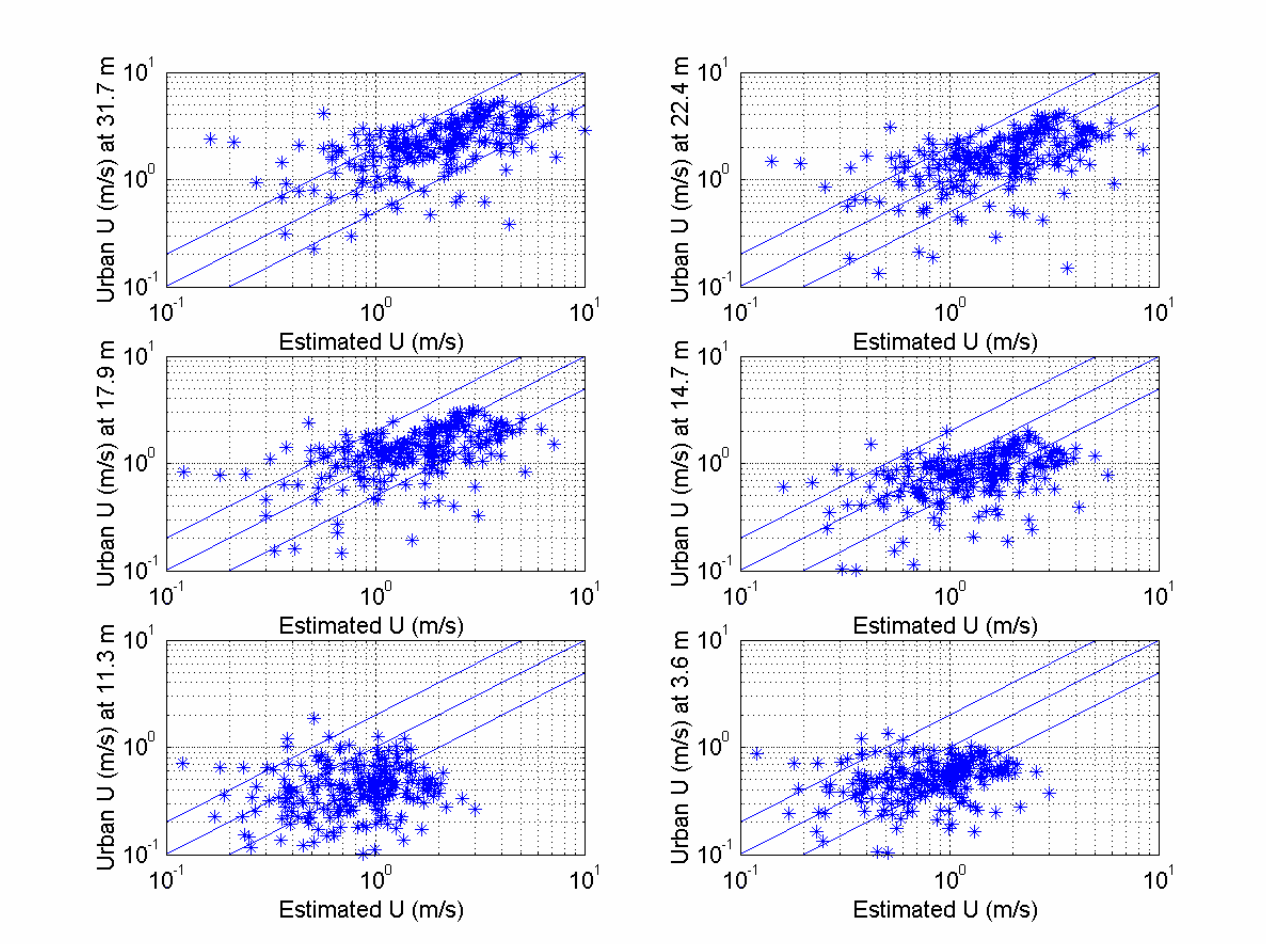

Figure 1: Scatter plots of wind speeds estimated using M-O similarity versus observed wind speeds at six heights over the urban area (U1) of BUBBLE.

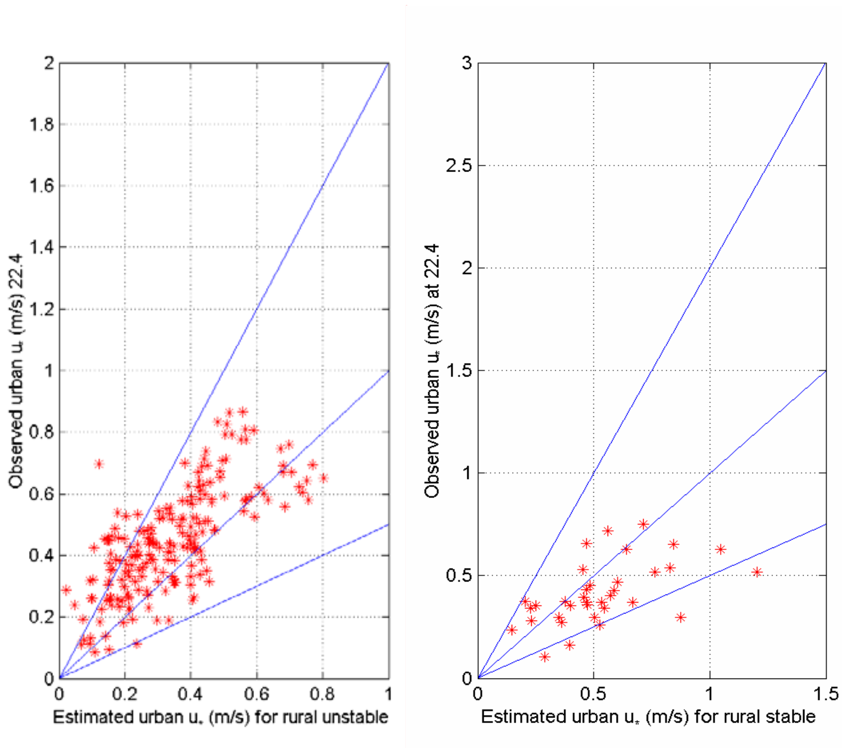

Figure 2. Scatter plot of observed u_* at 22.4 m of U1 versus internal boundary layer model estimates for (a) unstable case (i.e. when the rural Obukhov length is < 0), and (b) stable case (rural Obuhkov length is >0) .

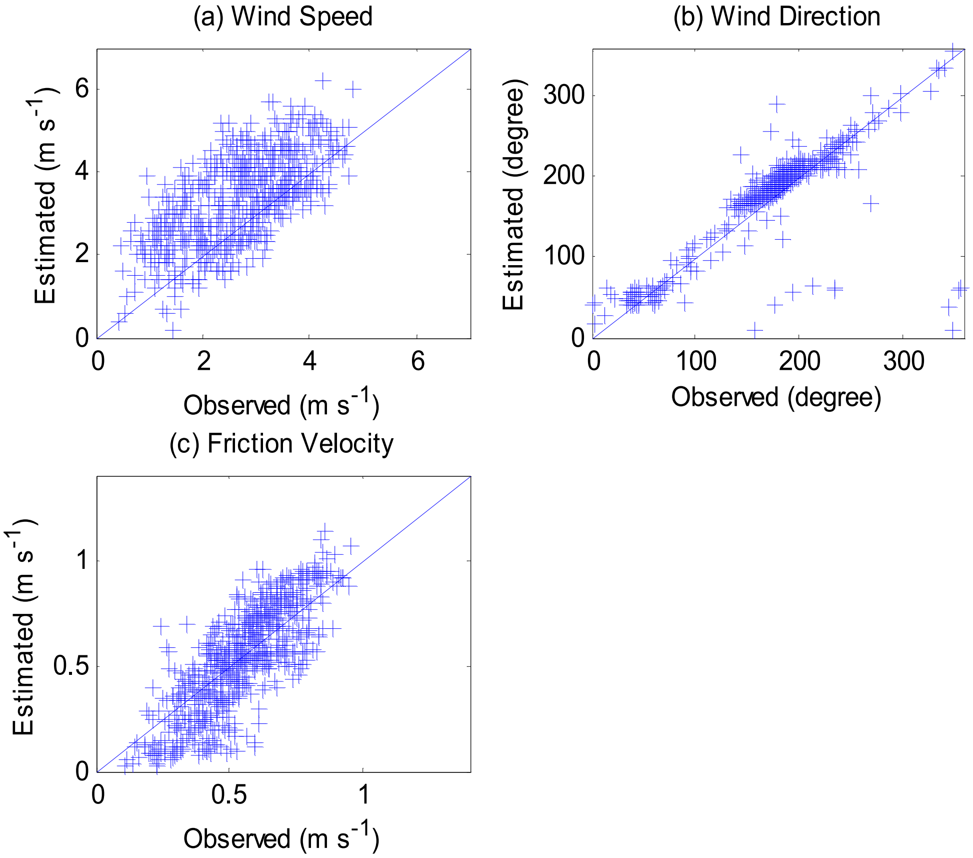

Figure 3. Scatter plot of TAPM-predicted versus observed (a) wind speed, (b) wind direction, and (c) Friction velocity at US ARL Tower 5.

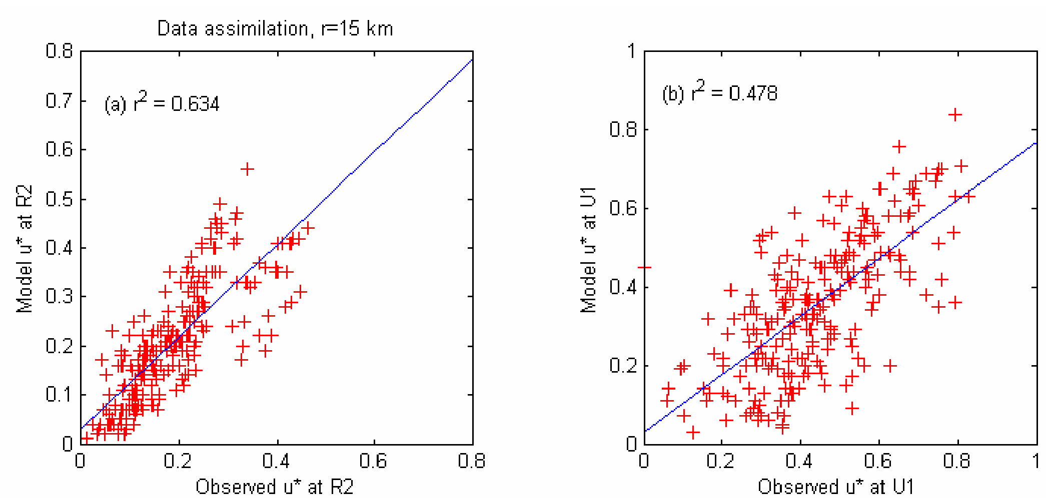

Figure 4. Comparison of TAPM-predicted u_* with observed values at (a) R2 – rural site, and (b) U1 – urban site.