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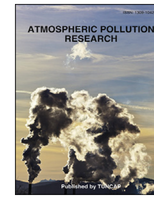

Quantifying decade-long effects of fuel and traffic regulations on urban ambient $PM_{2.5}$ pollution in a mid-size South American city

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A B S T R A C T

Most of urban air quality studies focus on the megacities of North America, Europe and, recently, Asia. Meanwhile, the most polluted urban areas in the world are rapidly growing large, mid-size and small cities of Asia, Middle East, Africa and South America. This raises a question: why relatively smaller cities are more polluted than the megacities? This study presents the first comprehensive decade-long analysis of the effects of fuel and transport regulations on $PM_{2.5}$ (particulate matter of aerodynamic diameter <2.5 μm) pollution in Quito, a medium-size city of South America. The effectiveness of a number of regulations is quantified through the elaboration of a high accuracy (98%) regression model. The model estimated that the $PM_{2.5}$ concentrations were reduced by 67.6 $\mu g/m^3$, combating the effect of city growth and intense motorization, reducing the annual $PM_{2.5}$ concentrations to 17.4 $\mu g/m^3$. This study is recommended as a guideline for thousands of other cities worldwide looking for optimal urban particulate pollution management.

1. Introduction

Since the beginning of the 20th century, global human population has increased 4.5 times, although most of the current growth is attributed to the urban areas in the less developed parts of the world (UN, 2015). Four billion people (54% of global population) urban population is expected to reach 6.4 billion (66% of global population) by 2050 (UN, 2015). More importantly, 98% of cities in low- and middle-income countries with more than 100,000 inhabitants do not meet World Health Organization (WHO) air quality limits (WHO, 2016a, b). This is resulting in estimated costs of up to 5% of GDP in developing countries (UNEP, 2015a), and 3.3 million estimated premature deaths worldwide (mostly due to ambient $PM_{2.5}$ - particulate matter with aerodynamic diameter under 2.5 μm) (Lelieveld et al., 2015). $PM_{2.5}$ pollution has been long identified as a significant cause of deteriorating cardiopulmonary health conditions (Pope and Dockery, 2006). Global atmospheric chemistry model projections based on a business-as-usual emission scenario estimate that the contribution of outdoor air pollution to premature mortality could double by 2050 (Lelieveld et al., 2015), unless something is done about the pollution in rapidly growing urban areas responsible for a great share of pollution production.

Most of the urban air quality studies, however, focus on the megacities or large cities (more than 10 or 5 million people,

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respectively) in the regions of North America, Europe and recently Asia. Meanwhile about 42% of global population, or 78% of all urban population, lives in not much considered cities with less than 5 million people (Demographia, 2016; UN, 2015). A limited research studies have been published sharing air quality problems in other regions like for example Latin America (Molina and Molina et al., 2004; Bella et al., 2006; Romieu et al., 2012; Romero et al., 1999), and those have also mainly focused on the most populous cities such as Sao Paulo, Mexico City, Buenos Aires, Rio de Janeiro, Santiago, etc.

As an extreme example, out of 109 most polluted cities ($PM_{2.5}$ concentrations $\geq$50 $\mu g/m^3$, more than five times exceeding WHO's recommendations for annual particulate exposure) only 5 are megacities and 6 are large cities, while 98 cities have population less than 5 million people – mid-size and small cities (WHO, 2014). The biggest fraction of population of the mentioned cities (39%, equal to over 90 million people) live in mid-size cities (1–5 million people) of Asia, Middle East, Africa and South America. In addition, the most polluted are the large and mid-size cities (average $PM_{2.5}$ concentrations 85 $\mu g/m^3$ and 72 $\mu g/m^3$, respectively), while the megacities are the least polluted from the group. This raises a question, of why the smaller cities are more polluted than megacities of the world?

The main source of urban pollution as estimated in Southern Hemisphere (and tropics) counting up to 26–36%, with an exception of Africa (where domestic fuel burning is a leading cause of urban air pollution), is traffic (Karagulian et al., 2015). Thus exposure to air pollutants is beyond the control of individuals and requires action by public authorities at the regional, national, and even international levels (WHO, 2016c). While most developing countries have yet to adopt significant measures to reduce urban pollution, such as fuel quality and vehicle emission reduction technologies, the municipality of Quito, and ultimately the Ecuadorian government have approved and implemented a number of regulations during the last decade. However, apart from a few national reports and a small number of scientific articles, not much is known about the air quality of Quito (Jurado, 1991; Puga, 1994; Jurado and Southgate, 1999; Carrillo et al., 2013; Rybarczyk and Zalakeviciute, 2016; Kleine Deters et al., 2017). Quito represents the category of thousands of unstudied mid-size and small rapidly growing problematic cities in the developing world, contributing to the growing number of premature deaths, and to the lack of scientific awareness critical for managing the urban air quality worldwide. In support, according to a recent study it has been shown that the fastest growing urban areas are mid-size and small cities, which makes them the most vulnerable to natural hazards (Birkmann et al., 2016).

This study is the first comprehensive analysis of regulation effect on fine particulate matter pollution in a South American mid-size city. The objectives are to identify the existing particulate pollution problems in Quito, by studying $PM_{2.5}$ concentrations at different points of the city; and to quantify the effect of air quality improvement initiatives on long-term $PM_{2.5}$ pollution in the city during the last 11 years.

2. Materials and methods

2.1. Site description

Ecuador is one of a few countries in South America with only 64% of the total population living in urban areas. However, as in most of the world, the trend has been changing in the last few decades and more people reside in the urban areas (UNDP, 2014). One of the two most populated cities of the country, the most populous high elevation city, the capital Quito, stretches north to south on a long plateau lying on the east flanks of the Pichincha volcano (summit 4800 m.a.s.l.) of the Andes cordillera at an average elevation of 2815 m.a.s.l. (EMASEO, 2011). Currently the city has expanded to a metro area of 4218 km^2 with a population of 2,239,191 according to the last census of 2010 (INEC, 2013a). The city is positioned in a number of terraces varying in elevation from 2700 to 3000 m.a.s.l., and expanding to nearby valleys at 2300–2450 m.a.s.l. Due to Quito's location on the equator, it has direct sunlight all year long, but due to its elevation, it has a spring-like climate with an average temperature of 14.5 °C (EMASEO, 2011).

2.2. Instrumentation and computations

The municipal office of environmental quality, *Secretaria de Ambiente,* has been collecting air quality and meteorological data since May 1, 2007 in a number of sites around the city. Previous to that the city has been performing emission inventories since 2003, with a smaller air quality monitoring network. The *Secretaria de Ambiente* run measurement sites are located in representative areas throughout the city, varying by elevations depending on municipal districts (Fig. 1). We analyzed the real time data from six automatic measurement stations: southern valley site – Chillos (elev. 2453 m.a.s.l., coord. 78°27′36″ W, 0°18′00″ S), south location – Camal (elev. 2840 m.a.s.l., coord. 78°30′36″ W, 0°15′00″ S), north sites – Carapungo (elev. 2660 m.a.s.l., coord. 78°26′50″ W, 0°5′54″ S) and Cotocollao (elev. 2739 m.a.s.l., coord. 78°29′50″ W, 0°6′28″ S), and central sites – Belisario, a district urbanized before 1947 (elev. 2835 m.a.s.l., coord.78°29′24″ W, 0°10′48″ S) and Centro, a district urbanized before 1880 (the old town, elev. 2820 m.a.s.l., coord. 78°30′36″ W, 0°13′12″ S).

Quito air quality stations are set up on the patios or terraces of buildings meeting the Environmental Protection Agency of the United States (USEPA) criteria for air quality monitoring stations. Particulate matter measurements were conducted using USEPA validated instrumentation. For $PM_{2.5}$ Thermo Scientific FH62C14-DHS Continuous, 5014i (EPA No. EQPM-0609-183) was used. The aerosol data were collected at 10 s intervals and then calculated to 24-h and annual averages using Igor Pro Software (Wavemetrics).

In addition, we were able to access $PM_{2.5}$ concentration data for two more years (2004 and 2005) from 2005 annual report (CORPAIRE, 2006a, b). And source apportionment estimates for 2003, 2005, 2007, 2009 and 2011 from annual air pollution inventories (CORPAIRE, 2006a, b; 2008, 2009; Secretaria de Ambiente, 2009; 2014).

Finally, to quantify the effects of each regulation on $PM_{2.5}$ concentrations we drew up a model based on a linear regression. The regression analysis was performed in Python with the use of the statistics module of the SciPy library. The objective of linear regression is to minimize a cost function, such as:

$$J(\theta) = \frac{1}{2m}\sum_{i=1}^{m}\left(h_\theta\left(x^{(i)}\right) - y^{(i)}\right)^2 \quad (1)$$

where m is the number of observations, y is the actual concentration in $\mu g/m^3$ and the hypothesis (or prediction) concentrations $h_\theta(x)$ in $\mu g/m^3$ is given by the linear model as follows:

$$h_\theta(x) = \theta_0 + \theta_1 x_1 \quad (2)$$

Where the coefficients θ_o and θ_1 are the intercept and slope of the linear regression, respectively; and x_1 is the feature value of the model (i.e., “year”). A batch gradient descent algorithm was used to perform this minimization, in which each iteration executed the following update: