A new emissions inventory for Athens and its use to improve air quality predictions

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Abstract

Aim of this paper is to describe the methodology followed to create a new emissions inventory for the Greater Athens area in 1990 and the results of its application as input to the photochemical dispersion model MARS. The sources considered are anthropogenic ones: traffic, domestic heating, industry and fuel storage. Emissions coming from road traffic, which is the most important source of air pollution in Athens, are calculated with a microscale methodology using the CORINAIR/COPERT emission factors. The EUMAC Zooming Model (EZM) is applied for May 25, 1990 using alternatively the new and an older version of the emissions inventory. The comparison of the model results reveals that the new inventory allows achieving a better agreement between model results and observations, especially as far as species of low reactivity are concerned.

1 Introduction

Emissions inventories are critical in air pollution modeling as they provide the input emissions data for air quality simulations and therefore affect modeling results. In this respect, reliable estimates of spatially and temporally disaggregated emissions are perhaps even more important than the absolute
aggregate emission levels; speciation of volatile organic compound emissions is also a key factor. An emissions inventory for the Greater Athens area (GAA) was compiled for the first time in the mid-80s [1], containing emissions from road traffic, central heating and industry for 1985 reference year. Since then it was attempted to complete and update this inventory several times, although little new information was available. In the framework of the APSIS intercomparison of model simulations [2] all previously available information on the emissions of air pollutants in the GAA was used to compile an emissions inventory at a spatial resolution of 2 km and a temporal resolution of 1 h. This 1990 inventory had a number of gaps due to the lack of necessary raw data, mainly with regard to the spatial and temporal allocation of emissions from road traffic and solvent use. Moreover, additional emission-relevant data for some stationary sources were not available until very recently.

The study reported in this paper deals with the general update of the Athens emissions inventory. The importance of using refined input emission data in air quality simulations was examined by using the EUMAC Zooming Model (EZM) [3,4] in conjunction with both the old and the new inventory for the analysis of the photosmog episode on May 25, 1990, e.g. the APSIS-B2 scenario.

2 The new emissions inventory

What is new in the 1990 Athens emissions inventory used in this study are the emissions estimates for the sectors road traffic, central heating and industry. More specifically, a recently developed methodology was applied for the estimation of hourly traffic emissions on street level, while as regards central heating new data and updated information were used. The following sections provide more details on the above. With regard to industrial emissions the best estimates currently available were included in the inventory [5].

2.1 Road traffic emissions

An analytical methodology for the compilation of a motor vehicle emissions inventory at appropriate spatial and temporal resolution for air quality simulations has been developed and applied for Thessaloniki, the second largest urban area in Greece [6]. The method involves two independent emissions estimates, one at macroscale (i.e. for the whole area in a year) and one at microscale (i.e. emissions in each street on an hourly basis) level. The aggregate results of these two estimates are then compared, and the most uncertain assumptions of the microscale approach are corrected so that they are in reasonable agreement with the macroscale estimates (which are generally regarded as more reliable since they are mainly based on sound statistical data). These corrected street by street and hourly emissions constitute the road traffic emissions inventory of the area. Necessary input data for the macroscale calculations are the total number of vehicles in the area, their classification into
size and technology groups and their main usage patterns (average distance driven annually by each car, average speed, distance driven with cold engines), while for the microscale calculations a large amount of information is necessary, mainly with regard to the hourly traffic load and composition in all major streets of the area as well as the average driving speed in each street and its daily variation. In order to simulate the spatial and temporal distribution of cold start driving, which accounts for a large fraction of the total vehicle emissions, the area is divided into three parts: the central business district, which is the destination of most trips during the working hours, the residential areas, from which many trips start early in the morning and end in the evening, and intermediate areas which combine residences and working places and therefore have mixed traffic characteristics. In each one of these areas and for every hour of the day a different fraction of the distance driven with cold engines is assumed. A similar approach is used for the estimation of spatially and temporally resolved evaporative VOC emissions.

Figure 1: Map of the Attica peninsula corresponding to the standard APSIS domain (left). Altitude isopleths are contoured at 100 m. 1 and 2 denote the ground-based measuring stations Geoponiki and Peristeri. The frame indicates the location of the enlargement (right) showing the main street network of Athens.

The same method was applied for the Greater Athens area. Macroscale data were available from relevant statistics and reliable estimates [7], while a small set of microscale traffic data also existed from previous studies. In addition a number of qualified assumptions were made, in order to complete the required input data set.
More specifically, such a motor vehicle emissions inventory requires data on traffic load, traffic composition and the corresponding driving speed in each street, as well as its variation over the day.

Traffic load data were available from state authorities [8] for the main streets of Athens, which are illustrated in Figure 1 (650 streets with traffic varying from 7,000 to 69,000 vehicles/day, accounting for about 60% of the total vehicle kilometers driven in the area); for the rest of the streets reasonable assumptions were made, depending on their location. However, there was little information on traffic distribution over the day. It was therefore assumed that road traffic in Athens follows the same temporal patterns as in the city of Thessaloniki, for which these data existed from a previous study [9]; Figure 2 shows the pattern derived from 1990 traffic data.

![Traffic Load](image)

Figure 2: Daily traffic variation, as derived from recordings in all main streets of Thessaloniki in 1990. The same pattern was used for the streets of Athens.

Little was known about the detailed traffic composition in the streets of Athens (i.e. the fraction of total vehicle kilometers driven by passenger cars, trucks, buses and motorcycles). The existing information covered about 20 major streets only. With the aid of these data the composition in each street was derived, along with its daily variation.

The situation was similar with regard to the driving speed. Data were available for a few major streets (ranging from 15 to 42 km/h) [10], assumptions were made for the rest of the street network, and the daily variation was derived with the aid of corresponding data from Thessaloniki, where an extensive database of driving speed recordings had been formed in the framework of the study mentioned above.

As cold start engine operation is responsible for a high portion of motor vehicle emissions, it is crucial to have a reliable estimate of their spatial and
temporal distribution. Apart from temperature variations over the day, which is not the most critical factor, the distance driven with cold engines is important. Based on knowledge of the main traffic characteristics of Athens and on the relevant experience of the Thessaloniki study, the day was divided into six distinct time zones, for which different fractions of the total vehicle kilometers driven with cold engine were assumed for each one of the three parts of the city (business district, residential areas and intermediate areas); this is displayed in Table 1.

Table 1: Fraction of total vehicle kilometers driven with cold engine. Example: 80% of vehicle kilometers in residential areas between 6 and 10 in the morning are assumed to be driven with cold engine.

<table>
<thead>
<tr>
<th>Time zone</th>
<th>Business district</th>
<th>Residential areas</th>
<th>Intermediate areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>0100-0500</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>0600-0700</td>
<td>0.10</td>
<td>0.80</td>
<td>0.30</td>
</tr>
<tr>
<td>0800-1000</td>
<td>0.10</td>
<td>0.80</td>
<td>0.30</td>
</tr>
<tr>
<td>1100-1200</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>1300-2100</td>
<td>0.30</td>
<td>0.10</td>
<td>0.20</td>
</tr>
<tr>
<td>2200-0100</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The emission calculations followed the COPERT methodology [11]. The aggregate emission results were then compared with the corresponding macroscale estimates that were produced through the application of COPERT for the whole Greater Athens area in 1990. The most uncertain assumptions of the microscale approach were thus controlled and partly modified in order to minimize discrepancies between the two calculations. Table 2 shows the emissions of carbon monoxide (CO), nitrogen oxides (NO\textsubscript{x}) and volatile organic compounds (VOC) for the year 1990 in the whole Greater Athens area, as calculated by COPERT.

Table 2: Traffic related CO, NO\textsubscript{x} and VOC emissions in the Greater Athens Area in 1990.

<table>
<thead>
<tr>
<th>Vehicle category</th>
<th>CO [kt/a]</th>
<th>NO\textsubscript{x} [kt/a]</th>
<th>VOC [kt/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline passenger cars</td>
<td>262.0</td>
<td>14.9</td>
<td>34.5</td>
</tr>
<tr>
<td>Diesel passenger cars</td>
<td>1.2</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Light duty trucks</td>
<td>44.4</td>
<td>3.6</td>
<td>8.8</td>
</tr>
<tr>
<td>Heavy duty trucks</td>
<td>7.5</td>
<td>7.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Buses</td>
<td>12.2</td>
<td>8.9</td>
<td>3.1</td>
</tr>
<tr>
<td>Two wheeled vehicles</td>
<td>16.6</td>
<td>0.1</td>
<td>7.6</td>
</tr>
<tr>
<td>TOTAL</td>
<td>343.9</td>
<td>35.8</td>
<td>56.6</td>
</tr>
</tbody>
</table>
The chemical reaction mechanism KOREM [12], which was used in the air quality simulations (see below), requires speciated emissions data of volatile organic compounds (methane, other alkanes, aromates, aldehydes and olefins). As far as road traffic is concerned, the VOC speciation of Loibl et al. [13] was used, which applies a different VOC split for the three types of vehicle emissions, i.e. hot, cold start and evaporative emissions.

In contrast to the old emissions inventory, the new version takes into account traffic emissions in the Mesogia plain as well. For this purpose, all relevant raw data available were used.

2.2 Central heating emissions
Emission factors used in the new emissions inventory for central heating facilities are identical to those assumed in the old inventory and originally recommended by PERPA [1]. Regarding the necessary activity data (i.e. the amount of fuel consumed for central heating in the area and its temporal variation), all available statistical information for the year 1990 was evaluated. More specifically, the total estimated emissions of CO, NO\textsubscript{x} and VOC in the Greater Athens area in 1990 were spatially disaggregated over the municipalities of the region, depending on the population of each municipality and the fraction of the buildings in each municipality that have a central heating system. The temporal disaggregation was performed on the basis of statistics on the fuel consumed for central heating in the cold season of the year (October through April) and the recorded hourly fuel consumption variation during a typical day of each month [14].

With regard to the speciation of central heating VOC emissions, the split of EPA [15] and Loibl et al. [13] were used.

2.3 Other emissions
Emissions related to gasoline storage, gasoline stations, chemical cleaning, car repair and consumers’ activities are treated as in the old emissions inventory.

Table 3 summarizes the aggregate emissions estimates of the new Athens inventory. In addition, the estimates of the old inventory are shown.

Table 3: CO, NO\textsubscript{x} and VOC emissions in the Greater Athens area in the year 1990 according to the old and the new versions of the emissions inventory.

<table>
<thead>
<tr>
<th>[kt/a]</th>
<th>CO Old</th>
<th>CO New</th>
<th>NO\textsubscript{x} Old</th>
<th>NO\textsubscript{x} New</th>
<th>VOC Old</th>
<th>VOC New</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road traffic</td>
<td>437.9</td>
<td>343.9</td>
<td>24.9</td>
<td>35.8</td>
<td>70.8</td>
<td>56.6</td>
</tr>
<tr>
<td>Central Heating</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>2.6</td>
<td>-</td>
<td>0.6</td>
</tr>
<tr>
<td>Industry</td>
<td>-</td>
<td>4.1</td>
<td>2.6</td>
<td>5.8</td>
<td>27.5</td>
<td>28.6</td>
</tr>
<tr>
<td>Fuel Storage</td>
<td>-</td>
<td>6</td>
<td>2.9</td>
<td>12.7</td>
<td>11.9</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>437.9</td>
<td>349</td>
<td>38.8</td>
<td>44.2</td>
<td>113.9</td>
<td>100.6</td>
</tr>
</tbody>
</table>
3 Application of the photochemical dispersion model MARS

The formation of photochemical smog in the GAA on May 25, 1990, i.e. the APSIS-B2 scenario [2], was simulated with the three-dimensional dispersion model MARS using (i) the old emissions inventory, i.e. the one used in the frame of APSIS, and (ii) the new emissions inventory. The simulation domain corresponded to the APSIS domain shown in Figure 1. Fifteen non-equidistantly distributed layers were considered in the vertical direction, the minimum spacing at ground level not exceeding 20 m. The necessary meteorological input, i.e. the wind field and the turbulent characteristics, were derived from nested grid simulations with the nonhydrostatic mesoscale model MEMO. Details on the wind field in the Attica peninsula are given elsewhere [16]. Chemical transformations were modeled on the basis of the KOREM mechanism [12], which corresponds to a modified version of the compact mechanism of Bottenheim and Strausz [17]. KOREM contains 20 reactive species in 39 reactions.

The results of the application of MARS based on the old emissions inventory are discussed in detail and compared with available measurements elsewhere [18]. Here only representative results of both the previous and the new applications are presented in order to investigate whether there is an improvement of the model results with the new emissions inventory or not. In Figures 3 and 4 predictions for both cases are compared with observed diurnal variations of the CO, NO, NO\textsubscript{2} and ozone concentrations at two locations in the Athens basin (Geoponiki and Peristeri, cf. Figure 1).

Qualitatively, the predicted concentrations are for both cases in satisfactory agreement with the corresponding observations. At nighttime, peaks of CO and NO were observed both at Geoponiki and Peristeri. The model tends to overestimate these peaks for reasons which remain to be analyzed. During the day, the predicted concentrations of CO and NO are in very good agreement with the observations, the only exception being the overestimation of the early morning NO peak at Peristeri. With regard to NO\textsubscript{2}, the model results correspond to the observations at Geoponiki (the zero measurements at 9 and 10 LST are apparently faulty), whereas at Peristeri NO\textsubscript{2} appears to be underestimated, in accordance with the overestimation of NO.

Most probably as a consequence of the described deviation between observed and predicted NO\textsubscript{x}, the observed rapid ozone formation at Peristeri, which indicates a high VOC reactivity of the air mass, is not reproduced by the model. A deeper analysis is needed to decide whether the delayed prediction of ozone formation should be attributed to the reaction mechanism or to the VOC treatment in the emissions inventory (e.g. VOC speciation or inadequate coverage of solvents).

The disagreement of the predicted and observed ozone concentrations at Geoponiki is another open question. The fact, however, that high ozone
Figure 3: Predicted diurnal variation of concentrations of CO, NO, NO₂ and ozone at Geoponiki on May 25, 1990, with both emissions inventories compared with observations.

Figure 4: Predicted diurnal variation of concentrations of CO, NO, NO₂ and ozone at Peristeri on May 25, 1990, with both emissions inventories compared with observations.
concentrations are measured simultaneously with NO concentrations of the
order of 100 ppb poses doubts on the credibility of the observations.

Coming now to the influence of the emissions inventory used on the
quality of the model predictions, it is apparent that in the case of CO the new
emissions inventory leads to a decisive improvement both at Geoponiki and
Peristeri. This improvement is mainly attributed to the considerably lower CO
emission levels of road traffic in the new inventory (see Table 3). A major part
of vehicle emissions was previously estimated on the basis of measurements
conducted on Greek cars, which displayed remarkably higher emission levels
than the average European car due to bad maintenance [11]. These measure-
ments, however, were carried out in 1982 and since then not only has the
vehicle fleet been renewed but also the maintenance level has improved
considerably because of increased public awareness. Therefore, the new
inventory was created by using the COPERT emission factors, representing the
average European car, rather than the outdated ones measured in Greece. The
significant improvement in the agreement between predicted and observed CO
concentration levels seems to confirm that the new inventory contains more
reliable traffic emission estimates.

Concerning NO, the agreement between observation and prediction is once
again better in the case of the new inventory, although the differences in the
results of the two model applications are rather low. Similarly, there is only a
marginal influence of the change in the input emissions data on the calculated
NO\textsubscript{2} and ozone concentration levels. For these reactive species the chemical
reaction mechanism as well as the VOC speciation may have an influence on
air quality modeling which is at least comparable to that of the absolute
emission levels. This highly interesting subject is currently being analyzed by
the aid of EZM simulations in conjunction with the more sophisticated EMEP
mechanism [19].

4 Conclusions

The new 1990 emissions inventory for the Greater Athens area is an
improvement compared with the old one, regarding all emissions, but primarily
those associated with mobile sources. Estimated motor vehicle emission levels
are more reliable and are allocated spatially and temporally on the basis of new
and more extensive data; some of the information on the diurnal variation of
traffic comes from a study carried out for Thessaloniki, but it appears justified
to apply these temporal patterns also for Athens and even several other
Mediterranean cities. Central heating emissions have been re-calculated and re-
allocated with the aid of more recent data. Finally, the new inventory contains
updated estimates of emissions from industrial activities.

In spite of the aforementioned improvements, there is still a significant
potential to compile a complete and more accurate inventory for Athens.
Significant gaps as far as VOC emissions in whole and the VOC split in
Vehicle emissions estimates could be improved if the traffic composition and the driving profile (primarily the average speed) of every main street were known. Furthermore, other emissions sources have to be included: forests, which reportedly emit significant amounts of VOC [20], as well as airport and harbor activities, which may have a strong impact on a local scale.

References

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