# P1.8 ESTIMATING WIND SPEED AT AN URBAN REFERENCE HEIGHT

Andreas Christen(1)*, Mathias W. Rotach(2)
(1) University of Basel, Institute of Meteorology, Climatology and Remote Sensing, Basel, Switzerland.
(2) Swiss Federal Institute of Meteorology and Climatology, MeteoSwiss, Zürich, Switzerland.

## 1 INTRODUCTION

In many applications and studies, standardized urban wind observations are requested. Measurements recorded at any urban site should be comparable with other simultaneously measured urban or rural wind speeds and/or representative as wind input data for dispersion modeling. Therefore, reference heights $z_{ref}$ for wind speed measurements in urban areas are in discussion (Rotach *et al.*, 2000). Currently, different reference heights are suggested, e.g. $z_{ref} = z_d + 10$ m or $z_{ref} = 1.25h$, with $z_d$ the zeroplane displacement and $h$ the mean building height. However, available urban observations are usually not from that height.

In this contribution we do not discuss the suitability of the different reference heights, but verify a procedure to estimate wind speed at any 'reference' height from measurements taken at any other height in the urban roughness sublayer.

## 2 THE COST 715 PROCEDURE

The recently suggested procedure of the European COST 715 Action (Rotach *et al.*, 2004a) uses three simple steps, based on the knowledge from a number of previous field and wind tunnel experiments.

**Step 1:** The urban zeroplane displacement $z_d$ and the roughness sublayer height $z_*$ are estimated from the mean building height and building density by empirical relationships.

**Step 2:** Various experiments demonstrated, that local Reynolds stress varies with height and shows a maximum at $z_*$, which is denoted as $u_*(z_*)$. The following parameterization for the vertical profile of $u_*(z)$ has been proposed by Rotach (2001), where $a$ and $b$ are empirical constants of 1.28 and 3.0, respectively:

$$\left(\frac{u_*(z)}{u_*(z_*)}\right)^b = \sin\left(\frac{\pi}{2}\frac{(z-z_d)}{(z_*-z_d)}\right)^a \quad \text{for } z_d < z < z_* \tag{1}$$

$$u_*(z) = u_*(z_*) \quad \text{for } z \geq z_* \tag{2}$$

Hence, from a (measured) local Reynolds stress $u_*(z)$ at any height $z$ above $z_d$, the profile of local Reynolds can be deduced with (1) and (2). If no measured local Reynolds stress is available at all, the parameterization of Hanna and Chang (1992) may be applied or Reynolds stress measurements from a rural site can be used to estimate $u_*(z_*)$ according to Bottema (1995), where $\alpha$ is an empirical factor of 0.0706:

$$\frac{z_{0,urban}}{z_{0,rural}} = \left(\frac{u_*(z_*)_{urban}}{u_{*,rural}}\right)^\alpha \tag{3}$$

**Step 3:** The wind profile is calculated by numerically integrating (4) which then returns the wind speed $u(z)$ at any height:

$$\frac{\partial u}{\partial z} = \frac{u_*(z)}{k(z-z_d)}\phi_m \tag{4}$$

$$\text{with } \phi_m = \left(1 - 19.3\frac{(z-z_d)}{L(z)}\right)^{1/4} \quad \text{for } L < 0 \tag{5}$$

$$\text{and } \phi_m = 1 + 6\frac{(z-z_d)}{L(z)} \quad \text{for } L > 0 \tag{6}$$

Note that (4) is based on a local Reynolds stress from the parameterization, and (5) and (6) use a local Obukhov length $L$ for each height layer. For simplicity, sensible heat flux density is assumed to be constant with height.

## 3 VERIFICATION OF THE PROCEDURE

This procedure has been thoroughly and independently tested with data from the Basel Urban Boundary Layer Experiment (BUBBLE, Rotach *et al.* 2004b). Long-term wind and turbulence profile measurements at the urban tower "Basel-Sperrstrasse" allow the validation of the procedure with various input configurations and measurement heights under different situations. The estimated 'reference' wind speeds calculated with the procedure are compared to wind speeds directly measured at 'reference' height.

The experimental tower 'Basel-Sperrstrasse' with a height of 32 m (up to $z/h = 2.2$) supported a vertical profile of six 3D-ultrasonic anemometer-thermometers at $z/h$ = 0.25, 0.77, 1.01, 1.23, 1.53 and 2.17 (for a detailed description of the instrumentation see Christen *et al.* 2004a, Paper 6.4, *this conference*). Data from December 1, 2001 to July 15, 2002 has been analyzed. From this initially 5424 hour long period,

---

* *Corresponding author address:*
Andreas Christen
Institute of Meteorology, Climatology and Remote Sensing,
Department of Geosciences, University of Basel
Klingelbergstrasse 27, CH-4056 Basel, Switzerland
e-mail: andreas.christen@unibas.ch

**Tab. 1:** Ratio between zeroplane displacement and mean building height $z_d/h$ calculated for the site "Basel-Sperrstrasse" for the different flow situations and with different approaches.

| Sector | All | *A* | *B* | *C* |
|---|---|---|---|---|
| *h* (m) | 14.6 | 14.0 | 13.2 | 19.4 |
| *Morphometry* | | | | |
| COST 715 Procedure | 0.70 | 0.70 | 0.70 | 0.70 |
| Kutzbach (1961) | 0.84 | 0.79 | 0.80 | 0.84 |
| Counihan (1971) | 0.73 | 0.60 | 0.63 | 0.74 |
| Raupach (1994) | 0.62 | 0.64 | 0.63 | 0.57 |
| Bottema (1995) | 0.69 | 0.62 | 0.64 | 0.70 |
| Macdonald et al. (1998) | 0.79 | 0.72 | 0.73 | 0.80 |
| Kastner-Klein and Rotach (2004) | 0.92 | 0.87 | 0.89 | 0.92 |
| *Measurements* | | | | |
| Neutral wind profile | 0.74 | 0.82 | 0.78 | 0.78 |
| Jackson (1981) | 0.67 | 0.61 | 0.73 | 0.58 |

3752 hours provide error free data simultaneously measured at all 6 ultrasonic anemometer levels.

The analysis was done separately for 3 flow directions. The sectors represent the approach direction of the main synoptic flow (*A*, 270°-310°) a convective summertime wind system (*B*, 310°-360°), and the main nocturnal cold air drainage (*C*, 90°-160°). The three wind sectors incorporate 75% of all situations. The surface in the directions of *A* and *B* is remarkably homogeneous, and consists of residential multi-storey row houses, enclosing large inner courtyards ($h$ = 13.6 m, plan aspect ratio $\lambda_P = 0.46$). The sector *C*, is more heterogeneous with commercial building blocks which are higher and larger ($h \approx 20$ m, $\lambda_P = 0.55$) than the typical residential areas in the source area of *A* and *B*. On average, the urban surface has an aerodynamically determined roughness length of $z_0$ = 2.1 m.

### 3.1 Zeroplane displacement

The zeroplane displacement $z_d$ in the COST procedure is simply estimated with the urban 'rule-of-thumb', $z_d = 0.7h$ (Grimmond and Oke, 1999). This value is compared to other empirical relations in Tab. 1. The morphometrical data was deduced from a high resolution digital building model with 1 m raster size and for a domain of 250 m around the site. The values deduced from the neutral logarithmic wind profile were calculated with the topmost 3 measurement levels. The neutral wind profiles suggest a slightly higher $z_d$ around 0.8*h* for this dense urban surface. In general the 'rule-of-thumb' is a pragmatic approximation. For further verification steps $z_d = 0.7h$ is considered.

### 3.2 Roughness sublayer height

The determination of the roughness sublayer height $z_*$ from measurement data is not a well investigated problem, and no standard procedures exist. This may be due to the fact that the roughness sublayer does not have a well defined upper boundary $z_*$ and different definitions exist. More realistic is a gradual transition from a three-dimensional, horizontal-non-homogeneous flow to a horizontally homogeneous flow in the inertial sublayer (IS). From the data we can retrieve different indications that help us defining a $z_*$.

**Tab. 2:** Probability for each of the six measurement levels at 'Basel-Sperrstrasse' to measure the highest $u_*(z)$ under different flow situations.

| Sector | All | *A* | *B* | *C* |
|---|---|---|---|---|
| Samples | 3752 h | 760 h | 535 h | 1489 h |
| $z/h$ = 2.17 | 19.3% | 18.4% | 19.1% | 2.4% |
| $z/h$ = 1.53 | **61.5%** | **40.1%** | **59.4%** | **95.2%** |
| $z/h$ = 1.23 | 11.9% | 27.2% | 12.7% | 1.2% |
| $z/h$ = 1.01 | 4.4% | 10.5% | 5.6% | 0.2% |
| $z/h$ = 0.77 | 1.1% | 0.9% | 1.5% | 0.5% |
| $z/h$ = 0.25 | 1.7% | 2.8% | 1.7% | 0.6% |

a) $z_*$ is the height were the maximal local Reynolds stress $u_{*max}$ is found.
b) $z_*$ is the height, where under neutral conditions surface layer values are reached.
c) $z_*$ is the height were the horizontal standard deviation $\sigma''_x$ of a local scaled turbulence parameter *x* (or the variability at a single point under different wind directions) approaches zero.
d) $z_*$ is the height were the vertical divergence $\partial Q/\partial z$ of turbulent fluxes of heat $Q_H$ and water vapor $Q_E$ reach zero ('blending height').

The different definitions result in a large variability of estimates. Previous field and wind tunnel measurements indicate that $z_*$ can be as low as 1.5*h* at densely built-up sites but up to 4*h* in low density areas (Grimmond and Oke, 1999, Rotach, 1999). Condition (a) is most relevant for the current parameterization. In the present context we interpret $z_*$ mainly as the height of the maximum Reynolds stress $u_{*max}$ is

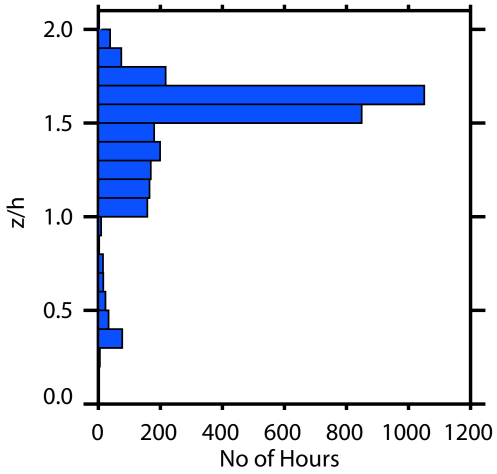

**Fig. 1:** Histogram of $u_{*max}$. For the exact height of $u_{*max}$ a cubic spline interpolation was performed between the 6 ultrasonic anemometer levels.

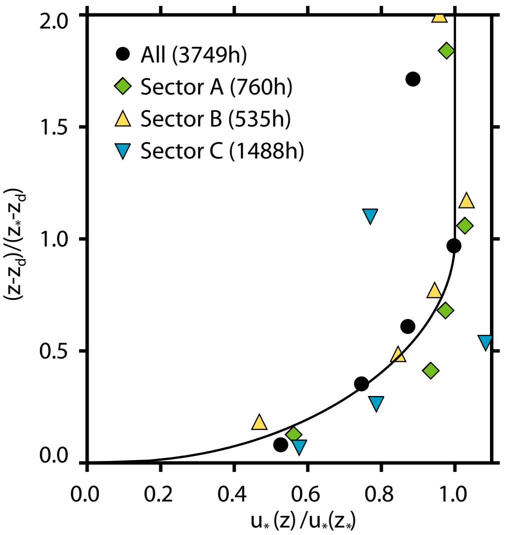

**Fig. 2:** Parameterization of the $u_*$ profile according formula (1) and (2) (line) in comparison with measured values of $u_*(z)/u_*(z_*)$ at 'Basel-Sperrstrasse' for the different wind direction classes.

measured, rather than the height, where the influences of individual roughness elements vanish.

On average, the level at 22.4 m shows the highest probability to measure $u_{*max}$ (Tab. 2). The height of $u_{*max}$ is surprisingly constant for the different flow situations. Fig. 1 shows the histogram for all wind directions (0-360°).

This low value of $z_*$ can be attributed to the compactness, high density and homogeneity of the urban surface. Comparable low values of $z_*$ are suggested by neutral surface layer values of the wind components (local scaling) and by the vertical divergence of sensible heat flux, which is negligible small above $z/h > 1.4$ (Christen and Vogt, 2004b). Other turbulence statistics like dissipation rate $\varepsilon$ or spectral characteristics are variable up to at least 2$h$. Wind tunnel results from the surface around "Basel-Sperrstrasse" show that horizontal inhomogeneities are measurable up to a height of 3.5h (Feddersen *et al.*, 2004, paper 6.5, *this conference*).

### 3.3 Parameterization of the vertical $u_*$ profile

Fig. 2 illustrates the parameterization for $u_*$ according formula (1) and (2). Symbols denote measured values of $u_*(z)/u_*(z_*)$ at 'Basel-Sperrstrasse' for the different wind direction classes. Observational data are processed with an individual $h$ for each of the wind sectors, a $z_d$ of 0.7$h$ and a $z_*$ of 1.55$h$.

The temporally averaged profile (0°-360°, filled circles in Fig. 2) fits well the parameterization and also the situations *A* and *B* have a good agreement. The cold air drainage from sector *C* however, shows low performance. This suggests, that either the attributed $h$ or $z_*$ do not represent the real forcing or the more heterogeneous source area modifies significantly the local structure of the momentum transport.

Formula (2) suggests to interpret any measured $u_*(z)$ above $z_*$ as $u_*(z_*)$. The observations show, that the measured profile of $u_*$ above $z_*$ is decreasing. This decrease is negligible small in the 'ideal' sectors *A* and *B* where the difference between $u_*$ at tower top and $u_*(z_*)$ is only -4% in the average. Again, the cold air drainage sector *C* shows low performance. Here, $u_*$ strongly decays by more than 20% from the second topmost measurement to tower top (Fig. 2). This can be an effect of a very local shear layer produced from the overflow of a nearby pike-roof which reaches up to $z/h$=1.66.

### 3.4 Determination of $u_*$ from a rural measurement.

In the case, a measurement of Reynolds stress is only available outside the city Formula (3) is applied to model the urban $u_*(z_*)$. The modeled urban $u_*(z_*)$ can be further put into (2) and (3) to determine the profile of $u_*(z)$.

In order to test this scenario, data from the rural site 'Village Neuf' was used. The site is located 4 km North of the city in an ideal and flat area with agricultural land use. The roughness length $z_0$ at this rural site was determined to be 0.07 m with the neutral logarithmic wind profile (3 levels).

Figure 3 shows the comparison between the measured urban $u_*(z_*)$ and the modeled urban $u_*(z_*)$ according formula (3). The plot shows only flow situations from sector *B*, when the rural site is in the upwind direction of the city. In this case, applying formula (3) leads to a systematical underestimation of the urban $u_*(z_*)$ by 30%. The underestimation is remarkably stronger in periods when the rural site lies

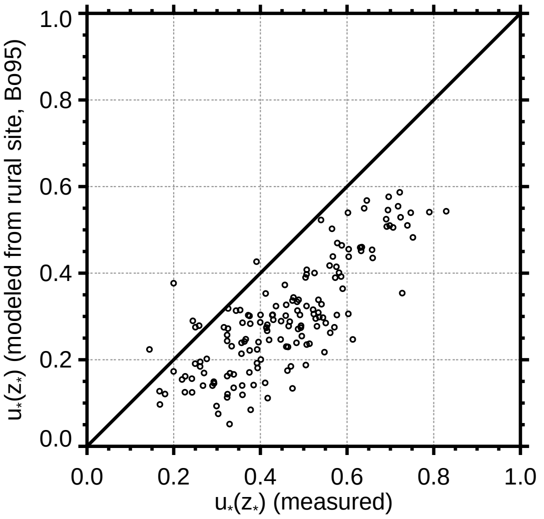

**Fig. 3:** Comparison of the measured urban Reynolds stress at $z_*$ with its modeled values based on the measurements from the rural site 'Village Neuf' according to Bottema (1995). Shown are hourly averages from May 6 to July 13, 2002, with wind from Sector *B*,. In this flow direction rural measurements are undisturbed by the city.

**Tab. 3:** Performance to predict wind speed at reference height $u$ ($z_d$+10m = 24.6 m) with different input configurations for all flow sectors. Data analysis was done for all stabilities and situations where the measured wind speeds at $z_{\mathrm{ref}}$ was between 1 and 10 m/s.

| Input $u$ | $u_*$ from urban measurement | | | $u_*$ from rural measurement | | |
|---|---|---|---|---|---|---|
| $z$, $z/h$ | $a$ | $r^2$ | $RMS$ | $a$ | $r^2$ | $RMS$ |
| 31.7 m, 2.17 | 0.93 | 0.73 | 0.66 | 1.22 | 0.71 | 0.97 |
| 22.4 m, 1.53 | 0.95 | 0.97 | 0.20 | 1.02 | 0.72 | 0.64 |
| 17.9 m, 1.23 | 1.03 | 0.97 | 0.25 | 0.89 | 0.68 | 0.87 |
| 14.7 m, 1.01 | 1.00 | 0.90 | 0.62 | 0.52 | 0.47 | 1.31 |
| 11.3 m, 0.77 | 1.08 | 0.41 | 3.90 | 0.16 | 0.16 | 1.62 |

downwind of the city (i.e. sector *C*, not shown). Then, the procedure shows an underestimation of the urban $u_*(z_*)$ by 70% on average. Flow from sector *A* results in an underestimation of 50%. This suggests, that beside local effects at the urban site, the procedure gives only reasonable results, when the wind flow at the rural site is undisturbed by the city.

### *3.5 Determination of the reference wind speed*

Table 3 compares the modeled wind speed at a 'reference height' ($z_d$ + 10 m, 24.6 m) to measured (interpolated) values at same height. The table lists the overall statistics for different input configurations in terms of the slope of a linear regression ($a$, with $u_{\mathrm{modeled}} = a\ u_{measured}$), the square of the linear Pearson correlation coefficient between measurement and modeled wind speed ($r^2$) and the root mean square error in m/s (RMS).

It is no surprise that results are sensitive to the distance $z_{input}$ - $z_{ref}$ i.e. levels that lie close to $z_{ref}$ (e.g. 22.4 m) result in a better performance and a higher correlation than levels with a larger vertical distance to $z_{ref}$. In general, modeled values with input parameters from below $z_{ref}$ systematically overestimate the measured wind speed at $z_{ref}$. The overestimation is most pronounced when an overall wind direction along the canyon axis is observed. The associated flow channeling within the street canyon increases local values of the input $u(z)$ and $u_*(z)$ close to the roofs and in the upper canyon part relatively to the horizontal average and as a consequence also $u_{ref}$ is overestimated by integrating upwards.

Taking the topmost measurement level as input for both $u_*$ and $u$ (31.7m, $z_{input} > z_{ref}$), the model underestimate $u(z)$ typically by 10%. This is mainly an effect of the disturbances in Sector C (Fig. 2), where the topmost $u_*(z)$ is remarkably lower than $u_*(z_*)$. The more homogeneous sectors A and B do not show this underestimation.

The calculations with rural $u_*$ values result in higher scatter between the modeled and in-situ measurements. The modeled urban $u_*(z_*)$ determined by the empirical formula (3) are strongly underestimated, which in consequence lowers the local gradients $\partial u/\partial z$ in (4). Calculations with numerical integration downward result in an overestimation and the ones with an upward integration show an underestimation. This effect could be avoided by altering the empirical factor $\alpha$ in Equation (3) and by using a rural site which is not anymore influenced by the city.

## 4 CONCLUSIONS

Overall, the results of the procedure are encouraging, and most configurations result in reasonable estimates of the wind speed at the reference height. The estimation of $z_*$ - interpreted as the height of maximum local Reynolds stress - is surely the most problematic input parameter of the procedure.

The performance of the procedure is strongly dependent on how representative the input wind measurements $u(z)$ are in the horizontal average. Larger errors are associated with flow directions that have strong inhomogeneities and a highly variable building height (i.e. the sector C). Also, input data from the street canyon below $h$ should be avoided.

## REFERENCES

Bottema M (1995): 'Aerodynamic Roughness Parameters for Homogeneous Building Groups', document Sub-Meso #18, Lab. de Mécanique des Fluides, Ecole Centrale de Nantes.

Christen A, Rotach MW, Vogt R (2004a): 'Experimental determination of the turbulent kinetic energy budget within and above an urban canopy'. *This conference.* Paper 6.4.

Christen A, Vogt R (2004b): 'Energy and Radiation Balance of a central European city'. Accepted by: *Int. J. Climatol.*

Counihan J (1971): 'Wind tunnel determination of the roughness length as a function of fetch and density of three-dimensional roughness elements'. *Atmos. Environ.* 5. 273-292.

Feddersen B, Leitl B and Schatzmann M (2004): 'Wind tunnel modelling of urban turbulence and dispersion over the City of Basel (Switzerland) within the BUBBLE project'. *This conference.* Paper 6.5.

Grimmond CSB, Oke TR. (1999): 'Aerodynamic properties of urban areas derived from analysis of surface form'. *J. Appl. Meteor.* 38 (9): 1262-1292.

Hanna SR, Chang JC (1992): 'Boundary-layer Parameterizations for Applied Dispersion Modeling over Urban Areas', *Boundary-Layer Meteorol.*, 58, 229–259.

Jackson, PS (1981): 'On the Displacement Height in the Logarithmic Velocity Profile', *J. Fluid Mech.* 111, 15–25.

Kastner-Klein P, Rotach MW (2004): 'Mean flow and turbulence characteristics in an urban roughness sublayer'. *Boundary-Layer Meteorol.*, 111, 55–84.

Kutzbach J (1961): 'Investigations of the modifications of wind profiles by artificially controlled surface roughness'. M.S. thesis, Department of Meteorology, University of Wisconsin, Madison, 58 p.

Macdonald RW, Griffiths RF, Hall DJ (1998): 'An improved method for estimation of surface roughness of obstacle arrays'. *Atmos. Environ.* **32.** 1857-1864.

Raupach MR (1984): Drag and drag partition on rough surfaces. Bound.-Layer Meteor. 71. 211-216.

Rotach MW (1999): 'On the influence of the urban roughness sublayer on turbulence and dispersion'. *Atmos. Environ.* 33 (24-25): 4001-4008.

Rotach MW, Batchvarova E, Berkowicz R, Brechler J, Janour Z, Kastner-Klein P, Middleton DR, Prior V, Sacré C, Soriano C (2000): 'Wind input data for urban dispersion modeling – Activities of working group 1 within COST 715'. *3rd Symposium on the Urban Environment*, 14-18 August 2000, Davis, CA, USA.

Rotach MW (2001): ‘Simulation of urban-scale dispersion using a Lagrangian stochastic dispersion model’, *Boundary-Layer Meteorol*., 99, 379-410.

Rotach MW, Batchvarova E, Berkowicz R, Brechler J, Christen A, Georgieva E, Janour Z, Krajny E, Middleton D, Osrodka L, Prior V, Soriano C (2004a): ‘Modification of flow and turbulence structure over urban areas’, in: Fisher B., Rotach MW, Piringer M, Kukkonen J, Schatzmann M. (Eds): ‘Meteorology applied to urban air pollution problems’. Final report of COST 715, *in preparation.*

Rotach MW, Vogt R, Bernhofer C, Batchvarova E, Christen A, Clappier A, Feddersen B, Gryning S-E, Martucci G, Mayer H, Mitev V, Oke TR, Parlow E, Richner H, Roth M, Roulet YA, Ruffieux D, Salmond J, Schatzmann M, Voogt J (2004b): ‘BUBBLE – a Major Effort in Urban Boundary Layer Meteorology’. Submitted to: *Theor. Appl. Climatol.*