Technical Expertise in the Context of the Commission's Communication on an Ozone Strategy

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Executive Summary

This report describes the results of an urban scale photochemical ozone study conducted for the European Commission (DGXI) in the context of the Commission's Communication on an ozone strategy. The EMEP and OFIS ozone models were used to estimate the effect of emission changes on future ozone concentrations in Europe, at both the regional and the urban scale.

The modelling work at the regional scale was conducted with the EMEP MSC-W ozone model, applied over a 6-month period using meteorology from 1990. Model calculations were performed for the 1990 situation, the year 2010 base-case (REF) and two scenarios proposed by IIASA (MFR, D7). Urban scale modelling was carried out using the OFIS model for Stuttgart and Athens the aim being to calculate the local scale ozone levels in both urban areas during a typical summer period.

In addition to simply employing the regional scenarios on the local scale, OFIS was applied for the case of applying additional emission reductions on top of the regionally assumed scenarios. The emission reductions impact on ozone was analysed in terms of AOT60, max. daily 8h ozone values, the max. daily 1h value, grid hours > 120 $\mu g/m^3$ (8h), grid hours > 180 $\mu g/m^3$ (1h), grid hours > 240 $\mu g/m^3$ (1h).

Comparison with available measurements show for Stuttgart a satisfactory agreement between model results and the observed behaviour. The model performance is less satisfactory in the case of Athens, as the model cannot resolve local circulation systems.

For the Stuttgart area, the reduction measures adopted in the MFR scenario appear to lead to the highest benefit in terms of the ozone burden. As far as the Athens area is concerned, the reduction measures adopted in the D7 scenario appear to lead to the highest benefit, most probably in view of the advantageous ratio between NO_x and VOC emissions according to this scenario. The model results furtheron reveal that in Central European airsheds like Stuttgart it is very important to combine emission reduction measures at both the regional and the urban scale. This is to a lesser extent valid for isolated areas like Athens where additional local efforts may prove effective.

The analysis of additional local scale NO_x vs. VOC emission reductions shows that lower ozone burdens result in the case of one-sided VOC emission reductions. On the contrary, one-sided NO_x emission reductions seem to lead to more ozone in the urban area, while benefits may occur at fairly high downwind distances. The calculations suggest that additional NO_x emission reductions of the order of 70-80% are required for an acceptable reduction of the overall ozone burden.

The study contains also examples for additional measures beyond the MFR scenario which could be taken in the conglomerations around Athens and Stuttgart.

The application of OFIS to 23 urban areas for the needs of other European studies (EU98 report, Priority study) suggests that the results of the present study for the city of Stuttgart may be transferred to the majority of EU urban areas.

Contents

1. Introduction

1.1 Background

To establish an effect-oriented (critical load and levels) and cost effective approach aimed at reducing tropospheric ozone, the NO_x reductions in conjunction with reductions of the VOC emissions have to be optimised. At the regional scale, NO_x control was found to be effective in reducing ozone concentrations in the more remote areas of Europe (e.g. Derwent et al., 1994). As the ozone phenomenology in urban areas is different from the general pattern (in cities NO_x generally suppresses the local concentration of ozone), NO_x emission reductions may lead to ozone increases in the urban area whereas in the close vicinity of a conurbation the available VOCs are limiting ozone formation. In contrast, far away from the source area the local ozone production rate is limited by the availability of NO_x. Considering that the ozone exposure is proportional to the population density, an accurate assessment of the effectiveness of emission interventions within densely populated areas is essential.

Much attention has been paid to formulate a conclusion regarding the relative effectiveness of various control measures, e.g., VOC vs. NO_x controls in urban areas. Comparisons of historical trends in ozone and precursor concentrations with trends in precursor emission levels can provide insights into the relative effectiveness of control strategies. Chinkin et al. (1996) compared correlation coefficients for NO_x and VOC emissions vs. ambient ozone for metropolitan areas in the Northeast of the United States and found somewhat better correlations between VOC and ozone as compared to NO_x although the statistical significance of these comparisons was not explored. The correlation coefficients were low overall, indicating that annual emission changes fail to explain a significant percentage of the variability in meteorologically adjusted ozone trends.

1.2 Study concept

The most appropriate method for analysing the consequence of emission interventions, particularly involving vehicle emissions, on future ozone concentrations in Europe, both in rural areas and cities, is the application of photochemical models. In order to achieve a sound representativity, the modelling work requires to cover an extended period (e.g. one summer) and a sufficient number of cities and emission scenarios.

Achievement of the above modelling objectives with only one model is in fact impossible with today’s computing technology. Such a model would require a comprehensive chemical mechanism to resolve the changes in photochemical ozone generation resulting from given changes in VOC speciation (e.g. from fuel reformulation). Modelling would be necessary on a European scale (e.g. 5000 km) over summer or annual periods, but with sufficient spatial resolution (e.g. 1 km) to account for the dispersion and chemistry occurring in and around the cities. No one model can handle all of these problems, so a strategy has to be devised to combine models capable of dealing with the most important issues in a reasonable way.

The strategy adopted in the present study combines two different but complementary photochemical oxidant models. The long-term, regional scale issues are dealt with using the EMEP MSC-W ozone model. Typically, ozone concentrations are calculated every 6 hours for a 150×150 km^2 grid covering the whole of Europe, and over a time period of 6-12 months. On the local scale, the Ozone Fine Structure (OFIS) model allows describing transport and chemical transformation processes in an urban plume at a very low computational effort. OFIS can be used to calculate ozone levels for individual situations as well as for deriving ozone exceedance statistics based on large scale anemological and long range transport information over a longer time period.

1.3 Study layout

The present study was conducted by a consortium headed by the Laboratory of Heat Transfer and Environmental Engineering of the Aristotle University Thessaloniki (henceforth: AUT; other consortium members: IER, Stuttgart and DNMI, Oslo) with the aim to analyse how urban ozone levels are affected by emission reduction measures at the local and/or regional scales. The study was subdivided into the following tasks (the responsible consortium member is indicated in the last column):

1.	Adaptation of three regional scenarios provided by IIASA to the emission database used for both urban areas to be considered (Athens and Stuttgart);	IER (+AUT)

2.	Calculation of regional ozone fields (and other necessary data) to be used as boundary conditions for the ozone fine structure (OFIS) model calculations;	DNMI
3.	Application of the OFIS model (short description in the section 3.2) for the case of simply employing the regional scenarios on the local scale and the case of applying additional emission reductions on top of the regionally assumed reduction scenarios with the aim to calculate the local scale ozone levels in both urban areas during a typical summer period;	AUT
4.	Presentation of the emission reductions impact on ozone in terms of max. daily 8h ozone values, the max. daily 1h value, grid hours > 120 $\mu g/m^3$ (8h), grid hours > 180 $\mu g/m^3$ (1h), grid hours > 240 $\mu g/m^3$ (1h);	AUT
5.	Analysis of combinations of additional NO_x vs. VOC emission reductions leading to the maximum reduction of the ozone levels in the conglomerations around Athens and Stuttgart as contrasted to the situation emerging in the case of simply employing the regional scenarios provided by IIASA;	AUT
6.	Identification of additional measures which could be taken in the conglomerations around Athens and Stuttgart for achieving recommendable additional emission reductions;	IER (+AUT)
7.	Assessment of the representativity of the study results, i.e. investigation to what extent the results of the urban case studies can be transferred to an EU wide level.	AUT

2. Definitions, statistics used

Concentration units used in this report are ppb (1 ppb = 1 part per billion by volume) and μgm^{-3}. At 20°C and 1013 mbar pressure, 1 ppb ozone is equivalent to 2.00 μgm^{-3}. A number of statistics have been used to describe peak concentrations and exposure to ozone:

1-hourly Max. Ozone - the maximum 1-hourly ozone concentrations calculated over the 6-month period April-September.

8-hourly Max. Ozone - the maximum 8-hourly ozone concentrations calculated over the 6-month period April-September.

AOT60 - the accumulated amount of ozone over the threshold value of 60 ppb, i.e. $AOT60 = \int \max(O_3 - 60ppb, 0.0)dt$. In this case, the integral of the daytime hourly values is taken over 6 months.

Grid hours > 120 μgm^{-3} (8h) - Ozone exceedance of the running 8h-mean 120 μgm^{-3} ($km^2 \times$days), i.e. $Ex120 = \sum_{days} \sum_{gridcells} indicator$, where the indicator for each day is set to one if the maximum running 8h-mean per grid cell exceeds120 μgm^{-3}.

Grid hours > 180 μgm^{-3} (1h) - Ozone exceedance of 180 μgm^{-3} ($km^2 \times$hours), i.e. $Ex180 = \sum_{hours} \sum_{gridcells} indicator$, where the indicator for each hour is set to one if the ozone concentration per grid cell exceeds 180 μgm^{-3}.

Grid hours > 240 μgm^{-3} (1h) - Ozone exceedance of 240 μgm^{-3} ($km^2 \times$hours), i.e. $Ex240 = \sum_{hours} \sum_{gridcells} indicator$, where the indicator for each hour is set to one if the ozone concentration per grid cell exceeds 240 μgm^{-3}.

C_{max} - Maximum daily 1h ozone concentration over the six month period.

C_{max}(urban) - Maximum daily 1h ozone concentration over the six month period at urban grid points.

% domain: percentage of total gridpoints where ozone exceeds 240 $\mu g/m^3$.

% urban: percentage of urban gridpoints where ozone exceeds 240 $\mu g/m^3$.

The above statistics reflect different concerns. The 1-hour and 8-hour statistics are for comparison with the EU health protection and information thresholds (180 μgm^{-3} = 90 ppb for 1-hourly values, and 110 μgm^{-3} = 55 ppb for 8-hourly values, Directive 92/72/EEC). In particular in the context of regional scale modelling analysis within EMEP (Barret and Berge, 1996) exceedances of the World Health Organisation (WHO) guideline for the protection of human health (120 μgm^{-3}, 8h average) are expressed as an AOT60, using the 60 ppb level as a threshold.

3. Modelling

3.1 Regional scale modelling - The EMEP MSC-W model

The EMEP ozone model has been described in detail elsewhere (Simpson, 1992, 1993, 1995). Briefly, the model is a one-layer Lagrangian model which follows the parcels of air along 98-hour long trajectories, picking up emissions of NO_x, NMVOC, SO_2 and CO from the underlying grid. Trajectories are calculated every 6 hours to 740 arrival points covering the whole of Europe, and generally for time-periods up to 6 months. The chemistry used in the most recent version of the model consists of 140 reactions between 68 species (Simpson et al., 1995). The grid is polar-stereographic, with a size of 150×150 km^2 at 60°N.

The meteorological data used are routinely produced and archived by MSC-W for use in EMEP long-range transport models, including the oxidant model. These data are derived from the Norwegian Meteorological Institute's numerical weather prediction (NWP) model, which is described in detail in Grønas and Hellevik (1982), Grønas and Mitbo (1986) and Nordeng (1986).

3.2 Local scale modelling - The Ozone Fine Structure (OFIS) model

The Ozone Fine Structure (OFIS) model was developed for the analysis of ozone levels in the vicinity of conurbations (Sahm and Moussiopoulos, 1998; Moussiopoulos and Sahm 1998). It belongs to the European Zooming Model system (EZM), a comprehensive model system for simulations of wind flow and pollutant transport and transformation which was developed in the frame of EUROTRAC (Moussiopoulos 1995). The EZM may be used either in conjunction with a regional scale model, e.g. the EMEP model, or as a stand-alone model system driven directly with measured data. Core models of the EZM are the nonhydrostatic prognostic mesoscale model MEMO (Kunz and Moussiopoulos, 1995) and the photochemical dispersion model MARS (Moussiopoulos et al., 1995).

Being directly related to MARS, OFIS corresponds to a coupled 1D - 2D approach:

- Background boundary layer concentrations are calculated with a three-layer box model representing the local-to-regional conditions in the surroundings of the city considered. This model uses at input non-urban emission rates as well as regional scale model results for meteorological quantities and pollutant concentrations.

- Pollutant transport and transformation downwind of the city (along the dominant wind direction) is calculated with a three-layer multibox model representing a substantially refined version of MARS-1D (Moussiopoulos, 1990).

The distinction of three individual layers of time depending thickness allows adequately describing the dynamics of the atmospheric boundary layer. At the same time, vertical transport is taken properly into account by considering the exchange between adjacent layers. For prescribing the thickness of the three layers, a 1D version of MEMO is utilised: The vertical profiles of temperature, mean wind speed and turbulent exchange coefficient as well as the mixing height are calculated both for the city surroundings and the urban plume assuming Monin-Obukhov similarity at the lower boundary. This methodology is identical to the one adopted in the multilayer model MUSE which is another simplified version of MARS (a few layers instead of ‘normal’ discretisation in the vertical direction; semi-implicit solver instead of a fully implicit one) (Sahm and Moussiopoulos, 1995). The mathematical analysis is based on the coupled, two-dimensional advection-diffusion equations for the ensemble averaged quantitities of reactive species. The equations are solved by operator splitting according to the method of lines, that is by solving the advection dominated terms separately from the diffusion dominated terms (in vertical direction) and the chemical reaction terms. The derivation of the advection, the vertical diffusion and the entrainment operator is then added as a source term to the chemical reaction equation system. The chemical reaction rate equation system in OFIS is solved with a backward difference solution procedure, i.e. by applying the Gauss-Seidel iteration scheme (Kessler, 1995). The model uses a variable time step with an upper limit for the integration time increment of 300 seconds.

The applicability of several versions of MARS, including MUSE, to urban photochemistry studies has been confirmed on the occasion of both research oriented and policy related studies.

3.3 Methodology

3.3.1 Specification of the considered cases

Model simulations were performed for each day between 1 April and 30 September 1990 assuming four different emission scenarios (see section 3.3.4). For this period, EMEP model results were supplied by DNMI at a spatial resolution of 150 km and a temporal resolution of 6 hours. In particular, DNMI provided meteorological data (wind speed and direction, surface temperature) and regional background concentrations of CO, NO, NO_2, O_3 and all other species included in the EMEP/MSC-W chemical reaction mechanism. In an attempt to account for the complex meteorological features of the Athens area (associated with a sea-breeze circulation system and/or stagnant conditions, i.e. a critical balance between synoptic and mesoscale circulations), the local time scale to transport an air parcel downwind was assumed to be twice the synoptic time scale.

Emission data for Stuttgart, specifically the diurnal variation of the emission rates for urban, suburban and rural areas at a temporal resolution of 1 hour were supplied by the Institute of Energy Economics and the Rational Use of Energy (IER), Stuttgart (see section 3.3.2). Corresponding data for Athens have been available at the AUT (see section 3.3.3). Background boundary layer concentrations were computed with the three-layer box model embedded in OFIS for a domain of 150×150 km^2 which was assumed to be rural area. For each day in the period considered, pollutant transport and transformation downwind of both urban areas was calculated in 5 km steps assuming the wind direction valid for the respective day, an initial plume width depending on the radius of the urban area and a plume widening angle of 30°. Care was taken that the landuse of the area beneath the urban plume is consistent to the assumed emissions: A 100% built-up area was considered where urban and suburban emissions occur, and ‘rural’ area farther downwind. Dry deposition was accounted for by using a three-resistance model approach.

Emissions of isoprene, probably the most important biogenic compound with regard to ozone formation, were calculated on-line in the OFIS model for rural areas. The default landuse for both rural areas has been set to 20% built-up and 80% forest. The forest has been subdivided to 55% oak, 15% other deciduous and 30% coniferous. The biomass density and the emission rates for isoprene were taken from a previous study

(Moussiopoulos et al., 1996) and are shown in *Table 1*. The correction terms for the temperature and radiation dependence of biogenic emission rates were calculated according to Guenther et al. (1991). The methodology for the calculation of the radiation terms needed for biogenic emission rate calculations was taken from Iqbal (1983).

Table1: Isoprene biomass density and emission rates

Landuse type	Biomass density (gm^{-2})	Emission rate Greece ($\mu gC\ g^{-1}h^{-1}$)	Emission rate Germany ($\mu gC\ g^{-1}h^{-1}$)
Oak	300	5.2	14.69
Spruce	1400	1.24	3.0
Other deciduous	1000	1.2	1.2
Other coniferous	1400	0.4	0.4
Crops	40	0.2	0.2

3.3.2 Methodology for generating the Stuttgart Emission Inventory

For the generation of emission data for the Stuttgart domain, IER applied the methodology described in brief as follows:

Emission data collected at IER for the Stuttgart area were used as a basis for the intersection process with a Geographical Information System (GIS). Point sources were directly included in the gridded data set, while area sources and line sources (major streets and highways) were intersected to match the district boundaries.

To reflect the special situation of the Stuttgart area, the domain was subdivided into three zones: urban (covering the Stuttgart city area), suburban (covering the densely populated belt of towns and villages surrounding the city) and finally the rural area covering the remaining grid cells.

Specific time curves were used for the sectors households and residential combustion (typical variations of heating patterns), industry (production indices and shift times), road transport (evaluation of information from roadside counters), power plants (utilisation profiles) and agriculture (typical variations of NH3 evaporation).

Finally, hourly emissions for each district have been calculated using annual emissions, time-curve-shares (where applicable) and geographical emission shares, distinguishing point sources and area sources and giving specific emission values for NO_x, CO, NH_3, SO_2 and 32 different VOC species[1].

The actual calculation has been conducted using a prototype version of the Emission Calculation Module (CAREAIR/ECM), which is currently being developed at IER (Friedrich et al., 1998).

3.3.3 Methodology for generating the Athens Emission Inventory

The Athens emission inventory comprises all available estimates of NO_x, CO, SO_2 and VOC emissions, the latter being allocated to selected groups of hydrocarbon compounds according to the source categories considered, at a temporal and spatial resolution of 1 hour and 2 km, respectively. In detail, the Athens emission inventory was compiled accounting for the following emission sources:

a) *Urban road traffic:* The raw emission data related to urban traffic were prepared on a detailed Geographical Information System (GIS) and consisted of NO_x, CO and VOC emissions. Emission estimations for the year 1990 were based on an analytical method considering all available traffic data, calibrated by a “top-down” approach (Samaras et al., 1997).

b) *Industry:* Industrial emissions were available in a gridded form and comprised NO_x, CO, SO_2 and VOC data. These emissions were adopted from the Auto Oil Study (European Commission, 1996). The calculation of the emissions was based on available data concerning fuel consumption (heavy oil, diesel and gas) of various industrial units and their location in each municipality of the Greater Athens Area (henceforth GAA). Industrial emission sources were distinguished into area and point sources, the latter corresponding to five major plants.

c) *Airport:* Emissions associated with the operation of the Athens airport were derived from information collected in the frame of the impact assessment study for the New Airport of Athens (Proyou et al., 1995).

d) *Space heating:* Emissions estimations for space heating facilities were based on emission factors originally recommended by PERPA (Toll et al., 1995) and necessary

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[1] VOC speciation according to Middleton and Stockwell, 1990

activity data (i.e. the amount of fuel consumed for central heating in the area and its temporal variation) derived from available statistical information for 1990.

e) *Other sources:* In addition to the above, extra-urban traffic and harbour emissions for NO_x, CO and VOC were also accounted for as in the recent Athens 2004 Air Quality Study (Moussiopoulos and Papagrigoriou, 1997). Considering the uncertainties regarding the spatial and temporal distribution and speciation of VOC emissions caused by fuel storage and other, mostly fugitive, VOC emissions, the total daily emissions for this source category were roughly estimated at 90 tons. It was assumed that 40% of these emissions are associated with industrial activities, while the rest was distributed proportionally to the population density.

As a prerequisite for the synthesis of the Athens emission inventory, an emission inventory model was developed which compiles all available credible datasets concerning emission data for the present situation in the GAA and, if desired, may extrapolate these data, following reasonable assumptions, to the future.

The methodology applied in order to obtain the Athens inventory involves:

a) *the gridding process:* All the aforementioned emission data were ultimately integrated in a 72×72 km^2 grid at a spatial resolution of 2 km. The discretisation of the urban traffic emissions was achieved using ARC/INFO (Environmental System Research Institute Inc., 1993). Emissions from the other source categories, i.e. emissions due to extra-urban traffic, industrial activities, harbour, airport and central heating, were already available in a gridded, ready-to-use form,
b) *the selection of an adequate temporal resolution:* The emission inventory contains data for each hour of the day considered as representative for the respective year, and
c) *the speciation of VOC emissions:* The emission data collected comprised NO, NO_2, CO, SO_2 and VOC (volatile organic compounds) emissions. If the latter are to be applicable for any chemical mechanism embedded in a photochemical dispersion model, the emission inventory has to include accurate and detailed information on the VOC splitting. Consequently, the total VOC emissions were subdivided into 43 organic species. The distribution was accomplished by applying appropriate splitting factors - functions of the 43 species and the source category - to the VOC emission data for each source category. As far as road traffic, airport and harbour emissions are

concerned, suggestions of Veldt (EMEP/CORINAIR, 1996) were adopted according to which different VOC speciations should be used for the various types of vehicle emissions. With regard to the speciation of industrial emissions the suggestions of Middleton and Stockwell (1990) were followed.

3.3.4 Assumed emission scenarios

Simulations were performed for the base case (1990 situation) and three scenarios for 2010 which were provided by IIASA (cf. Amann et. al, 1998). The first scenario, taken as the reference (REF) scenario, assesses the likely impacts of the most stringent outcome of the current reduction plans and the current legislation scenarios. The second, called the Maximum Feasible Reductions (MFR) scenario, illustrates the potential of a full application of current control technologies. The so-called D7 scenario aims at the combined optimisation for health (AOT60) and vegetation (AOT40) related targets. The emission information used for the urban areas has been appropriately adapted to the regional scenarios. The relative emission changes to the base case are shown for each scenario in *Table 2*.

Simulations with OFIS were also performed assuming emission reductions as given in *Table 2* only at local scale, i.e. using at input EMEP model results for the base case. In an attempt to quantify how the ozone levels in Stuttgart and Athens are affected by various NO_x and VOC emission reductions on top of the regionally assumed scenarios, the OFIS model was applied for eleven additional local scenarios accounting for gradual reductions of the VOC and NO_x emissions in 25% steps.

Table 2: Emission changes to 1990 for the three scenarios

	REF		D7		MFR	
	NO_x	VOC	NO_x	VOC	NO_x	VOC
Germany (countrywide)	-51%	-55%	-54%	-69%	-69%	-72%
Stuttgart	-57%	-44%	-57%	-61%	-66%	-68%
Greece (countrywide)	-17%	-32%	-18%	-41%	-47%	-43%
Athens	-47%	-51%	-47%	-65%	-65%	-69%

4. Results

4.1 Results for Stuttgart

4.1.1 Base case

Figure 1 (left) shows the study area and the wind direction statistics for Stuttgart during the analysed period as reflected in the data supplied by DNMI. In the preparatory meteorological simulations with the 1D version of MEMO it was found that the ground level wind direction deviates from the geostrophic one by on average 20° (anti-clockwise). Apparently, prevailing wind directions at surface level in Stuttgart are those from W-SW. Also, winds from NE appear to occur rather frequently in the area.

In *Figure 1 (right)* the AOT60 values cumulated over the period 1 April – 30 September 1990 as derived from measurements are shown. It should be noted that the situation in the individual measuring stations is inevitably influenced by a variety of local influences not considered in OFIS (emission inhomogeneities, terrain effects etc.). Yet, compared to the values obtained with OFIS (cf. *Figure 2, upper left*), the agreement is very satisfactory with regard to both maximum AOT60 levels and the area of their occurrence: The observed and predicted maximum levels exceed 15 ppm×h. As expected, highest AOT60 levels are predicted by OFIS to the E-NE of Stuttgart, i.e. the area which happens to be most of the time downwind of the city.

Compared to corresponding data derived from observations, OFIS successfully reproduces the observed maximum concentrations (in the range of 140-160 ppb).

4.1.2 Impact of emission reductions

Figure 2 shows furtheron the impact of the three regional emission reduction scenarios on the AOT60 levels. The spatial pattern remains similar, but the maximum AOT60 values obtained for all scenarios are significantly reduced (cf. *Table 3*). The reduction measures adopted in the MFR scenario appear to lead to the highest benefit in terms of AOT60 values (*Figure 2, lower right*).

Tables 3 and 4 (first column) show the impact of the above mentioned regional scenarios in terms of AOT60, maximum ozone concentration and ozone exceedances. Calculated AOT60 and Ex120 values are reduced from their 1990 values by about 50% with the

REF scenario, 75% with the D7 scenario and almost 80% (AOT60) and 85% (Ex120) with the MFR scenario. Calculated maximum daily and 8h-average ozone concentrations are reduced from their 1990 values by about 10% with the REF scenario, 25% with the D7 scenario and almost 30% with the MFR scenario. Interestingly, although the adoption of the REF scenario leads to a reduction of the overall maximum daily ozone concentration C_{max}, the maximum urban ozone concentration C_{max}(urban) is unchanged. The maximum 8h average ozone concentration in the urban area even increases by 7%. Hence, it requires reductions beyond the REF level in order to achieve an improvement within the urban area. The ozone exceedances Ex180 and Ex240 vanish with the adoption of interventions of the D7 and the MFR scenarios. A substantial reduction (by 85-90%) is possible also with the REF scenario.

Figure 3 illustrates that in Central European airsheds like Stuttgart it is very important to combine emission reduction measures at both the regional and the local scale (henceforth: regional+local scenarios). Compared to the base case, the domain averaged AOT60 values are found to decrease significantly for all three scenarios. There appears to be an even larger AOT60 decrease at distances of more than 40 km from the city centre (*Figure 3, left column*), whereas in the urban area itself the emission reductions are found to cause a less pronounced decrease of the AOT60 values. In contrast to the regional+local scenarios, emission reductions restricted to the local scale appear to lead in Stuttgart to higher domain averaged AOT60 values. If only the urban area is considered, the corresponding increases are significant. Also the maximum AOT60 values over the entire domain are found to increase by 30-40%, depending on the scenario. In contrast to this, in the case of the regional+local scenarios the maximum AOT60 values decrease significantly for all three scenarios.

4.1.3 Impact of additional local scale emission reductions

The impact of additional local scale emission reductions which were assumed on top of the regional scale scenarios is illustrated in *Tables 3 and 4*. In general, lower AOT60 values result in case of one-sided VOC emission reductions. On the contrary, one-sided NO_x emission reductions seem to lead to higher AOT60 values. Similar behaviour is found with regard to the maximum daily and 8h-average ozone concentration (*rows 3+4 of Table 3*), ozone exceedances of the running 8h-mean 120 $\mu g/m^3$ and hourly ozone exceedances of 180 and 240 $\mu g/m^3$, respectively (*rows 1-3 of Table 4*). With regard to the urban maximum daily and 8h-average ozone concentrations, the results indicate that one-sided NO_x emission reductions bring the peak values closer to the city (i.e. the urban maximum coincides with the total maximum, marked with underlined italics characters in *Table 3*).

From the percentage of gridpoints where ozone exceeds 240 $\mu g/m^3$ it can be seen that NO_x reductions of the order of 75% are necessary to achieve a benefit in terms of the ozone burden (*rows 4-5 of Table 4*).

4.2 Results for Athens

4.2.1 Base case

Figure 4 shows the study area and the wind direction statistics for Athens during the analysed period as reflected in the data supplied by DNMI. In the preparatory meteorological simulations with the 1D version of MEMO it was found that the ground level wind direction deviates from the geostrophic one by on average 20° (anti-clockwise). Apparently, the complex meteorological features of the Athens area (i.e. local circulation systems, here sea-breeze with winds dominating from SW) are not resolved in the regional scale.

Figure 5 (upper left) shows the calculated AOT60 values cumulated over the period 1 April – 30 September 1990. The predicted maximum levels exceed 12 ppm×h. Highest AOT60 levels are predicted by OFIS to the SE of Athens, i.e. the area which according to the regional scale information happens to be most of the time downwind of the city.

4.2.2 Impact of emission reductions

Figure 5 shows furtheron the impact of the three regional emission reduction scenarios on the AOT60 levels. The spatial pattern remains similar, but the maximum AOT60 values obtained for all scenarios are significantly reduced (cf. *Table 5*). The reduction measures adopted in the D7 scenario appear to lead to the highest benefit in terms of AOT60 values (*Figure 5, lower left*). This is obviously related to the advantageous ratio between NO_x and VOC emissions according to this scenario.

Tables 5 and 6 (first column) show the impact of the above mentioned regional scenarios in terms of AOT60, maximum ozone concentrations and ozone exceedances. Compared to 1990, AOT60 and Ex120 are reduced by more than 75% with the REF scenario, more than 90% with the D7 scenario and almost 75% with the MFR scenario. Correspondingly, maximum daily and 8h-average ozone concentrations are reduced from their 1990 values by about 30% with the REF scenario, 40% with the D7 scenario and almost 30% with the MFR scenario. The ozone exceedances Ex180 and Ex240 practically vanish with all three scenarios. As already stated above, the reduction measures adopted in the D7 scenario appear to lead to the highest benefit for all indicators examined.

Figure 6 illustrates that even in an isolated urban area like Athens it is important to combine emission reduction measures at both the regional and the local scale. Yet, regional scale transport phenomena appear to have a smaller influence on the local scale ozone burden compared to the situation in Central European airsheds. Local scale emission reduction interventions are therefore very important in such airsheds.

4.2.3 Impact of the additional local scale emission reductions

The impact of the additional local scale emission reductions which were assumed on top of the regional scale scenarios is illustrated in *Tables 5 and 6*. In general, similar conclusions may be drawn as in the case of Stuttgart.

5. Additional measures to reduce NO_x and NMVOC

5.1 Additional abatement options for Stuttgart

The starting point for the identification of additional measures to reduce NO_x and NMVOC emissions beyond the IIASA MFR scenario was the description of the latter in the 5th Interim Report (Amann et al., 1998).

IIASA's *Maximum Feasible Reduction* (MFR) Scenario describes the potential of a full application of current control technology, but excluding structural changes, changes in activity levels and non-technical measures. In addition to that, current and historically observed turnover rates of the capital have been assumed for the future.

By a thorough analysis of NO_x and NMVOC emitting sectors, the most relevant sectoral activities (road transport, fossil fuel combustion, solvent use) have been identified. Thus, determining areas on which to concentrate when defining additional reduction potential, the following aspects have been identified for further investigation:

- non-technical measures (e.g. road pricing, permit schemes etc.)
- increased fleet turnover for vehicles (leading to increased shares of cleaner cars)
- structural and modal changes (e.g. improved public transport systems)
- changes in activity levels (e.g. annual km driven per vehicle)
- measures not included in the MFR Scenario (e.g. other mobile sources, fuel switches in residential combustion etc.)

In addition to that, experience gathered in former ozone related projects (see Obermeier et al., 1995, 1997) was taken into consideration.

Since road transport plays a vital role for the emission of ozone precursors, special interest was placed upon the investigation of transport related measures. A variety of non-technical measures has been identified, which have either structural impact (e.g. switching from individual transport to public transport), or have a direct influence on emission patterns (e.g. speed limits leading to lower emission factors).

It is basically possible to implement measures on a long-term basis, or short-term to cope with peak ozone concentrations, but it has to be noted that long-term measures do have a far larger impact of overall concentrations of tropospheric ozone. For most of the identified measures a short-term implementation is not feasible at all, since they require structural changes or a specific infrastructure.

The potential for additional emission reduction has first been assessed on a sectoral basis, determining the share of emissions contributed by the specific activity. Then, the contribution of this sector to the annual total emissions was determined and thus an overall emission reduction calculated. *Table 7* shows additional measures which could be taken into account for improving urban air quality in Stuttgart.

5.2 Additional abatement options for Athens

In the GAA several projects are being carried out or are currently planned to be soon executed which will significantly improve the existing air pollution situation. Since the major contributor to the Athenian air pollution problem is road traffic most of these interventions are directly related to infrastructure changes in the transportation sector (e.g. the Athens Metro, new road construction projects, the re-allocation of the Athens airport etc.). In parallel with these, several other interventions the adoption of which will lead to significantly reduced air pollution levels in Athens are currently being implemented or are short before realisation. The most important measures related to the long-term air pollution abatement in Athens are: a) the Exhaust Gas Emission Control Card (EGECC), b) the creation of an environmental compliance control mechanism, c) the efficient central heating operation control, and d) the introduction of natural gas.

In the framework of the "Athens 2004 Air Quality" study (Moussiopoulos and Papagrigoriou, 1997) several additional interventions to the air pollutants emission situation in Athens were thoroughly analysed the aim being to assess their impact on air pollution levels. All proposed interventions were based on changes in the emissions caused by road traffic, which is, as mentioned, the most critical source category in Athens. These interventions focus on:

1. The accelerated introduction of clean cars in the Athenian fleet.
2. Traffic restriction measures:
   a. prohibiting the usage of the most polluting passenger cars in the interior of the city,
   b. reserving large areas in centre of Athens for pedestrians,
   c. restricting the circulation of heavy duty vehicles from the interior of the city, and
   d. limiting the circulation of heavy duty vehicles to certain times of the day.

As for the case of Stuttgart, the potential for additional emission reductions has initially been assessed on a sectoral basis. Then the contribution of each sector to the annual total emissions was determined and the corresponding overall emission reductions were calculated.

Table 8 shows the additional interventions which could be adopted for improving urban air quality in Athens as well as the emission reductions resulting from their implementation. With regard to the industrial, commercial and domestic sectors, additional measures related to the foreseen fuel changes and the penetration of natural gas in the Greek market, are also presented. It should be mentioned though that due to lack of accurate information on emission factors and fuel consumption for these sectors, only a rough estimation of the corresponding reductions was obtained.

6. Assessment of representativity

Checking the validity of the study concept for Europe as a whole, i.e. analysing to what extent the results are representative for urban air quality in Europe, would be beyond the scope of the present study. This has been done in other European studies (EU98 report on the state of the Environment; Priority study). Within these studies, OFIS was applied for 23 European cities. *Figures 7 and 8* show the measured and computed maximum and 6-month averaged ozone concentrations for the 12 cities for which measurements are available. The latter originate from the report “Europe’s Environment: The Second Assessment” (EEA, 1998), with the exception of data for Amsterdam which was taken from APIS/AIRBASE. Both figures contain OFIS results valid for the urban area (middle bar) and the whole domain (right bar) because the observational data source does not clarify the characteristics of the measurement location. In general, the agreement between the model results and observations is satisfactory. As expected, the model approach seems to fail for cities like Athens and Barcelona, i.e. areas with pronounced local circulation systems (sea-/land breeze circulations). In the case of Milan, the results obtained bring forward the need for more accurate emission information: The VOC/NO_x emission ratio in Milan (as also in Paris) is twice as high as for the other cities. Indeed, additional simulations for both cities with 50% reduced VOC emissions lead to significantly reduced average and maximum ozone concentrations which, in the case of Milan, are close to the observations.

7. Conclusions

The model combination consisting of the EMEP MSC-W ozone model and the Ozone Fine Structure (OFIS) model was successfully applied in the frame of this study, the main results of which can be summarised as follows:

- The ozone pattern in the vicinity of a conurbation deviates from the regional scale one. In particular, the impact of emission interventions on the ozone levels in a city is entirely different from their impact on the tropospheric ozone levels.
- The REF scenario leads to a significant reduction of the overall ozone burden: According this scenario, calculated AOT60 and Ex120 values are reduced from their 1990 values by about 50% in the case of Stuttgart and 75% in the case of Athens. The D7 and MFR scenarios lead to stronger decreases of the urban scale ozone levels compared to the REF scenario.
- For further ozone reductions primarily VOC emissions have to be reduced. NO_x reductions of the order of 75% would be necessary to achieve a benefit in terms of the ozone burden.
- For sensible reductions of the ozone levels in an urban area emission reductions are needed at both the regional and the local scales. The importance of the latter increases with the distance of the urban area from other areas with elevated emissions.
- With the exception of areas with complex meteorology (e.g. pronounced local circulation systems), the concept of the present study can be transferred to other EU urban areas.

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Table 3: Detailed results on the impact of various emission reduction scenarios for Stuttgart
AOT60$_{max}$: maximum AOT60 values, **AOT60$_{ave}$**: domain averaged AOT60 values,
C$_{max}$: maximum daily 1h ozone values, **8h$_{max}$**: max. daily 8h ozone values,
C$_{max}$(urban): maximum daily 1h ozone values at urban grid points, **8h$_{max}$(urban)**: max. daily 8h ozone values at urban grid points,

	VOC	**100%**				**75%**				**50%**			
	NOx	**100%**	**75%**	**50%**	**25%**	**100%**	**75%**	**50%**	**25%**	**100%**	**75%**	**50%**	**25%**
AOT60$_{max}$	BASE	14.73	18.13	23.57	33.46	13.35	15.99	21.10	29.78	12.14	14.02	18.64	25.95
	REF	7.65	9.21	11.41	13.65	6.24	7.87	9.51	12.30	4.96	6.47	7.86	10.76
	D7	4.14	5.64	6.85	9.18	3.36	4.71	6.02	8.17	2.68	3.83	5.16	7.08
	MFR	3.26	4.23	5.05	6.04	2.59	3.54	4.28	5.39	2.05	2.85	3.63	4.66
AOT60$_{ave}$	BASE	12.04	13.12	14.14	14.67	11.49	12.48	13.54	14.23	11.05	11.87	12.91	13.74
	REF	3.07	3.27	3.32	3.09	2.75	2.98	3.09	2.95	2.42	2.68	2.83	2.80
	D7	1.58	1.81	1.93	1.83	1.39	1.61	1.76	1.73	1.21	1.42	1.60	1.62
	MFR	0.83	0.94	0.97	0.84	0.69	0.81	0.86	0.79	0.56	0.68	0.76	0.72
C$_{max}$ /ppb	BASE	143	154	175	163	134	143	158	158	126	131	139	151
	REF	128	135	131	114	113	124	125	113	106	108	116	109
	D7	108	115	120	109	102	104	113	107	97	99	104	104
	MFR	101	108	109	99	97	99	104	97	93	94	98	95
8h$_{max}$ /ppb	BASE	127	138	159	155	117	129	144	149	112	120	128	140
	REF	117	123	123	111	104	114	116	109	98	101	108	105
	D7	99	106	111	105	95	98	106	102	90	93	98	99
	MFR	94	100	102	95	90	92	98	93	87	89	92	91
C$_{max}$(urban)	BASE	125	142	*175*	*163*	116	128	154	*158*	110	120	129	*151*
	REF	125	*135*	*131*	*114*	106	122	*125*	*113*	99	104	*116*	*109*
	D7	100	113	*120*	*109*	95	100	*113*	*107*	90	94	103	*104*
	MFR	95	107	*109*	*99*	92	97	*104*	*97*	88	90	97	*95*
8h$_{max}$(urban)	BASE	105	126	157	*155*	99	111	138	*149*	97	106	117	*140*
	REF	112	122	*123*	*111*	97	111	*116*	*109*	89	95	107	*105*
	D7	89	103	*111*	*105*	85	92	104	*102*	82	87	95	*99*
	MFR	86	97	*102*	*95*	82	89	97	*93*	80	83	90	*91*

Table 4: Detailed results on the impact of various emission reduction scenarios for Stuttgart
Ex120: ozone exceedance of the running 8h-mean 120 $\mu g/m^3$ (km^2×days),
Ex180/**Ex240**: ozone exceedance of 180/240 $\mu g/m^3$ (km^2×hours),
% domain: percentage of total gridpoints where ozone exceeds 240 $\mu g/m^3$,
% urban: percentage of urban gridpoints where ozone exceeds 240 $\mu g/m^3$.

	VOC	**100%**				**75%**				**50%**			
	NOx	**100%**	**75%**	**50%**	**25%**	**100%**	**75%**	**50%**	**25%**	**100%**	**75%**	**50%**	**25%**
Ex120 $\mu g/m^3$	BASE	535955	556983	572367	585380	525344	549539	568120	580509	511889	538273	559800	575068
	REF	233502	239325	242290	237818	227314	234415	236836	233191	216331	226653	230252	228384
	D7	124529	135255	134851	132473	117829	127120	131480	128748	105038	119831	126291	122929
	MFR	77433	80776	80742	72772	71906	76193	75780	69640	59992	69018	70234	65441
Ex180 $\mu g/m^3$	BASE	465138	673317	829397	880522	358496	532110	726766	798246	310807	403684	591706	700491
	REF	75353	96068	100844	51089	30450	56965	71073	37138	9302	25212	39587	25034
	D7	11590	24900	34345	17365	4036	11928	19143	12222	2403	3542	8761	9119
	MFR	6671	11066	10743	2787	1999	5657	6745	2198	0	770	2327	1395
Ex240 $\mu g/m^3$	BASE	7562	22919	65372	71318	2577	6406	33589	46451	62	2754	9234	22500
	REF	932	1814	1395	0	0	386	629	0	0	0	0	0
	D7	0	0	0	0	0	0	0	0	0	0	0	0
	MFR	0	0	0	0	0	0	0	0	0	0	0	0
% domain	BASE	25.56	46.82	45.94	33.45	12.01	19.85	37.10	31.12	0.61	10.65	18.08	24.12
	REF	3.01	5.01	3.75	0	0	1.89	2.64	0	0	0	0	0
	D7	0	0	0	0	0	0	0	0	0	0	0	0
	MFR	0	0	0	0	0	0	0	0	0	0	0	0
% urban	BASE	13.33	74.67	94.67	100.00	0	25.33	74.67	96.00	0	0	29.78	80.00
	REF	15.11	47.56	47.56	0	0	15.11	47.56	0	0	0	0	0
	D7	0	0	0	0	0	0	0	0	0	0	0	0
	MFR	0	0	0	0	0	0	0	0	0	0	0	0

Table 5: Detailed results on the impact of various emission reduction scenarios for Athens
AOT60$_{max}$: maximum AOT60 values, **AOT60$_{ave}$**: domain averaged AOT60 values,
C$_{max}$: maximum daily 1h ozone values, **8h$_{max}$**: max. daily 8h ozone values,
C$_{max}$(urban): maximum daily 1h ozone values at urban grid points, **8h$_{max}$(urban)**: max. daily 8h ozone values at urban grid points,

	VOC	**100%**				**75%**				**50%**			
	NOx	**100%**	**75%**	**50%**	**25%**	**100%**	**75%**	**50%**	**25%**	**100%**	**75%**	**50%**	**25%**
AOT60$_{max}$	BASE	12.35	22.54	28.95	45.37	5.41	12.96	21.14	34.31	3.34	5.04	12.73	23.00
	REF	2.58	6.62	11.55	20.17	0.78	2.89	6.54	14.71	0.39	0.77	2.65	9.23
	D7	0.57	2.53	6.06	13.94	0.30	0.83	3.15	9.96	0.23	0.32	1.07	6.12
	MFR	3.1	4.85	9.60	12.78	1.14	2.45	6.21	9.44	0.32	0.84	3.27	6.38
AOT60$_{ave}$	BASE	3.64	6.13	8.60	8.90	2.30	3.86	6.42	7.61	1.85	2.30	4.06	6.00
	REF	0.70	1.57	2.66	3.04	0.38	0.79	1.65	2.27	0.31	0.39	0.82	1.43
	D7	0.26	0.62	1.41	2.00	0.21	0.31	0.80	1.40	0.20	0.22	0.38	0.80
	MFR	0.62	1.10	1.50	1.33	0.25	0.58	0.93	0.96	0.92	0.22	0.44	0.58
C$_{max}$ /ppb	BASE	158	246	341	368	119	154	245	331	90	116	162	266
	REF	111	160	205	244	97	109	164	215	85	95	121	169
	D7	94	107	162	209	85	94	131	180	77	87	90	132
	MFR	111	149	177	189	92	120	142	172	86	87	118	148
8h$_{max}$ /ppb	BASE	133	191	278	319	105	130	201	284	84	103	132	222
	REF	95	126	170	213	83	94	137	190	70	81	100	145
	D7	81	92	136	184	71	81	109	154	64	73	78	116
	MFR	97	125	151	168	80	100	123	154	74	75	102	130
C$_{max}$(urban)	BASE	86	161	*341*	*368*	86	86	204	*331*	86	86	112	*266*
	REF	70	113	204	*244*	70	71	141	*215*	70	70	94	*169*
	D7	69	71	140	*209*	69	69	106	*180*	69	69	74	127
	MFR	83	129	177	*189*	65	97	134	*172*	65	69	106	*148*
8h$_{max}$(urban)	BASE	81	120	*278*	*319*	81	81	156	*284*	81	81	81	*222*
	REF	64	87	167	*213*	64	64	110	*190*	64	64	75	*145*
	D7	64	64	108	*184*	64	64	83	*154*	64	64	64	105
	MFR	64	98	149	*168*	61	75	107	*154*	61	61	85	*130*

Table 6: Detailed results on the impact of various emission reduction scenarios for Athens

Ex120: ozone exceedance of the running 8h-mean 120 μg/m^3 (km^2×days),
Ex180/**Ex240**: ozone exceedance of 180/240 μg/m^3 (km^2×hours),
% domain: percentage of total gridpoints where ozone exceeds 240 μg/m^3,
% urban: percentage of urban gridpoints where ozone exceeds 240 μg/m^3.

	VOC	**100%**				**75%**				**50%**			
	NOx	**100%**	**75%**	**50%**	**25%**	**100%**	**75%**	**50%**	**25%**	**100%**	**75%**	**50%**	**25%**
Ex120 μg/m^3	BASE	726334	920461	1015987	1052637	534826	779748	966769	1026856	402838	555642	845976	982421
	REF	176846	359223	513670	532656	71529	213271	396349	478705	42137	75297	239760	385126
	D7	64331	194724	373409	459724	41626	91214	261437	389069	36674	44531	119862	265540
	MFR	207137	321299	389803	321059	91576	211022	306093	268544	19775	80868	176326	187292
Ex180 μg/m^3	BASE	720838	2239397	3711765	3895910	69334	788374	2385481	3016508	0	42661	768200	1887478
	REF	18792	303833	806587	890223	241	27147	274472	445712	0	108	23835	121095
	D7	27	13699	211777	359745	0	27	40475	141634	0	0	0	36458
	MFR	33861	121300	220316	162208	0	20522	62622	100283	0	0	6441	41750
Ex240 μg/m^3	BASE	72067	587576	1247677	1019930	0	56360	510908	621151	0	0	44814	197553
	REF	0	7650	45391	81848	0	0	6049	36506	0	0	0	10607
	D7	0	0	4848	29425	0	0	629	12346	0	0	0	1067
	MFR	0	2489	13082	13896	0	0	3559	8205	0	0	0	2907
% domain	BASE	38.53	73.80	80.86	78.19	0	37.01	75.78	75.16	0	0	37.39	59.00
	REF	0	9.32	18.89	9.68	0	0	4.07	6.91	0	0	0	3.89
	D7	0	0	3.34	6.20	0	0	0.92	3.89	0	0	0	1.27
	MFR	0	2.28	4.43	3.90	0	0	2.84	2.87	0	0	0	1.04
% urban	BASE	0	31.56	96.00	100.0	0	0	87.56	100.00	0	0	0	94.67
	REF	0	0	84.44	99.11	0	0	30.22	91.56	0	0	0	84.44
	D7	0	0	13.78	91.56	0	0	0	84.44	0	0	0	13.78
	MFR	0	13.78	84.44	84.44	0	0	30.22	84.00	0	0	0	50.22

Table 7: Additional measures to improve urban air quality in Stuttgart

Measure	**Sectoral reduction** *(on top of MFR)* [relevant SNAP Group]	**Reduction of total emissions** *(on top of MFR)*
Reduction of individual transport[1] Comprising measures such as: • road pricing *(individual pricing of urban roads to reduce traffic volume)* • restricted areas for individual transport • promotion of park & ride systems • permit schemes for driving through urban areas • banning high-emission cars from urban areas *(combined with remote sensing)* • new public transport lines • reduced pricing for public transport • speed limits on city highways *(combined with increased speeding controls)* • promoting in-city bicycle use	~ -15% – -20% NO_x and NMVOC [applies mainly to Road Transport – Passenger Cars, SNAP 7.1]	~-7% – -10% NOx ~-6% – -8% NMVOC
Reducing the use of solid fuels in residential and commercial combustion[2]	-10% NMVOC [SNAP 2]	~-0,5% NMVOC
Full implementation of Low-NO_x-burners in residential & commercial combustion[2]	-10% NO_x [SNAP 2]	~-0,5% NO_x
Substitution of solvent content in household products (cleaning, sprays, detergents, etc.)	-20% NMVOC [SNAP 6]	~ -6% NMVOC
Implementation of emission control equipment in other mobile sources *(construction works, lawn mowers, etc.)*	-20% NO_x and NMVOC [SNAP 8]	~ -2,5% NOx ~ -0,5% NMVOC
Full (faster) implementation of EURO IV standards for Passenger Cars and Light Duty Vehicles	-10% NO_x and NMVOC [SNAP 7.1 and 7.2]	~ -3% NOx ~ -4% NMVOC
Full implementation of emission standards for Mopeds and Motorcyles	-1% NO_x -5% NMVOC	~ -0% NO_x ~ -0,5% NMVOC
Further reduction of solvent use in industry	-10% NMVOC [SNAP 6 and/or 4]	~ -4% NMVOC
City-Logistic-Concept (reducing the use of HDVs in the urban area by creating distribution points outside the city borders, from where LDVs can deliver goods on optimized routes)	-3% NO_x [SNAP 7.3]	~ -1% NO_x
Promotion of renewable energies (solar, wind, ...)	-2% NO_x [SNAP 1, 2, 3]	~ -0,5% NO_x

Improving energy efficiency in residential and commercial use (energy saving light bulbs, combined heat & power, advanced energy management)	-2% NO_x -1% NMVOC	~ -0,5% NO_x

Table 8: Additional measures to improve urban air quality in Athens

Measure	**Sectoral reduction** *(on top of MFR)*	**Reduction of total emissions** *(on top of MFR)*
Reduction of road transport emissions:		
- accelerated introduction of “clean cars” in the Athenian fleet	~ -25% – -30% NO_x and NMVOC	~ -18% – -22% NO_x and NMVOC
- prohibiting the usage of the most polluting passenger cars in the interior of the city	~ -7% – -9% NO_x and NMVOC	~ -5% – -7% NO_x and NMVOC
- reserving large areas in centre of Athens for pedestrians	Re-distribution of emissions (spatial)	Re-distribution of emissions (spatial)
- restricting the circulation of heavy duty vehicles from the interior of the city	Re-distribution of emissions (spatial)	Re-distribution of emissions (spatial)
- limiting the circulation of heavy duty vehicles to certain times of the day	Re-distribution of emissions (temporal)	Re-distribution of emissions (temporal)
Also comprising measures such as:		
- escalating work-time schedules		
- implementing ratification measures (for illegal parking, breaking adopted traffic restriction measures)		
- partial replacement of buses with electrically powered vehicles for the public (trams)		
- avoiding the use of private owned vehicles carrying less than two passengers in the city centre		
- City-Logistic-Concept (cf. *Table 7*)		
Infrastructure changes: - new road axes - changes in city transportation patterns (e.g. establishment of marine public transport) - promotion of park and ride systems - construction of parking areas	~ -5% – -7% NO_x ~ -16% – -18% NMVOC	~ -5% NO_x ~ -12% NMVOC
Fuel changes (industrial, commercial[2], domestic[2] sector))e.g. natural gas penetration) Additionally comprising measures such as: - intensive/regular fuel quality control for stationary sources (domestic central heating installations, industries, private and state-owned enterprises) - constructing mobile fuel control units for in situ measurements from all relevant sources (refineries, industries, filling stations)	~ -6% – -8% NO_x ~ -35% – -45% NMVOC	~ -2% – -4% NO_x ~ -8% – -10% NMVOC

[1] These measures could be implemented either permanently (-20%), or during ozone episodes (-15%); however, an implementation during ozone episodes would require a reliable ozone forecasting system, since short-term measures have to be implemented at least 2-3 days before peak ozone concentrations to be effective.

[2] Even though measures concerning residential and commercial combustion can reduce NO_x and NMVOC emissions from this sector, they are less effective to reduce ozone levels in summer, since these sources are mainly operated in winter time.

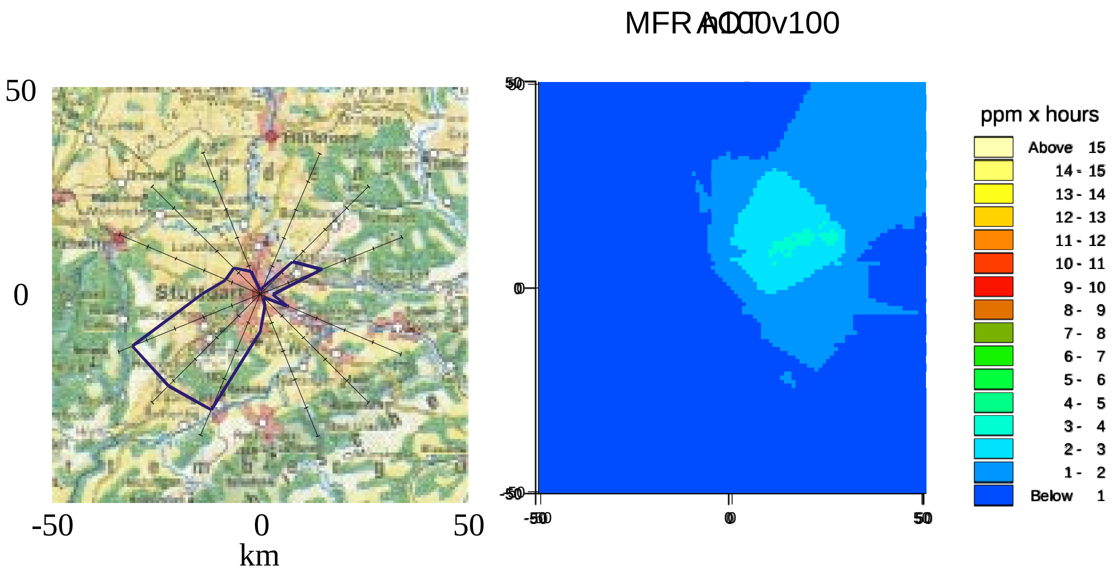
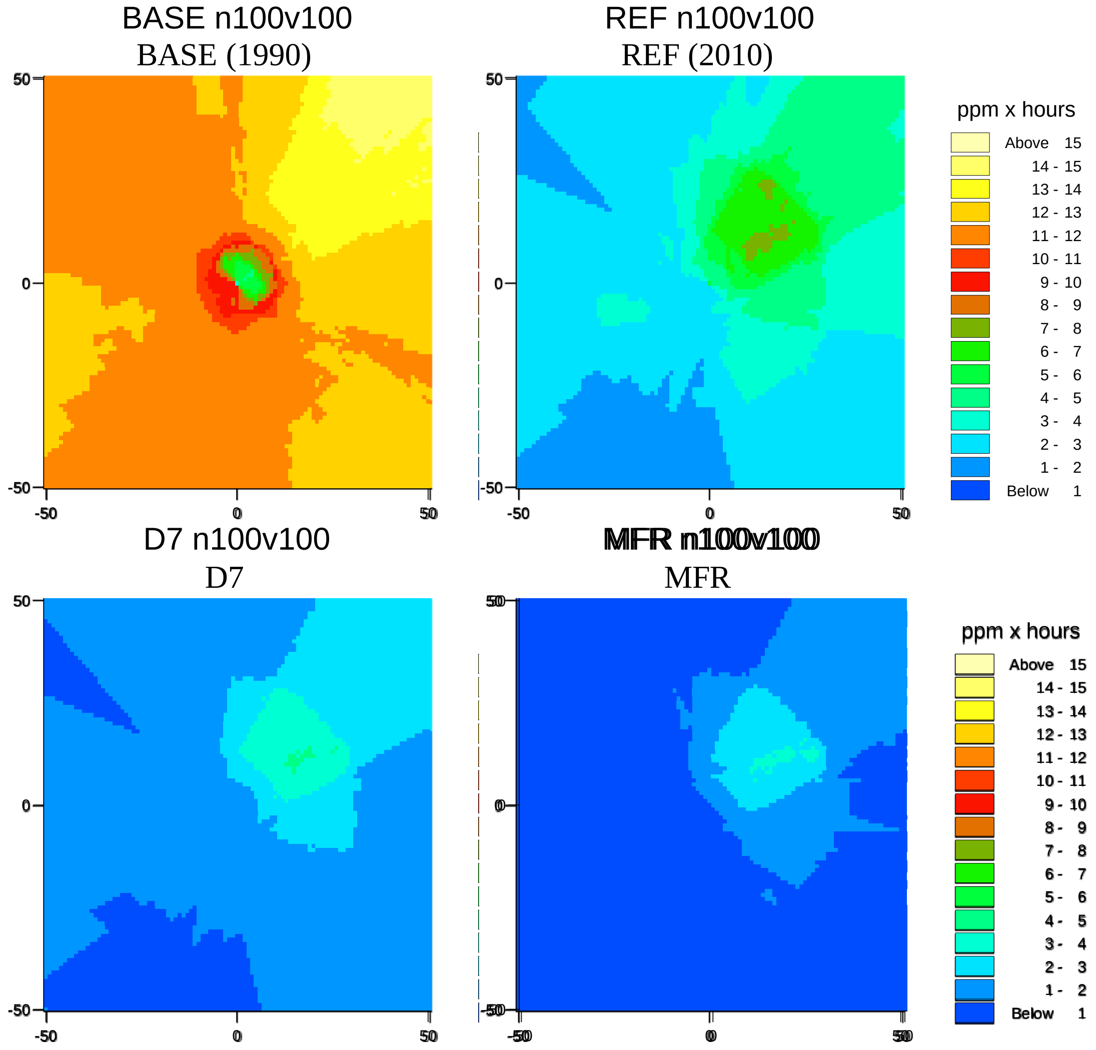


Figure 1: Simulation domain and wind direction statistics for Stuttgart as derived from EMEP model results (left) and AOT60 values derived from the measurements in Stuttgart for the period 1 April - 30 September 1990 (right).



BASE (1990)

REF (2010)

D7

MFR

Figure 2: AOT60 values calculated from OFIS for the base case (upper left), the REF scenario (upper right) the D7 scenario (lower left) and the MFR scenario (lower right).

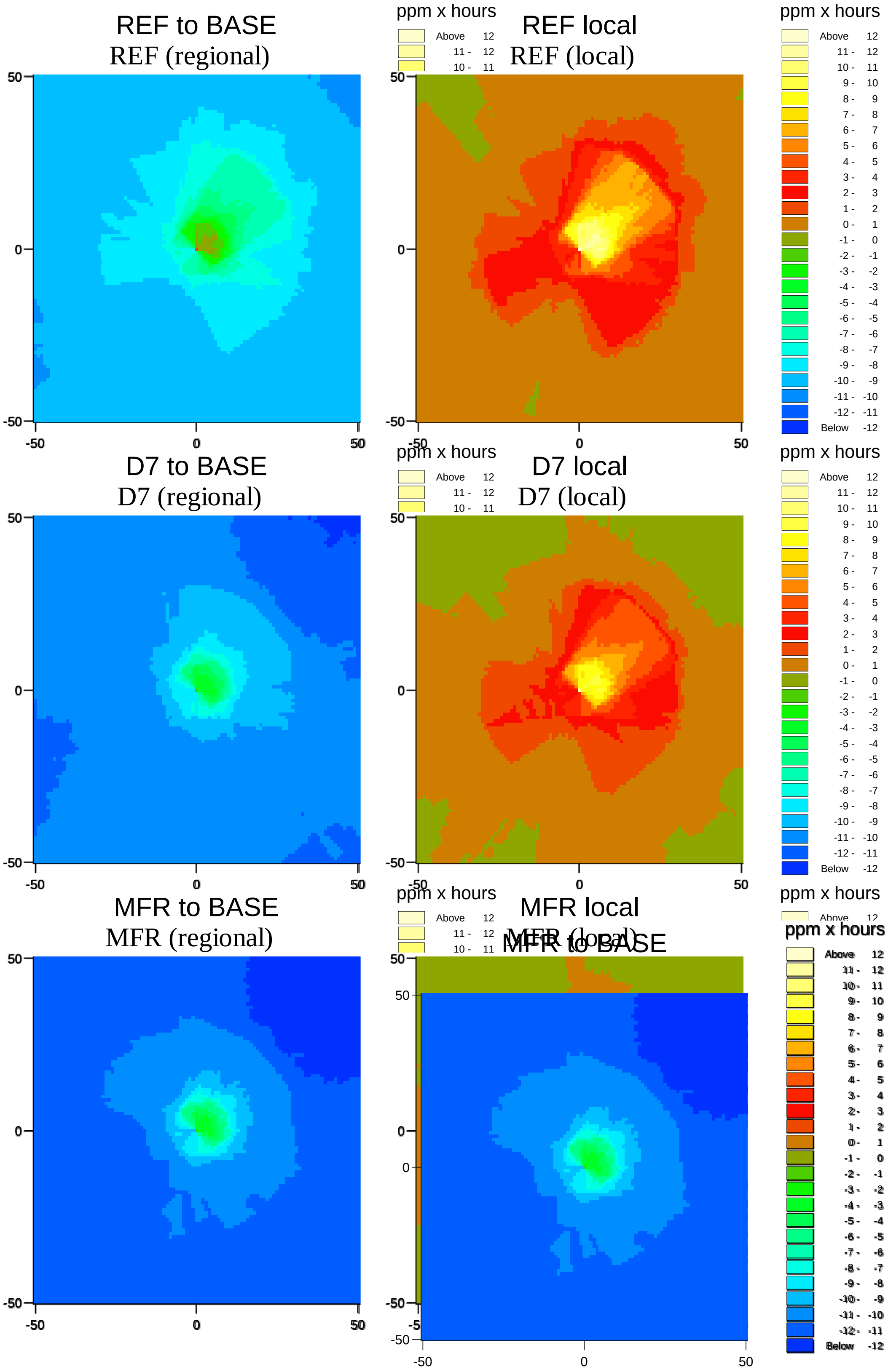


Figure 3: Differences of AOT60 values to the base case for Stuttgart (left column: regional+local scale emission reductions; right column: local scale emission reductions; REF scenario: top, D7 scenario: middle, MFR scenario: bottom).

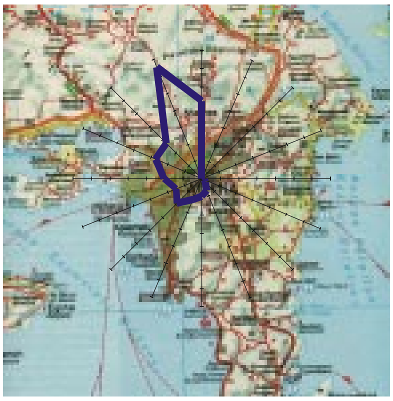


Figure 4: Simulation domain and wind direction statistics for Athens as derived from EMEP model results for the period 1 April - 30 September 1990.

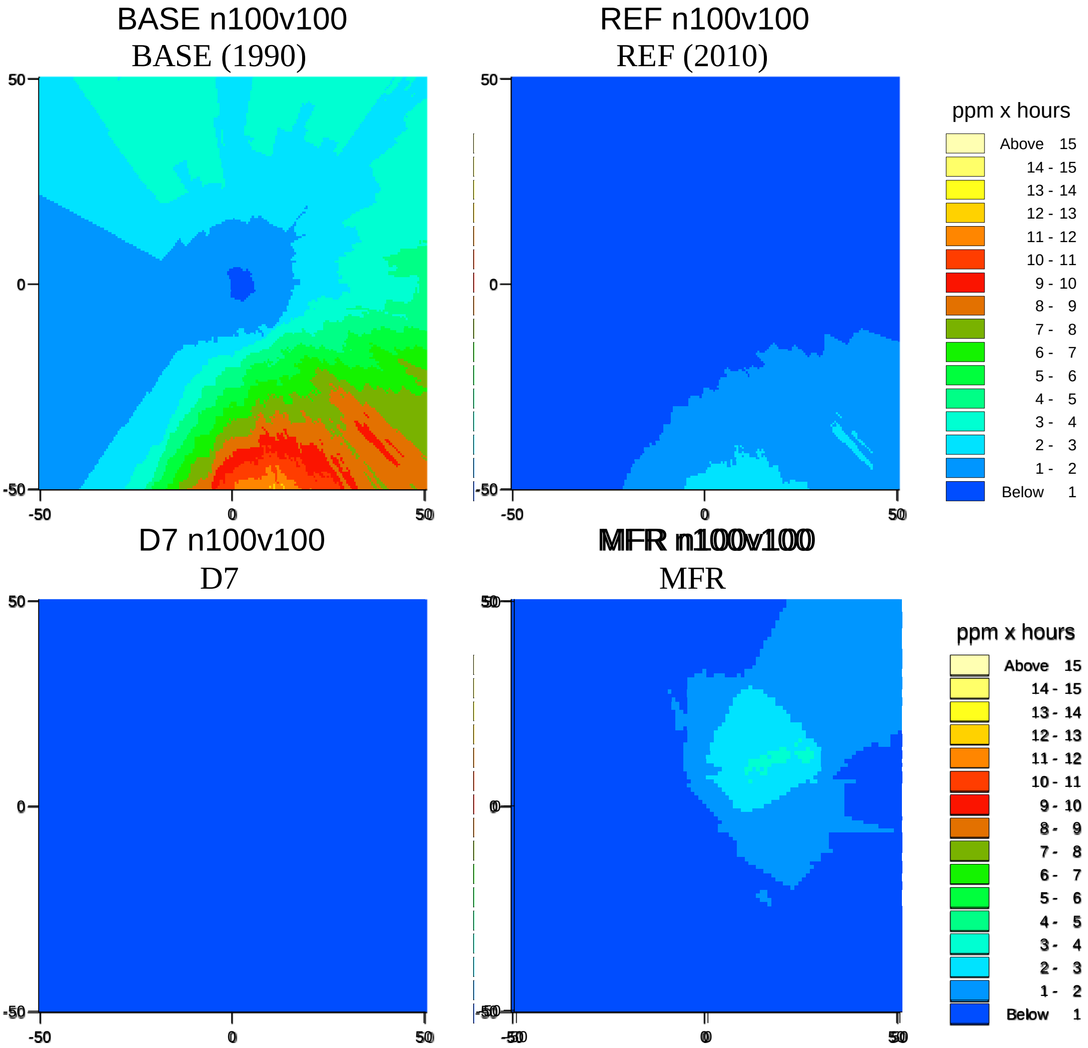


Figure 5: AOT60 values in Athens calculated with OFIS for the base case (upper left), the REF scenario (upper right) the D7 scenario (lower left) and the MFR scenario (lower right).

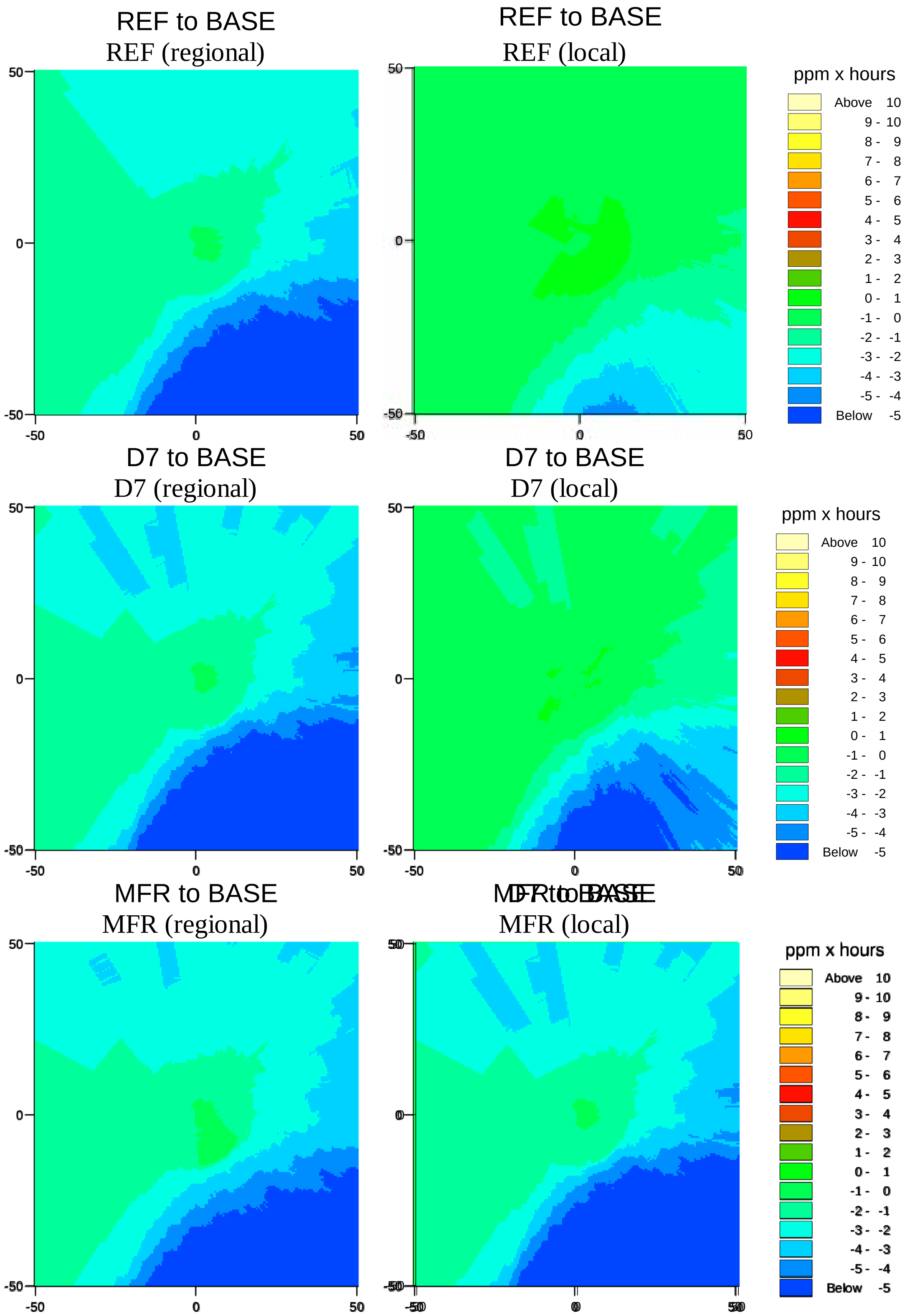


Figure 6: Differences of AOT60 values to the base case for Athens (left column: regional+local scale emission reductions; right column: local scale emission reductions; REF scenario: top, D7 scenario: middle, MFR scenario: bottom).

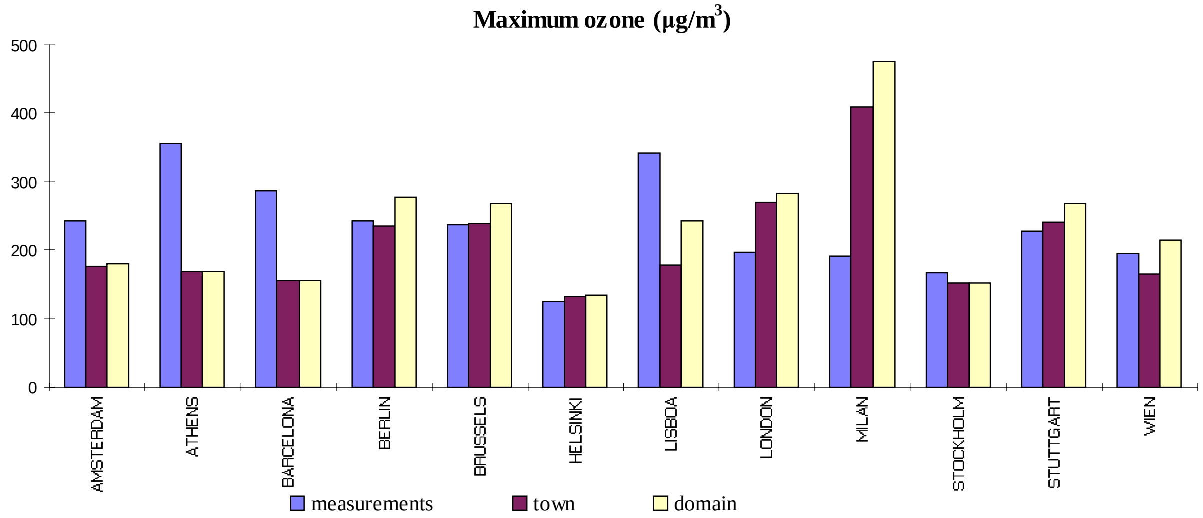


Figure 7: Measured and computed maximum ozone concentrations. Model results are shown for the urban area (middle bar) and the whole domain (right bar).

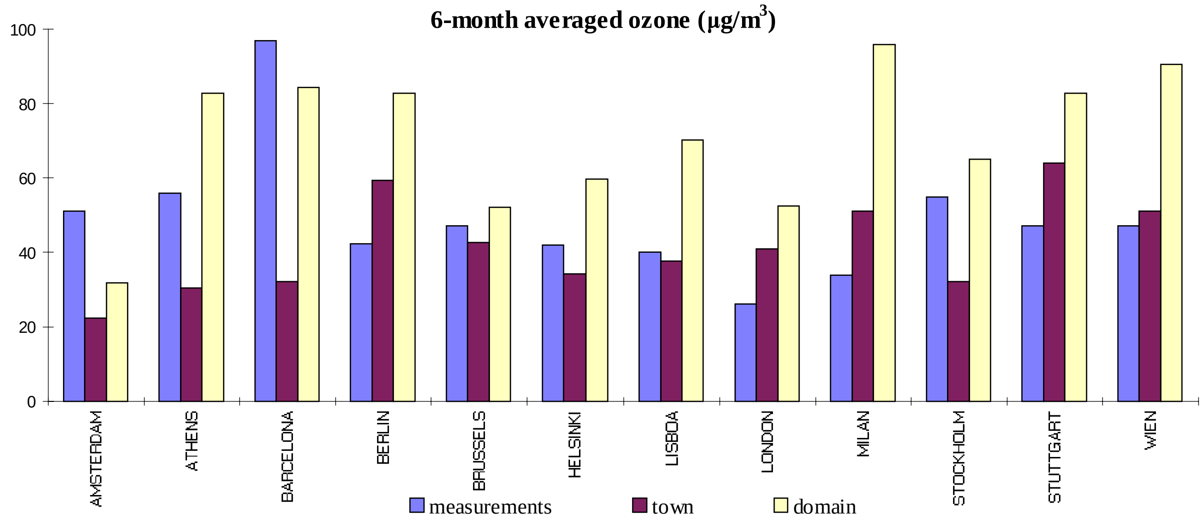


Figure 8: Measured and computed 6-month averaged ozone concentrations. Model results are shown for the urban area (middle bar) and the whole domain (right bar).