

# **Emission inventories and modeling activities for the development of air quality plans in Madrid (Spain)**

Rafael Borge, Julio Lumbreras, Javier Pérez, David de la Paz, Michel Vedrenne, Encarnación Rodríguez

Laboratory of Environmental Modelling.

Technical University of Madrid (UPM). C/ José Gutiérrez Abascal, 2. 28006- Madrid.

[rborge@etsii.upm.es](mailto:rborge@etsii.upm.es)

## **ABSTRACT**

Modeling 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 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<sub>2</sub>. 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 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

## **INTRODUCTION**

Modeling 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<sup>1</sup>. The development of reliable tools for air quality modeling at urban scale poses a very challenging task since urban environments are particularly complex for a number of reasons:

- Multiple pollutants are emitted from multiple sources

- Multiple spatial and temporal scales are involved in the chemical transformation and transport processes
- The simulation tools used to assess air quality levels have to be able to support the analysis and evaluation of a variety of policies and emission abatement measures aimed at the improvement of air quality

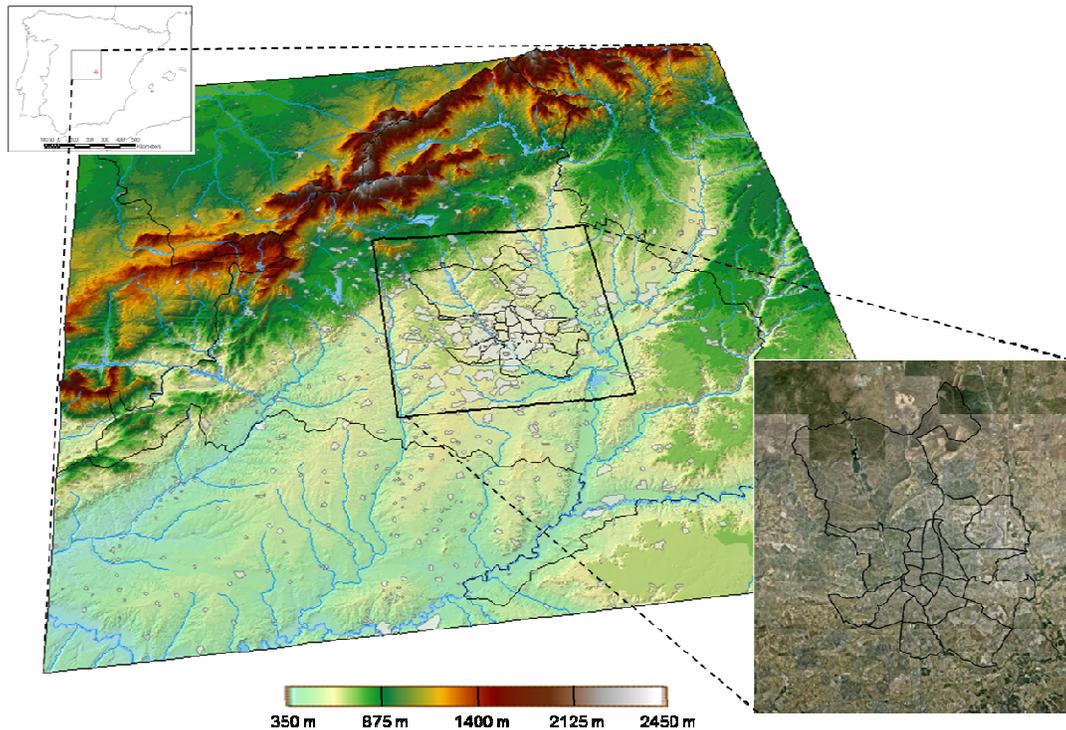
As environmental standards become more stringent (e.g. European Directive 2008/50/EC<sup>2</sup>), more reliable and sophisticated modeling tools are needed to simulate measures and plans that may effectively tackle air quality exceedances, common in large urban areas across Europe, particularly for NO<sub>2</sub><sup>3</sup>. 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 modeling 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 center of the Iberian Peninsula (Figure 1). The population of the city is roughly 3.4 million inhabitants, although 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 NO<sub>2</sub> annual average recorded in most of the traffic air quality monitoring stations across the city are well above the LV (40 µg/m<sup>3</sup>). Heavy traffic and a strong dieselization of the fleet in recent years are the main causes for this phenomenon.

Important modeling efforts are being made to improve our knowledge about air quality dynamics in Madrid and to nail down the most effective abatement options to meet the NO<sub>2</sub> LV in the near future. This work constitutes an extension of the integrated assessment modeling activities in Spain reported elsewhere<sup>4</sup>.



**Figure 1.** Location and general layout of the Madrid Greater Region and Madrid metropolitan area

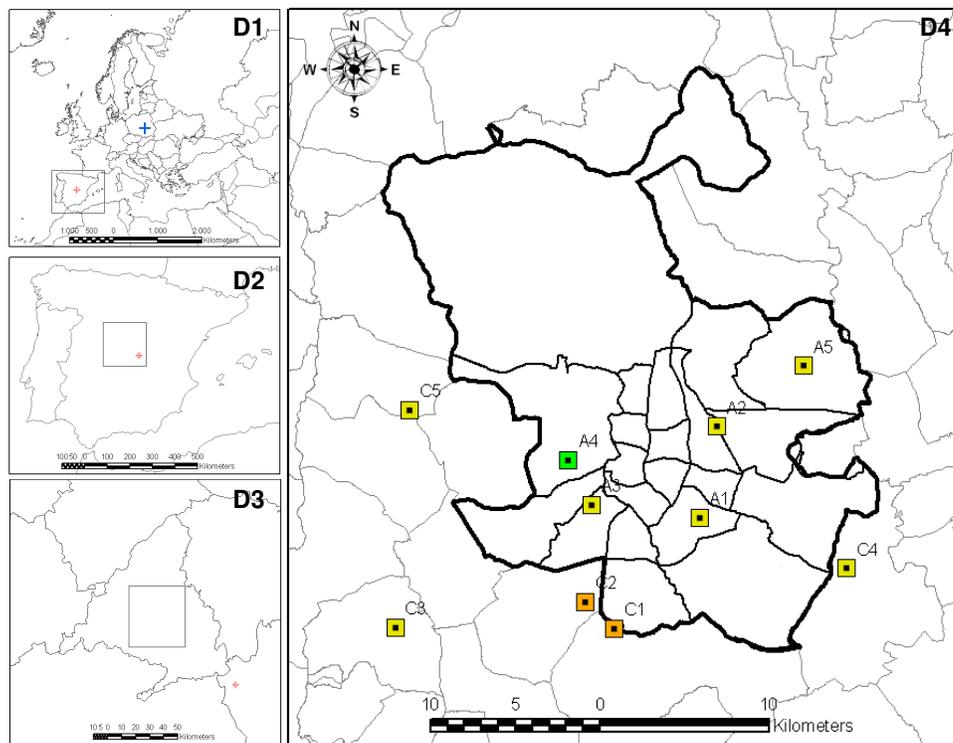
## MESOSCALE MODELING

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. No single model can consistently describe all these processes so a combination of models is needed to provide a consistent description throughout the scales. 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  $\text{NO}_x$  and tropospheric  $\text{O}_3$  (the main species involved in the complex dynamics of photochemical chemistry) from continental to urban scale. This is possible due to a series of features (further details can be found in Borge et al., 2009<sup>5</sup>):

- nesting capability
- scalable dynamics and thermodynamics (governing equations, variable states, coordinate system)
- modular coding structure and wide range of representation for scale-dependent processes

Four nested domains (Figure 2) were used in order to capture international, national, regional and local contributions to observed  $\text{NO}_2$  levels in Madrid with a maximum resolution of  $1 \text{ km}^2$  (Table 1). The mesoscale modeling system is based on the Weather Research and Forecasting (WRF)<sup>6</sup>, the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system<sup>7</sup> and the Community Multiscale Air Quality (CMAQ)<sup>8,9</sup>. Details about specific configuration and adaptation to the

Spanish conditions can be found respectively in Borge et al.<sup>10,11,12</sup>.

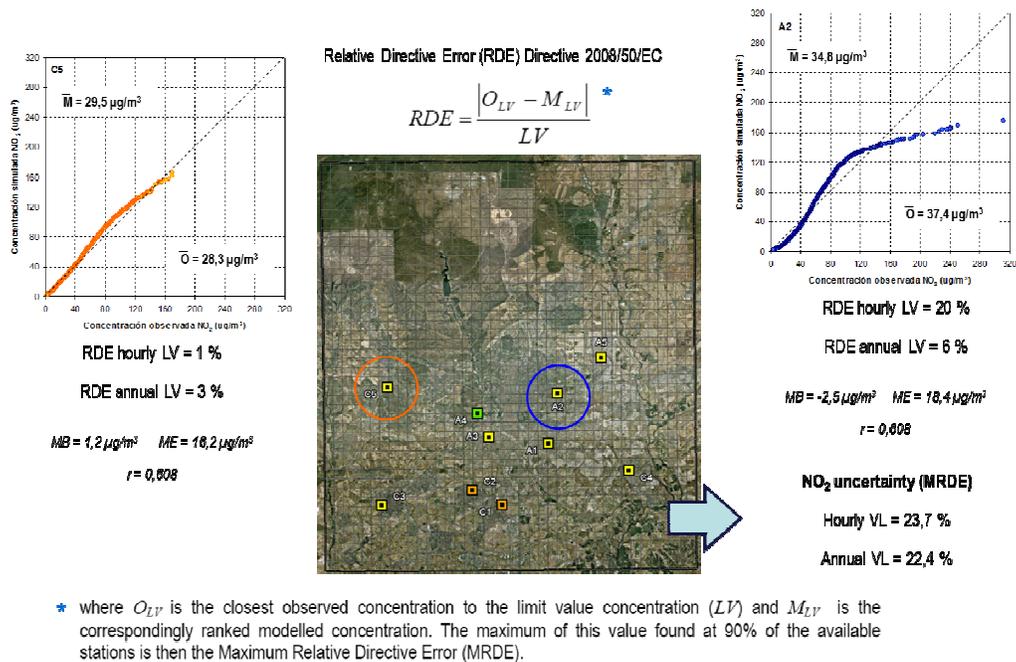


**Figure 2.** CMAQ modeling domains. The color squares represent the location of air quality monitoring stations used for evaluation proposes in the innermost modeling domain (1 km resolution). Squares in green, yellow and orange indicate the station type according to the air quality monitoring network (A – Madrid City Council, C – Madrid Greater Region).

**Table 1.** Spatial domains for the mesoscale modeling system

Domain	Geographic scope	X-Y dimensions (km)	Horizontal resolution (km)
D1	Europe	6144 x 5376	48
D2	Iberian Peninsula	1200 x 960	16
D3	Greater Madrid Area	192 x 192	4
D4	Madrid Metropolitan area	40 x 44	1

The mesoscale modeling system was found useful to describe urban background pollution levels, successfully meeting the EU benchmarks for regulatory NO<sub>2</sub> modeling. The model uncertainty according to the Relative Directive Error (RDE)<sup>2</sup> for this application reaches 23.7% (hourly LV) and 22.4% (annual LV), well below the maximum RDE criteria of 50% and 30% respectively (Figure 3). This corresponds to a global mean bias (MB) of -2.2 µg/m<sup>3</sup>, mean fractional bias of -14.1% and a global correlation factor (r) of 0.63.

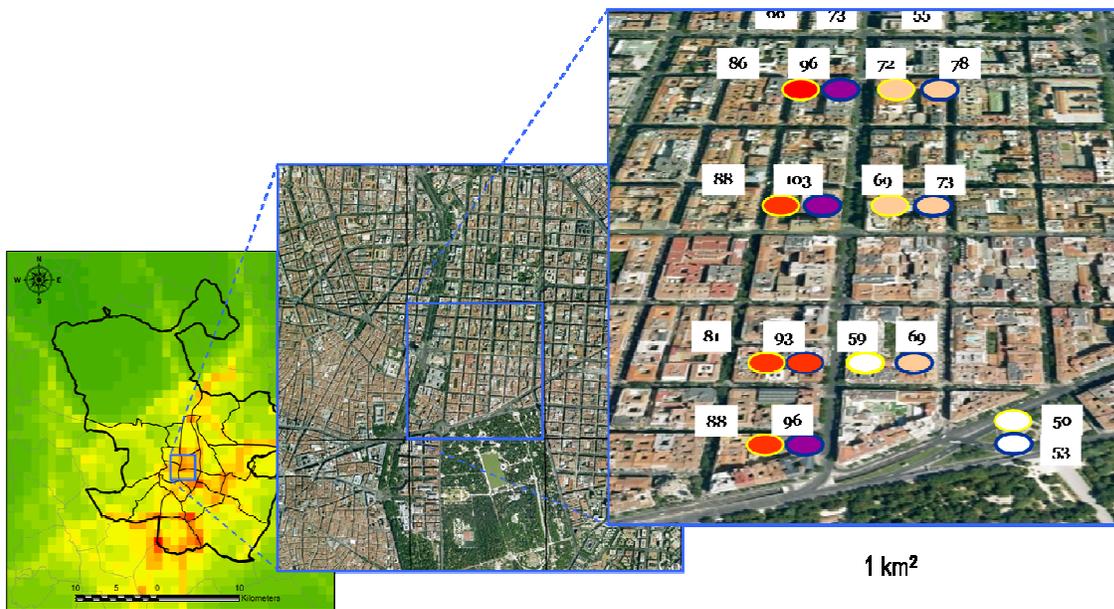


**Figure 3.** Computation and results of the RDE for the innermost domain and two examples for individual monitoring stations (C5 in the left and A2 in the right). C5 is a clear example of an urban background stations. Although A2 is also labeled as an urban background site is more influenced by direct traffic emissions.

## HOT SPOT MODELING

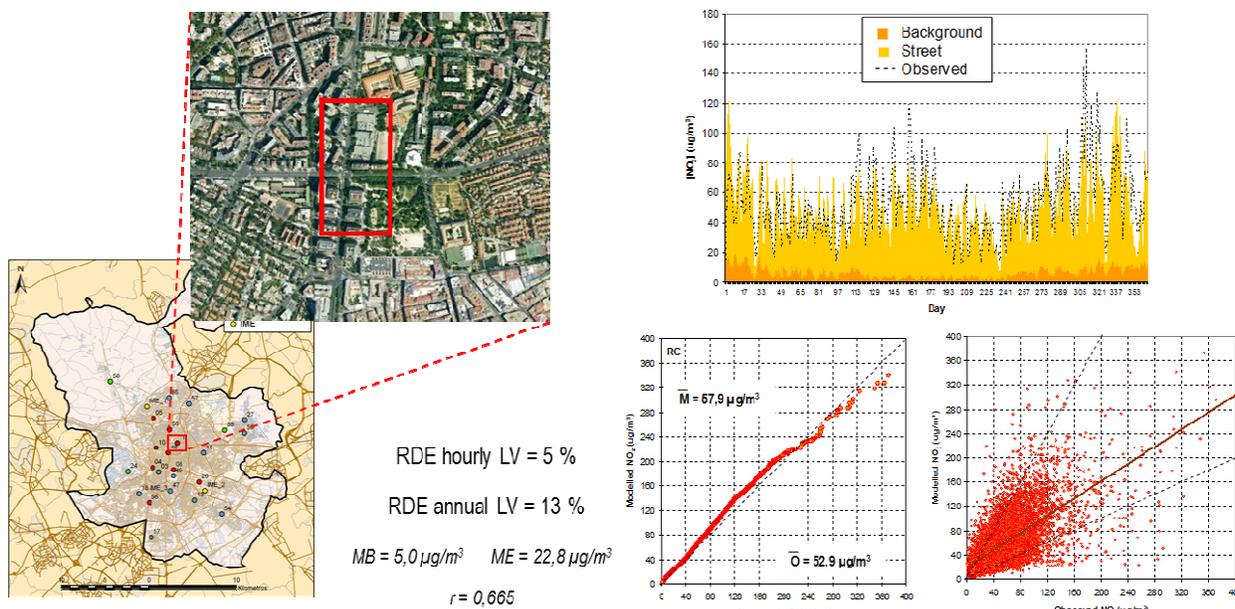
Despite a satisfactory performance of the mesoscale system, NO<sub>2</sub> presents strong concentration gradients that cannot be reproduced by Eulerian models since large concentration variations exist within the grid cell. Figure 4 illustrates the typical spatial variation of NO<sub>2</sub> at traffic locations. The figures in the white boxes indicate average NO<sub>2</sub> concentration values according to a measurement campaign with passive samplers performed in Madrid in 2009<sup>13</sup>.

Specific, local-scale tools are needed to capture street-level concentration gradients. Obstacle resolving models are high resolution flow models that can resolve the buildings. Most often CFD (Computational Fluid Dynamic (CDF) models are very expensive computationally and therefore they can only be applied for scientific research in restricted spatial and temporal domains. For this reason, simpler, parameterized operational street canyon models are preferred for planning and regulatory purposes. Street-scale systems, such as the Operational Street Pollution Model (OSPM)<sup>14</sup> used in this study, are based on a combined plume and box model that can simulate in-street emissions, eddies and diffusion (including traffic-induced turbulence) according to local building geometry. Besides the short computational time requirements, these models provide a rough representation of very fast chemistry (i.e. primary NO oxidation depending on O<sub>3</sub> background levels) that dominates NO<sub>2</sub> levels at traffic locations. Street canyon models however, need to be carefully coupled to the mesoscale model system (meteorology, background concentration) in order to obtain a consistent representation of air quality.



**Figure 4.** Example of sub-grid (1 km<sup>2</sup>) NO<sub>2</sub> variability in an urban area where air pollution is dominated by road traffic (Velazquez Street)

In this study, outputs from WRF and CMAQ have been used to provide wind conditions and pollution background concentration at roof level (paying special attention to avoid any double-counting), inputs to which street canyon models are very sensitive. In addition, consistent emissions data have to be used across the scales and models. In this application, a common traffic model is used to provide the activity data (intensity, fleet composition) and relevant variables (average speed, etc.) needed for traffic emission computation (as discussed in the next section).



**Figure 5.** Location and OSPM results (annual series, Q-Q and scatter plots) for a traffic station

The results indicate that when properly fed (meteorology, background pollution and traffic conditions), the street-canyon model can achieve a reasonable performance (RDE < 20%) even at heavily trafficked hot-spots with peak values close to 400  $\mu\text{g}/\text{m}^3$  (Figure 5).

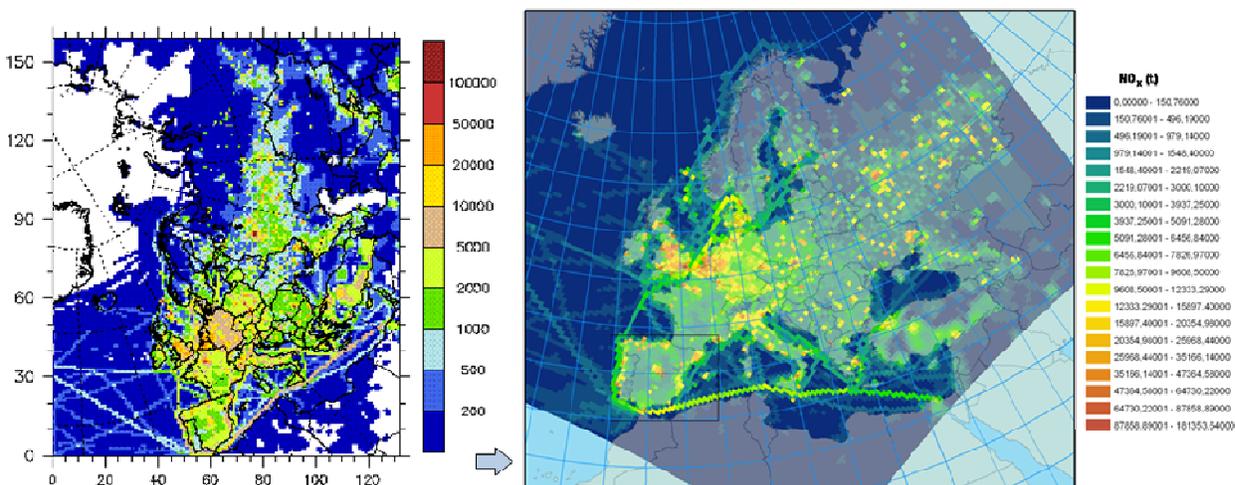
## EMISSION INVENTORIES

Emissions constitute a key input to air quality models since they are one of the main sources of uncertainty<sup>15</sup>. This issue is also relevant for the analysis of the alternatives to improve air quality in a given region in future years as a result of the implementation of pollutant emissions abatement<sup>16</sup>. As for the implications for multi-scale studies, emissions constitute one of the most challenging aspect. Emission-related inputs must be as detailed and specific as possible for the different domains involved in the simulation, and simultaneously they must be consistent across the scales<sup>4</sup>. In addition, they have to be flexible and detailed enough to reflect the outcome of relevant measures and meet the modeling system requirements<sup>11</sup>.

Consequently, a specific emission inventory has been developed/adapted for each of the four modeling domains in this application. Emission processing is performed by SMOKE in all cases.

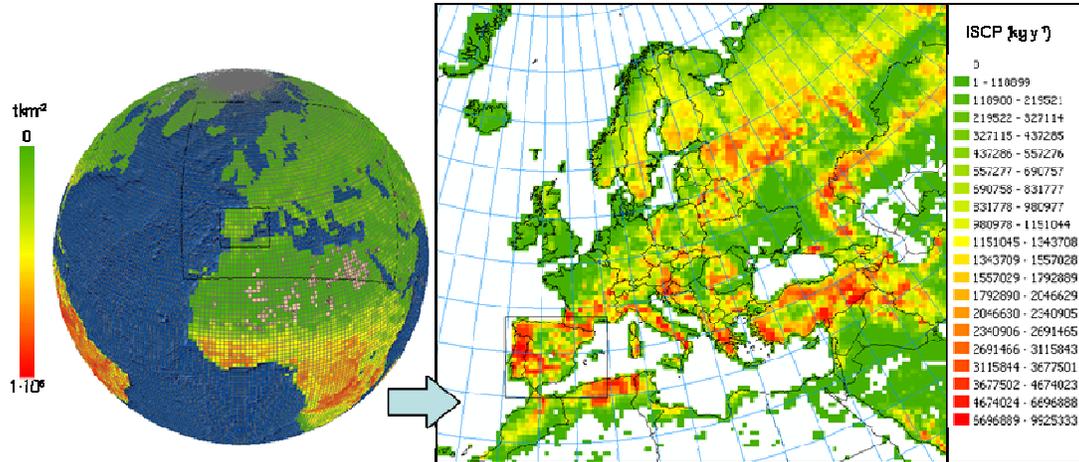
### D1 (Europe)

Anthropogenic emissions are taken from the EMEP inventory<sup>17</sup> (Figure 6). This is a gridded inventory (50 x 50 km<sup>2</sup>) that covers the whole Europe compiled from national submissions to the Convention on Long-range Transboundary Air Pollution (LRTAP), and therefore is consistent with national inventories. The temporal profiles and vertical distribution needed to resolve the emissions were those used in the EuroDelta experiment<sup>18</sup>. Biogenic VOCs (isoprene, monoterpenes and other biogenic volatile organic compounds) have been computed off-line (the Global Emission Inventory Activity -GEIA-) and processed into SMOKE considering the algorithms proposed by Guenther et al. (1996)<sup>19</sup> (Figure 7). Both inventories are consistent with the EMEP/CORINAIR methodology<sup>20</sup> used to compute emissions in the Spain's National Emission Inventory (SNAEI).



**Figure 6.** Example of EMEP (50x50 km<sup>2</sup>) emissions (left) and interpolation to D1 domain (right).

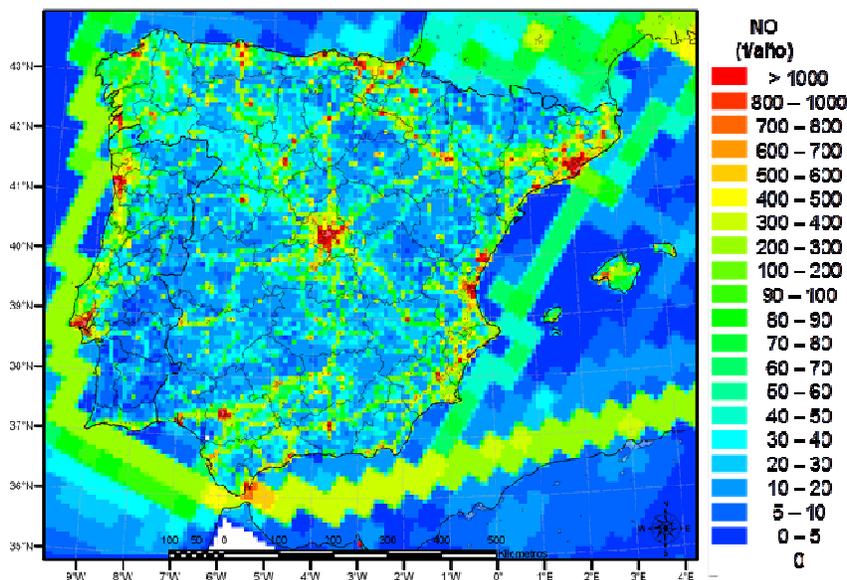
NO<sub>x</sub> from all sources.



**Figure 7.** Isoprene emissions from 1°x1° GEIA (left) and interpolation (land use-driven) to D1 domain (right)

### D2 (Iberian Peninsula)

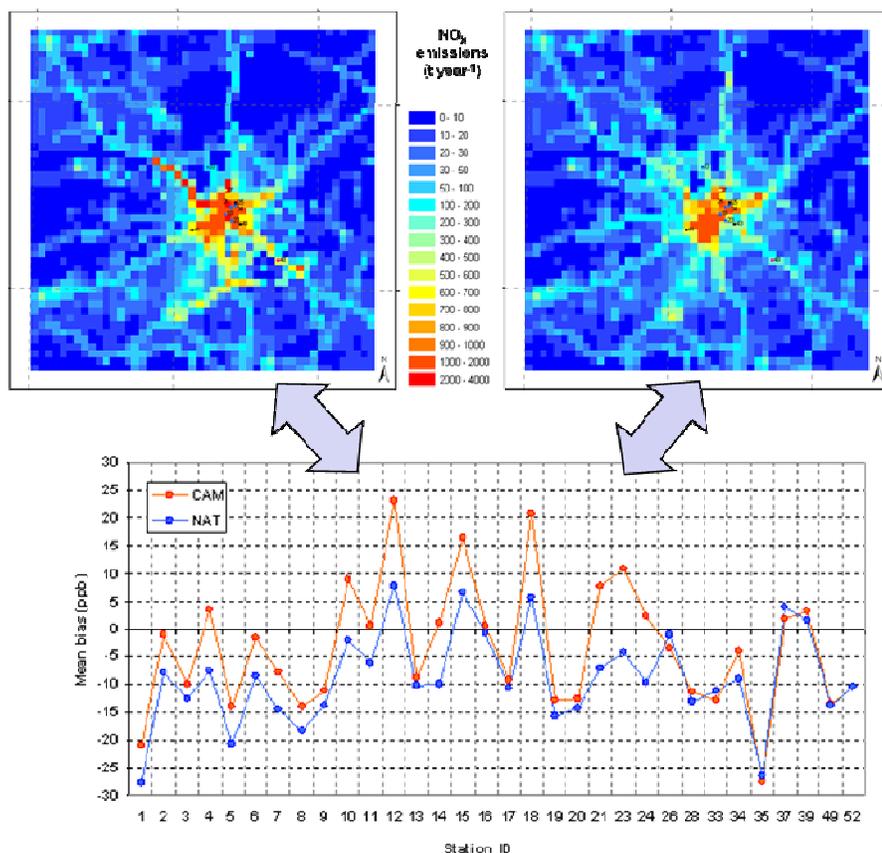
Emissions were taken from the National Emission Inventories of Spain (SNEI) and Portugal (PNEI) and processed with SMOKE. Hourly, 16-km resolved emissions (example in Figure 8) from 184 area-source categories were used along with detailed information regarding temporal patterns and release conditions of 1720 stacks belonging to 62 point-source categories. The inventory was chemically speciated according to the Carbon Bond CB05 mechanism<sup>21</sup>, a lumped structure chemical mechanism including 156 reactions and 69 species including aerosols. The chemical composition of VOCs, PM<sub>2.5</sub> and NO<sub>x</sub> emissions in the inventory was defined through 221 chemical profiles built from the relevant information in the EMEP/CORINAIR guidebook<sup>20</sup> and the US EPA ESPECIATE database<sup>22</sup>.



**Figure 8.** 16 km resolution NO emissions for the Iberian Peninsula

### D3 (Greater Madrid Region)

Emission inventory compilation and implementation for D3 was the result of a thorough intercomparison exercise of two official inventories available for this area (the regional inventory and the regional disaggregation of the SNAEI; Figure 9)<sup>23</sup>. The analysis relies on the fundamental hypothesis that the accuracy of an emission estimate may be assessed by the degree of agreement of air quality observations and the results of an air quality model (CMAQ) feed with that emission information<sup>24</sup>. The analysis of the differential response of the model at representative points in the modeling domain (Figure 9) along with the analysis of the differences on alternative emission estimates is used to find out which of the underlying methods and information used in both inventories is reflecting real emissions in a more proper way.



**Figure 9.** Comparison of emission estimates in D3 based on the SNAEI inventory (left) and the regional inventory (right) and response of the air quality model in particular locations (corresponding to air quality monitoring stations)

The results confirm the lack of consistency of national, regional and local emission inventories, a long-standing problem in multi-scale air quality modeling. The resulting inventory for D3 was a combination of emission data from both official inventories based on the understanding of the reasons for disagreements between them. Besides helping to figure out which inventory provided a better estimate, the study was useful to identify preliminary ways to conciliate future editions of both inventories.

#### D4 (Madrid metropolitan area)

The criteria for the design and computation of the emission inventory for the innermost domain can be summarized as follows:

- Combination of bottom-up and top-down emissions paying special attention to keep the consistency across domains / inventories
- Very detailed, source-specific methods
- Flexible and detailed enough to reflect the outcome of relevant emission reduction measures

According to our computations, road traffic (SNAP group 07) is responsible for 57% of NO<sub>x</sub> emissions in the modeling domain, as summarized in Table 2 (70% inside the city). Therefore, the inventory must have the capability to simulate strategies aimed at cutting down emissions from this sector such as:

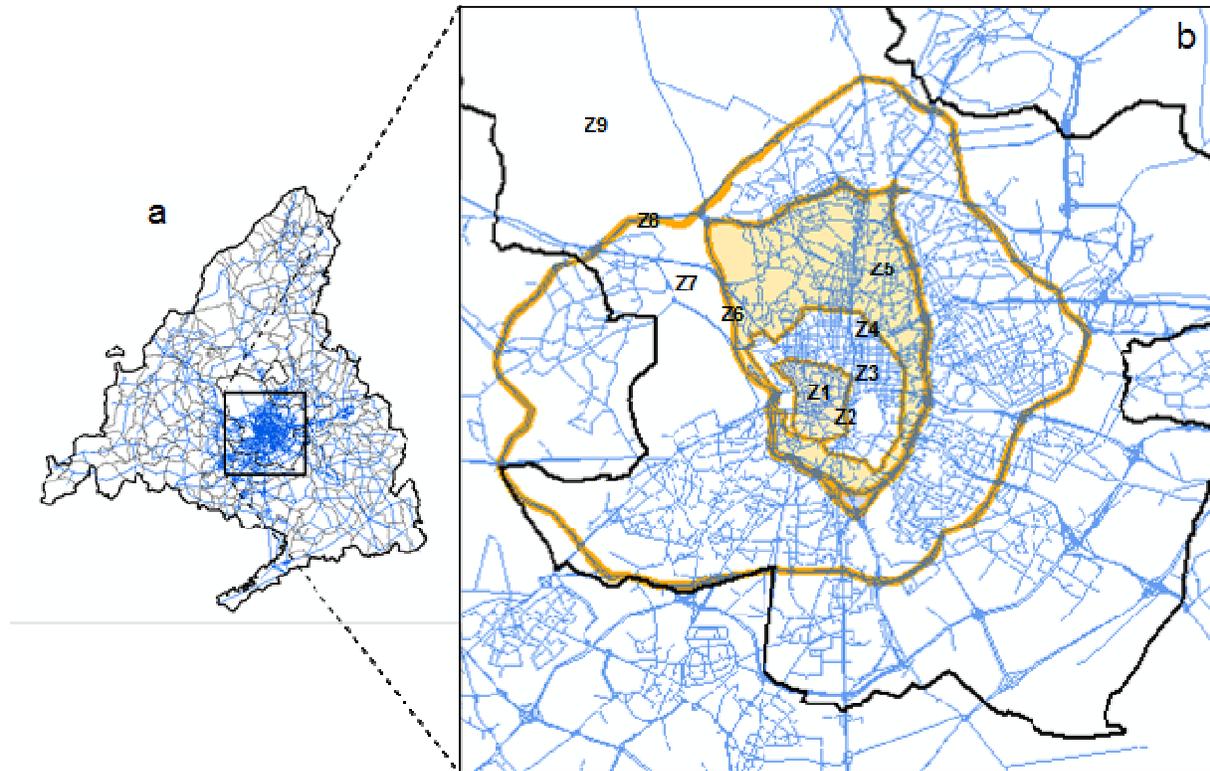
- Implementation of low emission zones (access restrictions by vehicle type, age or technology)
- Variation of speed limits
- Penetration of new technologies (combustion engines standards, hybrid and electric vehicles, etc.)
- Specific fleet turnover and limitations by segments (buses, taxis, light duty vehicles, passenger cars, etc.)
- Measures to alleviate urban congestion

**Table 2.** Summary of emissions (SNAP group level) in D4

SNAP Group	CO	NH <sub>3</sub>	NO <sub>x</sub>	PM <sub>10</sub>	PM <sub>2.5</sub>	SO <sub>2</sub>	VOC
01	225	0	243	50	29	1128	1
02	10004	0	3680	520	410	2731	1104
03	2238	0	10689	265	210	2494	1217
04	1083	130	108	51	32	70	3782
05	0	15	0	0	0	0	2056
06	0	212	0	0	0	0	48828
07	22070	250	27961	1506	1205	157	4365
08	2711	0	4171	360	360	287	769
09	441	2036	1769	26	26	6	5267
10	357	1543	56	90	13	0	17
11	32	605	125	0	0	0	4682
<b>Total</b>	<b>39161</b>	<b>4791</b>	<b>48802</b>	<b>2868</b>	<b>2285</b>	<b>6873</b>	<b>72088</b>

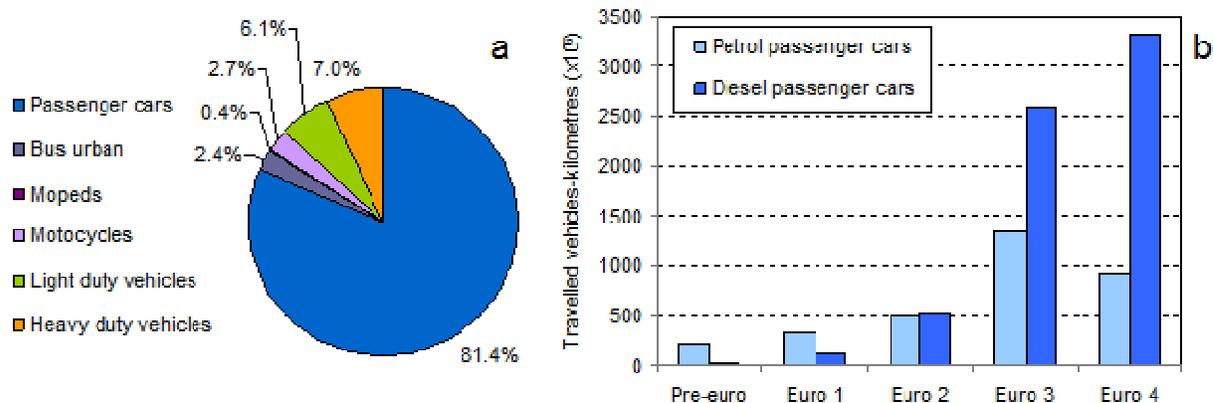
The reference model for calculating emissions from road traffic was COPERT IV<sup>26</sup>, which is an average speed model considering three different driving patterns (rural, urban and motorway). This model is currently integrated in the EMEP/EEA methodology for emission computation<sup>27</sup> and it is used by most European Countries in the compilation of their national emission inventories. Alternatively, emissions from road traffic were computed with HBEFA 3.1, which is a model based on traffic situations<sup>28</sup>. Details can be found elsewhere<sup>29</sup>.

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 10.



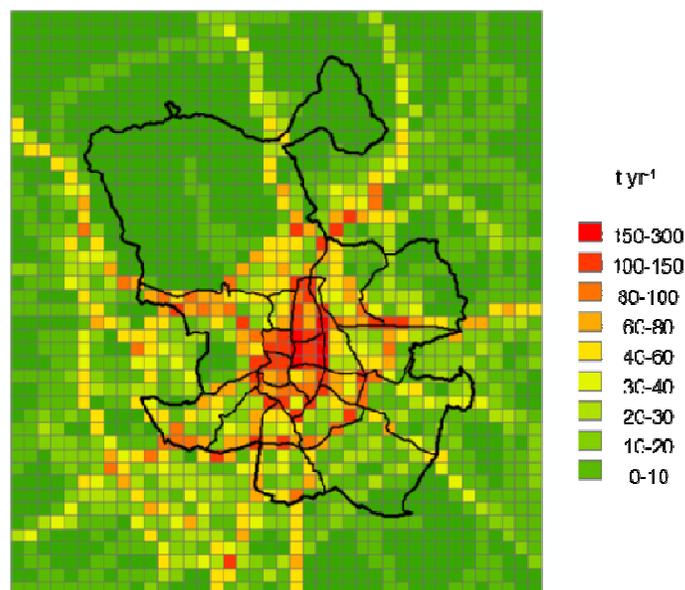
**Figure 10.** Road network of the traffic model (a) and zoom to the city center with indication of management areas (b), referred to as Z1 to Z9.

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. Fuel share has been estimated from official fuel – sales statistics and the regional energy balance. 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 as illustrated in Figure 11.



**Figure 11.** Distribution of travelled distance (12202 million vehicle-km in total) (a) and detail for passenger cars (b).

This information allow 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 modeling is carried out by overlapping<sup>11</sup>. Annual totals are shown in Figure 12.



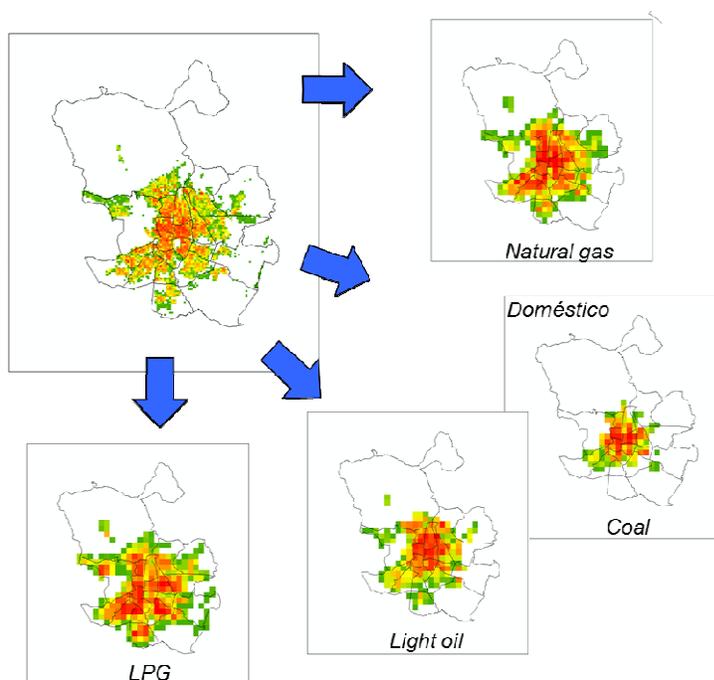
**Figure 12.** Distribution of NO<sub>x</sub> emissions from road traffic (ton yr<sup>-1</sup>)

In order to incorporate the specific features of each type of vehicle and flow conditions, 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/NO<sub>x</sub> ratio (a critical parameter to assess NO<sub>2</sub> 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<sup>27</sup>. They were mapped into CB05 species<sup>21</sup> to

produce 9 VOC profiles (along with the corresponding TOGtoVOC ratios) to represent VOC composition at management area level. At this stage US EPA<sup>22</sup> PM<sub>2.5</sub> speciation profiles have been used considering vehicle and fuel type.

As emission computation is performed at link level with 1 hour resolution, emissions can be aggregated into the 1 km<sup>2</sup> grid (Figure 12) or provided directly to the street canyon model, which constitutes a distinct advantage to keep consistency between the mesoscale and the street-scale models.

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 separated by fuel, as illustrated in Figure 13. This makes the simulation of fuel change or boiler turnover quite simple.



**Figure 13.** Bottom-up domestic boiler inventory for the Madrid city

## APPLICATIONS AND RESULTS

Once model-ready emissions were accomplished, the modeling system was used to perform a series of analysis and experiments that resulted in the definition of a complete strategy to meet the NO<sub>2</sub> air quality standards required by 2015 in Madrid. A brief summary of these applications is provided in this section.

### Source apportionment

Apportionment of NO<sub>2</sub> 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 NO<sub>2</sub> annual LV) provides essential information regarding:

- Basic emission abatement strategy / course of action
- Maximum feasible AQ improvement related to the main emitting sectors
- External constraints

A zero-out methodology was followed in this application. The contribution of a particular emission source or region can be estimated through the zero-out or brute force method (change in the pollutant concentration that would occur if that source is removed from the simulation, as illustrates Figure 11).

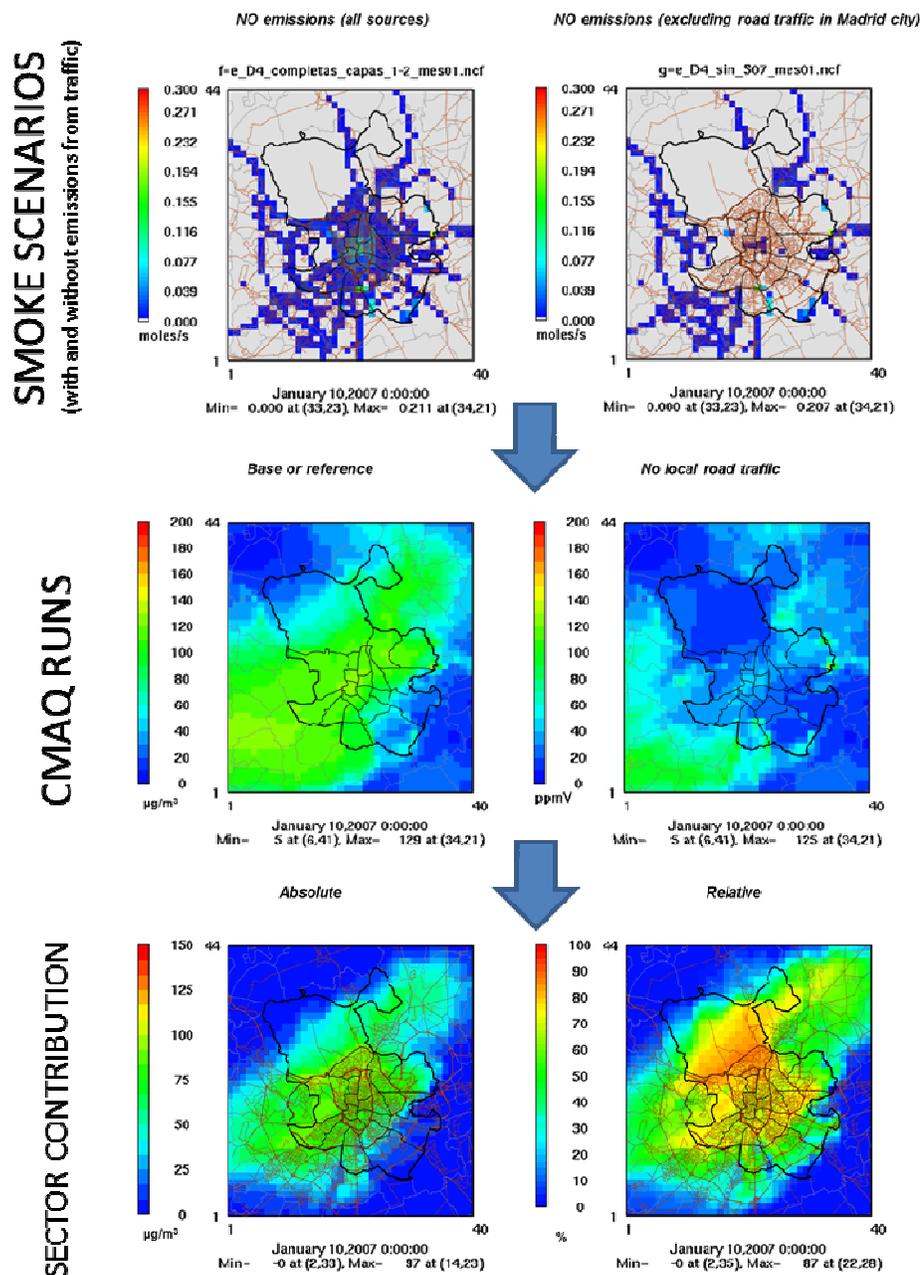
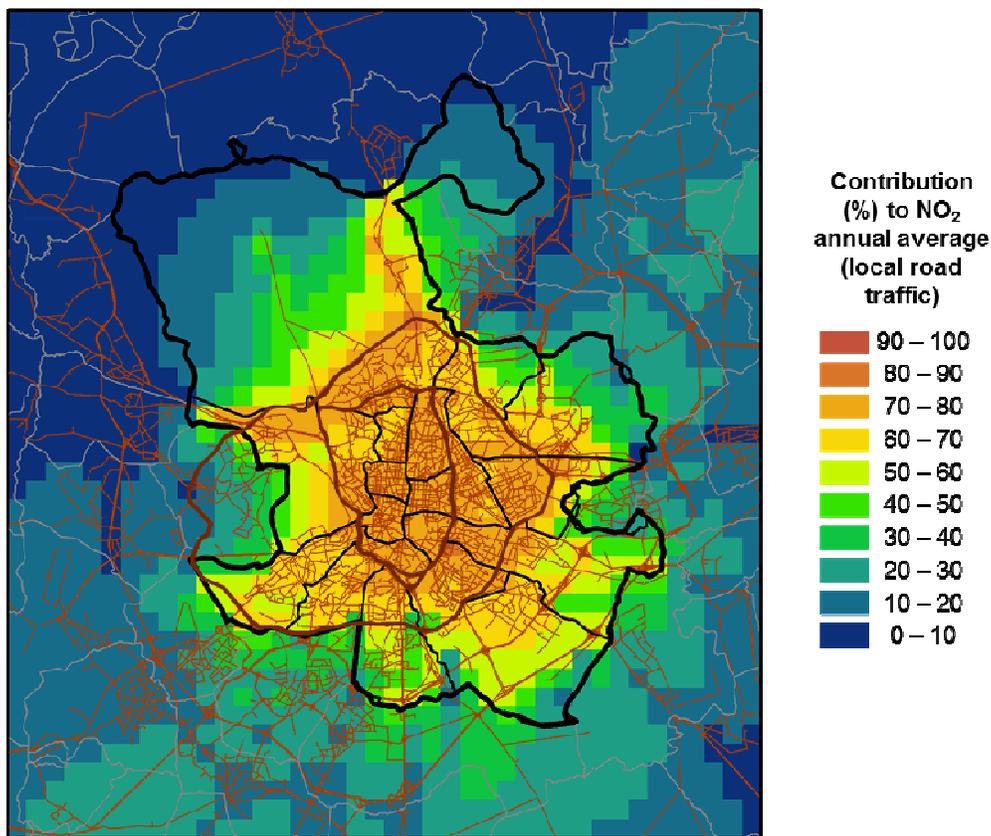


Figure 14. Source apportionment procedure (zero-out) in this study

This approach has been used in the past to isolate the response of complex, nonlinear systems to one particular sector in source apportionment and sensitivity analysis<sup>30</sup>. This method has limitations to accurately describe sensitivities<sup>31</sup> but it may be useful to approximate the effect of potential emission reduction in a particular source or origin area as pointed out in several studies before<sup>32, 33</sup>.

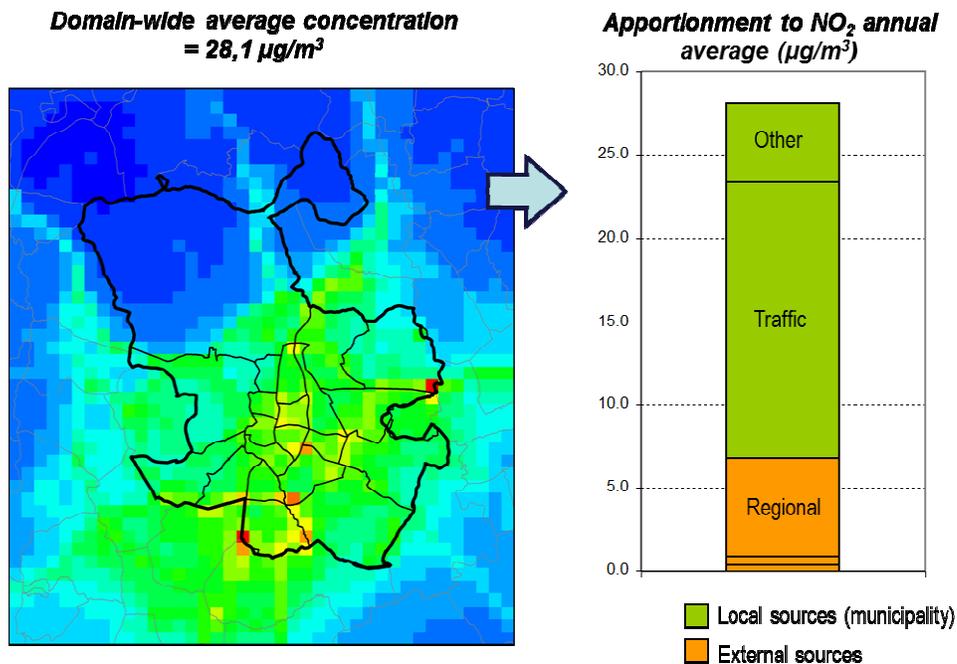
This source apportionment analysis was performed to understand both the contribution of International, National, Regional and Local sources to NO<sub>2</sub> levels and also the contribution of individual sectors within Local sources. Reductions of 100% (zero-out) were simulated for the most relevant anthropogenic emissions, including road transport, industry, residential, aviation, and commercial and institutional combustion. The total impact and therefore maximum theoretical benefits that can be harvested by implementing abatement options in these sectors, was derived from the comparison of the assessment of the individual runs with the base case (considering all emissions). Figure 15 illustrates this idea for the case of road traffic. It can be seen that in the city center is theoretically feasible to reduce NO<sub>2</sub> levels up to 90% only by applying restrictions in this sector.



**Figure 15.** Result of the source apportionment analysis for the road traffic sector (SNAP 07)

A similar approach was followed to estimate contributions of different geographic areas. In this case outputs from CMAQ runs using alternative boundary conditions and/or geographical masks were

compared to derive the amount of NO<sub>2</sub> that can be related to different origin areas. Figure 16 shows the average geographic apportionment structure for the whole D4. Further analyses confirm that Madrid is strongly dominated by local sources, mainly road traffic. National and international influence is negligible; clearly indicating that an efficient air quality plan should include measures aimed at limiting local road traffic with an additional effect at regional level (metropolitan area).



**Figure 16.** Result of the geographic source apportionment analysis (D4 domain average)

### Emission scenario

The development and modeling of future-year emission scenario is a crucial stage for the design of effective abatement options and assessment of the compliance with air quality standards. There are no universal solutions to improve air quality so the particular features of any reduction plan will depend on the causes of poor AQ levels. Nevertheless, a series of ‘good practices’ should be always beard in mind when developing scenarios, such as:

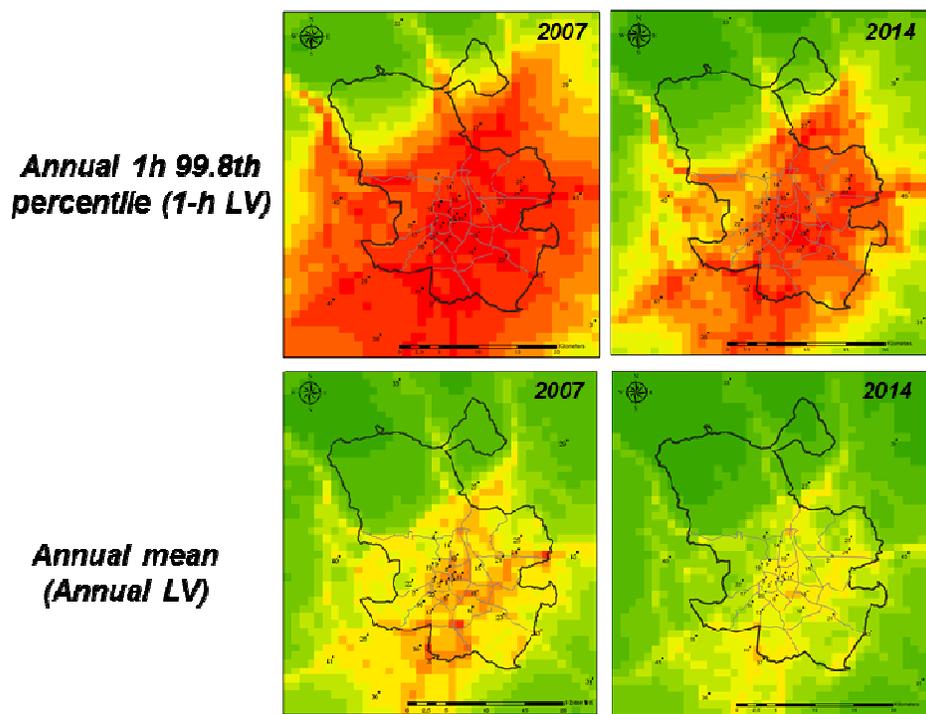
- abatement measures focused on the emission sectors responsible for air pollution (according to the source apportionment study carried out)
- emission projection model consistent with emission model/methods used for the reference year
- transparency and documentation
- plans and measures simulated as accurately as possible, highlighting critical hypotheses and parameters

Future-year emission estimate should be consistent with the methods applied for the base year emission inventory compilation. Changes or updates of computation methods may lead to important deviations in future year estimates and therefore misleading information about the effectiveness of particular measures. For instance, preliminary experiments revealed important differences (up to

20%) in NO<sub>x</sub> emissions for the Madrid metropolitan area depending on the road traffic emission model used<sup>29</sup>. Important differences are also found in critical parameters such as the NO<sub>x</sub> emission speciation (NO/NO<sub>x</sub> ratio) for future engine technologies. Further analysis and examples of consistent emission projection methods are provided in Lumbreras et al., (2008)<sup>34</sup>.

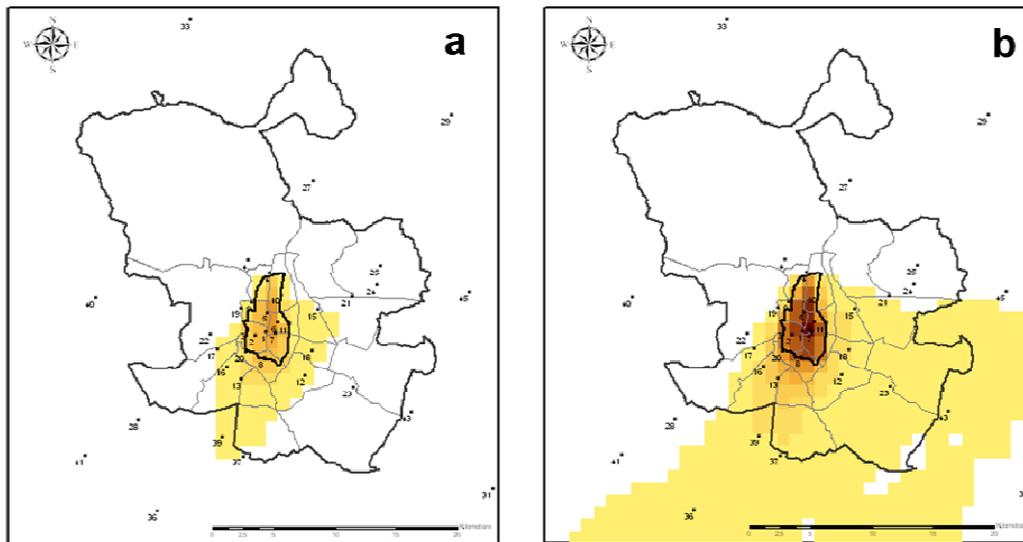
Up to 70 abatement measures have been assessed and evaluated for the final definition of the Air Quality plan. A global decrease of 31% in NO<sub>x</sub> emissions is expected in the year 2014, mainly due to measures in the road transport sector (40% decrease). Emissions, surrogate data and speciation 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 17 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 NO<sub>2</sub> levels may be reduced by 34% as an average; approximately 15 µg/m<sup>3</sup> in the city center, also with an important impact in the metropolitan area (-7 µg/m<sup>3</sup> as an average in the modeling domain). 1-hour concentration peaks may also decline by 40% approximately in most of the city.



**Figure 17.** Expected effect of the Madrid Air Quality Plan in NO<sub>2</sub> concentration values (1-hour limit value and annual limit value)

The modeling platform was also useful to estimate the effect of additional measures that may be applied under exceptional conditions or short-term exceedance situations, as illustrated in Figure 18. This can be accomplished by conveniently changing emission figures and surrogate data for specific SMOKE activities (linked to specific vehicle types and management areas).



**Figure 18.** Impact of passenger cars access restriction by 20% (a) and 50% under unfavorable meteorological conditions (24-h average NO<sub>2</sub>)

The same emissions can be used to feed the street-scale OSPM model to complement the analysis providing thus relevant information regarding compliance expectancy in hot spots.

## 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 modeling activities carried out in Madrid (Spain) to develop an AQP to comply with the stringent NO<sub>2</sub> 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<sub>2</sub> 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<sub>x</sub> emissions by 31% and would allow the fulfillment of NO<sub>2</sub> limit values in Madrid by the end of 2014.

## KEY WORDS

Modeling  
Urban air quality  
SMOKE  
Emission preparation for modeling  
NO<sub>2</sub>  
Madrid  
Spain

## ACKNOWLEDGEMENTS

The Madrid city Council provided the traffic model and partially supported this study. The CMAQ modeling system was made available by the US EPA and it is supported by the Community Modeling and Analysis System (CMAS) Center. The authors also acknowledge the use of emission datasets and monitoring data from the Dirección General de Calidad y Evaluación Ambiental of the MARM and the Portuguese Ministry of Environment.

## REFERENCES

- 1- European Environment Agency (EEA), 2011b. "Air quality in Europe – 2011 report". EEA Technical Report No 12/2011. ISBN: 978-92-9213-232-3. [Available online at: <http://www.eea.europa.eu/publications/air-quality-in-europe-2011>]
- 2- European Commission. "Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe". Official Journal L 152, 11.6.2008, p. 1–44 <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:152:0001:0044:EN:PDF>
- 3- Grice, S., Stedman, J., Kent, A., Hobson, M., Norris, J., Abbott, J., Cooke, S., 2009. "Recent trends and projections of primary NO<sub>2</sub> emissions in Europe". Atmospheric Environment 43, 2154–2167.
- 4- Borge R., Lumbreras, J., Rodríguez, M.E., 2007. "Integrated assessment modeling in Spain". US EPA 16th Annual International Emission Inventory Conference " Emission Inventories: Integration, Analysis, and Communications" Raleigh, North Carolina (USA). [Available at <http://www.epa.gov/tnn/chief/conference/ei16/session1/borge.pdf>], 16 pp.
- 5- Borge, R., Lumbreras, J., de la Paz, D., Rodríguez, M.E., 2009. "Air quality modelling. Bridging national and continental scales," pp. 2293-2299, 2009 [18th World IMACS/MODSIM Congress, Cairns, Australia].
- 6- Skamarock, W.C., Klemp, J.B. 2008. "A time-split nonhydrostatic atmospheric model". Journal of Computational Physics 227, 3465 - 3485.
- 7- Institute for the Environment. 2009. "SMOKE v2.7 User's Manual". University of North

- Carolina. Chapel Hill, NC. Available online at: <http://www.smoke-model.org/version2.7/html/ch01.html>.
- 8- Byun, D.W., Ching, J.K.S., 1999. "Science Algorithms of the EPA Models-3 Community Multi-scale Air Quality (CMAQ) Modeling System". EPA/600/R-99/030, US EPA National Exposure Research Laboratory, Research Triangle Park, NC.
  - 9- Byun, D.W., Schere, K.L., 2006. "Review of the governing equations, computational algorithms, and other components of the Models-3 community Multiscale Air Quality (CMAQ) modeling system". *Applied Mechanics Reviews* 59 (2) 51–77.
  - 10- Borge, R., Alexandrov, V., del Vas, J.J., Lumbreras, J., Rodríguez, E., 2008. "A comprehensive sensitivity analysis of the WRF model for air quality applications over the Iberian Peninsula". *Atmospheric Environment* 42, 8560–8574.
  - 11- Borge, R., Lumbreras, J., Rodríguez, M.E., 2008. "Development of a high-resolution emission inventory for Spain using the SMOKE modelling system: A case study for the years 2000 and 2010". *Environmental Modelling & Software* 23, 1026-1044
  - 12- Borge, R., López, J., Lumbreras, J., Narros, A., Rodríguez, E., 2010. "Influence of Boundary conditions on CMAQ simulations over the Iberian Peninsula". *Atmospheric Environment* 44, 2681-2695
  - 13- Karanasiou, A., Moreno, T., Amato, F., Lumbreras, J., Narros, A., Borge, R., Tobías, A., Boldo, E., Linares, C., Pey, J., Reche, C., Alastuey, A., Querol, X., 2011. "Road dust contribution to PM levels – Evaluation of the effectiveness of street washing activities by means of Positive Matrix Factorization". *Atmospheric Environment* 45, 2193-2201
  - 14- Berkowicz, R., M. Ketzel, R.M, Jensen, S.S., Hvidberg. M., Raaschou-Nielsen, O., 2008. "Evaluation and application of OSPM for traffic pollution assessment for a large number of street locations," *Environmental Modelling & Software* 23, pp.296-303, 2008.
  - 15- Russell, A., Dennis, R., 2000. "NARSTO critical review of photochemical models and modelling". *Atmospheric environment* 34 (12-14) 2261-2282.
  - 16- FAIRMODE, "Background document on the emission needs at local scale for AQ modelling (Working Group 2, subgroup 3)," 2010. [http://fairmode.ew.eea.europa.eu/fo1404948/sg3\\_background\\_document\\_oct10\\_draft.pdf](http://fairmode.ew.eea.europa.eu/fo1404948/sg3_background_document_oct10_draft.pdf)
  - 17- Vestreng, V., 2003. "EMEP/MSW Technical report. Review and Revision. Emission data reported to CLRTAP. MSW Status Report 2003". EMEP/MSW Note 1/2003. ISSN 0804-2446.
  - 18- Van Loon, M., Vautard, R., Schaap, M., Bergström, R., Bessagnet, B., Brandt, J., Builtjes, P.J.H., Christensen, J.H., Cuvelier, K., Graf, A., Jonson, J.E., Krol, M., Langner, J., Roberts, P., Rouil, L., Stern, R., Tarrasón, L., Thunis, P., Vignati, E., White, L., Wind, P., 2007. "Evaluation of long-term ozone simulations from seven regional air quality models and their ensemble average". *Atmospheric Environment* 41, 2083-2097.
  - 19- Guenther A.B., Greenberg J., Helmig D., Klinger L., Vierling L., Zimmerman P. and Geron C., 1996. "Leaf, branch, stand and landscape scale measurements of volatile organic compounds fluxes from U.S. woodlands". *Tree Physiology* 16, 17-24.
  - 20- European Environment Agency (EEA), 2009. "EMEP/EEA air pollutant emission inventory

- guidebook — 2009” (EEA Technical report No 9/2009). ISSN 1725-2237.
- 21- Yarwood, G., Rao, S., Yocke, M., Whitten, G., 2005. “Updates to the Carbon Bond Chemical Mechanism CB05”. Final Report to the US EPA, RT-0400675. Available from [http://www.camx.com/publ/pdfs/CB05\\_Final\\_Report\\_120805.pdf](http://www.camx.com/publ/pdfs/CB05_Final_Report_120805.pdf).
  - 22- Hsu, Y., Strait, R., Roe, S., Holoman, D., 2006. SPECIATE 4.0. Speciation Database Development Documentation. Final Report. EPA contract. Nos EP-D-06.001, work assignment Numbers 0-03 and 68-D-02-063, WA 4-04 and WA 5-05. EPA/600/R-06/161. November 2006. Available from [http://www.epa.gov/ttn/chief/software/speciate/speciate4/documentation/speciatedoc\\_1206.pdf](http://www.epa.gov/ttn/chief/software/speciate/speciate4/documentation/speciatedoc_1206.pdf).
  - 23- Vedrenne, M., Borge, R., de la Paz, D., Lumbreras, J., Rodríguez, M.E., 2012. “Comparison and assessment of two emission inventories for the Madrid Region”. Air Pollution XX. WIT Press, ISBN 978-1-84564-582-3, 12 pp.
  - 24- Borge, R., Lumbreras, J., de la Paz, D., Dilara, P., Tarrason, L., 2010. “Urban emissions and projections”. Proceedings of the 13th International Conference on Harmonization within Atmospheric Dispersion Modelling for Regulatory Purposes. Paris (France). ISBN: 2-8681-5062-4, pp 991.
  - 25- Ayuntamiento de Madrid (AM), 2010. “Inventario de emisiones de contaminantes a la atmósfera en el Término Municipal de Madrid”. Prepared by AED for the Madrid City Council (D.G. de Calidad, Control y Evaluación Ambiental. Servicio de Calidad del Aire).
  - 26- Ntziachristos, L., Gkatzoflias, D., Kouridis, C., Samaras, Z., 2009. “COPERT: A European Road Transport Emission Inventory Model”. In: Athanasiadis, I.N., Mitkas, P.A., Rizzoli, A.E., Marx Gómez, J. (Eds.) Information Technologies in Environmental Engineering, 491-504, Springer.
  - 27- Ntziachristos, L., Samaras, Z., 2009. “Methodology for the calculation of exhaust emissions – SNAPs 070100-070500, NFRs 1A3bi-iv” (EMEP/CORINAIR Atmospheric Emissions Inventory Guidebook chapter). Available at: <http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-road-transport.pdf>
  - 28- HBEFA, 2010. “Handbuch Emissionsfaktoren des Strassenverkehrs 3.1 – Dokumentation. Infras”. UBA Berlin/BUWAL, Bern/UBA, Wien Available from. [www.hbefa.net](http://www.hbefa.net).
  - 29- Borge, R., de Miguel, I., de la Paz, D., Lumbreras, J., Rodríguez, M.E. (2012). “Comparison of road traffic emission models in Madrid (Spain)”. Atmospheric Environment. *Under review process*.
  - 30- Cohan, D.S., Hakami, A., Hu, Y., Russell, A.G., 2005. “Nonlinear Response of Ozone to Emissions: Source Apportionment and Sensitivity Analysis”. Environmental Science & Technology 39, 6739–6748.
  - 31- Koo, B., Wilson, G.M., Morris, R.E., Dunker, A.M., Yarwood, G., 2009. “Comparison of Source Apportionment and Sensitivity Analysis in a Particulate Matter Air Quality Model”. Environmental Science & Technology 43, 6669–6675.
  - 32- Carmichael, G., Wild, O., et al., 2010. “Global and regional modelling”. In: Hemispheric

Transport of Air Pollution 2010, Task Force on Hemispheric Transport of Air Pollution (www.htap.org, 2010).

- 33- Leung, F.Y.T., Logan, J.A., Park, R., Hyer, E., Kasischke, E., Streets, D., Yurganov, L., 2007. "Impacts of enhanced biomass burning in the boreal forests in 1998 on tropospheric chemistry and the sensitivity of model results to the injection height of emissions". *J. Geophys. Res.* 112, D10313, doi:10.1029/2006JD008132.
- 34- Lumbreras, J., Borge, R., de Andres, J.M., Rodriguez, M.E., 2008. "A model to calculate consistent atmospheric emission projections. Application to Spain," *Atmospheric Environment*, 42/21, 5251-5266.