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ARIMA analysis of the effect of land surface coverage on PM_{10} concentrations in a high-altitude megacity

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ABSTRACT

This paper uses ARIMA models for daily temporal analysis of the effect of land surface coverage (LSC) on PM_{10} concentrations in a high-altitude megacity. Bogota, the capital of Colombia, is the urban center with the greatest population density and third-highest air pollution levels in Latin America. Six automatic monitoring stations were used; they were equipped with measurement instruments for PM_{10}, temperature and solar radiation as well as wind speed and wind direction. The duration of the sampling period was 6 years. The hourly PM_{10} sampling system included continuous-monitoring equipment that used beta ray attenuation. We analyzed atmospheric stability and the spatial distribution of LSC (vegetated, non-vegetated, impervious and water bodies) before applying the iterative process of Box-Jenkins for ARIMA models. ARIMA analysis indicates greater persistence in PM_{10} pollution in the presence of increased vegetated LSC (trees and grasslands); persistence decreased in the presence of more impervious LSC (roofs, pavements and footpaths). PM_{10} persistence is found to be 2 days (48 h). The best distance to demonstrate these findings is between 50 and 100 m, with respect to the monitoring stations' physical location. Urban areas with a predominance of vegetated LSC register lower PM_{10} concentrations than urban areas with a predominance of impervious LSC (average daily difference = 42.7%). This study's findings serve as a reference point for the development of differentiated strategies for air pollution control in line with urban LSC.

1. Introduction

Increased levels of respiratory disease in children and older adults caused by air pollution in urban areas is strongly correlated with increased levels of atmospheric particulate matter (Pope and Dockery, 2006; Chow et al., 2006; Wang et al., 2015). Higher levels of particulate matter (PM) are mainly associated with the concentration of industrial activities and quantity of motor vehicles in urban areas (Jian et al., 2012; Soto et al., 2014; Gocheva-Ilieva et al., 2014). Thus, many countries have decided to enhance active monitoring in urban areas to control this atmospheric pollutant. In consequence, the study of a possible relationship between PM concentrations and type of land surface coverage (LSC) in urban areas becomes urgent from a public health perspective. Climate conditions of the study area cannot be ignored for this type of analysis (Connell et al., 2005; Díaz-Robles et al., 2008). Zhang et al. (2012) and Seinfeld and Pandis (2016) reported that the distribution and transport of PM depended significantly on the condition of atmospheric stability (AS) and LSC (i.e., existing land use).

Studies in urban areas have reported a significant influence of LSC on PM_{10} concentrations. Chen et al. (2015) found that the presence of trees in Wuhan (China) reduced PM_{10} concentrations between 7 and 15%. Similarly, Islam et al. (2012) and Yin et al. (2007) reported a reduction of total suspended particulates (<100 μm) in urban areas by 55% (Khulna, Bangladesh) and 30% (Shanghai, China), respectively. McDonald et al. (2007) used GIS techniques, along with field research, to forecast an increase between 3.7 and 16.5% and 3.6 and 8.0% of the total tree coverage in conurbations of West Midlands and Glasgow (United Kingdom) would generate a reduction of 10% and 2% in primary PM_{10} concentrations, respectively. LSC with trees acts as an effective sink of

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gaseous and particulate atmospheric pollutants (Gallagher et al., 2002; Fowler et al., 2004). However, the mineral dust emanating from bare land was identified as the source of decreased air quality in several cities in Central Europe (e.g., Berlin and Zurich) (Wolf-Benning et al., 2009; Minguillon et al., 2012). Titos et al. (2014) reported that during dry summer conditions, more than 50% of PM_{10} corresponded to mineral dust re-suspended from bare soils and urban roads in Granada (Spain). Waked et al. (2014) found that 13% of average annual PM_{10} from Lens (France) could be traced to bare soils (mineral dust sources). Researchers have reached consensus on the main parameters that determine the dust and PM_{10} production, namely the saltation rate (kinetic energy by wind) and soil texture (Avecilla et al., 2016). Several authors found that the potential PM_{10} emissions increased as a function of silt and clay content decreased as a function of the soil's sand content (e.g., Carvacho et al., 2004; Funk et al., 2008). Liu et al. (2016) compared the removal efficiency of PM at different underlying surfaces in Beijing (China). The authors' results showed that urban forest surface had the best removal capacity because of its relatively low re-suspension rate. The PM removal efficiency of water bodies was higher than that of bare land due to the relatively higher PM re-suspension rates of bare land.

Studies show that AS plays an important role in the transport and dispersion of PM_{10}; it is significantly correlated to variations of temperature in altitude and wind speed (Zoras et al., 2006; Perrino et al., 2008; Chambers et al., 2015). Lee et al. (2013) indicated that, in the presence of extreme AS conditions (thermal inversion) in Seoul (South Korea), PM_{10} concentrations increased significantly (>100 μg/m^3). Vecchi et al. (2007) reported a 13% increase in PM_{10} concentrations under the prevailing conditions of nocturnal AS in Milan (Italy), despite a reduction in the active emission sources such as traffic, domestic heating and industrial activity. Under daytime conditions of atmospheric instability, PM_{10} concentrations tend to decrease (greater dispersion).

Air quality modeling has shown that more sophisticated multi-parametric meteorological models tend to significantly underestimate or overestimate air pollutant concentrations due to the complexity of phenomena involved (e.g., Argiriou, 2007; Kumar and Jain, 2010; Zhang et al., 2013; Seinfeld and Pandis, 2016). This complexity is due to the physicochemical processes undergone by pollutants, weather conditions, LSC, and uncertainty in the information of parameters in study. Thus, short- and long-term forecasts can be based on the statistical modeling of time series (Díaz-Robles et al., 2008; Kumar and Jain, 2010; Reisen et al., 2014). Athanasiadis et al. (2005) compared several statistical models (linear regression analysis-LRA, auto-regressive integrated moving average-ARIMA and principal components analysis-PCA) and classification algorithms (artificial neural networks, decision trees and conjunctive rules); the authors arrived at the conclusion that, in terms of the root-mean-square error, linear regression (0.128), and ARIMA (0.153) models were the most suitable for modeling urban air quality. ARIMA models developed for the statistical analysis of time series have been applied in several studies; these studies have reported a reasonable adjustment and utility for simulating and forecasting the behavior of atmospheric pollutants (e.g., Liu, 2009; Gocheva-Ilieva et al., 2014; Soni et al., 2014). ARIMA models have been deemed useful for assessing the temporal persistence of atmospheric pollutants have been reported (e.g., Turias et al., 2008; Kumar and De Ridder, 2010). For the sake of clarity, persistence refers to the continuation of a pollutant concentration pattern from one period to the next (Meraz et al., 2015). Specifically, these models provided an auto-regressive method ("memory" of the phenomenon) for interpreting data variability in time series for atmospheric pollutants (Hernández et al., 1992; Díaz-Robles et al., 2008; Hsu et al., 2014).

This study was done using data from a Latin-American megacity (8.85 million inhabitants in 2015). Bogota (Colombia) is a high-altitude city located in the Andes Mountains (04°36′35″ N, 74°04′54″ W); its average altitude is 2600 masl. The city's tropical mountain climate is characterized by large hourly temperature variations (maximum variation = 12 °C). The city is recognized as the urban center with the greatest population density (26,000 inhabitants/km^2) and third highest air pollution level in Latin America (Nelson et al., 2005; Sarmiento et al., 2015). In global terms, there have been few published studies that evaluate the behavior of PM_{10} in the urban centers of developing countries with similar physical characteristics and climate conditions; this lack of research has, in part, driven the development of this study.

This article used ARIMA models for the daily temporal analysis (2007–2012) of the influence of LSC on PM_{10} concentrations in a high-altitude megacity. The study was conducted using six automatic monitoring stations located in four zones in Bogota: Kennedy, Puente Aranda, Suba and Barrios Unidos. The monitoring stations used herein cover 23.9 km of the city's urban area.

2. Materials and methods

2.1. Research site description

Six automatic monitoring stations were placed in the localities of Kennedy (S1 and S2), Puente Aranda (S3), Suba (S4 and S5), and Barrios Unidos (S6) in Bogota, Colombia (see Fig. 1). The tropical mountain climate (cold weather) of the study sites had an average daily temperature (during the sampling period) between 13.3 and 14.3 °C, with hourly variations between 7.2 and 19 °C. Table 1 shows the main characteristics of the areas covered by each monitoring station. All six stations were equipped with PM_{10} measuring devices, in addition to devices to measure temperature, wind speed, and wind direction. S1, S5, and S6 stations were further equipped with instruments used to measure solar radiation. The monitoring stations covered a total of 23.9 km of the city's urban area (Fig. 1). The altitude of the monitoring stations was close to that of Bogota, between 2563 and 2590 masl.

2.2. PM_{10} sampling system

The sampling period lasted 6 years (01/01/2007-12/31/2012). The hourly PM_{10} sampling system consisted of continuous-monitoring equipment using beta ray attenuation (Met One Instruments, BAM 1020). The sampling protocol followed the guidelines set forth by the United States Environmental Protection Agency in EPA/625/R-96/010a-IO-1.2 (U.S.EPA, 1999). The equipment's constant flow rate was 16.7 l/min. The lowest detection limit was 3.6 μg/m^3 and 1.0 μg/m^3 for hourly and daily sampling intervals, respectively. Resolution in the measurement was 0.24 μg in a range of 1 mg. The precision was ±8% for hourly intervals and ±2% for daily intervals.

2.3. Atmospheric stability analysis

AS in the study areas was determined through the methodologies established by Pasquill (1961), Turner (1964) and Gifford (1976), with hourly data for wind speed and solar radiation (Zoras et al., 2006; Chambers et al., 2015). The predominant AS condition, measured as hourly occurrence frequency in the urban area covered by the monitoring stations (23.9 km of distance), was analyzed. Monitoring stations used for this calculation were S1, S5, and S6 (see Fig. 1). A Kruskal-Wallis test to assess the differences in hourly occurrence frequency between monitoring stations was applied (df = 24, per monitoring station). This is a non-parametric

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