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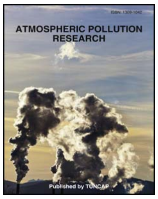

High-resolution air quality modeling in a medium-sized city in the tropical Andes: Assessment of local and global emissions in understanding ozone and PM_{10} dynamics

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ABSTRACT

Application of high-resolution air quality models in the Andes Region is scarce, especially in medium-sized cities of South America, which are undergoing a fast urban growth, increasing the risk associated with air pollution episodes. In this study, the WRF-Chem model was applied for analyzing the influence of local and global emission inventories (EI) in the representation of O_3 and PM_{10} concentrations in the medium-sized Andean city of Manizales, Colombia. Furthermore, the relative impact of anthropogenic emissions on O_3 and PM_{10} dynamics was evaluated. The use of local emission fluxes allowed significant improvements in O_3 representation, characterized by better performance metrics (MGE, RMSE and r coefficient of 7.6 ppb, 8.8 ppb, and 0.81 respectively) than that obtained from the use of the EDGAR-HTAP global database (MGE = 11.6 ppb, RMSE = 13.9 ppb and r = 0.64). In terms of PM_{10} concentrations, better metrics were obtained using the local EI (MGE = 10 $\mu g/m^3$ and RMSE = 11.5 $\mu g/m^3$), compared with those from the global EI (MGE = 28 $\mu g/m^3$ and RMSE = 28.8 $\mu g/m^3$). Analysis of the relative impact of anthropogenic emissions suggests that PM_{10} levels and ozone chemistry in the urban area of Manizales were controlled by emissions of its precursors from on-road vehicular sources and possible transport of O_3 at a regional scale from near rural zones. Results obtained highlight the importance of estimating and improving local EIs in medium-sized cities, for a more realistic analysis of emission impacts.

1. Introduction

During the last decades, the continuous growth of urban areas has produced high levels of traffic, industrialization and energy consumption, increasing emissions of air pollutants to the atmosphere. This phenomenon raised concern about air pollution episodes in urban environments and its adverse effects on human health, situation that is particularly severe in cities of emerging countries (D'Angiola et al., 2010; Franco, 2012). High levels of urbanization characterize Latin American cities, with 79.5% of population living in urban areas by 2014, behavior observed not only in megacities but also in medium-sized cities with population less than 1 million inhabitants (UN, 2014). This fact emphasizes the necessity of robust Air Quality Management Plans (AQMP), which include abatement strategies to tackle air pollution events and prevention policies to avoid future pollution episodes. For this purpose, numerical modeling has been recognized as an essential tool for studying and forecasting the impacts and dynamics of gases and aerosols on air quality (Freitas et al., 2009), being a fundamental component of AQMP (Borge et al., 2014). The use of air quality models allows, for example, studying emission source contributions to air pollution, as well as the evaluating changes in pollutant concentrations with respect to various emission scenarios (Zárate et al., 2007).

Thanks to the computational advances during the last decades, eulerian three-dimensional chemistry transport models (CTM) with fully coupled meteorology and chemistry have been widely used for air quality studies (Longo et al., 2013). Furthermore, the recognized influence of weather on air quality (e.g. in transport processes, removal and chemical transformation) and the effects of chemistry in meteorology (e.g. in cloud formation and radiation budget), encouraged the development of unified and on-line modeling systems (Grell et al., 2005). According to Grell and Baklanov, 2011, the on-line approach in

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CTM is numerically more consistent and gives a more realistic representation of the atmosphere, especially when a high-resolution domain is required.

The complexity of urban centers makes the implementation of CTM a challenging task (Borge et al., 2014). One of its essential components is the emissions inventory (EI), which provides information about the contribution of the different sources, generally on yearly basis and split according either a specific grid or administrative boundaries. Then, through the application of specific processing tools, emission input fluxes are derived from EI. They represent one of the terms of the mass continuity equation. According to Alonso et al. (2010), the increase in the use of CTM on local, regional and global scales, makes the estimation of EIs a key issue, supported also by the fact that the representation of primary and secondary pollutants can be significantly improved when high-resolution emissions are used. However, there are still important deficiencies in emissions estimation worldwide, especially in emerging countries. Different efforts have been made by international cooperation programs in order to provide gridded emission information at global and regional scales. Global EIs such as RETRO (REanalysis of TROpospheric chemical composition) and EDGAR (Emissions Database for Global Atmospheric Research) are available to scientific community for its use in numerical modeling studies (Butler et al., 2008). Although global EIs are characterized by their low spatial and temporal resolution, some recent versions of global emission datasets have increased considerably their spatial resolution (e.g. EDGAR-v4 with 0.1 × 0.1deg). However, the information provided by these global datasets could differ from local EIs due to factors such as the use of activity data at a national level (e.g. from the energy balance statistics of the International Energy Agency, IEA), different approaches in computing the geographical distribution of emissions within each country (e.g. as a function of population density), and differences in emission sources and pollutants (Gurjar et al., 2004; Butler et al., 2008). These characteristics increase uncertainties in the representation of emissions, especially in urban areas of South America, where majority of countries have serious deficiencies in emission data and measurement campaigns (Alonso et al., 2010).

The use of CTM in South American countries has focused mainly in large urban areas. Some examples are the study of ozone (O_3) formation in the Sao Paulo Metropolitan Region (SPMR) in Brazil (e.g. Da Silva and Andrade, 2013; Vara-Vela et al., 2016; Hoshyaripour et al., 2016) and the Metropolitan Region of Lima in Peru (Arellano, 2013); the study of aerosol dynamics in SPMR (Vara-Vela et al., 2016); the evaluation of a forecast system for southeastern Brazil (Andrade et al., 2015); the study of carbon monoxide (CO) and its use to obtain particulate matter (PM) predictions in Santiago, Chile (Saide et al., 2011); and the evaluation of industrial point-source emission scenarios in Buenos Aires, Argentina (Fernández et al., 2010). These studies reported the use of on-line CTM including local emission datasets. Furthermore, regional scale simulations in South America analyzed phenomena such as the effects of biomass burning emissions in the Amazon region (e.g. Freitas et al., 2007; Longo et al., 2010, 2013), the influence of vehicular emissions in transport of nitrogen oxides (NO_x), CO and O_3 (Alonso et al., 2010) and the study of windblown dust in Argentina (Cremades et al., 2017). Majority of these regional studies integrated both local and global emission datasets.

In Colombia, air quality studies using CTM are scarce and focused only in large cities such as Bogotá (the capital of Colombia) and Medellin, as they have not been fully integrated into air quality management systems. These cities reported previously the implementation of off-line CTM in studies such as the evaluation of two emission inventories in Bogotá (Zárate et al., 2007) and the analysis of NOx and VOC precursors in dynamics of O_3 formation in Medellín (Toro et al., 2006). Recent studies have reported the use of on-line CTM for the study of urban air pollution in Bogotá, analyzing the behavior of pollutants such as O_3, CO and PM_{10} (Kumar et al., 2014, 2016; Rincón, 2015; Nedbor-Gross et al., 2014, 2017). Clearly, medium-sized cities not only in Colombia but also in South American countries are scarce in air pollution studies, especially those using numerical models to understand the impact of emission sources on ambient air pollutant levels, and to study their dynamics of transformation and dispersion. These urban areas will experiment the fastest urban growth (UN, 2014), increasing the risk associated with possible air pollution episodes. However, the significant deficiencies in the knowledge of the local emission fluxes, combined with limited information about measurements of ambient air pollutants, produce additional difficulties in the application of CTM for the study of local air pollution dynamics.

The medium-sized city of Manizales, Colombia (urban population: 368000), is located on the western slopes of the central Cordillera of the Andes at 2150 m above sea level. Emissions from vehicular, industrial and volcanic sources influence the air quality in a city characterized by a limited area for growth and a relatively high urban density (~6800 inhabitants/km^2). Furthermore, the low local wind velocities registered in the urban area - not exceeding 4 m/s – could enhance local pollution episodes. A recent EI estimated in Manizales (González et al. 2017) revealed that on-road vehicular sources dominated the anthropogenic emissions, with higher vehicular releases of CO (43.4 Gg/yr) followed by non-methane volatile organic compounds (NMVOC) with 9.6 Gg/yr; mainly associated with the use of motorcycles. Other pollutants with more than 90% of contribution from anthropogenic sources were NO_x (4.9 Gg/yr) and PM_{10} (0.8 Gg/yr), being public transport (buses) its main emission source. NO_x and NMVOC are precursors of tropospheric ozone (O_3), an important secondary pollutant in urban environments due to its harmful effects on human health and vegetation (Wang et al., 2017), and its contribution to radiative forcing and climate change effects (Karlsson et al., 2017). PM_{10} is another pollutant of particular interest in the study of air quality over urban areas, linked with harmful effects on human health (Park et al., 2012). PM_{10} is the main pollutant measured by Manizales air quality monitoring network (AQMN) (González et al., 2015).

There is a lack of knowledge about the relative impact of anthropogenic sources (vehicular and industrial) on O_3 formation and PM_{10} ambient concentrations over Manizales, as well as on how the meteorology of this Andean region influences dispersion of theses pollutants in the urban area and nearby zones. Considering this background and the existing deficiencies in the application of CTM in South American medium-sized cities – characterized by a lack of local emissions information, this study established two objectives: First to evaluate the influence of using the local or a global EI on modelled air quality in a complex terrain area such as Manizales. This analysis seeks to study the advantages or limitations of using global emission datasets in a high-resolution simulation, and to determine if the local EI could improve the representation of air pollutant dynamics in Manizales. Second, to study the relative impact of on-road vehicular and industrial point-source emissions on PM_{10} concentrations and O_3 formation over this medium-sized Andean city.

2. Materials and methods

2.1. Model configuration and study design

The Weather Research and Forecasting with Chemistry (WRF-Chem) community model version 3.7.1 (Grell et al., 2005) was used for the air quality simulations. The Eulerian meteorological core of the model, The Advanced Research WRF (ARW), is fully compressible and non-hydrostatic. It is designed for both research and operational forecasting, includes two options of dynamic cores and several options of physical parameterizations (Skamarock and Klemp, 2008). Modeling of trace gases and particulates is performed simultaneously with meteorological fields in WRF-Chem following an on-line approach. The model uses the same time step for transport and vertical mixing, same parameterizations and grid configuration, being fully consistent with the meteorological component (Fast et al., 2006). Further details on WRF-