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Flow characteristics and particle mass and number concentration variability within a busy urban street canyon

Stephan Weber[a,*], Wilhelm Kuttler[a], Konradin Weber[b]

[a]*Department of Applied Climatology and Landscape Ecology, Institute of Geography, University of Duisburg-Essen, Campus Essen, D-45141 Essen, Germany*

[b]*Department of Mechanical and Process Engineering, Environmental Measurement Techniques, University of Applied Sciences Duesseldorf, D-40474 Duesseldorf, Germany*

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Abstract

Mean and turbulent flow characteristics together with particle concentrations were measured in a busy urban street canyon in Essen, Germany, at five (flow characteristics) and three heights (particles) above ground, respectively. Particle mass and number concentrations were sampled in the size range $0.3 < D_p < 10\,\mu m$. The flow characteristics within the canyon were significantly influenced by canyon geometry and were shown to have significant impact on particle concentrations. During flow being directed perpendicular to the canyon a vortex circulation leads to a doubling of ambient particles when the measurement site is situated upwind to ambient flow. The vertical profiles of fine particles have maximum vertical differences of 12% between measurement levels. In the upper part of the canyon, concentrations decrease due to enhanced turbulence and mixing. Significant differences in the dynamics of particle number concentration for different size ranges are analysed. While submicron particles are inversely related to turbulence parameters, i.e. lower concentrations during enhanced turbulence, coarser particles ($1 < D_p < 10\,\mu m$) are positively correlated to mixing within the canyon.

Keywords: Fine particles; Turbulence; Mean flow; Vertical profile; Urban street canyon

1. Introduction

High concentrations of airborne particles are associated with significant impacts on human health as found by recent epidemiological and toxicological studies (e.g. Brunekreef and Holgate, 2002; Davidson et al., 2005). This holds especially for the fine and ultrafine size ranges due to their ability to penetrate deep into the human body (Wichmann and Peters, 2000; Oberdörster and Utell, 2002). Possibilities to reduce the concentrations of airborne particles are discussed within the public and scientific communities not only since the introduction of the European limiting value for PM_{10} in January 2005 (EC, 1999). However, effective plans to manage and regulate urban air quality

*Corresponding author. Tel.: +49 201 183 3387; fax: +49 201 183 3239.

E-mail addresses: stephan.weber@uni-due.de (S. Weber), wiku@uni-due.de (W. Kuttler), Konradin.weber@fh-duesseldorf.de (K. Weber).

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require a detailed scientific knowledge about the particle sources and dynamics within the urban environment and influences introduced by ambient meteorology.

Street canyons are generally 'hot-spots' of gaseous and particulate concentrations in urban areas (e.g. Van Dingenen et al., 2004). This is due to high emissions induced by the traffic fleet together with limited dispersion within the built-up environment. However, due to the large differences in canyon geometry, traffic intensity, mixture of the traffic fleet and ambient meteorology street canyon concentrations are highly variable (Johnson and Hunter, 1999; Kuttler and Wacker, 2001; Kastner-Klein et al., 2004; Kim and Baik, 2004). Results from field measurements in differing canyon geometries report that pollutant concentrations driven by vortex circulation inside the canyon are normally higher on the upwind (leeward) than on the downwind side (Park et al., 2004; Tsai and Chen, 2004). Concentrations at both kerbsides can differ by a factor of 2 and higher (Boddy et al., 2005).

The picture of the vertical distribution of particles in canyons is still under debate. Zoumakis (1995) did show gaseous pollutants to decrease exponentially with height above ground. There is evidence for a similar behaviour of particles, which are emitted mainly near to the surface due to combustion processes, tyre and brake abrasion along with resuspension processes. For ultrafine particles a decrease with height is reported from field studies which measured near-surface and roof-level concentrations (Vakeva et al., 1999; Longley et al., 2004a, b). Other studies, however, indicate an increase or homogeneous profiles of particles in the near-surface canyon layer and over the entire canyon depth (Colls and Micallef, 1999; Park et al., 2004). Particle monitoring at traffic sites is often done at varying heights, e.g. due to infrastructural limitations at the sites. The EU directive 1999/30/EC (EC, 1999) allows, for instance, for sampling heights between 1.5 and 4 m above ground level (a.g.l.). Under specific local circumstances measurements can be taken up to 8 m a.g.l. The question arises as to whether an influence on measured concentrations exists, given some height dependence of particle distribution as described above.

During the canyon particle experiment (CAPAREX) a busy urban canyon was equipped with instruments at different heights to study mean flow, turbulence and in-canyon particle dispersion under changing meteorological conditions. Vertical particle profiles were measured to evaluate the dynamics and height-dependence of particle dispersion.

In the following sections site characteristics and measurement devices used in the study will be presented followed by results and discussion of flow characteristics and particle concentrations within the urban street canyon.

2. Study site

2.1. Canyon geometry

The field study was conducted from 19 July 2005 to 18 August 2005 at the kerbside of the federal expressway B224 (Gladbecker Straße) in the city of Essen, Germany (Fig. 1).

In the vicinity of the measurement site the street is orientated SE–NW (135–310°). Mean building height is $H = 17$ m while the canyon is $W = 21.6$ m wide resulting in a height to width ratio (H/W) of 0.79. The residential houses are mainly comprised of four floors. The canyon is symmetric with pitched roofed houses on both sides, however, actual roof shape and roof slopes slightly differ

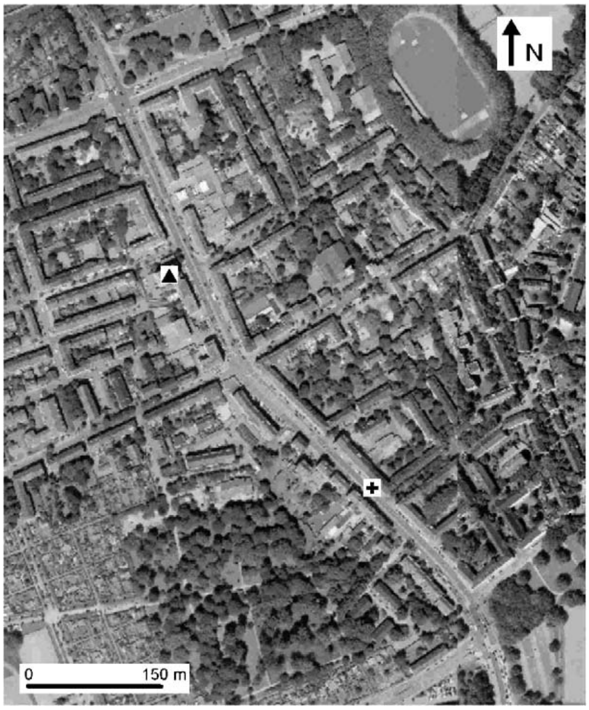

Fig. 1. Aerial view of the study area. The measurement site at B224 is marked by the black cross while the rooftop sonic at $z/H = 2.05$ is marked by the black triangle.

between both sides (e.g. roof slopes are steeper on the northern side).

The B224 is characterised by four traffic lanes, two directed towards the centre of Essen while the other two leading towards the northern parts of the Ruhr-Area.

2.2. *Traffic intensity*

Traffic intensity at B224 is high with approximately 49,000 vehicles $24\,h^{-1}$. The fraction of lorries considering the total traffic fleet is 10% on average. Continuous traffic measurements being conducted from 12 to 18 August 2005 did show two distinct traffic peaks during morning and afternoon rush-hours with maxima of about 1500 vehicles $30\,min^{-1}$ and 1700 vehicles $30\,min^{-1}$, respectively (not shown here). Due to a traffic light being situated ~200 m to the NW of the site traffic congestion is a frequent feature especially during the afternoon rush-hour when higher numbers of vehicles are about to travel from the centre of Essen towards the northern Ruhr-Area than towards the centre.

3. Material and methods

3.1. *Instrumentation*

A 10 m triangular lattice tower was installed 3 m off the house wall at the northern kerb of B224 (Fig. 2). It was equipped with four levels of ultrasonic-anemometers (Metek USA-1, Germany) and three levels of optical particle counters (OPC, Grimm Aerosol Model 1.107, Germany, for details see Table 1). Additionally, net radiation was measured at 3 m a.g.l. (Ph. Schenk, Austria) and relative humidity at 2.3 and 7.7 m a.g.l. (Th. Friedrichs, Germany). The fifth sonic at a height of 35 m a.g.l. was situated on a rooftop at a distance of 320 m to the NW of the tower (Fig. 1). Although it is located at some distance from the actual measurement site the data is important to characterise the ambient flow at some height above the urban canopy layer. To gather accurate urban wind and flux estimates sensors have to be placed above the roughness sublayer (blending height z^*) where the flow has adjusted to the underlying surface.

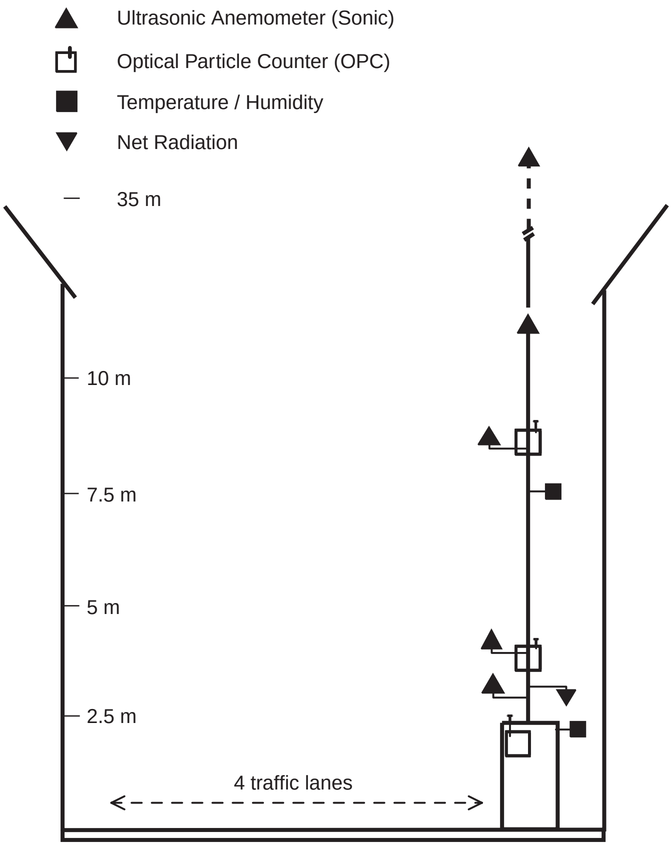

Fig. 2. Schematic plot of the CAPAREX experimental setup. The distance between tower and traffic lanes was approximately 0.5 m.

Table 1
Overview of measurement equipment

	Device	Quantity	Height a.g.l.	Height z/H	Sampling interval	Storage interval
Meteorology	Sonic	u, v, w, T_s	3.2	0.19	10 Hz	5 min
			4.0	0.24		5 min
			8.6	0.51		raw data
			11.2	0.66		5 min
			35.0	2.05		10 min
	Pyrradiometer	Q^*	3.0	0.18	10 s	5 min
	Capacitive hygrometer	rH	2.3	0.13	10 s	5 min
			7.7	0.45		
Particles	OPC Grimm 1.107	$0.3<D_p<10\,\mu m$	2.5	0.15	6 s	1 min
			3.9	0.23		1 min
			8.9	0.52		6 s

In urban areas z^* values are reported to vary between 1.5 and five times the mean building height (Roth, 2000). As a quality check for sensor placement integral turbulence characteristics (e.g. σ_w/u_*) can be calculated and compared to Monin-Obukhov surface layer scaling (Foken and Wichura, 1996). For the sensor at $z/H = 2.05$ good agreement was found (Section 4.3) so that a placement above z^* is assumed.

At the measurement tower base a container (1.8 m length × 1.0 m width × 2.25 m height) was housing data loggers and notebooks for data storage. The Grimm OPC measures particle number concentrations in the size range 0.3 μm < particle diameter, $D_p<32\,\mu m$ by a light scattering technique. Thereby the signal of a single particle passing a laser beam is counted by a recipient diode. The pulse height of the signal is detected by a multi-channel classifier and measured as particle size distribution. The signal is then converted into the particle mass fractions PM_{10}, $PM_{2.5}$ and PM_1. Grimm monitors are calibrated by using a wide range of aerosols and have shown to be suitable for analysis of urban particulate matter by comparison to gravimetric methods (Giugliano et al., 2005). The OPCs installed at the relative heights of $z/H = 0.15$ and 0.52 measured particle number and mass concentrations while at $z/H = 0.23$ only mass concentrations were measured (z = measurement height a.g.l., H = mean building height).

Due to length restrictions of the sampling nozzle the measurements at $z/H = 0.15$ had to be installed close to the roof of the container. Consequences on data quality will be discussed in a later part of the paper.

Table 2
Slope, intercept (in $\mu g\,m^{-3}$) and coefficient of determination calculated from 1 min averages of the OPC field comparison at B224 from 14 to 18 July 2005 ($n = 5297$)

OPC	PM_x	Correlation				
		$y = ax+b$			$y = ax$	
		a	b	r^2	a	r^2
1 vs. 2	PM_{10}	0.9	2.5	0.81	0.96	0.8
	$PM_{2.5}$	1	0.4	0.96	1.02	0.96
	PM_1	1.01	0.6	0.98	1.04	0.98
1 vs. 3	PM_{10}	0.77	1.06	0.85	0.81	0.85
	$PM_{2.5}$	0.95	0.68	0.95	0.92	0.95
	PM_1	0.95	0.18	0.96	0.94	0.96

3.2. Field comparison of OPC

Prior to the CAPAREX campaign the OPCs were tested against each other at the present site for a period of 5 days from 14 to 18 July 2005. Overall, agreement between the different devices was good for the fine particle fractions PM_1 and $PM_{2.5}$ with slopes of regressions close to 1 and little intercept (cf. Table 2). However, due to larger deviations of PM_{10} (~20%, cf. Table 2) the comparison of vertical particle profiles is limited to PM_1 and $PM_{2.5}$. We also computed coefficients for the regression forced through the origin ($y = ax$, cf. Table 2) to calculate simple correction factors with a strong statistical relationship (e.g. $r^2 = 0.98$ and 0.96 for PM_1). The measured concentrations are then corrected by constant correction values (e.g. 4% of the measured value in case of PM_1, OPC2).

However, the corrected particle concentrations will only come into account when concentrations from different heights a.g.l. will be compared. We will refer to them at the relevant part of the paper.

Due to technical problems with OPC3 at $z/H = 0.52$ it had to be changed to a new device on 29 July 2005. Unfortunately, field comparisons with the new device were not possible during the ongoing campaign. A post field comparison showed poor agreement between the new device and OPC1 while OPC2 still showed good agreement. The analysis of vertical particle profiles (Section 4.5) will therefore be restricted to the period from 18 to 29 July 2005, when the original three OPC were in operation.

3.3. Data handling

Sonic data during CAPAREX was generally sampled at 10 Hz. However, due to data storage capacity different averaging intervals were calculated online and stored to data storage cards or notebook computers (cf. Table 1). The sonics were installed vertically to the surface; no coordinate rotation was applied due to the complex three-dimensional flow within the urban canopy (for detailed discussion on this topic cf. Christen, 2005). For all sonic anemometers half-hourly means and covariances were calculated from 5 min block averages (10 min block average in the case of sonic at $z/H = 2.05$). Due to maintenance of the measurement equipment temporary loss of data was unavoidable; however, data loss for particles was $<3\%$ for the 5 week period. Due to a data storage failure, loss for sonic data was 11% at $z/H = 0.24$ and 14% at $z/H = 0.51$, respectively.

For subsequent data analysis reference wind speed and direction will be defined by the above canyon data gathered at two-times the mean building height ($z/H = 2.05$). The particle data will be classified into situations of along-canyon (ALC) or cross-canyon flow (CRC). Owing to the canyon orientation ALC flow from SE is defined $125^\circ < \text{ALC} < 145^\circ$ and from NW $300^\circ < \text{ALC} < 320^\circ$ from NW while other directions are classified CRC. Therefore CRC also accounts for situations that have components of CRC flow rather than strictly perpendicular flow.

For analysis data was time averaged over 30 min periods as either arithmetic means for scalars (i.e. particles) or vector averages for wind speed and direction. To visualise the dependency of particles on the reference flow arithmetic means were calculated for the different wind direction sectors (e.g. Fig. 6)

In a later part of the paper particle size dynamics will be studied. Therefore we classified particle data into a submicron ($0.3 < D_p < 1\,\mu m$) and into a coarser fraction ($1 < D_p < 10\,\mu m$) to account for the diverse emission sources within an urban canyon. Apart from the background aerosol other sources are those related to direct emission by combustion and those by tyre and brake abrasion and resuspension. The OPCs used in this study have a lower cut-off size of 0.3 μm. Therefore only a subset of primary vehicle emissions was sampled since primary particles by combustion are known to peak at size ranges < 100 nm (Ruuskanen et al., 2001; Wehner et al., 2002). However, with a subset of primary particles sampled classification into two size ranges enables to identify which parameters influence airborne concentration of particles of different size.

4. Results and discussion

4.1. Meteorology during CAPAREX

The study period from 19 July 2005 to 18 August 2005 was characterised by cyclonic weather conditions, precipitation events and overcast conditions. During two high-pressure periods at the beginning of August (1–5 August) and mid-August (16–18 August) warm and sunny conditions prevailed. During the CAPAREX study period the wind direction frequency distribution was dominated by westerly and southwesterly winds with a frequency of 50% of wind directions from the sectors W, WSW and SW. This wind frequency distribution is typical for this region of Germany and was comparable to the longtime average. Owing to the canyon flow classification described in Section 3.3, 93% of wind directions can be classified CRC while only 7% of the winds were directed along the canyon-axis.

4.2. Flow within the street canyon

Urban street canyons are characterised by significant modifications of the above canyon flow. During CRC skimming flow conditions wind speeds are reduced due to the roughness elements and canyon geometry. The in-canyon wind speeds at the present site are reduced to about 25% of the reference wind velocity in the bottom part of the canyon (Fig. 3a). A slight increase of wind velocity with canyon height can be observed which is in accordance to findings by Rotach (1995) and Eliasson et al. (2006). However, the reduction of local wind-velocities at the different heights above ground is varying depending on the direction of ambient flow (Fig. 3b). We calculated a sector scaled velocity (u_{ssv}) to analyse the reduction of wind velocity within the street canyon as a function of ambient wind direction. Therefore the local velocities measured at the different heights above ground were normalised by the corresponding above canyon reference velocity at $z/H = 2.05$, first, afterwards multiplied by the average absolute reference velocity in each direction sector according to

$$u_{ssv} = \left(\overline{u_{z/H}/u_{roof}}\right)\overline{u_{roof}}, \quad (1)$$

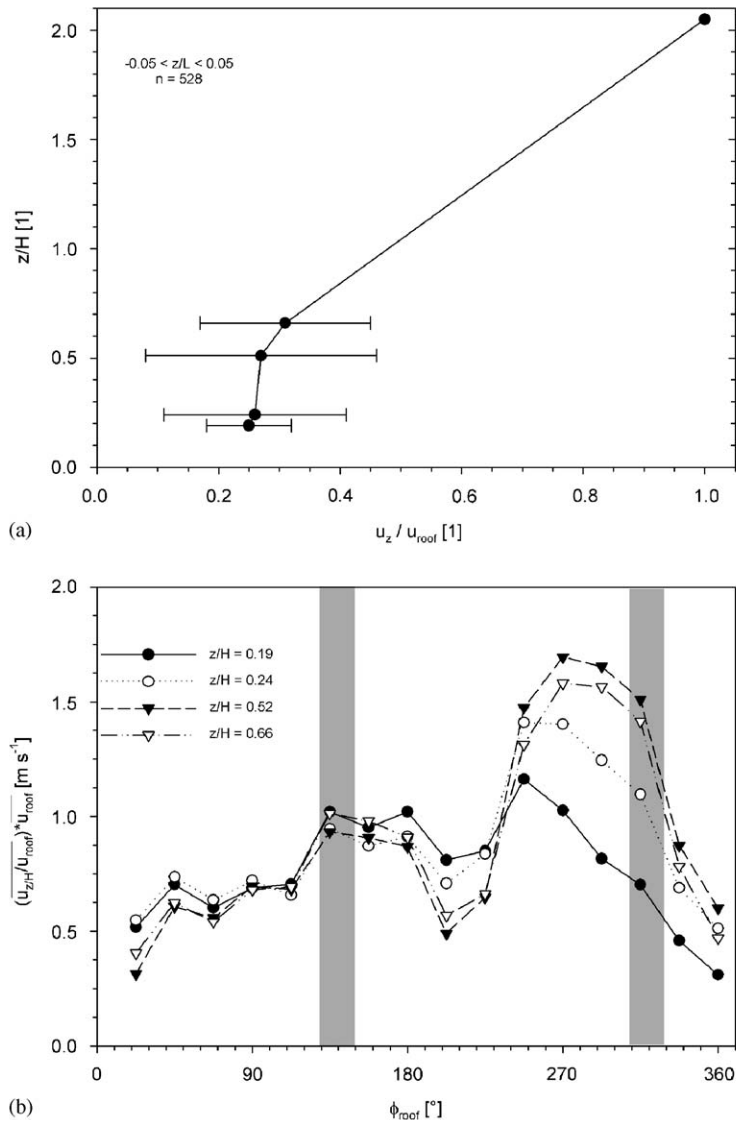

Fig. 3. (a) Vertical profile of wind velocities at different measurement heights normalized by reference wind velocity based on 30 min averages during neutral stability (defined as $-0.05 < z/L < 0.05$ where z is the height a.g.l. and L is the Obukhov length) in the study period from 19 July 2005 to 18 August 2005. The error bars indicate the standard deviation. z/L was calculated for the reference sonic at $z/H = 2.05$ as $z/L = -(g/\overline{T})(\overline{w'T'})/[u_*^3/k(z-d)]$, where g is the acceleration due to gravity, k von Karman's constant and d the displacement height assumed as $d = 0.66$ H. (b) Scaled wind velocity at the different heights as a function of ambient wind direction for all data. The shaded areas indicate the canyon-axis orientation. For the calculation of u_{ssv} see text.

where $\overline{u_{z/H}/u_{\mathrm{roof}}}$ is the mean sector averaged ratios of local and reference velocity and $\overline{u_{\mathrm{roof}}}$ the sector average reference velocity, all in $\mathrm{m\,s^{-1}}$.

The calculation of u_{ssv} is important to account for generally weaker winds from the N and E sectors ($<2\,\mathrm{m\,s^{-1}}$ on average) in comparison to the other direction sectors ($>3\,\mathrm{m\,s^{-1}}$). The lowest in-canyon velocities are observed for winds from the N and E sectors. But also higher rooftop wind speeds from SW are reduced to low in-canyon speeds when directed from $202.5^\circ<\phi<247.5^\circ$ (Fig. 3b). This is an important finding for in-canyon dispersion of pollutants since the wind is directed mainly from these sectors (cf. Section 4.1).

At the present site, a distinct channelling of wind directions along the canyon-axis can be observed in the upper part of the canyon at levels $z/H = 0.51$ and 0.66 regardless of the direction of the ambient flow (Fig. 4). In the lower part channelling effects are less distinct being associated with vortex circulation effects. According to Johnson and Hunter (1999) a single-vortex is expected to develop in canyons with $0.6<H/W<1.6$ when ambient flow is directed perpendicular to the canyon-axis whereas helical vortex circulations were observed for ambient flow being directed at some angle to the canyon-axis (see also Kastner-Klein et al., 2004; Ahmad et al., 2005; Eliasson et al., 2006). For CRC flow from the sectors $180^\circ<\phi<247.5^\circ$ a single vortex circulation within the canyon can be observed. While winds are channelled into the canyon-axis in the upper canyon, opposite wind directions in comparison to rooftop winds can be observed in the lower canyon parts. The vortex circulation is characterised by a downward vertical motion of canyon air due to the positioning of the measurement tower at the upwind kerbside. The inclination of the mean wind (vertical wind velocity angle) was calculated according to

$$\eta = -\arctan\left(\frac{\overline{w}}{\sqrt{\overline{u}^2+\overline{v}^2}}\right), \qquad (2)$$

where w is the vertical wind velocity and u and v the horizontal wind components, all in $\mathrm{m\,s^{-1}}$.

With winds flowing perpendicular from the N the development of a canyon-vortex is not that pronounced, although still present. This is most likely associated to different roof geometries at both sides having substantial influence on in-canyon dynamics (e.g. Kastner-Klein et al., 2004).

4.3. Turbulent flow regime within the canyon

The dispersion of pollutants is closely related to the characteristics of mean and turbulent flow within an urban canyon. At the present site turbulence parameters show a distinct increase in turbulence at the upper part of the canyon due to enhanced exchange and transport of momentum from the shear layer forming across the canyon top (cf. Fig. 5).

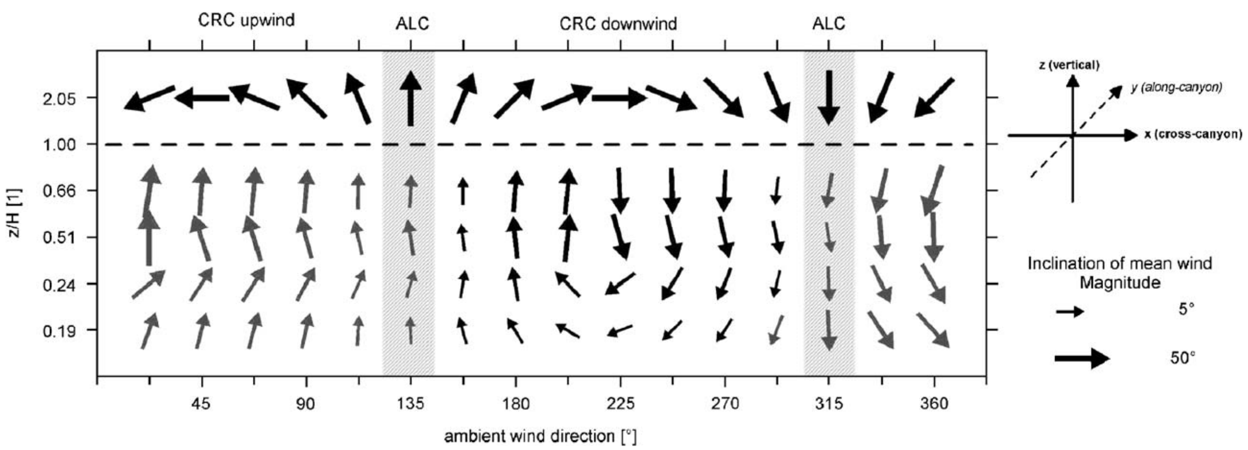

Fig. 4. Horizontal wind directions at different measurement heights as a function of reference wind direction at $z/H = 2.05$. Arrows are plotted with respect to the canyon-orientation (x–z plane, see inset in figure for definition of the planes), e.g. perpendicular flow from 225° is indicated by horizontal arrows. Grey arrows indicate upward directed vertical angles of attack, while black arrows specify downward motions. The hatched areas indicate the canyon-axis orientation. Data is based on 30 min averages during the study period from 19 July 2005 to 18 August 2005.

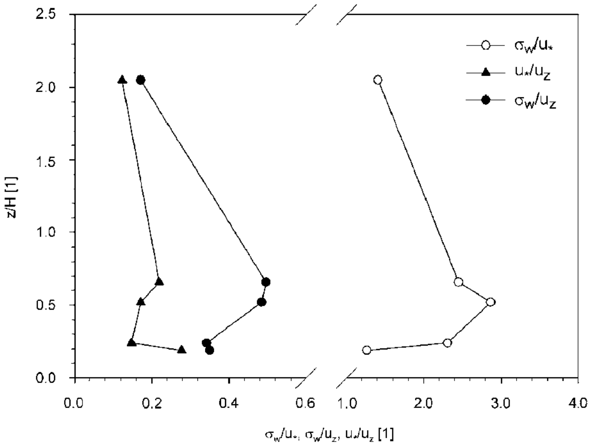

Fig. 5. Vertical profiles (medians) of Reynolds stress u_*/u_z, turbulence intensity σ_w/u_z and σ_w/u_* for neutral stability. Based on 30 min averages from wind direction sector SW, WSW and W during the entire study period.

The shapes of the vertical profiles of both, the turbulence intensity σ_w/u_z defined as the ratio of the standard deviation of vertical velocity scaled by the local mean wind velocity (Stull, 1988) and σ_w scaled by the friction velocity are in agreement to findings by others (e.g. Rotach, 1995; Christen et al., 2003). However, the values of $\sigma_w/u_* = 2.9$ at $z/H = 0.52$ and $\sigma_w/u_* = 2.4$ at $z/H = 0.66$ are somewhat larger (friction velocity was calculated as $u_* = [(\overline{u'w'})^2 + (\overline{v'w'})^2]^{0.25}$ to account for lateral contribution to turbulence.). This might be likely due to enhanced mixing in close proximity of the northern house wall where the measurement tower was installed. Similar findings are reported by Eliasson et al. (2006) who measured $\sigma_w/u_* > 2.5$ at $z/H \sim 0.6$ at a distance of ~2 m to the windward wall. The turbulence parameters measured above roof-level are generally lower in comparison to the in-canyon values and are comparable to neutral surface-layer scaling (Roth, 2000).

The vertical profile of Reynolds stress scaled by the above-roof velocity u_*/u_z increases with canyon-height but is characterised by a maximum at the lowest measurement level ($z/H = 0.19$). Normally a minimum of u_*/u_z would be expected at the lowest measurement level (e.g. Christen, 2005). The higher drag the surface exposes on the ambient flow at this level is likely to be related to the anemometer being located close to the roof of the container housing the measurement equipment and due to additional turbulence produced by moving vehicles in the near-surface layer of the canyon.

4.4. Particle mass and number concentrations

In this section, particle concentration variability will be studied focussing on the measurements gathered at surface level ($z/H = 0.15$). Depending on ambient meteorology, the presence of the canyon vortex and its sense of rotation (cf. Fig. 4) particle concentrations are found to vary significantly within the canyon. Higher concentrations for all particle size fractions are measured for the tower being situated upwind to the ambient flow (Fig. 6a). The resulting concentration differences for upwind and downwind situations vary by factors of 1.5, 1.6 and 1.8 for PM_{10}, $PM_{2.5}$ and PM_1, respectively. This is in the order of magnitude as has been found for other pollutants in different canyon geometries under perpendicular flow (e.g. Longley et al., 2003). As is discussed by Boddy et al. (2005) the vortex recirculation transports pollutants away from the tower during downwind conditions resulting in lower concentrations, while pollutants become trapped in the vortex and transported towards the tower during upwind conditions.

The particle size distribution and its dynamics also seem to be influenced by meteorological conditions. The ratios of particle mass fractions PM_1/PM_{10} and $PM_1/PM_{2.5}$ indicate higher loads of submicron particles during upwind compared to downwind conditions (Fig. 6b). This behaviour is qualitatively similar at all measurement heights (not shown here). Particles in the mass fractions PM_{10} and $PM_{2.5}$ are characterised by a weak increase in concentration during downwind situations when winds are directed nearly perpendicular to the canyon-axis ($200° < \phi < 250°$). Concentration increases for the PM_1 fraction cannot be observed (c.f. Fig. 6b). The increase of coarser particles is associated with higher in-canyon wind speeds and mixing during downwind situations (cf. Fig. 3b). Having in mind the different flow and turbulence characteristics and their dependence on ambient flow (cf. Sections 4.2 and 4.3), it is therefore important to analyse how dynamics and dispersion mechanisms of particles in different size ranges are influenced by meteorological and other parameters, i.e. traffic intensity.

Particle numbers classified into two size ranges as described in Section 3.3 are characterised by a different behaviour in relation to daily averages of wind speed and turbulence parameters. While submicron particle numbers decrease with increased mixing and turbulence the contrary is found for the

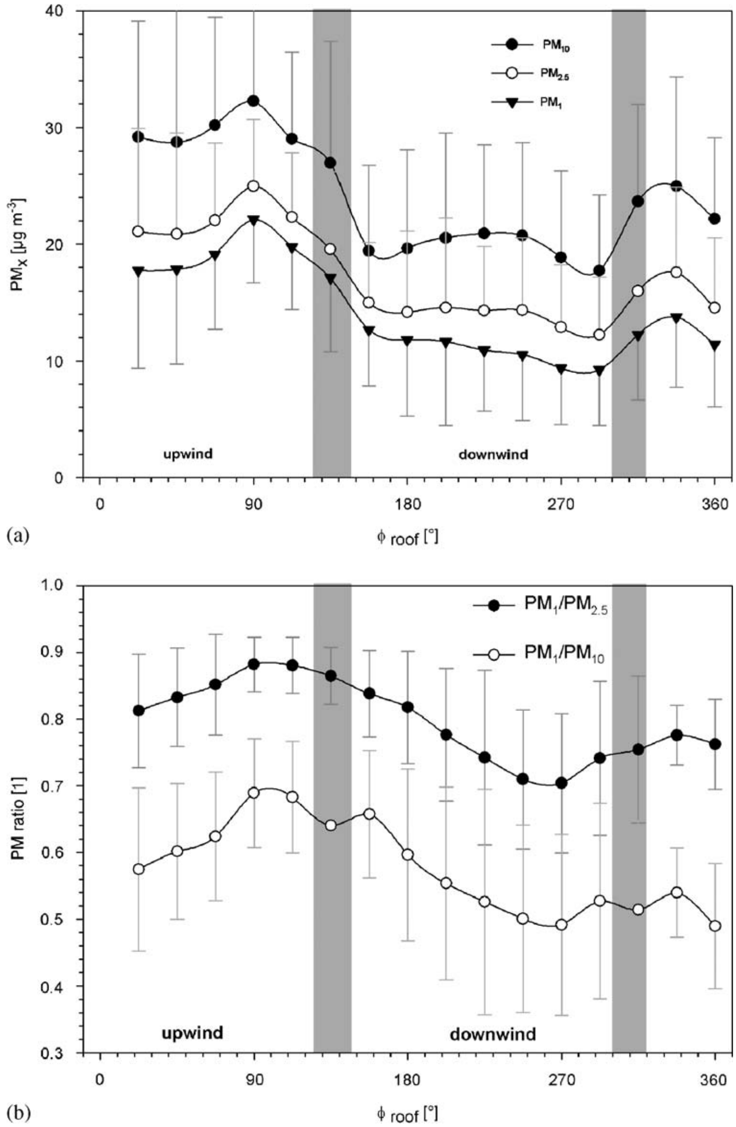

Fig. 6. Particle mass fractions as function of ambient wind direction (a) and ratios of particle mass fractions (b) at $z/H = 0.19$ for the study period from 19 July 2005 to 18 August 2005. The error bars indicate the standard deviation. For reasons of clarity only positive (negative for PM_1) standard deviations are plotted in (a). The shaded areas specify the canyon-axis orientation

coarse class (Fig. 7). Submicron particles are inversely related to turbulence as shown by the negative correlation with $\sigma_{w\,\mathrm{roof}}$ and u_{roof} (Table 3). Number concentrations of coarser particles are positively correlated with turbulence parameters and increase with enhanced turbulence indicating resuspension of afore emitted and suspended particles within the canyon. The influence of net radiation and stability on both size classes is weak and statistically not significant in most cases. The negative correlation of net radiation Q^* and coarser particles is mainly attributed to lower wind speeds during clear and calm weather conditions therefore favouring higher concentrations of submicron particles (cf. Fig. 7). Another effect might be attributed to enhanced gas-to-particle conversion during sunny periods. The number concentration of submicron particles is closely related to the amount of traffic and can satisfactorily be described by fitting a power function (Fig. 8). Number concentrations in the coarse size range are not significantly influenced by traffic intensity.

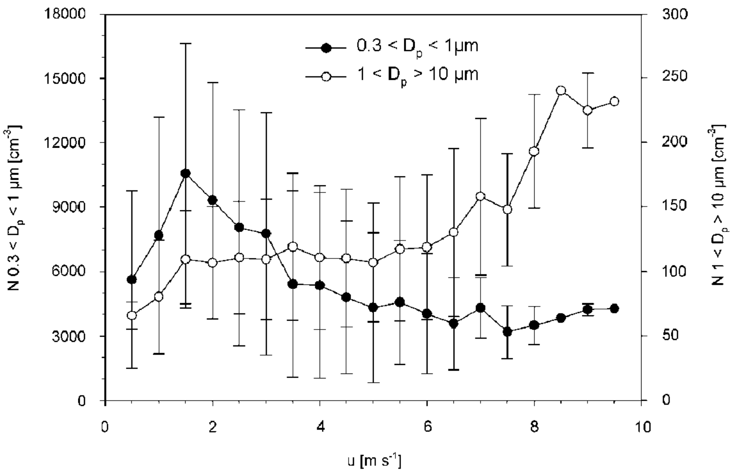

Fig. 7. Particle concentrations classified into two size classes as a function of ambient wind speed binned into 0.5 $m\,s^{-1}$ classes. Data is based on 30 min averages during the study period from 19 July 2005 to 18 August 2005.

Table 3
Pearson correlation coefficients r and r^2 (in brackets) of particle number concentrations measured by OPC1 at $z/H = 0.15$ vs. daily averages of different meteorological parameters ($Q^* > 0$)

Size class	u_{roof}	$\sigma_{\mathrm{w\,roof}}$	Q^*	z/L_{roof}
$0.3 < D_p < 1\,\mu m$	−0.45 (0.20)	−0.41 (0.17)	$0.15^{\#}$ (0.02)	$-0.13^{\#}$ (0.01)
$1 < D_p < 10\,\mu m$	$0.22^{\#}$ (0.05)	$0.14^{\#}$ (0.02)	−0.42 (0.18)	$0.18^{\#}$ (0.03)

Data marked # is not significant on the $p = 0.05$ level. Data is based on entire study period.

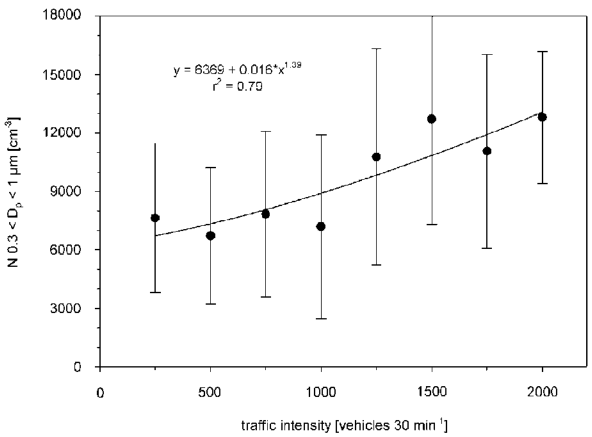

Fig. 8. Submicron particle number concentration ($0.3 < D_p < 1\,\mu m$) vs. traffic intensity in the period of continuous traffic registration from 12 to 18 August 2005. The error bars indicate the standard deviation.

The results demonstrate that the distribution of the particle load and size within the canyon is not stationary but a complex function of traffic intensity and meteorology (e.g. wind direction and turbulence).

4.5. Vertical particle concentration profiles

To compare vertical particle profiles during different situations (traffic intensity, ambient flow) measured concentrations were normalised to the value at $z/H = 0.15$ (Fig. 9a, b). On the left-hand side of Fig. 9 differences of particle concentration between the different levels are plotted.

Between the second and third measurement level at $z/H = 0.23$ and 0.52 the concentration profiles show a decrease of on average 8% and 7% for $PM_{2.5}$ and PM_1, respectively (Fig. 9a). This is due to the particle sources (combustion, tyre abrasion, resuspension) being situated near to the surface and enhanced mixing in the upper part of the canyon. However, in the near-surface layer from $z/H = 0.15$ to 0.23 an increase of particle concentrations is observed showing higher concentrations at 3.9 m than at 2.5 m a.g.l. In Fig. 9b the particle data was simply corrected by a constant factor according to

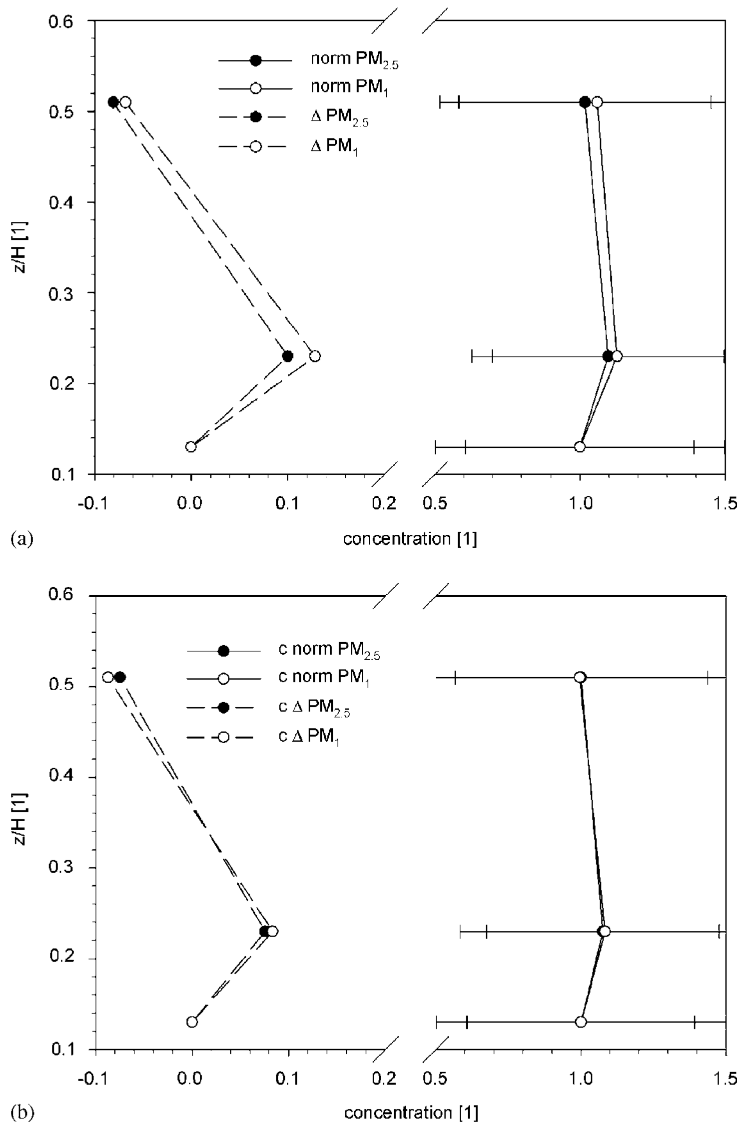

Fig. 9. Vertical profiles of particles (PM_1 and $PM_{2.5}$) measured during the period from 19 July 2005 to 29 July 2005. Profiles are plotted as normalised concentrations (norm) and differences between measurement levels (Δ) for uncorrected (a) and corrected particle data (b) according to the method described in Section 3.2.

the method described in Section 3.2. The shape of the profile does not change significantly. An increase from $z/H = 0.15$ to 0.23 is still existent but less pronounced with 7% and 9% for $PM_{2.5}$ and PM_1, respectively. As was introduced in Section 1 a similar increase was reported for PM_{10} measurements in the first 3 m of an urban canyon (Colls and Micallef, 1999) and from a wind-tunnel study for leeward flow situations (Park et al., 2004). Longley et al. (2004b) also reported that fine particle gradients can temporarily increase at the lowest measurement levels within a street canyon. This is, however, not a general feature of vertical pollutant distribution in canyons since most studies report maximum concentrations near the canyon bottom decreases with increasing height above ground (Zoumakis, 1995;Vakeva et al., 1999; Vogt et al., 2006). Lower concentrations measured at $z/H = 0.15$ might be attributed to a larger intense of turbulence near the container (cf. Section 4.2) or enhanced mixing due to traffic produced turbulence (Kastner-Klein et al., 2003; Ahmad et al., 2005). Vehicle motions clearly enhance turbulence at the lower levels of a canyon (Di Sabatino et al., 2003).

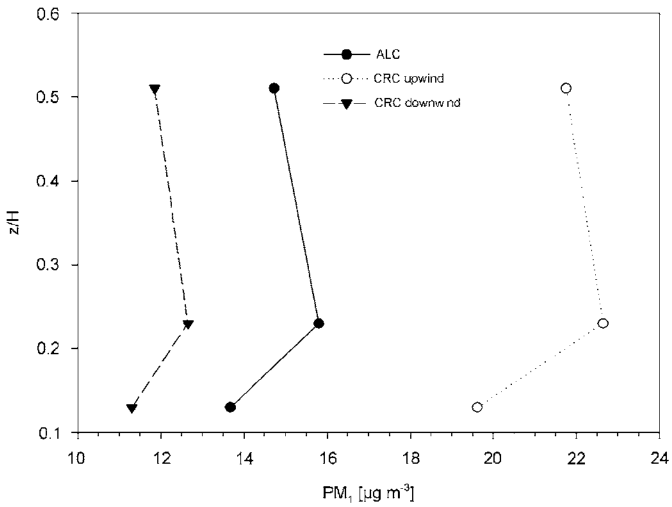

Fig. 10. Vertical profiles of PM_1 classified according to different flow regimes during the period from 19 July 2005 to 29 July 2005.

De Paul and Shieh (1986) measured the influence of traffic on turbulent velocity up to a height of $z/H = 0.2$. The measurements at the lowest level were likely influenced by the positioning of the sampling inlet also. It was installed on the container roof and was somewhat sheltered from upwards transported particles emitted at street level. Therefore lower concentrations are measured at street level. Since the shape of the profiles is similar in general, also under diverse ambient flow regimes (Fig. 10), we believe this effect to be mainly attributed to slight sheltering of the sampling inlet rather than to in-canyon particle dynamics.

When particle data is classified into ALC and CRC flow, a large variation in absolute concentrations comparable to the situation described for the near-surface level (cf. Section 4.4) can be observed (Fig. 10). Lowest concentrations are reached under CRC downwind conditions while under upwind conditions concentrations are larger by a factor of 1.8 when averaged over the three measurement levels. During ALC flow concentrations are higher compared to CRC downwind by a factor of 1.2. This is believed to be attributed to an ALC transport of particles induced by the vehicles motion as was also found in wind tunnel studies (Ahmad et al., 2005).

In terms of possible errors introduced when measuring particle concentrations at different heights within a canyon (cf. Section 1), the present results show that vertical concentration differences for PM_1 are at maximum 9% for corrected values, respectively (Fig. 9).

5. Summary and conclusions

During a 5 week period flow characteristics, turbulence properties and particles were measured at different heights within an urban street canyon. The flow field inside the canyon is highly influenced by buildings and canyon geometry. An in-canyon vortex was observed during flow being directed perpendicular to the canyon-axis. Concentrations of airborne particles in the canyon are highly variable being a complex function of ambient flow, turbulence and traffic intensity. By classification of particle data into two size ranges and a simple correlation analysis we worked out that submicron particle number concentrations are closely related to traffic intensity and inversely correlated to the intensity of turbulence. Coarser particles $>1\,\mu m$, on the other hand, are positively correlated to turbulence with increasing concentrations at higher wind speeds. Different transport mechanisms are responsible for the different behaviour of the two size classes. Larger particles being preferably emitted by abrasion of tyres and brakes are deposited onto surfaces and become resuspended at higher turbulence intensity. Submicron particles emanate from primary emission by vehicles mostly. They exhibit maximum concentrations during calm weather conditions and high traffic intensity.

The shape of the vertical distribution of the particle fractions $PM_{2.5}$ and PM_1 was similar under different meteorological conditions. Concentrations generally decrease in the upper part of the canyon due to enhanced mixing near the rooftop-level. At the near-surface level a decrease of particles was observed which is believed to be due to enhanced turbulent mixing by vehicle produced turbulence. Generally, the shape of the fine particle profiles was found to be quite homogeneous with height above ground. Errors introduced by sampling at different heights a.g.l. were found to be 12% at maximum or rather 9% at maximum for corrected values in the present canyon. However, more work on the vertical distribution of particles in street canyons has to be done to study particle profiles under different meteorological and traffic conditions.

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