Small-scale variability of particulate matter and perception of air quality in an inner-city recreational area in Aachen, Germany

Bastian Paas1,4*, Teresa Schmidt2,4, Stanimira Markova3,4, Isabell Maras1,4, Martina Ziefle2 and Christoph Schneider5

1Department of Geography, RWTH Aachen University, Germany
2Communication Science, RWTH Aachen University, Germany
3Computer Aided Architectural Design, RWTH Aachen University, Germany
4Project house HumTec, RWTH Aachen University, Germany
5Department of Geography, Humboldt-Universität zu Berlin, Germany

(Manuscript received April 30, 2015; in revised form December 22, 2015; accepted December 23, 2015)

Abstract
Spatial micro-scale variability of particle mass concentrations is an important criterion for urban air quality assessment. In this study we present results from detailed spatio-temporal measurements in the urban roughness layer along with a survey to determine perceptions of citizens regarding air quality in an inner-city park in Aachen, Germany. Particles were sampled with two different approaches in February, May, July and September 2014 using an optical particle counter at six fixed measurement locations, representing different degrees of outdoor particle exposure that can be experienced by a pedestrian walking in an inner-urban recreational area. A simulation of aerosol emissions induced by road traffic was conducted using the German reference dispersion model Austal2000. The mobile measurements revealed unexpected details in the distribution of urban particles with highest mean concentrations of PM$_{1;10}$ inside the green area 100 m away from bus routes (arithmetic mean: 22.5 µg m$^{-3}$ and 18.9 µg m$^{-3}$; geometric mean: 9.3 µg m$^{-3}$ and 6.5 µg m$^{-3}$), whereas measurement sites in close proximity to traffic lines showed far lower mean values (arithmetic mean: 7.5 µg m$^{-3}$ and 8.7 µg m$^{-3}$; geometric mean: 5.8 µg m$^{-3}$ and 6.5 µg m$^{-3}$). Concerning simulation results, motor traffic is still proved to be an important aerosol source in the area, although the corresponding concentrations declined rapidly as the distances to the line sources increased. Further analysis leads to the assumption that particularly coarse particles were emitted through diffuse sources e.g. on the ability of surfaces to release their frequent exposure to pollution emitters and other environmental stressors.

Keywords: particulate matter, micro-scale, air quality perception, vehicle emissions, dispersion modelling, Austal2000, recreational area, environmental pollution, personal exposure

1 Introduction
Particulate matter (PM) is an important environmental risk to health (WHO, 2013). Results of epidemiological studies suggest that both long-term and even short-term stays, e.g. during commuting or relaxing, at locations with high PM concentrations could have significant impacts on health such as respiratory and cardiovascular diseases (Pope et al., 2002; von Klont, 2005; Chow et al., 2006). The major proportion of the world’s population lives in cities (United Nations, 2014), where exceedances of air quality standards occur regularly. In general, town citizens are particularly affected due to
dependent particle exposure on the spatial micro-scale. Nonetheless, to approximate the personal PM exposure representative for entire city areas (e.g. for legislative reasons), fixed monitoring sites are regularly used due to the lack of dense monitoring networks. In ambient air the characterization of spatial PM exposure is complex since different particle size classes show divergent spatial distribution patterns (Birmili et al., 2013b). Explaining mass concentrations of fine particles and particle number as a function of time and location appears to be specifically challenging (Kozawa et al., 2012; Mishra et al., 2012; Spinazzé et al., 2015) due to the fact that combustion sources from traffic processes and industry emit mainly small particles situated in nucleation mode (Quiros et al., 2013; Ning and Sioutas, 2010). These aerosol fractions change their physical characteristics rapidly as a consequence of growth processes. Further, accumulation mode particles tend to have long residence time in the atmosphere and therefore dominate particle mass (Seinfeld and Pandis, 2006). These complex physical processes are applicable to the urban roughness layer in particular. In urban environments numerous diffuse particle sources can be found and dispersion is difficult to describe due to a variety of different surface structures and numerous spatial obstacles.

Beyond the factual health risk of PM (Venn et al., 2001), it is a basic question whether people are able to perceive the exposure to PM in the perceived climate comfort. On the one hand, not all people might show the same sensitivity or awareness for those stressors (Shirom et al., 2000), especially as city pedestrians might differ in age or health status and therefore might have a different responsiveness to climate stressors in general and aerosol concentrations in particular (Brook et al., 2010). On the other hand, it is well possible that people have established an overall perception of the on-site comfort as a holistic evaluation with particulate matter being an integral though unconscious part of it. Both hypotheses implicate different consequences. It is therefore important to understand whether there is a relationship between the physical stressor (i.e. aerosol concentration) and the specific perception of air quality and/or whether there is a relationship between the physical stressor and the integrative evaluation of on-site comfort. Numerous studies can be found concerning human perception of the urban environment. However, most of the work has focused on thermal comfort (Chen and Ng, 2012; Johansson et al., 2014). When perception was linked to air pollution, usually perceived risks were addressed or epidemiological studies were performed (Badland and Duncan, 2009). Most studies have been carried out through social and public opinion surveys which focused almost exclusively on people’s awareness or level of concern about air pollution (Nikolopoulou et al., 2011). Brody et al. (2004) started empirical research to examine the local level. Even in this case, the data was collected and analyzed at the neighborhood level and not measured or assessed at the local pedestrian level. Only recently have investigations on individual perception of exposure to PM been conducted on the micro-scale (Nikolopoulou et al., 2011). Local-scale studies have provided some information on place-specific conditions and evaluated how the location and its surroundings are important in the experience of air pollution but these studies disagree when it comes to an evaluation of air pollution sensation (Brody et al., 2004; Nikolopoulou et al., 2011).

Other impacts, for instance noise or thermal stress, influence human wellbeing and health in a variety of complex ways as well (Raimbault and Dubois, 2005; Yang and Kang, 2005; Gabriel and Endlicher, 2011; Maras et al., 2014). It is evident that monitoring, maintenance and planning of urban areas require an integrative approach to combine methods from natural sciences, engineering and social sciences. Taking this into account, a better understanding of highly-resolved distribution patterns of aerosols under given microclimate conditions in combination with the perception and sensation of urban space users regarding air quality parameters will help to achieve better environmental health standards inside cities at a local level (e.g. in intra-urban recreational areas).

This interdisciplinary work was designed to explore the spatial distribution patterns of the urban atmospheric aerosol by portable instrumentation in combination with a parallel survey to examine the sensation and perception of urban park users regarding air quality. We investigated different situations of outdoor exposure experienceable by a town citizen in an inner-city recreational area, in a generic medium-sized German city like Aachen. We identified localities of different particle exposure inside the exemplarily considered research site “Elisenbrunnen”, and examined seasonal differences regarding concentrations of particulate matter and overall perception of air quality. Furthermore, we considered the question whether or not urban park users are intuitively able to distinguish between dissimilar particle mass concentrations. We used the Austal2000 simulation tool to investigate the influence of emissions induced only by motor traffic at the research site. We compared the outcomes with physically measured values collected during measurements. The analysis focuses on the question whether the green area “Elisen Garten” inside the recreational area “Elisenbrunnen” in the city of Aachen has a positive impact on local atmospheric particle concentrations compared to the surrounding urban fabric structure. Bio-meteorological stress factors, i.e. thermal stress, and a psychophysical investigation on human perceptions of climatological stress factors were analyzed in related publications by Maras et al. (2016) and Schmidt et al. (2015).

2 Methods

2.1 Study area

Field experiments were carried out inside an inner-city public open space in the city of Aachen (pop. 245,000),
a typical German medium-sized town sitting in the tri-border region close to the Netherlands and Belgium. The investigation site spans an area of about 0.02 km² and is characterized by a well-attended inner city park, enclosed with buildings generally comprised of 4–5 floors. One of the most frequented roads by public transport buses (“Friedrich-Wilhelm-Platz”), inaccessible for individual private vehicles, including four main bus stops (102 coach connections per hour on weekdays), leads through the investigation area. The park is surrounded by sparsely busy roads in the Northeast (industrial vehicles for delivery only) and Southeast (“Hartmannstr.”) and a highly frequented alleyway used mainly by private cars (“Ursulinerstr.”). Unsurfaced footpaths subdivide the green area which contains mainly small flowerbeds and a lawn surface that is surrounded by deciduous trees (*Platanus x hispanica*) (Fig. 1). Six monitoring sites were chosen inside the study area for measurements and surveys featuring different surroundings (Fig. 2). Sites E and F were characterized as typical recreational spots inside the green area. Location C features a main bus station, whereas site B was located in proximity to the intersection “Friedrich-Wilhelm-Platz” “Ursulinerstr.” dominated by moving traffic. Monitoring sites A and D have been chosen in between to capture transfer passages from surroundings into the green area to provide a gradient.

2.2 Experimental design

Local measurements were conducted to determine mass concentration of suspended particles with aerodynamic diameters (DAE) between 0.25 µm and 10 µm (PM$_{0.25;10}$). Simultaneously, questionnaires accounting for an overview of the perception of urban park users were filled in.

Firstly, physical data were collected with the entire described measurement equipment at location A, B, C, E and F as one-day time series (weekdays, 10:00–17:00, 10-minute mean values) alongside the survey during a typical wintertime in February 2014. A similar approach was conducted at locations A, B, E and F during summer in July 2014. Initial conditions for each measurement campaigns were chosen to be the same for both periods, including radiation weather conditions with only partly clouded skies and no precipitation.

Further particle measurements were carried out at locations A–F with a semi-parallel approach using again a mobile single measurement device. Measurements were conducted during 7 selected weekdays (10:00–17:00) in February, May and September 2014 that were characterized by meteorological conditions prevailing at the study area with no precipitation in cyclonic weather situations and south-westerly winds (Fig. 3). The measurement location was changed every 5 minutes in an identi-
Figure 2: Research site “Elisenbrunnen” in Aachen (left illustration) including depicted measurement locations A–F (grey circles) and the area under study (white cross on black circle) located in Central Europe (upper right illustration) and located in Aachen (lower right illustration) including the weather station “Aachen-Hörn”, traffic related air quality monitoring station “Wilhelmstrasse” (VACW) and rural background air quality monitoring station “Burtscheid” (AABU) operated by the Northrhine-Westfalian State Office for Nature, Environment, and Consumer Protection (LANUV) marked with red dots.

Figure 3: Wind rose representing data collected during semi parallel measurements in February, May and September 2014 at the weather station “Aachen-Hörn” also used as inflow boundary conditions for traffic induced PM$_{10}$ distribution modelling.

2.3 Instrumentation

2.3.1 Grimm mobile optical particle counter

The particle measurements were taken using a mobile optical particle counter (OPC, Model EDM 107G, Grimm GmbH, Ainring, Germany). The OPC integrates the approaches of light scattering technology with single particle counting. A pulse height analyzer classifies the scattered light pulse signals into a size distribution in the range between 0.25–32 µm DAE containing 31 different size channels. Internally, the particle number size distribution is converted into mass concentrations of e.g.
PM$_{0.25;10}$ for an indicated time interval. The sensor operates at a volumetric flow rate of 1.2 L min$^{-1}$ and a time resolution of 6 s. All measurements with the OPC were carried out at the mean respiratory height of 1.6 m agl and stored as 1-minute mean values.

The OPC used had been factory calibrated on a regular basis (VDE standard 0701–0702) within the calibration validity period and was calibrated last time on 13/01/2015. Before calibration the latest inspection showed a deviation of $-0.6 \mu g m^{-3}$ ($-4.2 \%$) for PM$_{0.25;10}$ and a deviation of $-0.3 \mu g m^{-3}$ ($-2.7 \%$) for PM$_{0.25;1}$ of the OPC to the factory’s reference unit 107 S/N.

### 2.3.2 Fixed weather station Aachen-Hörn

Inflow boundary conditions as entry criteria for the modelling tool were set using data from the permanent weather station “Aachen-Hörn”, located in the outlying area of Aachen (6° 03′ 40″ E, 50° 46′ 44″ N), at 1800 m linear distance to the research site. Required values of wind speed and wind direction were collected as 10-minute averages (Schneider and Ketzler, 2015).

### 2.4 Simulation

The dispersion simulation of traffic related PM$_{10}$ emissions were performed with version 2.6.11 of Austal2000, a Langrangian particle model according to the Technical Instructions on Air Quality Control (TA Luft), appendix 3 (BMU, 2002). Road traffic emissions only (including emissions from combustion processes, blown up dust as well as tire and break abrasions) were simulated in a domain extending 420 m by 420 m with a spatial resolution of 2 m.

For a best possible comparison with field observations, the semi-parallel measurements taken during the same period of time were considered regarding the initial conditions for the simulation run (cf. 2.2). Corresponding meteorological data from “Aachen-Hörn” (see 2.3.2) actuated the preceded and implemented model TALdia to calculate a wind and turbulence field library. In situ traffic counts were conducted to initiate particle source emission rates. Aerosol discharges for differentiated vehicle classes for each street leading to the investigation area (Fig. 2) were then calculated using the guideline published by Keller et al. (2004) and Lohmeyer et al. (2004). The simulation domain considered the complex conditions of the research site in terms of a spatially high-resolved (1 m) terrain model (soil surface) and georeferenced CAD-model data (urban fabric and obstacles). Vegetation elements such as trees were not considered. Georeferencing of CAD data and displaying of the results were realized using ESRI software ArcGIS version 10.2.2.

### 2.5 Measurement data handling

#### 2.5.1 processing

There is a temporal variability of PM concentrations as a result of changing meteorological conditions and consequently an altering background particle transport towards the area under study during time series measurement campaigns (see Fig. 4). Therefore a daily correction factor for trend elimination and normalization of time series PM$_{0.25;10}$ values ($cF_{PM10}$) was developed. Therefore, the basic idea of Merbitz et al., 2012b was used and slightly modified. The correction factor $cF_{PM10}(d)$ is calculated separately for each day ($d$) at

![Figure 4: Time periods of PM$_{0.25;10}$ time series measurements (light grey bars) in comparison to 60-minute average concentrations of PM$_{10}$ at the government air quality site “Burtscheid” (dark grey dots) and “Wilhelmstrasse” in Aachen during the winter campaign (left illustration “WI”) and during the summer campaign (right illustration “SU”). Time and date is indicated in local time (UTC+01 during winter and UTC+02 during summer).](image-url)
the time when measurements took place as described in Eq. (2.1)

\[
cF_{\text{PM}10(d)} = \frac{1}{2} \left\{ \left( \frac{\prod_{i=1}^{\text{d}} c_i(AABU)}{c_i(AABU)} \right) \right\} + \left\{ \left( \frac{\prod_{i=1}^{\text{d}} c_i(VACW)}{c_i(VACW)} \right) \right\}
\]

Hence, daily geometric mean values \(c_d\) of PM\(_{10}\) from the suburban monitoring site Aachen Burtscheid (AABU) and the traffic related monitoring site Aachen Wilhelmstrasse (VACW), operated by the Northrhine-Westfalian State Office for Nature, Environment, and Consumer Protection (LANUV), were set in relation to monthly averages \(c_i\) (geometric means) and averaged arithmetically over both sites, covering the whole periods of both measurement campaigns in February and September 2014. The calculated correction factors \(cF_{\text{PM}10(d)}\) for all measuring days \(d\) are further used by multiplying \(cF_{\text{PM}10(d)}\) with the measured values on associated days \(d\) to remove meteorological bias from mere time series measurements collected at different locations and different times in order that these values become comparable. It is expected that the daily variability of urban PM-levels is better represented by a combination of both the suburban background station (AABU) and the traffic related air quality station (VACW) than by using only one reference site for daily normalization, since the area under study is situated among both regimes.

### 2.5.2 Data quality

In this study we compared measurement data from a mobile particle sensor with data sampled at government air quality stations that use a different principle of measurement. This implies that deterioration might be accepted when it comes to data quality.

To give an impression of data quality we made a comparison of the instruments at the government air quality monitoring site AABU in ambient air. The mobile OPC was compared there with the fixed-instrument consisting of a C14 source, detector and a light bile particle sensor with data sampled at government air station AABU in ambient air. The OPC was compared there with the fixed-instrument consisting of a C14 source, detector and a light bile particle sensor with data sampled at government air station AABU in ambient air.

Between 28/08/2015 and 30/09/2015, a total of 25 hours of comparison measurements were collected. One-hour averaged OPC data compared reasonably to the SHARP instrument values (slope 0.42, \(R^2\) 0.46, Fig. 5). Effectively, the OPC consistently overestimated PM10 data and measured on average 135\% of the PM10 indicated by the SHARP instrument including large scatter in the sample. The overestimation came as a surprise since the OPC features a sizing limit of 0.25\(\mu m\) (see 2.3.1). Therefore, particles in the size range below 0.25\(\mu m\) are not accessible to the OPC. Consequently, hereafter measurement data from the mobile OPC were analyzed as fraction values PM\((0.25;10)\), PM\((0.25;10)\) and PM\((1;10)\).

### 2.6 Survey

#### 2.6.1 Sample

A mixed method interview study with on-site users was carried out in order to identify perceptions towards air quality and on-site comfort. The questionnaire structure enabled a seasonal comparison regarding mass concentration of PM\((0.25;10)\) and participants’ perception. Overall, in both measurement campaigns 300 participants volunteered to take part. The mean age was 35.0 years (SD = 17.9) and the participants were between 10 and 95 years old. Of all participants 47.8\% were male and 52.2\% were female. In the winter campaign 124 pedestrians participated. The mean age was 37.0 years (SD = 19.3), with 65 women (53.3\%) and 57 men (46.7\%). In the summer campaign 176 pedestrians participated. The mean age was 33.6 years (SD = 16.7) with 90 women (51.4\%) and 85 men (48.6\%). Overall, this represents an even gender distribution. Urban park users were examined as they incidentally crossed our measurements site in the inner urban area.

#### 2.6.2 Method perception measurements and data analysis

In questionnaire-based interviews with pedestrians, demographic data as well as information on their individual social and living situations were assessed. In addition, the position of every participant was noted, i.e. whether they were sitting or standing, while they were being interviewed on perception of environmental conditions. The perception of their own weather comfort, air quality as well as on-site comfort was questioned and compared to measured physical data.
### Figure 6: Boxplot diagram of PM$_{0.25;10}$ concentrations in µg m$^{-3}$ measured as time series at different locations (A, B, C, E, F) inside the area under study “Elisenbrunnen” in Aachen during different weekdays in winter (left illustration “WI”) and in summer (right illustration “SU”) 2014. Raw measurement values are shown in grey boxes whereas normalized values are shown in black/white boxes (10-minute mean values). Boxes display 25 % / 75 % quantiles and medians. Squares represent the arithmetic mean and whiskers show the standard deviation.

Data were analyzed using paired sample t-tests in order to detect seasonal differences of particulate matter concentration and mean rating for perceived air quality. Further, the relationship between particulate matter and perceived on-site comfort was analyzed by using bivariate analysis (Spearman rank).

### 3 Results and discussion

#### 3.1 Measurement results – spatial distribution of particle mass concentration

Results of trend corrected PM$_{0.25;10}$ mass concentration time series unveiled surprisingly the highest arithmetic mean values (20.4–31.3 µg m$^{-3}$) at monitoring locations E and F inside the green area during wintertime (Fig. 6). Three times less average PM$_{0.25;10}$ concentrations were found at monitoring positions in proximity to busy roads (B, C). Experiments during summer revealed both overall higher particle concentration regarding PM$_{0.25;10}$ and a slightly altered PM$_{0.25;10}$ distribution pattern (Fig. 6). Measurement location F featured outstanding mean PM$_{0.25;10}$ concentrations (76.4 µg m$^{-3}$) as well as the highest median (67.7 µg m$^{-3}$) whereas at sites A and E concentrations around 22.5 µg m$^{-3}$ were detected. Slightly higher trend corrected aerosol concentrations (34.0 µg m$^{-3}$) were measured during summer at the motor traffic governed monitoring site B. In comparison, sites A and E had the comparatively lowest variations. In general, measurement values of PM$_{0.25;10}$ scattered mostly at monitoring sites inside the green area both in wintertime as well as during the summer campaign. Inside the park only, outliers with metered 10-minute mean values of PM$_{0.25;10}$ exceeding 100.0 µg m$^{-3}$ were recorded frequently.

Due to the unforeseen findings during the first measurement campaign during February 2014 we subsequently made a different approach to particle measurements (see Section 2.2). Surprisingly, measurement results of PM$_{1;10}$ regarding the semi-parallel approach show unexpected effects as well (Fig. 7) as compared to the observed time series results (cf. Fig. 6). For instance, the concentration of coarse particle fractions (PM$_{1;10}$) were higher at the park site E and F (arithmetic mean: 22.5 µg m$^{-3}$ and 18.9 µg m$^{-3}$; geometric mean: 9.3 µg m$^{-3}$ and 6.5 µg m$^{-3}$), 100 m away from motor traffic, than on the sidewalk in close vicinity to the main road at locations B and C (arithmetic mean: 7.5 µg m$^{-3}$ and 8.7 µg m$^{-3}$; geometric mean: 5.8 µg m$^{-3}$ and 6.5 µg m$^{-3}$). Due to the proximity to vehicles travelling at speeds between stop-and-go and 30 km h$^{-1}$, which cause significant turbulence, one would expect resuspended coarse particles and emissions from brake and tire abrasions to play a significant role at site B and C regarding PM$_{1;10}$. In contrast, the direct environment at park sites E, F and partly D featured a surface of dry grass and unsurfaced footpaths containing loose and dry top coating material. It can be stated that those surfaces made a dominant contribution to airborne particles of PM$_{1;10}$ due to resuspension. That gives an approach to explain the unexpected spatial pattern at the monitoring locations inside the park and the motor traffic related sites B and C. The observation of the largest
scatter in measured PM$_{1;10}$ concentrations at sites D, E and F support our assumption of the subsistence of coarse particles emitters through diffuse sources e.g. on the ability of surfaces to release particles by resuspension. Consistently, during different days 1-minute mean concentrations of PM$_{1;10}$ far exceeded 50 µg m$^{-3}$. This was probably due to recurrent gusting wind that blew up dust from unpaved surfaces. By contrast, particle fractions of PM$_{0.25;1}$ were distributed equally at all measuring points (arithmetic mean: 6.0–6.9 µg m$^{-3}$). Merely, a poorly distinctive spatial pattern was observed considering arithmetic mean PM$_{0.25;1}$ values with comparatively small differences between measurement locations. The highest average PM$_{0.25;1}$ concentrations were detected in proximity to the main road “Friedrich-Wilhelm-Platz” at monitoring sites B and C (arithmetic mean: 6.9 µg m$^{-3}$ and 6.6 µg m$^{-3}$; geometric mean: 6.3 µg m$^{-3}$ and 6.1 µg m$^{-3}$) and at measuring point F inside the green area (arithmetic mean: 6.9 µg m$^{-3}$; geometric mean: 6.4 µg m$^{-3}$), respectively. The observed pattern with the highest PM$_{0.25;1}$ concentrations in vicinity to motor traffic emitters was expected to be due to medium-sized particles out of brake and tire abrasion as well as secondary accumulation mode particles arising from combustion processes. However, the PM$_{0.25;1}$ mass concentration findings at site F made an exception. At least here it seems that the former described diffuse particle source inside the park has an impact on PM$_{0.25;1}$ mass concentrations as well – albeit to a vastly lesser extent.

Overall, it is evident that such small-scale spatial gradients of particle concentrations in the urban roughness layer can usually not be captured by single stationary measurements.

### 3.2 Simulation results – influence of traffic on PM$_{10}$ concentrations at the research site

Simulation results of excessive motor traffic emissions generated with meteorological conditions initially similar to the semi-parallel measurements reveal the highest traffic-related PM$_{10}$ concentrations in close vicinity to traffic lines particularly at the main road “Friedrich-Wilhelm-Platz” and the alleyway “Ursulinerstr.”, with the average contribution to the total mass concentration of PM$_{10}$ being in the range of 10.0 – 22.0 µg m$^{-3}$ (Fig. 8). Corresponding concentrations seem to decline rapidly further from the traffic sources. The average contribution of traffic-induced airborne particles to the total aerosol concentration at the research site under given meteorological conditions decreases to 3.0–10.0 µg m$^{-3}$ at distances as little as 10 m away from the two mentioned roads. According to simulation outcomes the direct impact of local motor traffic on PM$_{10}$ concentrations inside the park tends to be negligible. At inner park sites, the additions to rural and urban background concentrations and to other local diffuse particle sources (e.g. unpaved footpaths) resulting from motor traffic are estimated to be in magnitudes of 0.1–1.6 µg m$^{-3}$. Simulation results do not indicate that local traffic emissions cause...
Figure 8: Contour plot of the simulated distribution of average PM$_{10}$ concentrations induced by motor traffic only [µg m$^{-3}$] at 1.5 m agl for the research site “Elsienbrunnen”, Aachen, for different chosen weekdays in February, May and September 2014, 10:00–17:00, during cyclonic weather conditions including depicted measurement locations A–F (black dots). Upper right plot shows near-surface horizontal wind vectors (blue arrows) representative for mean inflow boundary conditions (Klug/Manier stability class 4, wind direction sector 250–260°).

Table 1: Mean PM$_{10}$ remainder ($\Delta$PM$_{10}$) for monitoring locations A–F calculating the difference between arithmetic mean PM$_{0.25;10}$ values of the semi-parallel measurements and the sum of arithmetic mean PM$_{10}$ data out of the simulation and the arithmetic mean background PM$_{10}$ concentration recorded at the rural background air quality monitoring station “Burtscheid” (AABU).

| monitoring location | A     | B     | C     | D     | E     | F     |
|---------------------|-------|-------|-------|-------|-------|-------|
| Mean PM$_{0.25;10}$ measured | 17.0  | 14.4  | 15.3  | 19.6  | 24.9  | 29.4  |
| Mean PM$_{10}$ simulated | 0.5   | 2.7   | 4.3   | 0.6   | 0.2   | 0.2   |
| Mean rural background PM$_{10}$ (AABU) |       |       |       |       | 11.4  |       |
| $\Delta$PM$_{10}$ | 5.0       | 0.2   | $-0.4$ | 7.6   | 13.3  | 17.9  |

In fact, simulation results illustrate the exact opposite when it comes to the comparison with spatial patterns of measured PM$_{0.25;10}$ and PM$_{1;10}$ concentrations (cf. Fig. 6 and Fig. 7). As expected, under southwest inflow situations particles tend to accumulate in the alleyway (“Ursulinerstr.”) and street canyons (“Friedrich-Wilhelm-Platz”), where dilution of aerosols is difficult, as well as in areas downwind from emission sources where particles get dammed up at obstacles. Simulated traffic induced average PM$_{10}$ concentrations with a distinctive gradient for the monitoring sites A–F complete the picture. Highest mean values were simulated for sites B and C with declining concentrations at locations A and D, whereas monitoring sites inside the green area with maximum distance to the traffic lines (E, F) show minimum average PM$_{10}$ concentrations (Fig. 8).

Approximations of PM$_{10}$ remainders ($\Delta$PM$_{10}$) indicate that local diffuse particle sources and urban background transport contribute to local PM$_{10}$ concentrations inside the green area of up to 17.9 µg m$^{-3}$, whereas the impact on measurement locations in vicinity to the main roads (measurement locations B and C) was calculated to be close to zero (Table 1). From this analysis we may conclude that resuspension of PM from unpaved grounds within the green park area would have been a major contribution to the elevated measured PM$_{0.25;10}$ and PM$_{1;10}$ levels at sites E and F and possibly also at site A and D within limits of specified uncertainties (cf. 2.5.2).

3.3 Urban park user perception of air quality

A first analysis addressed seasonal effects on physical influences like particulate matter and on perception
of air quality. The independent-samples t-test unveiled a significant difference in measurements of PM$_{2.5;10}$ time series ($t(212) = -10.3, p < 0.001$) in February 2014 (arithmetic mean = 19.6 µg m$^{-3}$, standard deviation (SD) = 7.5 µg m$^{-3}$) and in July 2014 (arithmetic mean = 41.5 µg m$^{-3}$, SD = 26.6 µg m$^{-3}$). These findings indicate higher PM stressors during the summer campaign than during measurements in February in Aachen. The significant difference between particulate matter concentration in winter and summer could be proved. Contrary to the significant differences between summertime and the winter campaign in Aachen regarding mean concentration of PM$_{2.5;10}$, the perception of air quality was assessed comparably. Results of air quality perception ratings show similar mean values in winter and summer, reaching mean values of 2.2 and 2.3 on a Likert scale ranging from 1.0 (= very bad) to 3.0 (= very good). The descriptive outcomes reveal a similar rating of on-site comfort of 4.6 (arithmetic mean) on the Likert scale both for winter- and summertime surveys (Fig. 9). As can be seen, the perception of on-site comfort did not coincide with the seasonal differences of mean PM$_{2.5;10}$ concentration. Hence, the exposure resulting from high overall mean PM$_{2.5;10}$ concentration during summer was not perceived within this evaluation.

However, there is a significant correlation between on-site (climate) comfort values and perception data of air quality ($r = 0.29; p < 0.000$), showing that participants’ evaluations coincide: the higher (i.e. more comfortable) the perceived air quality was, the higher was the perceived on-site comfort even though both measurements did not relate to the measured PM$_{2.5;10}$ concentration in both seasons.

### 4 Conclusions

This study showed the heterogeneous and complex mass concentration distribution of aerosols at very small scales similar to earlier studies (Birmili et al., 2013a, Merbitz et al., 2012c). The combination of experiments and the use of a micro-scale particle dispersion model allowed for an understanding of spatial gradients and the identification of different particle sources in the urban roughness layer of roughly an area of 400 m by 400m in the inner city of Aachen. Even though traffic is assumed to be the most important particle source across urban agglomerations, PM$_{2.5;10}$ and PM$_{1;10}$ metrics showed unexpected distribution patterns with highest mean concentrations inside a park several tens of meters away from trafficked roads. Semi-parallel particle measurements of PM$_{0.25;10}$, however, revealed an extensively equal distribution pattern in the whole area under study with only slightly increased mean concentrations close to the traffic lines. AUSTAL2000 simulation results of only traffic induced emissions of PM$_{10}$ showed a different distribution pattern compared to PM$_{2.5;10}$ and PM$_{1;10}$ measurements. The simulation, conducted with similar meteorological inflow boundary conditions observed during semi-parallel measurements, unveiled a major impact of road traffic on the aerosol concentration in the area under study similar in magnitude to related findings in other studies (Merbitz et al. 2012b). Mean PM$_{10}$ concentrations were simulated to be highest near to traffic lines. When moving away from traffic sources mean PM$_{10}$ concentrations seemed to rapidly decrease.
Figure 10: Scatter plot diagrams of measured PM$_{0.25;10}$ concentrations in µg m$^{-3}$ vs. air quality assessments on a 3-point Likert scale (3 = good; 2 = neutral; 1 = bad) during the winter campaign (left illustration “WI”) and vs. air quality assessments on a 6-point Likert scale (from 6 = very good to 1 = very bad,) during the summer campaign (right illustration “SU”).

The direct influence of local traffic PM$_{10}$ emissions on the park area tended to be negligible. Both the analysis of experimental data alone and the comparison to simulation results of only traffic induced PM emissions provides strong evidence for the hypothesis that surfaces of dried-out grass and unsurfaced footpaths in the park provided a big source of coarse airborne particles (PM$_{1;10}$) and give a plausible explanation for the unexpected spatial distribution patterns of PM$_{0.25;10}$ and PM$_{1;10}$ metrics. During the measurement campaign in February, May and September 2014 the contribution of diffuse resuspension particle sources to measured mean mass concentration of PM$_{0.25;10}$ was estimated to be between 13.3 and 17.9 µg m$^{-3}$ inside the park area.

Reflection on our results raises two questions: a) Can fixed site aerosol instrumentation provide representative statements for an entire city area regarding the urban space user’s exposure to particles, in particular when the city area as a general rule contains e.g. heterogeneous subsurfaces and numerous different particle sources? b) Is PM$_{10}$ as a single metric a good measure for air quality regulation regarding aerosols inside cities since different particle size fractions with different impacts on the human body (Kreyling et al., 2006) can be distributed in various ways (Ning and Sioutas, 2010)?

In terms of human perception, mass concentrations of PM$_{0.25;10}$ were not reliably assessed, neither in relation to seasons, nor in relation to air quality and on-site comfort. The low standard deviations suggest a rather comparable perception among urban park users, not taking into consideration the high age range (10–95 years) or gender. In marked contrast to findings from Nikolopoulou et al. (2011), who claimed a significant positive correlation between PM concentrations and perception of air quality during a similar study in similar PM concentration magnitudes, we can conclude that perception of air quality was imprecise and unrelated to the real exposure, regardless of age and gender. Nevertheless, data revealed a close relationship between the awareness of air quality and on-site comfort, thus corroborating the sensitivity of pedestrians to perception of urban stressors. Due to an undersized sample this study lacks a deeper investigation into what actually formed the park users’ opinion on air quality and on-site comfort, which is probably influenced more by factors like sense of place (Brody et al., 2004) or acoustic occurrences than by actual air quality conditions. The fact that exposure to airborne particles is indeed dangerous and has insidious adverse effects on human health although it is obviously not perceivable in investigated concentration magnitudes makes it even more important to reduce PM concentrations.

5 Acknowledgments

This project is part of the interdisciplinary Project House HumTec (Human Technology Center) at RWTH Aachen University. The financial support from the German federal and state governments through the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) is gratefully acknowledged. We would like to thank the scientific editor and two anonymous reviewers for very helpful comments on this manuscript. Thanks to students I. Zirwes and M. Moers who helped enthusiastically with field experiments and traffic counts. We acknowledge S. Wilhelm from the Northrine-Westfalian State Office for Nature, Environment, and Consumer Protection (LANUV) for providing PM$_{10}$ data from monitoring stations in Aachen. U. Janicke kindly helped with issues regarding AUSTAL2000.

References

Badland, H.M., M.J. Duncan, 2009: Perceptions of air pollution during the work-related commute by adults in Queensland, Australia. – Atmos. Env. 43, 5791–5795. DOI: 10.1016/j.atmosenv.2009.07.050.
Bekö, G., B.U. Kjeldsen, Y. Olsen, J. Schipperijn, A. Wierzbicka, D.G. Karotki, J. Toftum, S. Loft, G. Clausen, 2015: Contribution of various microenvironments to the daily personal exposure to ultrafine particles: Personal monitoring coupled with GPS tracking. – Atmos. Environ. 110, 122–129. DOI:10.1016/j.atmosenv.2015.03.053.

Birmili, W., J. Rehn, A. Vogel, C. Boehlke, K. Weber, F. Rasch, 2013a: Micro-scale variability of urban particle number and mass concentrations in Leipzig, Germany. – Meteorol. Z. 22, 155–165. DOI:10.1127/0941-2948/2013/0394.

Birmili, W., L. Tomsche, A. Sonntag, C. Oeplet, K. Weinhold, S. Nordmann, W. Schmidt, 2013b: Variability of aerosol particles in the urban atmosphere of Dresden (Germany): Effects of spatial scale and particle size. – Meteorol. Z. 22, 195–211. DOI:10.1127/0941-2948/2013/0395.

Brody, S.D., B.M. Peck, W.E. Highfield, 2004: Examining Localized Patterns of Air Quality Perception in Texas: A Spatial and Statistical Analysis. – Risk Analysis 24, 1561–1574. DOI:10.1111/j.0272-4332.2004.0050.x.

Broich, A.V., L.E. Gerharz, O. Klemm, 2012: Personal monitoring of exposure to particulate matter with a high temporal resolution. – Environ. Sci. Pollut. Res. 19, 2959–2972. DOI:10.1007/s11356-012-0806-3.

Brook, R.D., S. Rajagopalan, C.A. Pope, J.R. Brook, A. Bhatnagar, A.V. Diez-Roux, F. Holguin, Y. Hong, R.V. Luepker, M.A. Mittleman, A. Peters, D. Siscovick, S.C. Smith, L. Whitset, J.D. Kaufman, on behalf of the American Heart Association Council on Epidemiology and Prevention, Council on the Kidney in Cardiovascular Disease, and Council on Nutrition, Physical Activity and Metabolism, 2010: Particulate Matter Air Pollution and Cardiovascular Disease: An Update to the Scientific Statement From the American Heart Association. – Circulation 121, 2331–2378. DOI:10.1161/CIRCULATIONAHA.110.988071.

Chen, L., E. Ng, 2012: Outdoor thermal comfort and outdoor activities: A review of research in the past decade. – Cities 29, 118–125. DOI:10.1016/j.cities.2011.08.006.

Chow, J.C., J.G. Watson, J.L. Mauderly, D.L. Costa, R.E. Wynga, S. Vedal, G.M. Hidy, S.L. Altschuler, D. Marrack, J.M. Heus, G.T. Wolff, C.A. Pope, D.W. Dockery, 2006: Health Effects of Fine Particulate Air Pollution: Lines that Connect. – J. Air Waste Manag. Assoc. 56, 1361–1390. DOI:10.1080/10904406.2006.10464545.

Dons, E., L. Ist Panis, M. Van Poppel, J. Theunis, H. Willems, R. Torfs, G. Wets, 2011: Impact of time–activity patterns on personal exposure to black carbon. – Atmos. Environ. 45, 3594–3602. DOI:10.1016/j.atmosenv.2011.03.064.

Gabriel, K.M.A., W.R. Endlicher, 2011: Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. – Environ. Pollut. 159, 2044–2050. DOI:10.1016/j.envpol.2011.01.016.

German Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU), 2002: First General Administrative Regulation for the Federal Emission Control Law / Instructions for Pollution Control – TA Luft (in German); Gemeinsames Ministerialblatt 24, 511–605.

Johansson, E., S. Thorsson, R. Emmanuell, E. Krüger, 2014: Instruments and methods in outdoor thermal comfort studies – The need for standardization. – Urban Climate 10, 346–366. DOI:10.1016/j.urcl.2013.12.002.

Keller, M., P. De Hahn, W. Knörr, S. Hausberger, H. Steven, 2004: Handbook Emission Factors for Road Transport (in German). – UBA Berlin, BUWAL Bern, UBA Wien, Bern, Heidelberg, Graz, Essen. 127 pp.

Kozawa, K.H., A.M. Winer, S.A. Frulin, 2012: Ultrafine particle size distributions near freeways: Effects of differing wind directions on exposure. – Atmos. Environ. 63, 250–260. DOI:10.1016/j.atmosenv.2012.09.045.

Kreiling, W.G., M. Stenmler-Beinhke, W. Möller, 2006: Ultrafine Particle–Lung Interactions: Does Size Matter? – J. Aerosol Med. 19, 74–83. DOI:10.1089/jam.2006.19.74.

Laden, F., J. Schwartz, F.E. Speizer, D.W. Dockery, 2006: Reduction in Fine Particulate Air Pollution and Mortality: Extended Follow-up of the Harvard Six Cities Study. – American Journal of Respiratory and Critical Care Medicine 173, 667–672. DOI:10.1164/rccm.200503-443OC.

Lognemy, A., M. Stockhaus, A. Moldenhauer, E. Nitzsche, I. Düring, 2004: Calculation of traffic induced particle emissions due to blown up dust and abrasions for the land register of the State of Saxony. Workpackages 1 and 2 (in German). – Sächsisches Landesamt für Umwelt und Geologie, Dresden.

Maras, I., M. Butttstädt, J. Hahmnn, H. Hofmeister, C. Schneider, 2014: Investigating public places and impacts of heat stress in the city of Aachen, Germany. – Die Erde 44, 290–303. DOI:10.12854/erde-144-20.

Maras, I., T. Schmidt, B. Paas, M. Ziefle, C. Schneider, 2016: The impact of biometeorological factors on perceived thermal comfort at urban public places. – Meteorol. Z., 25, DOI:10.1127/metz/2016/0705.

Merritz, H., M. Butttstädt, S. Michael, W. Dott, C. Schneider, 2012a: GIS-based identification of spatial variables enhancing heat and poor air quality in urban areas. – Appl. Geogr. 33, 94–106. DOI:10.1016/j.apgeog.2011.06.008.

Merritz, H., F. Detalle, G. Ketzler, C. Schneider, F. Lenartz, 2012b: Small scale particulate matter measurements and dispersion modelling in the inner city of Liège, Belgium. – Int. J. Environ. Pol. 50, 234. DOI:10.1504/IJEP.2012.051196.

Ning, Z., C. Diouf, 2010: Atmospheric Processes Influencing Aerosols Generated by Combustion and the Inference of Their Impact on Public Exposure: A Review. – Aerosol Air Quality Res. 10, 43–58. DOI:10.4209/aaqr.2009.05.0036.

Padró-Martínez, L.T., A.P. Patton, J.B. Trull, W. Zamore, D. Brugge, J.L. Durant, 2012: Mobile monitoring of particle number concentration and other traffic-related air pollutants in a near-highway neighborhood over the course of a year. – Atmos. Environ. 46, 253–264. DOI:10.1016/j.atmosenv.2012.06.088.

Pope, C.A., R.T. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito, G.D. Thurston, 2002: Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. – JAMA 287, 1132–1141.

Quiros, D.C., Q. Zhang, W. Choi, M. He, S.E. Paulson, A.M. Winer, W. Wang, Y. Zhu, 2013: Air quality impacts of a scheduled 36-hour closure of a major highway. – Atmos. Env. 67, 404–414. DOI:10.1016/j.atmosenv.2012.10.020.
Raimbault, M., D. Dubois, 2005: Urban soundscapes: Experiences and knowledge. – Cities 22, 339–350. DOI: 10.1016/j.cities.2005.05.003.

Schmidt, T., I. Maras, B. Paas, J. Stienen, M. Ziefle, 2015: Psychophysical observations on human perceptions of climatological stress factors in urban environments. – In: Proceedings 19th Triennial Congress of the IEA 9, 14.

Schneider, C., G. Ketzler, 2015: Klimamesststation Aachen-Hörn. - Monatsberichte Februar, Mai, September / 2014, RWTH Aachen, Geographisches Institut, Lehr- und Forschungsgebiet Physische Geographie und Klimatologie.

Seinfeld, J.H., S.N. Pandis, 2006: Atmospheric chemistry and physics: from air pollution to climate change. 2nd ed. – J. Wiley, Hoboken, New Jersey, 1203 pp.

Shirom, A., S. Melamed, M. Nir-Dotan, 2000: The relationships among objective and subjective environmental stress levels and serum uric acid: The moderating effect of perceived control. – J. Occupational Health Psychology 5, 374–385. DOI: 10.1037/1076-8998.5.3.374.

Spinazzè, A., A. Cattaneo, D.R. Scocca, M. Bonzini, D.M. Cavallo, 2015: Multi-metric measurement of personal exposure to ultrafine particles in selected urban microenvironments. – Atmos. Env. 110, 8–17. DOI: 10.1016/j.atmosenv.2015.03.034.

Steinle, S., S. Reis, C.E. Sabel, 2013: Quantifying human exposure to air pollution – Moving from static monitoring to spatio-temporally resolved personal exposure assessment. – Sci. Total Env. 443, 184–193. DOI: 10.1016/j.scitotenv.2012.10.098.

United Nations, Population Division, Department of Economic and Social Affairs, 2014: World urbanization prospects: the 2014 revision. – United Nations, New York, 27 pp.

Venn, A.J., S.A. Lewis, M. Cooper, R. Hubbard, J. Britton, 2001: Living Near a Main Road and the Risk of Wheezing Illness in Children. – Amer. J. Respiratory Critical Care Medicine 164, 2177–2180. DOI:10.1164/ajrccm.164.12.2106126.

Von Klot, S., 2005: Ambient Air Pollution Is Associated With Increased Risk of Hospital Cardiac Readmissions of Myocardial Infarction Survivors in Five European Cities. – Circulation 112, 3073–3079. DOI: 10.1161/CIRCULATIONAHA.105.548743.

WHO, 2013: Health risks of air pollution in Europe – HRAPIE project. – Online available at http://www.euro.who.int/__data/assets/pdf_file/0017/234026/e96933.pdf?ua=1 (Accessed March 18, 2015).

Yang, W., J. Kang, 2005: Acoustic comfort evaluation in urban open public spaces. – Appl. Acoust. 66, 211–229. DOI: 10.1016/j.apacoust.2004.07.011.