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Using advanced dispersion models and mobile monitoring to characterize spatial patterns of ultrafine particles in an urban area

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ABSTRACT

In urban settings with elevated bridges, buildings, and other complex terrain, the relationship between traffic and air pollution can be highly variable and difficult to accurately characterize. Atmospheric dispersion models are often used in this context, but incorporating background concentrations and characterizing emissions at high spatiotemporal resolution is challenging, especially for ultrafine particles (UFPs). Ambient pollutant monitoring can characterize this relationship, especially when using continuous real-time monitoring. However, it is challenging to quantify local source contributions over background or to characterize spatial patterns across a neighborhood. The goal of this study is to evaluate contributions of traffic to neighborhood-scale air pollution using a combination of regression models derived from mobile UFP monitoring observations collected in Brooklyn, NY and outputs from the Quick Urban & Industrial Complex (QUIC) model. QUIC is a dispersion model that can explicitly take into account the three-dimensional shapes of buildings. The monitoring-based regression model characterized concentration gradients from a major elevated roadway, controlling for real-time traffic volume, meteorological variables, and other local sources. QUIC was applied to simulate dispersion from this same major roadway. The relative concentration decreases with distance from the roadway estimated by the monitoring-based regression model after removal of background and by QUIC were similar. Horizontal contour plots with both models demonstrated non-uniform patterns related to building configuration and source heights. We used the best-fit relationship between the monitoring-based regression model after removal of background and the QUIC outputs ($R^2 = 0.80$) to estimate a UFP emissions factor of 5.7×10^{14} particles/vehicle-km, which was relatively consistent across key model assumptions. Our joint applications of novel techniques for analyzing mobile monitoring data and the advanced dispersion model QUIC provide insight about source contributions above background levels and spatiotemporal air pollution patterns in urban areas.

1. Introduction

In the urban environment, it can be challenging to accurately estimate the contribution of local sources to ambient pollutant concentrations. This is especially true for ultrafine particulate matter (UFP), particles less than 0.1 μm in diameter, which have been increasingly associated with adverse health outcomes (Cho et al., 2009; Belleudi et al., 2010). Traditional line-source dispersion models often have great difficulty modeling concentrations of traffic-related air pollutants such as UFP in urban terrain (Briggs et al., 2000). This is both because advection and dispersion are strongly influenced by buildings (Britter and Hanna, 2003) and because of difficulties in accounting for the contributions from areas upwind (Jensen et al., 2009). Dispersion models (Gidhagen et al., 2005) and land-use regression models (Hoek et al., 2011) have been applied to model UFP concentrations, but they cannot take into account the influence of buildings found in complex urban environments.

An alternative approach for characterizing UFP in urban areas involves application of the Quick Urban & Industrial Complex (QUIC) dispersion modeling system. QUIC is a relatively fast response (on the order of minutes to hours) model that is designed to account for the effects of buildings, in part through the incorporation of specific building geometries (Nelson and Brown, 2010). QUIC has speeds and complexities in between the Gaussian model and a computational fluid dynamic (CFD) model. QUIC has been

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shown to have comparable results to CFD models applied to tracer gas observations in field experiments in Manhattan (Brown et al., 2010). QUIC includes a 3D wind field model based upon the ideas of Röckle (1990), in which the flow around buildings is explicitly addressed in a manner that ensures conservation of mass (Singh et al., 2008). These outputs are linked with a Lagrangian random-walk model, which simulates the movement of gases and aerosols while also calculating the concentration and deposition fields around buildings (Williams et al., 2004; Brown et al., 2010; Singh et al., 2008).

In spite of the potential utility of QUIC, it has rarely been applied to traffic pollution problems in urban settings. One study looked at the impacts of a long roadside sound barrier on UFP concentrations in North Carolina (Bowker et al., 2007). This study captured the effects of traffic and obstacles, but in a less-urban setting (a freeway in a suburban area with a mix of detached houses, sound barriers, and vegetation). Fernando et al. (2010) did apply QUIC to the problem of traffic emissions in a city, comparing stationary measurements of PM_{10} in an urban environment to QUIC-simulated concentrations, finding generally good agreement. However, as far as we are aware, no studies to date have applied QUIC in an urban area with some street canyons to evaluate spatial patterns of UFP concentrations.

Even with application of QUIC, there are significant challenges in characterizing UFP emissions, which can vary significantly between neighborhoods, streets, times, and vehicle mixes. Traditionally, emissions factors (EFs) based on dynamometer studies are widely used, but are now thought to be under-predicting real-world emissions, given the influence of vehicle fuel types, speed, and other factors (Jamriska and Morawska, 2001). Studies have been conducted to calculate UFP EFs under real-world conditions, with estimates ranging from approximately 2.1–13.5 $\times$ 10^{14} particles/vehicle-km (Imhof et al., 2005; Wang et al., 2010; Jamriska and Morawska, 2001; Birmili et al., 2009; Gramotnev et al., 2003). The variability in these estimates may reflect differing methodologies or sampling approaches, or could represent true variation as a function of vehicle mix and other site characteristics. There are also inconsistent conclusions about the relative emissions under urban start and stop conditions versus other traffic conditions, and little work has been published on US-specific EFs.

When emissions are highly uncertain, or there are limited data about them, in situ monitoring studies can be used to either calibrate dispersion models or to directly assess spatial patterns of concentrations in urban environments. These studies generally rely on a few stationary monitors to characterize concentrations in an area, providing limited ability to characterize the spatial patterns of contributions from a local pollutant source. Recently, short-term (a few days or weeks) mobile-monitoring studies using pedestrians (Zwack et al., 2011; Buonocore et al., 2009; Kaur et al., 2007) and vehicles (Baldauf et al., 2008; Westerdahl et al., 2009) have been conducted in urban areas to characterize spatial patterns of mobile-source air pollutants. However, it remains challenging to use monitoring studies alone to predict source contributions in unmonitored locations or time periods, and a hybrid monitoring-dispersion modeling strategy may be necessary to address UFP spatial patterns in an urban area.

In this study, our goal was to use a combination of mobile monitoring and dispersion modeling to characterize spatial patterns of UFPs and local source contributions in an urban area. We conducted a field monitoring campaign in Brooklyn, New York, in an area impacted by major roadways, and created a regression model to predict concentrations of UFPs and the gradient from a major elevated roadway. We also applied the QUIC dispersion model to this same area and major roadway, and used the best-fit relationship between the dispersion model and our monitoring-based regression model outputs to estimate an emissions factor for UFPs on the roadway. To our knowledge, this is the first attempt to use these approaches jointly to estimate UFP emissions and concentration patterns in an urban area.

2. Methods

2.1. Study area and monitoring equipment

The study area was located in the Williamsburg neighborhood of Brooklyn and was part of the New York Metropolitan Exposure to Traffic Study (NYMETS). It had dimensions of approximately 550 m (North-South) by 700 m (East-West), and consisted of the area north of the Williamsburg Bridge (WB) and west of the Brooklyn-Queens Expressway (BQE) (Fig. 1). This area was chosen as it was primarily impacted by the WB, and was small enough to be computationally practical within QUIC. The portion of the zone modeled in the current study was a sub-section representing approximately 25% of the larger study area that was monitored.

The monitoring protocol and statistical methods were fully described previously by Zwack et al. (2011), but are briefly described as follows. A 3-week mobile monitoring campaign was conducted in June 2007. A mobile monitoring protocol that included carrying the instruments in backpacks was designed to ensure thorough spatial coverage of the study area. Three sets of monitoring equipment were simultaneously deployed during an approximately 3 h monitoring session with one morning (approximately 9 AM–12 PM) and one afternoon session (approximately 2 PM–5 PM) per day. Model 3781 Water-based Condensation Particle Counters (WCPCs) were used (TSI, Minneapolis, MN) to measure 1-min averaged concentrations of UFPs. The 3781 WCPC can measure particle sizes down to 6 nm (TSI Incorporated, 2007); while it captures some particles larger than 100 nm, these would make minor contributions to total particle counts. The WCPCs were powered using small lead-acid batteries.

GPS devices were used to record the location of the backpack in both space and time. Other parameters recorded included temperature, relative humidity (RH), wind speed, wind direction, and traffic counts on the two major sources impacting this monitoring area, the BQE and the WB. Temperature and RH were measured using a HOBO Pro data logger (ONSET Computer Corporation, Bourne, MA). Wind speed and direction were continuously recorded over the entire study period using a WeatherWizard III weather station (Davis Instruments Corp., Hayward, CA) that was deployed on a 3-m mast above the roof of a three story apartment building inside of the monitoring zone (Fig. 1). Traffic was recorded on one lane in both directions on both the WB (width $\sim$ 36 m) and the BQE (width varying from $\sim$35–50 m) via automated traffic counters.

2.2. Monitoring-based regression model

The monitoring-based regression model used in this study was created using R version 2.10.1 (R Development Core Team, Vienna, Austria) along with version 1.6–1 of the *mgcv* package (Wood, 2006). Additive models incorporating the effects of traffic, distance to each source, wind speed, temperature and RH were created to assess the impacts of both the BQE and the WB simultaneously. The model was fit from the mobile monitored data using the *gamm* function of the *mgcv* library (using penalized regression splines with automatic smoothness estimation) and took the form of:

$$Y_i = \beta_0 + X_i\beta + f_{WB}(distance\ to\ WB_i) + f_{BQE}(distance\ to\ BQE_i) + f_s(s_i) + \varepsilon_i \quad (1)$$