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Modeling spatiotemporal variability of intra-urban air pollutants in Detroit: A pragmatic approach

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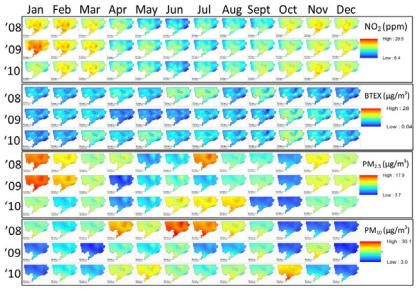
HIGHLIGHTS

- This method integrates temporally and spatially detailed air quality datasets.
- NO_2, BTEX, $PM_{2.5}$, and PM_{10} were investigated.
- A series of monthly concentration models was generated for the Detroit airshed.
- Temporal trends and neighborhood scale spatial variability were preserved.

GRAPHICAL ABSTRACT



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ABSTRACT

This study combined a three-year time series of air pollutant measurements from the Michigan Air Sampling Network (MASN) with spatially detailed datasets for two two-week periods in September 2008 and June 2009. The objective was to produce monthly pollutant concentration models for the city of Detroit, Michigan, USA from January 2008 through December 2010, in support of a related epidemiological study examining adverse birth outcomes in Detroit. Two gaseous analytes, NO_2 (nitrogen dioxide) and total BTEX (benzene, toluene, ethyl-benzene, and xylene), as well as two particulate matter size fractions, $PM_{2.5}$ and PM_{10}, were investigated. The September 2008 and June 2009 datasets were modeled using ordinary kriging to produce high spatial density concentration maps with 300 m by 300 m resolution across the city. A weighted average was applied to these maps to generate a series of monthly spatial models for each pollutant. Temporal variability was then incorporated by adjusting each monthly spatial model using an average bulk shift derived from MASN time series measurements for the corresponding month over the three-year study period.

The resulting models incorporate temporal trends while preserving neighborhood scale spatial variability. Seasonal variation was evident in NO_2 models, but not readily discernable in BTEX or PM models across the three year study period. The greatest spatial and temporal variability was observed in the BTEX distributions, which are inferred to be strongly influenced by local sources. The methodology employed assumes that the interpolated monthly models adequately capture spatial variability of the air pollutants across the study area, the spatial distribution of pollutant concentrations remained consistent while their magnitude fluctuated from month to month, and that the available time series measurements reflect temporal trends across the city of Detroit throughout the three-year study period.

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1. Introduction

Urban airsheds are heterogeneous and air pollution concentrations in urban areas vary over space and time (Kim et al., 2005; Pinto et al., 2004). As a result, epidemiological studies relating health outcomes to air pollution require both spatially and temporally resolved air pollutant models to estimate acute and chronic exposures. Distributed and prolonged air quality measurements are resource intensive, however, and study designs frequently balance tradeoffs between spatial and temporal resolution (Beevers et al., 2013). Consequently, there is a growing need to develop practical methods to integrate detailed spatial and temporal air quality data from multiple sources (Mayer, 1999; Ross et al., 2013; Wilson et al., 2005).

Air sampling networks established to monitor compliance with national ambient air quality standards (NAAQS) are important sources of outdoor air quality information in the United States. In Michigan, the Michigan Air Sampling Network (MASN) uses strategically placed monitors to assess air pollutant levels throughout the state (MDEQ, 2013). Comparable air sampling networks in other states and countries provide long-term air quality measurements that may be used to estimate exposure for surrounding communities (e.g., Dockery et al., 1993; Pope et al., 2009; Samet et al., 2000; Zanobetti et al., 2003). Although these regulatory monitoring networks provide valuable time series measurements, they commonly lack the spatial resolution needed to provide neighborhood-scale exposure estimates (Baxter et al., 2013; Ozkaynak et al., 2013; Sarnat et al., 2013; Wilson et al., 2005).

Alternatively, temporary networks of active or passive air samplers can provide a higher spatial density of measurements over limited, discontinuous periods of time (e.g., Miller et al., 2010; Ross et al., 2013). Short-term monitoring networks can be logistically difficult to implement and expensive to repeat (Cocheo et al., 2008); however, their measurements are readily incorporated into land use regression (LUR) and geostatistical interpolation (i.e., kriging) algorithms to generate pollutant concentration models at increased spatial resolution (e.g., Hoek et al., 2008; Jerrett et al., 2005a; Künzli et al., 2004; Sampson et al., 2011). LUR and kriging models share similar limitations (e.g., they require a large number of sampling sites and are not readily adaptable to changing meteorological conditions (Isakov et al., 2011)) but have different strengths. For example, LUR models can reproduce small scale features such as roadway configurations that contribute to mobile source pollutants (Mercer et al., 2011) whereas kriging smooths concentration estimates. Conversely, kriged models can provide measures of uncertainty using estimation error variance throughout the model domain (Vicedo-Cabrera et al., 2013).

The objective of this study was to create a series of spatially detailed ambient (outdoor) pollutant concentration models in support of an ongoing epidemiological investigation of associations among adverse birth outcomes and air pollutants in the city of Detroit, Michigan, USA. This study builds upon prior investigations that associated acute exacerbations of asthma in Detroit and Windsor with exposure estimates derived from spatially detailed air pollutant models covering a two-week sampling period (Lemke et al., 2013). The birth outcome investigation requires chronic exposure estimates over individual trimesters and the total duration of each pregnancy. Moreover, the births examined in the study occurred over a three year period, so that a time series of air pollutant models is needed to calculate exposures based on each mother's residential address.

This paper describes the space-time distribution modeling of nitrogen dioxide (NO_2), total benzene, toluene, ethylbenzene, and xylene (BTEX), and particulate matter with aerodynamic diameters less than 2.5 and 10 microns ($PM_{2.5}$ and PM_{10}) concentrations across Detroit during 2008–2010. Specifically, we present the methods used to combine spatially detailed models developed from measurements in an extensive temporary sampling network with temporally rich, but spatially sparse MASN measurements, along with the resulting monthly concentration models for each air pollutant during the three year period. Finally, we discuss and evaluate our assumptions about the compatibility, representativeness, and applicability of the datasets employed to spatial and temporal modeling within the Detroit airshed.

2. Data

Air pollution data for this study were derived from two sources. The first data set was developed by the Geospatial Determinants of Health Outcomes Consortium (GeoDHOC) (Miller et al., 2010; Lemke et al., 2013). The GeoDHOC conducted two two-week air sampling campaigns in Detroit, Michigan and Windsor, Ontario between September 5–20, 2008 and May 29–June 13, 2009. A total of 100 passive samplers and 50 active samplers were deployed during each sampling event (Fig. 1). Passive samplers measured NO_2, SO_2, and volatile organic compound (VOC) concentrations at an approximate spatial density of 5 km^2 per sample. BTEX compounds comprised 64% and 72% of total VOCs measured in 2008 and 2009, respectively. Active samplers measured polycyclic aromatic hydrocarbons (PAHs) and particulate matter (PM) in three size fractions at an approximate spatial density of 10 km^2 throughout both cities. Pollutant distribution models were created using ordinary kriging with a 300 m $\times$ 300 m grid spacing. Details of sampling, QA/QC, and mapping methods for the GeoDHOC data set are given by Miller et al. (2010). Analysis of the 2008 air samples demonstrated spatial variability in air pollutant distributions between and, more importantly, within Detroit and Windsor at neighborhood scales (Miller et al., 2010). Kriging variance maps, which illustrate the distribution of estimation uncertainty, are provided as supplemental information (Fig. S1) to this paper.

The second data set consisted of time series measurements at five MASN locations within the city of Detroit from 2008 to 2010 (Fig. 1) (MDEQ, 2008). Not all analytes were measured at each location (Table 1). Measurements at two nearby MASN locations outside the city (Allen Park and Dearborn) were excluded from the study because $PM_{2.5}$ and PM_{10} measurements at these sites did not differ materially in temporal trends from the Detroit station measurements during the period examined. Hence, only MASN samplers located in the city of Detroit were included in the study. Measurements at two National Air Pollution Surveillance (NAPS) monitoring stations in Windsor were also excluded because they are outside the study area.

The Detroit MASN data set includes single sampling locations for NO_2, VOCs including individual BTEX components, and PM_{10} (Table 1). The East 7 Mile location was the only active NO_2 sampling location in the study area during the study period. At this location, NO_2 is sampled continuously using automated chemiluminescence (Federal Reference Method (FRM) RFNA-0179-035) (U.S. EPA, 2013) and hourly concentrations were reported. BTEX concentrations at Southwestern High School were derived from air samples collected over a 24 h period every 12 days using SUMMA canisters. These samples were analyzed for VOCs using gas chromatography/mass spectrometry following EPA method TO-15 (U.S. EPA, 1999). PM_{10} concentrations were measured at the Southwestern High School site over a 24 h period every six days using a High-Volume Air Sampler (FRM RFPS-1287-064) (U.S. EPA, 2013).

$PM_{2.5}$ was measured at five Detroit MASN sampling locations during the 2008–2010 study period (Table 1). $PM_{2.5}$ was measured over a 24 h period using a $PM_{2.5}$ Sequential Air Sampler (Rupprecht & Patashnick Company, Incorporated Partisol®-Plus Model 2025,