City-Delta Phase 2

Final Report

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Final Report

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Contents

1 Introduction

The RAINS model addresses European scale air pollution with a spatial resolution of 50*50 kilometres, essentially dictated by the spatial resolution of the atmospheric dispersion model (i.e., the EMEP Eulerian model) whose results are incorporated into RAINS. For European-scale analysis, such a resolution is considered adequate for capturing the features of long-range transported pollutants and, with additional information, for conducting impact assessment with reasonable accuracy.

However, it is clear that ambient concentrations of some air pollutants show strong variability at a much finer scale (e.g., in urban areas, in street canyons, at hot-spots close to industrial point sources of emission, etc.), and that at least some of these differences result in small-scale variations of pollution impacts on humans and the environment. Thus, there is a need that CAFE addresses air quality problems that occur on a finer scale than the 50*50 km grid mesh that is considered adequate for regional scale pollution.

The City-Delta model intercomparison, initiated by IIASA in cooperation with the Institute for Environment and Sustainability of the Joint Research Centre (Ispra), MET.NO and EUROTRAC-2, has conducted a systematic comparison of regional scale and local scale dispersion models. The aim of this exercise is to identify and quantify the factors that lead to systematic differences between air pollution in urban background air and rural background concentrations.

City-Delta explores

- systematic differences (deltas) between rural and urban background AQ,
- how these deltas depend on urban emissions and other factors,
- how these deltas vary across cities, and
- how these deltas vary across models.

Based on the findings of City-Delta, the European Commission Environment Directorate General has set up a service contract B4-3040/361392/MAR/C1 City-Delta 2 with the objective to integrate the finding of the City-Delta project into the framework of the RAINS Integrate Assessment Model. The City-Delta 2 project has developed functional relationships that allow the estimation of urban levels of pollution ($PM_{2.5}$) as a function of rural background concentrations and local factors. The analysis addresses the response of health-relevant metrics of pollution exposure (i.e., mostly long-term concentrations with or without thresholds) towards changes in local and regional precursor emissions, including the formation of secondary inorganic aerosols. This enables the generic analysis of urban air quality for a large number of European cities based on information available in the RAINS model framework.

This final report describes the results obtained from the City-Delta2 project, in which six urban-scale dispersion models have been used to explore common emission control scenarios for four European

cities in a coordinated way. Functional relationships have been developed and implemented in the RAINS model, so that for the purposes of the CAFE project the implication of Community-wide emission control measures on urban air quality can be assessed.

2 Background

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2.1 The policy context

The Clean Air For Europe (CAFE) programme of the European Commission is a programme of technical analysis and policy development which will lead to the adoption of a thematic strategy on air pollution under the Sixth Environmental Action Programme in 2005. The major elements are outlined in the Communication on CAFE (COM(2001) 245). The programme was launched in 2001. Its aim is to develop a long-term, strategic and integrated policy advice to protect against significant negative effects of air pollution on human health and the environment.

The CAFE programme has the following specific objectives:

- To develop, collect and validate scientific information relating to the effects of outdoor air pollution, emission inventories, air-quality assessment, emission and air-quality projections, cost-effectiveness studies and integrated assessment modelling, leading to the development and updating of air-quality and deposition objectives and indicators and identification of the measures required to reduce emissions;
- To support the implementation and review the effectiveness of existing legislation, in particular the air-quality daughter directives, the decision on exchange of information, and national emission ceilings as set out in recent legislation, to contribute to the review of international protocols, and to develop new proposals as and when necessary;
- To ensure that the sectoral measures that will be needed to achieve air-quality and deposition objectives cost-effectively are taken at the relevant level through the development of effective structural links with sectoral policies;
- To determine an overall, integrated strategy at regular intervals which defines appropriate air-quality objectives for the future and cost-effective measures for meeting those objectives;
- To disseminate widely the technical and policy information arising from the implementation of the programme.

Among the problems that CAFE has to solve, the CAFE communication highlights ozone and Particulate Matter (PM) as priority pollutants. Both pollutants have adverse effects on human health.

Ground-level ozone is due to atmospheric emissions of nitrogen oxides and volatile organic compounds that are transformed in photochemical reactions to ozone. Ozone attacks vegetation and materials and has a strong effect on human health, where exposure to high levels is clearly linked with

increased mortality in the population. The World Health Organisation (WHO) health guideline value of 120 μg/m^3 (eight-hour average) is widely exceeded in Europe. Recent evidence has shown that there are also health effects, such as deaths brought forward in time, below the WHO guideline value. The effects where found also at low ozone levels but at the lower levels the uncertainties of the relationship where larger.

Particulate matter is emitted from combustion processes and mechanical wear, but also formed through atmospheric chemical and physical processes whereby the gas components are transformed into PM mass. In the case of PM there appears to be no concentration below which there are no effects on human health.

There are many uncertainties and complexities related to the formation and transport, and the mechanisms of damage of these two pollutants. In order to address these challenges effectively (and that also means cost-effectively) it is clearly desirable to tackle the problems in the context of an integrated programme.

It is in this policy context that the Institute for Environment and Sustainability (IES) of the Joint Research Centre (JRC) in Ispra has initiated the City-Delta project. The project is co-organised by IIASA (International Institute for Applied Systems Analysis, Laxenburg, Austria), The Norwegian Meteorological Institute (EMEP/MSC-W, Oslo, Norway), TNO-MEP-EUROTRAC (Apeldoorn, The Netherlands), and CONCAWE (Brussels, Belgium). The JRC-IES acted as co-ordinator of the project.

2.2 The objectives of the City-Delta project

The City-Delta project is an open model-intercomparison exercise to explore the changes in urban air-quality predicted by different atmospheric chemistry-transport- dispersion models in response to changes in urban emissions. City-Delta aims at the study of ambient levels of ozone and Particulate Matter ($PM_{2.5}$ and PM_{10}). In line with the CAFE programme, it is health-driven and consequently addresses metrics of long-term exposure to ozone, and fine (PM2.5) and coarse particles (particles between PM10 and PM2.5).

Assessments of health as well as of vegetation impacts require information about the long-term exposure to the various air pollutants. For ozone, studies revealed relations between the extent of vegetation damage and the AOT40, i.e. the hourly ozone concentrations in excess of 40 ppb cumulated over the vegetation period (three or six months). The new evidence of ozone health impact at levels below 120 μg/m^3 has been captured in the accumulated exposure to ozone above a certain evaluation threshold the SOMO35 indicator (defined as the sum of the maxima of the daily 8-hr running average ozone concentration in excess of 35 ppb). For PM the major long-term health effect, increased mortality, are captured through the annual averages PM 2.5.

City-Delta has the following specific objectives:

- To assess the performance of the participating models and compare them against available observational data from different cities;
- To identify the range of model responses towards emission reductions;
- To provide information on the effectiveness of Europe-wide emission controls compared to local measures;
- To provide quantitative information in relation to legal obligations, e.g. whether a certain trend in emissions will achieve air- quality limit values;
- To provide guidance on how urban air-quality could be included in a European-wide evaluation of the cost-effectiveness of emission control strategies.

2.3 Set up of the project and methodology

After some preparatory discussions in 2001, the kick-off meeting of the City-Delta project took place at the JRC-IES (Ispra, February 2002). This meeting was attended by 45 participants, including experts in the fields of monitoring, emissions, meteorology, and modelling. Most of the EU Member States were represented as well as some of the Candidate Countries. During this meeting all the technical details were discussed. A Steering Group was formed and the JRC-IES was asked to co-ordinate all the City-Delta activities, including the collection and management of all input and output data, setting up a City-Delta Web site, the distribution of data to the participating modelling groups, the organisation of further workshops and to guarantee the scientific quality of the activities. After the kick-off meeting an open announcement for participation was widely distributed, and approximately 20 modelling groups reacted positively and expressed their preparedness to participate with a total of 40 different model configurations.

The second Workshop was organised at IIASA (Vienna, June 2002), mainly to review and discuss the modelling input data (monitoring, emissions, and meteorological data). Monitoring data and high-resolution emission data were prepared by the local authorities and processed by JRC-IES. Emission inventories were complemented by EMEP data. The meteorological input data was provided by Meteo France. The first results of the validation against 1999 data were presented.

The third Workshop took place at the Institute of Environmental Protection (Katowice, December 2002). This meeting was dedicated to the 1999 validation results, and the discussion of the first results of the delta calculations (impact of emission reductions).

During the fourth Workshop, which was organised by CEAM (Valencia, April 2003), an in-depth analysis and discussion took place concerning the delta calculations. This first phase of the City-Delta project revealed major differences between the modelled and observed PM mass concentrations. All

chemistry models that simulate the fate of the various chemical components of PM result in a serious underestimation of observed PM mass concentrations. However, models agree to a large extent on the fate of anthropogenic primary particles and secondary inorganic aerosols. The decision was taken to pay more attention to the impact on PM ($PM_{2.5}$, PM_{10}, SULF, NITR, AMMO) of the various emission-reduction scenarios. It was also decided to bring the high-resolution city emission inventories in line with the EMEP emissions by performing a sector-wise scaling of all the emitted components onto the EMEP values. This was called City-Delta second phase in order to distinguish these new runs from the set of runs with the unmodified emission city inventories. Based on the results of City-Delta I and the ability of the models to reproduce ozone and PM levels, a contract was set up with the following modelling groups:

a. REM model, contact person: Dr R. Stern (Free University of Berlin, Germany). Model 03 (fine scale), Model 36 (coarse scale).
b. OFIS model, contact person: Prof N. Moussiopoulos (Aristotle University Thessaloniki, Greece). Model 15 (fine scale).
c. LOTOS model, contact person: Prof P. Builtjes (TNO/MEP, Apeldoorn, The Netherlands). Model 24 (fine), Model 25 (coarse scale).
d. CHIMERE model, contact person: Dr L. Rouil (INERIS, Paris, France). Model 32 (fine scale), Model 31 (coarse scale).
e. CAMx model, contact person: Dr M. Bedogni (AMMA, Milan, Italy). Model 34 (fine scale), 41 (fine scale).
f. EMEP model, contact person: Dr L. Tarrason (EMEP, Oslo, Norway). Model 21 (coarse scale).

The models e) and f) participated in this exercise using their own resources. Fine-scale models have a resolution of 5 or 10 km, coarse-scale models are at 50 km resolution.

The fifth workshop, organised by JRC-IES in collaboration with ARPA-Basilicata, took place in Matera (October 2003). The results for City-Delta phase 1 were reported, a number of inconsistencies in the emission inventories were discussed and solutions were proposed.

The final City-Delta Workshop took place at JRC-IES (Ispra) in October 2004. The workshop summarized the findings from the two phases of the City-Delta model intercomparison and reviewed a first implementation of the functional relationships that allow urban air quality to be addressed in a Europe-wide integrated assessment model.

In order to cope with the enormous amount of input and output data that was produced, the JRC-IES developed an interactive visualisation tool based on the language IDL to view the monitoring data, the emissions and the proposed emission reductions, to visualise the intercomparison of the validation results, and the intercomparison of the delta calculations.

3 Emission inventories

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3.1 Introduction

In the frame of this project, emission data were collected from different sources including both high spatial resolution information from the cities and low spatial resolution information to cover the regional background. In this section, an overview of the characteristics of these different sources of emission data is provided. The methodology to merge the regional and local scale emission inventories in order to provide the participants with a uniform emission data set is also discussed. Finally, the scaling procedure used in City-Delta2 to avoid inconsistencies between the local and regional emissions is presented.

3.2 Regional scale emissions: EMEP –TNO

EMEP total annual emissions were provided in the EMEP grid coordinate system (resolution of 50 km), for NO_x, SO_2, NMVOC, CO, NH_3 whereas $PM_{2.5}$ and PM_{10} were obtained from TNO with a similar resolution. A temporal disaggregation of these annual totals into hourly values has been achieved for gas phase species through monthly, daily and hourly temporal profiles prepared by IER for GENEMIS. Both the temporal profiles for monthly and daily variations are activity-sector and country dependent whereas hourly profiles are only sector dependent. Only monthly variations have been considered for PM including a country dependency but variations remain similar for all SNAP activity-sectors. Since EMEP-TNO gridded emissions were provided only as area totals per sector, point sources were accounted for by distributing the emissions at different heights depending on their activity sectors.

3.3 City-scale emissions: General characteristics

The city scale emission inventories which have been provided for City-Delta differ significantly in their spatial coverage and resolution, time disaggregation, VOC split, and reference year. Although these inventories have been modified by the scaling procedure described in Section 3.5, we hereafter describe the main characteristics of the original emission datasets.

Spatial coverage and resolution: City-Delta domains over which output data have been requested from the participants cover an area of 300 x 300 km^2 centred on the city of interest. Among the available inventories, only Paris covered this City-Delta output domain entirely with a spatial resolution of 3 km. For Berlin and Prague, approximately two thirds of the domain is covered, with a

spatial resolution of approximately 2 km for Berlin and 5 km for Prague. In the case of Milan, the fine scale emissions include the whole Lombardy region with a 5 km spatial resolution which represents about one third of the output domain.

Pollutants: Emissions for CO, NO_x, NMVOC and SO_2 were provided by all four cities, as was the case for CH_4 except for Prague. Emissions for NH_3 were only available for the cities of Milan and Paris. Estimates of PM emissions differ significantly in their degree of complexity from one city to another. They range from the rather complex estimates, as for Milan where PM factors are based on three different sets of emission factor sources (TNO-CEPMEIP, IIASA, Lombardy region) and include both point and area sources, to cities like Berlin where simple scaling factors are used between PM_{10} and $PM_{2.5}$ or TSP depending on the activity sector.

VOC Speciation: For all cities except Paris, NMVOCs have been split according to the speciation released by AEAT (AEAT/ENV/R/0545 report: Speciation of UK emissions of NMVOC, N.R. Passant, February 2002). This speciation provides a breakdown into 227 species for 9 SNAP sectors. The Paris NMVOC emissions have been split according to available literature information and partly from expert interviews.

Reference year: All emission estimates received in the frame of the City-Delta project were based on years included in the 1995-1999 period. In the case of Berlin, the reference year is region- and sector-specific. Details for the other cities are available in Table 3.1 below. In Figure 3.1 the spatial distribution of the NO_x traffic emissions for the different cities provides an illustration of the differences in resolution and spatial coverage of the emission inventories.

Areas within the modelling domains (300x300 km^2) where fine scale emissions are not available have been filled with EMEP regional scale emissions so that the City-Delta modelling community received a complete and consistent set of emissions over each of the modelling domains. The detailed NO_x emission sector-split for the different cities is illustrated in Figure 3.2. As can be seen from this figure, the repartition among the different activity sectors is quite different from city to city. A common feature for all cities, however, is the high proportion of emissions from traffic, although in Berlin industrial emissions are dominating.

Table 3.1: Overview of the city emission inventory main characteristics

	Area Covered	Res. (km)	Activ. Sect. Considered	Gas-phase pollutants	Ref year	VOC Split
Berlin	Berlin + Brandenburg + Sachsen + Sachsen-Anhalt states (61500 km2)	2 km	1)Industrial Comb. 2)Pub. Power & Non-Com. Processes 3)Commercial Comb. 4)Resid. Comb. 5) Road traffic 6)Other traffic	CO, SO_2 NO_x, CH4, NMVOC,	1995-1999	AEAT(2002) 227 species
Milan	Lombardy (27000 km2)	5 km	SNAP level 1	CO, NO_x, SO_2, NH_3, NMVOC, CH4	1997	AEAT(2002) 227 species
Paris	Whole domain (90000 km2)	3 km	1)High Stat. Sources 2)Low Stat. Sources 3)Traffic	CO, NO_x, SO_2, NH_3, NMVOC, CH4	1998 (except area sources, 1994)	GENEMIS 185 species
Prague	Czech Republic (60200 km2)	5 km	1)Large Point sources 2)Med. point sources 3)Small Point sources 4)Traffic	CO, NO_x, SO_2, NMVOC	1999	AEAT(2002) 227 species

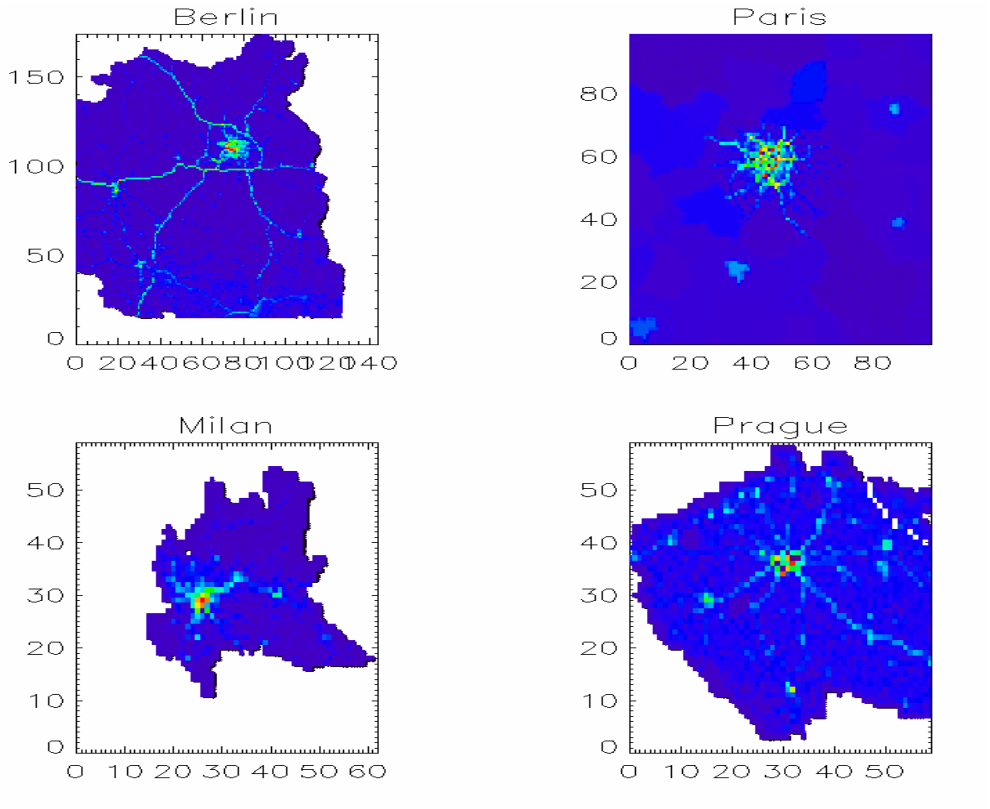

Figure 3.1: Comparison of NO_x traffic emissions for the different cities

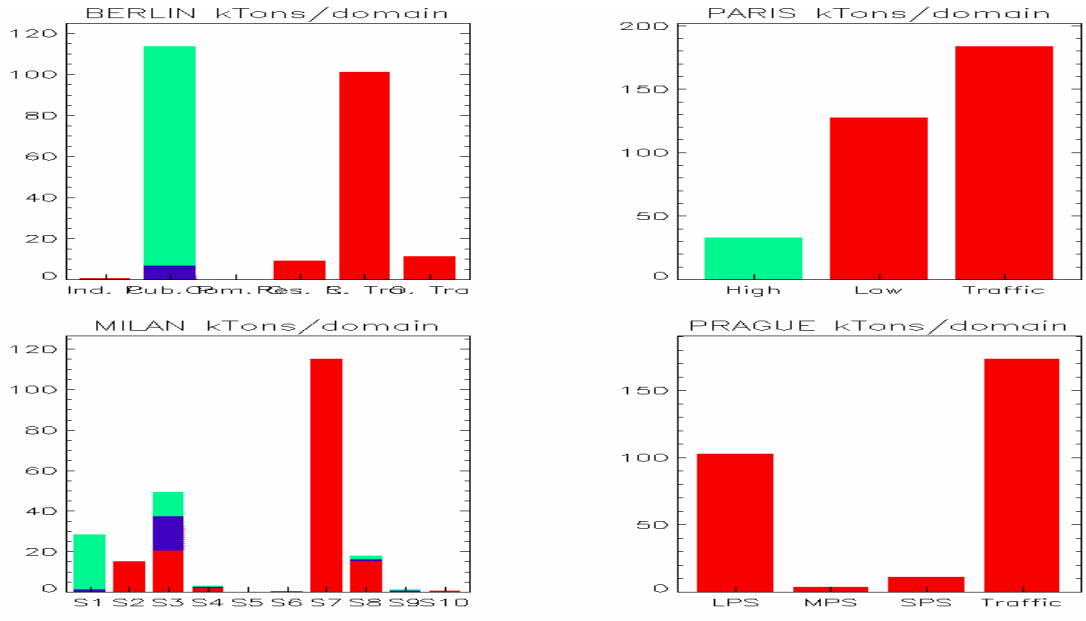

Figure 3.2: Overview of the NO_x emissions split in the different sectors, differentiating the area sources (in red), the low (< 50 m) (in blue) and the high (>50m) (in green) point sources

3.4 Merging city- and regional-scale emissions: Methodology

As the emission inventories provided in the frame of the City-Delta exercise should cover for each city a domain of 300 by 300 km^2, and since the local highly resolved city inventory did in general not cover the full domain, the regional EMEP-TNO emissions were used as a complement. The procedure to merge these two sources of emissions is the following:

- For cells inside the city inventory, only this latter information has been kept. If city sectors were not expressed in SNAP categories, a correspondence has been created to deliver emissions detailed in SNAP sectors.
- For cells outside the city inventory, EMEP information has been retained as follows: For each EMEP cell, the total provided by the city emission inventory within this cell is subtracted from the EMEP total. The remaining EMEP emissions are then distributed according to the surface covered by each small cell. If the total city emissions in one EMEP cell are larger than the corresponding EMEP total, zero emissions are attributed to this cell.

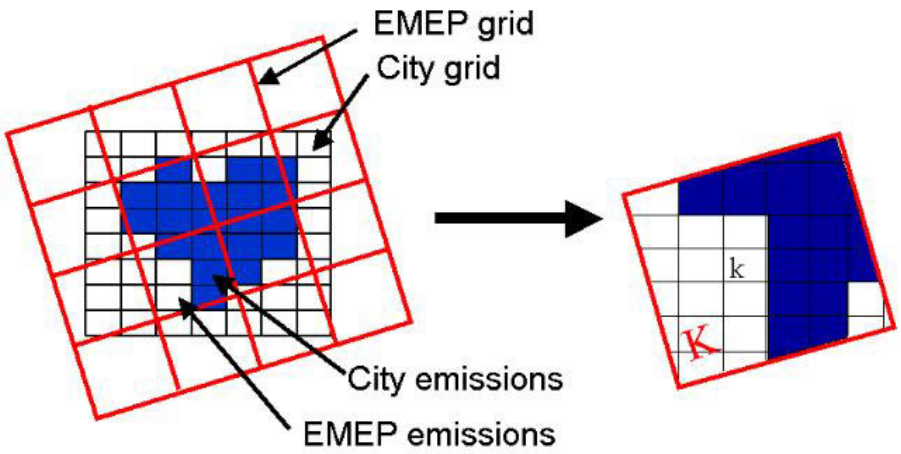

Figure 3.3: Schematic diagram of the merging process between the EMEP-TNO and the City scale inventories. The blue area indicates the cells covered by the city inventory. EMEP-TNO emissions are distributed on the high resolution cells of the inventory according to the formula where k and K are the high and low-resolution cell indices respectively and E_{city-K} is the total city emissions in the EMEP cell K. S is the surface.

3.5 Comparison of EMEP and city-scale emissions

Since one of the objectives of the project is to compare the response to emission reduction across cities and across scales and resolutions, i.e., between models using a grid resolution lower than 10 km and models such as EMEP using a grid spacing of the order of 50 km, it is important to compare total emissions for various resolutions. Figure 3.4 illustrates how the total emissions for different pollutants compare across resolutions. This comparison is obtained by comparing the emissions on the area covered by the city inventory. As seen from this figure, the city emissions may sometimes be quite different from the EMEP emissions.

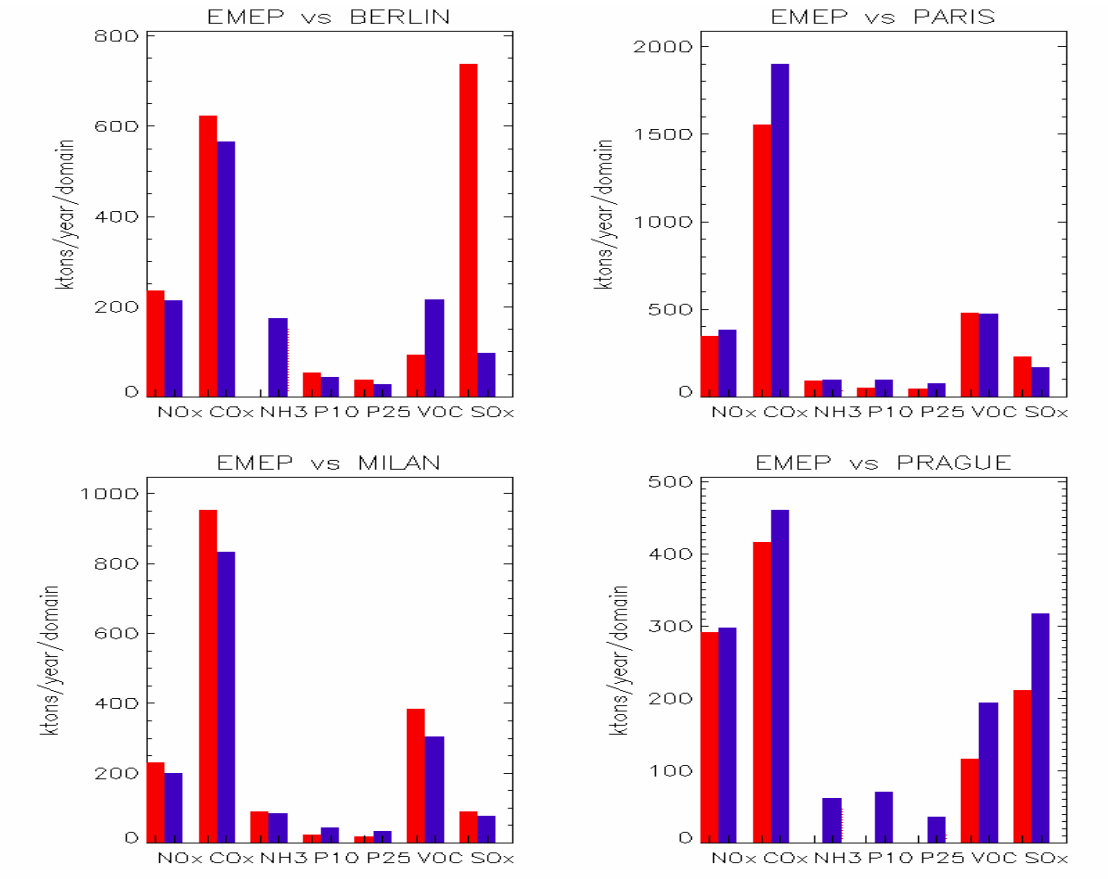

Figure 3.4: Comparison of the EMEP (blue) and city (red) emissions on each of the areas covered by the high resolution emission inventory.

This overall lack of consistency between emissions led to difficulties in interpreting the results during the first phase of City-Delta. In this second phase of the project, these inconsistencies were partly resolved by:

- scaling the city emission inventory in such a way that city emission totals are equivalent to their EMEP counterpart,

- converting city-specific sectors to their SNAP equivalents so that local and coarse scale models make use of the same activity sectors (see Table 3.2 below),
- imposing similar temporal profiles on both coarse and fine simulations. For this purpose, the SNAP dependent temporal profile from the regional simulations has been attributed to each city activity sector,
- imposing a similar VOC split to both coarse and fine simulations.

Table 3.2: Overview of the temporal, height, and sector scaling for the cities of Prague, Berlin and Paris in order to convert the city sectors to the EMEP emissions expressed in SNAP levels.

	CITY Sector	Height SNAP	Scaling SNAP	Temporal SNAP	VOC split
BERLIN	Indust. Comb.	As given in the city emissions without effective height	.5*3	3	Weighted On Scaling sectors
	Pub. Pow., Non. Comb. Proc.		1+4+9 +.5*3	1	
	Comm. Comb		(2+5+6)/2	2	
	Resid. Comb.		(2+5+6)/2	2 but 10 for NH_3	
	Road traffic		7	7	
	Other traffic		8	8	
PRAGUE	Large poll. sources	SNAP 3	(1+4+9 +.5*3)/2	3	
	Medium poll. Sources	SNAP 3	(1+4+9 +.5*3)/2	3	
	Small Poll. Sources	Ground	2+5+.5*3+6+8	2: CO, NO_x,Sox,PM 6: VOC 10: NH_3	
	Mobile Poll. Sources	Ground	7	6: VOC, NH_3	
PARIS	High Stat. Sources	50 m	1+.5*3+4+9	1	
	Low Stat. Sources	ground	2+.5*3+5+6+10*	2	
	Transport	ground	7+8	7	

In the cases of Berlin and Prague, NH_3 emissions were lacking and a simple approach has been used to avoid inconsistencies between regional and local city inventories. Emissions equivalent to the EMEP totals have been uniformly distributed over half of the area covered by the city emission inventory, this half part corresponding to the area where residential combustion emissions are at the

lowest level. For this pollutant, since emissions arise almost entirely from agriculture, the temporal disaggregation has been set to sector SNAP 10.

The scaling between EMEP and city emissions has been done activity sector and EMEP cell wise except for Milan and Prague. For these two cities, the scaling has been made so that the total of each activity sector is equivalent for the total area covered by the city emission inventory (not at the cell level as for the other two cities).

Emission scenarios for the 2010 CLE (corresponding to Current Legislation Emissions) and MFR (Maximum Feasible Reduction) projections have been delivered to the participants. The emission reduction percentages corresponding to these scenarios are given in Table 3.3 below.

Table 3.3: Total City-Delta2 emission reductions (in percent) for the CLE and MFR scenarios

	City	CLE	MFR
NO_x	Berlin	33	41
	Milan	28	47
	Paris	26	45
	Prague	34	67
VOC	Berlin	36	43
	Milan	38	59
	Paris	37	56
	Prague	3	45
PM_{10}	Berlin	55	66
	Milan	40	66
	Paris	48	71
	Prague	54	82
$PM_{2.5}$	Berlin	47	80
	Milan	44	71
	Paris	47	73
	Prague	47	80
SO_2	Berlin	25	37
	Milan	78	91
	Paris	34	73
	Prague	11	28

3.6 Biogenic emissions

Since natural emissions strongly depend on various factors such as temperature, land use, etc., it has been decided in City-Delta to leave modellers to calculate the biogenic emissions in their own way. These emissions have been kept constant in all scenario calculations.

4 Model results

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4.1 Scenarios

The requested scenario runs are summarised in the following table:

Scenario number	City Emissions	Regional emissions
0	2000	2000
1	CLE	CLE
2	MFR1	MFR1
3	MFR2	MFR2
4	MFR	MFR
5	MFR1	CLE
6	MFR2	CLE
7	MFR	CLE

The year 2000 is chosen as the base year for the emissions. CLE stands for the traditional Current Legislation Emission scenario. MFR1 stands for the MFR emission reduction (Maximum Feasible Reduction scenario) for NO_x, SO_2, $PPM_{2.5}$ and PPM_{10}, while other species are at the CLE level. MFR2 stands for MFR emission reductions for VOC, CO and NH_3 with the other species at CLE. The MFR scenario indicates MFR for all species. The regional emission scenarios are used to determine the boundary conditions for the small-scale models. Consequently, the scenarios 5, 6 and 7 are relevant only for the small-scale models.

4.2 Requested output

The requested output from the model runs is similar to the output requested of City-Delta I:

Ozone, NO_2	Hourly ground-level values for the Summer period April – September in the computational domain of 300 x 300 km^2 interpolated on a grid of 5, 10 or 50 km resolution
$PM_{2.5}$, PM_{10}, $PPM_{2.5}$, PPM_{10}, SULF, NITR, AMMO	Daily-averaged ground-level values for the full year on the same grid as ozone and NO_2.

5 Analysis of the model output

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In the following figures a comparison is made between the results of the fine-scale models (Models 03, 15, 24, 32, 34, 41 and the corresponding Ensemble) and the coarse–scale models (Models 21, 25, 31, 36 and the corresponding Ensemble). Observations are in black. The red colour represents the Ensemble average. For the figures related to validation, the nine monitoring stations (only eight in Prague) have been selected on the basis of their quality of the measurements and on their representativeness. The delta results are visualised for nine urban locations with the middle-point in the centre of the city.

Ozone is given in ppb, PM is given in $\mu g/m^3$.

5.1 Mean summer (April-September) ozone (cf. Figure 5.1)

For the cities of Berlin and Paris differences between coarse and fine resolution are relatively limited, and are restricted to the city-centre stations where some models predict large differences related to their spatial resolution (for example Model 24 and 25 in Berlin-Neukölln). In Prague and Milan the differences however are much larger between coarse and fine scale. The variability among the fine-scale models for these two cities is quite high. This can reach a factor of two for some stations.

5.2 Ozone exceedance days (60 ppb, 8hr average) (cf. Figure 5.2)

For Berlin the Ensemble for both coarse and fine scale models generally under-estimate the number of exceedance days with respect to observation. The coarse models slightly tend to predict larger values than the fine-scale models. However for Paris the Ensemble generally overestimates the observed values, where large values are reported for Model 15. Model 25 reports systematically the smallest number of exceedance days. For Prague some models show zero exceedance, but the validation is difficult to make because of a lack of observations at some of the stations.

5.3 Taylor diagram for mean summer ozone (cf. Figure 5.3)

In the Taylor diagrams three statistical indicators are visualised: Standard deviation (Stddev, distance to the origin), correlation coefficient (corr_coef, angular distance from the top counting clockwise) and the Centred Root Mean Square error (distance from any model marker to the observation marker as indicated by the black cross in the x-axis). In these diagrams each model marker is representative of all 9 stations previously mentioned. The correlation of all models in all cities ranges from 0.5 to

0.65. The standard deviation of the measurements is larger in Milan than in other cities and models exhibit difficulties in capturing these standard deviations as is indicated by the wider spread of the model predictions in this city. In other cities, however, all model results are grouped in a narrow region, which proves that they better capture the observational variability. In general, there is no significant difference between the coarse-scale models (indicated by a square symbol) and the fine-scale models (indicated by the cross symbol).

5.4 Annual mean PM_{10} (cf. Figure 5.4)

It is more difficult to draw conclusions on the models' ability to predict PM_{10} since few observations are available in this study. In general the fine-scale models slightly underestimate the observations but are closer to them than the coarse-scale models which also underpredict the observations. There seems to be a problem with Model 31 and 32 in Milan with a strong overestimation of the observed concentration. In Prague the same is true for Model 32 whereas its coarse version (Model 31) is in quite good agreement with the observations. Observations are much higher in Milan than in other cities and the fine-scale models show a larger variability in this city.

5.5 Taylor diagram: Annual mean PM_{10} (cf. Figure 5.5)

The correlation coefficient for the cities of Berlin and Paris is around 0.6, whereas it is around 0.4 for Milan and Prague. As for ozone, the standard deviation is much larger for Milan, and all models for this city significantly underestimate the standard deviation. From these diagrams Milan appears to be the city where models show a large variability in their predictions. This could be due to the specific geographic location of this city as well as to the general climate conditions.

5.6 Delta (CLE-2000) mean summer ozone (cf. Figure 5.6)

All coarse-scale models predict a reduction in the mean summer ozone concentration for the CLE scenario compared to 2000, with the single exception of Model 31 in Prague. The fine-scale models generally agree with a reduction in the cities of Paris and Milan, whereas for Prague and Berlin most fine-scale models predict an increase of mean ozone concentrations. The Ensemble reductions for the fine-scale and the coarse-scale are comparable for Paris. For Milan the coarse-scale Ensemble predicts a larger decrease than the corresponding fine-scale.

5.7 Delta (MFR-CLE) mean summer ozone (cf. Figure 5.7)

The differences between CLE-to-MFR reduction and 2000-to-CLE reduction are of the same order of magnitude for Berlin and Prague, but are more significant for 2000-to-CLE in Paris and Milan. Except for Berlin where the majority of the fine-scale models predict a decrease of ozone concentration, the response of these fine-scale models shows some variability in the other cities. Coarse-scale models generally predict a decrease except in Paris where the situation is not so clear.

5.8 Delta (CLE-2000) annual mean PM_{10} (cf. Figure 5.8)

All models in each city predict a decrease in PM_{10} levels. The decreases predicted in Milan (20 $\mu g/m^3$) are approximately 2 to 3 times larger than for the three other cities. The fine-scale models tend to predict more pronounced decreases than the coarse-scale models. Models 31 and 32 seem to be outliers for the city of Milan. If we exclude the outliers, the models show a consistent behaviour in their response to the 2000-to-CLE emission reduction. Note that Model 24 did not deliver results for the 2000 scenario for Prague, and model 25 not for the 2000 scenario in Paris.

5.9 Delta (MFR-CLE) annual mean PM_{10} (cf. Figure 5.9)

The conclusions drawn for point 5.8 remain valid for the CLE-to-MFR scenario, except that the reductions are now significantly smaller than for 2000-to-CLE. They are about 1 $\mu g/m^3$ for Berlin, Paris and Prague, and about 3 $\mu g/m^3$ for Milan. Models 31 and 32 systematically produce for all cities a larger delta than the other models.

5.10 City-overview: Mean summer daytime ozone (cf. Figure 5.10)

In this type of figure one can visualise the comparison between the Ensemble models for the fine and the coarse scales in the 4 cities. The Ensembles are constructed by calculating for each city the indicator on the average of the model results based on their values in an area which is representative of the city high-population area (approximately 50 x 50 km^2).

For the base case (2000) the Ensemble-fine is for all cities predicting lower daytime ozone mean levels with the differences being the largest in Milan (6 ppb). The Ensemble-coarse predicts larger reductions for the CLE scenario compared to the Ensemble-fine (CLE-2000). This remains the same for the NO_x-MFR (i.e. MFR1). The VOC-MFR (i.e. MFR2) responses are very similar for the Ensemble-fine and Ensemble-coarse. For the Ensemble-fine results, the three lower figures provide an idea of the impact of MFR emission-reductions applied only on the city area, while keeping the boundary conditions at CLE levels.

From these figures it appears that a NO_x reduction limited to the city-area is counter-productive, whereas the VOC reduction is effective both at regional and at city scale. However, it should be noted that the differences are only significant for the city of Milan. The combination of measures taken both at the regional and local scale (i.e. the ^ MFR figures) are more effective than measures limited to the local scale (^ CLE).

5.11 City-overview: SOMO35 indicator (cf. Figure 5.11)

The SOMO35 indicator proposed by WHO during the last meeting of the Task Force on Health in Bonn (May 2004) is defined as the sum over the summer period of the maxima of the daily 8-hr running average ozone concentration in excess of 35 ppb. The conclusions related to this indicator are similar to those valid for the mean summer daytime ozone (Section 5.10).

5.12 City-overview: Annual mean PM_{10} (cf. Figure 5.12)

For the base case (2000) the Ensemble-fine is for all cities predicting higher mean PM_{10} levels. The Ensemble-coarse predicts smaller reductions for the CLE scenario compared to the Ensemble-fine (CLE-2000). The NO_x-MFR (i.e. MFR1 which includes PPM) and VOC-MFR (i.e. MFR2) responses are very similar for the Ensemble-fine and Ensemble-coarse and are approximately a factor of two smaller than for the CLE-2000 reductions.

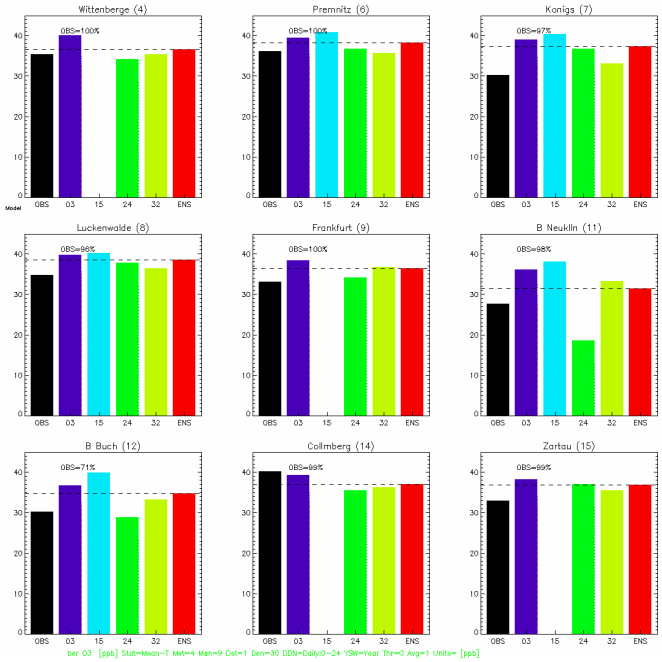
From these figures it appears that both the NO_x-PPM (MFR1) and VOC (MFR2) reductions limited to the city-area are effective. Strangely enough in Milan, the combination of measures taken both at the regional and local scale (i.e. the ^MFR figures) are more effective than measures limited to the local scale (^ CLE). This could be due to the behaviour of Model 31 and 32 in this city. For the other three cities about half of the improvement is coming from local measures, the other half being attributed to regional measures.

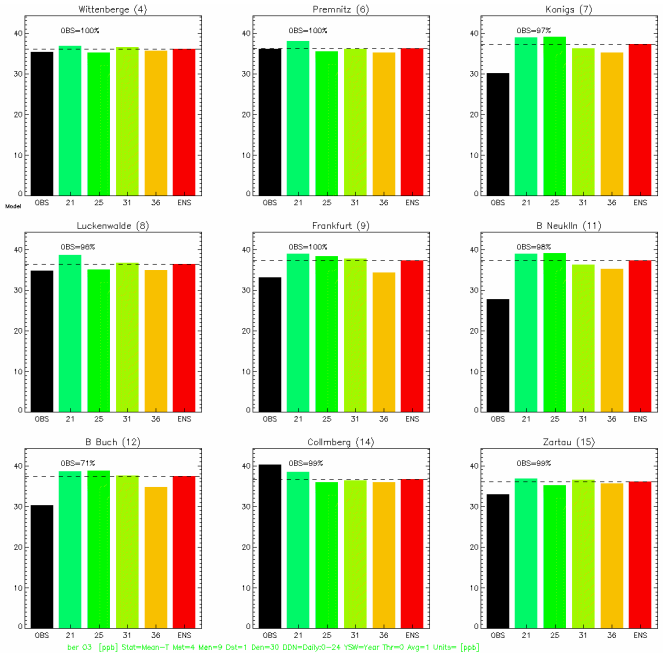
5.13 City-overview: Annual mean $PM_{2.5}$ (cf. Figure 5.13)

Similar remarks hold as in the case of PM_{10} (Section 5.12).

Figure 5.1:: Mean Summer (April-September) Ozone

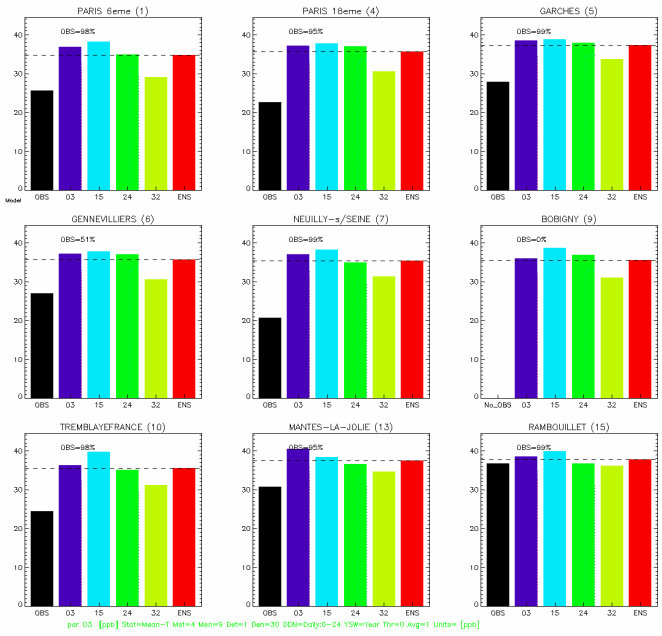
BERLIN

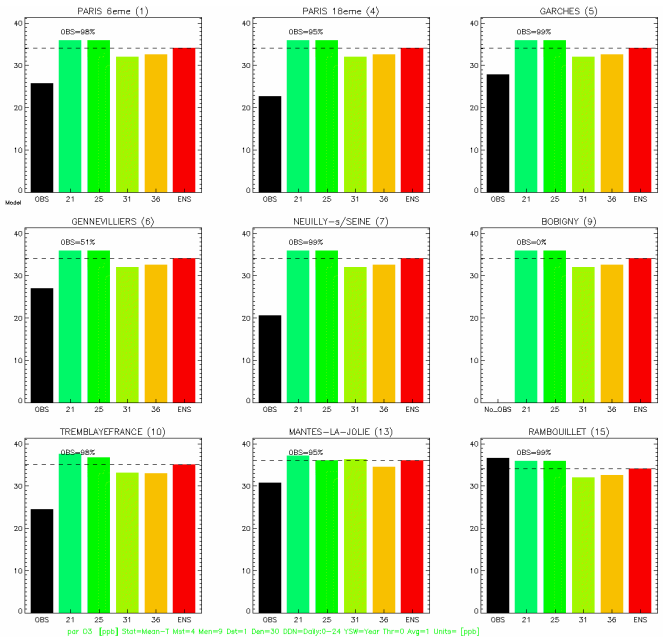




Fine-scale **Coarse-scale**

PARIS

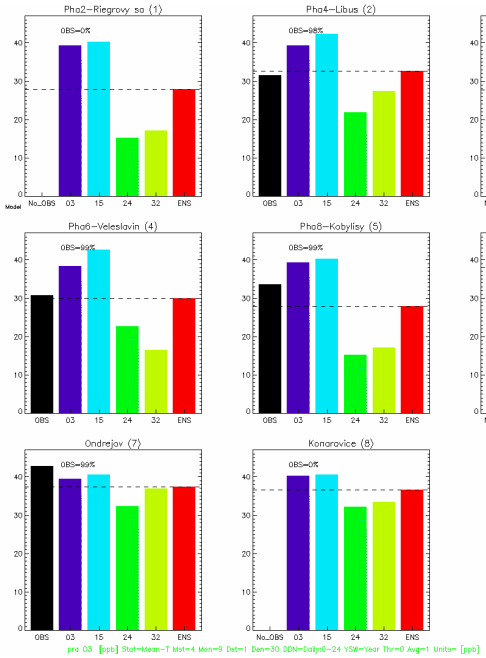


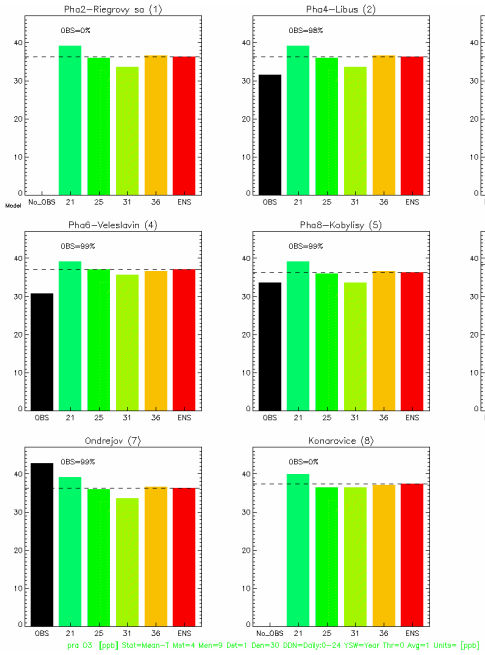


Fine-scale **Coarse-scale**

Figure 5.1 (cont.)

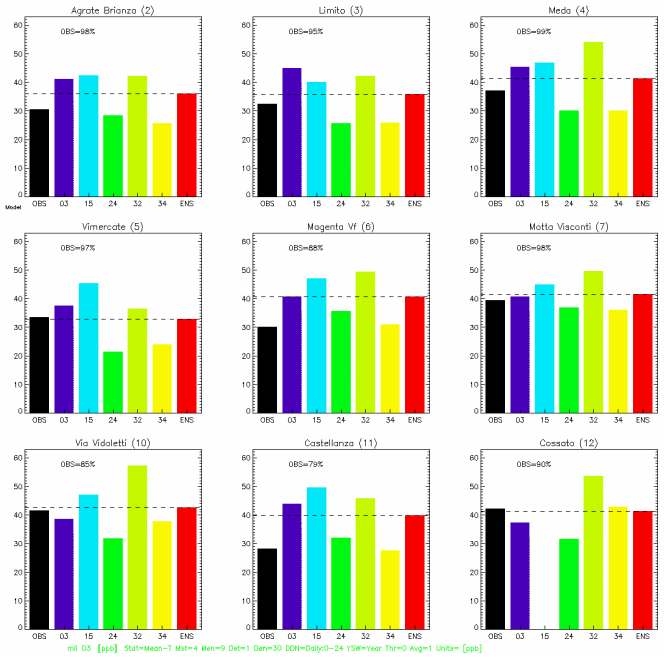
PRAGUE

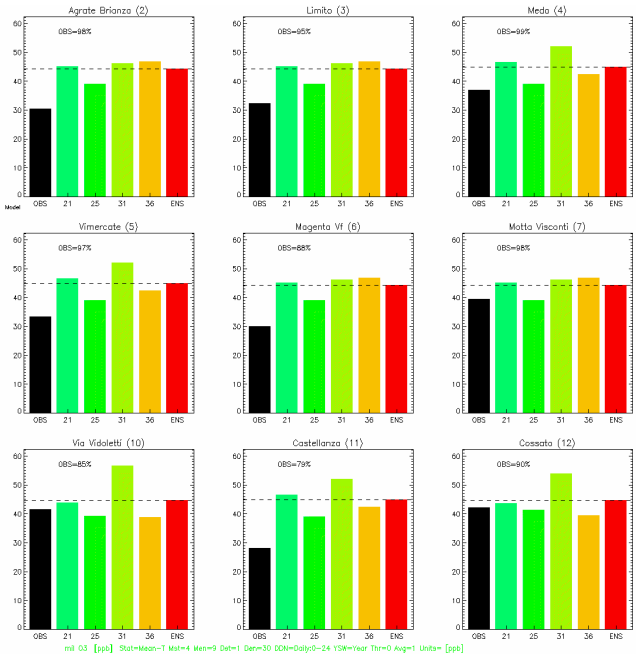




Fine-scale **Coarse-scale**

MILAN

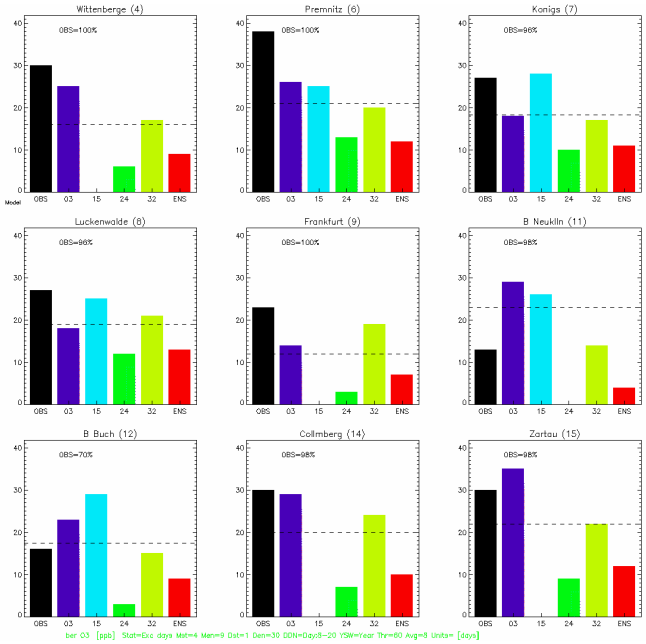


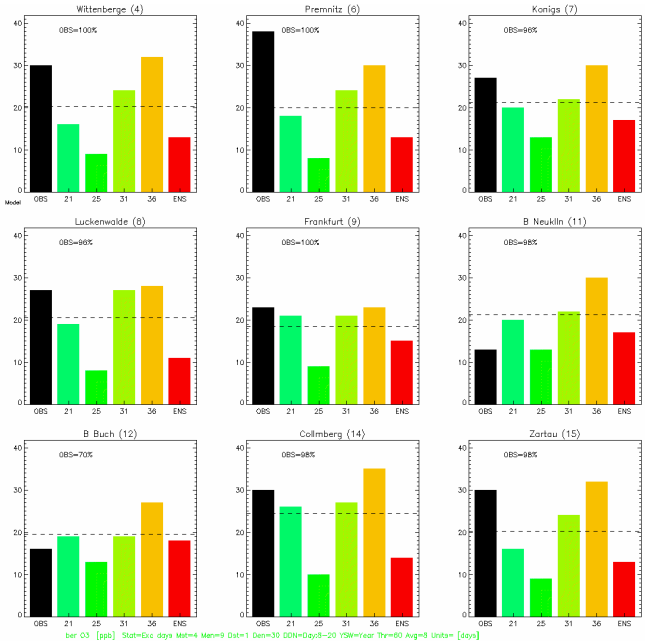


Fine-scale **Coarse-scale**

Figure 5.2: Ozone exceedence days (60 ppb, 8hr)

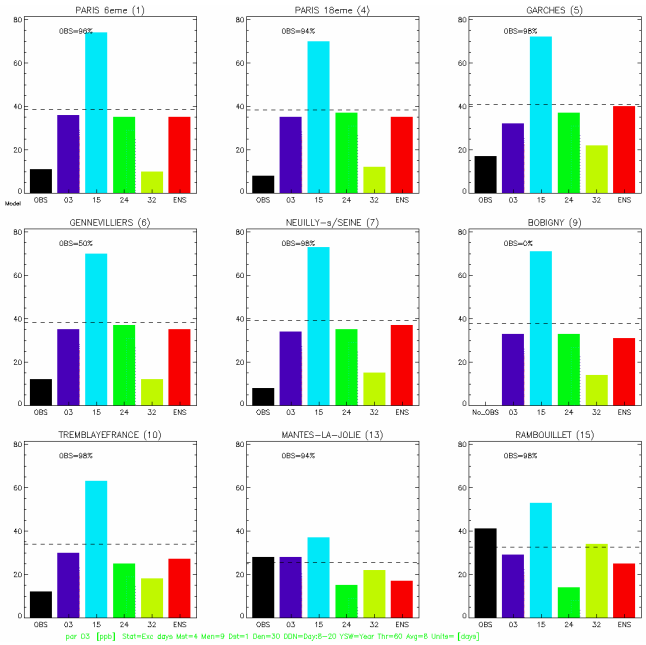
BERLIN

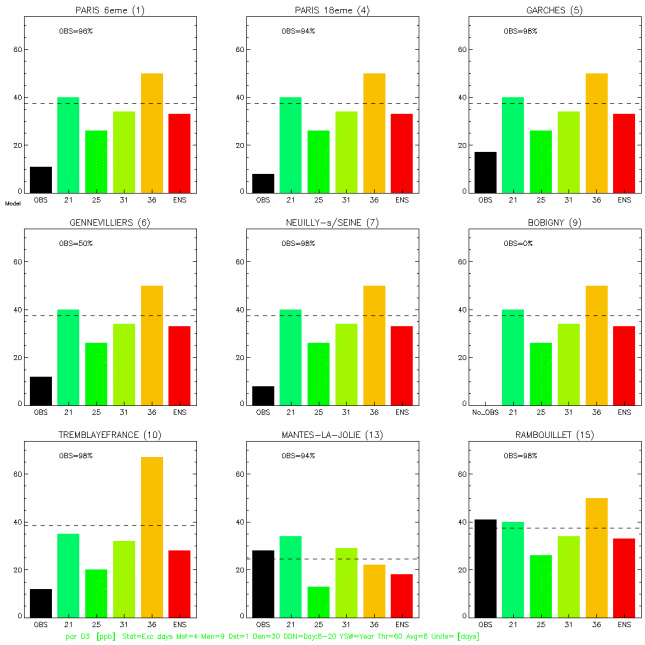




Fine-scale **Coarse-scale**

PARIS

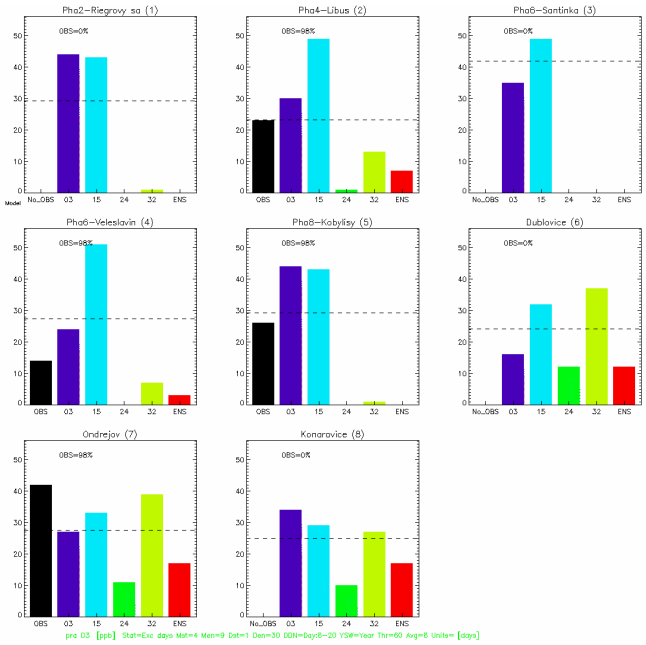


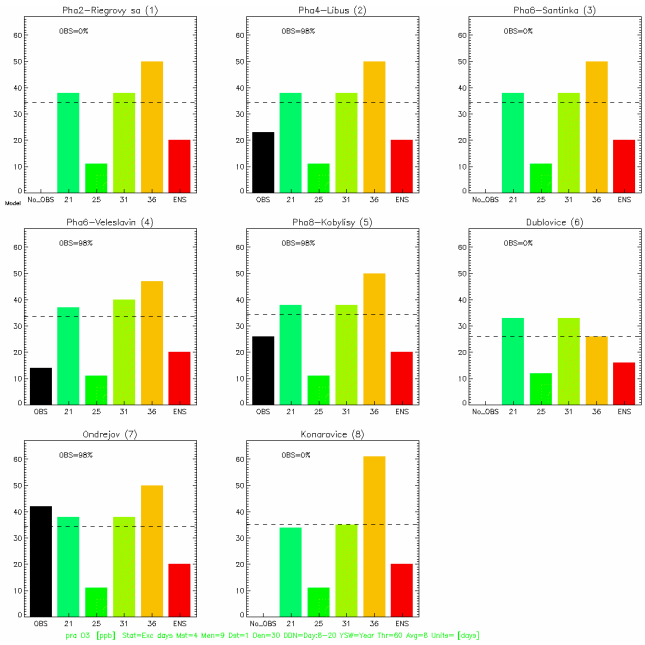


Fine-scale **Coarse-scale**

Figure 5.2 (cont.)

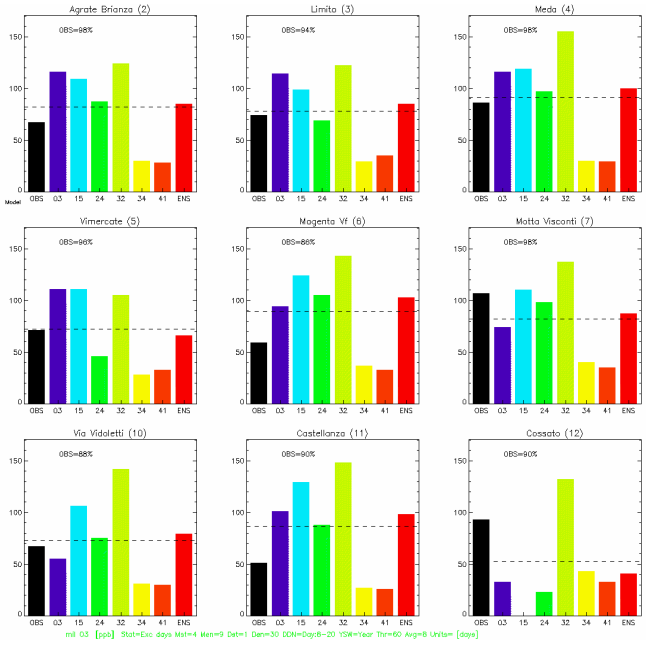
PRAGUE

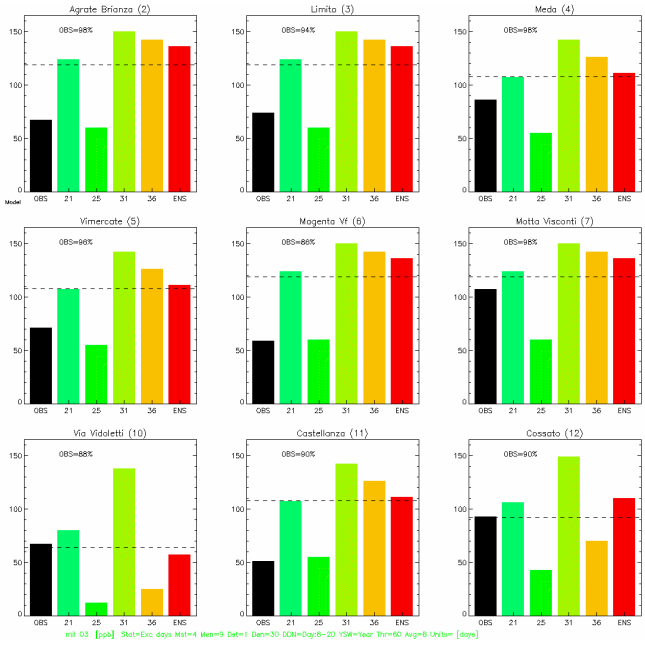




Fine-scale **Coarse-scale**

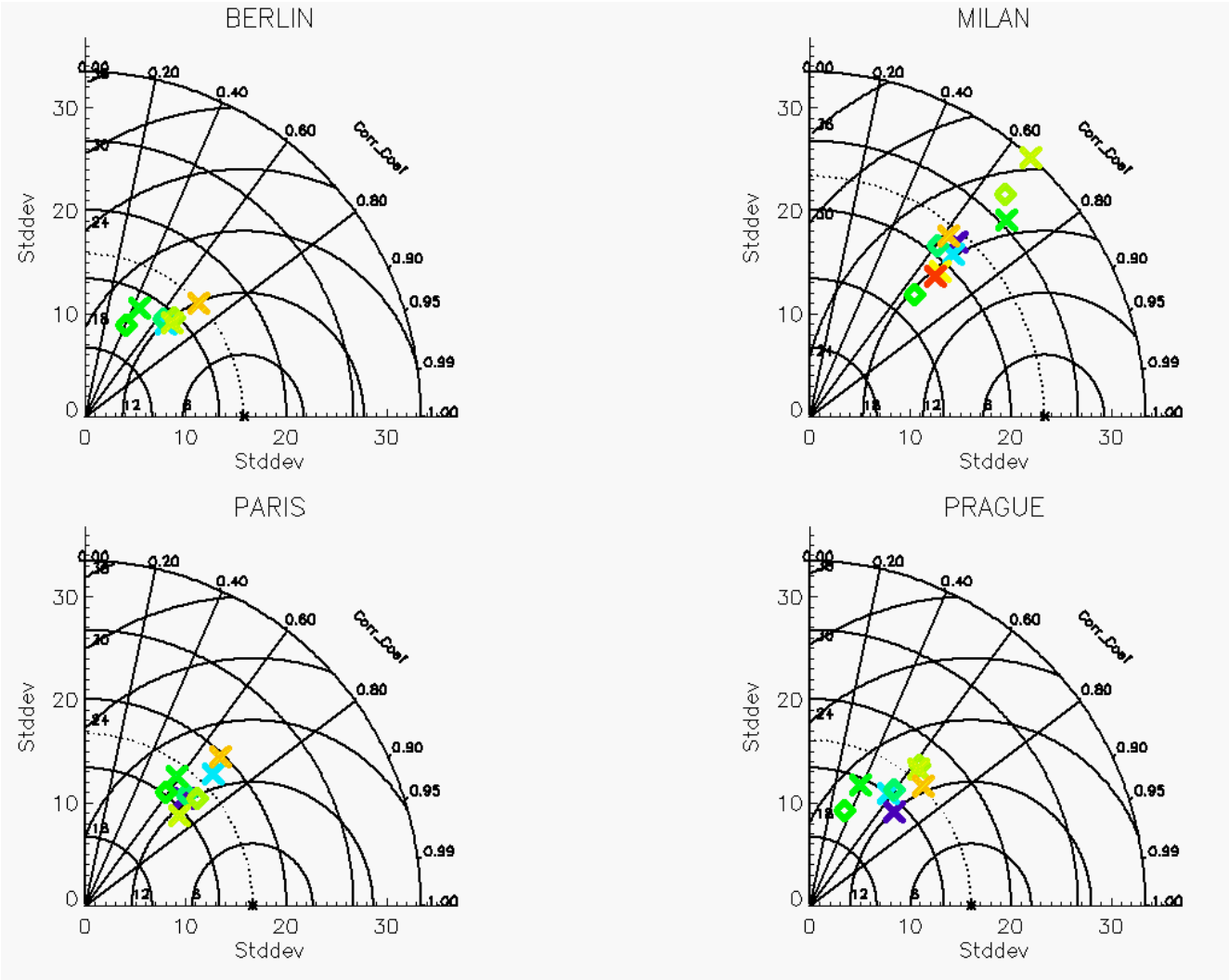
MILAN





Fine-scale **Coarse-scale**

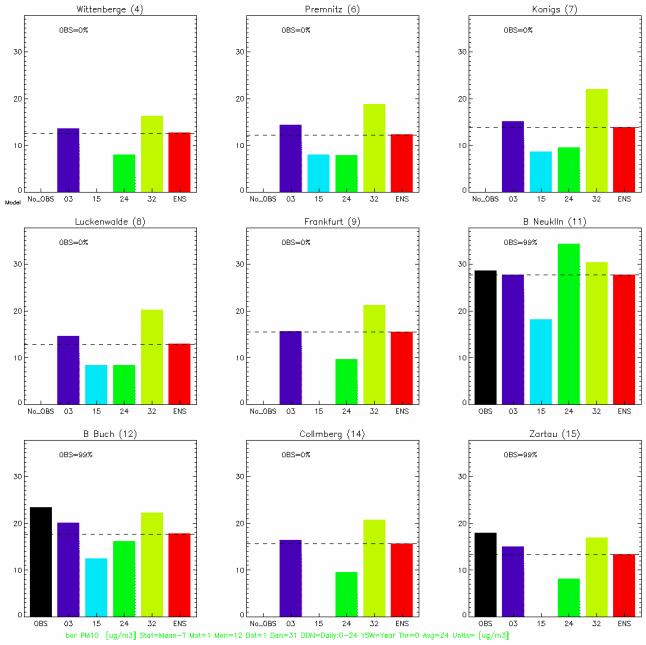
Figure 5.3: Taylor diagram for mean summer ozone



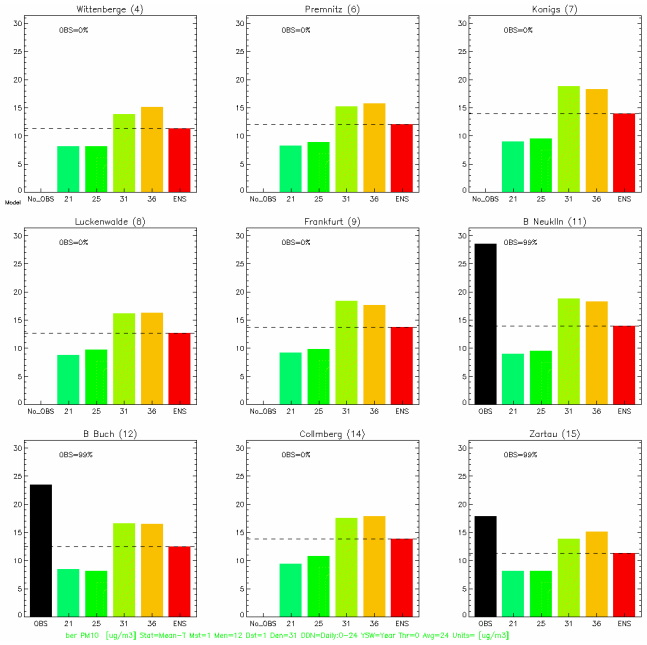
Fine-scale and coarse-scale models

Figure 5.4: Annual mean PM10

BERLIN

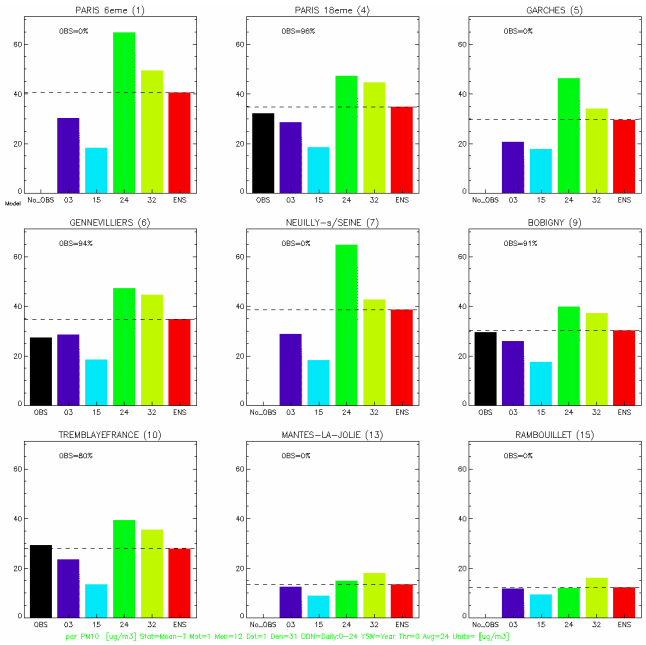


Fine-scale

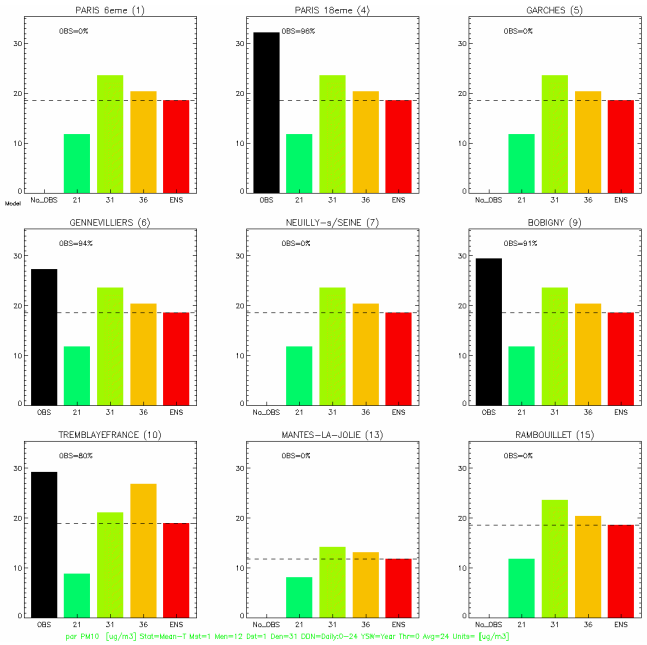


Coarse-scale

PARIS



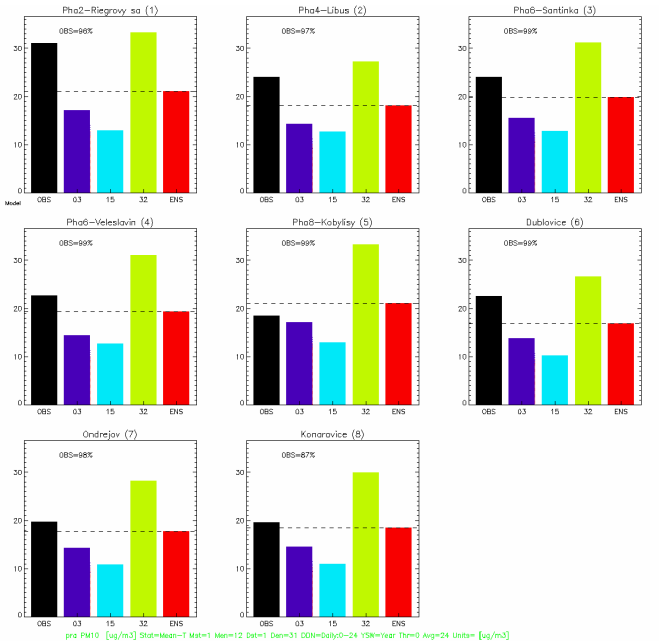
Fine-scale

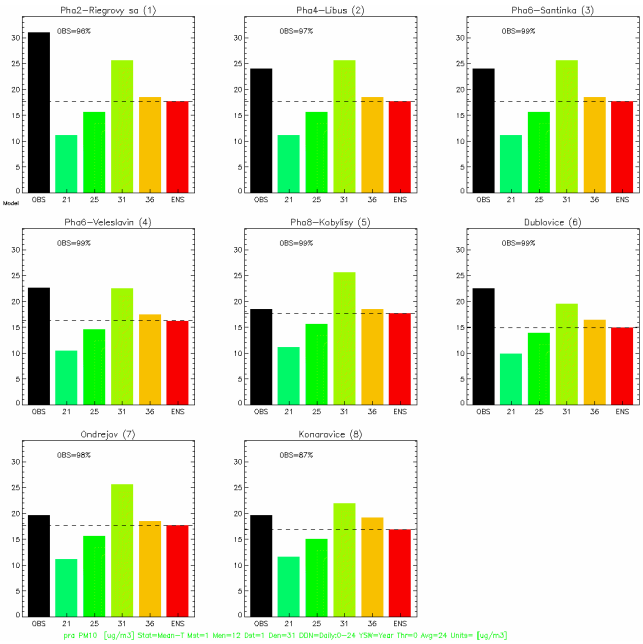


Coarse-scale

Figure 5.4 (cont.)

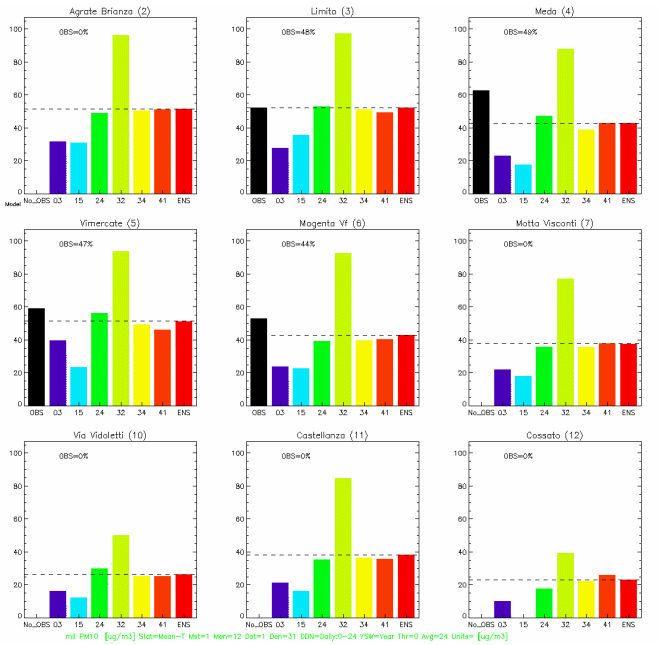
PRAGUE

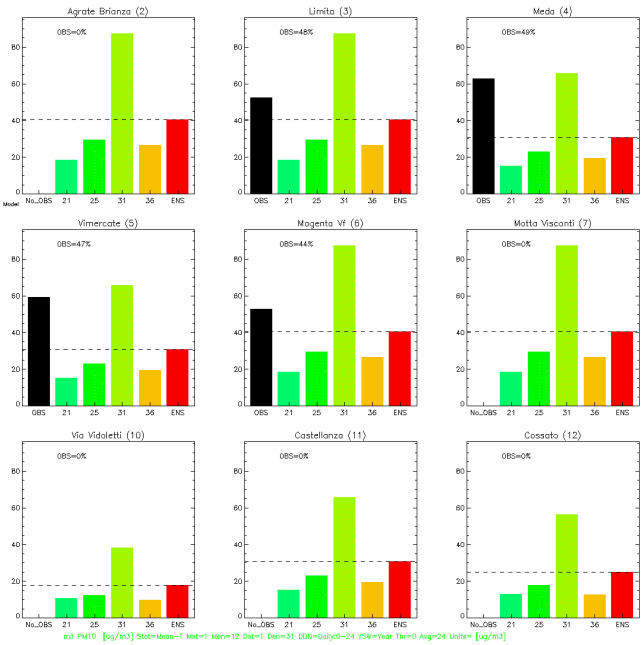




Fine-scale **Coarse-scale**

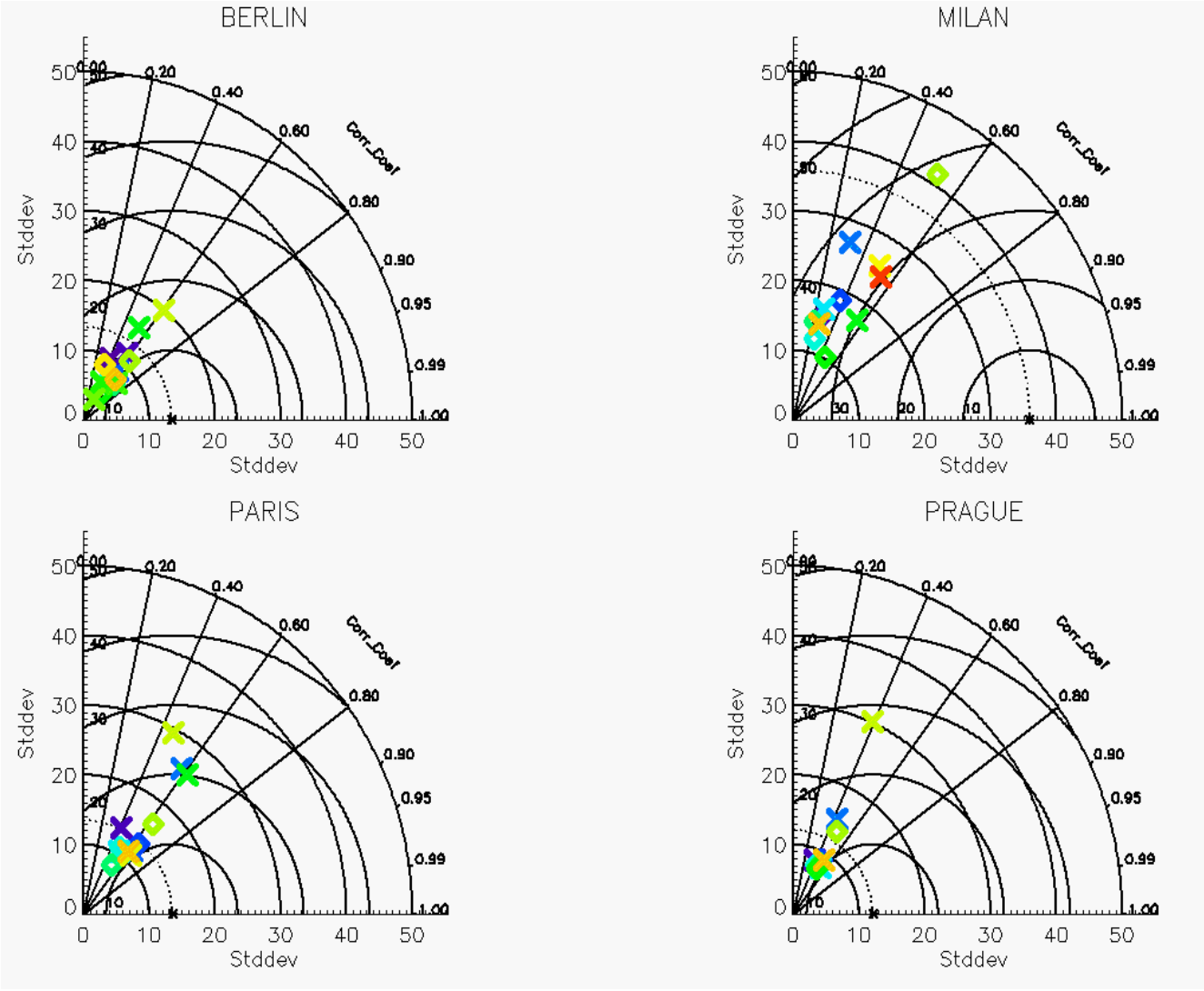
MILAN





Fine-scale **Coarse-scale**

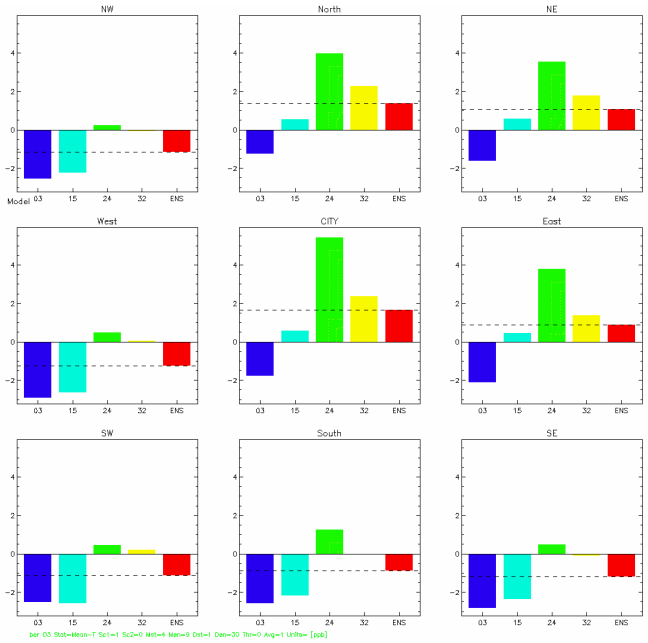
Figure 5.5: Taylor diagram: Annual mean PM10

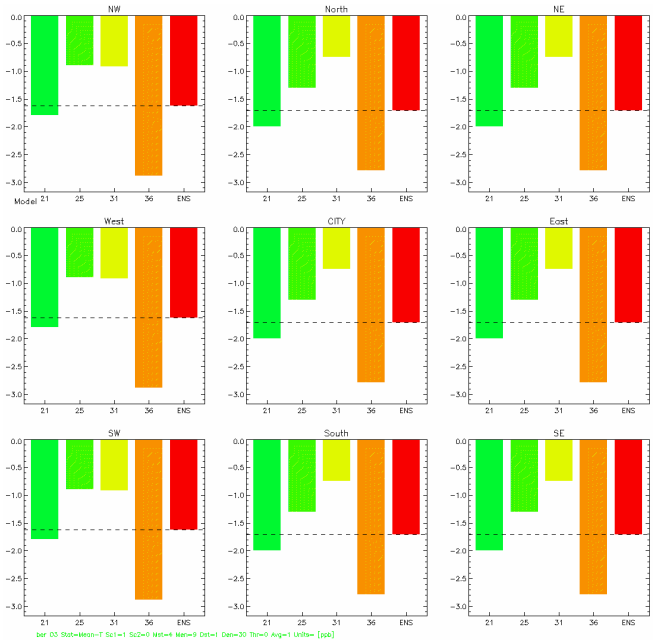


Fine-scale and coarse-scale models

Figure 5.6:: Delta (CLE-2000) mean summer ozone

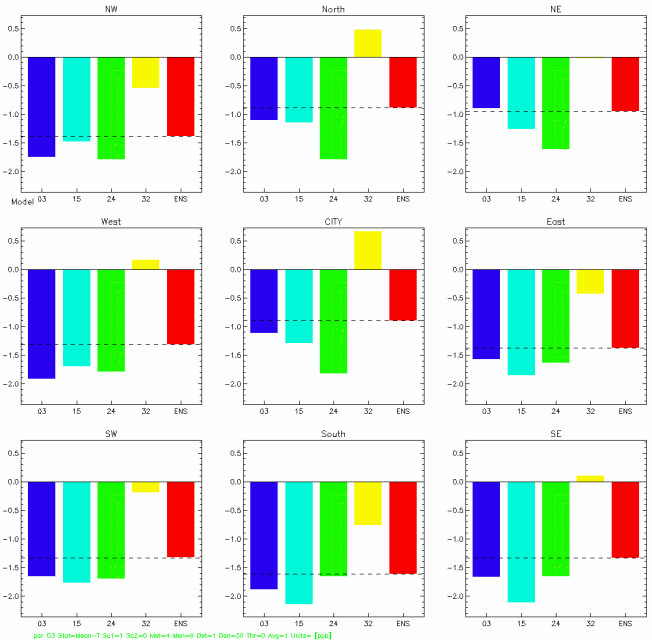
BERLIN

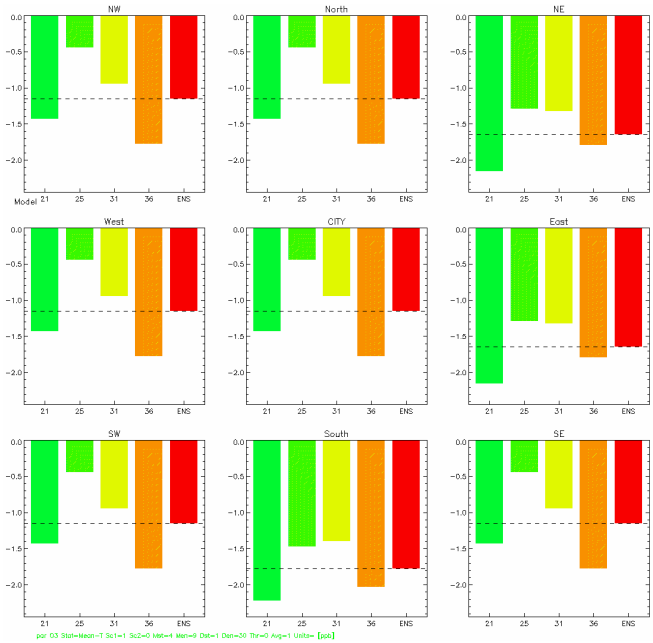




Fine-scale **Coarse-scale**

PARIS

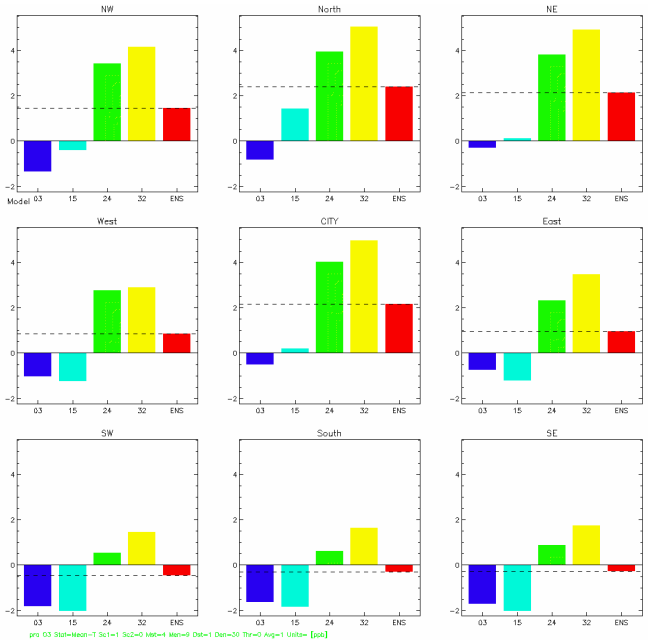




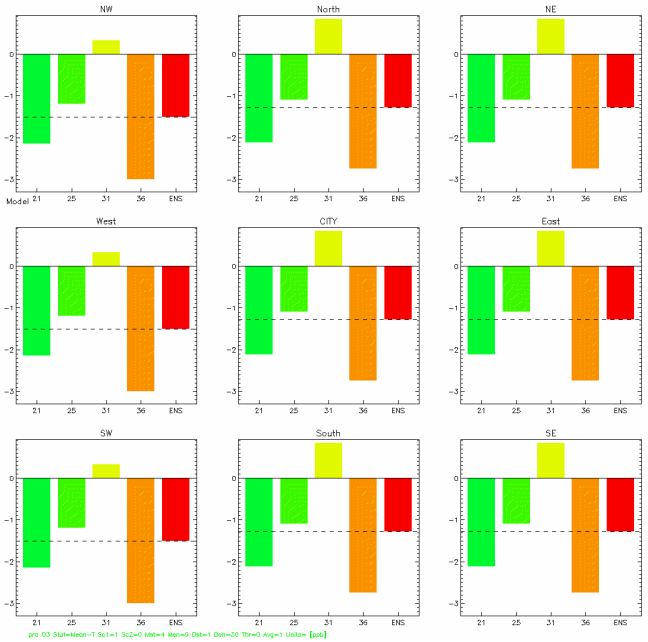
Fine-scale **Coarse-scale**

Figure 5.6 (cont.)

PRAGUE

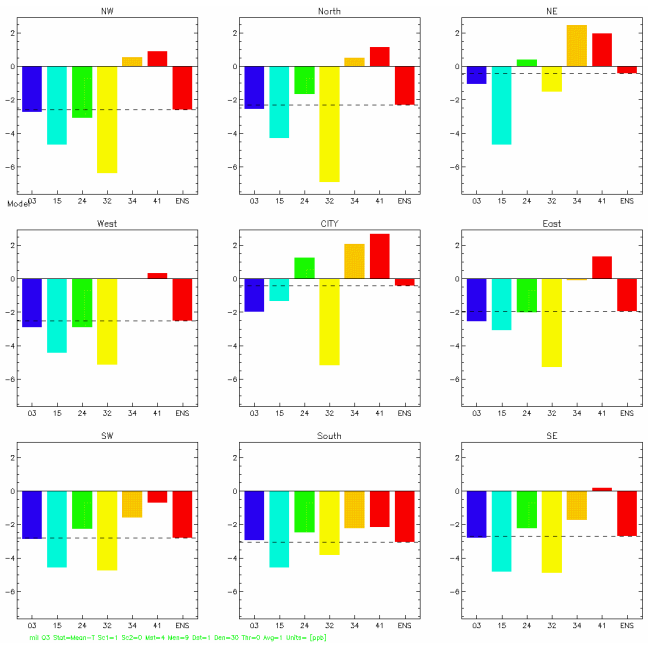


Fine-scale

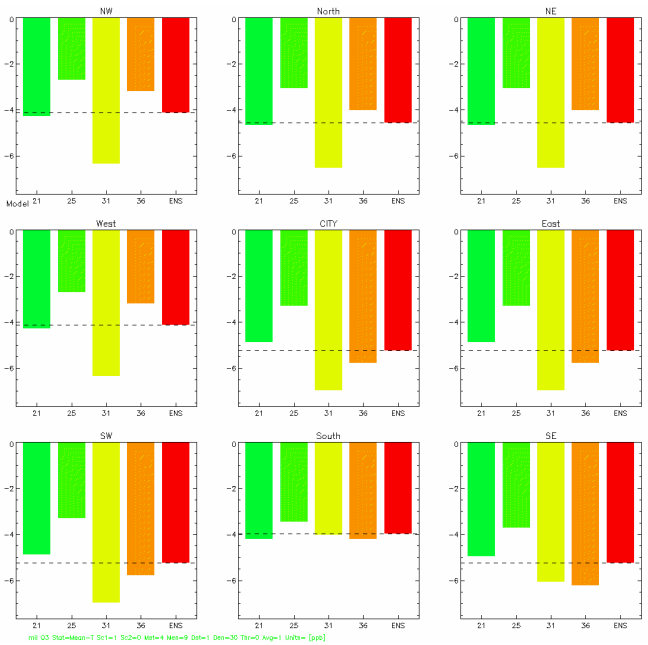


Coarse-scale

MILAN



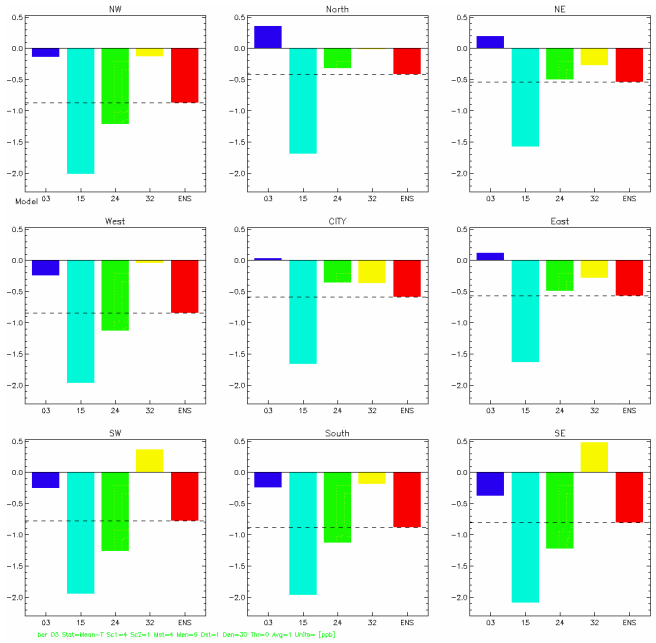
Fine-scale

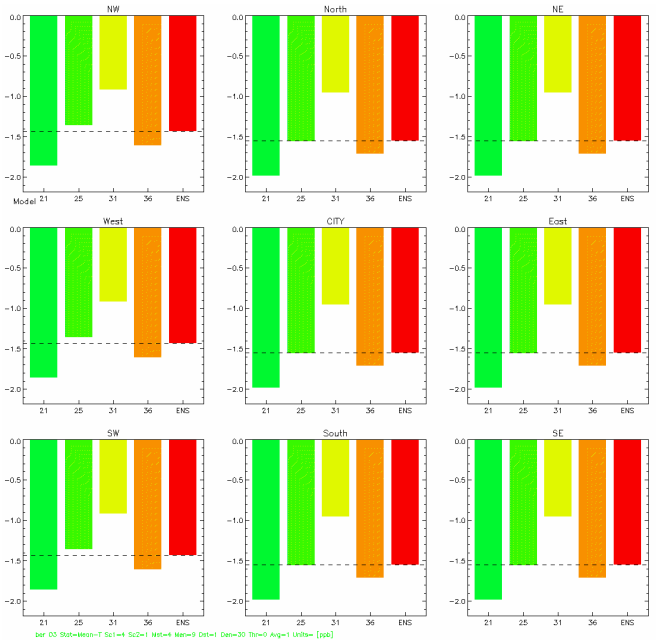


Coarse-scale

Figure 5.7: Delta (MFR-CLE) mean summer ozone

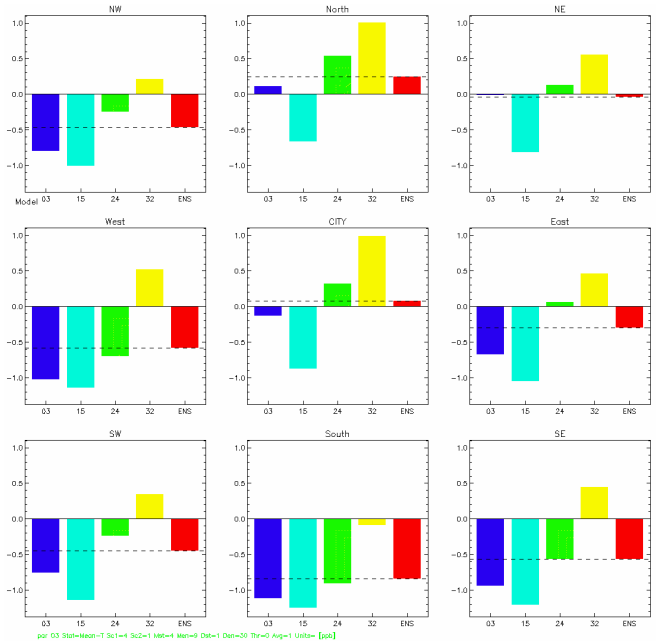
BERLIN

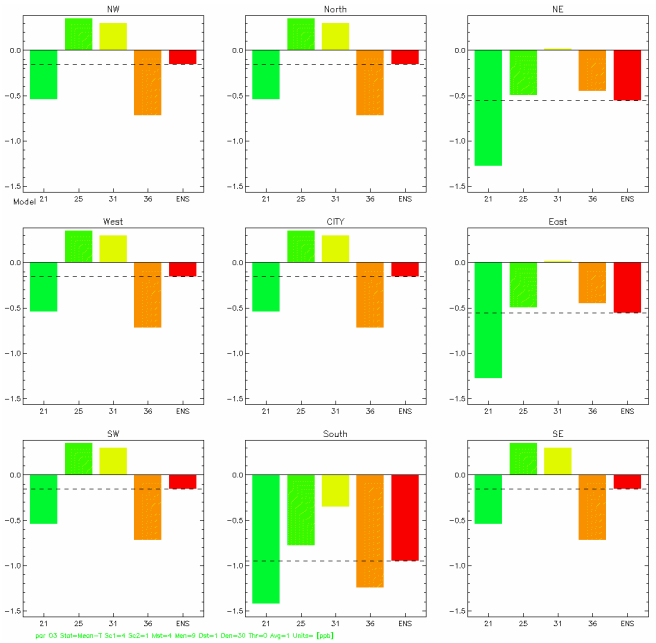




Fine-scale **Coarse-scale**

PARIS

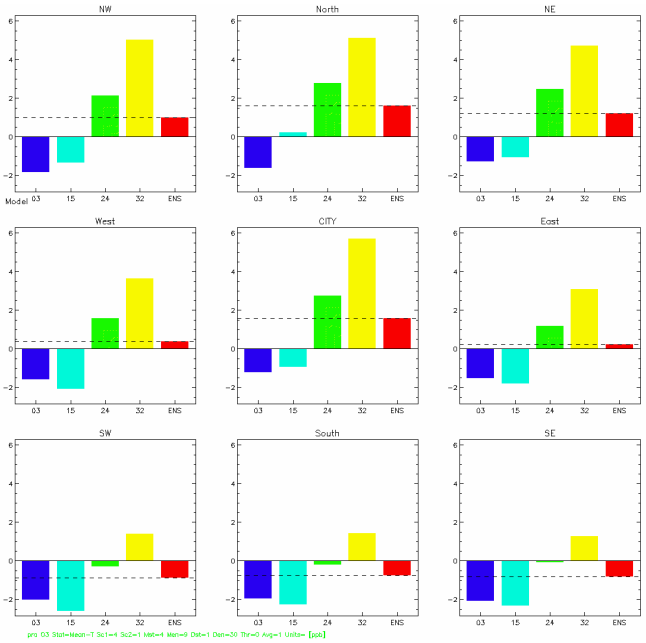




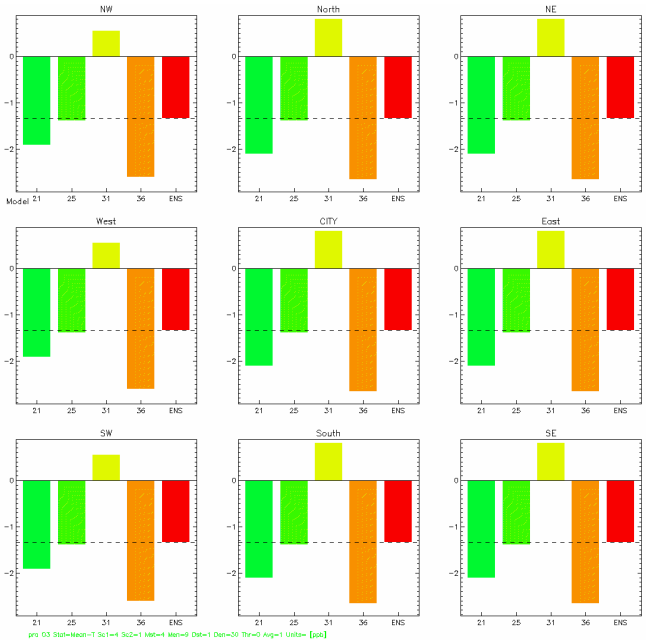
Fine-scale **Coarse-scale**

Figure 5.7 (cont.)

PRAGUE

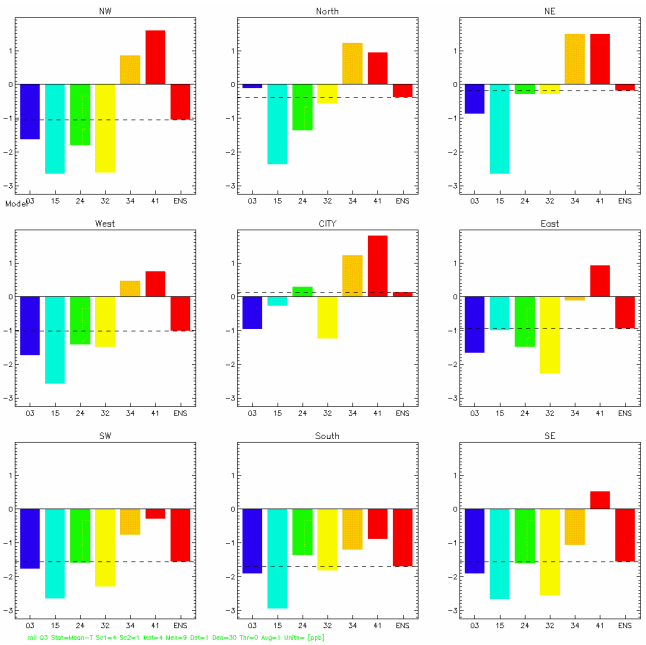


Fine-scale



Coarse-scale

MILAN



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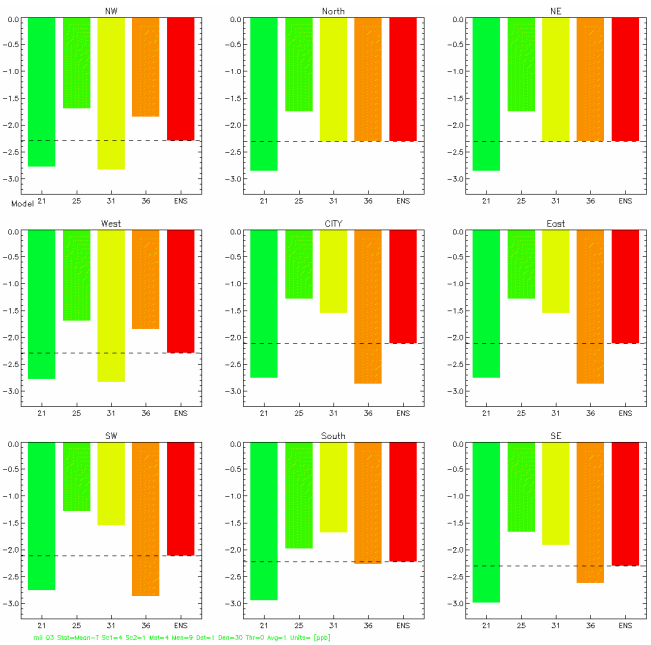
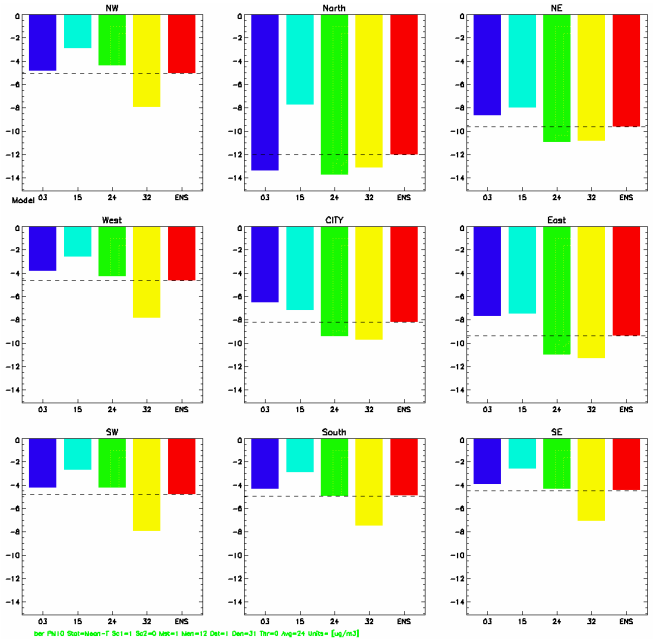


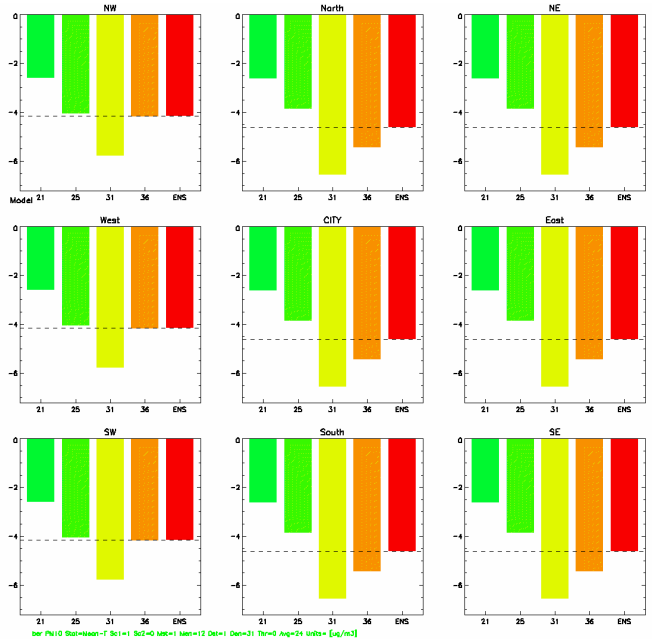
Coarse-scale

Figure 5.8: Delta (CLE-2000) annual mean PM10

BERLIN

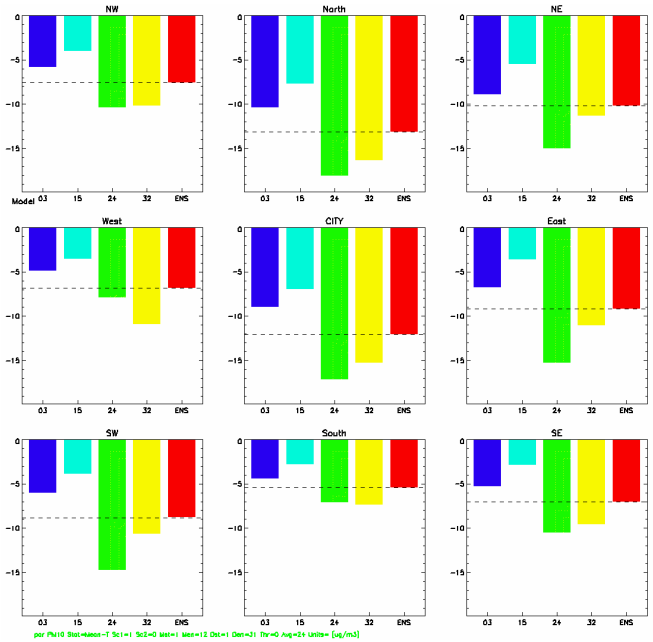


Fine-scale

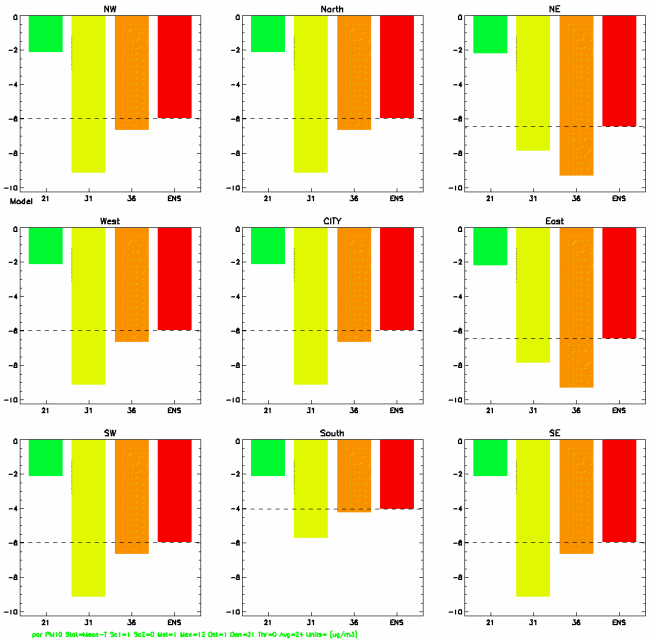


Coarse-scale

PARIS



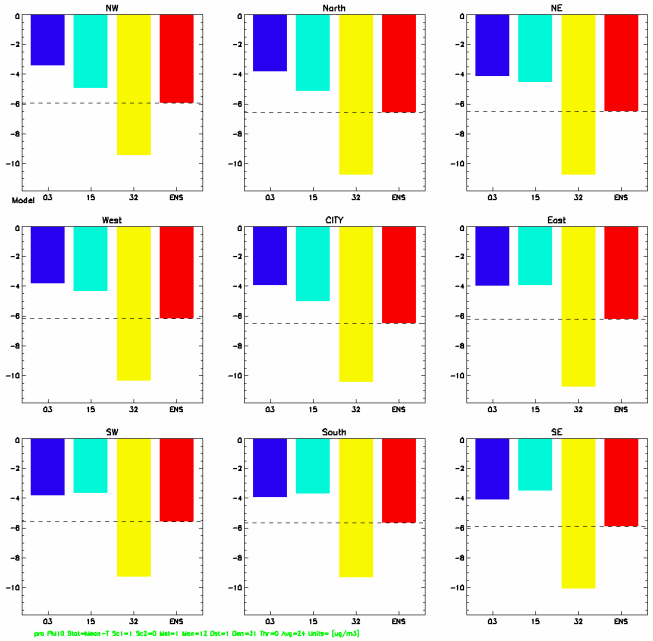
Fine-scale

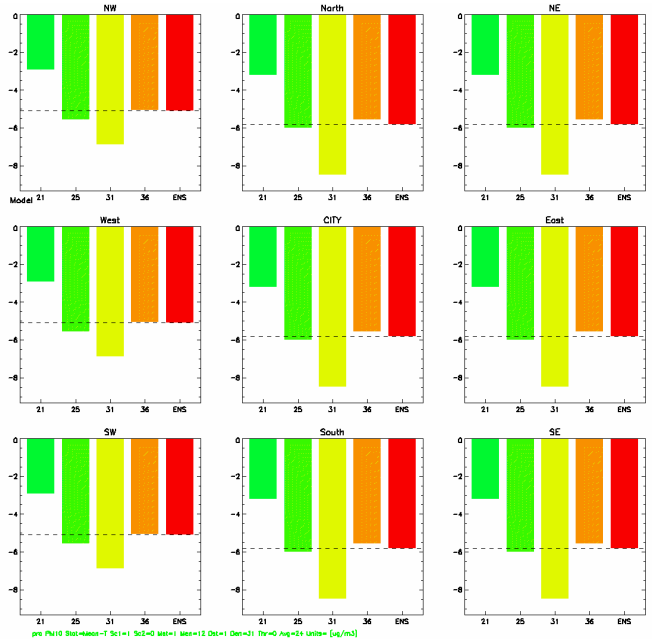


Coarse-scale

Figure 5.8 (cont.)

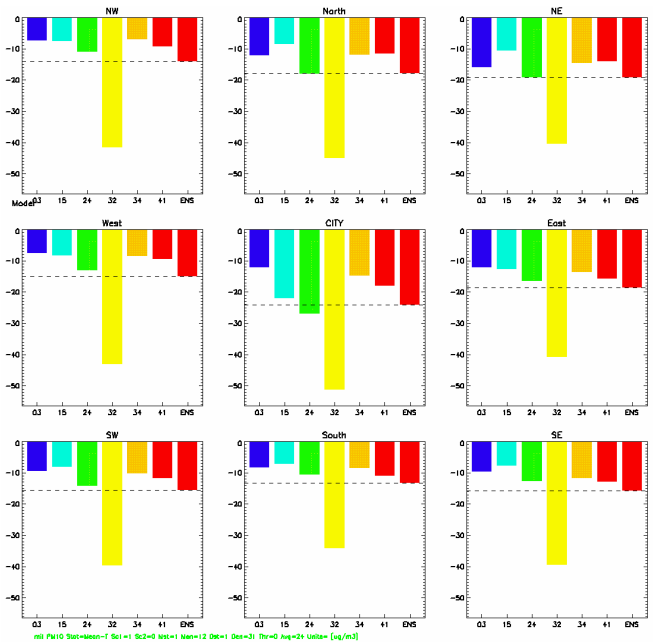
PRAGUE

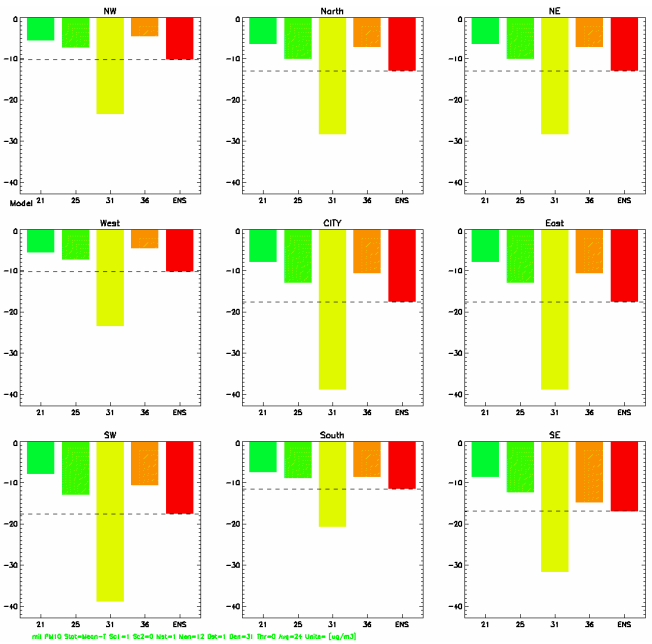




Fine-scale **Coarse-scale**

MILAN

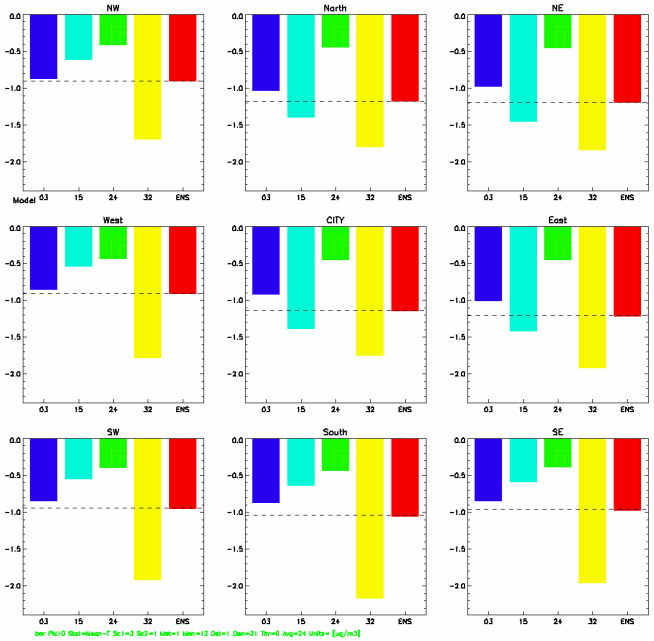




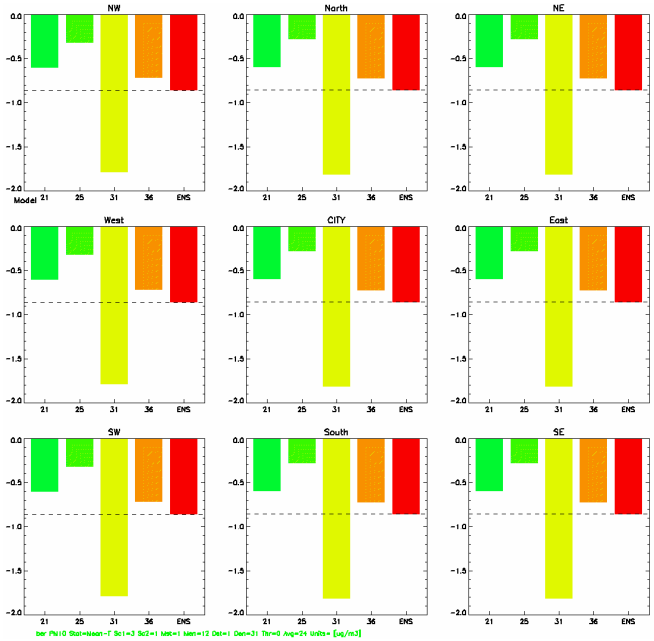
Fine-scale **Coarse-scale**

Figure 5.9: Delta (MFR-CLE) annual mean PM10

BERLIN

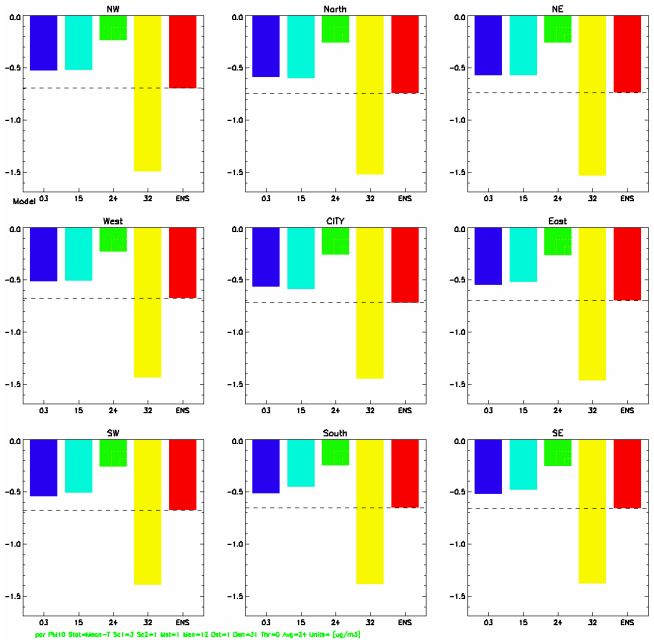


Fine-scale

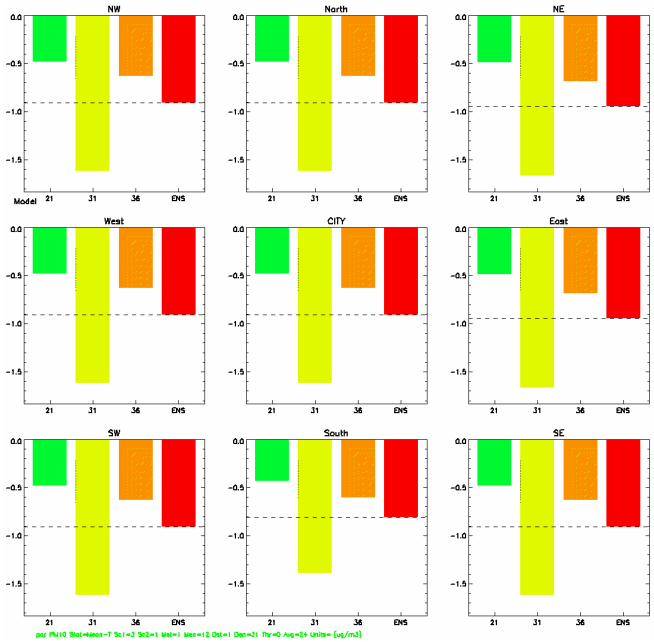


Coarse-scale

PARIS



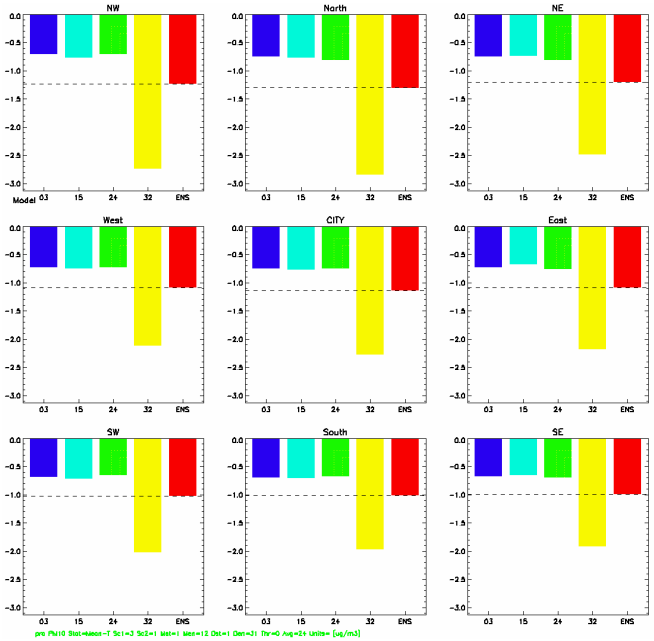
Fine-scale



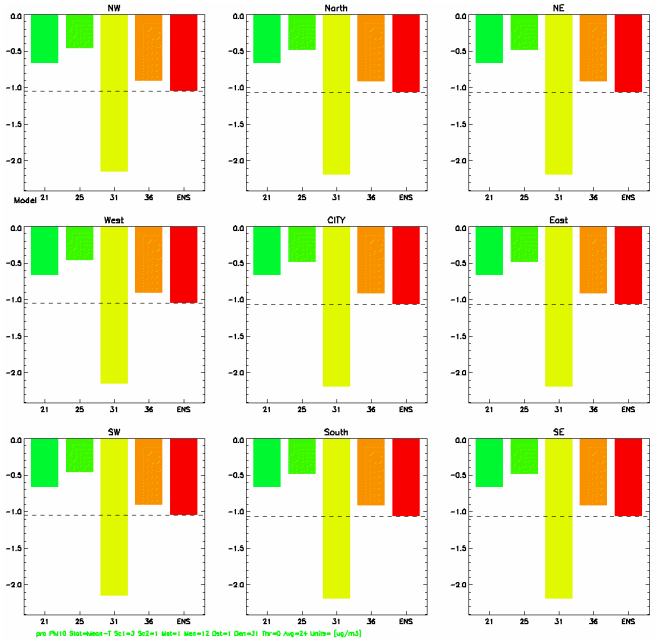
Coarse-scale

Figure 5.9 (cont.)

PRAGUE



Fine-scale



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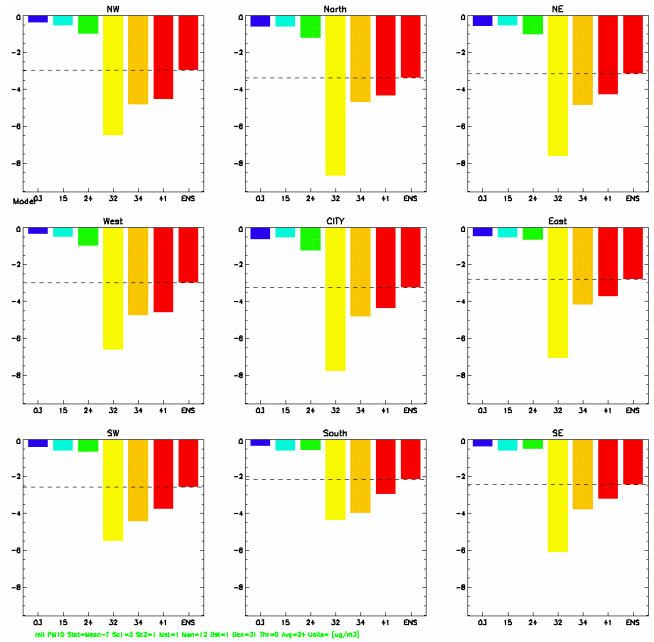

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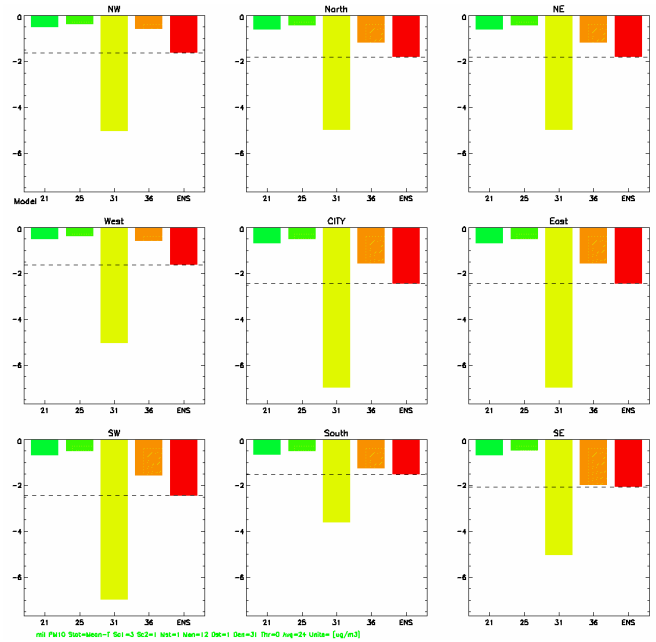
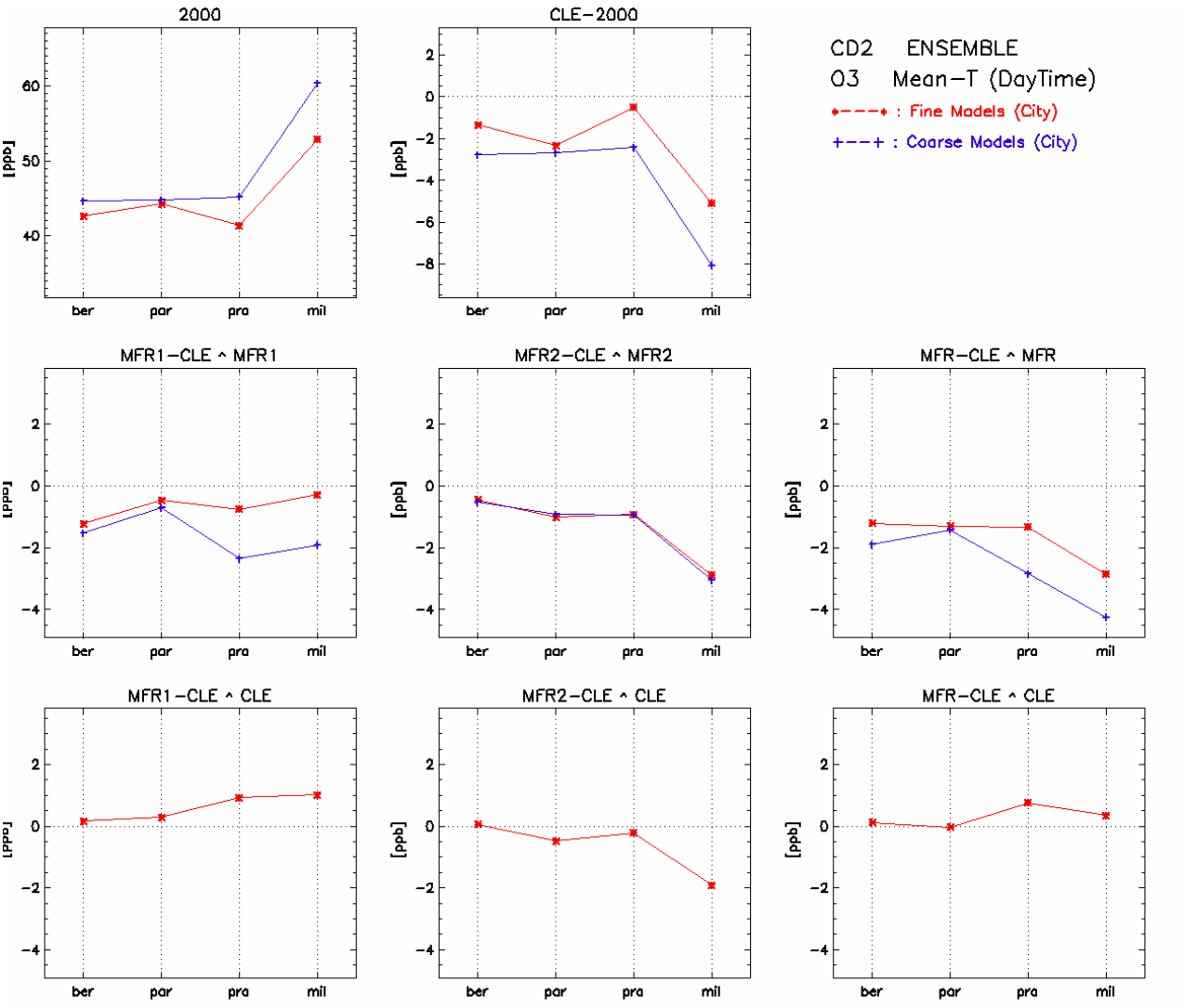


Coarse-scale

Figure 5.10: City-overview: Mean summer daytime ozone



Note:

MFR1-CLE ^ MFR1 = MFR for NO_x, SO_2, PPM2.5 and PPMc, and CLE for others (with boundary conditions kept at MFR1)
MFR2-CLE ^ MFR2 = MFR for VOC, CO and NH_3, and CLE for others (with boundary conditions kept at MFR2)
MFR-CLE ^ MFR = MFR for all pollutants (with boundary conditions kept at MFR)

MFR1-CLE ^ CLE = MFR for NO_x, SO_2, PPM2.5 and PPMc, and CLE for others (with boundary conditions kept at CLE)
MFR2-CLE ^ CLE = MFR for VOC, CO and NH_3, and CLE for others (with boundary conditions kept at CLE)
MFR-CLE ^ CLE = MFR for all pollutants (with boundary conditions kept at CLE)

Figure 5.11: City-overview: SOMO35 indicator

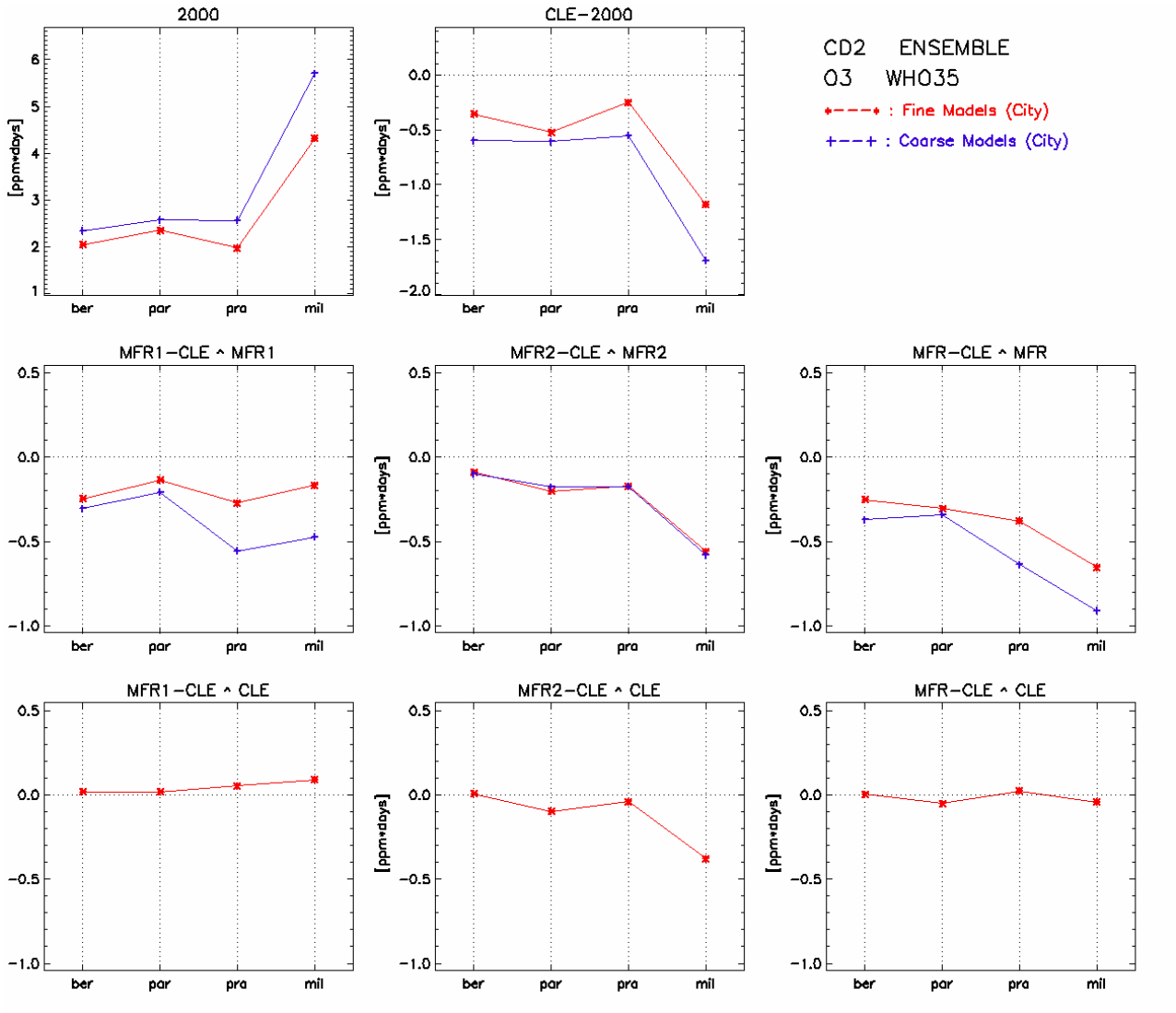


Figure 5.12: City-overview yearly mean PM10

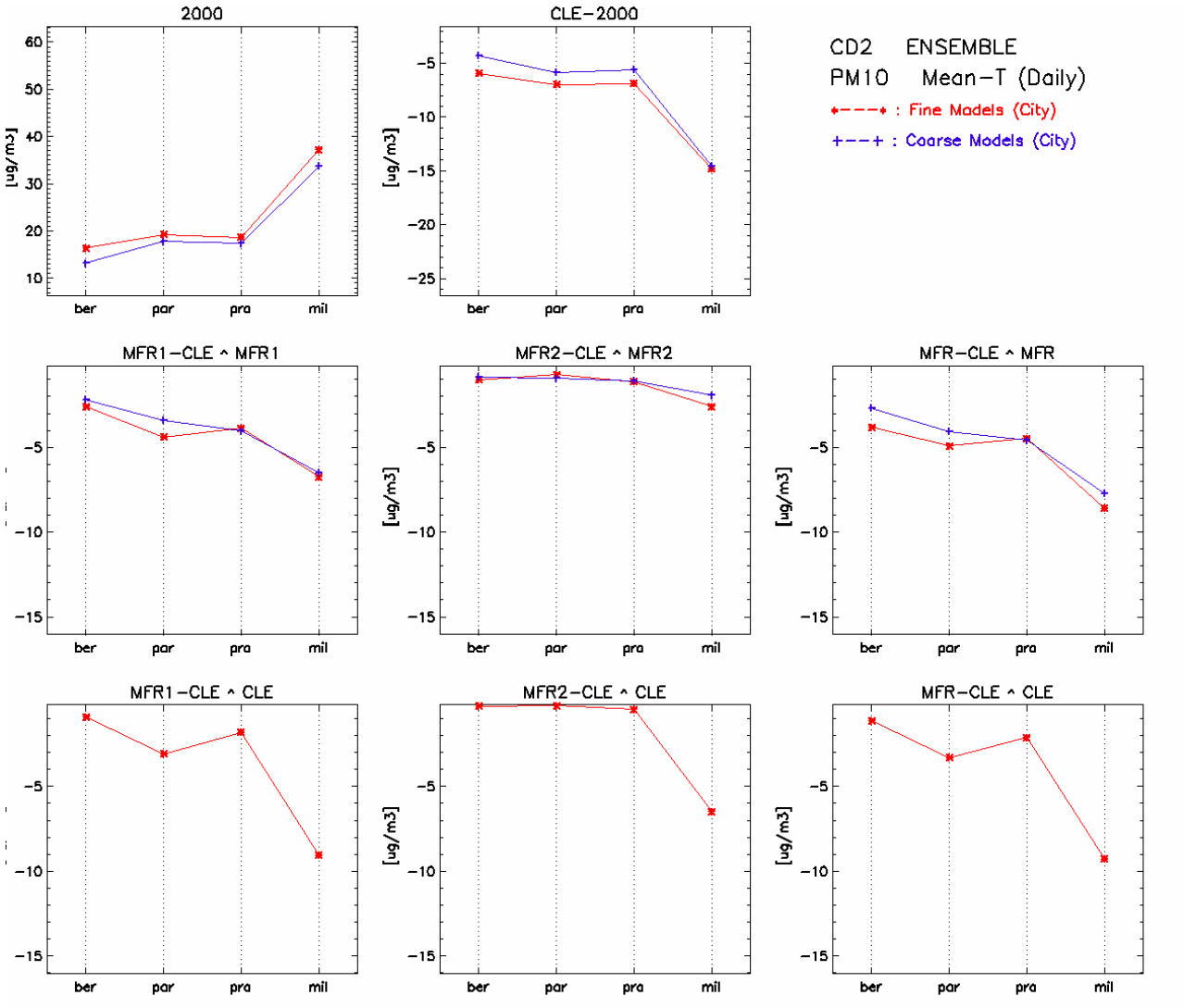
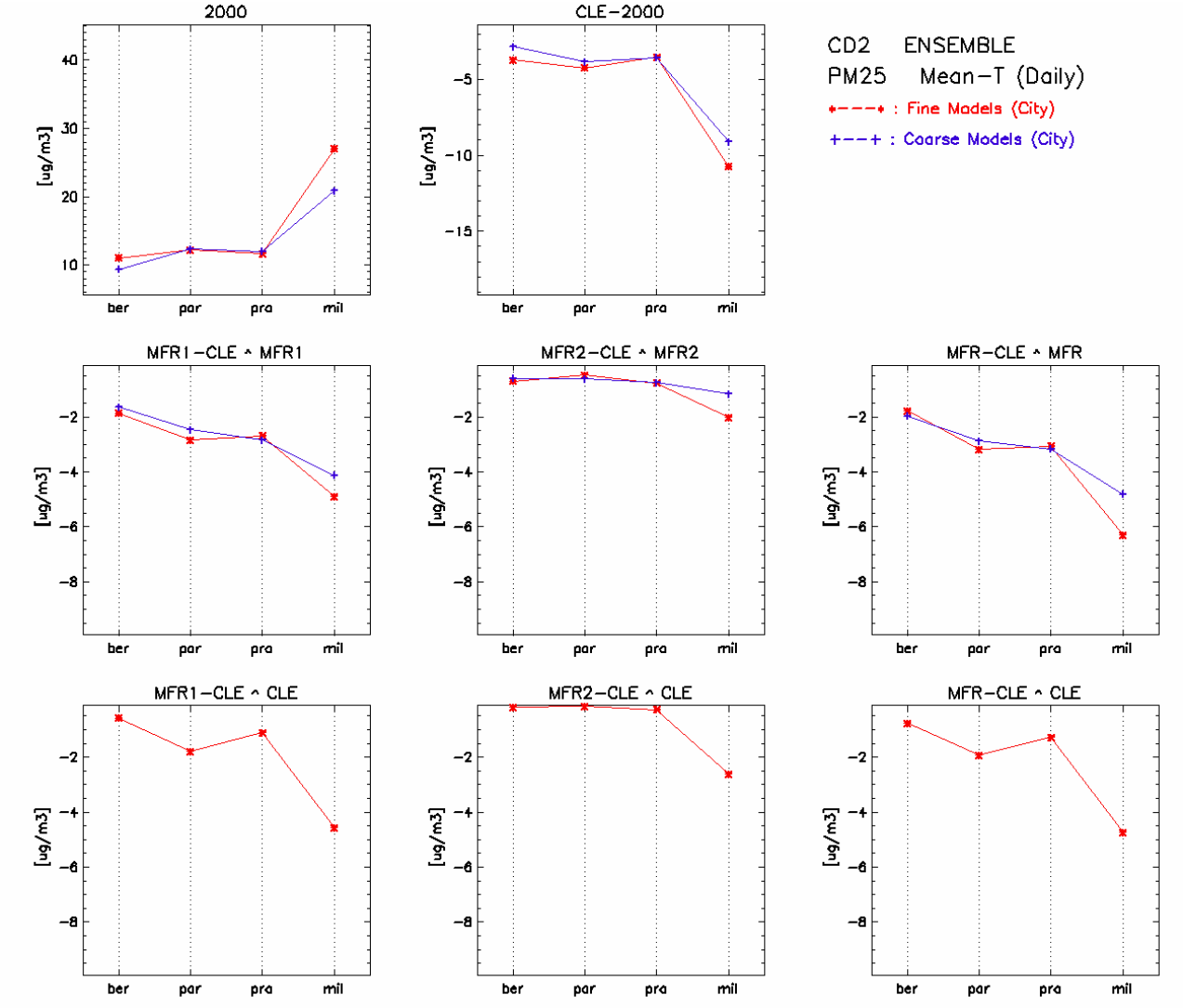


Figure 5.13: City-overview: Annual mean PM2.5



6 Functional relationships to estimate urban air quality

C. Heyes, L. White, M. Amann, W. Schöpp

It is one of the major objectives of the City-Delta project to develop functional relationships that allow calculating health-relevant metrics of urban air quality in the context of the Europe-wide integrated assessment conducted with the RAINS model.

For PM2.5, such relationships should determine urban background concentrations of PM2.5 as a function of grid average concentration as computed by a regional-scale dispersion model, emission densities in a city, which vary inter alia with emission control scenarios, and some topographic and meteorological parameters that reflect city-specific dispersion characteristics. To connect with the determinants of health impact methodologies (i.e., urban background concentrations), such functional relationships should quantify changes in long-term metrics of urban background of PM2.5 and ozone, rather than short-term peak concentrations or hot spots such as street canyons.

6.1 Analysis of observational data

To complement the analysis of the City-Delta model intercomparison, which aimed at the understanding of responses of urban air quality towards changes in emissions based on model analyses, an assessment was carried out for observational data. This analysis is based on the concept – supported by the findings of City-Delta – that a large fraction of $PM_{2.5}$ in urban background air originates from long-range transport. The data processing and analysis have been largely determined by practical considerations such as data availability and the quality and accessibility of the relevant data documentation. Investigation has concentrated on the cities of London and Berlin, both of which are represented in the City-Delta project with data available for 1999. In addition, it proved to be relatively straightforward to obtain London PM emissions and measurement data for 2001.

6.1.1 Data Sources

The primary PM emission inventory provided to City-Delta for London gives PM_{10} emission estimates for 1999 on a 2*2 km grid for both ground-level sources and stacks. Monitoring data are available for 1999 from nine sites, eight of which provide PM_{10} concentrations, and two $PM_{2.5}$.

The Berlin emission inventory provides estimates of PM_{10} emissions for a number of source sectors with a spatial resolution of 0.03125° longitude * 0.015625° latitude. Emissions of $PM_{2.5}$ are estimated as a sector-dependent fraction of PM_{10}. The Berlin emission inventories are applicable to years between 1996 and 1999, depending on source sector and origin. Measurements of PM_{10} from

1999 for three Berlin sites – two urban, one rural - are available from City-Delta. Additional PM_{10} measurement data for the Berlin area for 1999, 2000 and 2001 were obtained from the Airbase measurement database.

The UK National Atmospheric Emissions Inventory website (http://www.naei.org.uk/) provides information on the UK emissions of a wide range of pollutants including PM_{10}. Gridded PM_{10} emissions covering the whole of the UK with a spatial resolution of 1*1 km are available for each CORINAIR SNAP1 source sector for the year 2001. In the present study, most attention has been given initially to the road transport sector and total area source PM_{10} emissions.

The UK National Air Quality Information Archive (http://www.airquality.co.uk/archive/) contains extensive sets of UK measurements of air quality for periods from 1960 to the present, involving more than 1500 monitoring sites. Hourly measurements of PM_{10} concentrations have been made at more than 60 sites across the UK. Results from these sites for 2001 – to be consistent with the available emissions data – have been obtained for use in this study.

6.1.2 Results

Measurement data rather than model results have been used for these investigations. Annual average concentration values have been calculated; no use has yet been made of greater temporal resolution of the typically hourly concentration measurements available. To date, the study has focused on PM_{10} rather than directly on $PM_{2.5}$. This is because data on PM_{10} is, currently, much more widely available than $PM_{2.5}$ data, although the finer fraction is acknowledged to be more relevant to impacts on human health.

The aim of these preliminary analyses has been to investigate how measured PM concentrations within urban areas depend on the local PM emission density. This relationship should be examined to establish whether it is better expressed in terms of total PM emissions or as a function of the PM emissions from a specific source sector, such as road transport. Where a clear relationship exists, the most appropriate spatial resolution for the urban emissions needs to be determined.

6.1.2.1 London

Analysis of monitoring data shows a clear relation between the magnitude of the urban signal and the emission density within the city. An example for London finds a rather consistent linear relation between observed annual mean PM_{10} levels at the various urban background monitoring stations and the primary PM_{10} emission densities (from road transport) in the 5*5 km box around each measurement site (Figure 6.1). This figure is based on concentration measurements and emission estimates for London for the year 2001. It makes use of PM_{10} data rather than directly $PM_{2.5}$ because of the scarcity of available $PM_{2.5}$ measurements. Although it must be remembered that this is a

preliminary result for one location for one year, it would suggest not only that there is a reasonably good correlation between annual average PM_{10} concentrations at urban sites and the local road traffic emissions of PM_{10}, but also that the urban increment is not a large proportion of the measured PM_{10} concentration at urban background sites. For the London example shown here for 2001, the urban increment constitutes at most 27 percent of the measured urban background PM_{10} concentration.

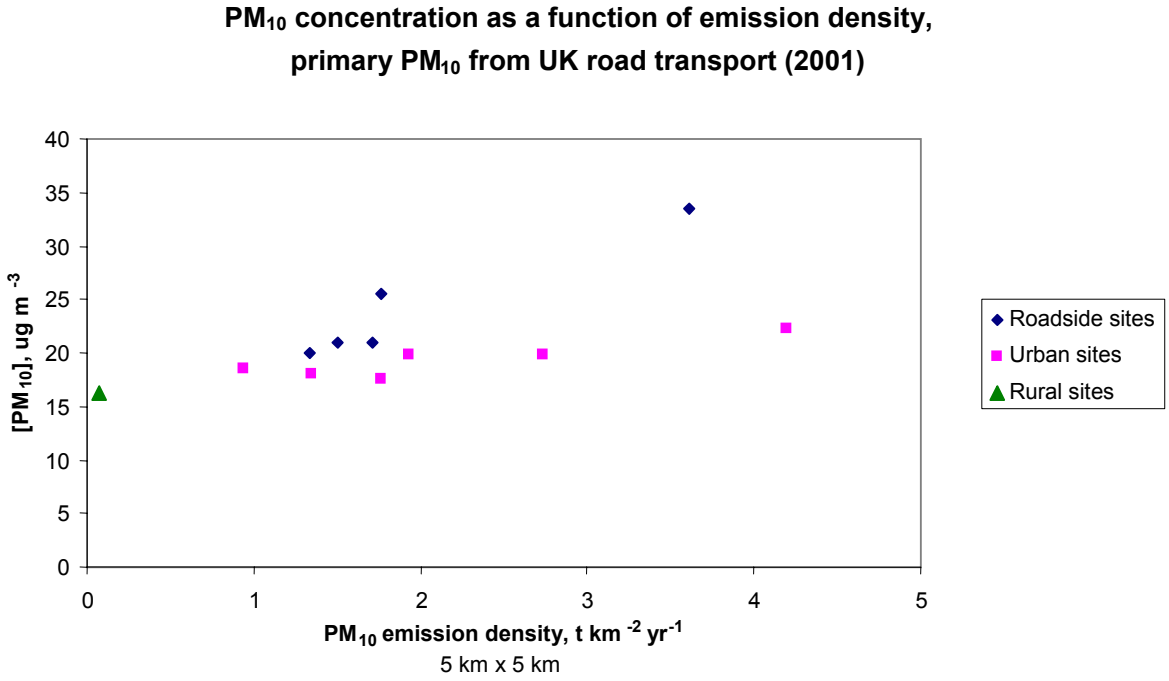


Figure 6.1: Relation between measured PM_{10} concentrations within London and the emission density of PM_{10} from road transport. Both the measurement data and the PM_{10} emission inventory are for the year 2001.

The example shown in Figure 6.1 used the emission density of PM_{10} emissions from road transport calculated over the 5*5 km grid cell in which each measurement station is located.

Figure 6.2 provides a comparison of the relationships found for total area source PM_{10} emissions averaged over different grid areas. Correlations appear to improve if emission densities are averaged over a larger area than 1*1 km; in this case, 5*5 km gives a better result for the urban background sites than 1*1, 3*3 or 9*9 km.

Figure 6.3 shows the corresponding comparison of averaging area if only emissions from road transport are considered. As a sideline, it is interesting to note that linear relations between observed annual mean PM_{10} levels and emission densities also emerge for roadside sites, though obviously with a steeper slope.

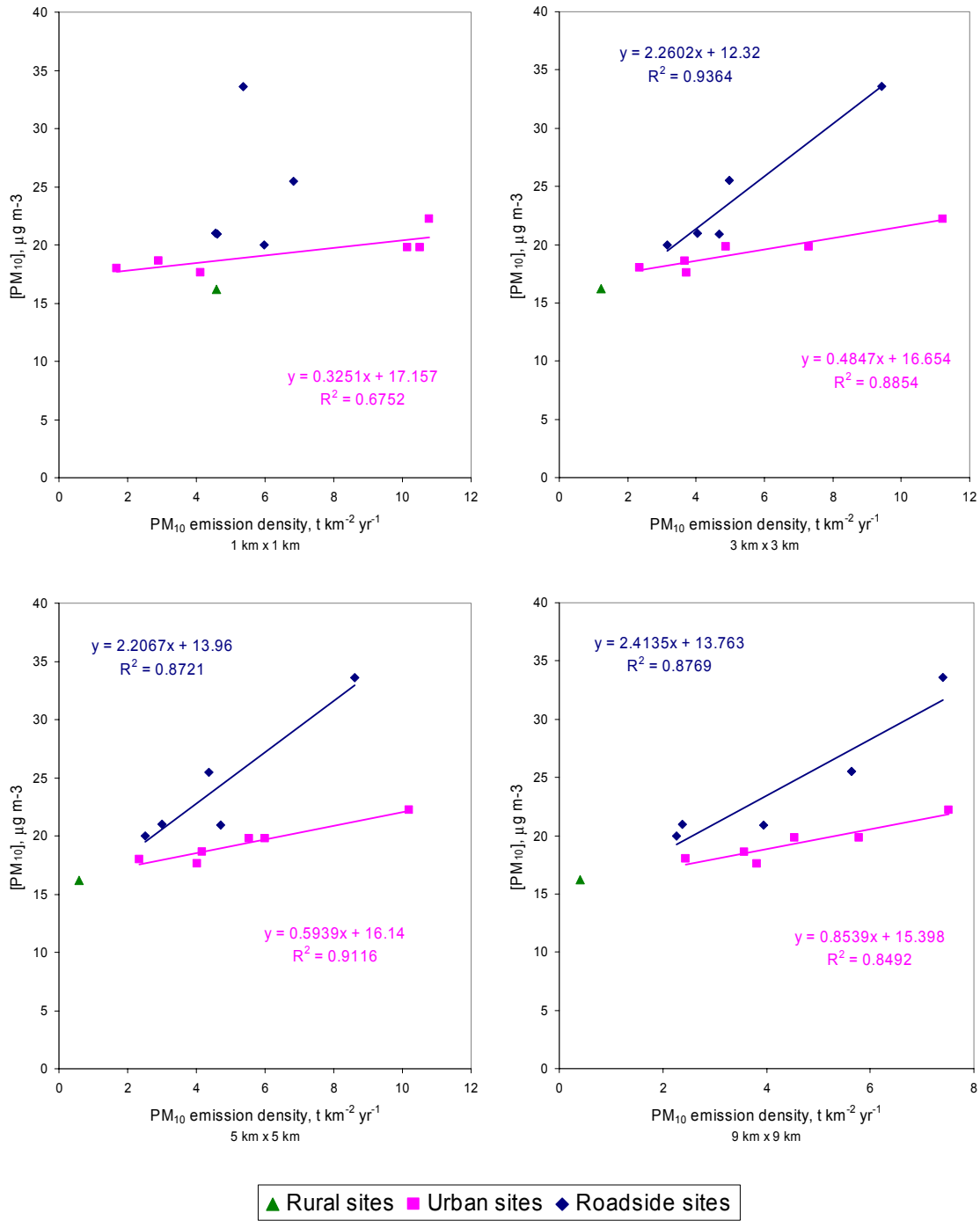


Figure 6.2: Relation between measured PM_{10} concentrations within London and the emission density of PM_{10} from all source sectors. Both the measurement data and the PM_{10} emission inventory are for the year 2001. The different panels show the effect of averaging the PM_{10} emissions over different grid sizes: 1*1 km, 3*3 km, 5*5 km or 9*9 km.

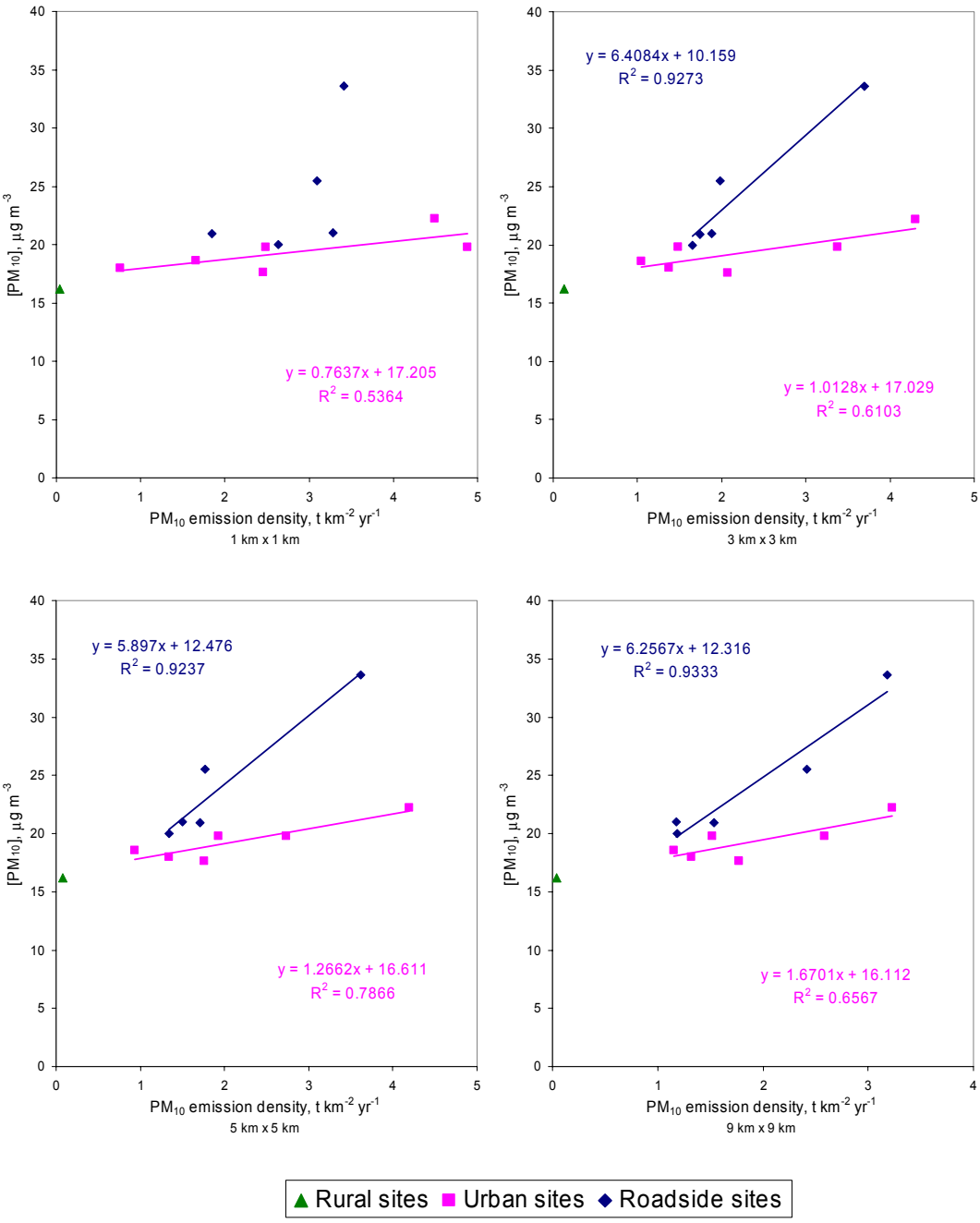


Figure 6.3: Relation between measured PM_{10} concentrations within London and the emission density of PM_{10} from road transport (SNAP1 sector 7). Both the measurement data and the PM_{10} emission inventory are for the year 2001. The different panels show the effect of averaging the PM_{10} emissions over different grid sizes: 1*1 km, 3*3 km, 5*5 km or 9*9 km.

The previous figures examined the urban signal within London itself and suggest a reasonably good correlation with PM_{10} emission density for measurement sites within London. It is interesting to see whether a similar picture emerges for the whole of the UK or whether the spatial variation in rural

background PM_{10} concentrations masks the trend with urban emission density. Figure 6.4 shows the 2001 annual average PM_{10} concentrations at all the available UK monitoring sites as a function of the emission density of PM_{10} from UK road transport.

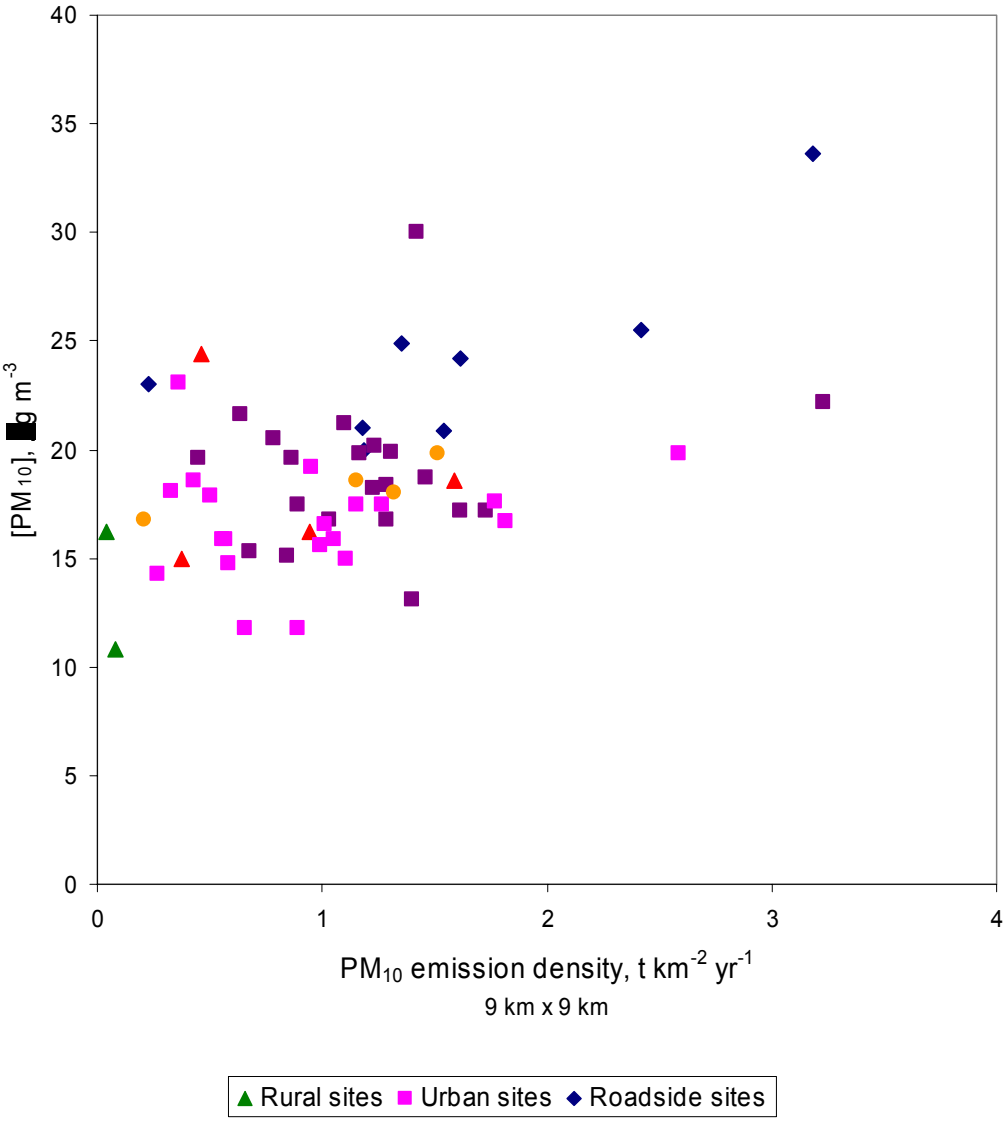


Figure 6.4: Relation between measured PM_{10} concentrations in the UK and the emission density of PM_{10} from road transport (SNAP1 sector 7). Both the measurement data and the PM_{10} emission inventory are for the year 2001.

Although a general trend is apparent in Figure 6.4, the data appear too scattered to allow a satisfactory functional relationship to be developed for an area as large as the UK. Data from smaller areas, *viz.*, 200*200 km and 100*100 km, based on the rural monitoring site closest to London, are shown in Figure 6.5. The correlation between measured PM_{10} concentrations and the

emission density of PM_{10} from road transport is seen to improve as the area investigated is reduced. The measurement station density is, however, insufficient to allow extending this investigation to grid areas of 50*50 km and smaller.

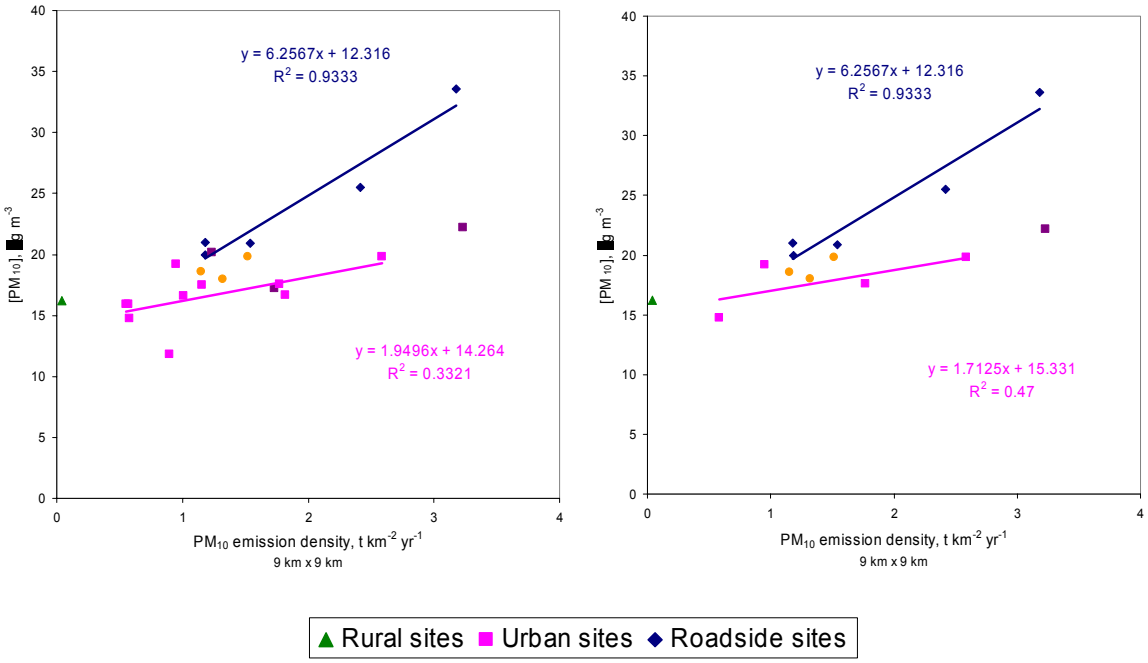


Figure 6.5: Relation between measured PM_{10} concentrations and the emission density of PM_{10} from road transport (SNAP1 sector 7) in the London area. Both the measurement data and the PM_{10} emission inventory are for the year 2001. The panel on the left shows data for an area of 200*200 km; the right-hand figure covers a 100*100 km area.

6.1.2.2 Berlin

Initial analysis of the City-Delta data for Berlin for 1999 generally supports the preliminary findings for London. Figure 6.6 shows the relation between measured PM_{10} concentrations within Berlin and the emission density of PM_{10} from road transport (upper row) and all area sources (lower row) for 1999 data.

Figure 6.7 and Figure 6.8 provide further examples of the PM_{10} concentration/emission density relationship using measurements from 2000 and 2001.

The use of Berlin measurement data for the years 2000 (Figure 6.7) and 2001 (Figure 6.8) has the advantage of providing a greater number of data points for the analysis but with the drawback of an implicit assumption that the PM_{10} emission densities in 2000 and 2001 are similar to those in 1999.

The example plots for Berlin examine the urban PM_{10} signal using different PM_{10} source categories (road transport, road transport + domestic combustion, or all area sources), with the emission densities averaged over a number of different grid areas. On the basis of the results displayed here, it is not possible to identify unequivocally which combination of source sector and averaging area provides the best fit. For Berlin, it seems that each of the combinations examined would give a reasonable basis for a functional relationship.

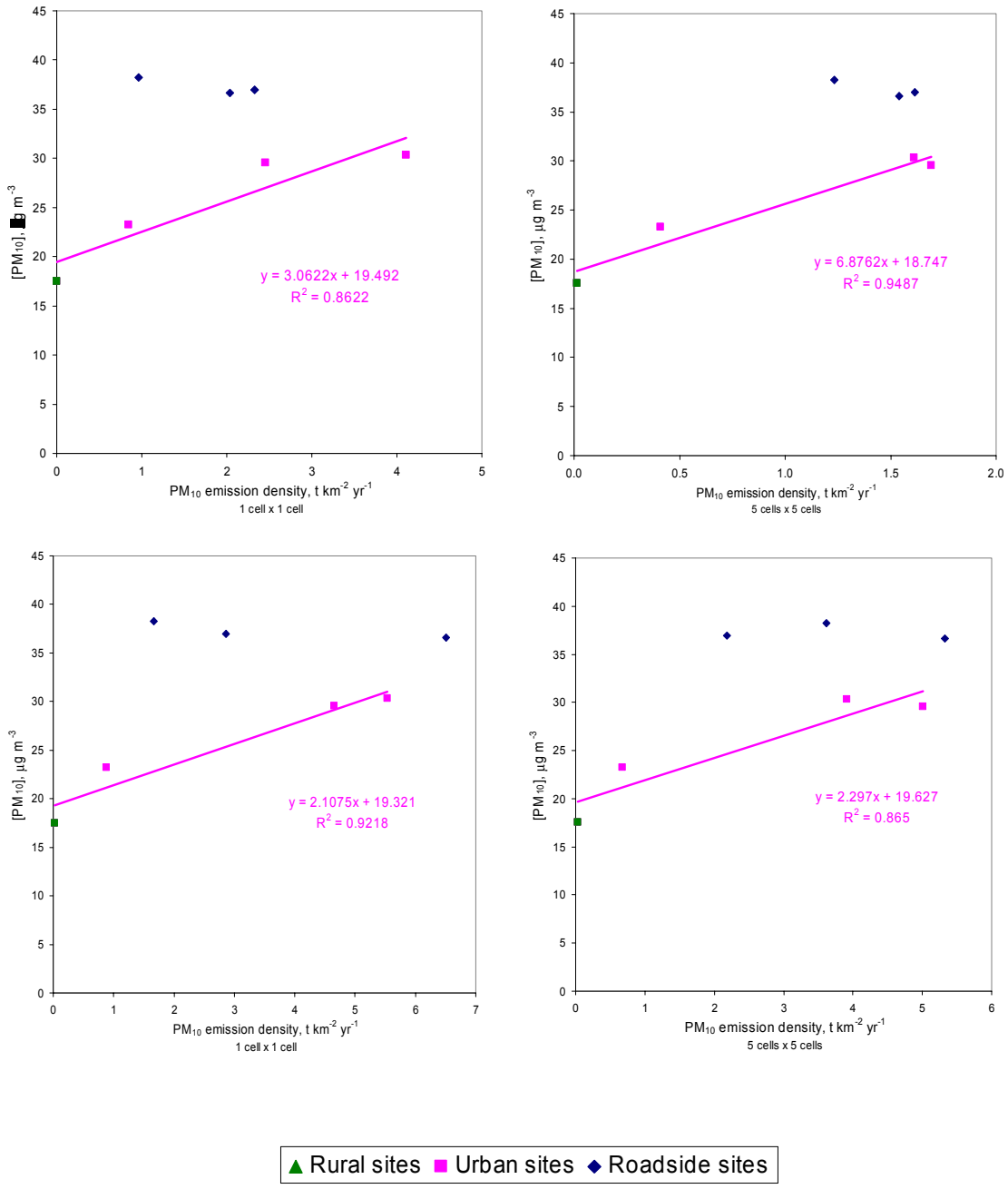


Figure 6.6: Relation between measured PM_{10} concentrations within Berlin and the emission density of PM_{10} from road transport (upper row) and all area sources (lower row). Both the measurement data and the PM_{10} emission inventory are for the year 1999. The different panels show the effect of averaging the PM_{10} emissions over different numbers of grid cells.

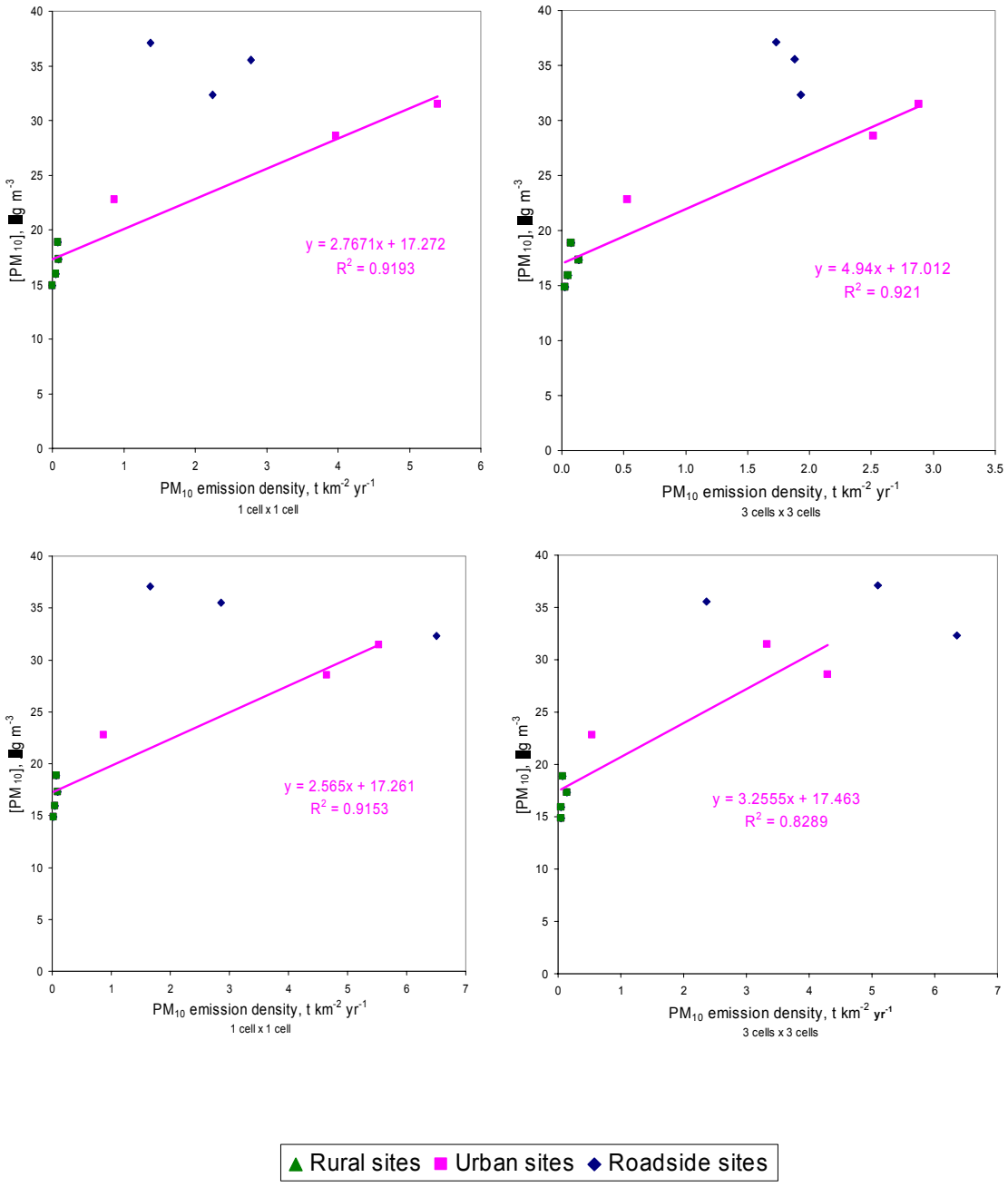


Figure 6.7: Relation between measured PM_{10} concentrations within Berlin and the emission density of PM_{10} from road transport + domestic sources (upper row) and all area sources (lower row). The measurement data in this figure are for the year 2000, the PM_{10} emission inventory is for 1999. The different panels show the effect of averaging the PM_{10} emissions over different numbers of grid cells.

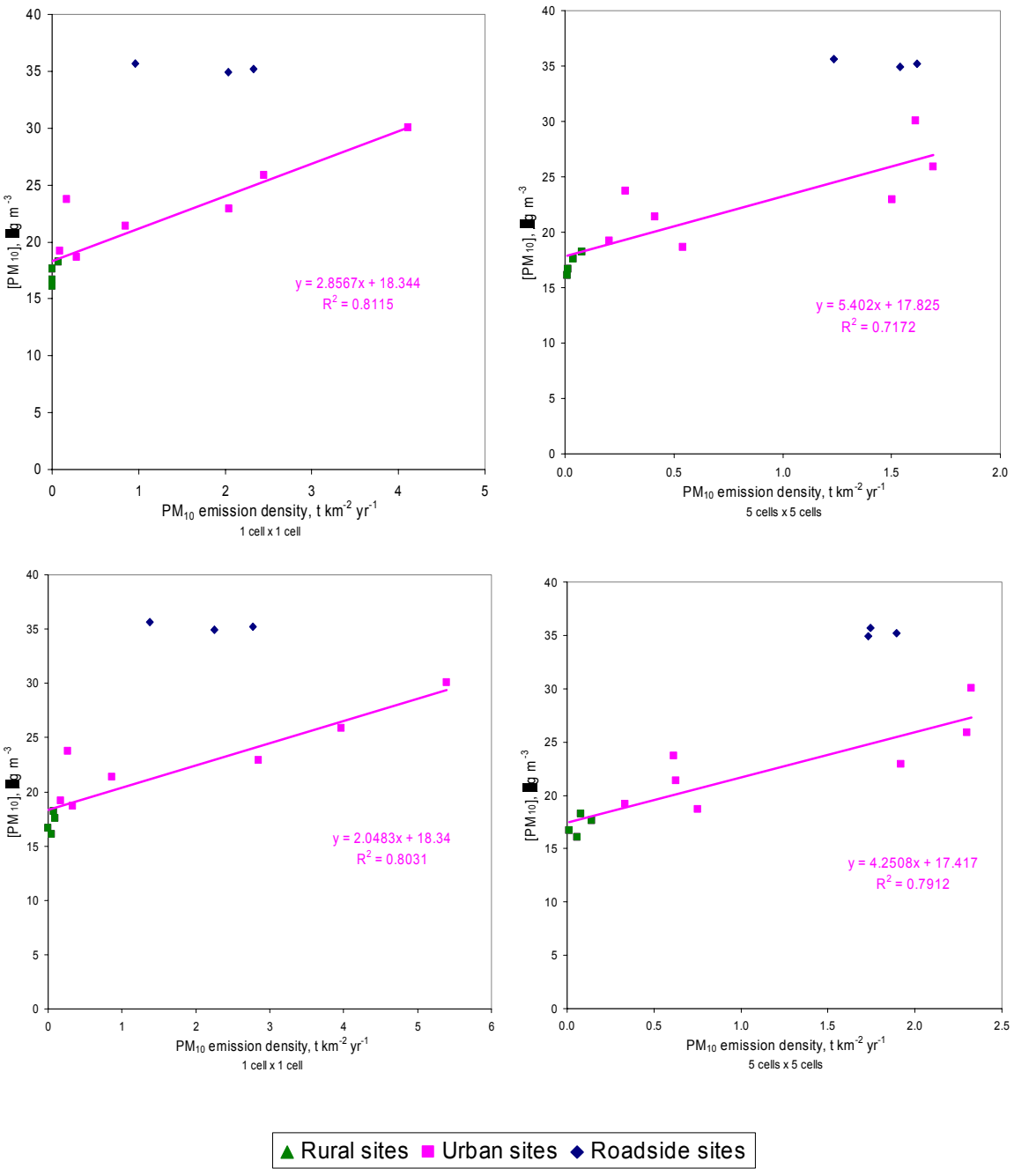


Figure 6.8: Relation between measured PM_{10} concentrations within Berlin and the emission density of PM_{10} from road transport (upper row) and road transport + domestic sources (lower row). The measurement data in this figure are for the year 2001, the PM_{10} emission inventory is for 1999. The different panels show the effect of averaging the PM_{10} emissions over different numbers of grid cells.

6.2 Analysis of model results

Analysis of measurement data in the previous section indicates a clear and possibly simple relationship between the primary PM concentration and the emission density of low level primary PM emissions in a city.

As concluded above, such a relationship can be identified from monitoring data between the urban increment in ambient PM concentrations (compared to a rural background station) and urban emission densities. For the purpose of introducing urban air quality into the RAINS model, such relationships should quantify the difference between urban background concentrations of PM2.5, which are considered as the driving force for the health impact assessment, and the grid average (50*50 km^2) PM2.5 concentration as computed by the regional-scale dispersion model. The regional dispersion model includes the emissions of a city within the grid cell and calculates the resulting grid-average PM2.5 concentrations, in principle by assuming the urban emissions uniformly distributed over the entire grid cell. To compensate for this effect (i.e., to reflect that the regional scale model already includes the urban emissions), the analysis relates the increase in PM2.5 concentrations to the differences between urban (local) and the grid-average emission densities.

For this purpose, the results from the City-Delta model calculations were analyzed to identify the differences between local sub-grid (C_{5x5km}) and grid-average ($C_{Average\ 50x50km}$) PM2.5 concentrations and the difference between local (sub-grid) (E_{5x5km}) and grid-average ($E_{Average\ 50x50km}$) emission densities of low level emission sources:

"C_{5x5km}-$C_{Average\ 50x50km}$"and "E_{5x5km}-$E_{Average\ 50x50km}$"

where:

"C_{5x5km}-$C_{Average\ 50x50km}$" is the difference in concentration between any given 5x5km grid in the 50x50km domain (centred on the city) and the average concentration of all 5x5 grids contained in the 50x50km domain

"E_{5x5km}-$E_{Average\ 50x50km}$" is the difference in emission density (t/km^2) between any given 5x5km grid in the 50x50km domain (centred on the city) and the average emission density of all 5x5 grids contained in the 50x50km domain

These relationships were examined for all modelling results based on the City-Delta model ensemble from each of the three scenarios (Base 2000, 2010CLE and 2020MFR), for the four City-Delta cities (Berlin, Paris, Milano and Prague). Results are displayed in Figure 6.9 to Figure 6.12. Local emission densities were determined for low level sources only, taking into account emissions from the domestic and transport sectors and, in absence of more detailed information, assuming half of the industrial emissions to be emitted from low sources.

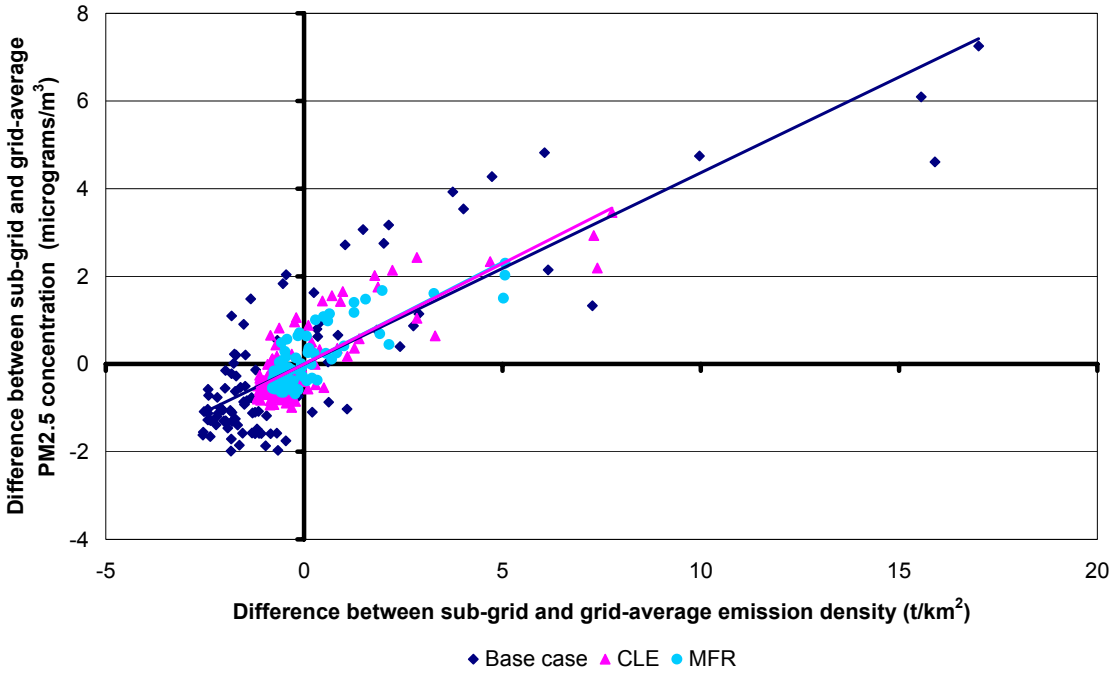


Figure 6.9: Sub-grid variations in annual mean PM2.5 concentrations versus sub-grid variations in emission densities of low sources, for all 5*5 km2 grid cells in the Berlin City-Delta model domain, for the base case and the CLE and MFR scenarios, as computed by the City-Delta model ensemble

Table 6.1: Slopes and correlation coefficients estimated for the different scenarios for Berlin for the results of the City-Delta model ensemble

	Slope	R^2
Base case	0.44	0.70
CLE case	0.46	0.67
MFR case	0.46	0.67
All cases	0.44	0.69

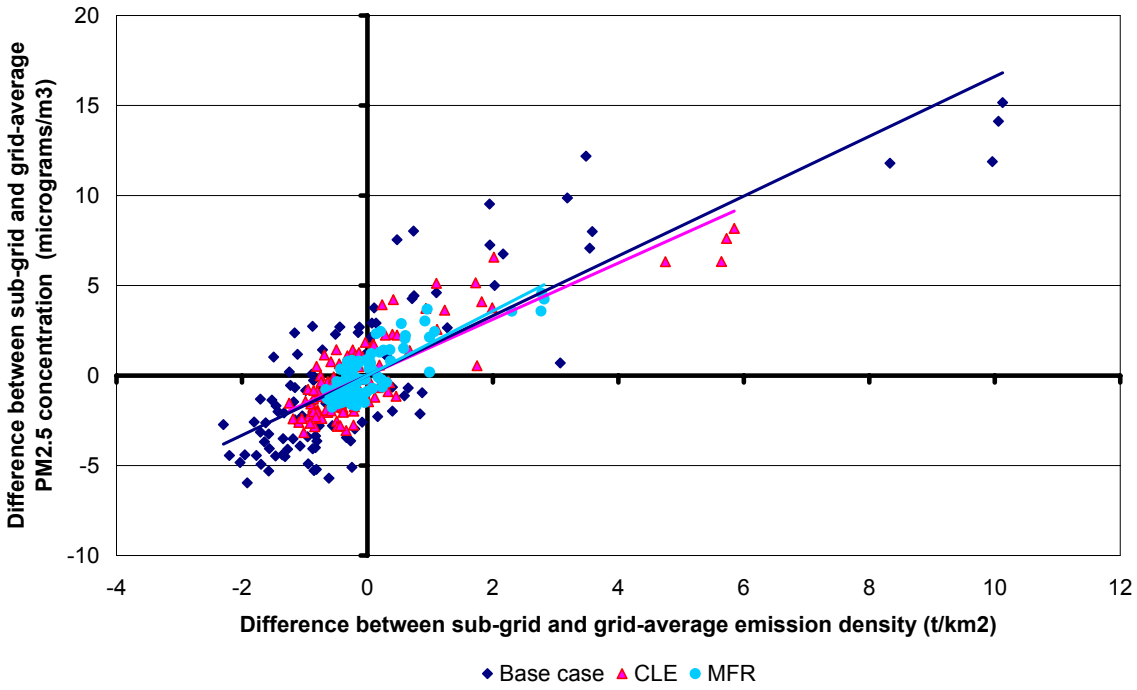


Figure 6.10: Sub-grid variations in annual mean PM2.5 concentrations versus sub-grid variations in emission densities of low sources, for all 5*5 km2 grid cells in the Milano City-Delta model domain, for the base case and the CLE and MFR scenarios, as computed by the City-Delta model ensemble

Table 6.2: Slopes and correlation coefficients estimated for the different scenarios for Milano for the results of the City-Delta model ensemble

	Slope	R^2
Base case	1.66	0.68
CLE case	1.56	0.68
MFR case	1.79	0.67
All cases	1.65	0.68

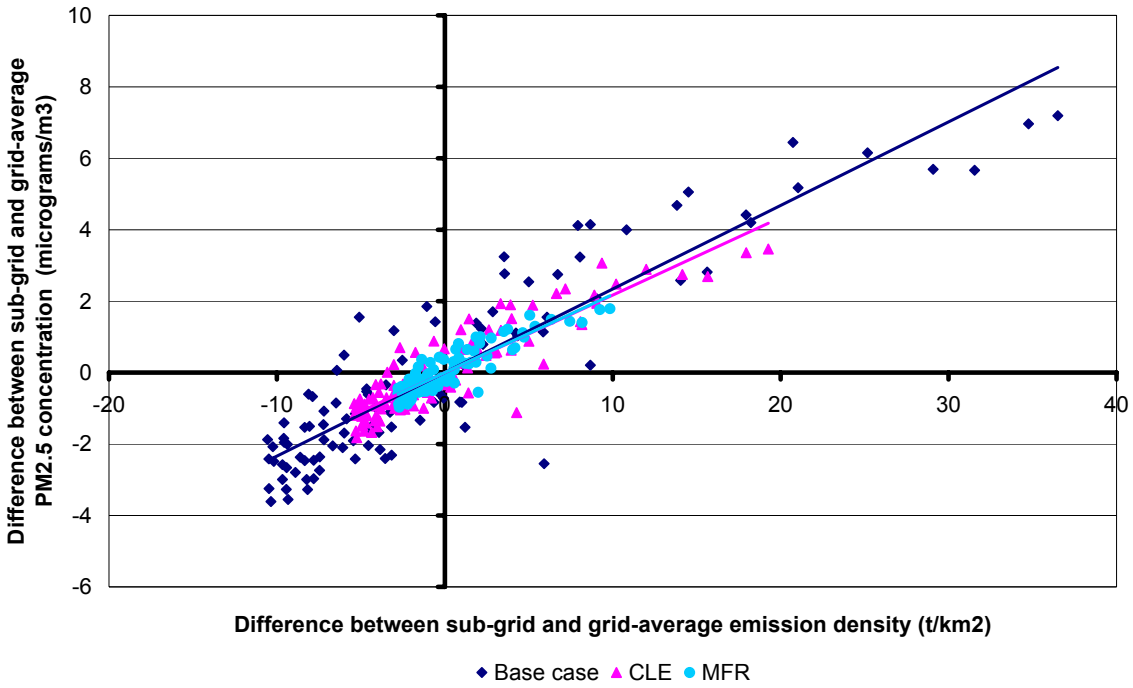


Figure 6.11: Sub-grid variations in annual mean PM2.5 concentrations versus sub-grid variations in emission densities of low sources, for all 5*5 km2 grid cells in the Paris City-Delta model domain, for the base case and the CLE and MFR scenarios, as computed by the City-Delta model ensemble

Table 6.3: Slopes and correlation coefficients estimated for the different scenarios for Paris for the results of the City-Delta model ensemble

	Slope	R^2
Base case	0.234	0.83
CLE case	0.217	0.82
MFR case	0.218	0.82
All cases	0.229	0.82

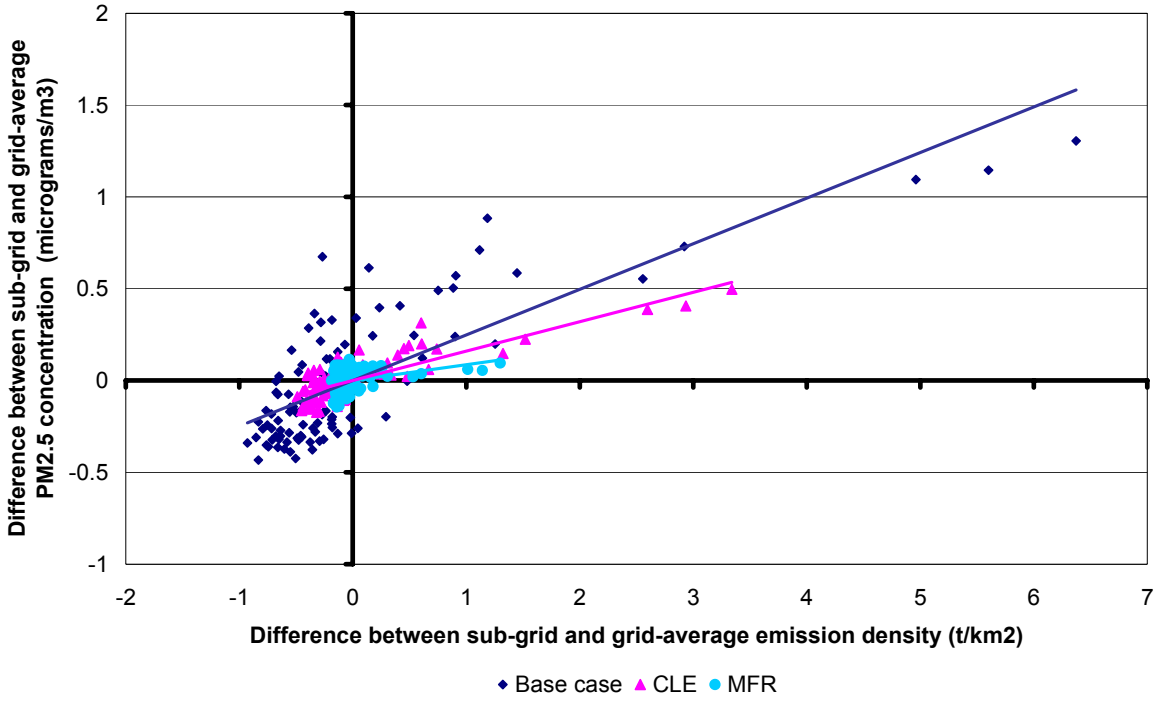


Figure 6.12: Sub-grid variations in annual mean PM2.5 concentrations versus sub-grid variations in emission densities of low sources, for all 5*5 km2 grid cells in the Prague City-Delta model domain, for the base case and the CLE and MFR scenarios, as computed by the City-Delta model ensemble.

Table 6.4: Slopes and correlation coefficients estimated for the different scenarios for Prague for the results of the City-Delta model ensemble

	Slope	R^2
Base case	0.25	0.63
CLE case	0.16	0.69
MFR case	0.09	0.09
All cases	0.22	0.60

The analysis reveals very consistent relationships between local deviations in PM2.5 concentrations from the grid average concentrations and differences in local emission densities. Most strikingly, the slopes of the linear regressions identified for each city appear as rather invariant for the different emission scenarios, suggesting for a given city a robust association between emission density of low level sources and the increment of PM2.5 concentrations almost independent of the absolute level of emissions. If results are approximated by linear regressions, slopes vary for the three considered

emission scenarios by eight to nine percent for Berlin and Paris and by 15 percent for Milano. For Prague, odd results for the maximum feasible reduction scenario need further analysis.

While there are certain variations across cities, these increases can be approximated by linear regressions with correlation coefficients (R^2) between 0.60 and 0.80 (with the exception of the maximum feasible case for Prague). The variation in the quality of the fit can be explained by different influences of large point sources on urban air quality for the four cities considered. If there are large point sources within the city domain (e.g., Prague), urban PM concentrations will follow less closely the distribution of emissions from low level sources than in cities without large point source emissions (e.g., Paris). A better representation of the influence of large point source emissions on the air quality of individual European cities would require detailed information about present (and future) emissions of individual large plants, which is, however, at the moment not generally available for all European cities.

A third finding is that the slopes of the regressions show considerable differences for the four cities (between 0.22 and 1.65), while urban emission densities are rather comparable. Thus, if results from the four cities are pooled together, additional explanatory variables need to be identified to derive a robust and universally applicable functional relationship.

As an exploratory analysis, the slopes obtained from the regression analyses for the four cities were plotted against annual mean wind speeds derived from the meteorological database of the EMEP model for the grid cells in which the cities are located. The hypothesis behind this exercise is that annual mean wind speed should reflect the air exchange of a city, which in turn determines to what extent an urban emission will contribute to ambient concentration in a city before it leaves the city domain. Wind speed in a city is influenced by the synoptic meteorological conditions as well as by the topographic situation of the city, e.g., whether a city is located on flat terrain with good ventilation conditions or in a valley or basin with frequent inversion situations, which inhibit the transport of polluted air out from the city.

The initial analysis presented in Figure 6.13 is based on European wind speed data representative for the main conditions of a 50*50 EMEP grid cell for use in long-range dispersion models and thus not necessarily representative for the wind speed within individual cities (some of which are located in valleys, e.g., Prague). However, a general relationship can be detected especially when the wind speeds for the cities were adjusted through interpolation with data from neighbouring EMEP grid cells (blue dots in Figure 6.13). Such adjustment recognizes that the footprint of the EMEP grid does not match the foot print of the 50x50km domain of the fine scale modelling (centred on the city) that was used to develop the individual city slopes. In no case was the wind speed adjusted more than 15 percent. Obviously, the analysis presented in this figure has to be considered as preliminary, since it is only based on data for four cities and relies on large-scale wind speed data.

However, until further data on local wind speeds become available, the exploratory analysis applies the 'adjusted' relationships for the further analysis.

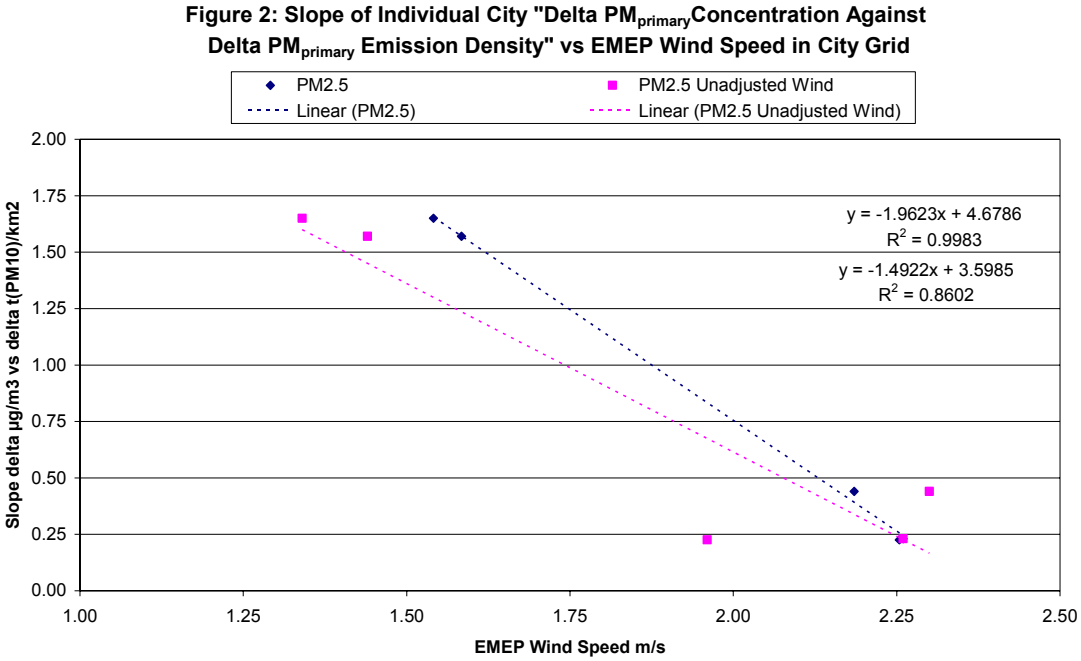


Figure 6.13: Slopes of urban increments in PM concentrations versus the annual mean wind speed extracted from the EMEP meteorological data for the 50*50 km grid cell in which the city is located

6.3 Functional relationships for the RAINS model

With the relationships identified above, it becomes possible to estimate urban background concentrations of PM2.5 in the RAINS model. This assessment starts from the grid average PM2.5 concentration estimated by the regional-scale EMEP dispersion model and adjusts these values by urban emission densities and urban wind speed data:

$$\Delta PM_{sub\text{-}grid} = (ED_{sub\text{-}grid} - ED_{EMEP}) * (k1 - k2*V_{wind}) \quad \text{Equation 6.1}$$

with

$\Delta PM_{sub\text{-}grid}$ .. Difference in PM concentration between sub-grid (urban/rural) area and average of the EMEP grid cell

ED_x ... Emission density for low sources (x=urban/rural/EMEP grid average)

V_{wind} … Annual mean wind speed

k1, k2 … Parameters derived from the City-Delta ensemble model

Emission densities are readily available for the EMEP grid cells as they establish one input to the EMEP dispersion model calculations, but due to the lack of urban emission inventories for most of the European cities they are generally unavailable for individual cities. Thus, the RAINS model calculates urban emission densities (for a given emission control scenario) based on the fundamental assumption that the spatial distribution of low level sources follows to a large extent the population densities:

$$ED_{sub\text{-}grid} = E_{sub\text{-}grid} / A_{sub\text{-}grid} = \quad \text{Equation 6.2}$$
$$= E_{EMEP} * (P_{sub\text{-}grid} / P_{EMEP}) / A_{sub\text{-}grid} =$$
$$= E_{EMEP} * (P_{sub\text{-}grid} / P_{EMEP}) * (A_{EMEP} / A_{EMEP}) / A_{sub\text{-}grid} =$$
$$= ED_{EMEP} * (PD_{sub\text{-}grid} / PD_{EMEP})$$

with

E_x ... Emissions (x=urban/rural/EMEP grid average)

P_x … Population (x=urban/rural/EMEP grid average)

PD_x … Population density (x=urban/rural/EMEP grid average)

A_x … Area (x=urban/rural/average over EMEP grid cell).

With this relation, the sub-grid emission density in Equation 6.1 can be expressed as

$$ED_{sub\text{-}grid} = ED_{EMEP} * (PD_{sub\text{-}grid} / PD_{EMEP}), \quad \text{Equation 6.3}$$

so that Equation 6.1 emerges as

$$\Delta PM_{sub\text{-}grid} = (ED_{sub\text{-}grid} - ED_{EMEP}) * (k1 - k2*V_{wind}) =$$
$$= (ED_{EMEP} * (PD_{sub\text{-}grid} / PD_{EMEP}) - ED_{EMEP}) * (k1 - k2*V_{wind}) =$$
$$= ED_{EMEP} * (PD_{sub\text{-}grid} / PD_{EMEP} - 1) * (k1 - k2*V_{wind}) \quad \text{Equation 6.4}$$

Thus, calculation of urban emission densities, while scenario-specific, requires the following input data:

- Emission densities of low level sources in an EMEP cell (for a given emission control scenario)
- Population densities in the urban and rural areas of an EMEP grid cell
- Annual mean wind speed in an EMEP grid cell – or eventually within the city.

With this, Equation 6.1 to compute the urban increment of PM turns into the following formulation, which can be readily included in the RAINS model:

$$\Delta PM_{sub\text{-}grid} = ED_{EMEP} * (PD_{sub\text{-}grid} / PD_{EMEP} - 1) * (k1 - k2 * V_{wind}) \qquad \text{Equation 6.5}$$

This formulation takes the gridded sectoral primary PM2.5 emissions for low-level sources from EMEP for 2000 as a starting point (i.e., transport (SNAP7), domestic (SNAP2), and 50 % of industry (SNAP3)) and scales for an emission control scenario the gridded sector emissions of 2000 using the country-wide sectoral change in emissions.

6.4 Input data to the RAINS calculations

Equation 6.5 is implemented in the RAINS model to compute the urban increment in PM2.5 concentrations, using additional information on

- Emission densities for low-level sources,
- Share of urban population in each EMEP grid cell
- Annual mean wind speeds.

Emission densities of low-level sources for the year 2000 are directly extracted from the emission inventory used as input to the EMEP model, which is available in gridded form distinguishing 11 SNAP sectors. For low level sources in urban areas, emissions of SNAP sector 7 (Transport), SNAP sector 2 (Domestic) and 50 percent of the emissions of SNAP sector 3 (Industry) are considered. For future emission control scenarios, emission data for the year 2000 (Figure 6.14) are scaled at a sectoral level by the changes of sectoral emissions occurring in the country for that scenario.

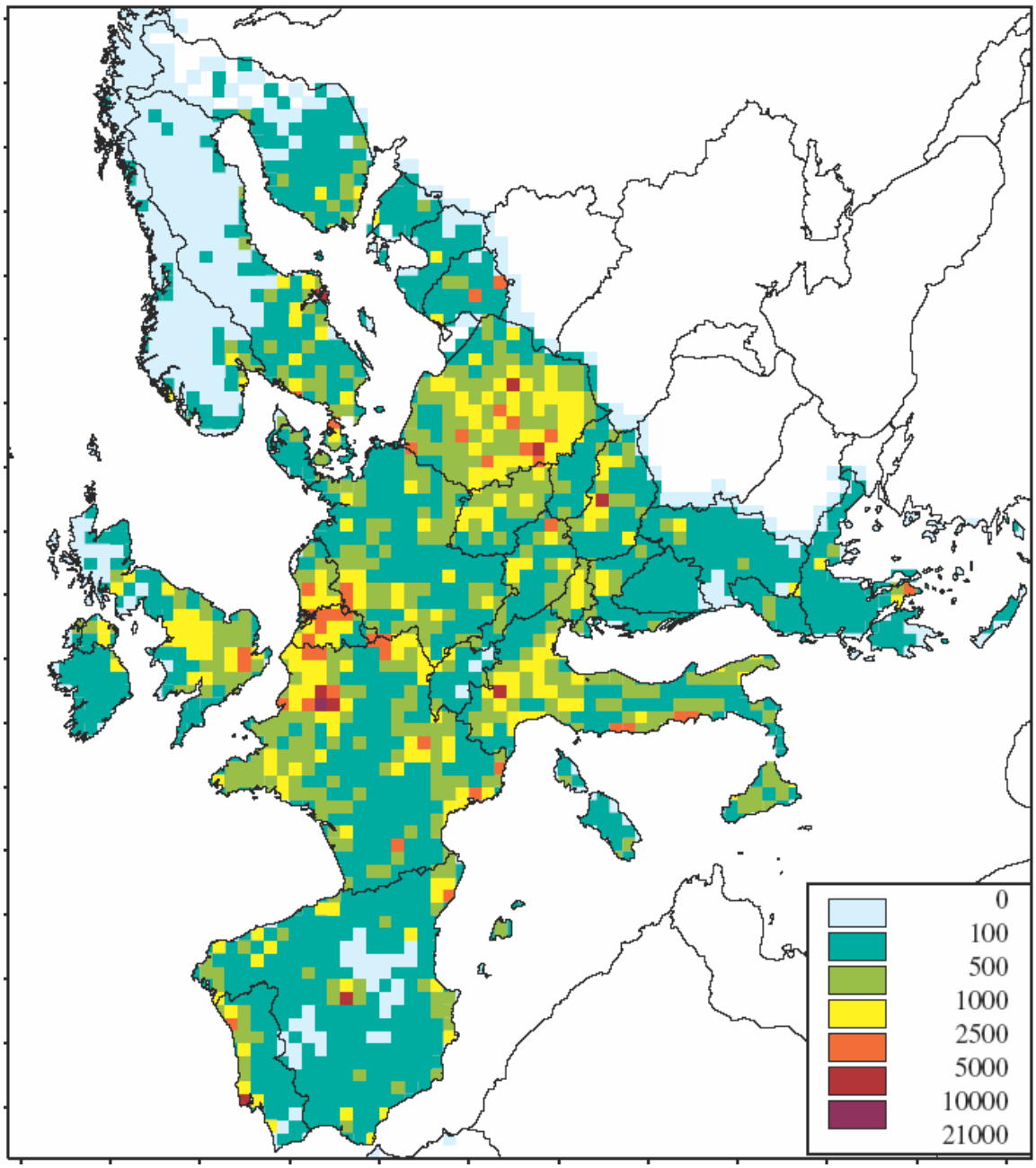


Figure 6.14: Density of primary PM2.5 emissions from low-level sources for the year 2000 (in tons/km^2) as used as input to the EMEP model calculations

In addition, RAINS calculations require as a grid-specific input the ratio of urban population densities over the population density of the entire grid cell ($PD_{sub\text{-}grid} / PD_{EMEP}$ in Equation 6.5) to reflect situations that emissions are not uniformly distributed within a grid cell, but are concentrated in the urban areas, which might constitute only a small fraction of the entire grid cell area. For large cities, which cover a full 50*50 km^2 grid cell (e.g., London), this ratio turns into one, indicating that there is no sub-grid variation between urban and rural areas within the grid cell. To determine these ratios, population and land use data from the LANDSCAN (2000) database have been used and processed with a geographical information system to derive these grid-specific parameters (Figure 6.15). These ratios are particularly high in small cities surrounded by unpopulated area.

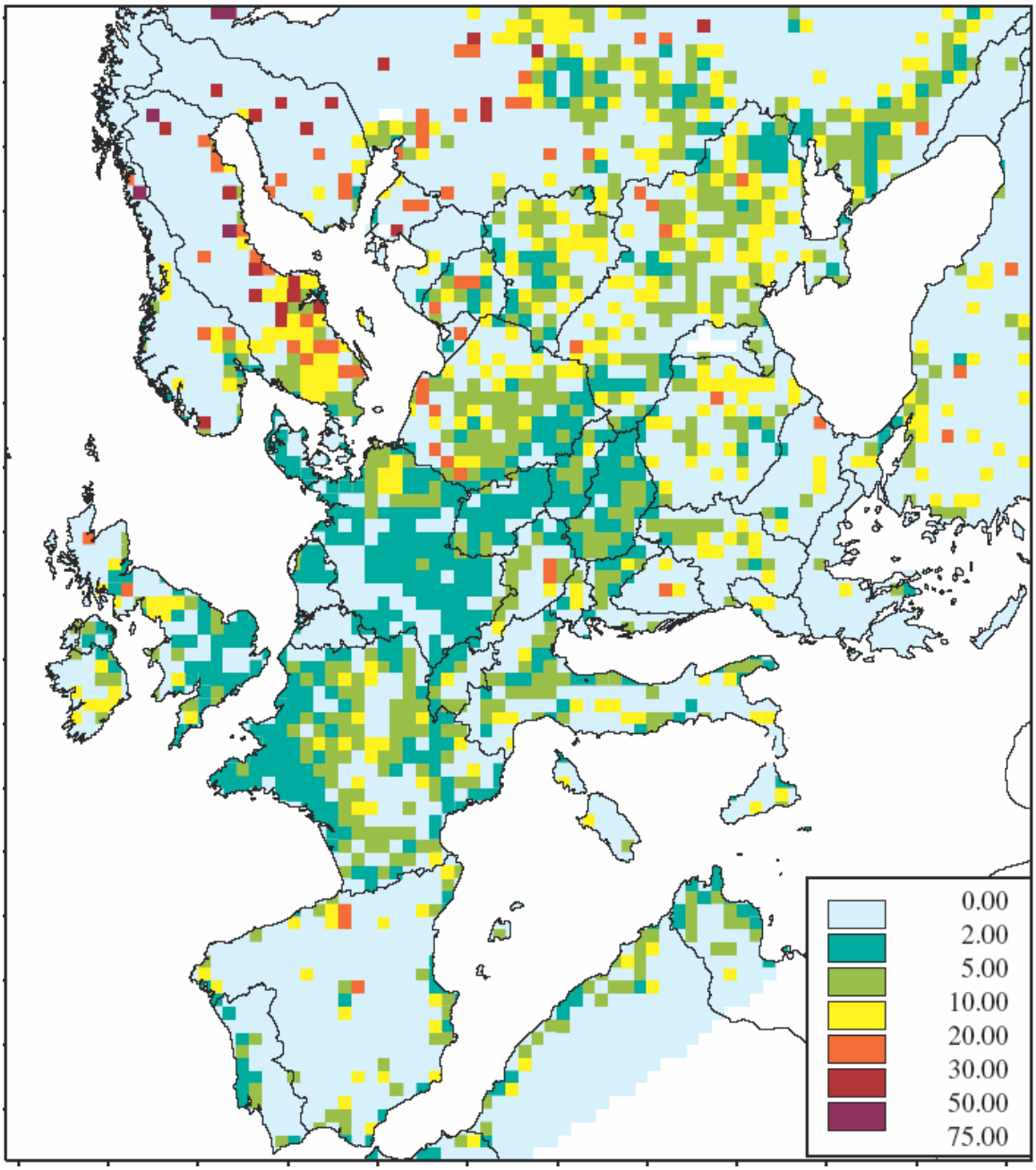


Figure 6.15: Ratio of urban population densities over the population density of the entire grid cell ($PD_{sub\text{-}grid} / PD_{EMEP}$ *in* Equation 6.5)

As a third element, Equation 6.5 considers wind speed to determine the urban increments of PM2.5 concentrations. The present implementation of the functional relationships rely on the wind speed data contained in the EMEP meteorological database, which reflect large scale grid-average wind conditions that are appropriate for modelling of the atmospheric long-range transport. As discussed above, this data set might not be representative for the conditions within urban areas and should be replaced by more appropriate data in the future.

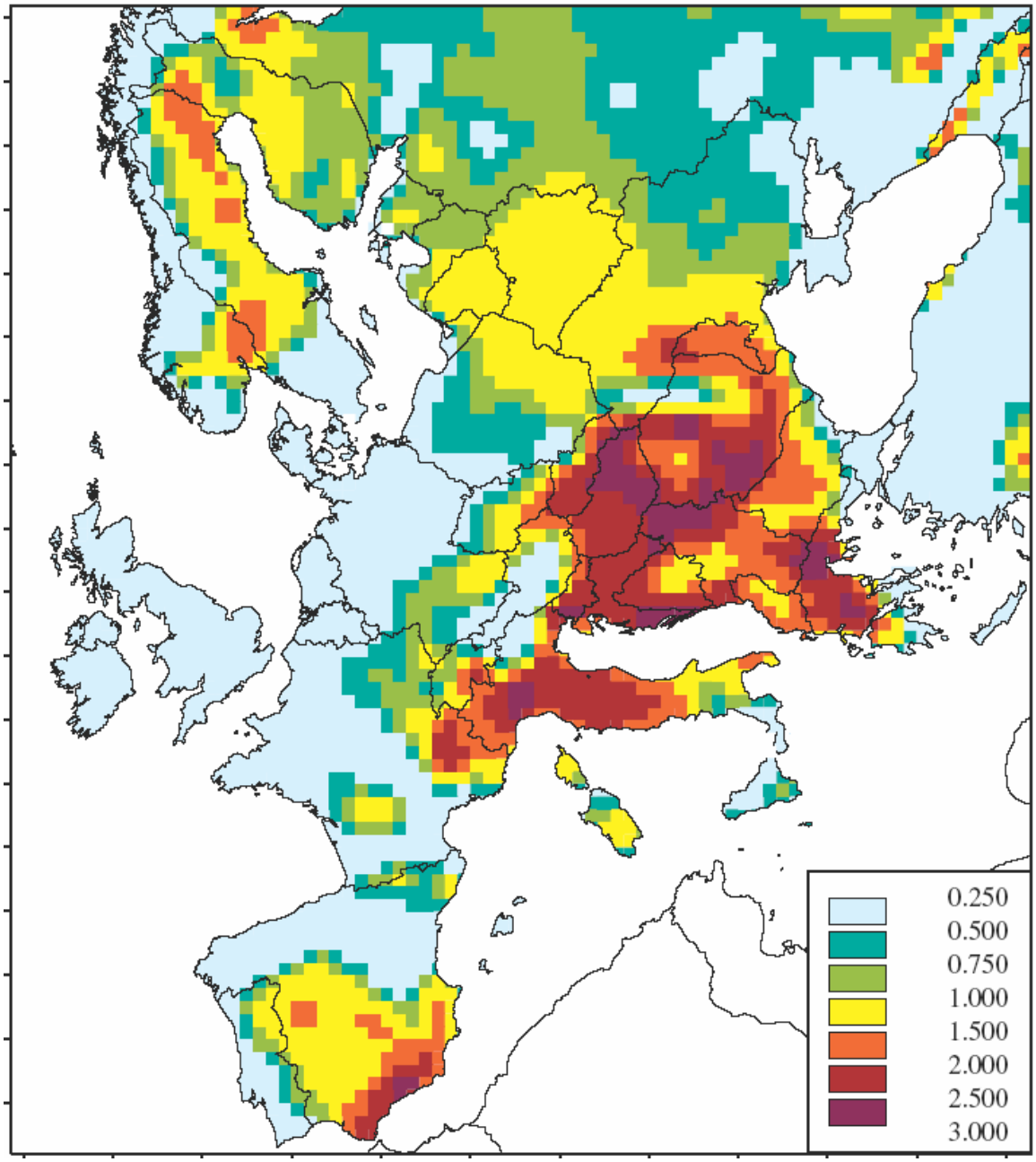


Figure 6.16: The wind-speed dependent term *(k1 - k2*V_{wind})* in Equation 6.5, based on wind speed data from the EMEP Eulerian model. High values of this term indicate stagnant conditions, low values correspond to high wind speeds.

6.5 Preliminary results

With these data, the urban increments to annual mean PM2.5 concentrations in urban areas resulting from urban emissions on top of the concentrations computed by the regional scale (50*50 km^2) dispersion calculations have been calculated according to Equation 6.5. As shown in Figure 6.17, large increments occur in Mediterranean and Nordic cities, while increments in central Europe are

lower. While such large increments in Mediterranean and Nordic cities are confirmed by the sparse observational data, the lower values computed for central Europe, especially for Germany, need further analysis. A number of aspects are of relevance:

- Some of the large European cities in this region (e.g., London, Paris) extend over one or several entire EMEP grid cells, and are thus (at least in theory) already fully captured by the regional scale model with its 50*50 km^2 resolution.
- In densely populated areas (e.g., in the Benelux region) there are only low spatial differences in population densities between urban and the surrounding rural areas. Consequently, there is also very little difference in PM2.5 concentration. This is confirmed, e.g., by the Belgian measurements for the twin sites of Gent and Wassemunster as reported in Puteaud *et al.* (2002). Also PM2.5 measurements in various cities of Northrine-Westfalia (Germany) show very little variation (see http://www.lua.nrw.de/).
- The preliminary calculations rely on EMEP grid average wind speeds, which might not be representative for cities, especially when they are located in valleys and basins. While in the northern part of Central Europe high wind speeds dominate at the large scale, the employed data set might miss conditions for individual cities. Work continues to acquire a more appropriate data set for this analysis.
- Some uncertainty is introduced by the population density related term in Equation 6.5. At present, data are extracted from the LANDSCAN dataset, which derives land use and population data for administrative units. While differences between urban and rural population densities might indeed be small for many German areas, the spatial definitions of the administrative units ("Landkreise") underlying the data set might dilute existing differences. Further work will be necessary to compile a revised data set with a sharper distinction between urban and rural areas.

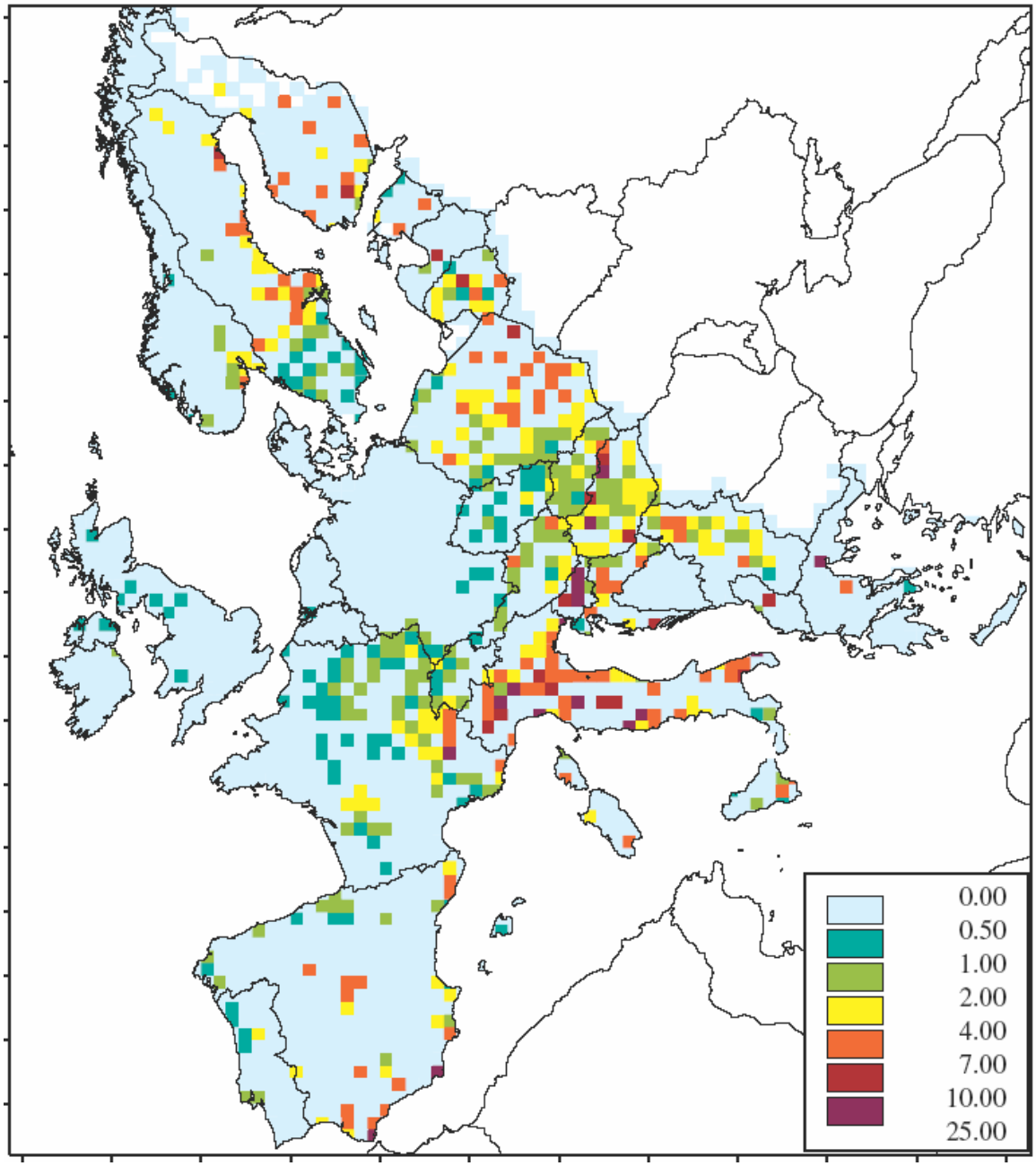


Figure 6.17: The urban increment of PM2.5 (in µg/m^3, annual mean concentrations) calculated with the functional relationship for the year 2000. These urban increments are additional to the concentrations computed by the regional scale calculations of the EMEP model using the 50*50 km spatial resolution.

To compute total PM2.5 concentrations in urban areas, the urban increment as displayed in Figure 6.17 needs to be complemented by the grid average PM2.5 concentrations as computed by the regional scale EMEP dispersion model (Figure 6.18). It is important to mention that these calculations include the contribution from primary emissions of PM2.5 from anthropogenic sources

and from secondary inorganic aerosols, but they exclude the contributions from natural emissions and from secondary organic aerosols. As shown in the graph, some of the largest cities (e.g., Paris, Katowicze, Lyon, Marseille, Athens, the London conurbation, etc.) are directly visible in the regional scale calculations, since they extend over entire EMEP grid cells. In such situations, the urban (sub-grid) increment computed by the functional relationships will be low.

It is also important to mention that some other large cities (e.g., Berlin), which are more isolated surrounded by areas with relatively low population and emission densities, do neither show up in the regional scale calculations nor in the computations of the urban increment. This is caused by the fact that a number of cities is exactly located at the borderlines of the EMEP grid system and thus fall into two or four EMEP grid cells. The logic of the regional scale calculations considers in such situation only the respective share of emissions in each grid cell and assumes that to be evenly distributed over the entire area. Thus, as is the situation for e.g., Prague, the urban emissions, while located in reality in an area of approximately 15*15 km^2, are smeared out over four grid cells, i.e., over 100*100 km^2), and thus are not seen any more for the regional model as a city. The same applies to the functional relationships, which are presently constructed under the assumptions that a city is located in the centre of a 50*50 km^2 grid cell. A further refinement of the methodology will be necessary to address these specific situations in a more accurate way.

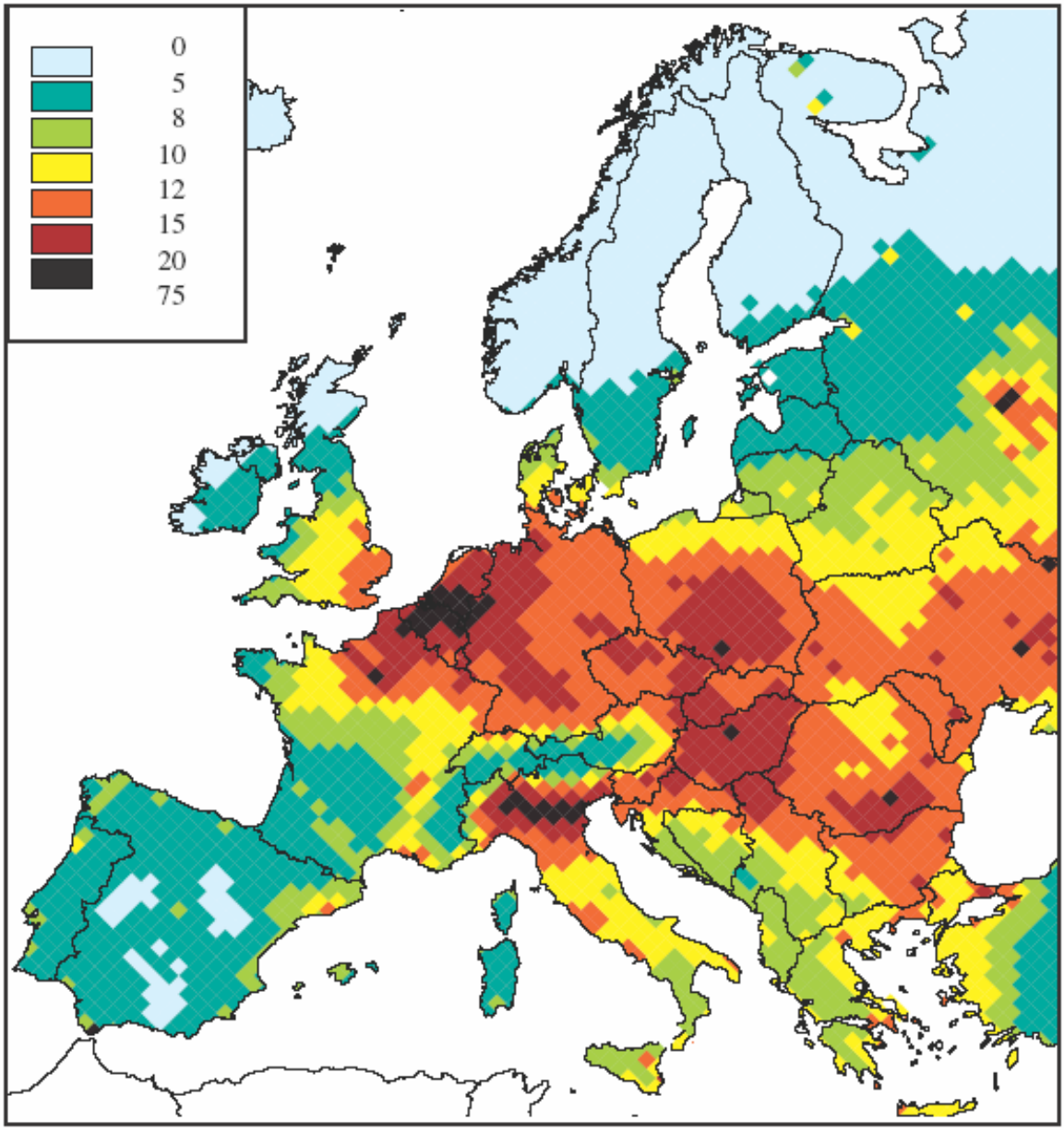


Figure 6.18: Grid-average annual mean PM2.5 concentrations as computed by the EMEP Eulerian model with the 50*50 km2 spatial resolution. This includes contributions to PM2.5 from anthropogenic primary PM emissions and from secondary inorganic aerosols, but does not account for PM2.5 from natural sources and from secondary organic aerosols.

6.5.1 Comparison with monitoring data

To validate the approach, the results obtained from the functional relationships together with the outcome of the regional scale calculations have been compared with monitoring data. Unfortunately, there are very few quality-controlled observations of PM2.5 concentrations available

that could be used for this exercise. For the validation of City-Delta2, the following datasets have been used:

- Puteaud et al., 2002, providing data from research stations for a number of European locations
- Landesumweltamt Essen (2004), on-line data on PM2.5 for Northrine-Westfalia (Germany)
- Puxbaum et al. (2004) PM2.5 data from the AUFHEP project for four Austrian monitoring sites
- The PM position paper (EC, 2004)
- Rouil et al. (2002) Data from French monitoring stations (personal communication)
- Data from the ECHRS-II study for 21 European cities (Kuenzli et al., 2004)
- Two Swiss stations (Gehrig et al., 2003)
- Helsinki Metropolitan Council's air quality monitoring data and Laakso et al. (2003)
- Data for Milano (Vecchi et al., 2004)

In total, annual mean concentrations of PM2.5 could be established for 45 urban background stations. Additional data are available for stations at street canyons, but they should not be used for comparison with the City-Delta calculations aimed at urban background pollution.

These observational data were compared with the results from the City-Delta calculations, considering the component calculated by the regional-scale EMEP model and the urban increment as described above. Since neither the regional scale model nor the urban increment include PM2.5 from natural sources, a certain allowance has been made to account for their contribution. As a rough estimate, the natural contribution from mineral dust was assumed at 3 $\mu g/m^3$ in the Mediterranean countries (based on the chemical analysis of Spanish monitoring data by Querol et al. (2003). For Scandinavia, a contribution of 1 µg/m3 was assumed, based on data reported in EC (2004). For all other countries, 2 $\mu g/m^3$ were assumed, which is supported, e.g., by the chemical analyses presented in Puxbaum et al. (2003) for Austria and in EC (2004) for the UK. Lack of information did not allow making assumptions on the contribution of secondary organic aerosols, both from natural and anthropogenic sources. In addition, primary organic aerosols from natural sources are not included in this estimate. While most monitoring results have been obtained with gravitational methods, a number of stations applied TEOMs or beta-absorption techniques to measure PM2.5 concentrations. To correct for a potential systematic bias in the resulting observations, a factor of 1.3 was applied, and both results are indicated in the graph.

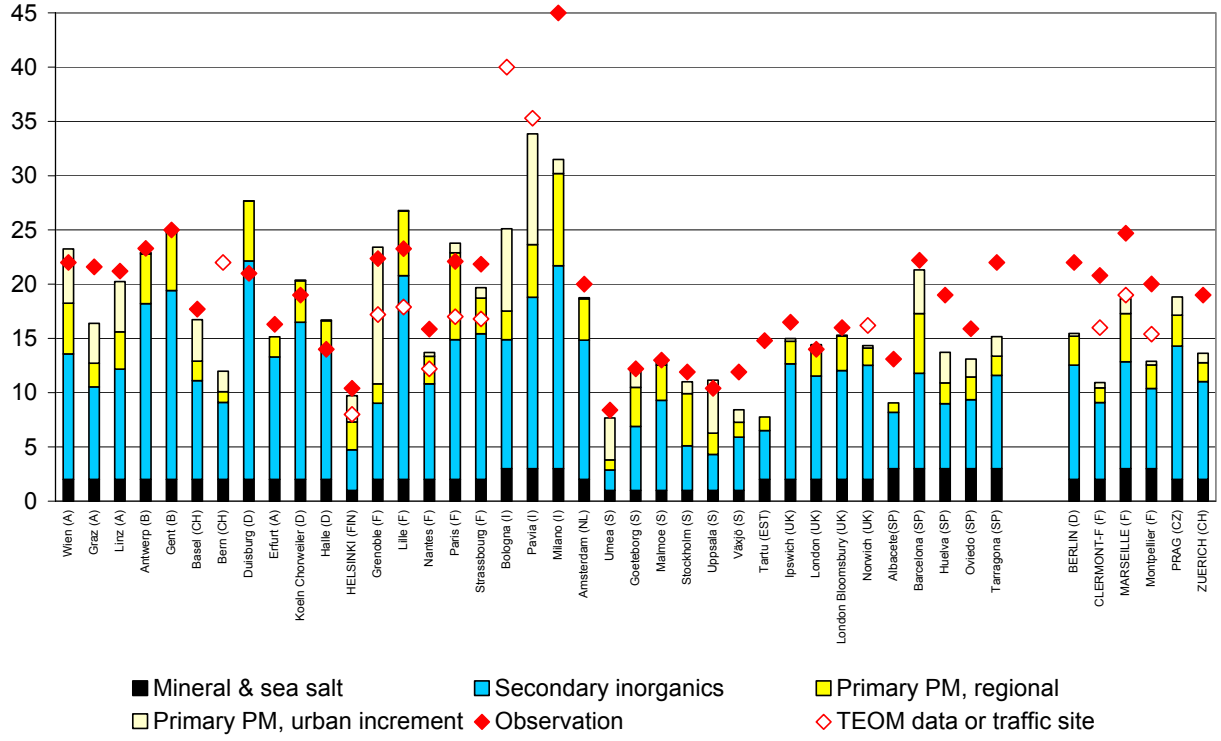


Figure 6.19: Comparison of calculated contributions to annual mean PM2.5 concentrations with observations (in µg/m^3)

The results of the comparison are presented in Figure 6.19 for two groups of cities: (i) cities, which are located entirely within one EMEP grid cell (left block), and (ii) cities, which extend over two or four grid cells (right block).

For cities, which are fully inside one EMEP grid cell, the model results (with the assumptions made on the contribution of mineral and sea salt) reproduce in most cases rather well the observations and especially their geographic variation over Europe. Systematic underestimates are detected for cities located in valleys or basins (e.g., Graz, Bern, etc.), where the wind speed data used for this initial analysis are not representative for the urban areas. There is a serious underestimate between 3 and 7 µg/m^3 for all Spanish cities (except Barcelona), which cannot be readily explained. Also for Italian stations model estimates systematically underestimate the observations. Possibly the omission of organic aerosols (from natural and anthropogenic sources) could make the largest difference in Spain, but this needs further analysis with chemically decomposed observational data.

The figure clearly indicates that the functional relationships add rather different amounts to the results of the regional scale calculations, ranging from nil, e.g., in the Benelux region, to 10 and more µg/m^3 in Padua and Grenoble. However, in all cases these computed urban increments yield a systematic and significant improvement of the model estimates across all European stations.

The second group of stations is located in cities, which reside within more than one EMEP grid cell. As explained above, the applied methodology for systematic reasons will under-predict observed concentrations, as is indeed confirmed in Figure 6.19. Further work will be necessary to adapt the modelling approach to account for such situations.

7 Implementation in the RAINS model

The City-Delta methodology as outlined above has been implemented in the RAINS model and used for the scenario analysis for the CAFE Working Group on Target Setting and Policy Advice. With the improved estimate of urban air quality, the RAINS model can then quantify the loss in life expectancy that is attributable to the human exposure towards PM2.5 in urban background air. Illustrative results of these calculations are provided in Table 7.1. These calculations are carried out for each 50*50 km cell of the EMEP grid system for rural populations, and applying the urban increment computed along the City-Delta approach to estimate the additional pollution burden to which urban population is exposed.

Following this approach, the RAINS model has been applied to explore the cost-effectiveness of further emission control measures. Figure 7.1 displays the losses in life expectancy, calculated on a grid basis for the urban and rural population, for the CAFE baseline projection for the year 2020 and for three selected scenarios for further emission controls.

Table 7.1: Loss in statistical life expectancy attributable to the exposure to PM2.5 from anthropogenic emissions of primary PM and secondary inorganic aerosols (in months).

	Baseline 2020	**25% gap closure A1/1**	**50% gap closure A1/2**	**75% gap closure A1/3**	**MTFR 2020 excl. Euro5/6**
Austria	4.9	4.5	4.1	3.7	3.3
Belgium	8.9	8.3	7.7	7.1	6.6
Cyprus	*)	*)	*)	*)	*)
Czech Rep.	5.7	5.2	4.7	4.2	3.7
Denmark	4.5	4.2	3.9	3.6	3.2
Estonia	2.8	2.6	2.5	2.3	2.2
Finland	2.0	1.9	1.8	1.7	1.7
France	5.4	4.9	4.5	4.1	3.7
Germany	6.5	5.9	5.4	4.9	4.4
Greece	4.9	4.8	4.6	4.5	4.4
Hungary	7.4	6.5	5.7	5.4	4.8
Ireland	2.9	2.6	2.4	2.2	2.0
Italy	5.0	4.6	4.2	3.9	3.7
Latvia	3.3	3.1	2.9	2.7	2.5
Lithuania	4.4	4.1	3.8	3.6	3.3
Luxembourg	6.8	6.1	5.5	4.9	4.3
Malta	5.7	5.6	5.4	5.3	5.2
Netherlands	8.6	7.9	7.3	6.7	6.1
Poland	6.4	5.9	5.4	5.0	4.6
Portugal	3.0	2.8	2.5	2.3	2.1
Slovakia	6.3	5.6	5.1	4.6	4.1
Slovenia	5.6	5.2	4.7	4.3	3.8
Spain	2.9	2.7	2.5	2.4	2.2
Sweden	2.6	2.4	2.2	2.1	1.9
UK	4.6	4.2	3.8	3.4	3.0
EU-25	5.3	4.9	4.5	4.1	3.8

*) will be supplied later

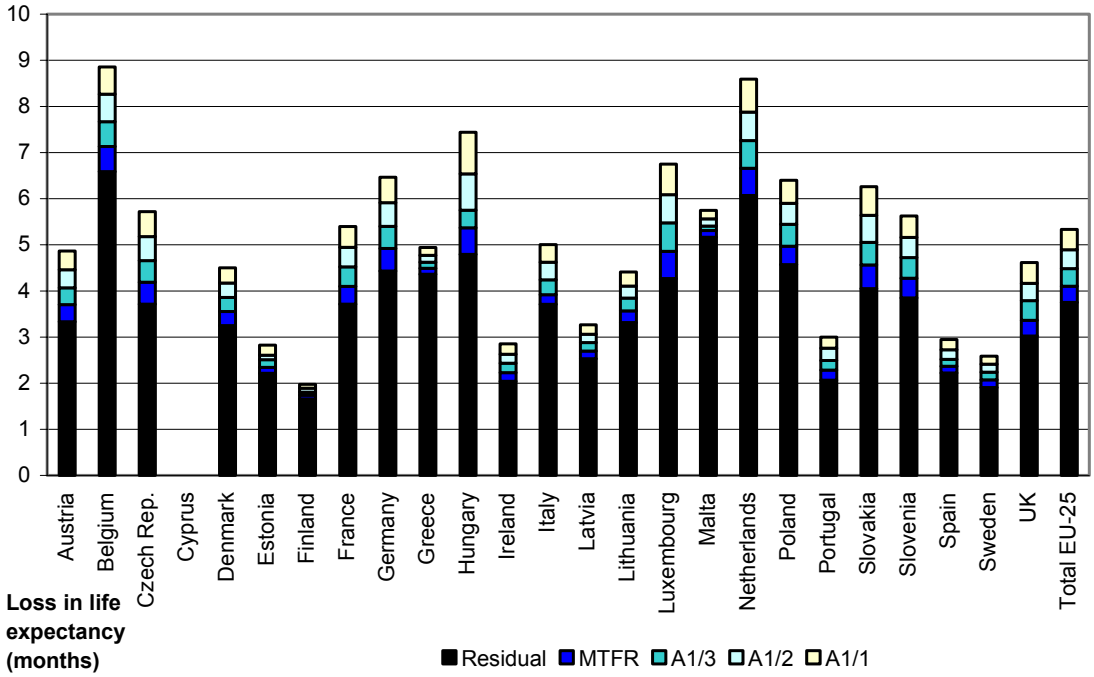


Figure 7.1: Loss in statistical life expectancy attributable to the exposure to PM2.5 originating from identified anthropogenic emissions (in months). Calculations include urban PM2.5 levels calculated with the City-Delta approach.

8 Ozone in urban areas

The City-Delta model intercomparison has also collected data on ozone in urban areas, as calculated with regional and urban-scale problems. From this model intercomparison it was concluded that model results are highly sensitive to the quality of the emission inventories, and high quality emission inventories especially for urban areas are necessary for good model performance. In general, model reproduce well the present situation, they agree on the ozone changes expected from current legislation in 2010, and there is agreement on relatively little scope for further improvements from emission controls beyond the current legislation.

For ozone in urban areas, analysis showed a distinctive spatial pattern at a scale considerably smaller than the 50*50 km resolution of regional scale models. Within the urban area, ozone levels are substantially lower than in the surrounding background air due to the titrating effect of NO_x emissions. If NO_x emissions are reduced, this titrating effect declines, and ozone levels within the urban area increase eventually approaching the levels of the surrounding background (Figure 8.1).

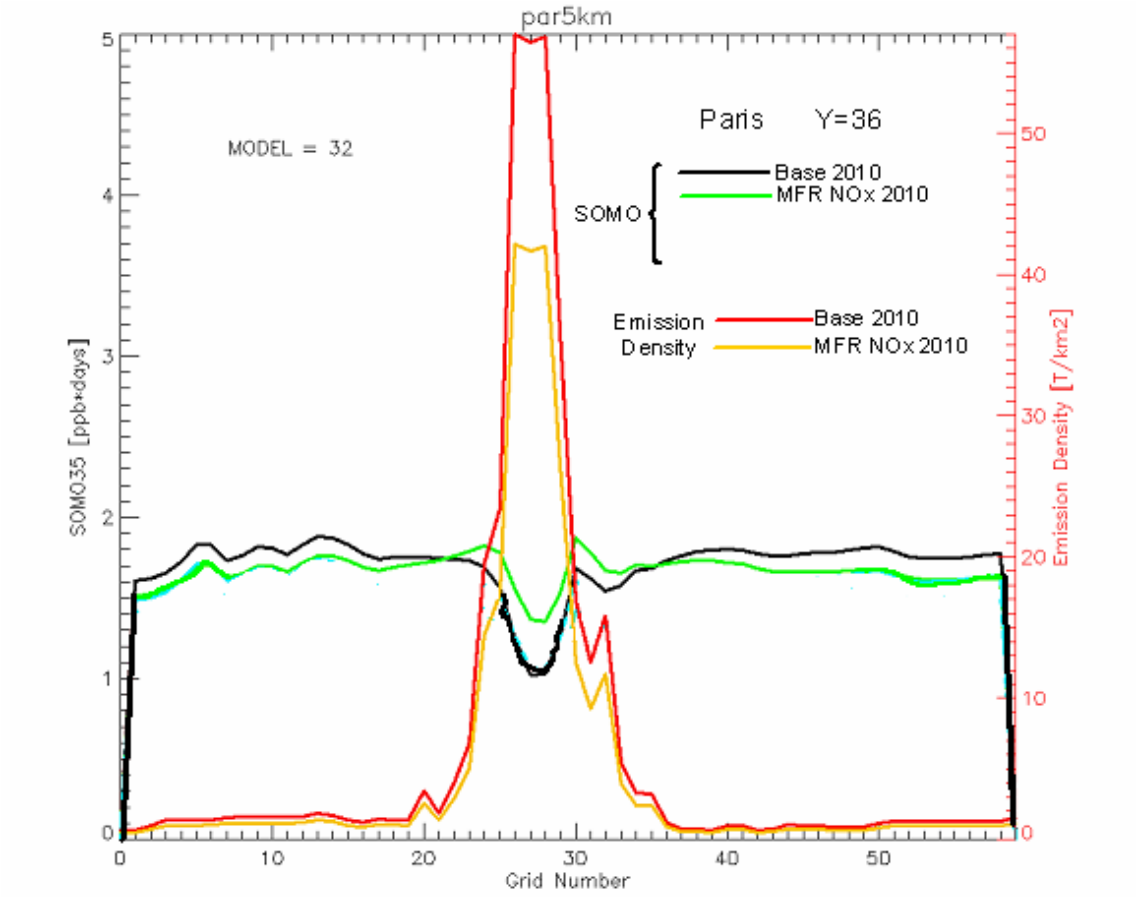


Figure 8.1: Emission densities and ozone concentrations along a cross-section through the Paris model domain for the baseline (black line) and maximum feasible NO_x controls.

In contrast, VOC reductions also reduce ozone levels within cities, essentially at the same level that occurs in the rural domain (Figure 8.2). Based on this findings, a possible City-Delta approach could approximate the response in urban ozone levels towards VOC control by the regional-scale response of a VOC control scenario. For NO_x reductions, ozone reductions observed at the regional-scale will not materialize within the city, and for sufficiently large NO_x reductions ozone within cities would eliminate the difference between urban and regional ozone levels.

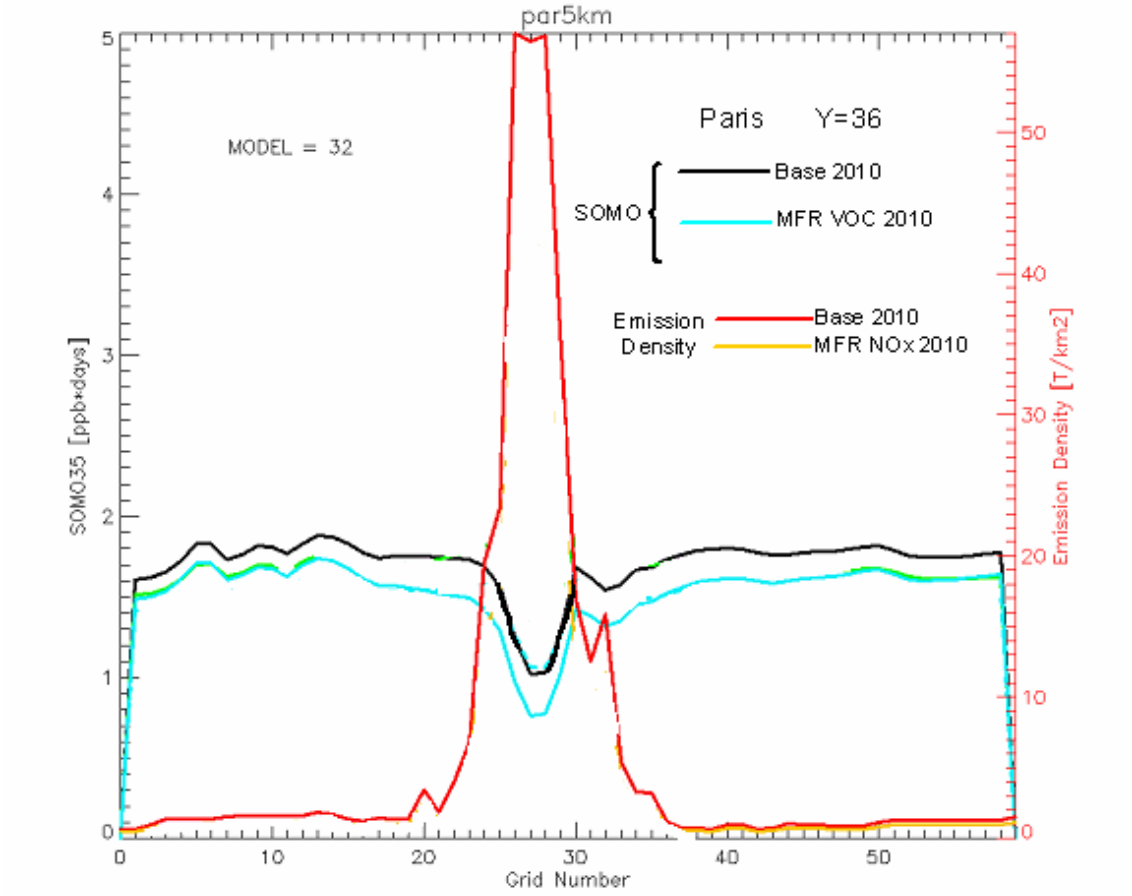


Figure 8.2: Emission densities and ozone concentrations along a cross-section through the Paris model domain for the baseline (black line) and maximum feasible VOC controls.

Due to lower priority given in the CAFE programme towards the quantification of health impacts from ozone compared to that of PM2.5, functional relationships that would allow representation of this effect in the RAINS model have not been developed.

9 Summary

The City-Delta project has analyzed the relationships between regional and urban air quality levels. The analysis proceeded along two lines: Based on monitoring data for Berlin and London, statistical analysis has been conducted to identify relationships between urban air quality, regional background concentrations and local emission densities from low-level sources. Since monitoring data are scarce, and since such relationships cannot be observed for future emission reduction cases, this analysis has been complemented by model calculations for a number emission control scenario calculations for four European cities with six different atmospheric dispersion models.

The results from these calculations have been used to extrapolate the functional relationships derived from monitoring data to other cities and beyond the range of observed emissions. Functional relationships have been developed and implemented in the RAINS model that allow computing urban air quality from regional scale calculations, so that for the purposes of the CAFE project the implication of Community-wide emission control measures on urban air quality can be assessed. Due to the dominating importance of the exposure to fine particulate matter for health impacts compared with the role of ozone, priority was given in this analysis to the development of a methodology for PM2.5.

The resulting estimates for PM2.5 compare well with observations of urban background concentrations for a wide range of European cities with very different geographical, climatic and pollution-related conditions. Discrepancies remain for a number of cities. The initial approach under-predicts PM2.5 concentrations for urban areas with special topography (e.g., in valleys or basins) due to the use of wind speeds that are representative of open land conditions. It also systematically under-predicts concentrations in cities, which extend over several EMEP grid cells, and it underestimates concentrations in Spanish cities.

Most of these issues could be resolved by further refinements of the approach, so that eventually a powerful method will be available to assess the implication of Community-wide emission control measures on urban air quality throughout Europe.

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