PROFILE MEASUREMENTS OF SELECTED TURBULENCE CHARACTERISTICS OVER DIFFERENT URBAN SURFACES

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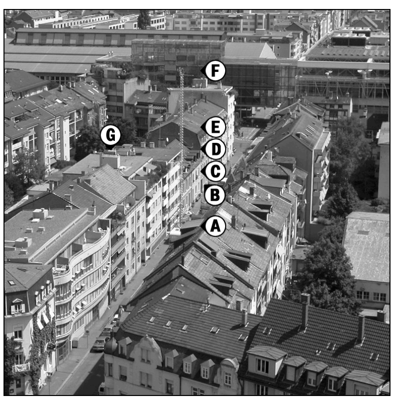
Abstract: In the framework of the Basel Urban Boundary Layer Experiment (BUBBLE, 2001-2002) a number of measurement towers were installed in the City of Basel (Switzerland). Turbulence and flux characteristics were measured at these sites nearly over one year from approximately 2.2 times the building height down into street canyons and backyards. Vertical profiles of selected turbulence characteristics are presented from three sites (2 urban, 1 suburban). The discussion includes mean and turbulent wind, with TKE, local Reynolds stress and skewness of vertical wind. The results confirm that the largest gradients are found around roof level. It is shown how profiles are altered by the direction of the approaching flow relative to the canyon. Overall, the three different sites show high similarity. This points out that mean profiles are useful, even in the complicated 3-dimensional flow environment of the urban roughness sublayer.

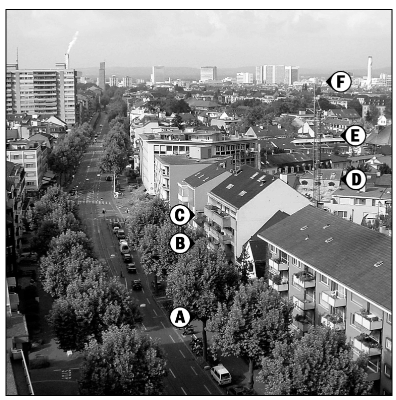
Keywords: Urban roughness sublayer, turbulence, field measurements, ultrasonic anemometer profiles.

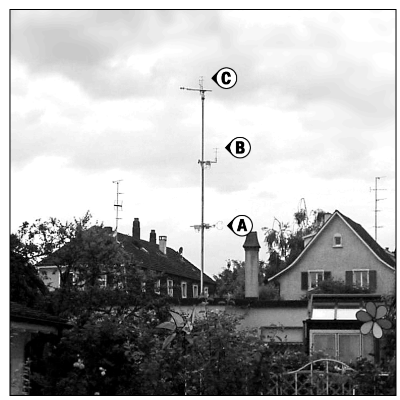
1. SITES AND INSTRUMENTATION

The Basel Urban Boundary Layer Experiment (BUBBLE) is an effort in the frame of the European COST 715 action to increase the understanding of exchange and dispersion processes in urban areas. Numerical modelling, remote sensing, a large field measurement campaign and a wind tunnel investigation will lead to a more detailed picture of the urban boundary layer (Rotach, 2002). As part of the field experiments in 2001/2002 in the city of Basel, two micrometeorological towers were operated in dense urban areas over 9 and 11 months (*Basel-Sperrstrasse* and *Basel-Spalenring*). A third tower was installed for 5 weeks in a suburban backyard in summer 2002 (*Allschwil-Rämelstrasse*). The sites were chosen in order to achieve homogeneous source areas for the upper levels in terms of terrain (flat), building height and building structure.

Tab. 1: Description of the micrometeorological towers operated during BUBBLE with measurement heights z of the turbulence instruments.







Basel-Sperrstrasse (BSPR) Non vegetated urban street canyon 611890 / 268365[2], 255 m a.s.l.	**Basel-Spalenring** (BSPA) Vegetated urban street canyon 610360 / 267140[2], 278 m a.s.l.	**Allschwil-Rämelstrasse** (ALLS) Vegetated suburban backyard 609250 / 267180[2], 277 m a.s.l.
h=14.6 m[1], d/h = 1.0 ℓ_p=0.57[1], attached buildings in blocks	h=18 m, d/h = 1.8 ℓ_p=0.42[1], attached buildings in blocks	h=7.5 m ℓ_p=0.28[1] single buildings
Ultrasonic Anemometers F 31.7 m Gill HS (20Hz) E 22.4 m Gill R2 (20.8Hz) D 17.9 m Gill R2 (20.8Hz) C 14.7 m Gill R2 (20.8Hz) B 11.3 m Gill R2/Metek USA-1 (20Hz) A 3.6 m Gill R2/Metek USA-1 (20Hz)	Ultrasonic Anemometers F 37.6 m Metek USA-1 (20Hz) E 29.9 m Metek USA-1 (20Hz) D 21.8 m Metek USA-1 (20Hz) C 16.6 m Metek USA-1 (20Hz) B 13.9 m Metek USA-1 (20Hz) A 5.6 m Metek USA-1 (20Hz)	Ultrasonic Anemometers C 15.8 m Metek USA-1 (20Hz) B 12.1 m Metek USA-1 (20Hz) A 8.3 m CSI CSAT3 (20Hz)

h: building height, d: canyon width, ℓ_p: plane area density.
[1] inside 250m circle, [2] Coordinates in m Easting / Northing (CH1903).

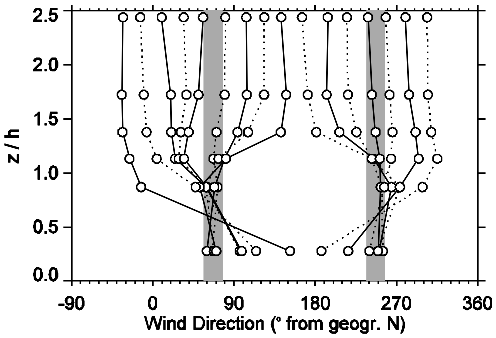


Fig 1. Channelling of flow into the street canyon: Local horizontal wind direction at the six measurement heights in dependence from the overlying wind direction at *2.2h* for *Basel-Sperrstrasse.* The grey bars indicate the street canyon orientation (67°-247°). Selection criteria: All data from November 1, 2001 to July 15, 2002 (approx. 4600 hours of valid data) with wind speed at *2.2h* > 1 m s^{-1}.

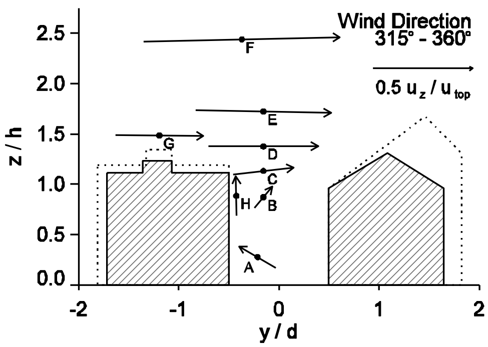


Fig 2. Ensemble canyon crossection at *Basel-Sperrstrasse*. Shown are vector means of lateral and vertical wind components for flow situations in a sector perpendicular to the canyon (flow from 315-360°, 250 hours). The Labels A to F refer to instruments that are mounted on the tower. Additional measurements were carried out near the building wall (H) and on the roof (G).

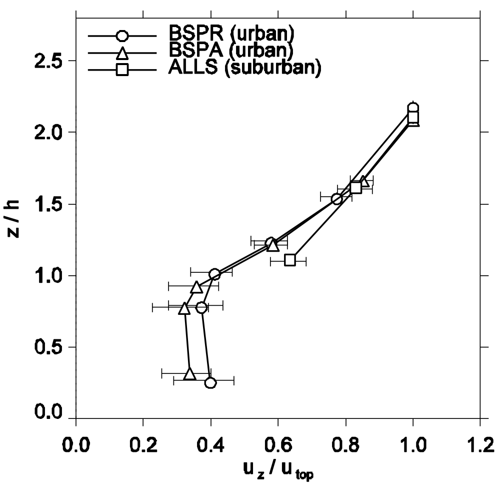


Fig 3. Ensemble wind profiles at all three sites derived from the sonic anemometers for the whole operation periods.

All three micrometeorological towers were equipped with a profile of ultrasonic anemometer-thermometers (sonics) reaching up to 2.2 times the mean building height *h* (Tab. 1). From all individual instruments 20 Hz raw data were continuously collected on one computer per site. The profile at *Basel-Spalenring* was divided into a canyon part within alley trees (A to C) and a tower part that is shifted toward the backyard (D to F). At the suburban site all sonics were mounted above *h*.

2. DATA HANDLING AND PROCESSING

Most of the instruments at *Basel-Sperrstrasse* and *Basel-Spalenring* were checked prior to the field measurements in a wind tunnel. From the tunnel study, instrument individual correction matrices were deduced and the corrections were applied to the field data. Integral statistics were calculated based upon simple 60min block averages of the wind components with Reynolds decomposition into a mean wind $\overline{u}_i$ and turbulent wind part u'_i. The coordinate system is oriented with a strictly vertical *w*. Data are filtered for acquisition errors, spikes and plausibility.

For further analysis, data are grouped into 16 different wind direction classes based upon the overlying wind direction**.** Averaged profiles are calculated for each class separately. All 16 class averaged profiles are equally weighted averaged to an "ensemble profile". This reduces effects due to the orientation of the canyon relative to the local wind rose. Error bars enclose 50% of all data starting at the median.

In this presentation we focus on mean and turbulent characteristics of the wind components. Profiles of heat fluxes, temperature and concentration parameters are discussed elsewhere. As shown in a preliminary study on this dataset (Christen et al., 2002) stability does not have a dominant impact: 65% of the cases at the two urban sites are unstable, 30% are neutral and only 5% stable (at 2*h*). To simplify profiles, stability dependences are not shown.

3. RESULTS

Mean Wind

At the two urban sites, channelling increases with decreasing height (shown for *Basel-Sperrstrasse* in Fig. 1). An asymmetry is observed at both canyon sites because the instruments were mounted closer to one building wall (*y*/*d* = 0.16 at *Basel-Sperrstrasse*, *y*/*d* = 0.37 at *Basel-Spalenring* with *y*: distance to canyon centre, *d*: canyon width). Under flow situations perpendicular to the canyon axis a simple vortex develops at *Basel-Sperrstrasse* (Fig. 2). Here we observe a wind direction at the canyon floor that is opposite to the direction above.

Figure 3 shows ensemble profiles for all three sites. Fig 5 (top) illustrates the dependence from the overall wind direction at *Basel-Sperrstrasse* with data from 11 cup anemometers. Similarly to plant canopy profiles, the canyon profiles show an inflection point at 1.1*h* and a second maximum in the canyon itself.

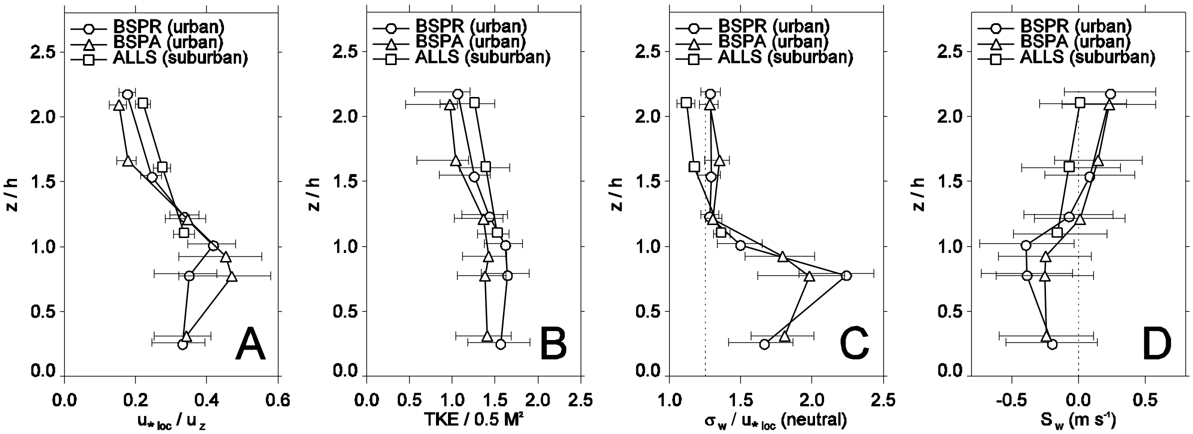


Fig. 4. Ensemble profiles of turbulence parameters. BSPR: Basel-Sperrstrasse (no vegetation in canyon, Nov 2001 – Jul 2002), BSPA: Basel-Spalenring (wide and vegetated canyon Aug 2001-Jul 2002), ALLS: Allschwil-Rämelstrasse (suburban backyard, Jun / Jul 2002). The dashed line in C indicates the "ideal" surface layer value of 1.25 (Panofsky and Dutton, 1984).

Momentum Fluxes

Local Reynolds stress u_{*loc} was calculated using formula $u_{*loc} = [(\overline{u'w'})^2+(\overline{v'w'})^2]^{0.25}$ with a vertical orientation of w. The rotation of the wind direction due to the channelling of the flow into the canyon (Fig. 1) makes the contribution of $\overline{v'w'}$ to u_{*loc} significant. $\overline{v'w'}$ enlarges u_{*loc} between 5% (at 2h) and 20% (at h and inside canyon). However, the local u_{*loc} values near the roofs and inside the canyon must be interpreted carefully because the theoretical assumptions (horizontal homogeneity) cannot be fulfilled at all. Inside the canyon not only vertical transport of momentum but also lateral transports towards the walls are important. Hence, the momentum transport is not covered totally by u_{*loc}. Figure 4a gives typical values for u_{*loc} scaled by the mean horizontal wind velocity at the respective measurement height u_z. Highest values for u_{*loc}/u_z were observed at both urban stations between of 0.8h and h, where the high drag is caused by the large and exposed roof areas. In this part of the profile characteristic values around 0.5 with high run to run variability are measured. The vegetated canyon at *Basel-Spalenring* leads to higher u_{*loc}/u_z values. In general u_{*loc}/u_z is slightly higher than values reported from previous studies in equivalent heights (Rotach, 1995, Feigenwinter et al. 1999, Roth 2000).

u_{*loc}/u_z strongly depends on the wind direction of the approaching flow relatively to the canyon (Fig. 5, bottom). At roof-level the flow perpendicular to the canyon leads to u_{*loc}/u_z-values which are twice the ones observed under an along canyon flow: during cross canyon situations u is slower at roof-level and additionally higher u_{*loc} values are present due to the higher drag and decoupling at canyon top. At 2h the ratio u_{*loc}/u_z is around 0.2 at all sites and nearly independent from wind direction. This indicates that single roughness elements and the canyon orientation do not have an influence any more.

Turbulent Motions

As a result of the high drag at rooftop and inside the canyon the normalized turbulent kinetic energy *TKE* increases with decreasing height. In Fig. 4b, *TKE* is normalized by the square of the local mean scalar wind M (three dimensional). Above 1.5h slightly higher *TKE* / 0.5 M^2 values are observed at the suburban site than at the two urban sites. This could be explained by the lower plane area density (ℓ_p=0.28) of the suburban surface (single buildings) which has a higher z_0/h value.

Figure 4c illustrates profiles of locally scaled standard deviations of vertical wind. Similar to other studies above urban surfaces (Roth, 2000), σ_w/u_{*loc} values from the upper measurements at all three sites fit well to the "ideal" surface-layer value of 1.25 under neutral situations (Panofsky and Dutton, 1984). Below 1.25 h the values at both canyon sites increase significantly towards a maximum at 0.8h (1.9-2.3). The vertical motions are dominant in the canyon itself with $|w|/u$ between 0.2 and even > 1 near the walls. This explains the much larger variations in w. Down to the canyon floor the values are decreasing at both sites.

Vertical Skewness

Below 1.3h and especially around rooftop highly negative skewnesses (~-0.4 $m^3\ s^{-3}$) are found in the w-component that are caused by injections of air into the canyon (Fig. 4d). This part of the profile shows under all flow situations negative values at both canyon sites. The vertical skewness measured directly above the roofs (1h-1.2h) is stronger negative under cross canyon flow than under along canyon flow (not shown). Inside the canyon

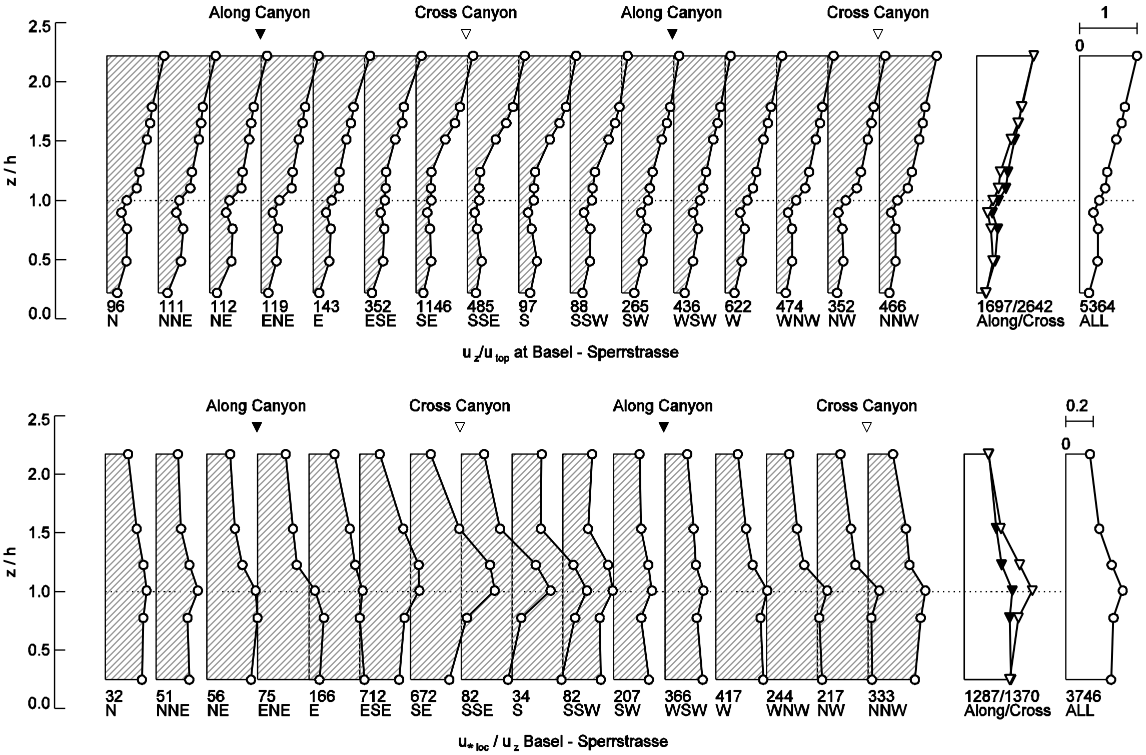


Fig. 5. Mean profiles of horizontal wind speed (cup anemometers) and Reynolds stress scaled by local wind velocity u_{*loc}/u_z. in dependence of the overall wind direction at 2.2*h* at *Basel-Sperrstrasse*. The numbers above the wind directions indicate the total of 60min runs leading to the profile. "Along" and "Cross" refer to ensemble profiles with flow ±34° along the canyon (black triangles) or ±34° perpendicular to it (white triangles).

it is just the other way round. At canyon floor the skewness of the *w*-component is sensitive to the mean value of the *w*-component, which is depending on the rotation of the vortex: Above 1.3*h* by the majority of the 16 wind direction classes positive values are observed that are related to ejections.

4. CONCLUSIONS AND OUTLOOK

The ensemble vertical profiles of flow and turbulence characteristics at the three presented sites are strongly similar in shape and quantity. This shows that mean profiles over a large bandwidth of wind directions are useful, even in a complicated 3-dimensional flow environment like in the urban roughness sublayer. In general, largest gradients are found around roof level and in the upper canyon part. The results fit well with previous observations and also show similarities to features of flow over plant canopies (e.g. inflection point, momentum transport). However, the flow structure and turbulence parameters inside the street canyon are strongly depending on the position in the canyon and the direction of the approaching flow.

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