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Emission inventories and modeling requirements for the development of air quality plans. Application to Madrid (Spain)

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HIGHLIGHTS

- A comprehensive and flexible urban emission inventory was developed for Madrid.
- Options for multi-scale consistency are discussed (from European to street level).
- Urban background NO_2 concentration levels well described by CMAQ (MB −2.2 μg/m^3).
- NO_2 concentration levels in Madrid are dominated by local traffic (up to 90%).
- A 31% reduction of NO_X emissions may allow Madrid meeting the NO_2 European standards.

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ABSTRACT

Modeling is an essential tool for the development of atmospheric emission abatement measures and air quality plans. Most often these plans are related to urban environments with high emission density and population exposure. However, air quality modeling in urban areas is a rather challenging task. As environmental standards become more stringent (e.g. European Directive 2008/50/EC), more reliable and sophisticated modeling tools are needed to simulate measures and plans that may effectively tackle air quality exceedances, common in large urban areas across Europe, particularly for NO_2. This also implies that emission inventories must satisfy a number of conditions such as consistency across the spatial scales involved in the analysis, consistency with the emission inventories used for regulatory purposes and versatility to match the requirements of different air quality and emission projection models. This study reports the modeling activities carried out in Madrid (Spain) highlighting the atmospheric emission inventory development and preparation as an illustrative example of the combination of models and data needed to develop a consistent air quality plan at urban level. These included a series of source apportionment studies to define contributions from the international, national, regional and local sources in order to understand to what extent local authorities can enforce meaningful abatement measures. Moreover, source apportionment studies were conducted in order to define contributions from different sectors and to understand the maximum feasible air quality improvement that can be achieved by reducing emissions from those sectors, thus targeting emission reduction policies to the most relevant activities. Finally, an emission scenario reflecting the effect of such policies was developed and the associated air quality was modeled.

1. Introduction

Modeling is an essential tool for the development of atmospheric emission abatement measures and Air Quality Plans (AQP). Frequently, these plans are related to urban environments where the emission sources as well as the exposed population are concentrated (Vlachokostas et al., 2009; EEA, 2011). Developing a set of reliable tools for air quality modeling at urban scale is a very challenging task due to the fact that urban environments are particularly complex. The environments are characterized by the presence of several pollutants emitted from multiple sources. Moreover, a series of different spatial and temporal scales are involved in the chemical transformation and transport processes of such pollutants. The inherent complexity of urban environments requires simulation tools to assess air quality levels to be able to support the analysis and evaluation of a variety of policies and emission abatement measures (Denby et al., 2011).

As environmental standards increase in strictness, more reliable modeling tools are needed to simulate any measure or plan intended to effectively tackle air quality exceedances. This fact implies the need to count on reliable and flexible inventories that integrally describe the emissions of urban sources, in accordance with the requirements of

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the applied air quality models (FAIRMODE, 2010). There are a number of global and regional inventories that have been found useful to support air quality modeling studies (Pouliot et al., 2012; European Commission, 2009; Vestreng, 2003). Even at the urban scale, numerous inventories have been developed all over the world (Sturm et al., 1999; Sowden et al., 2008; Venegas and Mazzeo, 2006; Ho and Clappier, 2011 among others). However, there is a lack of harmonized and scientifically sound methodologies to address the compilation of urban scale inventories and to secure their consistency with existing regional and national inventories (Vedrenne et al., 2012).

Nitrogen dioxide is a clear example of a legislated air pollutant (EU Directive 2008/50/EC) with important implications for human health (Latza et al., 2009) that still poses an important challenge. Despite recent efforts made in Europe, ambient air concentrations of NO_X lag clearly behind the decreasing trend of NO_X emissions (Guerreiro et al., 2010). This is relevant for the compliance of NO_2 limit values, especially in urban environments. In 2010, 22 of the 27 EU Member States recorded exceedances of the limit value (EEA, 2012). Madrid (Spain) is one of the European cities where NO_2 is the main air quality issue and is legally bounded to develop an AQP to meet the required limit values (further details are provided in Section 2).

Specifically from the perspective of emission inventories, NO_X are also especially interesting since actual emission rates and chemical speciation depend to a large extent on how engines and combustion devices are operated and maintained as well as technological changes. This is particularly true for the road transport sector (Lee et al., 2013; Simmons and Seakins., 2012; Liu et al., 2009; Grice et al., 2009) which often constitutes the single most important source of NO_X emissions in urban environments. In addition, urban scale inventories usually need a fine spatial and temporal resolution, which cannot be achieved by downscaling methods or top-down inventories. This implies that methods to relate emissions with transport patterns and relevant activity data are need in the compilation of local inventories (Ariztegui et al., 2004).

The present study describes the modeling activities carried out for Madrid (Spain). The developed work is an illustrative example of the combination of models and emission data that are needed to provide a comprehensive picture of air quality at the urban scale and thus, provide the basis for the formulation of AQP.

2. Case Study

Madrid is the capital and largest city in Spain, located in the center of the Iberian Peninsula with a total population of 5 million people in its metropolitan area. Despite the experienced population and traffic increase, air quality levels have improved in the city over the last decade. However, some pollutants like nitrogen dioxide (NO_2) still exceed the limit values (LV) according to the European legislation. The NO_2 annual average recorded in most of the city's traffic air quality monitoring stations is usually above the LV (40 μg/m^3). This phenomenon is basically attributed to heavy traffic levels and to a strong dieselization of the fleet in recent years (Kassomenos et al., 2006).

In 2007, 80% of the monitoring stations exceeded the ambient air quality standards. As a consequence, important modeling efforts are being made to improve the knowledge about air quality dynamics in Madrid and to identify the most effective abatement options to meet the NO_2 LV in the near future. This work constitutes an extension of the integrated assessment modeling activities in Spain, which intends to provide useful tools for local policymakers to this respect (Borge et al., 2007). In particular it reports on the methods and results of the development and assessment of a local AQP enacted by the Madrid municipality (Madrid City Council, 2012) with a temporal horizon up to 2015. According to the latest data available (year 2012), the situation has improved substantially although 10 (out of 24) monitoring stations still report NO_2 annual means above the LV.

3. Methods

3.1. Mesoscale modeling

Urban concentration levels depend on the atmospheric phenomena that occur at different spatial scales, namely from international scales of thousands of km to street levels of a few meters (Monteiro et al., 2007). Additionally, these levels present complex interactions with a large variety of chemicals in the atmosphere. Up to now, no single model can describe these processes consistently so a combination of models is needed to address such description. Moreover, the choice of the model is basically dependent on the purpose of the simulation. In this context, last-generation, 3D Eulerian models equipped with full photochemical schemes can consistently describe transport and transformation processes of NO_X and tropospheric O_3 (the main species involved in the complex dynamics of photochemical chemistry) from continental to urban scale.

The mesoscale modeling system is based on the Weather Research and Forecasting (WRF) (Skamarock and Klemp, 2008), the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system (Institute for the Environment, 2009), and the Community Multiscale Air Quality (CMAQ) (Byun and Ching, 1999; Byun and Schere, 2006). Details about specific configuration and adaptation to the Spanish conditions can be found respectively in Borge et al. (2008a, 2008b; 2010a).

Four nested domains (Fig. 1) were used in order to capture international, national, regional and local contributions to NO_2 to ambient concentration in Madrid with a maximum resolution of 1 km^2 (Table 1). Each domain used dynamic boundary conditions from its immediate mother domain, except D1 that was run with fixed lateral chemical boundary conditions (details regarding CMAQ boundary conditions can be found in Borge et al., 2010a). A similar nesting approach was applied for the simulation of meteorology. The mother domain for the WRF model (slightly larger than D1 shown in Fig. 1) was run with initial and boundary conditions from the National Centers for Environmental Prediction (NCEP) Global Tropospheric Analyses with 1° × 1° spatial resolution and temporal resolution of 6 h. This mesoscale configuration was found useful to describe urban background pollution levels, meeting the EU benchmarks for regulatory NO_2 modeling. The model uncertainty according to the Relative Directive Error (RDE) for this application reaches 23.7% (hourly LV) and 22.4% (annual LV), well below the maximum RDE criteria of 50% and 30%, respectively (Fig. 2). This corresponds to a global mean bias (MB) of −2.2 μg/m^3, a mean fractional bias of −14.1% and a global correlation factor (r) of 0.63.

3.2. Hotspot modeling

Despite a satisfactory performance of the mesoscale system, NO_2 presents strong concentration gradients that cannot be reproduced by mesoscale Eulerian models since large concentration variations typically exist within the extension of a grid cell. Such gradients have been observed in many urban environments (e.g. Vardoulakis et al., 2011) including specific measurement campaigns with passive samplers performed in Madrid (Karanasiou et al., 2011). In order to depict street level concentration gradients, specific and local-scale tools are needed; either high-resolution flow models that can resolve the buildings or semi-empirical street canyon models able to capture this variability (Vardoulakis et al., 2003).

To this respect, CFD (Computational Fluid Dynamic) models are very expensive computationally and can only be applied to spatially and temporally restricted domains. For this reason, simpler, parameterized operational street canyon models are preferred for planning and regulatory purposes (Vardoulakis et al., 2007). Street-scale systems, such as the Operational Street Pollution Model (OSPM) (Berkowicz et al., 2008) used in this study, are based on a combined plume and box model that can simulate in-street emissions and dispersion (including traffic-induced turbulence) according to local building