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Statistical modelling of particle number concentration in Zurich at high spatio-temporal resolution utilizing data from a mobile sensor network

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HIGHLIGHTS

- Computation of highly resolved 30 min particle number concentration maps for the city of Zurich.
- Statistical models utilizing PNC data from a mobile sensor network and geoinformation.
- Maps revealing the high spatio-temporal variability of PNC in the urban environment.
- Route finding algorithm as an example for PNC map based applications.

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ABSTRACT

Highly resolved pollution maps are a valuable resource for many issues related to air quality including exposure modelling and urban planning. We present an approach for their generation based on data from a mobile sensor network and statistical modelling.

An extensive record of particle number concentrations (PNCs) spanning more than 1.5 years was compiled by the tram-based OpenSense mobile sensor network in the City of Zurich. The sensor network consists of 10 sensor nodes installed on the roof of trams operating on different services according to their regular operation schedules. We developed a statistical modelling approach based on Generalized Additive models (GAMs) utilizing the PNC data obtained along the tram tracks as well as georeferenced information as predictor variables. Our approach includes a variable selection algorithm to ensure that individual models rely on the optimal set of predictor variables. Our models have high temporal and spatial resolutions of 30 min and 10 m by 10 m, respectively, and allow the spatial prediction of PNC in the municipal area of Zurich.

We applied our approach to PNC data from two dedicated time periods: July–Sept. 2013 and Dec. 2013–Feb. 2014. The models strongly rely on traffic related predictor variables (vehicle counts) and, due to the hilly topography of Zurich, on elevation. We assessed the model performance by leave-one-out cross-validation and by comparing PNC predictions to measurements at fixed reference sites and to PNC measurements obtained by pedestrians. Model predictions reproduce well the main features of the PNC field in environment types similar to those passed by individual trams. Model performance is worse at elevated background locations probably due to the weak coverage of similar spots by the tram network.

We end the paper by outlining a route finding algorithm which utilizes the highly resolved PNC maps providing the exposure minimal route for cyclists.

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1. Introduction

Particle number concentration (PNC) in ambient air has obtained increased attention in recent time. The number distribution of ambient particles is clearly dominated by particles with a

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diameter less than 300 nm (Kumar et al., 2010). Particles, especially those of the smallest size fraction, potentially impair human health.

Ambient particles can be of primary origin (e.g. combustion processes) or result from secondary formation (e.g. atmospheric photochemistry, condensation of semi-volatile vapours). In many cities, road vehicles are the dominant source of ambient particles. Contributions from other sources such as combustion by-products from industries, ship exhausts, construction works, cooking, biomass burning, sea spray and photochemical nucleation are less important in general (Heal et al., 2012; Kumar et al., 2010).

The effect of ultrafine particles (UFPs; often defined as particles with a diameter less than 100 nm) on human health is being intensively investigated, particularly due to the increasing use of engineered nanoparticles (nanotechnologically produced solid particles). Recent studies point out that inhaled UFPs may enter the lung tissues and systemically spread in the human body reaching many organs including the heart, liver, kidneys and brain (Heal et al. (2012); Cassee et al. (2013), and references therein). Health effects caused by ultrafine particles in ambient air have been investigated in several studies. However, their findings are not consistent concerning the impact (Heal et al. (2012), and references therein). This might be related to difficulties in obtaining accurate personal UFP exposure estimates as required in epidemiological studies.

Routine monitoring programs for ambient PNC are less comprehensive than for particle mass, addressed e.g. by PM2.5 and PM10 (mass of particles with a diameter less than 2.5 μm and 10 μm, respectively). One reason for this is that PNC is not regulated, i.e. ambient limit values do not exist. However, the spatial and temporal variability of PNC is considerably higher than for particle mass, especially in cities with small-scale variances in source activities (e.g. traffic) and the density of the built environment. Therefore, a small number of highly precise and costly PNC measuring instruments yields accurate time-series but information about the spatial variability remains limited. Nevertheless, PNC is at one site permanently measured in Zurich.

Options for improving the knowledge of the small-scale PNC field are the use of a larger number of instruments and mobile measurement platforms. Several studies discuss the development of mobile platforms for the measurement of PNC and point out the spatial variability of the concentration field in urban environments (Bukowiecki et al., 2002, 2003; Kittelson et al., 2004; Pirjola et al., 2004; Weijers et al., 2004). Kehl (2007) and Hagemann et al. (2014) explored the potential of tram-based measurements of air pollutants including particulate matter in Zurich and Karlsruhe, respectively. In principle, by installing a sensor box on top of a tram Kehl (2007) used a similar measuring concept as applied in this study. Utilizing the vehicle fleet of a public transport company is a feasible component of an operational system for long-term routine measurements.

Progress in instrument and sensor technology has yielded enhanced devices with respect to usability, cost and size (Fierz et al., 2011; Mead et al., 2013). These developments lead to viable sensor networks. In the framework of the OpenSense project initiated in 2012 a mobile sensor network has been developed and maintained in the city of Zurich (Hasenfratz et al., 2015). This effort resulted in an extensive record of PNC data spanning about 1.5 years (~50 million samples).

Several methods have been applied to derive pollutant concentration fields from measurements (e.g. Jerrett et al., 2005). A widespread approach is statistical modelling, and in particular land-use regression (LUR) modelling. LUR models assume a (linear) dependency of the pollutant concentration on spatial predictors (Briggs et al., 1997; Hoek et al., 2008). Typically, existing LUR models are based on measurements obtained during campaigns and yield seasonal or annual mean concentrations. Such LUR models for the UFP number concentration were presented by Abernethy et al. (2013); Hoek et al. (2011); Ragettli et al. (2014); Rivera et al. (2012); Sabaliaukas et al. (2015); Saraswat et al. (2013).

PNC maps for Zurich with seasonal to semi-diurnal resolution have been derived based on the PNC data set of the OpenSense network using LUR (Hasenfratz et al., 2015) and Gaussian Process Models (Li et al., 2014). Both models employed a spatial resolution of 100 m by 100 m.

In this study, we generate PNC maps with 10 m by 10 m spatial and 30 min temporal resolution based on statistical modelling utilizing measurements from the OpenSense mobile sensor network and georeferenced data. We selected two time periods directly succeeding instrument maintenance for our study: July 2013 to September 2013 and December 2013 to February 2014. Our study explores the potential of statistical models to reveal small-scale differences in PNC in the urban environment.

2. Data and methods

2.1. Modelling domain

The modelling domain comprises the municipal area of Zurich (91.9 km^2) which is located in the Swiss plateau at the northern end of lake Zurich (Fig. 1). Elevation in this domain ranges from 390 to 870 m a.s.l. Zurich had a population of 398′575 in 2013. Its urban area is dominated by service industry and residential areas. There are no heavy industry and only few industrial emission sources. Woodlands and agricultural areas make up more than 25% of the municipal area.

2.2. Particle number concentration (PNC) data

2.2.1. Tram-based PNC measurements

The PNC measurements used in this study were obtained by the OpenSense mobile sensor network (Li et al., 2012; Hasenfratz et al., 2015). This network was initially deployed in July 2012 and extended from 5 to 10 sensor nodes in January 2013. The sensor

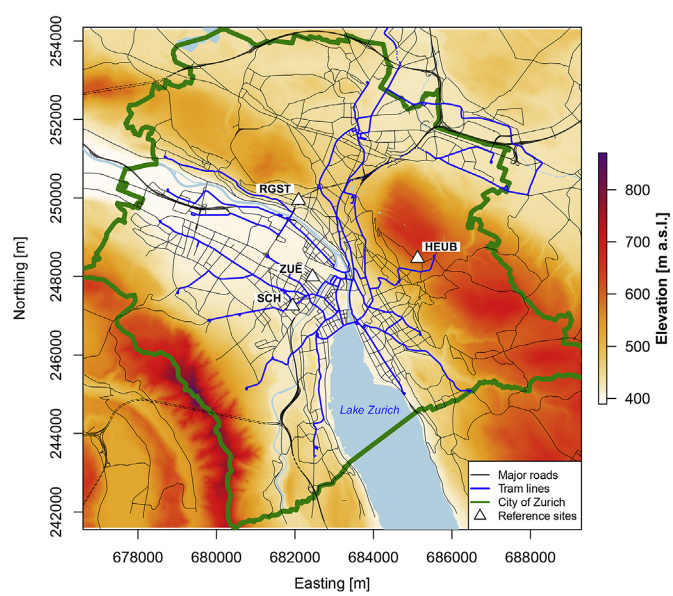

Fig. 1. Map of the municipal area of Zurich. The white triangles depict the locations of the permanent monitoring sites (Table 1). The reddish colors depict elevation above sea level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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