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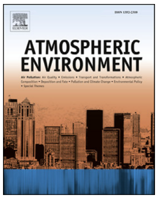

Land use regression modeling with vertical distribution measurements for fine particulate matter and elements in an urban area

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HIGHLIGHTS

- Vertical variations were observed for $PM_{2.5}$, Si, Ti and Fe.
- Traffic and industrial land were important factors in land use regression models.
- Significant effects of floor level were observed in the $PM_{2.5}$, Si and Fe models.
- Vertically distributed measurements should be considered in future studies.

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ABSTRACT

Land use regression (LUR) models have been developed and applied to evaluate long-term exposure to air pollutants in residential area. However, adopting LUR models for vertical distributions of $PM_{2.5}$ elemental composition has not been studied extensively. Developing this type of LUR model in various urban areas is essential to examine the influence of sampling height from ground level on the modeling prediction of these pollutants. The purpose of this study was to examine spatial variations of exposures to $PM_{2.5}$ and $PM_{2.5}$ composition in an urban area and build LUR models with vertical distribution measurements. $PM_{2.5}$ samples were collected at twenty low-level sites (first to third floors), five mid-level sites (fourth to sixth floors), and five high-level sites (seventh to ninth floors). LUR models considering local land use data and traffic information were developed for $PM_{2.5}$ and elements (i.e., silicon (Si), sulfur (S), potassium (K), titanium (Ti), manganese (Mn), iron (Fe), nickel (Ni), copper (Cu), and zinc (Zn)). The results demonstrated that the vertical ratios were higher than 1 (i.e., highest concentrations at low-level sites) for $PM_{2.5}$, Si, Ti, and Fe. Their median ratios ranged from 1.05 to 1.18. The explained variances (R^2) of LUR models ranged from 0.46 to 0.80. Traffic and industrial land were major variables in most models, and the floor level was identified as a significant predictor in the $PM_{2.5}$, Si, and Fe models. This indicated the necessity of collecting vertically distributed measurements in future LUR studies for reducing the exposure bias in epidemiological studies.

1. Introduction

Epidemiological studies have indicated that long-term exposure to particulate matter (PM) may induce adverse effects on health (Chan et al., 2008; Chuang et al., 2007; Pope et al., 2004; Qiu et al., 2012; Yang et al., 2004). In these studies, the particles with aerodynamic diameters of less than 2.5 μm ($PM_{2.5}$) or 10 μm (PM_{10}), measured at air quality monitoring stations, have been widely used to estimate human exposure to PM. Although early research typically did not consider the intraurban variability of exposure, several relatively recent studies have determined such variability (Beelen et al., 2007; Hoek et al., 2002; Jerrett et al., 2005). Consequently,

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land use regression (LUR) models, combining air monitoring data collected at multiple sites, and multiscale predictor variables, acquired from the geographic information system (GIS) (Hoek et al., 2008; Ryan and LeMasters, 2007), have been developed to provide improved exposure estimates. Previous LUR studies have involved building models for nitrogen dioxide, nitrogen oxides, volatile organic compounds, PM, and PM absorbance (elemental carbon) (Eeftens et al., 2012; Henderson et al., 2007; Hoek et al., 2008; Johnson et al., 2010; Yorifuji et al., 2010). A few studies have employed LUR models of polycyclic aromatic hydrocarbons and metal elements in $PM_{2.5}$ to determine the influence of exposure to PM composition on health (de Hoogh et al., 2013; Noth et al., 2011, 2013; Wu et al., 2014).

Most of these studies have considered only horizontal measurements in evaluating the spatial variability of exposure using LUR models (de Hoogh et al., 2013; Eeftens et al., 2012; Henderson et al., 2007; Hoek et al., 2008; Johnson et al., 2010; Noth et al., 2011). However, high-rise buildings are a typical type of residence in urban areas. In a previous study, substantial vertical variation was observed in $PM_{2.5}$ and Si in Kaohsiung, Taiwan (Wu et al., 2014). LUR models for vertical exposure to ambient pollutants have not been studied extensively. It is essential to develop this type of LUR model for various urban areas to determine the influence of sampling height from the ground level on the modeling prediction of air pollutants. The purpose of this study was to examine spatial variations of exposures to $PM_{2.5}$ and $PM_{2.5}$ composition in Taipei metropolis and build LUR models with vertical distribution measurements.

2. Materials and methods

2.1. Study area

The data regarding $PM_{2.5}$ and $PM_{2.5}$ composition were collected from Taipei metropolis, Taiwan, in 2010, supported by the Environmental Protection Administration of Taiwan. Taipei metropolis, including Taipei City and New Taipei City, is situated in Northern Taiwan and has a population of approximately 6.5 million; high-rise buildings are typical for the study area. Two major highways traverse Taipei metropolis, and traffic emissions are high in urban areas.

2.2. Ambient air pollution monitoring

Thirty $PM_{2.5}$ sampling sites were selected according to the protocol of previous projects (Eeftens et al., 2012; Wu et al., 2014). Twenty low-level sampling sites between the first and third floors were selected as street sites ($n = 10$) and urban background sites ($n = 10$). The traffic intensity of street sites was estimated to be 25,000 vehicles per day or more according to the limited traffic count data. To measure $PM_{2.5}$ concentrations on various floors, mid-level sampling sites ($n = 5$) from the fourth to sixth floors, and high-level sampling sites ($n = 5$) from the seventh to ninth floors, located in the same or nearby building of the low-level sites, were also selected. Due to the difficulty in obtaining agreement from residents or home owners in the study area for $PM_{2.5}$ sampling, the mid-level sites were selected as urban background sites while the high-level sites were street sites. Furthermore, a continuous-monitoring site was used as a reference site to adjust for temporal variations of the measurements.

The $PM_{2.5}$ sampling sites were monitored from January 2010 to October 2010. Six sampling sites were measured simultaneously per month, including two sets of vertical sites (i.e., mid- and high-level vs. low-level sites). Each site was monitored twice with a 5-month interval. Each $PM_{2.5}$ measurement was collected for a 2-week period, according to the protocol of previous projects (Eeftens et al., 2012; Wu et al., 2014), using 37-mm Teflon filters with Harvard Impactors (Air Diagnostics and Engineering, Inc., Harrison, ME, USA). The sampling pump was operated for 15 min every 2 h during the 2-week period to prevent filter overloading. Additional $PM_{2.5}$ samples were collected every 2 weeks at the reference site from January 2010 to October 2010. Because of the refusal of participants in the second sampling period at one mid-level and four low-level sampling sites, only 25 sampling sites were used in the following data analysis and model building (Fig. 1).

2.3. $PM_{2.5}$ analysis

$PM_{2.5}$ composition, namely silicon (Si), sulfur (S), potassium (K), titanium (Ti), manganese (Mn), iron (Fe), nickel (Ni), copper (Cu), and zinc (Zn), was analyzed based on their high percentages of detectability and environmental relevance. These elements were mainly emitted from multiple sources, as follows: Si, Ti, and Fe from resuspended dust and industrial activities; S from fuel combustion, secondary inorganic aerosols, and diesel vehicles; K from the burning and disposal of biomass; Mn, Cu, and Zn from industrial processing and abrasive vehicular emissions, and Ni from the combustion of fuel and industrial oil (de Hoogh et al., 2013; Lin et al., 2005; Watson et al., 2008). They were identified and quantitatively determined using energy-dispersive X-ray fluorescence spectrometry at the National Taiwan University (Wu et al., 2014). Thin-film standards (Micromatter, Vancouver, Canada) were used to establish calibration curves for trace elements, and the measured concentrations were verified with National Institute of Standards and Technology (NIST) certified reference material (SRM#2783). Method detection limit (MDL) was calculated based on three times of the standard deviation of 10 blank Teflon filters.

2.4. Predictor variables

Predictor variables, including local land use data and traffic-related information, were extracted using GIS (ArcGIS 9.3; ESRI, Redlands, CA, USA). To evaluate the concentration contrast between various floors, the floor level was included as a potential predictor. In addition, human activities have been suggested as potential sources to $PM_{2.5}$ (Gauvin et al., 2002; Van Ryswyk et al., 2013) and thus the population was also considered.

The land use data obtained from the National Land Surveying and Mapping Center were as follows: the surface area of high-density residential land (HDRES), low-density residential land (LDRES), industry (INDUSTRY), port (PORT), urban green space (URBGREEN) and semi-nature (NATURAL). Traffic information, from the Institute of Transportation, Ministry of Transportation and Communications, were defined as follows: total length of all major roads and all road segments (MAJORROADLENGTH, ROADLENGTH), the inverse distance to the nearest major road and the nearest road (DISTINVMAJOR1, DISTINVNEAR1) and the inverse distance squared to the nearest major road and the nearest road (DISTINVMAJOR2, DISTINVNEAR2). Predictor variables with multiple buffer sizes were applied to estimate the influence of spatial variability on $PM_{2.5}$ exposure. The buffer sizes of population and land use variables considered were 100, 300, 500, 1000, and 5000 m; and traffic data within the buffer distances of 25, 50, 100, 300, 500, and 1000 m were used in LUR models.

2.5. Land use regression building

Linear regression models were developed using a supervised stepwise selection procedure. Detailed descriptions have been provided by previous studies (Eeftens et al., 2012; Wu et al., 2014).