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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:

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

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

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 α is an empirical factor of 0.0706:

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

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

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

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

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

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,

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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
<i>Morphometry</i>				
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
<i>Measurements</i>				
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 $0.8h$ 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

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%

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_* .

- z_* is the height where the maximal local Reynolds stress u_{*max} is found.
- z_* is the height, where under neutral conditions surface layer values are reached.
- z_* is the height where the horizontal standard deviation σ'_x of a local scaled turbulence parameter x (or the variability at a single point under different wind directions) approaches zero.
- z_* is the height where 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 $1.5h$ at densely built-up sites but up to $4h$ 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

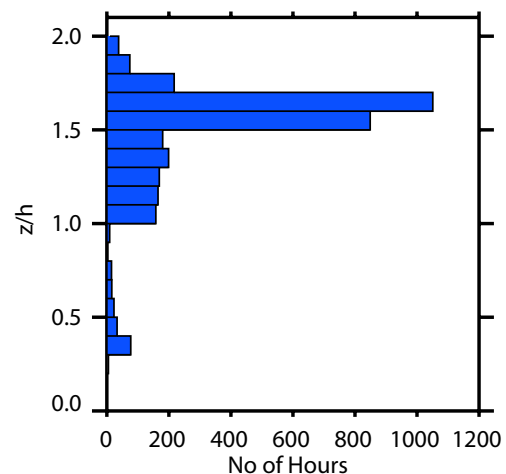


Fig. 1: Histogram of u_{*max} . For the exact height of u_{*max} , a cubic spline interpolation was performed between the 6 ultrasonic anemometer levels.

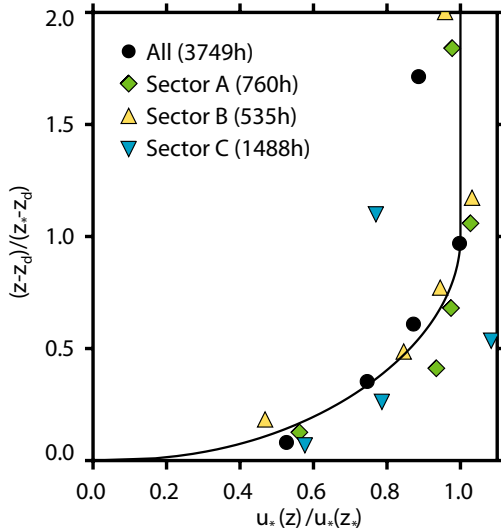


Fig. 2: Parameterization of the u_* profile according formula (1) and (2) (line) in comparison with measured values of $u_*(z)/u_*(z_*)$ at 'Basel-Sperrstrasse' for the different wind direction classes.

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 ε or spectral characteristics are variable up to at least $2h$. 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_0 of $0.7h$ and a z_* of $1.55h$.

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 up-wind 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

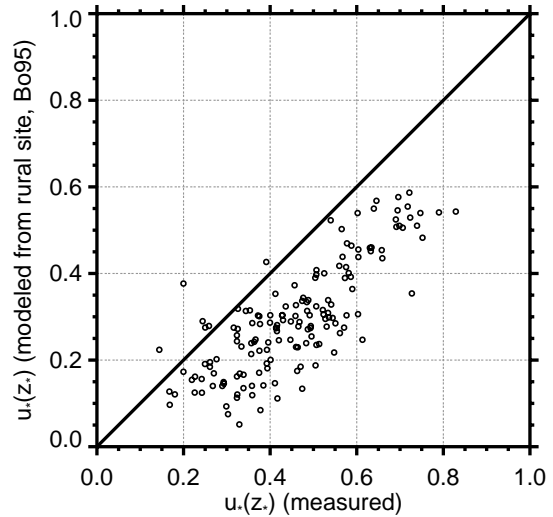


Fig. 3: Comparison of the measured urban Reynolds stress at z_* with its modeled values based on the measurements from the rural site 'Village Neuf' according to Bottema (1995). Shown are hourly averages from May 6 to July 13, 2002, with wind from Sector B. In this flow direction rural measurements are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

Tab. 3: Performance to predict wind speed at reference height u ($z_{ref}+10m = 24.6$ 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_{ref} was between 1 and 10 m/s.

Input u $z, z/h$	u_* from urban measurement			u_* from rural measurement		
	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 $u_{modeled} = a u_{measured}$), 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 α 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.

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