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Assessing the impact of fine particulate matter ($PM_{2.5}$) on respiratory-cardiovascular chronic diseases in the New York City Metropolitan area using Hierarchical Bayesian Model estimates

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ABSTRACT

An enhanced research paradigm is presented to address the spatial and temporal gaps in fine particulate matter ($PM_{2.5}$) measurements and generate realistic and representative concentration fields for use in epidemiological studies of human exposure to ambient air particulate concentrations. The general approach for research designed to analyze health impacts of exposure to $PM_{2.5}$ is to use concentration data from the nearest ground-based air quality monitor(s), which typically have missing data on the temporal and spatial scales due to filter sampling schedules and monitor placement, respectively. To circumvent these data gaps, this research project uses a Hierarchical Bayesian Model (HBM) to generate estimates of $PM_{2.5}$ in areas with and without air quality monitors by combining $PM_{2.5}$ concentrations measured by monitors, $PM_{2.5}$ concentration estimates derived from satellite aerosol optical depth (AOD) data, and Community-Multiscale Air Quality (CMAQ) model predictions of $PM_{2.5}$ concentrations. This methodology represents a substantial step forward in the approach for developing representative $PM_{2.5}$ concentration datasets to correlate with inpatient hospitalizations and emergency room visits data for asthma and inpatient hospitalizations for myocardial infarction (MI) and heart failure (HF) using case-crossover analysis. There were two key objective of this current study. First was to show that the inputs to the HBM could be expanded to include AOD data in addition to data from $PM_{2.5}$ monitors and predictions from CMAQ. The second objective was to determine if inclusion of AOD surfaces in HBM model algorithms results in $PM_{2.5}$ air pollutant concentration surfaces which more accurately predict hospital admittance and emergency room visits for MI, asthma, and HF. This study focuses on the New York City, NY metropolitan and surrounding areas during the 2004–2006 time period, in order to compare the health outcome impacts with those from previous studies and focus on any benefits derived from the changes in the HBM model surfaces. Consistent with previous studies, the results show high $PM_{2.5}$ exposure is associated with increased risk of asthma, myocardial infarction and heart failure. The estimates derived from concentration surfaces that incorporate AOD had a similar model fit and estimate of risk as compared to those derived from combining monitor and CMAQ data alone. Thus, this study demonstrates that estimates of $PM_{2.5}$ concentrations from satellite data can be used to supplement $PM_{2.5}$ monitor data in the estimates of risk associated with three common health outcomes. Results from this study were inconclusive regarding the potential benefits derived from adding AOD data to the HBM, as the addition of the satellite data did not significantly increase model performance. However, this study was limited to one metropolitan area over a short two-year time period. The use of next-generation, high temporal and spatial resolution satellite AOD data from geostationary and polar-orbiting satellites is expected to improve predictions in epidemiological studies in areas with fewer pollutant monitors or over wider geographic areas.

1. Introduction

Fine particulate matter ($PM_{2.5}$), defined as particles with aerodynamic diameters $\leq 2.5\ \mu m$, has been shown to influence the frequency and severity of respiratory and cardiovascular

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diseases (e.g., Rom and Samet, 2006; Pope et al., 2004; Peters et al., 2001; Norris et al., 1999). $PM_{2.5}$ also increases inflammatory proteins and heart rate variability (HRV) in healthy volunteers (Samet et al., 2009). A common goal of public health programs in the United States is a reduction in the frequency and severity of such diseases (Talbot et al., 2009). In order to track the effects of an ambient air pollutant, such as $PM_{2.5}$, on public health, accurate measurements of the air pollutant are necessary in both time and space. $PM_{2.5}$ concentrations measured by the United States Environmental Protection Agency's (U.S. EPA's) national ground-based ambient air pollutant network provide a foundation for air pollution monitoring. The locations of individual $PM_{2.5}$ monitors across the nation are determined primarily by the requirements of state and local air pollution control agencies based on federal regulatory requirements for monitoring National Ambient Air Quality Standards (NAAQS) non-compliance areas and high-priority metropolitan areas. As a result, the national distribution of monitors does not follow a uniform or a probabilistically-based sampling plan, which would ensure some degree of optimal coverage for all areas of the country. Instead, most $PM_{2.5}$ monitors are located in urban and suburban areas, and consequently, there are significant gaps in coverage, particularly in rural regions. In addition, a subset of $PM_{2.5}$ monitors make measurements only every 3 or 6 days. As a result, there are substantial gaps in temporal coverage of $PM_{2.5}$ concentrations measurements across the nation as well.

Previous studies have addressed the spatial and temporal gaps in data from air pollution monitors in order to reduce characterization errors and more accurately predict the association of concentration data and health outcomes for epidemiological research (e.g., Goldman et al., 2010; Sarnat et al., 2010). One approach to augment the limited amount of available ambient air monitoring data is to combine these data with air quality model predictions using a statistically-based model, such as a Hierarchical Bayesian Model (HBM; McMillan et al., 2010). The HBM uses observed monitor concentration values and so-called surrogate concentration values, such as air quality model output and remotely-sensed data, to predict the “true” concentration surface values. The HBM gives more weight to highly accurate monitoring data in areas where monitoring data exist, and relies on bias-adjusted surrogate data in non-monitored areas. This approach provides the ability to predict important pollution gradients and uncertainties that might otherwise be unknown if only using interpolation results based solely on air quality monitoring data. The results derived from the HBM are useful for studies focused on health outcomes across large regions.

Recognizing the potential of the HBM technique to address spatial and temporal gaps in ambient $PM_{2.5}$ monitoring data, the Centers for Disease Control and Prevention (CDC) and U. S. EPA sponsored the development of an HBM as part of the Public Health Air Surveillance Evaluation (PHASE) project, which ran from 2004 to 2006 (CDC, 2016). PHASE was designed to identify spatial and temporal interpolation tools that can be used to generate daily surrogate measures of exposure to ambient air pollution, and relate those measures to available public health data. This initial version of the $PM_{2.5}$ HBM combined U.S. EPA $PM_{2.5}$ monitoring data and $PM_{2.5}$ predictions from the Community Multi-scale Air Quality (CMAQ) model (McMillan et al., 2010). The output from the PHASE HBM was incorporated into the CDC National Environmental Public Health Tracking Network (NEPHTN) for use by national, state, and local epidemiologists (Vaidyanathan et al., 2013).

While the initial PHASE-based version of HBM, which incorporated $PM_{2.5}$ monitor data and CMAQ $PM_{2.5}$ concentration predictions, represented a step forward in terms of generating $PM_{2.5}$ concentration fields that are accurate in time and space, it did not take advantage of remotely-sensed data. Remote sensing data, such as measurements of aerosol optical depth (AOD) taken by the MODerate resolution Imaging Spectroradiometer (MODIS) instruments on NASA's Terra and Aqua satellites, can provide information about $PM_{2.5}$ concentrations in areas where ground-based monitors do not exist. Satellite AOD is a unitless measure of the scattering and absorption of sunlight by particulate matter in a vertical column of the atmosphere between the satellite and Earth's surface. AOD is related to $PM_{2.5}$ concentrations, and many studies have shown that AOD can be used to estimate ground-level $PM_{2.5}$ concentrations (e.g., Hoff and Christopher, 2009; van Donkelaar et al., 2010; Weber et al., 2010). Although satellite AOD data do not represent the exact surface concentrations of $PM_{2.5}$, they capture the spatial distribution of the pollutant field in a way that monitor point measurements cannot (Liu et al., 2009; Gutierrez, 2010). In recent years, there has been interest in using satellite AOD data to assess the health effects of exposure to air pollutants (e.g., Kloog et al., 2011). However, previous studies have been limited to using satellite modeled data to conduct ecological studies of human health effects (e.g., Anderson et al., 2012a). This study sought to use satellite data to assess health effects of $PM_{2.5}$ using individual-level health data in a case-crossover analysis.

Satellite AOD represent physical observations of ambient $PM_{2.5}$ and therefore have the potential to supplement $PM_{2.5}$ monitor data and CMAQ model output combined by the HBM. A key objective of this study was to determine if the inclusion of MODIS AOD surfaces into the HBM results in $PM_{2.5}$ concentration surfaces that are more accurately able to predict associations and risks related to hospital admittance and emergency department (ED) visits for specific health outcomes at the individual patient level. The initial PHASE-based HBM was modified to allow for the incorporation of MODIS AOD-based estimates of surface $PM_{2.5}$ concentrations in addition to the basic components of $PM_{2.5}$ monitor data and CMAQ model output. $PM_{2.5}$ concentration surfaces generated by the HBM were compared to data on visits to the ED for asthma and inpatient hospitalizations for acute myocardial infarction (MI) and heart failure (HF). Case-crossover analyses were conducted to estimate the impact of short-term variations in $PM_{2.5}$ concentrations on the health effect outcomes using the methodology described in Haley et al. (2009). The case-crossover method has been used in recent years to assess the association of transient environmental exposures on acute health events (e.g., Schwartz, 2004). This design has been shown to yield similar associations as the traditional Poisson time series and the Cox Regression analysis (Peters et al., 2006; Fosbøl et al., 2014), with the added advantage of controlling for individual level confounding factors, trend and seasonality, and allowing assessment of effect-modification (Carracedo-Martínez et al., 2010). In this design, study subjects serve as their own controls, and the study is not subject to confounding by between-subject time-invariant unknown or unmeasured factors.

The New York City Metropolitan area of New York State was selected for this study based on geographic location, prior research on remote sensing of air pollution in those locations and availability of the New York State Department of Health (NYSDOH) to participate. The study area included New York City and the surrounding NY counties of Nassau, Suffolk, Westchester and Rockland (Fig. 1). Although the study area represents a limited geographic region, it was selected to allow for direct comparison to previous research. To facilitate comparison of results to the work of the PHASE project, the study period for this project covered the years 2004 through 2006. The expected outcome was that $PM_{2.5}$ concentration surfaces, as generated with the addition of satellite AOD data, would be more accurate for predicting asthma, acute MI, and heart failure health outcomes compared to surfaces that only incorporated $PM_{2.5}$ monitor data and CMAQ model output.