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Spatial–temporal variations of particle number concentrations between a busy street and the urban background

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HIGHLIGHTS

- We evaluated spatial–temporal variations of PNC between a street and the background.
- We investigated the association between PNC and other variables at the street.
- Median PNC was 3 times higher at the street but correlated well with the background.
- PNC was strongly associated with traffic by-products such as black carbon.
- PNC at the street was highly dependent on wind direction.

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ABSTRACT

To estimate spatial–temporal variations of ultrafine particles (UFP) in Helsinki, we measured particle total number concentrations (PNC) continuously in a busy street and an urban background site for six months, using condensation particle counters (CPC). We also evaluated the effects of temperature, wind speed and wind direction on PNC, as well as the correlation between PNC and $PM_{2.5}$, PM_{10} and black carbon (BC) at the street. We found that on weekdays, hourly median PNC were highly correlated with BC ($r = 0.88$), moderately correlated with $PM_{2.5}$ ($r = 0.59$) and weakly correlated with PM_{10} ($r = 0.22$). Number concentrations at the street were inversely proportional to temperature and wind speed, and highly dependent on wind direction. The highest PNC occurred during northeastern winds while the lowest occurred during southwestern winds. As these wind directions are nearly perpendicular to the street axis, the formation of wind vortices may have influenced the dispersion of UFP in the site. Although the temporal correlation for PNC was moderately high between the sites ($r = 0.71$), the median concentration at the street was 3 times higher than the urban background levels. The results indicate that people living or passing by the busy street are exposed to UFP concentrations well above the urban background levels. Thus, the study suggests that urban microenvironments should be considered in epidemiological studies. In addition the results emphasize that regulations based solely on $PM_{2.5}$ and PM_{10} concentrations may be insufficient for preventing the adverse health effects of airborne particles.
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1. Introduction

Exposure to airborne particulate matter (PM) may trigger a series of adverse health effects, especially in the respiratory and cardiovascular systems (Dockery and Pope, 1994; Oberdörster et al., 2005). Particulate matter is size-classified as thoracic (PM_{10}, aerodynamic diameter < 10 μm), fine ($PM_{2.5}$, aerodynamic diameter < 2.5 μm) and ultrafine (UFP, aerodynamic diameter < 100 nm) (Kulkarni et al., 2011). Although the components and mechanisms underlying the toxicity of PM remain unclear, several studies suggest that inhaling a large number of UFP may independently contribute to the adverse health effects of airborne particles (Terzano et al., 2010; Song et al., 2011; Li et al., 2013). Because UFP are negligible in mass but dominant in number, current air quality regulations based on mass concentrations of $PM_{2.5}$ and PM_{10} are inadequate for controlling UFP concentrations.

Road traffic is a major source of UFP in urban areas. As these particles tend to concentrate close to the sources (Morawska et al., 2008), they are unevenly distributed in cities. Thus, people

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spending time near busy city centres, where traffic concentrates, are more likely to experience adverse health effects than people spending time for instance at urban background areas. Exposure levels may further increase in urban air pollution hotspots, such as busy street canyons, roads and tunnels. In a street canyon, the buildings flanking the street act as obstacles for the dilution of air pollutants into the atmosphere, favouring accumulation (Vardoulakis et al., 2003). Studies confirm that UFP concentrations in street canyons are often higher than the background levels (Mishra et al., 2012; Morawska et al., 2008). The spatial variability of UFP concentrations suggests that measurements from one single site may be insufficient to accurately estimate the exposure levels of the urban population, especially when regarding air pollution hotspots. Therefore, it is important to evaluate the variability of UFP concentrations, both spatially and temporally, within sites of the urban area. Several studies on spatial–temporal variations of UFP in Helsinki show high variability of absolute concentrations and moderate to high temporal correlation among sites of the metropolitan area (Buzorius et al., 1999; Hussein et al., 2005). In microenvironments such as street canyons, however, this pattern may vary. In a study in Germany, Tuch et al. (2006) reported weak temporal correlation of UFP concentrations between a street canyon and an urban background site only 1.5 km apart ($r = 0.30$, for 1-h means). Moreover, the UFP concentrations in the street canyon were approximately double of the urban background concentrations. Studies on spatial–temporal distributions of UFP regarding microenvironments such as street canyons are often based on short-term measurements (a few days or weeks) and temporal correlations are only rarely evaluated, especially in Helsinki. Pirjola et al. (2012) measured PNC and size distributions in three urban microenvironments (including the street evaluated in this study) and an urban background of Helsinki. Although Pirjola et al. (2012) provided valuable insights on local dispersion, temporal variations and size distributions of UFP, the measurements at the microenvironments only covered rush hours of two workdays. Moreover, temporal correlations were not investigated.

Our study aimed to evaluate temporal correlation and the contrast in absolute particle total number concentrations (PNC) between an air pollution hotspot and the urban background. For this purpose, we measured PNC simultaneously in a section of a busy street (Mannerheimintie 55–57) and an urban background (University of Helsinki–Kumpula campus) during the period of 20.01–10.06.2010, using condensation particle counters (CPC). The street is an important route to downtown Helsinki and this sector is among the most polluted sites monitored by the Helsinki Region Environmental Services Authority (HSY). In addition to spatial–temporal variations, we also investigated the effects of temperature, wind speed and wind direction on PNC concentrations and the correlation between PNC concentrations and $PM_{2.5}$, PM_{10} and black carbon (BC) at the street. Diurnal variations of PNC, NO, traffic, $PM_{2.5}$, PM_{10} and BC were also investigated.

2. Material and methods

2.1. Description of the sites

We measured at two sites of Helsinki between 20.01 and 10.06.2010. The street sector evaluated (Töölöntulli street canyon) is located at Mannerheimintie 55–57 (coordinates: 60°11'25.21 N, 24°54'56.60 E) (Fig. 1a and b), and is about 3 km northwest from downtown Helsinki. The instruments were placed in a container parked on the northern sidewalk. The station was surrounded by residential and commercial buildings (e.g.: restaurants), a disperse forest (300 m north), the seashore (800 m southwest) and two gas stations (70 m east and 300 m west (Fig. 1b)). The street sector is about 40 m wide and flanked by 21 m high buildings (HSY, 2011) ($H/W = 0.53$). On the northern sidewalk, the buildings form a continuous wall parallel to the street. On the southern sidewalk, the buildings are perpendicular and there are gaps between them (courtyards and trees) (Fig. 1b). Although the gaps on the southern side may improve ventilation compared to a typical street canyon, the combination of street geometry and high traffic intensity result in accumulation of pollutants in the site. For this reason, the site is often considered a street canyon (e.g.: HSY, 2011; Pirjola et al., 2012).

The street has four traffic lanes and two tramway tracks. The traffic intensity was about 44 400 vehicles per workday in 2010 (about 10% heavy duty) (HSY, 2011). The speed limit in the site was 50 km h^{-1}. However, during rush hours the traffic speed may decrease considerably ($\sim$20 km h^{-1}) (Hellman, 2011). The closest intersection (19 400 vehicles per workday (HSY, 2011)) and traffic lights were about 40 m away.

The urban background station (Fig. 1a) is located at the University of Helsinki (Kumpula campus), which is about 4 km northeast from downtown Helsinki and 3 km northeast from the street canyon. The aerosol particles were measured in a container located on a rocky hill, 26 m above sea level (60°12′10.34 N, 24°57′40.26 E). The site is surrounded by residential and university buildings, parking lots ($\sim$10 m away), a disperse forest and a busy road leading to downtown ($\sim$100 m east) (Aalto et al., 2005).

2.2. Instrumentation

Particle total number concentrations (PNC) in the street canyon were measured using a Grimm butanol condensation particle counter (CPC) Model 5.401, with detection limit from 5 nm to >3 μm. The sampling line comprised of a 2 m long stainless steel (SS) tube (inner diameter (i.d): 48 mm), and the flow rate was 0.3 l min^{-1}. A silica gel diffusion dryer (Topas) was used to remove humidity from the air. In the urban background station, PNC were measured using a TSI 3022 butanol CPC with detection limit from 7 nm to >3 μm. The sampling line consisted of a 5 m long centreline (SS tube; i.d: 25 mm), connected to a 0.1 m SS tube (i.d: 4 mm), a 1.0 m long conductive silicone tube (i.d: 6 mm) and a silica gel diffusion dryer (Topas). An additional 0.5 m silicone tube connected the dryer to the CPC. The flow rate was 50 l min^{-1} in the centreline and 1.5 l min^{-1} in the remaining tubes and CPC. Due to the high flow rate, the diffusion losses in the centreline are negligible. In both sites, the samples were collected 4 m above the ground and the data was averaged per minute. Although the CPCs were not compared prior to the experiment, both instruments were calibrated. The Grimm CPC was calibrated once a year by the manufacturer and the TSI CPC was calibrated once a year following the method described in Aalto et al. (2005). Thus, despite the instrumental differences, the results should be fairly comparable. The CPC instruments do not provide information on particle size. However, it is well-documented that UFP dominate over 80% of the size distributions in traffic influenced areas (Morawska et al., 2008). In Mannerheimintie street about 80–94% of the particles are below 40 nm in diameter (Pirjola et al., 2006). Thus, the use of the CPC for estimating UFP concentrations is reasonable.

Nitrogen monoxide (NO), black carbon (BC), $PM_{2.5}$ and PM_{10} concentrations were only evaluated at the street. NO was measured using a Horiba APNA 370 instrument with detection limit of 0.5 ppb. The sampling line comprised of a 2 m long SS tube (i.d: 40 mm) connected to a 1 m Teflon tube (i.d: 4 mm). The results were reported as 20 °C, as requested by European air quality guidelines (Directive 2008/50/EC).

BC was measured with a Thermo Electron Corporation Multi Angle Absorption Photometer (MAAP) with detection limit of

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