APPLICATION OF SCINTILLOMETRY IN THE URBAN ATMOSPHERE

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1. INTRODUCTION

The spatial heterogeneity of urban surfaces presents a particular challenge to the measurement of turbulent fluxes. This is particularly true in the roughness sub-layer close to the urban surface where the mosaic of rooftop and street canyon surfaces present a very 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 roughness sub-layer (RSL), nor the relative importance of rooftop versus street canyon surfaces in determining the overall characteristics of the urban boundary layer. This has consequences not only for our understanding of the processes driving the urban boundary layer but also for our ability to model pollutant dispersion pathways in urban areas especially from street canyons.

Scintillometers, which offer the capability of measuring spatially-averaged turbulence fluxes, have the potential to make a significant contribution to our understanding of turbulent transport processes in the RSL. This paper addresses some of the methodological challenges associated with the measurement of turbulence and use of scintillometers in the atmospheric urban RSL.

2. THEORY

Scintillometers have been widely used in rural environments as an alternative technique for measuring turbulent fluxes of heat and momentum (Hartogensis *et al.* 2002; Hill *et al.* 1992; Thiermann and Grassl 1992). The temperature structure parameter (C_T^2) and dissipation (ε) can be determined directly from the inner length scale of turbulence (l_o) and C_n^2 and turbulence parameters are calculated using an iterative solution to the following equations:

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

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

$$L = \frac{Tu_*^2}{kgT_*} \quad (3)$$

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where ν is kinematic viscosity of air, k is von Karman constant (here taken to be 0.4), g is acceleration due to gravity, z is measurement height, z_d is zero-plane displacement height, L is Obukhov length, T is temperature, $\zeta = ((z\text{-}z_d)/L)$, ϕ is non-dimensional dissipation rate for TKE and ϕ_C is non-dimensional structure parameter for temperature. ϕ_ε and ϕ_C are calculated using MOS theory. The software provided with the scintillometer uses the following form of the MOS equations from Thiermann and Grassl (1992):

$$\phi_\varepsilon(\zeta) = (1-3\zeta)^{-1} - \zeta \quad (4)$$

$$\phi_{CT}(\zeta) = 4\beta\left[1 - 7\zeta + 75(\zeta)^2\right]^{-1/3} \quad (5)$$

where β is Obukhov-Corrsin constant (0.86) and

$$\phi_{CT} = 4\beta\phi_N\phi_\varepsilon^{-1/3} \quad (6)$$

with

$$\phi_N = 0.74(1-9\zeta)^{-1/2} \quad (7)$$

These equations differ slightly from the more widely utilised forms of the equation based on variants of Wyngaard and Coté (1971) and Wyngaard (1973) employed by studies such as Andreas (1989), Hill *et al.* (1992), Green *et al* (2001) and Hartogensis *et al.* (2002).

MOS theory cannot be directly applied in the RSL where empirical constants of normalized turbulence statistics *vs*. stability relationships are often different compared to those based on observations in the homogeneous surface layer (*e.g.* Roth, 1993; Roth and Oke, 1993; Roth, 2000). The objective of this paper is to investigate the suitability of relationships such as (4) and (5) used for scintillometry in the urban RSL. The respective non-dimensional urban dissipation functions are calculated based on the high-frequency end of vertical wind and temperature spectra (inertial sub-range) obtained from eddy correlation measurements (*e.g.* Roth and Oke, 1993; Kanda *et al*., 2002).

3. EXPERIMENTAL

Observations were conducted as part of the BUBBLE field experiment (Rotach *et al*. 2004). The main instrumented tower was located in a densely urbanized part of Basel, Switzerland - “Sperrstrasse” site - characterised by comparatively uniform land-use.

The tower was instrumented with sonic anemometers at 3.6, 11.3, 14.7, 17.9, 22.4 and 31.7 m (which corresponds to about 2 times the mean building height z_H) on booms extending towards the middle of the street canyon. Further sonic anemometers were located 11.3 m above canyon floor 0.65 m from the north wall of the canyon and at 19.3 m (3.5 m above local roof height) on the rooftop. The sonic anemometer on the tower at 14.7 m above the canyon (Gill R2) and at 3.5 m above the roof (CSAT) coincide with the mid-points of two scintillometers (Scintech SLS20) mounted just below roof level diagonally across the street canyon at 13.5 m above street level (optical path length 116 m) and at 19.3 m above street level about 3-5 m above the irregular roof height along the north side of the canyon (optical path length 171 m), respectively (Fig. 1). Data from these two sonic anemometers and the two scintillometers will be used in the analysis below. Prior to the experiment the two scintillometers were inter-calibrated at a grassland site and showed good agreement with each other.

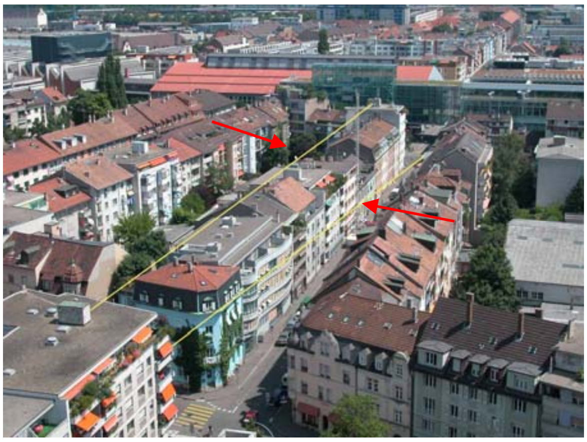

Fig. 1: View of the Sperrstrasse observation site. Micrometeorological tower is erected near the North (left) wall at the midpoint of the canyon in the center of the image. The paths of the canyon and roof scintillometers are indicated by yellow lines. Mid-points (marked by red arrows) coincide with locations of sonic anemometers used for the calculation of the dissipation functions.

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 (Fig. 1). However, given the data are weighted using a bell-shaped curve applied to the raw data, conditions close to both the receiver and transmitter have little effect on the calculated turbulence parameters.

Sonic anemometer output was recorded at about 20 Hz. The measurements at z/z_H = 2 were rotated into the mean wind (horizontal and vertical rotation), detrended and averaged over 60 minutes. Only one rotation in to the mean horizontal wind and no detrending was applied to the canyon (z/z_H = 1) and rooftop (z/z_H = 1.3) sonic measurements which were averaged over 30 minutes. Webb and temperature variance corrections were applied were applicable. Dissipation values were determined based on estimates in the inertial subrange of the respective vertical velocity and temperature spectra between non-dimensional frequency f (= nz/U, where n – natural frequency, U – mean wind speed) = 3 – 6 (rooftop) and 4 – 10 (canyon). Care was taken to exclude data from wind directions with potential of flow interference due to the tower or other sensors mounted upwind. Cases with very low sensible heat fluxes or wind speeds were also excluded.

Estimates using a digital city model suggest that z_H in the 250 m region around the tower is 14.6 m. Using the standard 'rule of thumb' (Grimmond and Oke 1999), z_d at the site can be assumed to be (z_H*0.7) or 10.2 m. Thus for the street canyon scintillometer effective measurement height z′ (= z - z_d) = 3.3 m. Using the FSAM source area model (Schmid 1994) as a guide, the dominant source area for the roof top site was shown to be located within 10 - 200 m of the instrument which includes roof surfaces, street surfaces and the surrounding courtyards, many of which include lower height buildings. Using a simple land classification scheme suggests that the reference surface for the calculation of z_d from the 17 m buildings under the scintillometer path was not dominated by street level surfaces but by surfaces 10 m above this at the height of the courtyard infill and tree tops. Using this assumption and the morphometric method of Bottema (1995) z_d = 5.7 and z′ = 3.6 m for the rooftop scintillometer (see Salmond *et al*., 2003 for details). Similarly, z′ = 20 m for the sonic at 31.7 m.

4. REVISED MOS RELATIONSHIPS FOR ROOFTOP AND CANYON LOCATIONS

Close to the urban surface the flow is highly directional with wakes just above and behind buildings and other structures and preferential flow directions induced by the geometry and arrangement of canyons. To investigate the potential dependence of turbulence characteristics on flow direction in respect to the canyon orientation the data was divided into 8 groups, each representing a 45 deg wind direction sector. The majority of the data is from wind directions parallel to the canyon (*i.e.* 45-90 and 225-270 deg) and small angles to the canyon (270-315 deg).

Relatively few data points are available for flow perpendicular to the canyon. No trends could be observed between individual sectors and any systematic differences were masked by the large scatter of the data (not shown). The results presented below are therefore based on all data points from all sectors.

Figs. 2 and 3 show the current data compared against results from the homogeneous surface layer (green lines labeled WC71, TG92 or WC71TG92; Eqs. 4-7) and urban forms based on two experiments carried out at z/z_H > 2 (red lines labeled K02; Kanda *et al.* 2002). Results at both locations exhibit a lot of scatter in particular those obtained above the canyon. In the case of ϕ_ε the empirical fit deviates strongly from previous relationships.

The prominent dip of the urban values in ϕ_ε between z'/L = -0.5 and 0.0 observed in previous urban results (Kanda *et al.* 2002) is less pronounced in the present data at roof level (Fig. 2, top) and even absent over the canyon (Fig. 3, top). The results suggest ϕ_ε < 1 above the canyon at neutrality, *i.e.* absence of equilibrium between production and dissipation of TKE.

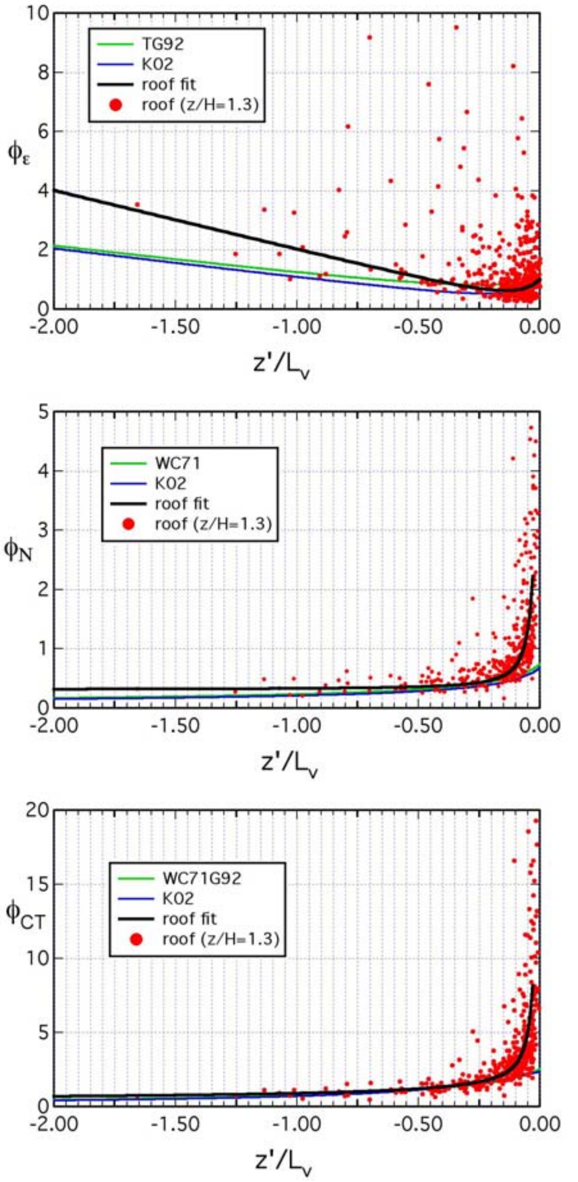

Fig. 2: Non-dimensional dissipation functions for TKE (top), temperature variance (middle) and non-dimensional structure parameter for temperature (bottom) plotted against non-dimensional stability parameter measured at 3.5 m above rooftops (z/z_H = 1.3). Black line is fit to red data points (see text for Eq.).

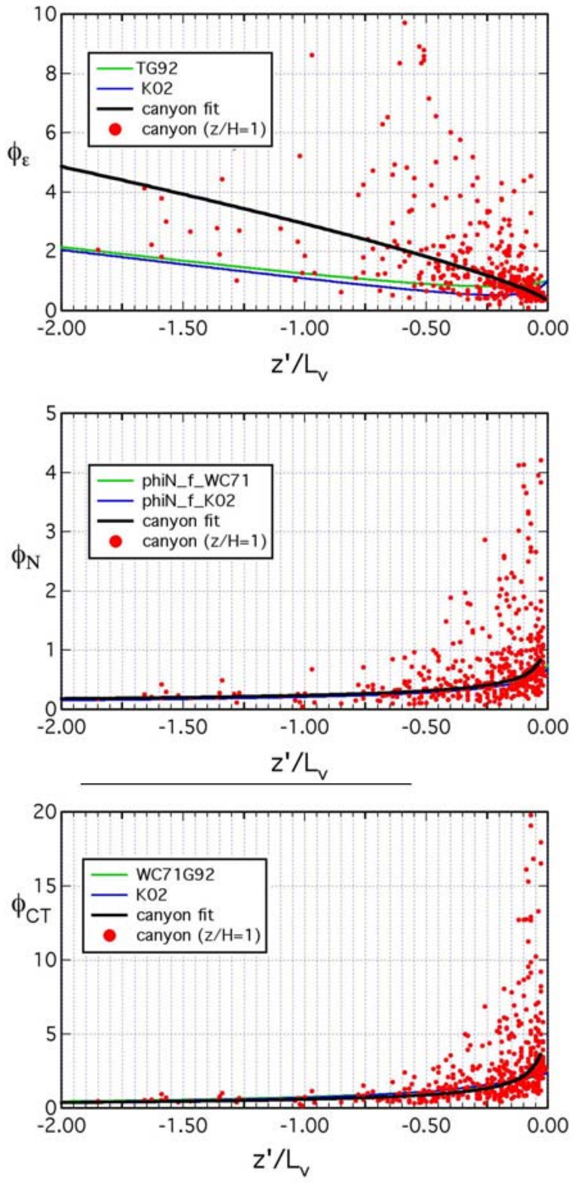

Fig. 3: Same as Fig. 2 but measured at roof level over the center of a canyon (z/z_H = 1).

The urban values for ϕ_N increase strongly towards z'/L = 0.0 as shown in Fig. 2 and 3 (middle). This is expected since T_* tends towards zero when conditions are close to neutral. This feature is better captured in the new empirical fits compared to previous relationships. At larger instabilities urban and rural forms are similar.

ϕ_{CT} is calculated according to Eq. 6 and its characteristics therefore reflect those of the individual ϕ_ε and ϕ_N results.

The following equations are the empirical fits to the urban data presented in Figs. 2 and 3:

Above rooftop (z/z_H = 1.3):

$$\phi_\varepsilon(\zeta) = (1-5\zeta)^{-2} - 2\zeta \qquad -5 < \zeta < -0.01 \qquad (8)$$

$$\phi_N(\zeta) = 0.31 + 0.02|\zeta|^{-1/3} \qquad -5 < \zeta < -0.03 \qquad (9)$$

Above canyon (z/z_H = 1)

$$\phi_\varepsilon(\zeta) = 0.33 + 2.6|\zeta|^{0.8} \qquad -5 < \zeta < -0.01 \qquad (10)$$

$$\phi_N(\zeta) = 0.8(0.3 - 20\zeta)^{-0.4} \qquad -5 < \zeta < -0.03 \qquad (11)$$

The large scatter observed in the present results is a consequence of the inhomogeneous flow close to the city surface and suggests that the derived dissipation functions should not be applied to individual data points. Comparison of sensible heat fluxes measured by eddy correlation and scintillometry using the traditional and new functions, respectively, show better agreement in the latter case (not shown). The new relationships therefore improve the performance of the scintillometer at low heights over the buildings or canyons. The success of scintillometry in the RSL is possibly also due to its relative insensitivity to the form of the dissipation functions when compared to the influence of the effective height, z′, which is difficult to define in areas of inhomogeneous roughness.

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