Meteorologische Zeitschrift, Vol. **17**, No. 3, 251-261 (June 2008)

Article

Coupling of urban street canyon and backyard particle concentrations

STEPHAN WEBER *[1] and KONRADIN WEBER[2]

[1]Department of Applied Climatology and Landscape Ecology, Institute of Geography, University of Duisburg-Essen, Campus Essen, Germany
[2]Department of Mechanical and Process Engineering Environmental Measurement Techniques, University of Applied Sciences, Duesseldorf, Germany

(Manuscript received November 16, 2007; in revised form March 19, 2008; accepted March 19, 2008)

Abstract

Differences in particle mass and number concentrations between a busy urban street canyon (north-south orientation, about 50,000 vehicles 24 h^{-1}) and an adjacent backyard were measured with optical particle counters. The influence of meteorological quantities, especially turbulent flow within the urban canopy layer, was also studied. Particle mass concentrations PM_{10} and PM_1 were consistently larger within the street canyon due to enhanced emission and resuspension. For the study period this resulted in higher concentrations in the canyon of on average 30 % (PM_{10}) and 22 % (PM_1). Although elevated transport of submicrometer particles was related to easterly wind directions, the largest relative concentration differences between both sites were associated to cross-canyon flow from westerly wind directions. This is due to the canyon vortex being able to direct polluted air masses to the measurement site during flow being directed perpendicular to the canyon axis. For less polluted air within the backyard the backyard vortex is of minor influence. We found different influence of thermal and mechanical turbulence on the temporal evolution of concentration differences at both sites. Thermal turbulence was positively correlated with particle concentrations, while the latter was characterised by negative correlation coefficients.

Zusammenfassung

Unterschiede in der Partikelanzahl und Partikelmassenkonzentration zwischen einer stark befahrenen Straßenschlucht (N-S Exposition, ca. 50.000 Kfz 24 h^{-1}) und einem angrenzenden Hinterhof wurden mittels kontinuierlicher Messungen mit optischen Partikelzählern untersucht. Der Einfluss meteorologischer Größen auf Konzentrationsunterschiede zwischen Straßenschlucht und Hinterhof stand im Fokus der Arbeit. Dabei wurden insbesondere turbulente Strömungsprozesse innerhalb der Stadthindernisschicht untersucht. Im Beobachtungszeitraum zeigte die Straßenschlucht aufgrund erhöhter Emission und Resuspension von Partikeln im Mittel ein um 30 % (PM_{10}) bzw. 22 % (PM_1) höheres Konzentrationsniveau im Vergleich zum Hinterhof. Trotz erhöhter Einträge von Partikeln < 1 μm während östlicher Anströmung des Untersuchungsgebietes, wurden die größten relativen Konzentrationsdifferenzen während Queranströmung der Straßenschlucht aus westlichen Windrichtungen festgestellt. Dabei transportierte die sich unter Queranströmung innerhalb der Straßenschlucht einstellende Rotorzirkulation die belasteten Luftmassen gegen die Straßenseite, an der die Partikelzähler installiert waren. Im weniger vorbelasteten Hinterhof war die Rotorzirkulation von untergeordneter Bedeutung. Weiterhin konnten unterschiedliche Einflüsse von thermisch und mechanisch induzierter Turbulenz auf die zeitliche Dynamik der Konzentrationsunterschiede im Tagesgang festgestellt werden. Für den fühlbaren Wärmefluss zeigte sich eine positive Korrelation mit der Partikelmassenkonzentration, mechanische Turbulenz war negativ korreliert.

1 Introduction

The spatial and temporal distribution of air pollutant concentrations within urban areas is complex and highly variable. This is mainly due to the degree of urban diversity, i.e. diurnal courses of different pollutant emissions from anthropogenic and natural sources as well as horizontal and vertical variations due to the complex three-dimensional structure and flow regime within cities (e.g. OKE, 1987; ARYA, 2001).

*Corresponding author: Stephan Weber, Department of Applied Climatology and Landscape Ecology, Institute of Geography, University of Duisburg-Essen, Campus Essen, 45141 Essen, e-mail: stephan.weber@uni-due.de

To analyse the distribution of particulate pollutant concentrations within cities a number of studies concentrating on different spatial scales were published in recent years (e.g. HARRISON et al., 2001; RUUSKANEN et al., 2001; HUEGLIN et al., 2005; GIUGLIANO et al., 2005; KAUR et al., 2007). However, relatively little is known about particle concentration differences between urban street canyons and adjacent backyards.

Backyards are discussed to be somewhat privileged in comparison to the urban neighbourhood in terms of e.g. climate comfort, pollutant concentrations or environmental noise levels (e.g. BAUER and ALEXANDER, 1996; FORSSEN and HORNIKX, 2006). While in some

0941-2948/2008/0286 $ 4.95
DOI: 10.1127/0941-2948/2008/0286

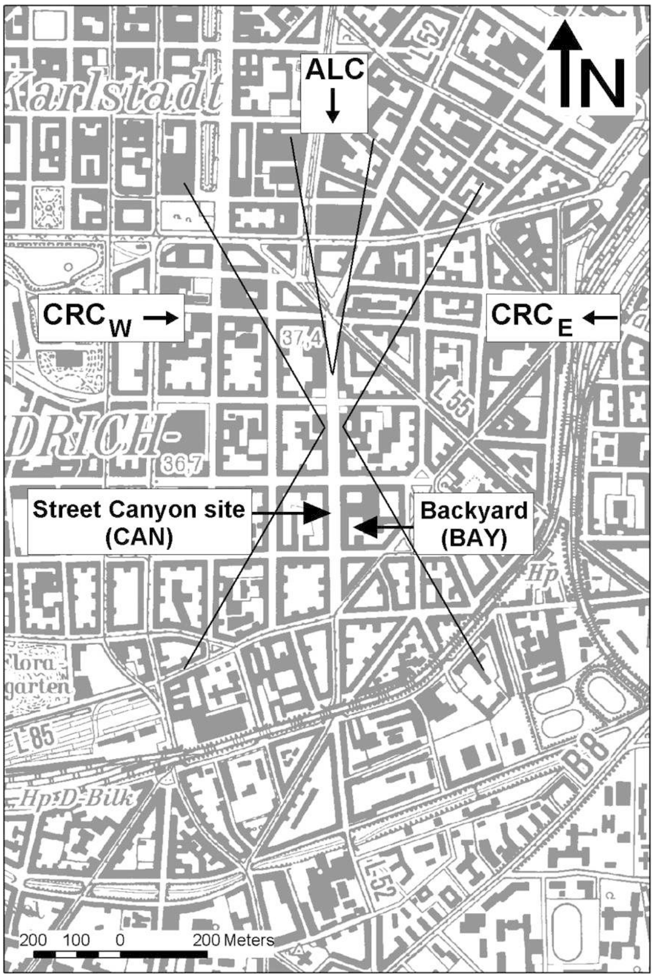

Figure 1: Overview of the measurement sites and the surrounding urban environment in Duesseldorf, Germany (Base map: topographical map 1:25,000 TK25). Arrows point to the measurement sites in the street canyon and backyard. The different sectors (solid lines) indicate wind direction sectors for flow classification into along and cross-canyon flow (ALC, CRC$_E$ and CRC$_W$) as described in section 3.3.

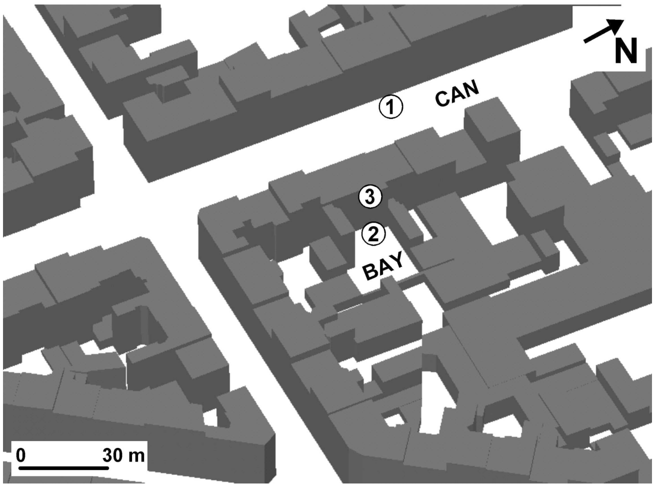

Figure 2: Three-dimensional sketch of the measurement sites at CAN and BAY (1: CAN, 2: BAY, 3: BAY$_t$). Roofs areas are not depicted in this figure.

regions around the globe significant pollutant emission in backyards might be introduced due to the uncontrolled burning of domestic waste (e.g. WEVERS et al., 2004; HEDMAN et al., 2005), the majority of urban backyards is used as recreational area or storage space (in this study we refer to backyards that are completely enclosed by buildings/walls). Therefore most of them are characterised by little or no traffic movements and local emissions of pollutants.

Until now studies on the behaviour of urban street canyon and backyard microenvironments were focussing on differences of thermal or bioclimatic quantities and gaseous air pollutant concentrations (MAHRINGER, 1963; GERTIS et al., 1983; POPP, 1996; SCHWEGLER, 1999; SHASHUA-BAR et al., 2006). Backyards were generally characterised by conditions of enhanced thermal comfort in comparison to the surrounding street canyons/neighbourhood, e.g. decreased direct downward shortwave radiation due to shading effects, lower radiation temperatures and damped daily temperature amplitudes (e.g. GERTIS et al., 1983). The concentrations of air pollutants were shown to be significantly lower within backyards. Average daily weekday concentration of gaseous pollutants CO, NO and NO_2 were lower by 43 %, 78 % and 36 %, respectively, in comparison to an urban street canyon (BAUER and ALEXANDER, 1996). VOGT et al. (2006) observed CO_2 concentration differences of about 15 ppm between a street canyon and a backyard in Basel, Switzerland, during flow perpendicular to the canyon.

Although local emission of pollutants is normally limited within backyards, dispersion also is restricted due to the enclosed building structure. Wind tunnel results indicate that wind speed within a backyard decreases to about 13 % of the wind speed at the top of the model atmosphere (for flow being directed perpendicular to the backyard, e.g. SHARPLES and BENSALEM, 2001). This value declines to about 6 % with increasing plan area density (ratio of plan area of buildings/roughness elements to plan area of total surface) in the vicinity of the model backyard. Similar results were reported by HALL et al. (1999).

The foregoing observations indicate that meteorology might significantly influence particle concentration differences between canyon and backyard sites. Earlier results demonstrated important effects of different meteorological situations, especially the turbulent state of the near-surface boundary layer, on particle concentrations in an urban street canyon (WEBER et al., 2006a, 2006b). Therefore focus in this study was put upon the consequences of different meteorological forcing and turbulent mixing on particle concentrations in a street canyon and a backyard.

Table 1: Overview of instrumentation and measurement heights (in m above ground level) during the study.

Quantity	Modell, Manufacturer	CAN	BAY	BAY_t	REIS
u, v, w, T_s	Sonic USA1, Metek (Germany)	3.7 m	3.7 m	–	–
D_p	OPC 1.107, Grimm-Aerosol (Germany)	3.2 m	3.8 m	13 m	–
T, rH	Temp./Humidity Sensor, Grimm-Aerosol	3.2 m	3.8 m	13 m	–
ϕ, u	vane, cup anemometer, Lambrecht (Germany)	–	–	–	22 m

2 Study site

Measurements were performed from 20 September to 14 November, 2006 within an urban street canyon and an adjacent backyard in Duesseldorf, Germany (Fig. 1). The street canyon is situated in the central part of Duesseldorf about 3.5 km E of river Rhine. The surroundings of the measurement sites can be characterised as typical urban land-use, e.g. residential housing, backyards, urban parks.

The street canyon (CAN) is symmetric with pitched roof houses at both sites (mean building height H at roof level ∼17 m above ground level). Due to a road width (W) of about 30 m the height to width ratio is about H/W = 0.59. Total daily traffic intensity in the canyon adds up to about 50,000 vehicles 24 h^{-1}. The canyon is orientated North-South (Fig. 1).

The backyard (BAY) is situated to the E of CAN and is completely enclosed by buildings and brick walls (Fig. 2). It covers a surface area of around 400 m^2. The building/wall heights vary between 17 m in the western part of the backyard (adjacent to CAN) and 4 m in the eastern parts of BAY. The height to width ratio therefore varies between 0.17 and 0.68. The backyard is sparsely vegetated and is used as a hotel car park with a low traffic intensity of < 10 vehicle movements per day. A solid rolling gate (no air movement possible) which allows access to the backyard is permanently closed unless a vehicle enters the hotel car park.

3 Material and methods

3.1 Instrumentation

Particle concentrations were measured at heights of 3.2 m above ground level (agl) in CAN and at 3.8 m (BAY) and 13 m agl (BAY_t) in the backyard with three optical particle counters (OPC, see Tab. 1 and Fig. 2 for details). At both sites the instruments were mounted at a distance of approximately 3 m off the westward house walls. The horizontal distance between the measurement sites CAN and BAY is about 50 m.

The OPC measures number concentrations in the size range 0.25 μm < Particle Diameter (D_p) < 32 μm by a light scattering technique. 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 multichannel classifier and measured as particle size distribution in 32 size channels. The size distribution is then converted into the mass fractions PM_{10}, $PM_{2.5}$ and PM_1 by the instrument software assuming appropriate densities of urban aerosol for the different size classes. Above a threshold of 70 % relative humidity dry and particle-free air is mixed to the aerosol sample to prevent humidity effects (e.g. condensational growth). Particle concentrations were sampled at a 6 s time resolution and stored as 1 min averages to data storage cards.

Air temperature (T) and relative humidity (rH) were measured by a sensor attached to the OPC. Both quantities were estimated as 1 min averages and stored to data storage cards. Horizontal and vertical wind vectors u, v, w and acoustic temperature T_s were measured at a sampling rate of 10 Hz by two three-dimensional sonic anemometers at 3.7 m agl in CAN and BAY. The raw data files were stored to a desktop computer. During the post-processing half-hourly averages and covariances for both sonics were calculated from the raw data.

Since it was not possible to perform above roof wind measurements on-site, data of the suburban station Duesseldorf-Reisholz (REIS) of the North Rhine Westphalia State Agency for Nature, Environment and Consumer Protection (LANUV NRW) at 22 m agl was used. The station is situated in the SE of Duesseldorf at a distance of 6 km from the study site. Wind speed (u_{REIS}) and direction (ϕ_{REIS}) were measured by a wind vane and cup anemometer, respectively. Due to the low building density in the surrounding of REIS wind data can be characterised as undisturbed and will be used as reference wind in further data analysis. For all meteorological quantities and particle data 30 min averages were calculated and used in subsequent data analysis.

Precipitation data was also not available on-site. To check for any influence of precipitation on measured particle concentrations data from the German weather service station at Düsseldorf-Airport was used (station No. 10400, Lat. 51° 17’, Lon. 06° 46’, daily precipitation sums). It is situated in the N of Duesseldorf at a horizontal distance of about 8 km from the study site.

3.2 Quality check of OPC measurements

To check for possible deviations of particle concentrations between the OPC’s used in this study, instruments

Table 2: Intercomparison of OPC's prior to the measurement campaign at the street canyon site. Data from the period 9–14 August 2006 (data basis: 1 min averages, n = 3940, independent variable: OPC BAY). OPC's are labelled according to the later measurement site.

Mass fraction	OPC	slope	offset	r^2	slope	r^2
			y = ax + b		y = ax	
PM_{10}	BAY_t	0.97	1.02	0.93	1.01	0.92
	CAN	0.98	2.05	0.93	1.06	0.92
$PM_{2.5}$	BAY_t	1.06	-0.55	0.97	1.04	0.97
	CAN	1.07	0.59	0.97	1.09	0.97
PM_1	BAY_t	1.08	-0.61	0.98	1.05	0.98
	CAN	1.08	0.45	0.98	1.10	0.98

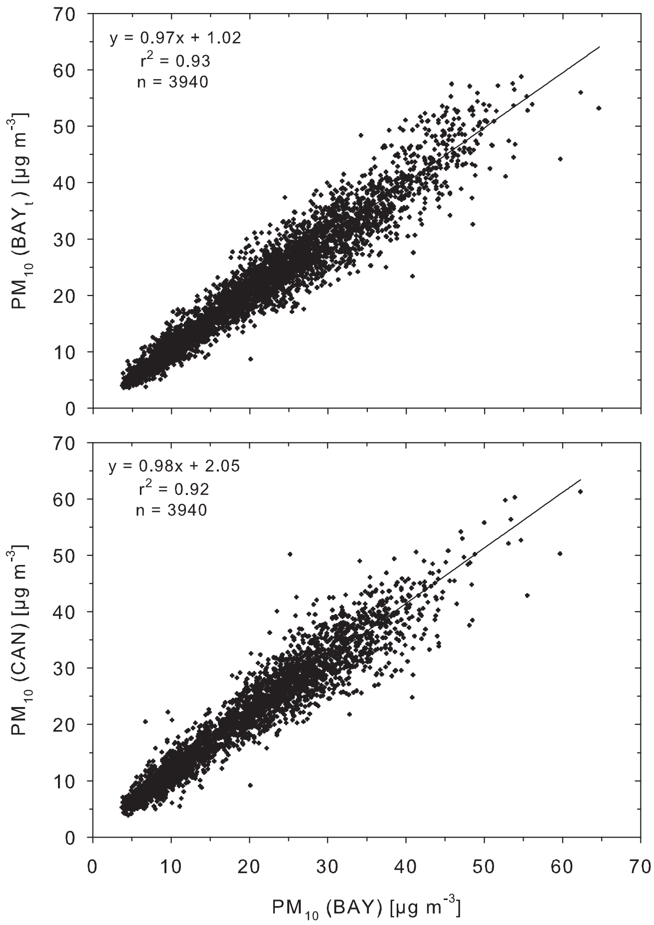

Figure 3: Comparison of three OPC's prior to the measurement campaign at the CAN site (based on 1 min averages). OPC's are labelled according to the later measurement site.

were collocated at the CAN site prior to the experiment. The sampling heads were separated less than 0.5 m from each other. PM_{10} mass concentrations during this period spanned a range from about 5 to 65 μg m^{-3} (Fig. 3). The measurements indicated good comparability and statistical relationship between the three instruments (Tab. 2). In order to compare absolute concentrations between measurements sites in subsequent data analysis a simple linear correction based on the regression analysis (r^2 > 0.92) was used to correct for small deviations between the OPC's.

The absolute accuracy of the OPC mass concentrations was evaluated by comparison to TEOM measurements at the CAN site. The TEOM data was taken from routine observations performed by the North Rhine Westphalia State Agency for Nature, Environment and Consumer Protection (LANUV NRW). During a period of 20 days the OPC's were installed at the roof of the LANUV measurement container in close proximity to the TEOM sampling inlet. Based on daily averages calculated from the raw data of TEOM and OPC, the three optical counters underrepresented TEOM PM_{10} concentrations by less than 10 % (r^2 > 0.89, data not shown here). However, due to the lower OPC cut-off at 0.25 μm a certain amount of ultrafine/fine particle mass is 'not seen' by the instrument. Ultrafine/fine particles < 0.18 μm were observed to be responsible for up to 12 % of $PM_{2.5}$ mass in Pittsburgh, US (Cabada et al., 2004). With a characteristic $PM_{2.5}/PM_{10}$ ratio of around 0.7 in a similar urban street canyon (Weber et al., 2006b) the underestimation of absolute PM_{10} particle mass by the present OPC can be estimated to be about 15 %. However, since this study focuses on spatial differences and dynamics of PM concentrations between sites equipped with optical counters identical in construction, underestimation of absolute particle mass is negligible in this study.

3.3 Data handling

In order to study possible effects of different wind directions on the coupling of particle concentrations between BAY and CAN we classified situations of cross-canyon and along-canyon flow at CAN according to the reference wind directions at REIS. We classified cross-canyon flow at CAN from easterly directions (CRC_E) when 30° < ϕ_{REIS} < 150° and from westerly directions (CRC_W) when 210° < ϕ_{REIS} < 330° (cf. Fig. 1). Along-canyon flow (ALC) was classified for a sector of 20° around the street canyon axis from either north 350° < ϕ_{REIS} < 10° or south 170° < ϕ_{REIS} < 190°.

A sector of 120° chosen for classification of CRC flow is relatively large and does incorporate flow situations which are not strictly perpendicular to the canyon. During those situations flow regimes inside canyons

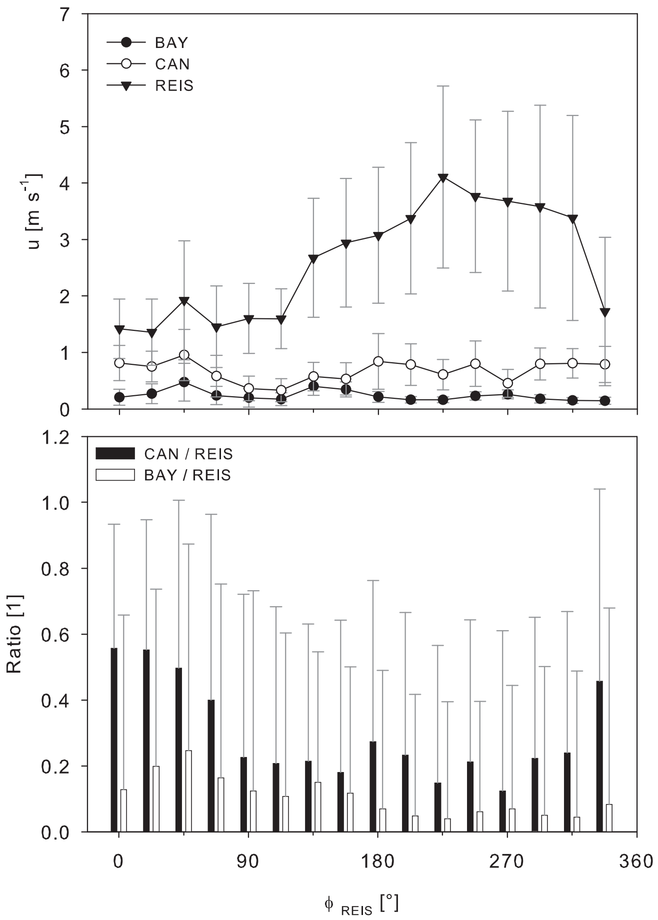

Figure 4: Average wind speed at the different measurements sites (top) and normalised wind speeds at CAN and BAY_b (bottom) classified in 22.5° direction sectors according to the wind direction at REIS.

are known to be rather 'corkscrew-like' than being a single-vortex circulation (JOHNSON and HUNTER, 1999; KASTNER-KLEIN et al., 2004). However, a smaller angle for classification of CRC-flow of, say 45° around the street canyon axis, would have resulted in a relatively small data set for subsequent analysis. With the present method of flow classification we extracted data covering 37 % and 33 % of the entire data set for CRC_W and CRC_E respectively. ALC flow situations accounted for 7 % of the study period.

4 Results and discussion

4.1 Meteorological conditions and urban canopy layer flow regimes

The wind direction frequency distribution at REIS had its maximum from south easterly directions (43 %) with a second peak from W and SW (28 %) during the study period. Due to channelling effects of the Rhine valley direction frequency distributions with maxima from SE are typical for this region of Germany.

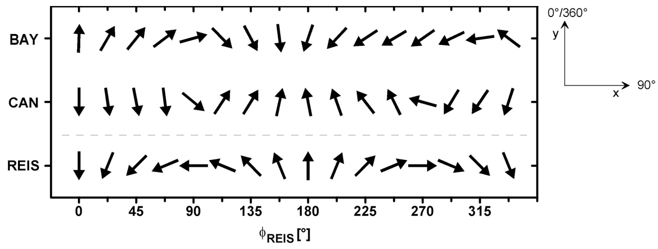

Figure 5: Vector averaged wind directions (arrows) at CAN and BAY calculated from sonic data in relation to the wind direction at REIS in an x-y plane (see inlet), e.g. westerly flow from 270° at REIS demonstrates the vortex circulation in both CAN and BAY by wind from north-easterly/easterly directions with 55° (BAY) and 105° (CAN). Data is bin-averaged into 22.5° direction sectors. Due to the N-S orientation of the street canyon flow from 90° and 270° at REIS indicates flow perpendicular to the street canyon axis.

While the wind speed at REIS is about 3 m s^{-1} on average (cf. Tab. 3) the highest wind speeds are measured for SW directions (Fig. 4 top). However, at CAN and BAY wind speeds are considerably reduced by urban roughness. This agrees with published wind tunnel results (HALL et al., 1999; SHARPLES and BENSALEM, 2001). Average wind speed reaches 0.63 m s^{-1} (CAN) and 0.27 m s^{-1} (BAY) respectively (Tab. 3). The maximum reduction of flow within the urban canopy layer (UCL) is observed for SW flow decreasing to only 4 % (BAY) the value at REIS (Fig. 4 bottom). While at CAN the direction sectors NW, N and NE are reduced to about 50 % of the reference wind speed the reduction for the remaining sectors is considerably larger.

In comparison to CAN reduction of average wind speed within the UCL is even more pronounced at BAY but is less dependent on the direction of the approaching flow. Wind is reduced to between 10 to 20 % of the reference wind in the western sectors and 5 to 10 % in the other sectors. Therefore dispersion of air pollutants is limited at both sites due to considerable reduction of UCL wind speeds.

Another important factor for dispersion of pollutants is associated with local scale circulations within the UCL, e.g. street canyon vortex circulations transporting pollutants towards or away from a measurement location (e.g. BODDY et al., 2005; WEBER et al., 2006a). A vortex develops at CAN during periods when the flow is directed perpendicular to the street canyon axis (Fig. 5). With wind being directed from the remaining direction sectors flow is more or less channelled into the orientation of the street canyon at CAN. However, at BAY a vortex circulation develops regardless of the direction of the reference wind due to the completely enclosed building/wall structure at BAY. The deviation between the wind direction at REIS and BAY is about 189° (23°) on average indicating opposite wind directions at BAY in relation to REIS.

Table 3: Overview of mean meteorological conditions during the study period. Standard deviations are given in brackets (n/a: data not available).

Quantities	CAN	BAY	REIS
u [m s^{-1}]	0.63 (± 0.36)	0.27 (± 0.15)	3.0 (± 1.46)
ϕ [°]	174 (± 33)	19 (± 52)	185 (± 54)
u_* [m s^{-1}]	0.16 (± 0.07)	0.16 (± 0.10)	n/a
σ_w [m s^{-1}]	0.26 (± 0.08)	0.34 (± 0.15)	n/a
$\overline{w'T'}$ [K m s^{-1}]	0.009 (± 0.019)	0.010 (± 0.010)	n/a

4.2 Coupling of particle concentrations between street canyon and backyard

Particle mass concentrations

For the eight week study period average concentrations for PM_{10} (PM_1) of 26.6 μg m^{-3} (16.2 μg m^{-3}), 33.5 μg m^{-3} (18.9 μg m^{-3}) and 22.5 μg m^{-3} (12.7 μg m^{-3}) were measured at BAY, CAN and BAY_t, respectively. Apparently the different sites are characterised by distinct concentration differences for coarse and fine particles. On average CAN shows concentrations which are higher by 30 % for PM_{10} and 22 % for PM_1 in relation to BAY (Fig. 6). The concentration difference between both sites agrees with the results presented for gaseous pollutants (BAUER and ALEXANDER, 1996). Similar observations for particulate pollutants are not published according to the authors' knowledge.

When comparing concentration differences between CAN and BAY_t an increase to 34 % and 32 % for PM_{10} and PM_1 respectively can be observed. In a street canyon in Hannover, Germany, PM_{10} concentration differences up to a factor of 2 between canyon and roof-top station were reported (SCHATZMANN et al., 2006). This is due to the roof areas being prone to increased turbulent exchange (e.g. CHRISTEN, 2005; ELIASSON et al., 2006) making dilution and mixing of particles with less polluted urban background air more effective at roof level. The vertical difference within the backyard (BAY/BAY_t) is near unity for the coarse fraction on average but slightly larger by about 7 % for PM_1 at ground level (Fig. 6).

For particle concentrations classified to the direction of the approaching flow (cf. section 3.3) different patterns of concentrations emerge (Fig. 7). In general the canyon site is characterised by larger average concentrations in comparison to BAY during all flow classifications. However, some differences can be observed for the coarse and submicrometer particle fractions. During CRC_W the canyon vortex transports particles to the westward wall where the measurement site is located. This results in highest absolute PM_{10} values for CRC_W. This is in agreement to other studies reporting higher concentrations by factors of 1.5 to 2 for the leeward side of the canyon (BODDY et al., 2005; WEBER et al., 2006a).

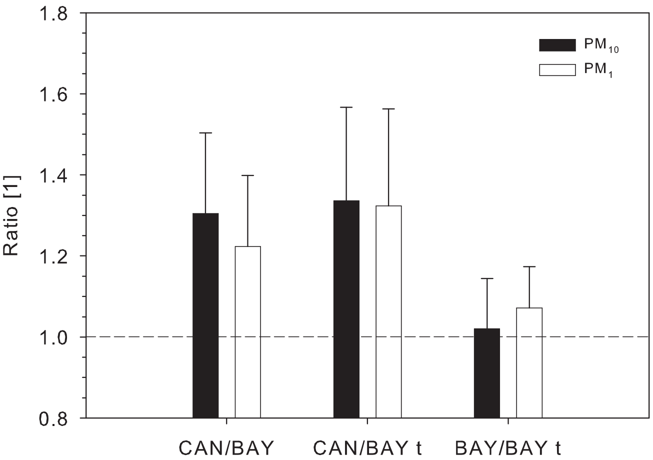

Figure 6: Mean ratios of particle concentrations between the different measurement sites for the study period from 20 September to 14 November, 2006. Vertical error bars indicate standard deviations.

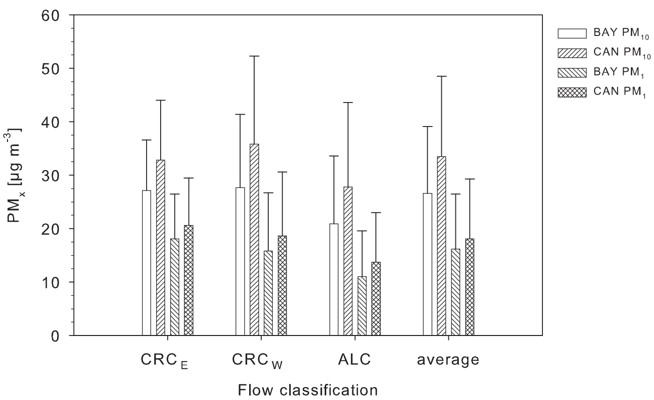

Figure 7: Average concentrations of PM_{10} and PM_1 at BAY and CAN classified to different directions of flow during the study period as defined in section 3.3 of the text. Vertical error bars indicate the standard deviation.

The PM_{10} values at BAY do not notably differ between CRC_W and CRC_E. The average difference in PM_{10} concentrations is only 0.6 μg m^{-3}. Therefore the vortex which also develops in BAY during CRC_W (cf. Fig. 5) and transports air towards the measurement device apparently has minor influence on resulting concentration differences. This points out that air within the backyard is generally less polluted since local emissions of coarse particles (e.g. brake and tyre abrasion from traffic, JOHANSSON et al., 2007) are negligible within BAY. Above that, background air transported from either westerly or easterly directions seems to be relatively similar in terms of coarse particle loading since vortex circulation of backyard air towards the OPC (during CRC_W) and away from the OPC (during CRC_E) has no significant influence on particle concentrations.

For the submicrometer fraction the maximum average concentration occurs during CRC_E both in CAN and BAY (Fig. 7). This seems not to be related to any microscale circulation pattern but to some enhanced transport of submicrometer particles from E.

Both PM_{10} and PM_1 show minimum concentrations during ALC which is mainly due to enhanced venting of canyon and backyard air. Average horizontal wind speeds in CAN are larger by a factor of 1.35 during ALC in comparison to the average of the entire study period (data not shown here).

A plot of the differences in concentration ratios between CAN and BAY stresses the influence of urban canopy layer flows, namely the vortex circulation. Regardless of the direction of the approaching flow the concentration ratio CAN/BAY is always larger than unity. However, the highest differences between CAN and BAY occur during westerly flow with ratios of up to 1.42 and 1.32 for PM_{10} and PM_1, respectively (Fig. 8). This effect is due to the vortex circulation within CAN and BAY. More polluted air masses within CAN are directed towards the OPC situated at the westward house wall. The same holds for BAY, however, air within BAY is less polluted as discussed above. Even if more submicrometer particles are transported with easterly flow, higher PM_1 concentration differences between both sites also occur for westerly flow since the vortex during easterly flow transports particles away from the BAY OPC. This stresses the fact that the vortex has significant influence on the particle concentration in polluted air masses, while for the less polluted air masses in BAY the canopy layer vortex is of minor influence.

Particle number concentrations

Elevated concentrations in the submicrometer size range for flow from the E are also supported when plotting number concentrations classified according to the flow directions (Fig. 9). Situations during CRC_E are characterised by larger concentration in comparison to the other classifications and entire study period respectively. Average total particle numbers in the size range $0.3 < D_p < 1\ \mu m$ are 105 cm^{-3} and 90 cm^{-3} for CAN and BAY during the entire study period. They increase to about 116 cm^{-3} and 103 cm^{-3} for CAN and BAY during CRC_E flow. In the previous section we discussed micrometeorological influences not to be responsible for increase of submicrometer particles during easterly flow.

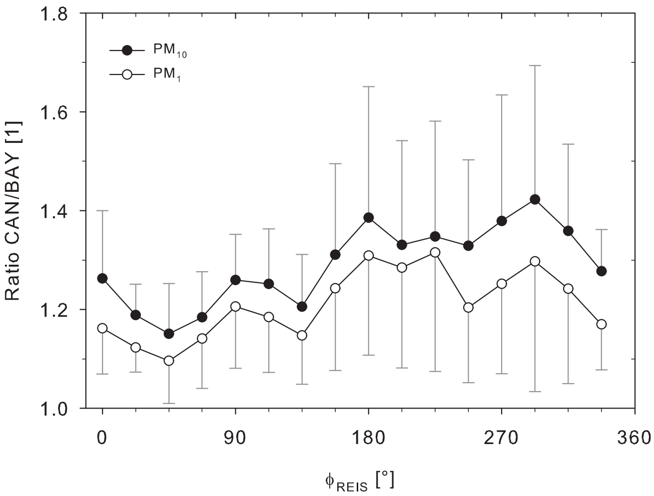

Figure 8: Average ratios of particle concentrations between CAN and BAY for PM_{10} and PM_1 in dependence of the reference wind direction at REIS. Data is binned into 22.5° wind direction classes. Vertical error bars indicate the standard deviation.

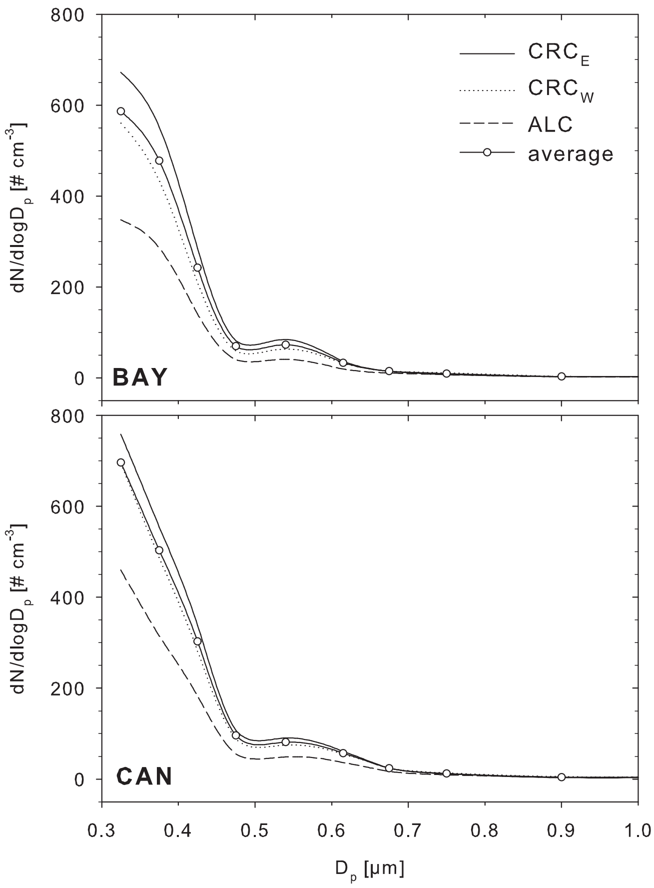

Figure 9: Average particle number concentrations at BAY (top) and CAN (bottom) plotted as $dN/dlogD_p$ according to the different directions of flow and the average of the entire study period.

Therefore some medium or long-range transport of submicrometer particles must be responsible for elevated concentrations during CRC_E.

Table 4: Pearson correlation coefficients of meteorological quantities and particle mass and number concentrations at the measurement sites. Data is significant on the p = 0.05 level.

		PM_{10} [μg m^{-3}]	PM_1 [μg m^{-3}]	$0.3<D_p<0.5$ [# cm^{-3}]	$0.5<D_p<1$ [# cm^{-3}]
u_{REIS} [m s^{-1}]	BAY	–0.30	–0.38	–0.31	–0.21
	CAN	–0.30	–0.39	–0.34	–0.26
σ_w [m s^{-1}]	BAY	–0.20	–0.17	–0.05	–
	CAN	–0.15	–0.25	–0.17	–0.08
$\overline{w'T'}$ [K m s^{-1}]	BAY	0.14	0.12	0.17	0.12
	CAN	0.23	0.20	0.20	0.15

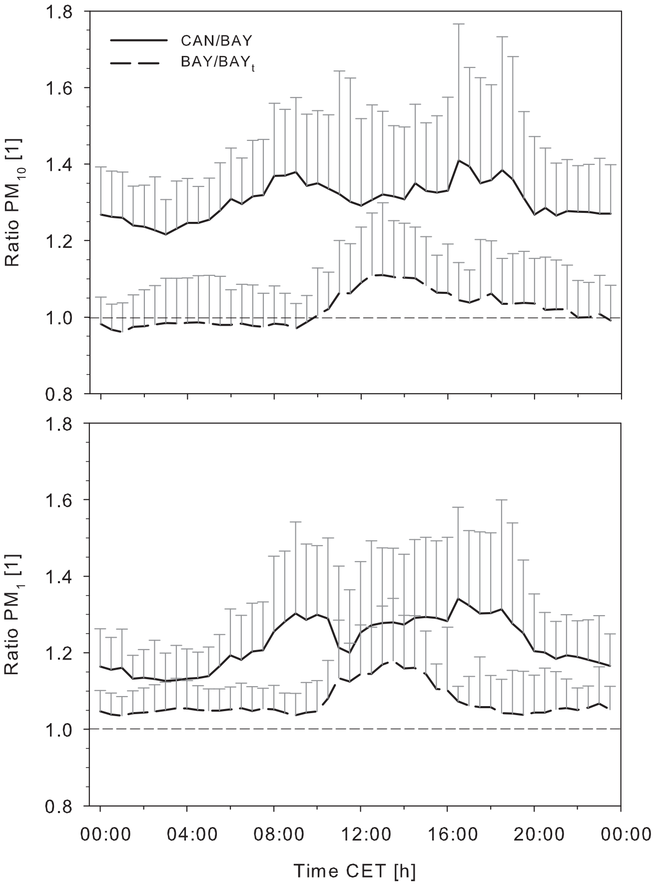

Figure 10: Mean ratios of particle concentrations between the specified sites for PM_{10} (top) and PM_1 (bottom) during the study period. Vertical error bars indicate standard deviations. For reasons of clarity of the plot only positive standard deviations are shown

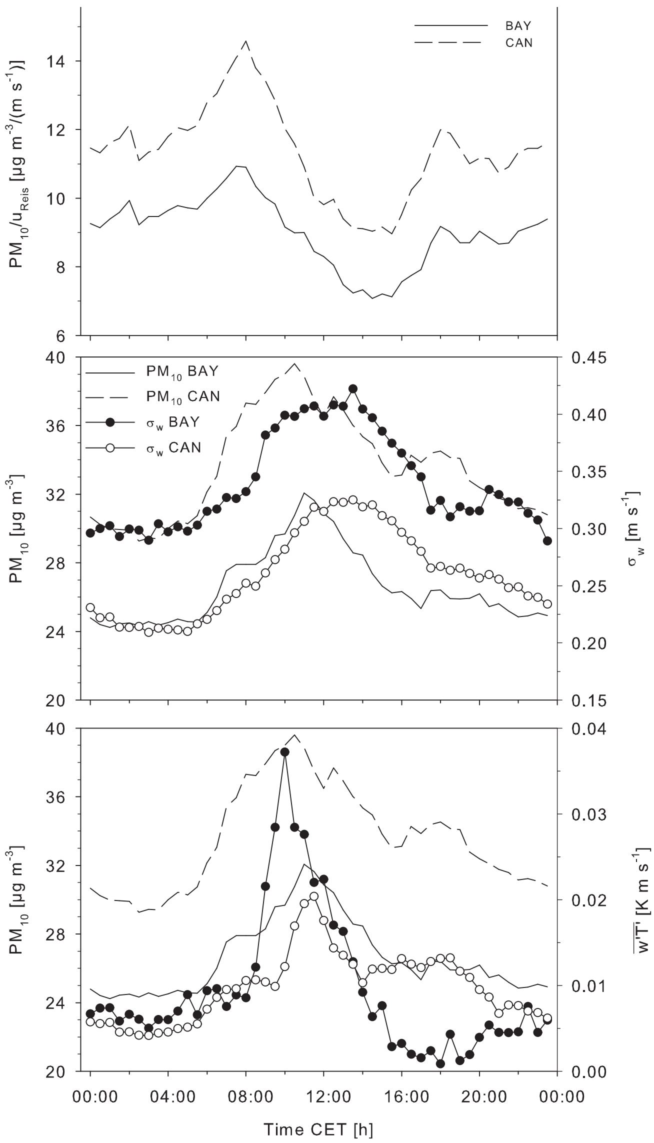

Figure 11: Average diurnal courses of the PM_{10} time series normalised by average wind speed at REIS (top) PM_{10} and σ_w (middle), PM_{10} and $\overline{w'T'}$ (bottom) at BAY and CAN for the entire study period from 20 September to 14 November, 2006.

Influence of precipitation

Precipitation events during the study period were mainly associated to westerly flow directions as documented by a correlation of precipitation measurements at Duesseldorf-Airport (cf. section 3.2) with large-scale circulation regimes as classified according to GERSTENGARBE et al. (1999). Events with the highest precipitations sums were linked to the circulation regimes NWA (northwest-anticyclonic), NWZ (northwest-cyclonic) and SWZ (southwest-cyclonic). These circulation regimes accounted for 85 % of the precipitation amount during the study period (data not shown here). Scavenging or wash-out effects of particles during precipitation will lead to particle concentration decreases, which are more effective for the coarse particle fraction due to a higher wet-deposition velocity of coarse particles in comparison to fine particles by about two orders of magnitude (MAQUA et al., 1987; SEINFELD and PANDIS, 1998). Since time periods of westerly flow are apparently more influenced by wash-out than easterly flow a stronger decrease of particle concentrations during westerly flow becomes likely. However, this was not subject of the present analysis which is more interested in concentration differences between the street canyon and the backyard.

4.3 Temporal coupling of particle concentrations and influence of turbulence

In this section we try to shed light on the temporal evolution of particle concentrations over the diurnal course. Generally, the temporal evolution of concentration differences between CAN and BAY is similar for both fine and coarse particles (Fig. 10). The difference CAN/BAY is greater than unity throughout the course of day, i.e. concentrations measured at CAN are consistently larger. Significant impact of traffic on the PM_{10} and PM_1 concentration differences during the morning and afternoon rush-hours can be observed (Fig. 10). In the time periods from around 06 to 09 CET and 16 to 19 CET concentration increases by about 10 to 15 % are evident at CAN. During these periods atmospheric dilution is weak and can not compensate for the strong increase of particle emission/resuspension from traffic. In order to evaluate the effect of atmospheric dilution by mean wind the PM_{10} time series was normalised by average wind speeds at REIS (Fig. 11 top). The temporal evolution of this time series is in phase with the temporal evolution of the CAN/BAY ratio (Fig.10). This is due to both weaker wind speeds and a more stably stratified atmosphere especially during the morning and strong increase of particle emission from traffic.

During noon hours increasing ambient wind speed and mechanical turbulence, indicated by the standard deviation of vertical wind speed σ_w (Fig. 11 middle), going along with the general growth of the mixing layer height through the course of the day dilute pollutant concentrations within the urban boundary layer (e.g. SCHÄFER et al., 2006). This can be observed both in the normalised and the absolute PM_{10} time series (Fig. 11).

The vertical concentration differences in the 'backyard atmosphere' (BAY/BAY_t) are characterised by a peak of the near surface concentrations around noon (11 to 15 CET, Fig. 10). The relative concentration difference increases by about 15 %. Since this increase is not coupled to the peak of traffic intensity during the morning/afternoon rush hours some other mechanism has to trigger this local peak. It seems that influences of thermal turbulence can explain the evolution of the concentration time series. Fig. 11 (bottom) indicates the temporal coherence of the increase of both the kinematic sensible heat flux and PM_{10} concentrations. Similar observations were reported from particle number concentration/flux measurements performed within a street canyon and above a city (DORSEY et al., 2002; LONGLEY et al., 2004).

Considering more effective dilution at roof level height due to higher wind speeds and turbulent exchange (e.g. ROTH, 2000; CHRISTEN, 2005) the vertical near-surface concentration difference about noon can be satisfyingly explained by the different effects of mechanical and thermal turbulence.

The meteorological influence of turbulence parameters was further studied by means of a correlation analysis (Tab. 4). Generally, the magnitude of the correlation coefficients is not large which is due to a high day-to-day variability in PM concentrations often forced by considerable variations in the background aerosol, e.g. variations in background aerosol due to long-range transport (JOHANSSON et al., 2007; SALVADOR et al., 2007). However, we found a clear negative correlation of particle concentrations with mechanical turbulence and dilution of the urban boundary layer as indicated by the horizontal wind speed at REIS (u_{REIS}) and σ_w (Tab. 4). Thermal turbulence on the other hand is positively correlated to particle mass and number concentrations. However, it should be noted that besides the effects of thermal turbulence other processes (e.g. photochemistry, gas-to-particle conversion) will also be important in affecting the temporal evolution of particle concentrations in the UCL.

Nocturnal vertical structure in BAY

The nocturnal PM_{10} backyard ratio which is smaller than unity (Fig. 10 top) shows that coarse particles are able to deposit to the backyard during night time. With a nocturnal BAY/BAY_t ratio of about 0.96 deposition is not large, however, similar effects are not observed for neither CAN PM_{10} nor submicrometer particles. This is believed to be due to two factors: there is still traffic movement within CAN at night which leads to emission and resuspension of particles into the near-surface layer. On the other hand, deposition velocity of PM_{10} is about two orders of magnitude larger than PM_1 (e.g. FINLAYSON-PITTS and PITTS, 2000) resulting in more effective deposition of coarse particles to the surface of the backyard.

5 Summary and conclusions

During an eight week study period particle concentration differences between a busy urban street canyon and an adjacent backyard were measured by means of optical particle counters. On average, distinct concentration differences between the sites were obvious for both coarse and submicrometer particles. The ratio of CAN/BAY is generally larger than unity due to enhanced emission and resuspension of particles within the canyon. BAY on the other hand is characterised by a negligible influence of local particle emissions.

By classifying particle concentrations to the suburban reference wind direction a significant influence of the canyon vortex circulation on concentration differences between CAN and BAY was evaluated. Average maximum differences between CAN and BAY can amount up to 42 % (PM_{10}) and 32 % (PM_1) during westerly flow although both sites are separated only 50 m horizontally.

However, the vortex has important influence on the more polluted air masses within the canyon while mixing of less polluted air inside the backyard showed only little influence. The temporal evolution of particle concentration differences between canyon and backyard was influenced by thermal and mechanical turbulent mixing. While the first quantity was positively correlated to particle concentrations (mixing of particles into the near-surface air) the latter was negatively correlated to particle concentrations due to dilution of polluted air. This study demonstrates that micrometeorological quantities, i.e. mechanical and thermal turbulence, can have important influence on the evolution of particle concentration within the UCL. They have to be taken into account for adequately monitoring, modelling and forecasting particle concentrations in the urban environment.

Acknowledgements

The help of Markus NEKES (University Duisburg-Essen), Günther VAN HAREN and Christian FISCHER (University of Applied Sciences Duesseldorf) in maintaining the instruments during the measurement campaign is highly appreciated. LANUV NRW is acknowledged for providing meteorological data of the station Duesseldorf-Reisholz. Logistic and funding support of the city authorities of Duesseldorf (Environmental Agency) is highly acknowledged.

References

ARYA, P.S., 2001:. Introduction to micrometeorology. – International Geophysics Series, 42. Academic Press Inc., San Diego, 415 pp.

BAUER, E., J. ALEXANDER, 1996: Lufthygiene und klimatologische Messungen in Innenhöfen der Stadt Trier. 3. Fachtagung BIOMET, 4.–5.12.1996. – Annalen der Meteorologie **33**, 21–26.

BODDY, J.W.D., R.J. SMALLEY, N.S. DIXON, J.E. TATE, A.S. TOMLIN, 2005: The spatial variability in concentrations of a traffic-related pollutant in two street canyons in York, UK-Part I: The influence of background winds. – Atmos. Environ. **39**, 3147–3161.

CABADA, J.C., S. REES, S. TAKAHAMA, A. KHLYSTOV, S.N. PANDIS, C.I. DAVIDSON, A.L. ROBINSON, 2004: Mass size distributions and size resolved chemical composition of fine particulate matter at the Pittsburgh supersite. – Atmos. Environ. **38**, 3127–3141.

CHRISTEN, A., 2005: Atmospheric turbulence and surface energy exchange in urban environments. – Results from the Basel Urban Boundary Layer Experiment (BUBBLE), Stratus 11, University of Basel. 140 pp.

DORSEY, J.R., E. NEMITZ, M.W. GALLAGHER, D. FOWLER, P.I. WILLIAMS, K.N. BOWER, K.M. BESWICK, 2002: Direct measurements and parameterisation of aerosol flux, concentration and emission velocity above a city. – Atmos. Environ. **36**, 791–800.

ELIASSON, I., B. OFFERLE, C.S.B. GRIMMOND, S. LINDQVIST, 2006: Wind fields and turbulence statistics in an urban street canyon. – Atmos. Environ. **40**, 1–16.

FINLAYSON-PITTS, B.J., J.N. PITTS, 2000: Chemistry of the upper and lower atmosphere. – Academic Press, San Diego, 969 pp.

FORSSEN, J., M. HORNIKX, 2006:. Statistics of A-weighted road traffic noise levels in shielded urban areas. – Acta Acustica United with Acustica **92**, 998–1008.

GERSTENGARBE, F.W., P.C. WERNER, U. RÜGE, 1999: Katalog der Großwetterlagen Europas (1881–1998) nach Paul HESS und Helmuth BREZOWSKY. – Potsdam Institut für Klimafolgenforschung, Potsdam, Offenbach.

GERTIS, K., G. HAUSER,J. RATH, 1983: Besonnungs– und Temperaturverhältnisse in Innenhöfen. – Bauphysik **5**, 157–168.

GIUGLIANO, M., G. LONATI, P. BUTELLI, L. ROMELE, R. TARDIVO, M. GROSSO, 2005: Fine particulate ($PM_{2.5}$–PM_1) at urban sites with different traffic exposure. – Atmos. Environ. **39**, 2421–2431.

HALL, D.J., S. WALKER, A.M. SPANTON, 1999: Dispersion from courtyards and other enclosed spaces. – Atmos. Environ. **33**, 1187–1203.

HARRISON, R.M., J. YIN, D. MARK, J. STEDMAN, R.S. APPLEBY, J. BOOKER, S. MOORCROFT, 2001: Studies of the coarse particle (2.5–10 μm) component in UK urban atmospheres – Atmos. Environ. **35**, 3667–3679.

HEDMAN, B., M. NASLUND, C. NILSSON, S. MARKLUND, 2005: Emissions of polychlorinated dibenzodioxins and dibenzofurans and polychlorinated biphenyls from uncontrolled burning of garden and domestic waste (backyard burning). – Env. Sci. Technol. **39**, 8790–8796.

HUEGLIN, C., R. GEHRIG, U. BALTENSPERGER, M. GYSEL, C. MONN, H. VONMONT, 2005: Chemical characterisation of $PM_{2.5}$, PM_{10} and coarse particles at urban, near-city and rural sites in Switzerland. – Atmos. Environ. **39**, 637–651.

JOHANSSON, C., M. NORMAN, L. GIDHAGEN, 2007: Spatial & temporal variations of PM_{10} and particle number concentrations in urban air, – Environ. Monit. Assess. **127**, 477–487.

JOHNSON, G.T. , L.J. HUNTER, 1999: Some insights into typical urban canyon airflows. – Atmos. Environ. **33**, 3991–3999.

KASTNER–KLEIN, P., R. BERKOWICZ, R. BRITTER, 2004: The influence of street architecture on flow and dispersion in street canyons. – Meteor. Atmos. Phys. **87**, 121–131.

KAUR, S., M.J. NIEUWENHUIJSEN, R.N. COLVILE, 2007: Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. – Atmos. Environ. **41**, 4781–4810.

LONGLEY, I.D., M.W. GALLAGHER, J.R. DORSEY, M. FLYNN, K.N. BOWER, J.D. ALLAN, 2004: Street canyon aerosol pollutant transport measurements. – Science Total Environ. **334–335**, 327–336.

MAHRINGER, W., 1963: Ein Beitrag zum Klima von Höfen im Wiener Stadtbereich. – Wetter und Leben **15**, 137–146.

MAQUA, M., H. BONKA, H.-G. HORN, 1987: Deposition Velocity and Washout Coefficient of Radionuclides Bound to Aerosol Particles and Elemental Radioiodine. – Radiat. Prot. Dosimetry. **21**, 43–49.

OKE, T.R., 1987: Boundary layer climates. – Methuen, London, 435 pp.

POPP, P., 1996: Measurements of the air pollution at a street intersection and the surrounding neighbourhood in the city of Leipzig. – Gefahrstoffe – Reinh. Luft **56**, 295–299.

ROTH, M., 2000: Review of atmospheric turbulence over cities. – Quart. J. Roy. Meteor. Soc. **126**, 941–990.

RUUSKANEN, J., T. TUCH, H. TEN BRINK, A. PETERS, A. KHLYSTOV, A. MIRME, G.P.A. KOS, B. BRUNEKREEF, H.E. WICHMANN, G. BUZORIUS, 2001: Concentrations of ultrafine, fine and $PM_{2.5}$ particles in three European cities. – Atmos. Environ. **35**, 3729–3738.

SALVADOR, P., B. ARTINANO, X. QUEROL, A. ALASTUEY, M. COSTOYA, 2007: Characterisation of local and external contributions of atmospheric particulate matter at a background coastal site. – Atmos. Environ. **41**, 1–17.

SCHÄFER, K., S. EMEIS, H. HOFFMANN, C. JAHN, 2006: Influence of mixing layer height upon air pollution in urban and sub-urban areas. – Meteorol. Z. **15**, 647–658.

SCHATZMANN, M., W. BÄCHLIN, S. EMEIS, J. KÜHLWEIN, B. LEITL, W.J. MÜLLER., K. SCHÄFER, H. SCHLÜNZEN, 2006: Development and validation of tools for the implementation of European air quality policy in Germany (Project VALIUM). – Atmos. Chem. Phys. **6**, 3077–3083.

SCHWEGLER, M., 1999: Untersuchungen zur Luftqualität in hofbildenden Bebauungsstrukturen. – Essener Ökologische Schriften, Bd. 11, Westarp Wissenschaften, Hohenwarsleben, 101 pp.

SEINFELD, J.H., S.N. PANDIS, 1998: Atmospheric Chemistry and Physics – From Air Pollution to Climate Change. – Wiley Interscience, New York, 1326 pp.

SHARPLES, S., R. BENSALEM, 2001: Airflow in courtyard and atrium buildings in the urban environment: A wind tunnel study. – Sol. Energy **70**, 237–244.

SHASHUA-BAR, L., M.E. HOFFMAN, Y. TZAMIR, 2006: Integrated thermal effects of generic built forms and vegetation on the UCL microclimate. – Build. Environ. **41**, 343–354.

VOGT, R., J. EITEL, E. PARLOW, 2006: Coupling of backyard to street canyon CO_2 concentrations. – Sixth International Conference on Urban Climatology ICUC-6, Göteborg, Sweden, 12.–16.06.2006.

WEBER, S., W. KUTTLER, K. WEBER, 2006a: Flow characteristics and particle mass and number concentration variability within a busy urban street canyon. – Atmos. Environ. **40**, 7565–7578.

—, —, —, 2006b: Meteorologische Beeinflussung von Partikelanzahl- und massenkonzentrationen (PM_{10}, $PM_{2.5}$, PM_1) in einer Straßenschlucht. – Gefahrstoffe – Reinh. Luft **66**, 489–494.

WEVERS, M., R. DE FRE, M. DESMEDT, 2004: Effect of backyard burning on dioxin deposition and air concentrations. – Chemosphere **54**, 1351–1356.