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COMPARISON OF TURBULENT FLUXES FROM ROOF TOP VERSUS STREET CANYON LOCATIONS USING SCINTILLOMETERS AND EDDY COVARIANCE TECHNIQUES

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ABSTRACT
This paper addresses measurement and methodological issues associated with the use of scintillometers in the urban roughness sub-layer (RSL) using measurements from scintillometers located in a densely urbanized part of Basel, Switzerland. Measurements were made both across the top of a street canyon and along the adjacent roof tops to provide a comparison between the turbulent fluxes resulting from the two dominant components of the urban surface. Effective measurement heights were estimated using a novel method based on fetch and source area considerations. Modified forms of the Monin-Obukhov Similarity (MOS) equations (for urban areas) were used to calculate fluxes.

1. INTRODUCTION

Traditional approaches to the measurement of turbulent fluxes in urban areas typically involve the use of single point measurements from eddy covariance instruments mounted on towers well above the urban surface. Such measurement approaches are not well suited to the heterogeneous characteristics of the roughness sub-layer (RSL) where the mosaic of roof top and street canyon surfaces presents a particularly complex three dimensional source area. As a consequence most studies try to avoid this region and little is known about the spatial heterogeneity of turbulent fluxes within the RSL, nor the relative contribution of each surface type to the overall energy balance.

Scintillometers, which offer the ability to make path-averaged measurements of turbulent fluxes of heat and momentum, provide an alternative approach to obtaining more spatially representative data sets in the RSL. Small aperture scintillometers, which primarily measure fluctuations in the refractive index parameter caused by small turbulent eddies (e.g. de Bruin *et al.* 2002), are particularly well suited for use close to the urban surface. Further, increased spatial sampling of turbulent eddies enables the use of shorter flux averaging times.

2.1 Theory

Scintillometers have been widely used in rural environments as an alternative technique for measuring turbulent fluxes of heat and momentum (e.g. Thiermann & Grassl 1992; Hartogensis *et al.* 2002). The present study uses two small aperture displaced-beam scintillometers (Scintech SLS20). Atmospheric turbulence attenuates the radiation from two parallel laser beams and results in changes to the inner length scale of turbulence (l_o) and refraction index structure parameter (C_n^2) measured by the receiver. The temperature structure parameter (C_T^2) and dissipation (ε) can be determined directly from these variables and turbulence parameters calculated using Monin-Obukhov Similarity (MOS) and an iterative solution to the following equations (Kanda *et al.* 2002):

$$u_*^{2} = v^{2}\left(\frac{7.4}{l_o}\right)^{8/3}\left[k(z-z_d)\right]^{2/3}\phi_\varepsilon^{-2/3}(\zeta) \tag{1}$$

$$T_*^{2} = C_T^{2}\left[k(z-zd)\right]^{2/3}\phi_{CT}^{-1}(\zeta) \tag{2}$$

$$L = \frac{Tu_*^{2}}{kgT_*} \tag{3}$$

where ϕ_ε is the non-dimensional dissipation rate for TKE, ϕ_{CT} the non-dimensional structure parameter for temperature, v the kinematic viscosity of air, k the von Karman constant, g the acceleration due to gravity, z the measurement height, z_d the zero-plane displacement height, T the temperature and $\zeta = ((z-z_d)/L)$. The Scintech software uses MOS equations derived from (Thiermann & Grassl 1992). These equations are based on experimental evidence and differ slightly from the more widely utilised forms of the equation (based on variants of Wyngaard (1973) and Wyngaard & Cote (1971)) that are employed by studies such as Hartogensis (2002).

Conventional MOS theory cannot be directly applied to the urban case. However, previous studies in urban areas have shown good agreement between scintillometer measurements of turbulent fluxes using modified forms of

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MOS equations and those from eddy covariance techniques (Kanda *et al.* 2002; Lagouarde *et al.* 2002). In this paper we use the modified form of the MOS equations developed by Kanda *et al.* (2002) for Tokyo:

$$\phi_{\varepsilon}(\zeta) = (1 - 10.5\zeta)^{-1} - \zeta \quad (4)$$

$$\phi_{CT}(\zeta) = 4\beta\left[0.68(1 - 9.69\zeta)^{-1/2}\right]\left[(1 - 10.5\zeta)^{-1} - \zeta\right]^{1/3} \quad (5)$$

where β is the Obukhov-Corrsin constant.

2.2 FIELD EXPERIMENT

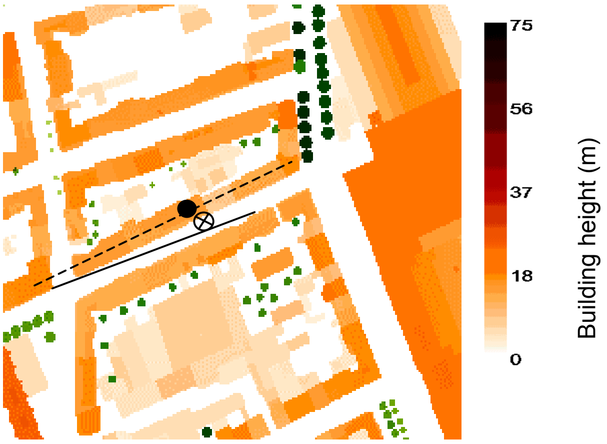

Figure 1 Raster image to show location of sonic anemometers, scintillometer paths, building height and trees approximately 200 m around the Sperrstrasse site. © GVA Grundbuch- und Vermessungsamt Basel-Stadt

The scintillometers were located in the urban roughness sub-layer in a densely urbanized part of Basel, Switzerland, close to the main instrumented tower at the BUBBLE Basel-Sperrstrasse site (Rotach 2002). This tower was located near the mid-point of the block and instrumented with sonic anemometers at 3.6, 11.3, 14.7, 17.9, 22.4 and 31.7 m (approximately 2z_h) on booms extending towards the middle of the street canyon. A further sonic anemometer was located 11.3 m above canyon floor 0.65 m from the north wall of the canyon. One scintillometer was mounted just below roof level diagonally across the Sperrstrasse street canyon at 15.1 m above street level (optical path length 116 m) (Figure 1). The second instrument was located 19.3 m above street level about 3-5 m above the irregular roof height along the north side of the Sperrstrasse canyon (optical path length 171 m). A further sonic anemometer was located at 19.6 m (3.5 m above local roof height) on the roof top at the mid-point of the scintillometer path. Prior to the experiment the two scintillometers were inter-calibrated at a grassland site and showed good agreement with each other.

Data were collected between June 26th and July 12th 2002 during the summer intensive observation period of the BUBBLE project. Due to practical considerations, both the street canyon and roof top scintillometer paths crossed a road intersection. However, given the bell-shaped weighting curve applied to the raw data, conditions close to both the receiver and transmitter have little effect on the calculated turbulence parameters. Due to space considerations emphasis in this paper is placed on the sensible heat flux data only.

Scintillometer path	**Street canyon scintillometer**	**Roof top scintillometer ('rule of thumb' z_d)**	**Roof top scintillometer (z_d from Bottema, 1995 incl. courtyard infill)**
Measurement height above street canyon (z)	13.5 m	19.3 m	19.3 – 10 = 9.3 m
Mean building height (z_h)	14.6 m	14.6 m	17 - 10 = 7 m
Zeroplane displacement (z_d)	0.7*14.6 = 10.2 m	10.2 m	5.7 m
Effective measurement height z' (z-z_d)	13.5-10.2 = 3.3 m	19.3 – 10.2 = 9.1 m	9.3 - 5.7 = 3.6 m

Table 1 Mean height and zeroplane displacement for roof top and street canyon scintillometer paths

MOS theory relies on appropriate specification of the height of measurement (here line-of-sight) above z_d. Estimation of this height becomes problematic in the complex transition zone near the roof top. Based on data from a digital city model the estimated mean building height in the 250 m region around the tower is 14.6 m. Based on a standard 'rule of thumb' approximation (Grimmond & Oke 1999), we assume z_d at the site is (z_h*0.7) or 10.2 m (Table 1). However, whilst this value of z_d was appropriate for the canyon scintillometer (as shown in Figure 2) it gives a significant over-estimate of the roof top fluxes for the roof path. (The mean error between the sensible heat flux (Q_H) calculated from the roof top scintillometer and sonic was -82.9 W m^{-2} and daytime scintillometer fluxes peaked at over 800 W m^{-2}, more than twice the corresponding eddy covariance values.)

Clearly a more accurate way to estimate z_d is needed for the roof top scintillometer. Using the FSAM source area model (Schmid 1994) the dominant source area for the roof top sonic was shown to be typically located within 200 m of the instrument. The raster image (Figure 1) illustrates that this includes buildings with roof tops, street surfaces and the surrounding courtyards, many of which include lower height buildings. Using a simple land classification scheme with 4 categories – 17 m buildings, 10 m buildings (courtyard infill), tree cover and street canyon) the landuse for each of the 8 wind sectors was determined. The results show that in some sectors street canyons account for less than 6% (mean 15%) of the total landuse, whilst the 10 m courtyard buildings account for up to 50% (mean 25%) land area. This suggests the reference height for the 17 m buildings under the scintillometer path was not street level but effectively 10 m above this at the height of the courtyard infill and tree tops. Using this assumption and the morphometric method of Bottema (1995) to calculate z_d we get a revised z_d value of 5.7 m giving an effective measurement height of 3.6 m (Table 1). This gives much better agreement between the scintillometer and roof top sonic with the mean error of Q_H reduced to –13.2 W m^{-2}.

3. RESULTS

Figure 1 shows good correlation between Q_H from the 14.7 m canyon sonic and the canyon scintillometer. As expected, the increased spatial averaging of the turbulent eddies in the scintillometer fluxes results in a smoother diurnal cycle compared to the eddy covariance data. Interestingly, the nighttime heat fluxes (which are always positive) from the scintillometer are consistently higher than the sonic anemometer values. This phenomenon is particularly pronounced between 00:30 and 06:30 on 7th and 8th July. On the other hand the daytime scintillometer values tend to be equal to or smaller than the sonic values.

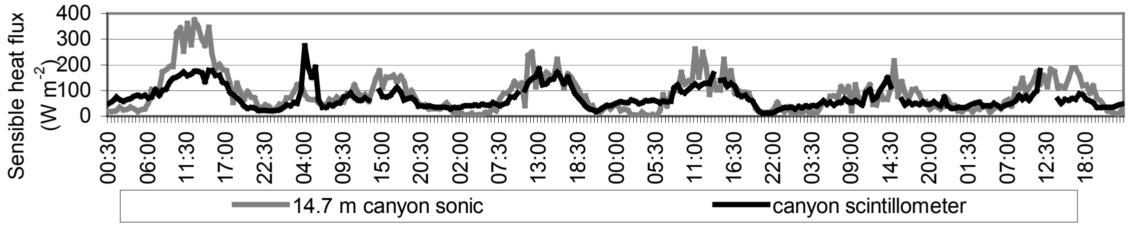

Figure 2 Comparison of the sensible heat fluxes (Q_H) from the canyon scintillometer and 14.7 m canyon sonic anemometer between 00:30 July 5th – 23:00 July 10th 2002 (All times in CET.)

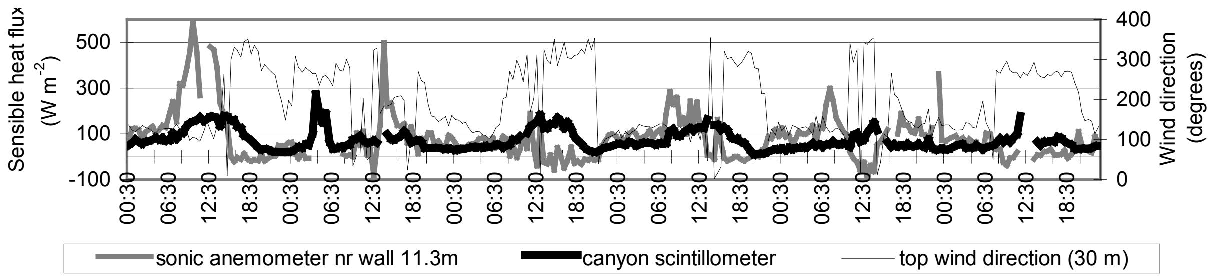

Figure 3 Sensible heat fluxes from canyon scintillometer, sonic anemometer located at 11.3m near north wall (south facing) and wind direction across the top of the street canyon between 00:30 July 5th – 23:00 July 10th 2002

Data from the sonic anemometer mounted close to the north wall of the street canyon suggests that this may be due to the spatial averaging of the data across both the centre and sides of the street canyon. For example at 21:30 on July 7th both the scintillometer and mid-canyon sonic Q_H values drop to a minimum of 20 W m^{-2} while the flux up the north wall is near zero. Between 21:30 and 22:30 the wind switches from the daytime flow (350^0) to the night time flow (110^0) which coincides with a marked jump in Q_H up the north wall to 100 W m^{-2} and an increase in both the mid-canyon and scintillometer fluxes to 55 W m^{-2}. By 02:30, however, on July 8th the mid-canyon heat flux has decreased to near zero (5 W m^{-2}) while the flux up the north wall and scintillometer values remain constant. This suggests that the scintillometer path (which encompasses both conditions near the centre of the street canyon and near to the walls) provides a measure of conditions across the street canyon as a single unit.

Throughout the diurnal period the heat flux along the north wall of the street canyon is particularly sensitive to wind direction (Figure 3). During the nights of July 7-8th and 8-9th the flux only increases when the mean wind direction switches from the prevalent daytime direction (NW) to the more typical nighttime (SE) flow. At this time the dynamical controls on the development of a circulation vortex in the street canyon are counter to the thermal controls because the north (south-facing) wall is likely to retain more heat than the south wall. The absence of a well developed vortex could account for the increased heat flux along the north side of the canyon.

It is interesting to note that the largest discrepancy between the daytime sonic and scintillometer heat fluxes occurs during the morning of July 5th (and to a lesser extent on July 7th & 8th particularly between 10:30 – 1300) when the night time wind flow regime persists until mid afternoon (Figure 3). Given the increased magnitude of the heat flux along the north wall during this time, it is possible that the absence of a well developed circulation within the canyon results in large difference between the magnitude of the flux along the north and south walls. This again suggests that the increased spatial averaging of the scintillometer data may provide a measure of the street canyon heat flux that is less biased towards conditions on one side of the street.

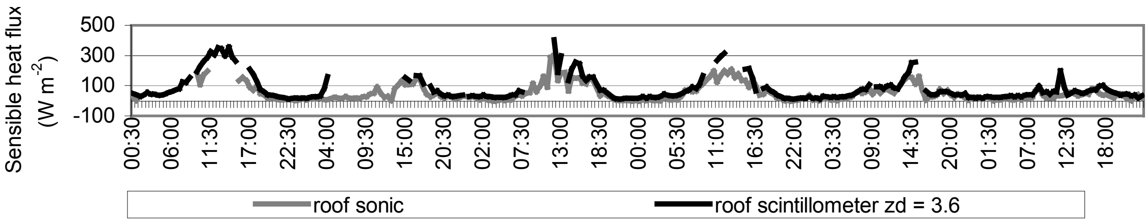

Figure 4 Comparison of the sensible heat fluxes from the roof top scintillometer and roof top sonic anemometer between 00:30 July 5th – 23:00 July 10th 2002

Figure 4 illustrates that Q_H from the roof top scintillometer (using the revised morphometric estimation of z_d) shows generally good agreement with the roof top sonic at night but tends to be larger during daytime. If the magnitudes of the respective scintillometer fluxes are correct, and street canyon and roof top surfaces form the two dominant landuse forms of the urban area, their combined fluxes (weighted by percentage landuse cover) can be anticipated to equal the areally-averaged eddy covariance flux observed at 31.2 m for the same source area. To test this the roof top and street canyon fluxes were weighted according to the simple landuse classification with wind direction developed above. (It was assumed that the 10 m buildings from the courtyards displayed similar heat flux characteristics to the 17 m roof tops and trees were not included in the analysis.) Figure 5 demonstrates that, despite the simplicity of the scheme, the weighted canyon and roof top scintillometer fluxes provide a good estimation of the local scale surface sensible heat flux observed above the city.

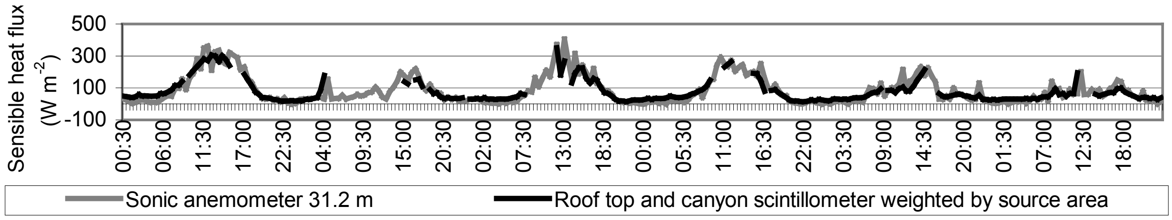

Figure 5 Comparison of the sensible heat fluxes from the sonic anemometer at 30 m and the area-weighted mean of the canyon and roof top scintillometer fluxes between 00:30 July 5th – 23:00 July 10th 2002

4. CONCLUSIONS

Scintillometers are shown to be appropriate tools for the measurement of turbulent heat fluxes in the RSL with careful determination of z_d and the use of urban forms of the MOS equations. Results indicate that, in the complex zone near the roof top interface, path-averaged data from scintillometers may provide more representative measurements of turbulent heat fluxes from different urban surfaces compared to traditional single point eddy covariance approaches.

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