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Spatial variations in the associations of term birth weight with ambient air pollution in Georgia, USA

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ABSTRACT

Birth weight is an important indicator of overall infant health and a strong predictor of infant morbidity and mortality, and low birth weight (LBW) is a leading cause of infant mortality in the United States. Numerous studies have examined the associations of birth weight with ambient air pollution, but the results were inconsistent. In this study, a spatial statistical technique, geographically weighted regression (GWR) is applied to explore the spatial variations in the associations of birth weight with concentrations of ozone (O_3) and fine particulate matter ($PM_{2.5}$) in the State of Georgia, USA adjusted for gestational age, parity, and six other socioeconomic, behavioral, and land use factors. The results show considerable spatial variations in the associations of birth weight with both pollutants. Significant positive, non-significant, and significant negative relationships between birth weight and concentrations of each air pollutant are all found in different parts of the study area, and the different types of the relationships are affected by the socioeconomic and urban characteristics of the communities where the births are located. The significant negative relationships between birth weight and O_3 indicate that O_3 is a significant risk factor of LBW and these associations are primarily located in less-urbanized communities. On the other hand, $PM_{2.5}$ is a significant risk factor of LBW in the more-urbanized communities with higher family income and education attainment. These findings suggest that environmental and health policies should be adjusted to address the different effects of air pollutants on birth outcomes across different types of communities to more effectively and efficiently improve birth outcomes.

1. Introduction

Birth weight is a strong predictor of infant morbidity and mortality and an important indicator of overall infant and child health. Low birth weight (LBW), defined as live births weighing less than 2500 grams (g), is a major determinant of mortality, morbidity, and disability in infancy and childhood, and can affect the subsequent health status of individuals (WHO, 2015). World Health Organization (WHO) estimated about 30 million LBW babies born worldwide every year (WHO, 2015). LBW is also a leading cause of infant mortality in the United States (Carmichael et al., 1998; Tierney-Gumaer and Reifsnider, 2008). Thus, LBW is a significant health challenge in the U.S. and around the world and a reduction in LBW can contribute to an overall improvement in population health. A comprehensive understanding of the causes of LBW and the factors that affect birth weight can provide important information to formulate more effective health policy and preventive initiatives. These factors include biological (e.g. gene), socioeconomic (e.g. income and education), behavioral (e.g. exercise, maternal drinking and smoking), political (e.g. health policy and accessibility to prenatal care), and environmental (e.g. noise, land use, water pollution, and air pollution) variables that may have impact on the health of pregnant women and fetal development.

Numerous studies have been conducted around the world to explore the associations of birth outcomes, including birth weight, LBW, and preterm birth, with maternal exposure to air pollution (Basu et al., 2004; Bell et al., 2007; Kloog et al., 2012; Madsen et al., 2010; Twum et al., 2015; Yorifuji et al., 2015). The examined air pollutants included sulphur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), and fine particulate matters (PM) with an aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$), and coarse PM of aerodynamic diameter of less than 10 μm (PM_{10}). Although the previous studies provided considerable evidence to support an association between birth weight and ambient air pollution, the results are inconsistent and the causal mechanisms remain unclear (Madsen et al., 2010). For example, higher concentrations of air pollutants have been associated with a reduced birth weight or an elevated risk of LBW in some studies (Basu et al., 2004; Bell et al., 2007; Kloog et al., 2012; Twum et al., 2015; Yorifuji et al., 2015). Kloog et al. (2012) examined the effect of $PM_{2.5}$ on birth weight of 634,244 births in the State of Massachusetts, USA between 2000 and 2008 and found that birth weight was negatively associated with $PM_{2.5}$. In contrast, many studies did not find significant

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relationships between some air pollutants and birth weight or risk of LBW (Berrocal et al., 2011; Madsen et al., 2010; Vinikoor-Imler et al., 2014). Berrocal et al. (2011) applied a hierarchical model to specify the relationship between birth weight and personal exposure to $PM_{2.5}$ in 14 counties in North Carolina in years 2001 and 2002, but did not find a significant effect of $PM_{2.5}$ on birth weight. Moreover, some studies even found a protective effect of air pollutants on birth weight (Dadvand et al., 2013; Hao et al., 2015; Parker and Woodruff, 2008). Parker and Woodruff (2008) modelled birth weight as a function of county-level $PM_{2.5}$ exposure for the births in the US during the period of 2001–2003 for the entire country and by regions, and reported that birth weight was positively related to $PM_{2.5}$ in the model using the nationwide data, but both positive and negative relationships were identified for different regions. Hao et al. (2015) applied multilevel logistic regression models to evaluate the associations between LBW and $PM_{2.5}$ exposure in USA, and different associations (significant negative, non-significant, and significant positive) were found in different census divisions.

The comparison of the results among the previous studies reveals that the association of birth weight with air pollution actually vary geographically. An air pollutant considered significant in affecting birth weight in one study may have no significance in other places. The spatial variation in the relationships between birth weight and air pollutants discovered among different studies may be due to the differences in study design, covariates selection, exposure estimation, and time of assessment (Parker and Woodruff, 2008; Madsen et al., 2010; Shah and Balkair, 2011). In addition, because the physical and social environment, such as pollution sources, intensity of emissions, meteorology, and pollution control technologies and policies, differ significantly over space, it is likely that the chemical composition and intrinsic toxicity of an air pollutant varies spatially, so that the impact of an air pollutant on a health outcome such as birth weight can be spatially altered (Basu et al., 2014; Bell et al., 2010; Coker et al., 2015; Darrow et al., 2011; Laurent et al., 2014). Furthermore, many contextual neighborhood and individual factors, ranging from socioeconomic status (SES), demographics, housing characteristics, behavioral factors, to accessibility to health care, usually vary significantly over space, so they may affect the susceptibilities of pregnant women to air pollution and subsequent birth outcomes, thereby complicating observed associations between birth outcomes and air pollution (Coker et al., 2015; Hajat et al., 2013; Tu et al., 2012).

Therefore, it is reasonable to expect spatial variation in the observed associations between birth weight and ambient air pollution. Only a few previous studies, however, have examined the spatial variation in associations of birth outcomes with air pollution (Berrocal et al., 2011; Coker et al., 2015; Dadvand et al., 2013; Hao et al., 2015; Parker and Woodruff, 2008). Most of them first divided the study area into different regions (e.g. countries, states, or census divisions), and then analyzed the associations by regions (Dadvand et al., 2013; Hao et al., 2015; Parker and Woodruff, 2008). For example, Parker and Woodruff (2008) discovered the regional variations in the associations of birth weight with air pollution by building different models for different US regions. The associations obtained from that study did not vary continuously over space, but abruptly changed across the boundaries of the regions, and no variation could be analyzed inside each region. Thus, the variations in the associations were not much different from the various results we can get by comparing multiple previous studies. Coker et al. (2015) applied a multivariate logistic regression model with multilevel spatially structured and unstructured random effects set in a Bayesian framework to model the spatial effects of $PM_{2.5}$ on LBW in Los Angeles, and estimated the continuous spatial variation in the association of LBW with $PM_{2.5}$ across census tracts, but didn't analyze other pollutants. To our best knowledge, no studies have explicitly examined the continuous spatial variation in the association of birth weight or LBW with air pollutants other than $PM_{2.5}$. In addition, no published research has reported the impact of socioeconomic characteristics of the communities where the births are located on the associations of birth outcomes with air pollution.

Traditionally, the associations of birth weight or LBW with air pollution have been analyzed using conventional statistical methods, such as ordinary least squares (OLS) regression for continuous dependent variables (e.g., birth weight) or logistic regression for dichotomous dependent variables (e.g., LBW). In those studies, concentrations of air pollutant, with other confounding factors, such as socioeconomic, demographic, and behavioral factors, were typically used as the independent variables, while birth weight or LBW was the dependent variable. These methods are global statistics that analyze the average situation for the entire study area (Fotheringham et al., 2002), and they assume that relationships are stationary. As indicated in our review of the literature, this assumption is routinely violated because observed relationships are known to vary.

In recent years, a growing number of studies have applied a local spatial statistical technique called geographically weighted regression (GWR) to explore the spatial variations in relationships between health issues and risk factors (Chan et al., 2014; Gilbert and Chakraborty, 2011; Goovaerts et al., 2015; Tu et al., 2012; Zhang et al., 2012). However, no previous studies have applied this technique to analyze the associations of birth outcomes with ambient air pollution. GWR attempts to capture spatial variations by estimating regression model parameters for each individual regression point (the location of each observation). The local estimation of model parameters is obtained by weighting all neighboring observations using a distance decay function, assuming that the observations nearby have more influence on the regression point than the observations further away. In addition to the local parameter estimates, GWR also produces other local regression results, including the values of *t*-test on the local parameter estimates, the local R^2 values, and the local residuals for each regression point. The spatial variations in the relationships between dependent and independent variables can be shown by comparing the local regression results among different regression points. Therefore, GWR may serve as a useful tool to explore the spatial variations in the associations of birth weight with air pollutants.

We have applied GWR to study the spatial variation in the associations of birth weight with socioeconomic, environmental, and behavioral factors in the State of Georgia, USA in a previous study (Tu et al., 2012). However, that study did not include air pollutants due to the lack of air pollution data, but used percentage of urban land as a proxy of air pollution instead. The current study maintains all the independent variables and methodologies used in the previous research but includes air pollutants to the analyses so that the spatial variation in the associations of birth weight with ambient air pollution can be investigated, and also includes gestational age and parity as independent variables. The primary objectives of this research are (1) to compare the differences in the relationships between birth weight and concentrations of $PM_{2.5}$ and O_3 analyzed by OLS and GWR; (2) to examine how the relationships between birth weight and concentrations of $PM_{2.5}$ and O_3 produced by GWR vary over space; and (3) to explore how the spatially varying relationships of birth weight and concentrations of $PM_{2.5}$ and O_3 are affected by socioeconomic and urban characteristics of communities. As GWR is an exploratory spatial data analysis (ESDA) technique, we do not intend to study the causal relationship between LBW and its risk factors or any critical values of the air pollutants that might cause LBW. Our goal is to explore how the associations between birth weight and ambient air pollution vary in the communities with different socioeconomic characteristics. We hope that the results gleaned from this study can help formulate community specific prevention and intervention policies.

2. Data sources and methods

2.1. Birth outcomes and maternal behavioral variables

Individual birth weight and maternal behavioral variables data were derived from the electronic birth certificate data (BCD) collected by the