Impact of the pollutant emission reduction in the atmospheric pollution of the region of Madrid by using a photochemical model

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Abstract

Recent emission inventories reflect that the Greater Madrid Area (GMA) acts as a large source of pollutants, with road traffic being the major contributor to the total NO\textsubscript{x}, VOC and CO emissions. Consequently, photochemical smog episodes are relatively frequent and important. Modelling analysis has been used to study the impact of emission reductions in the ozone generation. The TVM-CHEM model has been used to simulate the photosmog formation over the GMA during two summer days in which thermal low pressure dominates atmospheric conditions. The EMEP and RACM mechanisms have been used. The general dispersion pattern predicted by them was found to be quite similar and predictions fit quite well the observations from air quality stations. The impact of different possible abatement scenarios was studied. In particular, the influence of traffic emissions versus the rest of all anthropogenic emission sources has been analysed. The reduction of traffic emissions seems not to be enough to reduce efficiently air pollution and further anthropogenic emission reductions are needed to accomplish with quality standards.

1 Introduction

The objectives of this work have been to evaluate the photochemical TVM-Chem model [1] with different built-in chemical mechanisms and to estimate the impact of the pollutant emission reduction in the atmospheric pollution of the
region of Madrid. The evaluation of this model is a very important step for being used as a tool to increase the understanding of the phenomena involved in the photochemical pollution in the Greater Madrid Area. Furthermore, it is also needed for getting confidence in the results of simulations under hypothetical scenarios of pollutant emissions and hence, for determining what emission reduction is needed to reduce the atmospheric pollution levels below the air quality standards.

2 Models

The photochemical TVM-Chem model [1] consists of two models: a mesoscale meteorological model (TVM) and a model for computing the dispersion, chemical reactions and deposition of pollutants (called Chem).

The TVM model [2], [3] is a non-hydrostatic, anelastic and Bousinesq model based on the vorticity equations for simulating the mesoscale flows over complex terrain. TVM includes a soil model based on the ‘force-restore’ approximation for computing surface soil temperature, the Penmann-Monteith formulation for the surface soil specific humidity and the Sasamori scheme for radiation. The turbulence fluxes are computed by means of a 1.5 order closure based on prognostic equations of turbulent kinetic energy. Among several atmospheric modelling exercises (including validation and comparison with other models) in Europe and America, we can point out the cases of Fos (France) [4], Athens [5] and Madrid [6], [7].

The Chem model is an Eurelian model for air quality solving the advection-diffusion equation by using the three dimensional meteorological fields computed by TVM. Dry deposition is computed by means of a resistance scheme. The original implemented mechanism was LCC [8], [9] which includes 44 gas phase species coupled by means of 106 chemical reactions. Recently the authors have worked in the implementation of two mechanisms: RACM – 72 chemical species with 234 reactions – [10] and EMEP – 68 species and 137 reactions – [11], [12]. The TVM-Chem model with LCC mechanism has been used in photochemical pollution studies in Athens and Geneve [1]).

3 Modelled cases

The modelled cases correspond to two summer days (July 14th, 1992 and July 15th, 1995) when strong solar radiation and high temperature took place. The synoptic meteorological situation is characterised by the formation of thermal low-pressure system, which is dominant during most of the summer time in the Iberian Peninsula. This meteorological system is more intense during the day when the solar heating is stronger whereas it weakens during the night. This system affects to the lower layers up to 3000 m high and it is usually embedded in a subtropical anticyclone. Recent studies have shown that mesoscale circulations in the Greater Madrid Area are very sensitive to small changes in the position of the thermal low pressure [7], [13].
The spatial domain includes the Greater Madrid Area which is a large conurbation of 5 million inhabitants and consists of about 2 million motor vehicles. Several provinces much less populated than Madrid are included in the domain, which covers a 350x300 km$^2$ area for the meteorological simulations and 270x200 km$^2$ for the photochemical modelling. An irregular grid was used for meteorology with a maximum resolution of 5x5 km$^2$ (65x55 cells) while a 54x50 grid of 5x5 km$^2$ of resolution was assumed for the photochemical modelling. The simulations were done with RACM and EMEP mechanisms and TVM-Chem.

Figure 1: Map of the meteorological domain showing the main geographical features.

4 Input data

The input data consists of meteorological information obtained from sounding and surface stations, digitized terrain model, land use data, initial and boundary concentrations of species (some of them were known from air quality stations), photolysis constants and pollutant emission data. Most of the meteorological and pollutant concentration data were obtained during experimental campaigns.

Spatially and time disaggregated pollutant emission data for the photochemical grid were estimated by following a macroscale or “top-down” methodology by using the MEIAM (Mesoscale Emission Inventory for Air pollution Modelling) model [14], [15]. Provincial annual emission data for SO$_2$, NO$_x$, NMVOC, CH$_4$, CO, CO$_2$, N$_2$O and NH$_3$ estimated by the Spanish Environment Ministry for 1990-1993 by following the CORINAIR methodology were used. Data for 1995 were extrapolated applying the best non-linear
regression functions to the 1990-1993 trends for each pollutant and SNAP activity. Spatial and time resolution was 5x5 km$^2$ and 1 hour, respectively. The followed procedure consists of four steps:

1. Collection or estimation of several types of data such as provincial annual emission data, point and area sources (geographical databases and several statistics), time profiles of operation of the pollutant sources and traffic information (several types of statistics, digitized roads, traffic loads, etc.).
2. NMVOC speciation into 18 species, following the procedure of Loibl (1993) [16].
3. Time disaggregation by using the annual, week and daily operation profiles for the different types of pollutant sources estimating the provincial hourly emissions for every pollutant and SNAP activity.
4. Spatial disaggregation by applying the apportioning factors and the geographical databases and using a geographical information system. The result is the hourly pollutant emission in every 5x5 km$^2$ cell of the 270x200 km$^2$ domain.

The steps 2-4 constitute the core of the MEIAM model. In Figure 2, the emissions of four pollutants at 13:00 (local official time), July 14th, 1992, are shown.

![Figure 2: Spatial distribution of SO$_2$, CO, NO$_x$ and NMVOC emissions at 13:00 (local official time), July 14th, 1992.](image)

5 Results

Although the synoptic meteorological situations for the selected days for modelling were quite similar (thermal low pressure system), little differences in the low pressure position produced 3000m-ASL winds of about 4 m/s but the
wind directions were quite different (150° and 300°, respectively). The resulted evolutions of the boundary layer wind fields were quite different, especially between noon and midnight, which have a very notable impact in the estimated transport of primary pollutants. In both cases, the drainage flowing from N and NE are dominant in the Greater Madrid Area, being stronger in the July 14th, 1992 case. However, at noon and in the afternoon, the 10-m winds are, mostly, from the SE direction in the Greater Madrid Area, whereas in the July 15th, 1995 case, the winds blow, generally, from SW and W. These results are in agreement with the observations in surface stations and aerological soundings (Martín et al, [7]).

The spatial distributions of ozone concentration predictions at different daily times for the July 14th, 1992 obtained by using the chemical mechanisms RACM and EMEP are quite similar. In Figure 3, the results for the EMEP simulations are shown. At 03:00 UTC, ozone levels are very low. The emissions from the Greater Madrid Area and the lack of solar radiation promote the ozone consumption, reflected as a long nocturnal hole oriented to the WSW as a result of the emissions transported by nocturnal drainage winds. At 12:00 UTC, the ozone formation takes place on the southern slopes of the Sistema Central and, especially, at the western area, up to 100 km away from the city. This is the result of the accumulation of the precursors emitted in the early morning and transported from Madrid area by easterly winds. Ozone levels are important, being higher than 100 ppb, exceeding the threshold levels for the population awareness and vegetation protection. During the afternoon, the area with maximum ozone levels is moving to the north, passing through the Sistema Central, reaching the North Plateau at 18:00 UTC. This is due to the change in the wind direction, blowing from the SSE during the afternoon, transporting precursors emitted in Madrid. It is important to point out that ozone predictions are about 100 ppb in the Northern Plateau (more than 100 km away from Madrid).

Results fit pretty well with observed data at the stations (Figure 5, see station locations in Figure 4). The prediction of the maximum levels is good, in general. The peak hour is very well reproduced at Hoyo station, close to the slopes of the Sistema Central. At Villanueva, placed in the western area of Madrid province, the maximum predicted is delayed one hour related to the observed one. Both stations are, clearly, in the area affected by high ozone levels. The delay at CIEMAT station, placed close to the border of the city, in the northwest, is a little larger. In this case, both the predicted and observed maxima are of less important as compared to the other stations. The San Martin station, placed in the southern area of Madrid province, is out of the area with high ozone levels and predictions fit very well observed concentrations during the day, although an overprediction during the night can be noticed.

The comparison of the model results with observed data at the stations is difficult. Predicted concentrations are computed by using very smoothly input data, associated to grid cells of 5x5 km² resolution. These levels are compared to the observed data at very punctual locations which show the influence of the environment and emissions at a resolution that the model does not reach.
Moreover, little variations in the estimate of the pollutants transport could have an important impact in the prediction of ozone levels. This is clear in the case when the station is at the border of the pollution plume as CIEMAT and San Martin stations, placed just on the border of the nocturnal hole of consumption of ozone, an area with a very high concentration gradient.

Figure 3: Evolution (03, 12 and 18 UTC) of surface ozone level estimated by TVM/EMEP (below) for the July 14th, 1992.

Figure 4: Map showing the ozone stations deployment.
Figure 5: Comparison between daily predicted (solid line) and observed ozone concentrations (dotted line) by using TVM/RACM (left) and TVM/EMEP (right) mechanisms for the July 14th, 1992 in the Hoyo, San Martín, Villanueva and CIEMAT stations.

For the July 15th, 1995, Figure 6 shows the daily evolution of spatial distribution of surface ozone concentrations estimated by using the chemical mechanism RACM. At 03:00 UTC, ozone levels are, as for the July 14th, 1992, very low, with a nocturnal hole, associated to the ozone consumption, produced by precursors emissions from the Greater Madrid Area. In this case, the affected area is smaller due to the less intense drainage winds existing.

At 12:00 UTC, the ozone formation in this area is notable, although levels are lower than those for the July 14th, 1992 and the affected area is closer to the city. In this case, there is not a transport so efficient during the night as in the former case. Nevertheless, at 18:00, the change is relevant, the area of maximum levels is moved to the east and its extend and intensity have increased reaching levels higher than 100 ppb about 80 km far away from the city. In this scenario, the dominant winds from the west are moving precursors emissions from Madrid to the east, where an intense ozone formation occurs. The ozone measurements made by CIEMAT using an aircraft showed high levels of ozone in the order of 100 ppb in that region at around 800 m AGL [17]. The ozone concentration used to be quite homogeneously distributed in the lower levels of the troposphere during the afternoon under thermal low conditions because of the convective mixing. This makes reasonable to assume that surface ozone levels were of the same order, according to model predictions.

The distribution of the measurement stations was different for this day (Figure 4). Only the stations of San Agustín, to the north of the city, and Perales, to the east, were affected by high levels of ozone. Moraleja station, placed to the SW of the city, is out of the area of the ozone plume impact. The highest levels were observed in Perales, exceeding 90 ppb. The model predicts well the peak hour, although this maximum is slightly underpredicted. The diurnal evolution is quite well predicted by the model. During the night, the model predicts very low ozone levels. In San Agustín, the predictions are quite good, especially between 05:00 and 17:00 UTC. However, in Moraleja, ozone concentrations are
overpredicted during the day and underestimated from 06:00 to 08:00 UTC (Figure 6).

From the results, we can conclude that the dispersion model TVM, both with the RACM and EMEP mechanisms, give similar and reasonable good predictions of ozone concentrations for the studied cases. The area affected by the photochemical pollution due to the emissions from Madrid has a large extent, invading clearly other neighbour provinces.

![Figure 6: Evolution (03, 12 and 18 UTC) of surface ozone concentration estimated by TVM/RACM for the July 15th, 1995 (left) and comparison between predicted (solid line) and observed daily ozone concentrations (dotted line) at San Agustín (top), Moraleja (middle) and Perales (bottom).](image)

6 Impact of the motor vehicle traffic emissions

Several simulations of photochemical pollution in the Greater Madrid Area under different hypothetical pollutant emission scenarios have been done in order to estimate the influence of the motor vehicle traffic. The reference scenario was that of July 14th, 1992. The simulated cases assumed that different percentages of total anthropogenic (100%, 75%, 50% and 30%) or traffic emissions (200%, 100%, 75%, 50%, 30% and 0%) with respect to the reference scenario were emitted. The results (Figure 7) showed that the abatement of traffic emissions does not reduce the maximum ozone concentration below the population awareness threshold taking into account that the maximum ozone concentration for the reference scenario was 110 ppb. Additional reductions from other anthropogenic emissions are needed. However, the traffic emission reductions produce an important decrease in the area affected by high ozone levels as shown in reference to the AOT60.
Figure 7: Estimated maximum ozone concentrations (left) and AOT60 (right) levels for several emission scenarios.

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References


