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Spatial and temporal variability of air pollution in Birmingham, Alabama

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HIGHLIGHTS

- Spatial and temporal variations of outdoor air pollutant concentrations affect exposure.
- Interpolation of monitoring data can delineate spatial pollutant gradients in many urban areas.
- Pollutant gradients are defined more accurately using meteorological and co-pollutant data.
- No single monitor represents air quality throughout some urban areas.

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ABSTRACT

Quantification of the spatial and temporal variations of outdoor air pollutant concentrations provides important information for epidemiological and other air-pollution studies, many of which have relied in the past on data from a single, centrally-located air pollution monitoring site. A method is developed for combining air pollution measurements from multiple monitors and monitoring networks to generate daily air pollution concentration fields representing spatial variations over distances of approximately 1–10 km. Meteorological and co-pollutant data are used to estimate missing site measurements, yielding more realistic concentration fields as the number of monitoring locations with available data increases. Monitoring data are interpolated with weights computed from intersite pollutant correlations, which decay with distance, so distances between interpolation points and monitoring sites are factored into the interpolation weights. The approach minimizes the influence of source-oriented sites that represent limited areas, because data from such sites exhibit low intersite correlations and yield interpolation weights that decay rapidly to zero. Interpolated values represent pollutant concentrations averaged over spatial scales that depend on intersite distances and the interpolation grid, and do not delineate sharp spatial gradients associated with roadside or near-source conditions. The approach yields quantified interpolation errors the values of which depend on measurement uncertainties, intersite distances, and the representativeness of monitoring site locations. The method is illustrated using an 11-year period of measurements of ozone, $PM_{2.5}$, and PM_{10} concentrations from Jefferson County, Alabama. The principal city is Birmingham, which is influenced by regional-scale air pollution and by local emissions from mobile sources, industrial facilities, and residential communities. Emission sources are not distributed uniformly throughout Birmingham, the ridge-and-valley topography complicates dispersion of local emissions, and monitoring data indicate that air pollutant concentrations vary spatially as well as temporally. No single monitor represents air quality across the entire study area.

1. Introduction

Accurate measures of exposure are needed for epidemiological analysis of the effects of air pollution on human health. Personal exposure to air pollutants depends on many factors, especially including the amount of time spent indoors, the time spent in areas having high emissions of air pollutants, a person's daily movements, and the indoor and outdoor ambient concentrations occurring each day. The most direct approach to quantifying actual exposures is to use personal monitors for the pollutants of interest. However, personal monitoring methods are not available for many pollutants and some people find the monitors to be intrusive and

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awkward. Another approach is to measure ambient levels of pollutants and relate those concentrations to personal exposures using a model (e.g., Ott et al., 1988; Winer et al., 1989; Briggs et al., 2003). Due to the complexity of quantifying actual personal exposures and the lack of individual time-activity data in retrospective studies, many epidemiological studies of air pollution have used outdoor data obtained at one or more monitoring sites as a surrogate measure of exposure. An implicit or explicit assumption in such studies is that personal exposures are related mainly to ambient pollutant concentrations. Continuing efforts to improve quantitative exposure characterization have led to different approaches that use broadened outdoor monitoring combined with models (e.g., Mauderly and Wyzga, 2011).

Health effects (Brunekreef and Holgate, 2002) have been linked with proximity to sources such as vehicle traffic (e.g., Brunekreef et al., 1997; Wilkinson et al., 1999; Buckeridge et al., 2002; Hoek et al., 2002; Lee et al., 2010), leading to increased interest in air pollution data sets having spatial as well as temporal resolution. Health effects associated with within-city $PM_{2.5}$ gradients may be several times greater than estimated from models relying on comparisons between communities (Jerrett et al., 2005). Pollutant concentrations typically decay to ambient levels over distances on the order of a few hundred meters from highways, and special studies are typically needed to fully characterize roadside concentrations.

Coupling monitoring data with land-use information potentially captures proximity to roadways or other emission sources (e.g., Gilbert et al., 2005). Kanaroglou et al. (2005) develop a method for designing a dense network of air pollution monitoring stations and derive an exposure assessment model using monitoring data in conjunction with land use, population, and biophysical information. Different procedures for optimizing network design exist (e.g., Kumar, 2009; Kanaroglou and Jerrett, 2009). Marshall et al. (2003, 2005, 2006, 2008) combined monitoring data with modeling and additional information to spatially resolve exposures. Hogrefe et al. (2009) used an emissions-based air quality model to estimate gridded fields of $PM_{2.5}$ mass and species concentrations in conjunction with observational data, which models the dispersive characteristics of the atmosphere but remains limited to the grid-cell size of the model.

In general, monitoring networks are not specifically designed to provide data for use in epidemiological studies, as receptor locations are often intended to capture the maximum impacts from emission sources or are otherwise not optimal for exposure assessment (U.S. EPA, 2008a). Studies that have used outdoor air pollutant concentrations as a surrogate for exposure have often relied on the record from a single, centrally located monitoring site; this choice has sometimes depended on the availability of long-term, consistent air quality data. Data from a single, centrally-located air quality monitor may support an epidemiological study if the temporal variation of pollutant concentrations suffices to reveal statistically significant associations (Mulholland et al., 1998). Data from multiple air quality monitors can improve measurement accuracy and representativeness. For example, Ivy et al. (2008) interpolated data from multiple monitoring sites in Atlanta to census tracts, then recombined population-weighted interpolated values to create metrics more representative of air quality on an urban scale than were the original monitoring data. Biases associated with source-oriented monitoring data were reduced and the temporal completeness of the data record was improved (Ivy et al., 2008). $PM_{10-2.5}$ data from a short-term (three one-week sampling periods) network of 33 passive samplers located in Iowa City, and having a mean intersite distance of 4.4 km, were heterogeneous and indicated that spatially resolved data would reduce exposure misclassification, in comparison with data from a single, centrally-located monitor (Ott et al., 2008).

A new measurement-based approach is developed here that is potentially useful for areas where long-term data are available from multiple monitoring locations, but the monitoring networks are not as dense as a typical short-term saturation network. The method is illustrated using 1999–2009 ozone (O_3) and particle concentrations ($PM_{2.5}$ and PM_{10}) from Birmingham, Alabama, a city with complex terrain and meteorology, and a range of local emission sources that include major stationary sources, transportation, and residential and suburban areas. Previous work (Blanchard et al., 2006) indicates that parts of the city experience differing concentrations of air pollutants due to a large number of industrial facilities. Monitoring data are interpolated by using intersite pollutant correlations to determine interpolation weights and minimize the interpolation error variance. Missing measurements are estimated from meteorological and co-pollutant data, which improves the resolution of concentration fields compared with concentration fields that are determined without replacement of missing data. The method is designed to generate daily air pollution concentration fields representing spatial averages over distances of approximately 1–10 km, compatible with the spatial scale of representativeness of air quality monitoring sites and with the resolution of grid-based Eulerian models.

2. Methods

2.1. Measurements

Data were obtained from the EPA Air Quality System (AQS) (U.S. EPA, 2009), the archives of the Southeastern Aerosol Research Characterization network (SEARCH) (Atmospheric Research and Analysis, 2009; Edgerton et al., 2005, 2006; Hansen et al., 2003), and the archives of the Interagency Monitoring of Protected Visual Environments (IMPROVE) (IMPROVE, 2010). The AQS data include measurements from the Environmental Monitoring for Public Access and Community Tracking (EMPACT) program, the EPA's Chemical Speciation Network (CSN) (previously known as the Speciated Trends Network, STN), and the federal reference method (FRM) network.

Monitoring sites operating during the period 1999 through 2009 are depicted in Fig. 1 and site characteristics and histories are summarized in Table 1. The first full year of $PM_{2.5}$ mass concentration and composition data is 1999 for most sites, but O_3 and PM_{10} mass concentration measurements were made in earlier years at some locations. The spatial coverage for O_3 and $PM_{2.5}$ mass concentrations is better than for other pollutants. Twelve locations report O_3 data, although only the two SEARCH sites monitor O_3 during the months of November through February. Eleven sites (including Centreville, SCTR) report $PM_{2.5}$ mass concentrations, but two (Jasper [JASP] and Pelham High School [PHSP]) collect samples every third day. The IMPROVE measurements from BIRM and Sipsey (SIPS) were also made once every third day, on the same sampling schedule as CSN. The CSN samplers in Jefferson County are MetOne SASS instruments (a five-channel sampler) (MetOne, 2008); the mass measurements are determined from a Teflon filter. SEARCH measurement methods are documented in Hansen et al. (2003).

Hourly $PM_{2.5}$ mass concentration measurements (made by tapered element oscillating microbalance, or TEOM) at EMPACT sites began in July 2001; the eight EMPACT monitors also have FRM measurements made once every third day beginning in 1999. Hourly PM_{10} measurements were made at four locations. The EPA designates TEOM instruments as equivalent to reference methods for PM_{10} (EPA certification EQPM-1090-079) and as a "correlated acceptable continuous monitor" for $PM_{2.5}$ (Thermo Scientific, 2008). Nearly all the hourly $PM_{2.5}$ measurements at EMPACT sites were made using TEOM instruments heated to 50 degrees Celsius (°C). In some circumstances, semi-volatile materials may be lost