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Wintertime spatio-temporal variation of ultrafine particles in a Belgian city

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ABSTRACT

Simultaneous measurements of ultrafine particles (UFPs) were carried out at four sampling locations situated within a 1 km^2 grid area in a Belgian city, Borgerhout (Antwerp). All sampling sites had different orientation and height of buildings and dissimilar levels of anthropogenic activities (mainly traffic volume). The aims were to investigate: (i) the spatio-temporal variation of UFP within the area, (ii) the effect of wind direction with respect to the volume of traffic on UFP levels, and (iii) the spatial representativeness of the official monitoring station situated in the study area. All sampling sites followed similar diurnal patterns of UFP variation, but effects of local traffic emissions were evident. Wind direction also had a profound influence on UFP concentrations at certain sites. The results indicated a clear influence of local weather conditions and the more dominant effect of traffic volumes. Our analysis indicated that the regional air quality monitoring station represented the other sampling sites in the study area reasonably well; temporal patterns were found to be comparable though the absolute average concentrations showed differences of up to 35%.

1. Introduction

Exposure to ultrafine particles (UFPs; those below 100 nm in size) is of great concern to the air quality management community because of their adverse impacts on human health (Atkinson et al., 2010; Peters et al., 1997). Recent studies have shown significant contributions to excess mortality due to the exposure to traffic-derived UFP in urban areas (Kumar et al., 2011a). Even brief exposure of healthy people to traffic UFP seems to induce some effects (Jacobs et al., 2010; Bos et al., 2011). Over 80% of particles, by number, in polluted urban environments are represented by UFP (Morawska et al., 2008) whilst their corresponding mass accounts for less than 20% of the total PM mass concentration (Kittelson, 1998). Atmospheric formation of UFP is site and time specific (Kulmala et al., 2004) and the transformation processes that change their number and size distributions differ both temporally and spatially (Kumar et al., 2011b). On-road UFP contains both nucleation (<50 nm) and accumulation mode (>50 nm) particles. Particles in the nucleation mode are of major scientific interest because of their composition and potential health effects. Once formed, UFP number concentrations of this mode are usually higher than those in the accumulation mode in a roadside environment (Kittelson, 1998).

Mean UFP number concentrations in urban background areas, along the roadsides in street canyons, and in vehicle wakes or exhaust plumes range from 10^3 to 10^4 cm^{-3}, 10^4 to 10^6 cm^{-3} and 10^4 to 10^7 cm^{-3}, respectively (Carpentieri and Kumar, 2011; Kumar et al., 2010; Berghmans et al., 2009). The UFP number concentrations along the roadside show an association with the vehicle flow characteristics. For instance, increasing vehicle speed increases the emissions of UFP (Kittelson et al., 2004). Studies carried out near highways show that number concentrations of particles decrease exponentially with the increasing downwind distance from the highways (Buonanno et al., 2009). Such a decrease was observed up to ~300 m and beyond, at which point levels of UFP number concentrations approached the local urban background (Morawska et al., 1999; Zhu et al., 2002). Many traffic related pollutants show a similar decrease. Likewise, a few studies have monitored UFP number concentrations at different urban sites to understand the spatial variability of UFP (Holmes et al., 2005). Direct comparison of the results from such studies is not possible since the study design was different in terms of traffic characteristics and site locations. At urban background sites particle size distributions are much more stable, and are likely to

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be more unimodal compared to the multimodal and rapidly changing distributions close to traffic sites (Harrison et al., 1999). Finally, the physical characteristics of UFP are more closely related to the number of heavy duty vehicles than to the number of light duty vehicles (Holmes et al., 2005; Westerdahl et al., 2005).

Epidemiological studies typically use one or only a few central monitoring stations as a proxy for personal exposure to particulate matter air pollution. However, central monitoring sites may not accurately characterize the spatial complexities of the UFP concentrations across an urban area. Consequently, investigating the intra-urban variability of UFP has become a priority area of study. The aim of this study is to investigate the spatio-temporal variability of the number concentration of UFP within a 1 km^2 urban grid. Additionally, we also want to study the effect of wind direction with respect to the volume of traffic on UFP levels, and evaluate the spatial representativeness of the official monitoring station situated in the study area.

To achieve these objectives, UFP number concentrations are simultaneously measured at four different sites in a Belgian city (Borgerhout, Antwerp). All the sites have different traffic volumes and surrounding environments.

2. Methodology

2.1. Description of sampling location

Measurements were carried out in the Borgerhout district (51°13′ N and 4°26′E) of Antwerp, Belgium, a port city of approximately 500,000 inhabitants. Borgerhout has a surface area of 3.93 km^2 and houses about 44,080 inhabitants (as of April 4th 2011). This is a typical urban commercial and residential area with busy traffic. Measurement campaigns were carried out during the winter of 2010 at four different sites (described in Table 1) simultaneously for one month (12th February until 12th March 2010). All the measuring sites are situated within an area of about 1 km^2 in the surroundings of a permanent official air quality monitoring station of the Flemish Environmental Agency, VMM (see Fig. 1). Specific differences between siting (e.g. exact distance to the axis of the road) and meteorological conditions (low dispersion conditions during winter) may be reflected in the UFP measurements (see Section 3).

The location of the sampling sites is shown in Fig. 1:

Site 1: Plantin en Moretuslei (PlMl) is a major access road to the city with an east–west orientation, with busy traffic intersections and four lanes (two in each direction).

Site 2: Districtshuis (Dis) represents a street canyon which is close to an open space and has a north–south orientation. The road has two traffic lanes and moderate levels of traffic.

Site 3: Kleine Beerstraat (KB) is a two lane street canyon. The site experiences moderate traffic, including two tram lines. The road has a northwest–southeast (i.e. 300ºN) orientation. The sampling location was at the southern corner of the street.

Site 4: VMM is located about 450 m to the east of site 1 (PlMl), experiencing very similar traffic levels as site 1. The sampling location at this site was ~10 m away from the moving traffic behind a 0.5 m wide and 1.5 m high bushy vegetation screen. This is also the regional monitoring station of Flemish Environment Agency (VMM). Unfortunately, data were only available for 1 week (5/3/2011–12/3/2011) at this location.

Further details on the traffic at each site are presented in Table 1.

Table 1
Description of measurement sites.

Site name	Orientation relative to traffic[a]	The distance from traffic (m)	Weekday traffic volume (veh day^{-1})	Weekend traffic volume (veh day^{-1})	Heavy duty fraction on weekday (and weekend) (%)
Site 1 (PlMl)	10	20	37,000	25,000	7% (3%)
Site 2 (Dis)	105	3	5000	4000	5% (2%)
Site 3 (KB)	210	2	4000	3000	4% (2%)
Site 4 (VMM)	10	10	37,000	25,000	7% (3%)

[a] Showing the orientation of the site perpendicular to the road.

2.2. Instrumentation

Measurements of UFP were performed using the GRIMM "Nano-Check" model 1.320 (GRIMM), which is operated with a Grimm 1.108 optical aerosol spectrometer in a weatherproof housing model 1.165. The Nanocheck uses a diffusion charger and Faraday cup electrometer. The mean particle diameter is determined by varying (high and low) the voltage trough the electrometer. Comparison of the two resulting currents versus a factory calibration curve gives the mean particle diameter. The Nano-Checks were installed at each of the four sites for simultaneous measurements, enabling a temporal comparison of UFP concentrations measured by identical instruments. Each instrument was calibrated by GRIMM using NaCl particles (size range 27.8–177.0 nm). The Nano-Check can count total particle number concentrations between 25 and 300 nm, besides providing the mean diameter of the measured size range. A sampling frequency of 5 min was used; the sampling inlet of the instruments was about 1.6 m above ground level. Using a cut-off point at 25 nm, reduces the uncertainty involved in measuring volatile and unstable nucleation mode particles that have a relatively short atmospheric life time (Morawska et al., 2008). The deployed instruments are thus fit for long term representative measurements of UFP. The size range of the instruments is beyond the upper cutoff size of UFP, however, in urban environments UFPs account typically for 90% of total particle number concentration (see Morawska et al., 2008, and references therein). The lower cut-off point can be seen as a limitation of this study, however the use of similar instruments guarantees the quality and representativeness of the data and the analysis presented of the Aitken and agglomeration modes.

The Nanocheck-GRIMM configuration uses a dilution system in which the sampled air is diluted with clean and dry air. Dilution is started at a relative humidity (RH) of 50%. The dilution factor is approximately 2. Whereas dilution for PM fractions (0.23–20 μm) — using the GRIMM 1.108 aerosol spectrometer — was included in the software, we found out that the dilution factor for UFP number concentrations measured by Nanocheck was not taken into account in the software of the configuration used. Therefore, the correct concentrations were calculated afterwards using the accurate dilution factor. The dilution factor was determined for each instrument after the sampling campaign. Flow was measured at the sampling inlet with dilution 'on' (0.6 $l min^{-1}$) and 'off' (1.2 $l min^{-1}$). The resulting ratio is the corresponding dilution. The flow in the spectrometer was always 1.2 $l min^{-1}$ and was within 10% of the measured flow at the sampling inlet with dilution 'off'. Because the dilution issue was not known at the start of the measurement campaign, data had to be corrected afterwards. Therefore, measurements of UFP number concentrations at a relative air humidity of >50% were multiplied using the dilution factor. Because dilution was switched on and off based on a relative humidity measurement at a 6 s interval and UFP number concentration measurements were made at 5 min intervals, some data had to be excluded from the dataset because the mixing state changed during the 5 min averaging. The resulting dilution factors range between 1.79 and 1.94 for the different instruments. In addition, an intercomparison of the instruments was performed at the end of the measurement campaign resulting in correction factors ranging from 1.00 to 1.37 relative to the instrument used at site 1 (PlMl).

Fig. 1. Schematic map of the measurement grid area around the VMM monitoring station in Borgerhout (Antwerp, Belgium). http://maps.google.be/

Wind speed and direction were determined with a Vaisala WXT520 ultrasonic anemometer, installed at site 3 (KB) at 2 m above ground level, set up with a 0.1 m s^{-1} resolution and 0.3 m s^{-1} accuracy, in order to accurately determine wind speed under low wind speed conditions. Regional meteorological data was also collected at a meteorological station in the North of the city (at about 10 km from the study area) at a height of 30 m above ground level and was, therefore, undisturbed by the configuration of the streets and buildings.

Vehicle counts and speeds were recorded in four vehicle categories (cars, vans, small and big trucks/buses) using double inductive loop detectors at Sites PlMl and Dis; video counting was performed to obtain traffic data at Sites KB and VMM.

2.3. Criteria for representativeness

Two different metrics were used for assessing the representativeness of the official air quality monitoring station for the UFP concentrations and gaseous pollutants within the study area (Mishra and Murty, 2003):

- Root mean square difference, RMSD $= \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2}$, representing the difference between simultaneous values at two sites, where x_i and y_i are values at two different sites. RMSD values closer to zero indicate "similar" time series whereas higher values demonstrate different time series. There is no upper boundary and the range of values depends on the variation of the concentration values. UFP number concentrations and mean diameter values were normalized by dividing them by their average values.
- Pearson's correlation reflects the degree of linear relationship between two variables, ranging between +1 (perfect positive linear relationship) and −1 (perfect negative linear relationship); '0' indicates a lack of any correlation.

3. Results and discussion

3.1. Brief summary of general meteorological and traffic observations

Fig. 2 shows the wind direction measured at site 3 (KB) and at the regional meteorological station (wind direction at 30 m height). As shown in Fig. 2, the local wind direction is highly affected by surroundings, resulting in a main wind direction parallel to the street (NW–SE) that might also be influenced by moving traffic or trams. The full line represents the data for the entire sampling campaign (for the meteorological station) whereas the dotted line shows the wind direction for the one week at four locations. As shown in the plot, the main wind direction in the one-week campaign is NE; At the VMM site, sampling was performed only this week. Mean air temperature averaged over the entire sampling period was 3.9 °C, varying between −2.7 and 12.2 °C. Wind speed in the street canyon was calm (on average 0.70 ± 0.33 m s^{-1} at site KB) during the measurement

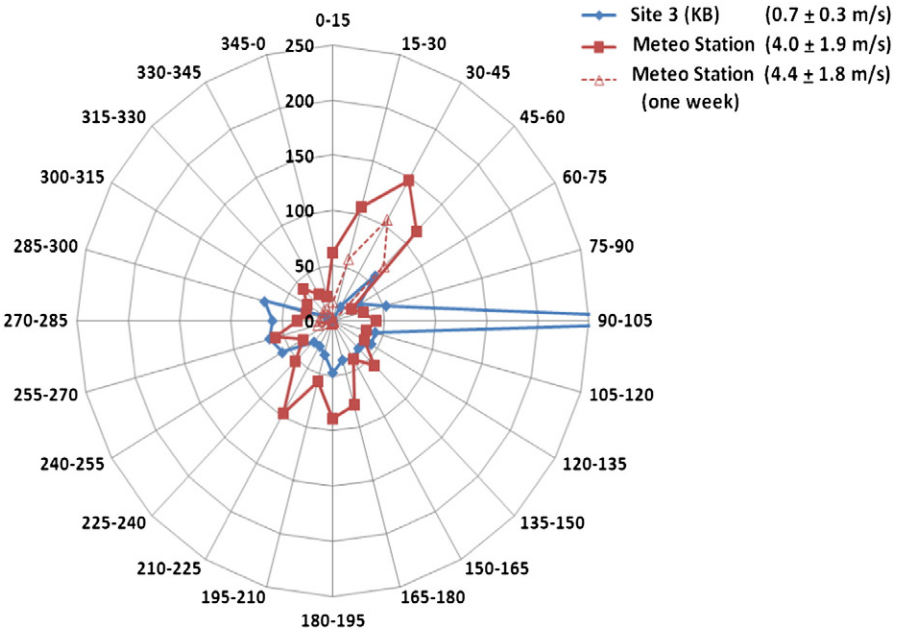

Fig. 2. Wind direction at meteorological station and site 3 during the entire sampling campaign. The x-axis is showing wind direction and the y-axis is showing frequency of observed wind direction.

period, having a minimal effect of wind turbulence on the UFP dispersion (Kumar et al., 2008a). As expected, wind speed measured at the meteo station (at 30 m height) is higher (4.0 ± 1.9 m s^{-1}).

All four sites containing functional Nano-Checks experienced different levels of traffic, with the highest at PlMl and VMM (both were located on the same road) followed by the sites Dis and KB (Table 1). Electricity driven tram lines were present only at KB, though these are unlikely to have a strong influence on UFP concentrations (Kardel et al., 2012). As expected, passing of HDVs strongly influenced the UFP concentrations at all sites. It was frequently observed during the daily personal visits to the measurement sites that UFP concentrations increased substantially seconds after the HDVs departed from the vicinity of a measurement site. All the sites followed a similar diurnal pattern of UFP concentrations, but the individual short term variations at each site were noteworthy.

3.2. Diurnal pattern of UFP concentrations and count mean diameter

Fig. 3a, b and c shows the temporal variation of UFP concentrations for weekdays (9th of March and 5th of March, respectively) and for a Sunday (7th of March) at all four locations. As expected, the UFP concentrations follow the diurnal variation of the traffic volumes at individual sites. An increase in UFP concentrations was observed during morning and evening traffic rush hours. On the 9th of March (Fig. 3a), the mean UFP concentrations during night time were of the order of ~12,000 cm^{-3} at all the sites. However, the morning peak was reached between 7 and 8 am (GMT + 1) when UFP levels increased up to 35,000 cm^{-3} at sites VMM and PlMl and up to 50,000 cm^{-3} at Dis and KB. This day, regional wind direction was mainly from NE.

However, on the 5th of March (Fig. 3b), when wind direction was mainly SW, morning peak concentrations increased up to 75,000 cm^{-3} at PlMl and up to 50,000 and 60,000 cm^{-3} at Dis and KB sites, respectively. The evening peak on the 9th of March was observed at all the sites between 4 and 8 pm when the UFP number concentrations were lower compared to the morning peaks i.e. up to ~30,000 cm^{-3} at KB, VMM and PlMl and up to 40,000 cm^{-3} at Dis. On the 7th of March (a Sunday; Fig. 3c), the diurnal pattern of UFP number concentrations was less pronounced at all locations. This is because traffic flows are reduced compared to weekdays (see Table 1).

Also plotted in Fig. 3 are the mean diameters of the UFP size distribution. These follow an opposite trend, showing an increase in UFP number concentrations as the mean diameter gets smaller and vice-versa. There could be two possible explanations for this trend. Firstly, the UFP number concentrations in the UFP size range are higher when the count mean diameters are smaller during periods with high vehicular emissions. Likewise, lower UFP concentrations at the time of larger count mean diameter could be caused by a substantial amount of smaller nucleation mode particles (<50 nm) which are likely to coagulate and get adsorbed onto the surface of already existing particles in the accumulation size range (Mäkelä et al., 1997). The overall mean particle diameter in our study area was ~50 nm during the entire sampling period.

3.3. Spatio-temporal variations of UFP number concentrations at different sites

Table 2 provides a comprehensive summary of all the UFP measurements made over the entire one month sampling period (except for the VMM site, where only data for 1 week was available). Between brackets, corresponding numbers for the one-week period are shown. For the one week period, maximum mean UFP concentrations were found at the Dis site, followed by the KB, PlMl and VMM sites, respectively. The variation between the highest and the lowest mean UFP concentrations was 35% within the grid area, showing similar UFP concentrations at the lower end (i.e. ranging between 18,181 cm^{-3} at the VMM and 24,460 cm^{-3} at the Dis). However, when comparing the one-month sampling campaign at the three sites other trends are observed. Highest concentrations are observed at PlMl (23,219 cm^{-3}) and lowest at KB (21,586 cm^{-3}), corresponding to the relative traffic intensities.

For the one month data the mean diameters at three sites followed the opposite trend in comparison to the mean UFP concentrations; lowest value (48 nm) at PlMl and the highest (52 nm) at the Dis. The inter quartile range at the four sites during the one week period were lowest at the PlMl and VMM (10,728 and 8967, respectively), 11,617 at KB and highest at Dis (13,091). The coefficient of variance (CV) of UFP concentrations does not follow the same trend as the inter quartile range (i.e. highest, 63, at PlMl and the lowest at Dis).

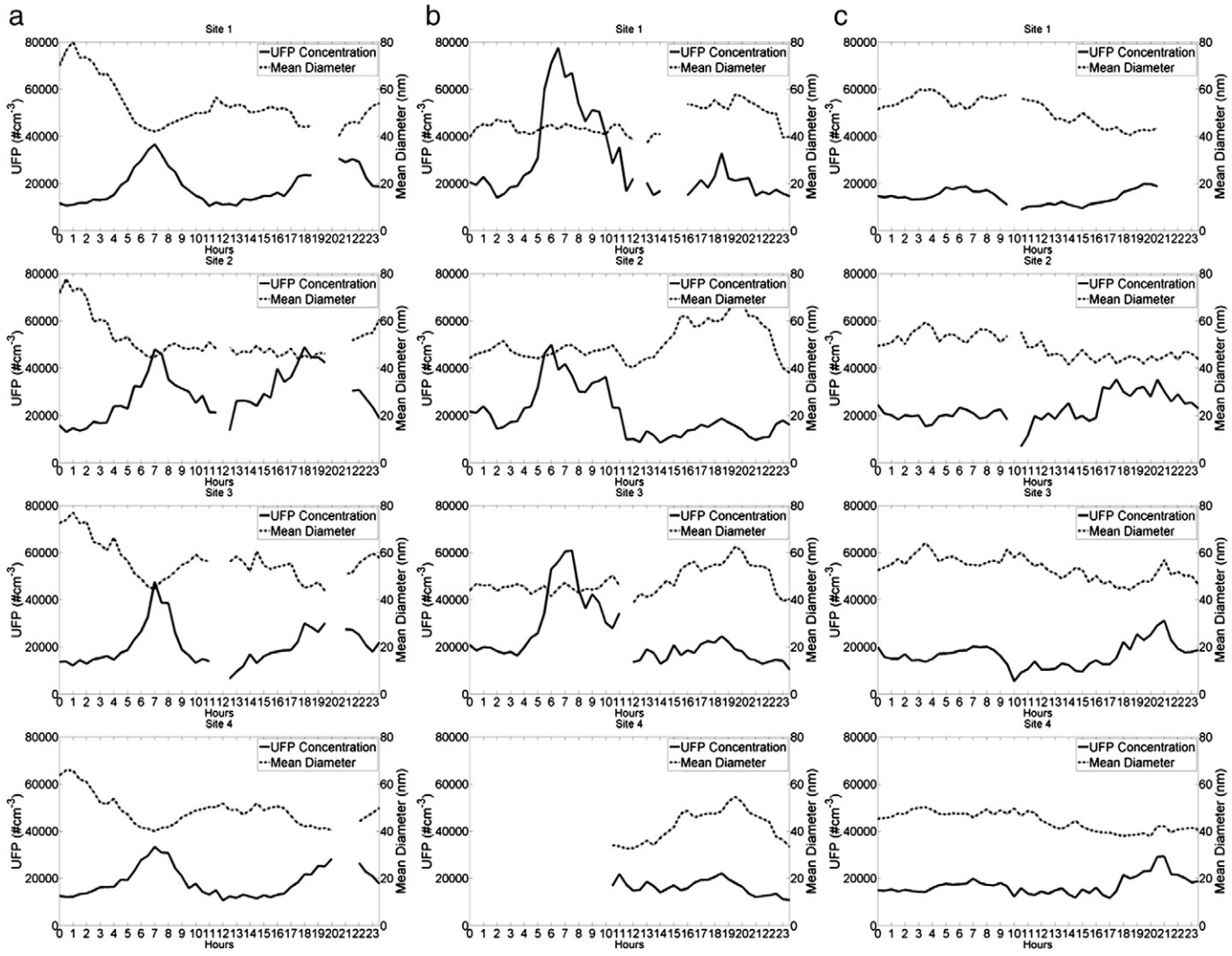

Fig. 3. Typical diurnal trend of UFP number concentration and particle mean diameters on (a) 9th March 2010, (b) 5th March 2010, and (c) 7th March 2010 at the sites PlMl (site 1), Dis (site 2), KB (site 3), and VMM (site 4).

A closer inspection of the UFP concentration trends, inter quartile ranges and the CV shows that traffic volume was not the only deciding factor in the variations of the UFPs at the chosen sites, this was also the distance from the moving traffic and the wind direction. The pair of sites with the same traffic volume (PlMl and VMM) shows similar concentrations for the one week period. However, at

Table 2
Summary of UFP number concentrations measured at different sites in a Belgian city, Borgerhout (Antwerp).

Instrument used (measured metric; unit)	Sites	Mean	Std. dev.	Median	Min.	Max.	Lower quartile	Upper quartile	Coefficient of variance	N*
Nano-Check (UFP concentrations; # cm^{-3})	1 (PlMl)	23,219 (20,015)	14,129 (12,628)	19,517 (16,145)	2528 (4795)	87,210 (77,496)	13,703 (12,132)	28,883 (22,860)	61 (63)	1295 (324)
Nano-Check (UFP concentrations; # cm^{-3})	2 (Dis)	22,810 (24,460)	12,934 (11,839)	20,628 (22,813)	1768 (4969)	88,004 (88,004)	13,190 (17,035)	29,316 (30,126)	57 (48)	1292 (317)
Nano-Check (UFP concentrations; # cm^{-3})	3 (KB)	21,586 (20,497)	11,249 (10,470)	19,278 (17,859)	2168 (5375)	80,355 (60,870)	13,866 (13,623)	27,486 (25,240)	52 (51)	1279 (316)
Nano-Check (UFP concentrations; # cm^{-3})	4 (VMM)	NA (18,181)	NA (9421)	NA (16,335)	NA (4639)	NA (69,208)	NA (12,663)	NA (21,630)	NA (52)	NA (301)
Nano-Check (UFP mean diameter; nm)	1 (PlMl)	48 (49)	8 (8)	46 (48)	28 (29)	80 (80)	42 (44)	53 (54)	16 (16)	1295 (324)
Nano-Check (UFP mean diameter; nm)	2 (Dis)	52 (50)	9 (7)	50 (49)	32 (32)	96 (78)	46 (45)	57 (54)	18 (14)	1292 (317)
Nano-Check (UFP mean diameter; nm)	3 (KB)	51 (52)	8 (7)	49 (51)	29 (29)	80 (77)	44 (47)	56 (56)	16 (14)	1279 (316)
Nano-Check (UFP mean diameter; nm)	4 (VMM)	NA (45)	NA (6)	NA (44)	NA (28)	NA (66)	NA (41)	NA (49)	NA (14)	NA (301)

N*: number of data points.

Table 3
Average UFP number concentrations (# cm^{-3}) during the winds originating from the traffic sector and non-traffic sector. Wind is measured at meteorological station and site 3 for the entire period. In brackets are shown the number of points used to calculate the mean.

UFP number concentrations	Wind measured at meteorological station		
	Traffic sector	Non-traffic sector	Other sector
Site 1 (PlMl)	24,692 (488)	18,905 (522)	28,597 (285)
Site 2 (Dis)	18,802 (300)	31,094 (354)	20,096 (638)
Site 3 (KB)	20,225 (490)	19,852 (499)	26,865 (290)
Site 4 (VMM)*	56,217 (3)	17,102 (253)	21,706 (45)
UFP number concentrations	Wind measured at site 3 (KB)		
	Traffic sector	Non-traffic sector	Other sector
Site 3 (KB)	17,988 (154)	19,081 (308)	23,207 (817)
Site 3 (KB) broader wind sector**	22,707 (753)	19,046 (342)	NA

* Site 4 (VMM) only one week UFP data (5–12 March).
** Site 3 broader traffic sector = 270–135.

some days, concentrations are lower compared to sites that are located very close to the road but have less traffic, revealing that wind direction in relation to site orientation had a large effect.

At the VMM site (mean concentrations ~ 18,181 cm^{-3}) the distance between the moving traffic and the sampling location was only two thirds of the distance at PlMl (mean concentrations ~ 20,015 cm^{-3}). These observations are in contrast to those reported by Buonanno et al. (2009) where the UFP number concentrations were found to decrease by nearly 50% of the roadside values at about 30 m away from the highway. A smaller drop is expected in our case, compared to highway measurements, because of the limited dispersion of UFP number concentrations due to surrounding buildings (Kumar et al., 2008b, c; Buonanno et al., 2011) and the absence of the monitoring of short-lived nucleation mode particles (Carpentieri and Kumar, 2011). In addition, wind was mainly not coming from the road side at the time of simultaneous measurement at these locations.

3.4. Effect of synoptic wind direction on UFP levels

The measured UFP concentrations are compared to the measured synoptic wind direction at the meteorological central site and at the local station at site KB (see Table 3). The effect of wind direction was investigated by dividing the data into groups, namely traffic sector and non-traffic sector. The traffic sector was defined as 60° from perpendicular to the road as a conservative number. At locations very close to traffic, it can be expected that a broader wind sector influences the UFP number concentrations at the sampling site. The resulting traffic sectors were 180–250° (VMM and PlMl), 225–345° (Dis) and 330–90° (KB). The result of this comparison is shown in Table 3. In addition to regional wind direction, local wind direction at KB was also used for analysis.

The UFP concentrations at the PlMl site were found to be nearly 30% higher for winds coming from the traffic sector (~24,692 cm^{-3}) compared to winds coming from the non-traffic sector (~18,905 cm^{-3}), as shown in Table 3. As opposed to this trend the UFP concentrations at the Dis site were about 40% lower (i.e. 18,802 cm^{-3}) for winds coming from the traffic sector compared with the non-traffic sector winds (~31,094 cm^{-3}). For the KB site, UFP concentrations were found to be similar for non-traffic sector winds (19,852 cm^{-3}) compared with the traffic sector winds (20,225 cm^{-3}). For the one week that was measured at the VMM site, only three data points were within the traffic sector. However, more data points were just outside the non-traffic sector as discussed in Section 3.2. When comparing traffic and non-traffic sector, taking locally measured wind directions into account and using a broader traffic sector (270–135°) at site 3 (KB), UFP concentrations are 20% higher for the traffic sector (22,707 cm^{-3}) as compared to the non-traffic sector (19,046 cm^{-3}).

3.5. Cross-correlation of UFP

Inter-correlations between the UFP concentrations at different sites showed a significant relationship (i.e. R^2 values between 0.52 and 0.86; see Table 4). Likewise, the comparison of the mean diameters of UFP between the different sites showed mostly higher correlations (ranging between 0.6 and 0.84) than those found for the UFP concentrations.

The highly correlated pair of sites for UFP concentrations and count mean diameter was PlMl and VMM with a R^2 value of 0.86 and 0.84, respectively. These two sites were experiencing similar levels of traffic volume, which can explain the good correlation. Note that the data at the VMM site are only for one week sampling. However the correlations of both VMM (for one week) and PlMl (for one month) were higher for KB (0.79 and 0.74 respectively) than for Dis (0.55 and 0.52 respectively). As described earlier, the sampling locations at the KB site and the Dis site were situated in the parking space next to the moving traffic, with the Dis site experiencing a slightly higher level of traffic volume compared to the KB site. The possibility of fresh vehicular emissions (with smaller diameter of UFP) reaching the samplers at these sites was higher than that at the other locations. Despite the fact that these sites were experiencing about 10 times less traffic than the PlMl site (which was close to a major access road) they had similar UFP concentrations at some days.

The Pearson correlation coefficient between the VMM and other monitoring sites was 0.86, 0.79 and 0.55 for the PlMl, KB and Dis, respectively. These values are relatively close to +1 which indicates a reasonably good representativeness of the VMM station, except for the Dis site. The higher correlation between VMM and PlMl was probably because both of them were situated on the same road with similar traffic and microclimatic conditions (i.e. road orientation, height of buildings).

3.6. Representativeness of central monitoring station (VMM) for UFP levels within the grid

Table 5 shows the RMSD values for UFP for the individual sites. The RMSD values for UFP (ranging from ~0.38 to 0.71) was found to

Table 4
Correlation matrix (R^2) of 30 minute average UFP values measured using the Nano-Check at different sites in Borgerhout for UFP number concentrations (# cm^{-3}) and MD (mean diameter). The values in bold show R^2 values of more than 0.66.

Metric (site)	UFP; # cm^{-3} (PlMl)	UFP; # cm^{-3} (Dis)	UFP; # cm^{-3} (KB)	UFP; # cm^{-3} (VMM)	MD (PlMl)	MD (Dis)	MD (KB)	MD (VMM)
UFP; # cm^{-3} (1 PlMl)	1.00	0.52*	**0.75***	**0.86***				
UFP; # cm^{-3} (2 Dis)		1.00	**0.68***	0.55*				
UFP; # cm^{-3} (3 KB)			1.00	**0.79***				
UFP; # cm^{-3} (4 VMM)				1.00				
MD (1 PlMl)					1.00	**0.72***	**0.84***	**0.83***
MD (2 Dis)						1.00	**0.74***	0.60*
MD (3 KB)							1.00	**0.84***
MD (4 VMM)								1.00

* $p<0.005$.

Table 5
Root mean square difference (RMSD) values at different sites with respect to the VMM site for various pollutants.

	Site 1 (PlMl)	Site 2 (Dis)	Site 3 (KB)
UFP number concentrations	0.38	0.71	0.47
UFP mean diameter	0.42	0.67	0.40

be relatively low, and even less for mean count diameter (ranging from ~0.40 to 0.67), suggesting a reasonably good uniformity of exhaust emissions within the grid area. Lowest RMSD values for UFP number concentrations were for the PlMl site, showing the best representativeness among all sites. One of the key reasons was that the site is located ~450 m eastward on the same road as VMM.

Pearson correlation shown in the previous section indicated that all sites show a relative good correlation compared to the VMM monitoring station. The values are closer to +1 for PlMl and KB which indicates a reasonably good representativeness of the VMM station, compared to Dis site. Local traffic can increase the UFP number concentrations under certain conditions resulting in a poor representativeness of the monitoring station.

4. Summary and conclusion

The UFP concentrations were measured at 4 different sites within a 1 km^2 grid area in a Belgium city. All sites followed a similar diurnal pattern of UFP variation, but the site-specific variations due to local conditions, mainly traffic volume, were also clearly evident. Increased concentrations were observed during rush hours which, as expected, resulted in a substantial increase in the mean UFP concentrations at the different sites. The variation between the highest and the lowest mean UFP concentrations was 35%. Local traffic conditions reduced the level of correlation among different sites. Comparison of the sites experiencing similar traffic, but different dispersion conditions, suggested a profound influence on UFP concentrations. The key reasons bringing the differences in dispersion conditions between the sites were presumably due to different distances from the moving traffic, different heights of the street canyons, and the presence of open spaces next to the measurement sites.

The influence of wind direction within the grid was mixed. Taking into account regional meteo data did not show differences between the traffic and the non-traffic sector in a street canyon. However, a broader traffic sector taking into account regional wind directions showed increased UFP concentrations for the traffic sector. Conversely, increased concentrations are measured at PlMl site, which is more open, for the traffic sector using regional wind direction.

The representativeness analysis indicated a reasonably good representation of the sampling locations within the 1 km^2 grid area by the regional air quality monitoring station. However, one of the locations experiencing only local traffic showed different UFP concentrations under certain meteorological conditions, resulting in a worse correlation. This means that measuring UFP at the VMM-site can help studying their dynamics and the exposure assessment of the local populations within the sampling grid, however local variation exist. It is worth noting that this conclusion is only valid for the particles in the 25–300 nm size range, and the results might only be generalized with caution. Given the volatile nature of particles smaller than 25 nm, much larger variability within an urban area is expected which can consequently reduce the correlation coefficients among different sites. Simultaneous measurements of UFP number concentrations were conducted for short periods in this study. Further research is warranted to assess the contribution of traffic sources to average annual and peak hour concentrations.

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