MODELLING ACTIVITIES FOR THE DEVELOPMENT OF AIR QUALITY PLANS IN MADRID (SPAIN)

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Abstract
Modelling is an essential tool for the development of 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 modelling 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 modelling tools are needed to simulate measures and plans that may effectively tackle air quality exceedances, common in large urban areas across Europe, particularly for NO₂. 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 modelling activities carried out in Madrid (Spain) highlighting the 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, including:
- source apportionment studies to define contributions from the continental, national, regional and local scale in order to understand to what extent local authorities can enforce meaningful abatement measures
- source apportionment studies (zeroing-out) 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
- emission scenario development reflecting the effect of such policies
- definition of additional measures to be applied under high-pollution episodes

Key words: Urban air quality modelling, NO₂, Air quality planning, WRF, SMOKE, CMAQ, Madrid, Spain

INTRODUCTION
Modelling is an essential tool for the development of emission abatement measures and air quality (AQ) plans. Most often these plans are related to urban environments where both emission sources and exposed population concentrate (EEA, 2012). The development of reliable tools for air quality modelling at urban scale poses a very challenging task since urban environments are particularly complex for a number of reasons (multiple pollutants and sources, multiple temporal and spatial scales involved and the need to implement effective abatement measures). As environmental standards become more stringent (e.g. European Directive 2008/50/EC), more reliable and sophisticated modelling tools are needed to simulate measures and plans that may effectively tackle air quality exceedances, common in large urban areas across Europe, particularly for NO₂ (Grice et al., 2009). This implies the need to count on reliable and flexible inventories that describe the emissions of urban sources thoroughly and in accordance with the requirements of the air quality models applied. This study reports the modelling activities carried out in Madrid (Spain) as an illustrative example of the combination of models and emission data needed to provide a comprehensive picture of air quality at the urban scale and therefore, provide the basis for air quality plans development.

Case study
Madrid is the capital and largest city in Spain, located in the centre of the Iberian Peninsula. The Madrid metropolitan area is home to more than 5 million people. Despite economic growth, air quality levels have improved in Madrid over the last decade. Nevertheless, some pollutants still exceed the limit values (LV) according to the European legislation. The NO₂ annual average recorded in most of the traffic air quality monitoring stations across the city are well above the LV (40 µg/m³). Heavy traffic and a strong dieselization of the fleet in recent years are the main causes for this phenomenon.
METHODOLOGY
Urban concentration levels depend on atmospheric phenomena that occur at different spatial scale, from international (thousands of km) to street level (m) and present interactions with a large variety of chemicals in the atmosphere. The choice of the model type would depend on the main purpose of the simulation. In this context, last-generation, 3D Eulerian models including full photochemical schemes can consistently describe transport and transformation processes of NOX and tropospheric O3 from continental to urban scale so they are suitable for the development and analysis of urban-scale strategies.

Air quality modelling system
Four nested domains (Figure 1) were used in order to capture international, national, regional and local contributions to observed NO₂ levels in Madrid with a maximum resolution of 1 km². The mesoscale modelling system is based on the Weather Research and Forecasting (WRF) (Skamarock and Klemp, 2008), the Sparse Matrix Operator Kernel Emissions (SMOKE) modelling system (Institute for the Environment, 2009) and the Community Multiscale Air Quality (CMAQ) (Byun and Sehre, 2006). Details about specific configuration and adaptation to the Spanish conditions can be found respectively in Borge et al. (2008a, 2008b, 2010).

The system was found useful to describe urban background pollution levels, successfully meeting the EU benchmarks for regulatory NO₂ modelling. 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. This corresponds to a global mean bias (MB) of -2.2 \( \mu g/m^3 \), mean fractional bias of -14.1% and a global correlation factor (r) of 0.63. Some other statistics and indicators regarding this particular application can be found in Pederzoli et al (2012).

Emission inventories
Emissions constitute a key input to air quality models since they are one of the main sources of uncertainty and are critical for the analysis of the alternatives to improve air quality (FAIRMODE SG3, 2010). In addition, they have to be flexible and detailed enough to reflect the outcome of relevant measures and meet the modelling system requirements (Borge et al., 2008b). Consequently, a specific emission inventory has been developed/adapted for each of the four modelling domains in this application. Emission processing is performed by SMOKE in all cases. Details on the data and procedure developed to compile emission inventories for domains D1 (Europe), D2 (Iberian Peninsula) and D3 (Greater Madrid Region), are given in Borge et al. (2012).
According to our computations, road traffic (SNAP group 07) is responsible for 57% of NOX emissions in the modelling domain (70% inside the city). Therefore, the inventory must have the capability to simulate strategies aimed at cutting down emissions from this sector such as implementation of low emission zones, variation of speed limits, penetration of new technologies, specific fleet turnover and limitations by segments, measures to alleviate urban congestion, etc.

The reference model for calculating emissions from road traffic was COPERT IV (Ntziahristos et al., 2009). The main source of the information used to feed COPERT was the traffic model of the Municipality of Madrid. It is a macroscopic simulation model for equilibrium dynamic traffic assignment supported by a Geographic Information System (GIS) where the road network of the metropolitan area of Madrid is represented by 14,938 links. Each of these road segments falls in any of the 9 management areas shown in Figure 2. Traffic flows and average hourly speeds were available at link level while fleet composition has been estimated at management area level. Fleet characterization was done according to a series of field campaigns by the Madrid Municipality to reflect the age and structure of the actual running fleet. Passenger cars are responsible for more than 80% of total travelled vehicles-km. The passenger car fleet of Madrid (3327200 vehicles) is relatively new (average age of 4.9 years) and strongly dominated by diesel vehicles (more than 70% of passenger cars share). This information allows the computation of emissions for each vehicle type (passenger cars, light duty vehicle, heavy duty vehicles, buses, motorcycles and mopeds) at link level with 1-hour temporal resolution. Subsequent spatial allocation of emissions in the Eulerian grid for air quality modelling is carried out by overlapping with the 1 km² mesh. Emissions from SNAP 07 were mapped into 63 SMOKE categories (combination of vehicle type and management areas). This approach allows simulating area-specific or vehicle-specific measures in a rather straightforward way. Each of them was assigned a specific NO/NOX ratio (a critical parameter to assess NO2 ambient concentration in urban environments) to reflect the diesel/gas share for every kind of sector in different areas of the city. The last version of COPERT provides information of more than 60 individual volatile organic compounds. They were mapped into CB05 species (Yarwood et al., 2005) to produce 9 VOC profiles to represent VOC composition at management area level.

Besides road traffic, all the relevant sectors have been represented with a sufficient detail. Relatively important sources such as those of the domestic, residential and commercial sector (SNAP 02) have been inventoried under a bottom-up approach and high disaggregation.

APPLICATIONS AND RESULTS
Once model-ready emissions were accomplished, the modelling system was used to perform a series of analysis and experiments that resulted in the definition of a complete strategy to meet the NO2 air quality standards required by 2015 in Madrid. A brief summary of these applications is provided in this section.
Source apportionment
Apportionment of NO₂ levels is an explicit requirement in the development of an air quality plan intended to demonstrate future compliance under the European Legislation. Nonetheless, this kind of exercise is actually needed to define meaningful abatement options. The analysis for the relevant time period (e.g. annual basis for the NO₂ annual LV) provides essential information regarding the basic emission abatement strategy, maximum feasible AQ improvement and external constrains. A zero-out or brute force method was followed in this application (Borge et al. 2012). According to the results, NO₂ pollution in Madrid is due basically to local sources, mainly road traffic, constituting the main target sector, responsible up to 90% of NO₂ levels in the city centre and 60% as an average in the modelling domain.

Emission scenario
Up to 70 abatement measures have been assessed and evaluated for the final definition of the Air Quality plan. A global decrease of 31% in NOₓ emissions is expected in the year 2014, mainly due to measures in the road transport sector (40% decrease). Emissions, surrogate data and speciation profiles were updated to reflect the expected composition of fleet and other structural measures. The simulation of a 2014 scenario including the 70 abatement measures included in the Air Quality Plan points out that compliance could be achieved. Figure 3 compares CMAQ outputs for 2007 (base year) and 2014 (implementation of the air quality plan). According to this comparison it can be inferred that annual NO₂ levels may be reduced by 34% as an average; approximately 15 μg/m³ in the city center, also with an important impact in the metropolitan area (-7 μg/m³ as an average in the modelling domain). 1-hour concentration peaks may also decline by 40% approximately in most of the city.

![Figure 3. Expected effect of the Madrid Air Quality Plan in NO₂ concentration values (1-hour limit value and annual limit value)](image)

CONCLUSIONS
The development and assessment of an Air Quality Plan (AQP) in an urban area constitutes a very complex task from the air quality modelling point of view. The definition of effective abatement measures implies the need of a previous analysis of source apportionment regarding both, the geographic origin of pollutants and the identification of sources responsible for their emission. These analyses involve rather different temporal and spatial scales and require the combination and harmonization of models and data. Emission inventories play a crucial role in this context, since the assessment of a given measure will entirely depend on how accurate is the representation of that measure in terms of emissions. Therefore, the emission processing system used in this kind of applications should be able to combine...
information from a variety of sources and it needs to be flexible and detailed enough to reflect the outcome of relevant emission reduction measures.

This paper summarizes the modelling activities carried out in Madrid (Spain) to develop an AQP to comply with the stringent NO$_2$ European standards. The study demonstrates how the SMOKE system is able to accommodate emissions from at least four emission inventories from the European scale EMEP inventory to a very detailed bottom-up emission inventory for the Madrid city. The source apportionment exercises made for this AQP indicate that NO$_2$ ambient concentration values are strongly dominated by local sources with a remarkable contribution from road traffic. Therefore, a package of 70 measures, mostly targeted at this sector, was proposed and simulated. According to the results of this study, this scenario would cut down NO$_x$ emissions by 31% and would allow the fulfillment of NO$_2$ limit values in Madrid by the end of 2014.

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REFERENCES


