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Spatio-temporal variation of urban ultrafine particle number concentrations

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HIGHLIGHTS

- Spatial variation of short-term (20-min) UFP concentration was assessed in Basel.
- Hybrid models were built to predict UFP levels on sidewalks.
- The main predictor (explained ≤50%) was the suburban background UFP level.
- Best models included both GIS variables and field observations ($R^2 = 0.7$).
- Concurrent UFP on the sidewalks and nearby residences correlated well ($R^2 = 0.8$).

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ABSTRACT

Methods are needed to characterize short-term exposure to ultrafine particle number concentrations (UFP) for epidemiological studies on the health effects of traffic-related UFP. Our aims were to assess season-specific spatial variation of short-term (20-min) UFP within the city of Basel, Switzerland, and to develop hybrid models for predicting short-term median and mean UFP levels on sidewalks. We collected measurements of UFP for periods of 20 min (MiniDiSC particle counter) and determined traffic volume along sidewalks at 60 locations across the city, during non-rush hours in three seasons. For each monitoring location, detailed spatial characteristics were locally recorded and potential predictor variables were derived from geographic information systems (GIS). We built multivariate regression models to predict local UFP, using concurrent UFP levels measured at a suburban background station, and combinations of meteorological, temporal, GIS and observed site characteristic variables. For a subset of sites, we assessed the relationship between UFP measured on the sidewalk and at the nearby residence (i.e., home outdoor exposure on e.g. balconies). The average median 20-min UFP levels at street and urban background sites were 14,700 ± 9100 particles cm^{-3} and 9900 ± 8600 particles cm^{-3}, respectively, with the highest levels occurring in winter and the lowest in summer. The most important predictor for all models was the suburban background UFP concentration, explaining 50% and 38% of the variability of the median and mean, respectively. While the models with GIS-derived variables ($R^2 = 0.61$) or observed site characteristics ($R^2 = 0.63$) predicted median UFP levels equally well, mean UFP predictions using only site characteristic variables ($R^2 = 0.62$) showed a better fit than models using only GIS variables ($R^2 = 0.55$). The best model performance was obtained by using a combination of GIS-derived variables and locally observed site characteristics (median: $R^2 = 0.66$; mean: $R^2 = 0.65$). The 20-min UFP

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concentrations measured at the sidewalk were strongly related ($R^2 = 0.8$) to the concurrent 20-min residential UFP levels nearby. Our results indicate that median UFP can be moderately predicted by means of a suburban background site and GIS-derived traffic and land use variables. In areas and regions where large-scale GIS data are not available, the spatial distribution of traffic-related UFP may be assessed reasonably well by collecting on-site short-term traffic and land-use data.

1. Introduction

In European cities, a large fraction of the population lives very close to major traffic arteries (Perez et al., 2013). These residential locations are exposed to various traffic-related stressors, including traffic noise, fresh exhaust-related emissions such as toxic nanoparticles or ultrafine particles (UFP, particles <100 nm), and coarse particles from brake and tire abrasion or re-suspended road dust. All of these stressors may affect health through various, partially interlinked pathways (Foraster, 2013; Foraster et al., 2014a, 2014b).

Previous investigations have shown high spatial and temporal variability of UFP number concentrations in urban environments and have documented the dependence of UFP levels on traffic volume, the built environment and meteorological characteristics (Boogaard et al., 2010; Hoek et al., 2011; Morawska et al., 2008; Ragettli et al., 2013; Rivera et al., 2012). The distance to the source of emissions is a major determinant of UFP levels in urban areas (Hagler et al., 2010; Zhou and Levy, 2007), while the distribution of UFP is often affected by physical constraints such as trees or buildings in the vicinity (Fuller et al., 2012). For traffic counts as well as noise, short-term measurements of 15–20 min have been shown to be sufficient for characterizing and modeling long-term exposure conditions (Allen et al., 2009; van Roosbroeck et al., 2007). The time and cost benefits of such a measurement protocol makes it appealing for measuring also UFP concentrations, which are unregulated and, therefore, rarely monitored.

One cost-effective method of predicting UFP levels would be to use models based on commonly available information on land use and traffic volume. A few studies have applied land use regression (LUR) modeling, using UFP measurements and variables derived from geographic information systems (GIS) to characterize long-term average UFP concentrations for a particular city (Abernethy et al., 2013; Hoek et al., 2011; Rivera et al., 2012). However, spatio-temporal assessments of UFP levels have rarely been done, and the use of short-term measurement protocols to predict short-term number concentrations has not been further evaluated.

The tri-national study, Tri-Tabs (Projet Tri-national Trafic, Air, Bruit et Santé), aimed to identify and compare the spatial characteristics of UFP and traffic-related noise, by measuring short-term (20 min) traffic-related noise, UFP levels, and local traffic density along sidewalks in three European cities (Basel, Switzerland; Girona, Spain; and Grenoble, France) and to investigate the correlation and applicability of these variables to long-term exposure assessments. The current analysis is based on the Basel data of the Tri-Tabs study. We aimed to both assess the season-specific spatial variation of short-term (20-min) UFP number concentrations along sidewalks in the city of Basel, and to subsequently develop models using observed site-specific characteristics, GIS-derived traffic and land-use parameters, and data from one fixed monitoring site to predict the spatial distribution of short-term UFP levels. We also assessed the correlation between the 20-min UFP measurements taken from the sidewalk and the 20-min UFP measurements taken nearby at the same address but directly outside of the homes such as on the balcony, thus, representing the concentrations in front of the windows or doors where people are living. Such “home outdoor” measurement sites at the building façade are commonly used in epidemiological studies on the health effects of traffic-related air pollution to characterize people's exposure. However, if one could use sidewalk data instead, it could have major advantages for exposure assessment studies. Measurements taken at street sites are rather simple as there is no need to require access to private space. Even so, in light of the small-scale spatial variation of UFP, sidewalk measurements may not be sufficient to characterize exposure at the façade.

2. Methods

2.1. Study location

Ultrafine particles, traffic volume and other site characteristics were monitored across the city of Basel, Switzerland (Fig. 1). The city, located in the Rhine valley, has about 192,000 inhabitants and is characterized by average temperatures between 3 °C and 6 °C in the winter, and between 21 °C and 25 °C in the summer. The city (approx. 37 km^2) has a high building density, with buildings usually consisting of three to five stories, and a population density of approx. 5000 inhabitants per km^2. The region is a relatively low-pollution area with an annual mean PM_{10} (particle matter, particles smaller $\leq$ 10 μm) suburban background concentration of 18 μg m^{-3} in 2011. However, due to considerable regional traffic, annual air pollution levels along busy streets (PM_{10}: 27 μg m^{-3}; NO_2: 61 μg m^{-3}) are above the limit values.

2.2. UFP measurements and traffic monitoring

Short-term measurements of UFP number concentrations and traffic volume were carried out as part of the Tri-Tabs project. Monitoring was performed for 20 min on the sidewalk at 60 locations. The sites were selected to capture city-specific, traffic-related air pollution characteristics and were geographically well distributed across the city. Three types of monitoring sites were established: street-level, urban background, and regional background. Site selection was based on pre-defined criteria – similar to those in Cyrys et al. (2012) – related to the distance to major roads, street density, building density and population density (see Table 1). The national street network (VECTOR25, 2008) from the Swiss Federal Office of Topography (swisstopo) was used for the analysis. A major road was defined as a highway or main road (first and second class streets) with a width larger than 4 m and traffic running in both directions. Maps of the population density and building density were obtained from the Statistical Office Basel City.

All 20-min measurements were performed during non-rush hours (9:30–16:00), to represent the long-term traffic mean (van Roosbroeck et al., 2007) and site-specific UFP concentrations (Diapouli et al., 2007). Monitoring took place on different (non-rainy) days and at various times at up to six sites per day. Monitoring was repeated in three seasons in 2011, given that spring and fall are quite similar in terms of air quality: spring (March 25–April 18), summer (June 2–June 30) and winter (November 25–December 19). The number of light, heavy and motorcycle