

Bericht zum Forschungs- und Entwicklungsvorhaben FKZ 202 43 270 auf dem Gebiet des Umweltschutzes „Entwicklung von Modellen zur Identifizierung von Schadstoffquellen -insbesondere im Verkehrsbereich- im Rahmen der 22. BImSchV - Dokumentation, Weiterentwicklung, Validierung und Maßnahmenplanung für ein bundeseinheitliches Vorgehen“

Analyzing the response of a chemical transport model to emissions reductions utilizing various grid resolutions

Rainer Stern

Robert Yamartino



**Freie Universität Berlin
Institut für Meteorologie
Troposphärische Umweltforschung**

Carl-Heinrich-Becker-Weg 6-10
12165 Berlin

May 2006

Final report
for
FE-Vorhaben (UFOPLAN Nr. 202 43 270)

„Entwicklung von Modellen zur Identifizierung von Schadstoffquellen -
insbesondere im Verkehrsbereich- im Rahmen der 22. BImSchV -
Dokumentation, Weiterentwicklung, Validierung und
Maßnahmenplanung für ein bundeseinheitliches Vorgehen“

**Analyzing the response of a
chemical transport model to emissions reductions
utilizing various grid resolutions**

Rainer Stern, Inst. of Meteorology, Free University of Berlin, Germany
Robert J. Yamartino, Integrals Unlimited, Portland, ME USA

for:
Umweltbundesamt
II 6.1
Postfach 1406
06813 Dessau

Institut für Meteorologie
Freie Universität Berlin
May 2006

Berichts-Kennblatt

BerichtsnummerUBA-FB	2.	3.
4. Titel des Berichts Analyzing the response of a chemical transport model to emissions reductions utilizing various grid resolutions		
5. Autor(en), Name(n), Vorname(n) Stern, Rainer Yamartino, Robert		8. Abschlußdatum Mai 2006
6. Durchführende Institution (Name, Anschrift) Freie Universität Berlin, Institut für Meteorologie Carl-Heinrich-Becker-Weg 6-10 12165 Berlin, Integrals Unlimited, Portland, ME USA		9. Veröffentlichungsdatum Mai 2006
		10. UFOPLAN-Nr. 202 43 270
		11. Seitenzahl 28
		12. Literaturangaben 33
7. Fördernde Institution (Name, Anschrift) Umweltbundesamt, Postfach 1406, D-06813 Dessau		13. Tabellen und Diagramme -
		14. Abbildungen 13
		15. Zusätzliche Angaben
16. Kurzfassung Das chemische Transportmodell REM-CALGRID wurde auf den Großraum Berlin in 4 verschiedenen Auflösungen von 30 km bis zu 1km angewandt. Im Vergleich mit Messungen erbrachte die Rechnung mit der höchsten Auflösung die besten Ergebnisse. Die modellierte Wirksamkeit von Maßnahmen (CLE2010 Szenario und eine 50% Reduzierung aller anthropogenen Emissionen) als Funktion der horizontalen Gitterauflösung zeigte, dass das urbane Signal deutlich unterschätzt wird, wenn die Auflösung zu gering ist. Dies bedeutet, dass die Wirksamkeit von Maßnahmen in Stadtgebieten unterschätzt wird, falls sie auf großräumigen Modellrechnungen beruht. In Stadtgebieten mit einer inhomogenen Emissionsverteilung kann sogar eine Maschenweite von 5 km zu gering sein, um das urbane Signal vollständig zu erfassen. .		
17. Schlagwörter EU-Richtlinien zur Luftqualität, Ausbreitungsrechnung, REM-CALGRID-Modell, Auswirkungen von Maßnahmen, Gittereffekte		
18. Preis	19.	20.

Report Cover Sheet

Report No.UBA-FB BBBB	2.	3.
4. Report Title Analyzing the response of a chemical transport model to emissions reductions utilizing various grid resolutions		
5. Autor(s), Family Name(s), First Name(s) Stern, Rainer Yamartino, Robert		8. Report Date May 2006
6. Performing Organisation (Name, Address) Freie Universität Berlin, Institut für Meteorologie Carl-Heinrich-Becker-Weg 6-10 12165 Berlin, Integrals Unlimited, Portland, ME USA		9. Publication Date May 2006
		10. UFOPLAN-Ref. No. 202 43 270
		11. No. of Pages 28
		12. No. of Reference 33
7. Sponsoring Agency (Name, Address) Umweltbundesamt, Postfach 1406, D-06813 Dessau		13. No. of Tables, Diagrams -
		14. No. of Figures 13
15. Supplementary Notes		
16. Abstract Applying the REM-CALGRID chemical transport model to the greater area of Berlin in four different grid sizes decreasing from 30 km down to 1 km, it turned out that model performance was best for the run with the highest grid resolution. The modelled effectiveness of control measures (CLE2010 scenario and a 50% reduction of all anthropogenic emissions) in an urban area as a function of a horizontal grid resolution showed also, that the urban increment is underestimated by the regional model resolution of 30 km. This implies that the effects of measures will be underestimated in urban areas if they are based on a regional scale model application. In urban areas with a highly inhomogeneous emission pattern even a resolution in the range of 5 km as used in the City-Delta exercise, can be too large for a complete capture of the urban signal.		
17. Keywords EU directives for air quality, dispersion modelling, REM-CALGRID-model, grid size effects, effectiveness of control measures		

Contents

1.	Introduction	4
2.	The RCG model.....	5
3.	The four domains and model set-up	7
4.	Harmonizing of Emissions	9
5.	Base case simulations	10
6.	Scenario runs	17
7.	Summary and conclusions	24
8.	References	24
9.	Figure captions	27

1. Introduction

Many efforts are underway in Europe to control the emission sources that are responsible for harmful air pollution effects. The ambient air quality framework directive 96/62/EC (FWD) of the European Commission provides an EU-wide framework for national, regional and local measures to assess, manage, and protect European air quality. The Clean Air For Europe (CAFÉ) programme of the European Commission (<http://europa.eu.int/comm/environment/air/cafe/index.htm>) encompasses technical analysis and policy development and focuses on the development of long-term, strategic and integrated policy advice for the improvement of Europe's air quality. The likely evolution of air quality in Europe is assessed taking into account the effects of current and planned emission control legislation and future economic development. The assessment is based on a Europe-wide evaluation of the cost-effectiveness of emission-control strategies utilizing the results of the EMEP regional-scale, Eulerian chemical transport model (Amann et al., 2005). This model has been used to calculate source-receptor relationships that reflect the response of air quality to changes in emissions at a spatial resolution of $50 \times 50 \text{ km}^2$. Such an integrated assessment modelling resolution is sufficient to cover all the aspects of long-range transport across Europe, but is too coarse to resolve the inhomogeneities in urban emissions patterns or the resulting high-concentration pollution patterns in areas where a large fraction the European population lives. Thus, a question arises whether concentration changes (or deltas), resulting from emissions deltas and calculated using a coarse-resolution regional model, can be transferred from the regional scale to the urban scale. This question was the motivation for the City-Delta Project (Cuvelier et al., 2006, Vautard et al., 2006). Based on an extended inter-comparison of 17 urban and regional atmospheric transport models applied to six different European cities, this project developed functional relationships that quantify the increments in concentrations that occur within cities compared with those modelled for the regional environment. These relationships describe the difference between the concentrations averaged over $5 \times 5 \text{ km}^2$ in an urban core and the average concentrations calculated over a $50 \times 50 \text{ km}$ grid cell covering the whole urban area and its surroundings. This so-called urban increment shall be used later in a modified version of the RAINS cost-effectiveness, optimization model (Amann et al., 2005). In the City-Delta exercise, each model was applied in its own standard configuration without attempting to harmonize input data except for emissions. The urban increment was derived from the differences of model predictions utilizing the two model resolutions combined with the "ensemble modelling" concept (Cuvelier et al., 2006, see also <http://aqm.jrc.it/citydelta/>), where it is assumed that the average of the model responses, or "ensemble response", gives the most reliable prediction of the emission reduction impact.

The aim of the present study was to supplement City-Delta by using a single model to analyze the relationships between regional and urban air quality levels and the modelled effectiveness of control measures in an urban area as a function of horizontal grid resolution over the range from 30 km down to 1 km. This study should help answer the questions of (a) how reliably regional scale model calculations can be used to compute air quality in urban areas and (b) what grid size

seems to be adequate to describe air quality within a city. In this German EPA (Umweltbundesamt) funded project, photochemical and aerosol modelling simulations over Europe, Germany, the Federal State Brandenburg and the agglomeration/metropolitan area of Berlin for all of 2002 were performed using the REM-CALGRID (RCG) chemical transport model.

For the year 2002, RCG was applied on four grids for the following three cases:

- Base case simulation 2002;
- The CLE-scenario (Implementation of current legislation until 2010); and,
- A 50% emissions reduction of all anthropogenic species in each domain.

2. The RCG model

The REM-CALGRID model is an urban/regional scale model development designed to fulfil the requirements of the ambient air quality framework directive 96/62/EC of the European Commission (Stern et al., 2003). Rather than creating a completely new model, the urban-scale photochemical model CALGRID (Yamartino et al., 1992) and the regional scale model REM3 (Stern, 1994; Hass et al., 1997) were used as the starting point for the new urban/regional scale model, REM-CALGRID (RCG). The premise was to design an Eulerian grid model of medium complexity that can be used on the regional, as well as the urban, scale for short-term and long-term simulations of oxidant and aerosol formation.

The model includes the following features:

- A generalized horizontal coordinate systems, including latitude-longitude coordinates;
- A vertical transport and diffusion scheme that correctly accounts for atmospheric density variations in space and time, and accounts for all vertical flux components when employing either dynamic or fixed layers;
- A new methodology to eliminate errors totally from operator-split transport and ensure correct transport fluxes, mass conservation, and that a constant mixing ratio field remains constant;
- Inclusion of the recently improved and highly-accurate, monotonic advection scheme developed by Walcek (2000). This fast and accurate scheme has been further modified to exhibit even lower numerical diffusion for short wavelength distributions;
- Updated releases of the SAPRC-93 and CBM-IV photochemical reaction schemes including Carter's (1996) 1-product isoprene scheme and SO₂ oxidation to SO₄;
- Two equilibrium aerosol modules, that treat the thermodynamics of inorganic aerosols;

- An equilibrium aerosol module, that treat the thermodynamics of organic aerosols
- Simple modules to treat the emissions of sea salt aerosols and wind blown dust particles
- A simple wet scavenging module based on precipitation rates;
- An emissions data interface for long term applications that enables on-the-fly calculations of hourly anthropogenic and biogenic emissions, and greatly facilitates emissions reduction scenario studies.

RCG uses the bulk approach for the aerosol modelling. Aerosol dynamics are not considered. The model employs two different equilibrium aerosol modules: a) The MARS-A module (Binkowski and Shankar, 1995) that treats the thermodynamics of the inorganic sulfate, nitrate, ammonium aerosols and water, and b) the ISORROPIA module that additionally treats sodium and chloride aerosols (Nenes et al., 1999). Secondary organic aerosols (SOA) that are formed by condensation of biogenic and anthropogenic hydrocarbon oxidation products are considered employing the SORGAM module developed by Schell et al. (2001).

The sea-salt aerosol emissions are parameterized according to Gong et al. (1997) as a function of size and wind speed. For the calculation of land-use dependent wind blown dust emissions the following release mechanism are treated: Direct release of small dust particles by the wind (Loosmore and Hunt, 2000), and indirect release by collisions with bigger soil grains, that are lifted by the wind but return to the surface because of their weight („saltation“ process, Claiborn et al., 1998).

The aerosol components are assigned to two size fractions: fine mode PM_{2.5} and coarse mode PM₁₀-PM_{2.5}. The anthropogenic emissions data base has to provide the primary emissions split into these two size categories. The anthropogenic PM emissions are allocated to 4 model species: one coarse mode species PMCO_{prim} = PM₁₀-PM_{2.5}, 3 fine mode species, EC, OC, and a mineral rest (MR). The photochemical mechanisms include the oxidation of SO₂ to gaseous sulphate, which is assumed to be gaseous sulphuric acid. The aerosol modules treat the thermodynamics of the inorganic aerosols, depending on the gas phase concentrations of nitric acid, ammonia, sulphuric acid, HCl, humidity and temperature. In RCG, all secondary aerosols are assigned to the PM_{2.5} fraction. All aerosols are transported and subjected to wet and dry deposition. PM₁₀ concentrations are then defined as the sum of primary PM₁₀ and secondary organic and inorganic aerosols via the relation:

$$\text{PM}_{10} = \text{PMCO}_{\text{prim}} + \text{EC} + \text{OC} + \text{MR} + \text{SO}_4 + \text{NO}_3 + \text{NH}_4 + \text{SOA} + \text{Na} + \text{Cl}$$

RCG uses a resistance-based model (aerodynamic resistance, viscous sub-layer resistance, surface resistance) for the computation of dry deposition rates as a function of geophysical parameters, micrometeorological conditions, and gaseous or particle pollutant species including the gravitational settling speed of particles. Species dependent deposition velocities are calculated for each land-use class within each grid cell, and deposition fluxes are computed by summing over the fractional land-use terms.

Meteorological data needed by RCG at hourly intervals consist of layer-averaged gridded fields of wind, temperature, humidity and density, plus 2-d gridded fields of mixing heights, several boundary layer and surface variables, precipitation rates and cloud cover. All this meteorological data is produced employing a diagnostic meteorological analysis system based on an optimum interpolation procedure on isentropic surfaces. The system utilizes all available synoptic surface and upper air data (TRAMPER, Tropospheric Realtime Applied Procedure for Environmental Research, Reimer and Scherer, 1992).

The RCG model also requires annual emissions of VOC, NO_x, CO, SO₂, CH₄, NH₃, PM10, and PM2.5, split into point and gridded area sources. Mass-based, source group dependent NMVOC profiles are used to break down the total VOC into the different species classes of the chemical mechanisms. Hourly emissions are derived during the model run using source-group dependent, month, day-of-week and hourly emissions factors. Biogenic VOC-emissions are derived using the E94 emissions factors for isoprene and OVOC (Other VOCs) as described in Simpson et al. (1995). Terpene emissions factors are taken from the CORINAIR emission hand-book. These biogenic calculations are based on the land-use data for deciduous, coniferous, mixed forests and crops. Light intensity and temperature dependencies are also considered.

Monthly varying lateral and top boundary conditions for ozone are taken from climatological background data (Logan, 1998). Boundary data for all other species are chosen as time- and space-varying typical background values similar to the procedure used in the EMEP-model.

RCG model evaluation was performed mainly within the framework of several European model inter-comparison studies (Stern et al., 2003; Hass et al., 2003; Van Loon et al., 2004; Cuvelier et al., 2006). The comparison of the RCG results with the results of other models involved in these model intercomparison studies shows that the RCG medium complexity model is performing very well in comparison to other models.

3. The four domains and model set-up

For this study, the RCG model was run in a Latitude/Longitude (Lat./Lon.) coordinate system at four different horizontal grid resolutions to assess the air quality in Berlin:

- A European scale grid, covering N. Europe with resolution of 0.25° (Lat.) by 0.5° (Lon.) (i.e., nominally about 30-km);
- Nest 1: a national scale grid, covering Germany and having twice the resolution of grid #1 (i.e., approx. 15-km);
- Nest 2: A German Federal State grid, covering Brandenburg and Berlin, and having 8 times the resolution of grid #1 (i.e., approx. 4-km); and,

- Nest 3: An urban scale grid, covering Berlin, and having 32-times the resolution of grid #1 (i.e., approx. 1-km).

Figure 1 shows the four different modelling areas. For all domains, RCG was applied using the CBM-photochemical mechanism, the ISORROPIA module for the inorganic aerosol formation and the SORGAM module for the organic aerosol formation. The model was run with five vertical layers: a 20 m thick surface layer, two equal-thickness layers below the mixing height, and two above the mixing height and extending to the domain top at 3000m. Grid-dependent meteorological input data were produced employing the TRAMPER diagnostic meteorological analysis system based on an optimum interpolation procedure on isentropic surfaces. The system utilizes all available synoptic surface and upper air data as well as topographical and land use information. The boundary conditions for the nested applications (Nests 1-3) were taken from the next larger grid. The European scale run uses monthly-varying lateral and top boundary conditions for ozone taken from climatological background data. Boundary data for all other species are fixed and chosen as typical background values.

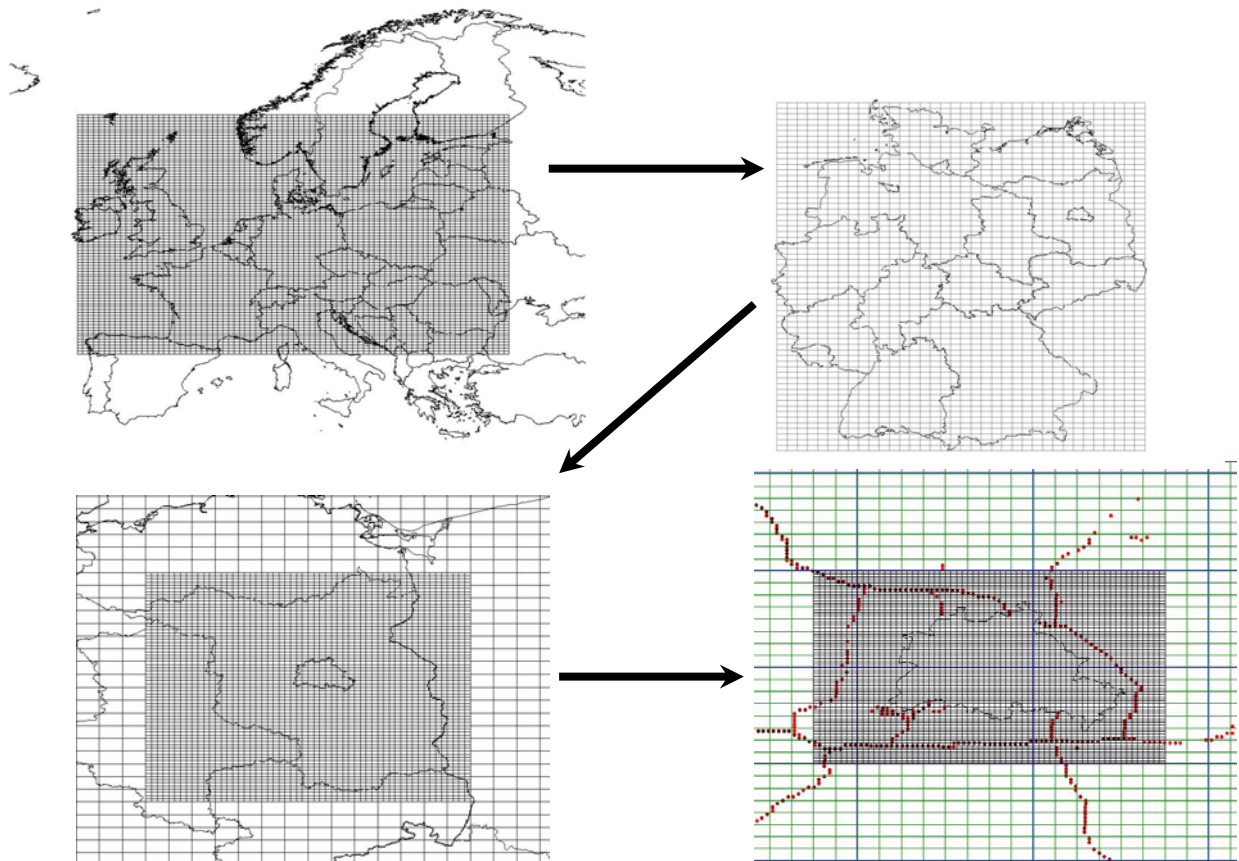


Figure 1 : RCG modelling domains. Upper left: European scale grid with resolution of 0.25° Lat., 0.5° Lon. Upper right: Nest 1, national scale (Germany) grid with resolution of 0.125° Lat., 0.25° Lon. Lower left: Nest 2, the Federal State (Brandenburg) grid with resolution of 0.03125° Lat., 0.0625° Lon., embedded in Nest 1. Lower right: Nest 3, urban grid Berlin with resolution of 0.0078125° Lat., 0.015625° Lon., embedded in Nest 2 (and Nest 1) and also showing in red the major “ring” motorway around Berlin.

4. Harmonizing of Emissions

A major problem for nested grid applications is the necessity of establishing consistency between the top-down emission data, typically used on the continental and regional scales, and the bottom-up emission estimates, typically used in urban-scale modelling. This study utilized two different sets of emissions data: the regional TNO emissions inventory (Visscherdijk and van der Gon, 2005), which covers all of Europe at a horizontal resolution of 0.125° latitude and 0.25° longitude; and, the local inventories of the States of Brandenburg and Berlin, available at a resolution of $1 \times 1 \text{ km}^2$ (Kerschbaumer and Stern, 2005). The sectoral totals of the TNO emissions data set conform to the country submissions to EMEP for the year 2000, i.e. the national totals agree with the officially reported national emissions to the Convention on Long Range Transboundary Air Pollution (CLTRAP, see EMEP, 2003). The local emissions are also for the reference year 2000, and both emission inventories have a future emissions projection for 2010 based on the assumption of the so-called CLE-scenario (Current Legislation scenario, which assumes full implementation of the presently decided emissions-related legislation in all EU-countries, see Amann et al., 2005). However, as could be expected, the two inventories differ substantially for the Brandenburg and greater Berlin areas covered by Nests 2 and 3, respectively. Because the differences between the TNO emissions and the urban emissions were too large to be neglected for the focus of this study, the TNO emissions within the Nest 2 and Nest 3 area were substituted by the fine-scale local emissions. On the other hand, the expected relative emission changes from 2000 to 2010 for the local inventory were set identical to those of the regional TNO data set for Germany on a sector-by-sector basis. This procedure guaranteed the use of harmonized emissions at all scales and assures that differences in the calculated concentration data were solely due to the differing grid resolution and not due to differing emissions. The modified regional scale TNO inventory was used for the European and Nest 1 model runs, the local inventory for the Nest 2 and Nest 3 runs. The emission totals in the European grid cells covering the greater Berlin area are identical at all scales, but the emission density distribution is different, depending on the resolution of the grid (Figure 2).

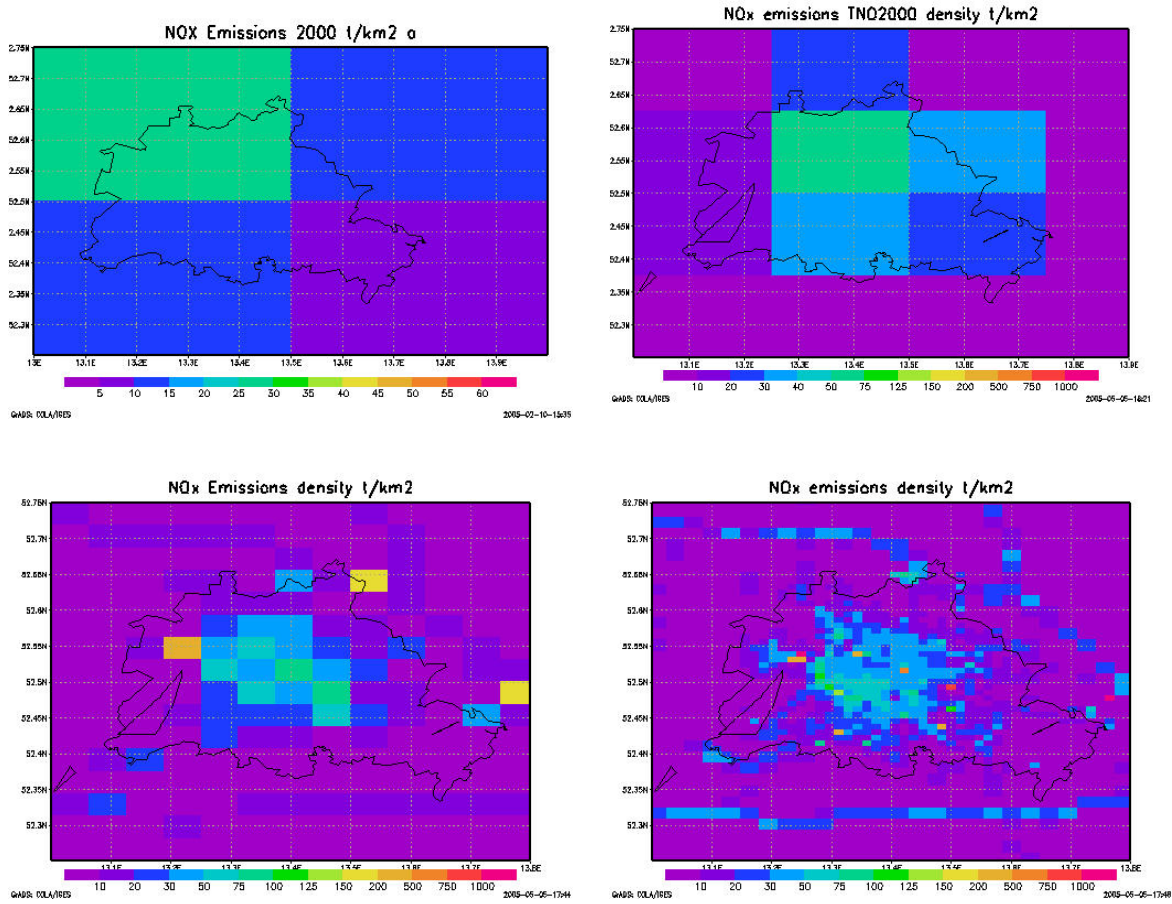


Figure 2 : NO_x annual emissions density in t/km² at four scales for the greater Berlin area. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid Lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1. Note the different scaling for the European grid.

5. Base case simulations

The base case simulation results at all scales were compared to available PM₁₀- and NO₂-measurements in the greater Berlin area to quantify how regional model predictions differ from those obtained with finer resolution modelling. Examination of concentration isopleths plots for NO₂ (Figure 3) indicates that the European- and national-scale grids fail to capture any of the inner-urban concentration variability. The city core of Berlin starts to be resolved by the 4x4 km² grid of Nest 2, but really becomes clear only in the 1x1 km² grid of Nest 3. The calculated NO₂-concentration ranges in the greater Berlin area are 10-22 µg/m³ for the European scale, 10-26 µg/m³ for Nest 1, 10-30 µg/m³ for Nest 2, and 10-35 µg/m³ for Nest 3. A similar picture emerges for PM₁₀ (Figure 4). The respective PM₁₀ concentration ranges are 15-22 µg/m³ for the European scale, 15-28 µg/m³ for Nest 1, 15-28 µg/m³ for Nest 2, and 15-33 µg/m³ for Nest 3.

Figure 5 shows the comparison of the calculated NO₂ and PM₁₀ annual mean values with the measurements at all stations which are not directly influenced by nearby traffic emissions. In particular, for NO₂, the agreement between predictions and observations steadily improves from the European scale to the Nest 3 scale. The European scale model run and also the Nest 1 model run completely fail to capture the high NO₂ observations. The Nest 2 model runs does a much better job, but the best simulation of the peak values is achieved in the Nest 3 model run. The model performance for PM₁₀ is clearly worse than that for NO₂ at all scales, but it is also obvious that a PM₁₀ model calculation with a regional grid resolution is not able to reproduce the observed pattern in urban areas. For PM₁₀, the Nest 1 run exhibits a little better correlation than the Nest 2 run, while Nest 2 yields a nearly perfect regression slope of 0.98 and suggests an under-prediction by about 5.5 µg/m³. However, in view of the small number of stations one should be careful not to over-interpret these statistical results. Again, most of the observations are underestimated, which is a well-known feature of current PM₁₀ simulations (van Loon et al., 2004). This underestimation can primarily be attributed to un-inventoried particle sources, known to exist but difficult to quantify (e.g., biogenic sources; wind blown dust from agricultural sources and natural surfaces; re-suspension of road dust). Also particle-bound water which contributes to gravimetrically measured PM mass can be responsible for some of the underestimation, because the models usually only consider dry aerosol mass (Tsyro, 2005). In Nest 1 and Nest 2, the underestimation is approximately the same (i.e., about 5-6 µg/m³) in all observed concentration ranges. In Nest 3, the lower observed PM₁₀ concentrations at the border of the Nest 3 modelling area are underestimated to the same degree as in Nest 1 and Nest 2, but the peak observations in the urban core are captured better. If the uniform underestimation can be attributed to too low a background level, this would lead to Nest 3 overestimation of some of the observed, urban core PM₁₀ concentrations. This situation might indicate possible errors in the 1x1 km² emission inventory, which are then diffused in the data sets with a higher spatial aggregation. Presently however, there are too few stations to draw final conclusions.

Figure 6 shows the concentration difference between the European scale run and the nested runs at the NO₂- and PM₁₀ measurements stations in Berlin and surroundings. These differences can be interpreted as the urban increments that cannot be resolved by regional scale model runs having grid resolutions of 30 km or larger. The stations are further characterized as urban (city), suburban and rural/suburban stations. At most city stations, the urban increments increase with decreasing grid size. The urban increments for Nest 3 (resolution approx. 1 km x 1 km) are as large as 16 µg/m³ for NO₂ and 10 µg/m³ for PM₁₀; however, away from the urban core, the increments decrease, and even turn negative, for stations in the suburbs and rural outskirts. Figure 7 shows the urban increments for PM_{2.5} and SIA, the sum of the secondary inorganic aerosols. The SIA urban increments are very small because most of the secondary aerosols are formed during the long range transport outside of the city. PM_{2.5} exhibits quite a large urban increment at the urban core stations indicating that in the city center of Berlin the primary contribution to the total PM_{2.5} concentration can be rather large.

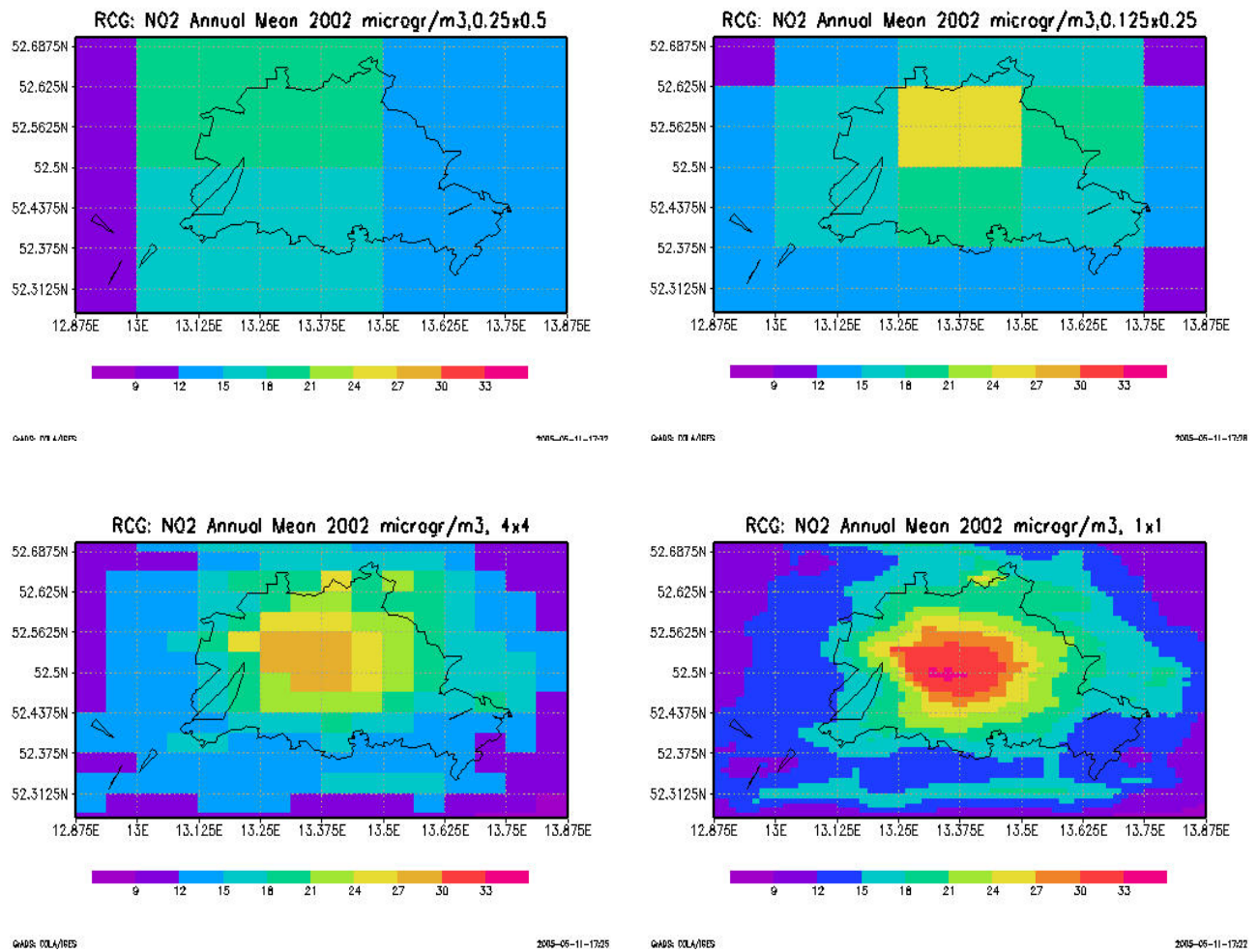


Figure 3 Calculated NO₂ annual mean at four scales for the greater Berlin area. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid Lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1.

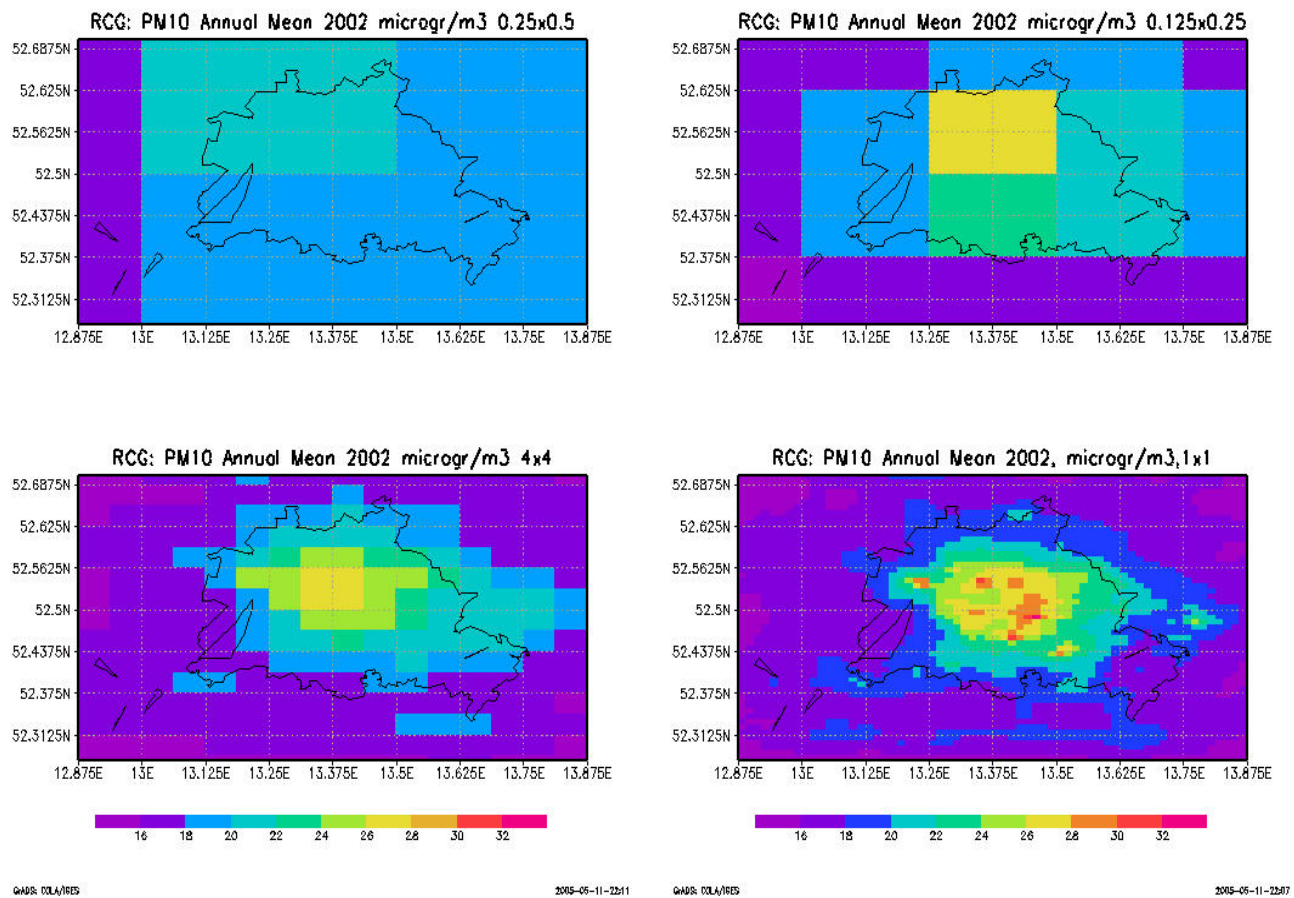


Figure 4 Calculated PM10 annual mean at four scales for the greater Berlin area. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid Lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1.

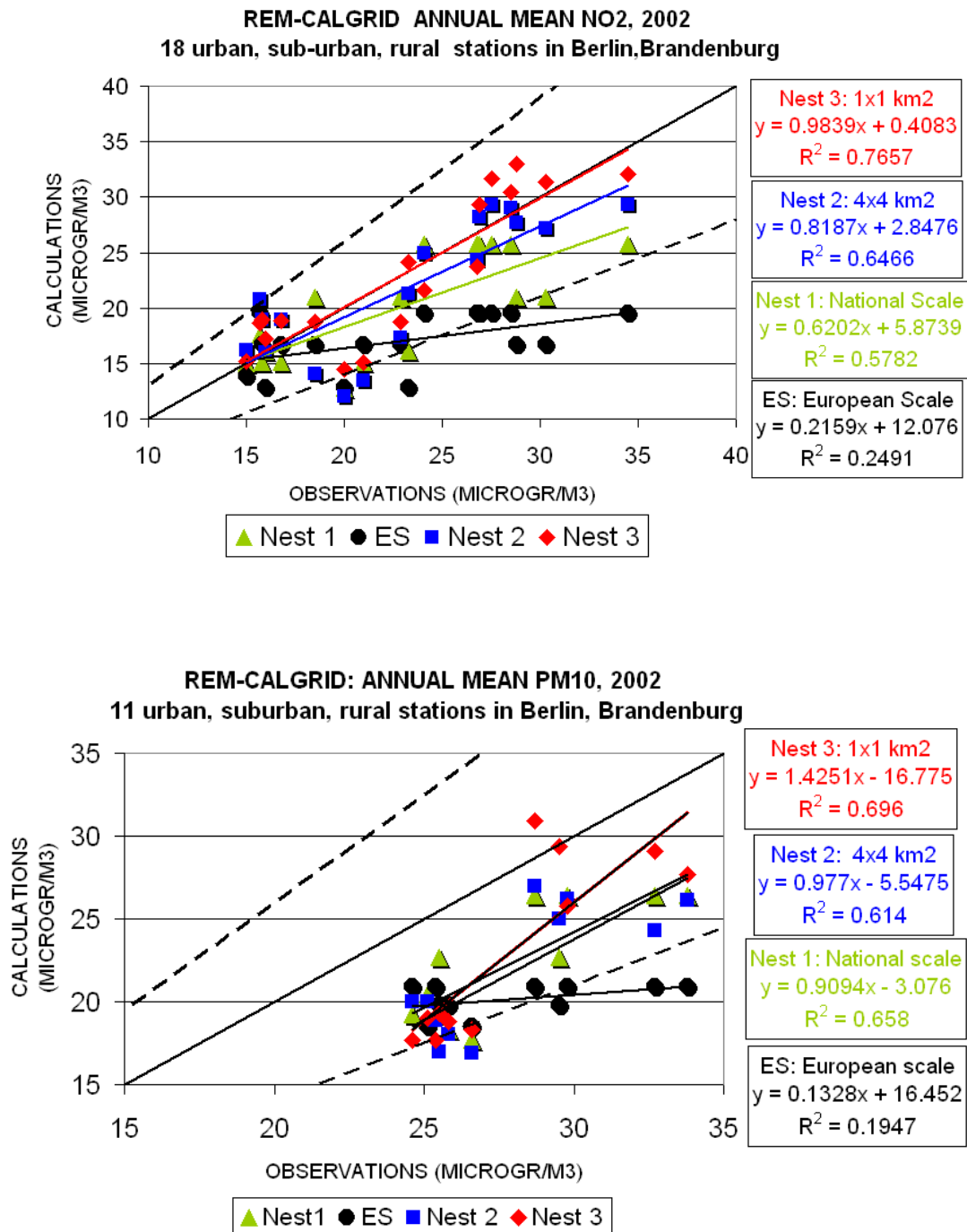


Figure 5 Scatter diagram of observed and calculated NO₂ and PM₁₀ annual means in the greater Berlin area at four scales, including regression lines and correlation coefficients. Dashed lines indicate the range of +/- 50% of the observations. For further explanations see text.

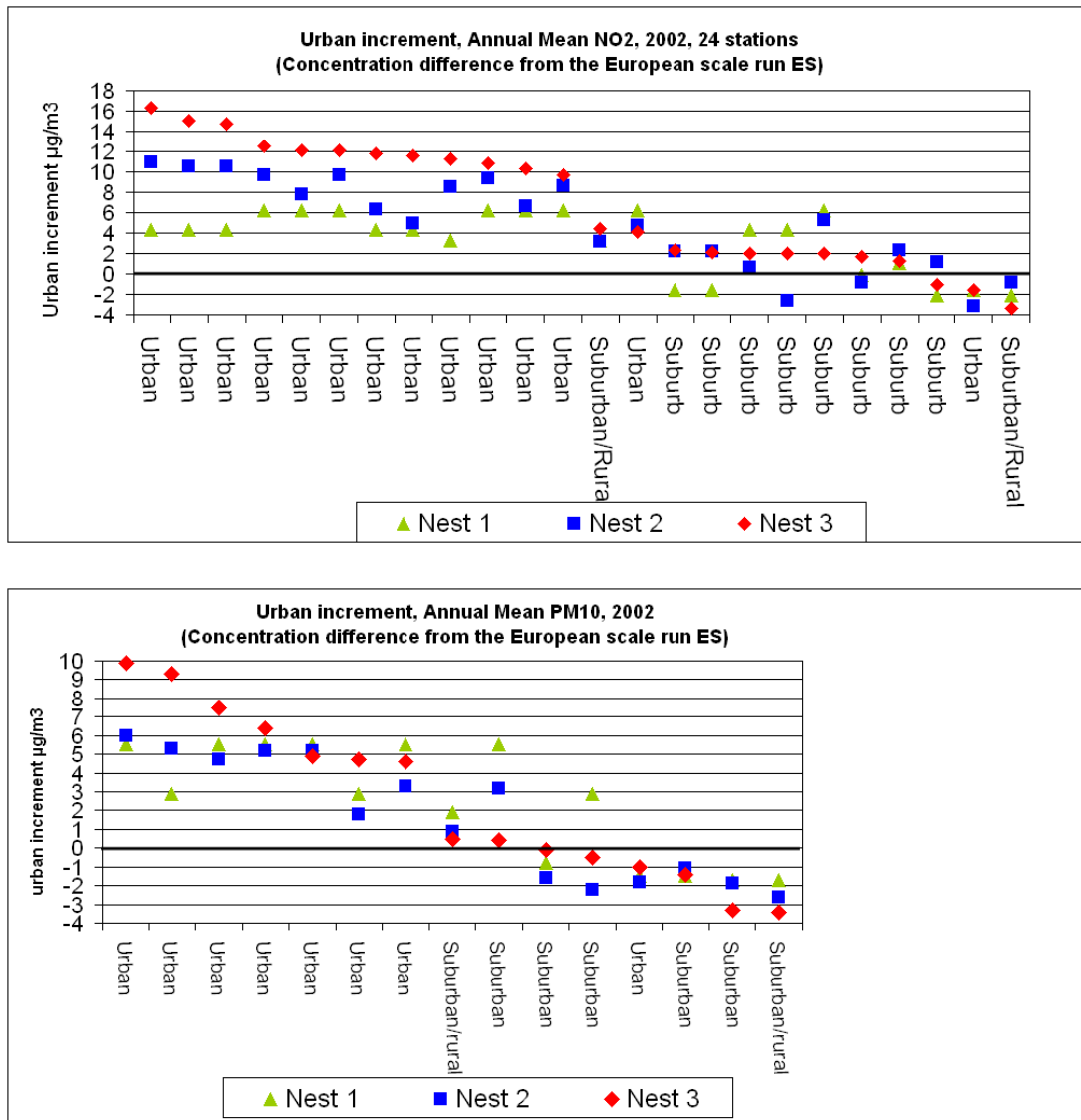


Figure 6 NO₂ and PM₁₀ annual mean urban increments in $\mu\text{g}/\text{m}^3$ at NO₂ and PM₁₀ measurement locations in the Berlin area, characterized as urban, suburban and rural/suburban type stations. For further explanations see text.

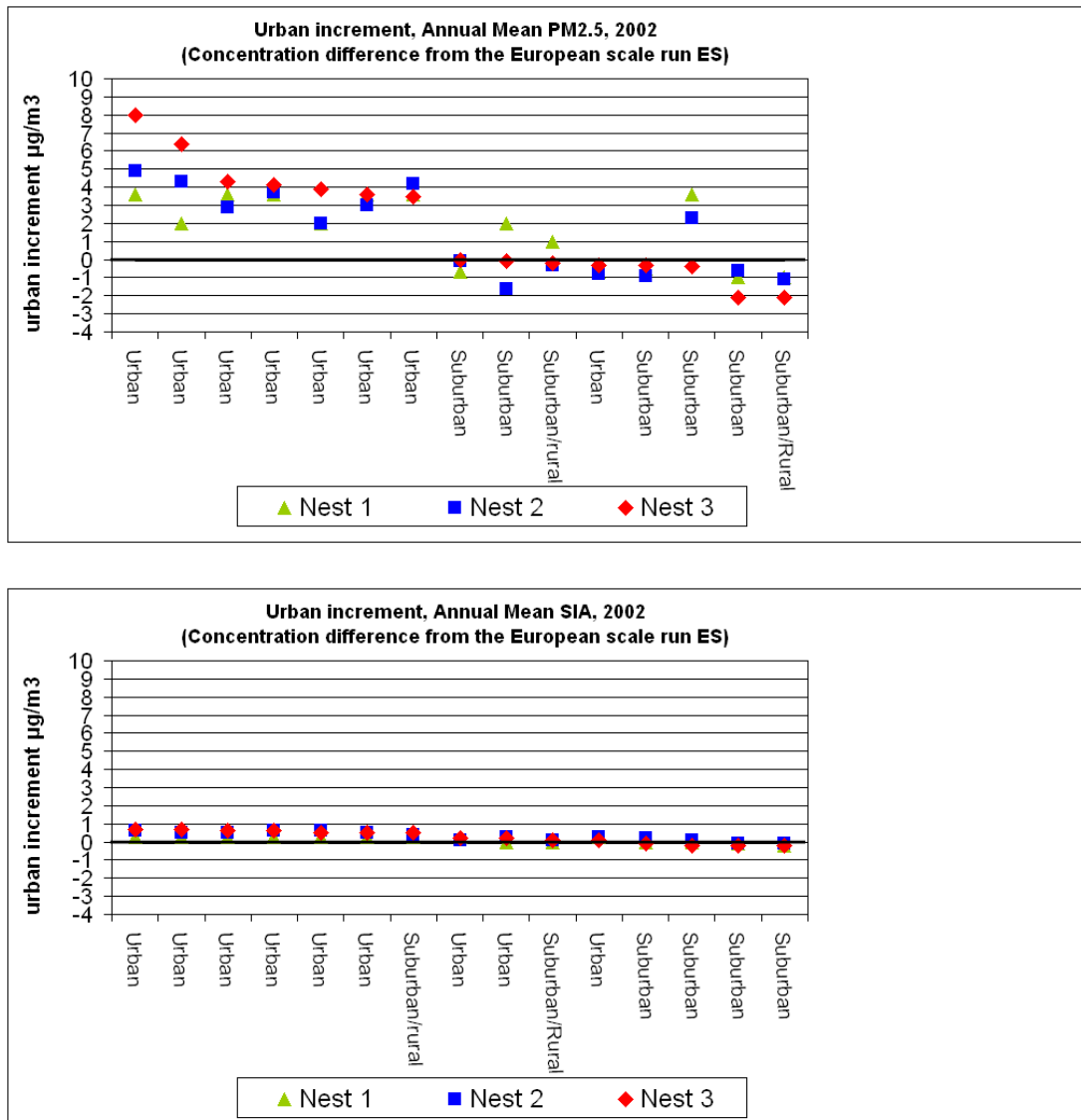


Figure 7 PM_{2.5} and SIA (sum of the secondary inorganic aerosols) annual mean urban increments in $\mu\text{g}/\text{m}^3$ at PM₁₀ measurement locations in the Berlin area, characterized as urban, suburban and rural/suburban type stations. For further explanations see text.

6. Scenario runs

Both scenarios, the 50% reduction of all anthropogenic emissions and the implementation of the CLE scenario, were performed at the four grid resolutions. For Germany, the CLE 2010 scenario implies an average reduction of the NO_x emissions of 29%. The respective reductions for NMVOC, SO₂ and PM₁₀ are 30%, 31% and 14%, respectively, relative to the 2000 emissions figures. The predicted NO₂ concentration reductions based on the CLE scenario assumptions indicate that for the greater Berlin area calculated NO₂ decreases are estimated at 3-5 µg/m³ in the European scale run, 2-6 µg/m³ for the Nest 1 and Nest 2 runs, and 2-7 µg/m³ for the Nest 3 run (Figure 8). The highest resolution Nest 3 run shows the most inhomogeneous concentration delta field over the Berlin area, with larger deltas in the city core and smaller deltas at the outskirts of the city, and these inhomogeneities are progressively diffused as one moves to the coarser resolution runs. Such smearing at coarser resolutions distorts the efficacy of the CLE strategy in that it suggests greater reductions in the urban outskirts and smaller reductions in the urban core. A similar picture emerged for PM₁₀ predictions (Figure 9). The respective PM₁₀ concentration decreases in the greater Berlin area due to the CLE 2010 emission decreases are: 2-3 µg/m³ for the European scale run, 2-4 µg/m³ for Nest 1 and Nest 2, and 2-5 µg/m³ for Nest 3.

Figure 10 shows the scale dependent concentration deltas at 25 NO₂ and 15 PM₁₀ measurement sites in the greater Berlin area. The deltas predicted in Nests 1 thru 3 are expressed relative to (or normalized by) the deltas calculated in the European scale run. At city stations, the concentration decreases due to the CLE scenario and predicted by the high-resolution model run can be up to 50% larger than those estimated by regional models. On the other hand, the regional run tends to predict somewhat larger decreases than the higher resolution modelling runs at the suburban outskirts of the city.

In the second scenario, involving the uniform 50% reduction of all anthropogenic emissions, the absolute differences of the concentration deltas calculated in the four scales are larger than for the CLE-scenario runs (Figure 11, Figure 12), due to the larger emissions reduction rates. In the city center, also the normalized concentration deltas are higher (Figure 13). The concentration decreases due to a 50% reduction of all anthropogenic emissions predicted by the high-resolution model run can now be up to 70% larger than those estimated by the regional model run.

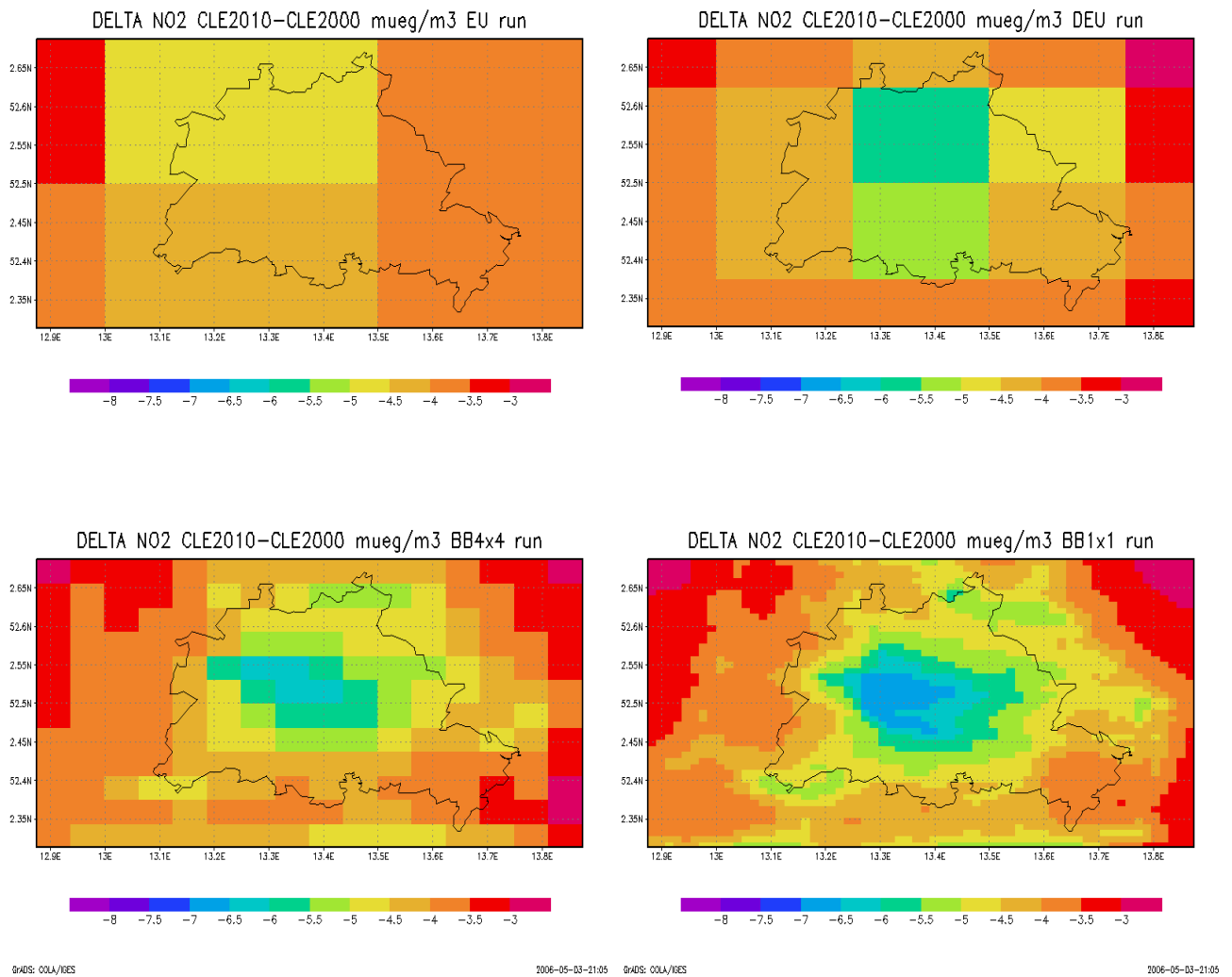


Figure 8 Calculated changes ($\mu\text{g}/\text{m}^3$) in the annual mean NO₂ concentrations from the emission situation 2000 to the CLE emission situation 2010. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1

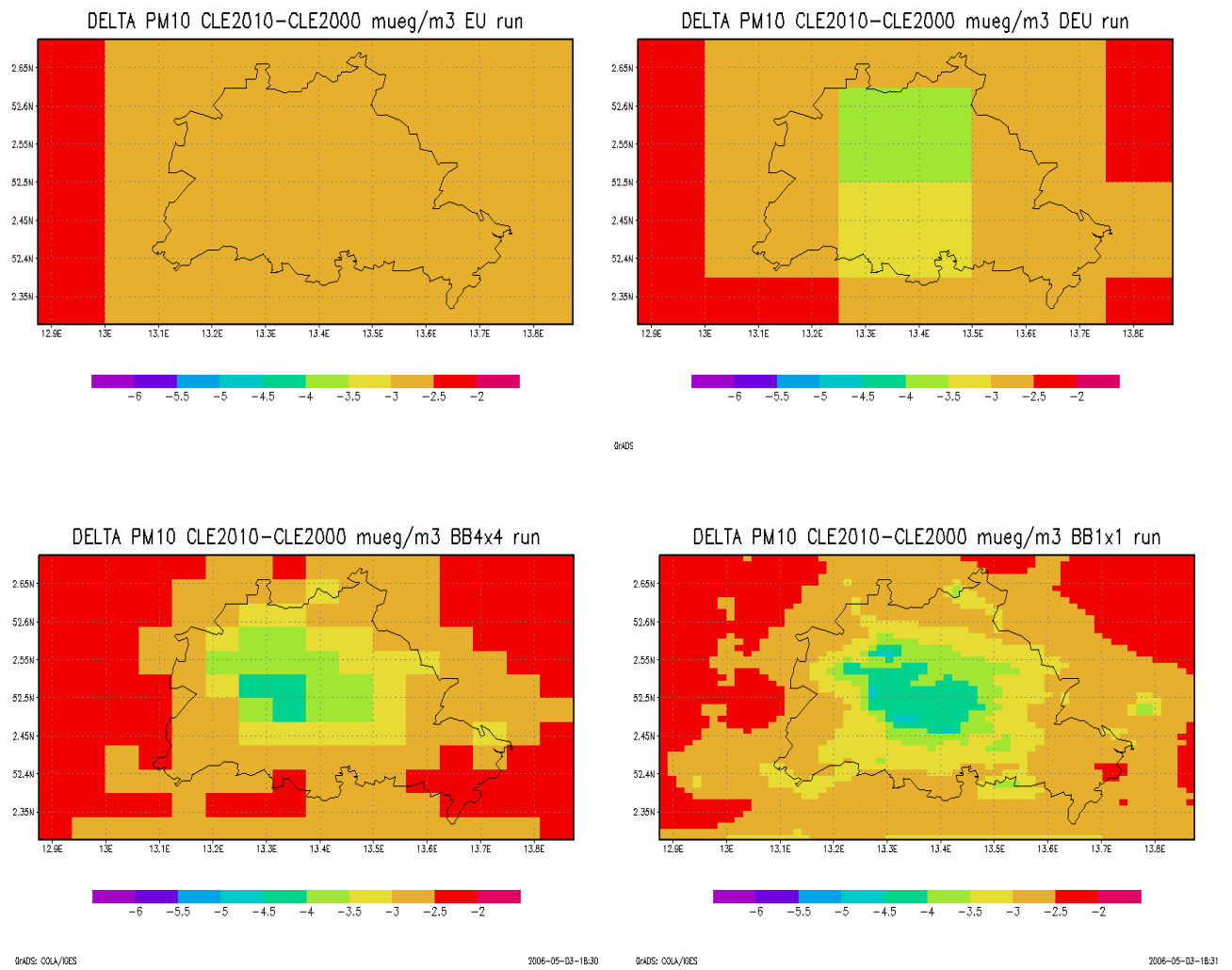


Figure 9 Calculated changes ($\mu\text{g}/\text{m}^3$) in the annual mean PM10 concentrations from the emission situation 2000 to the CLE emission situation 2010. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1

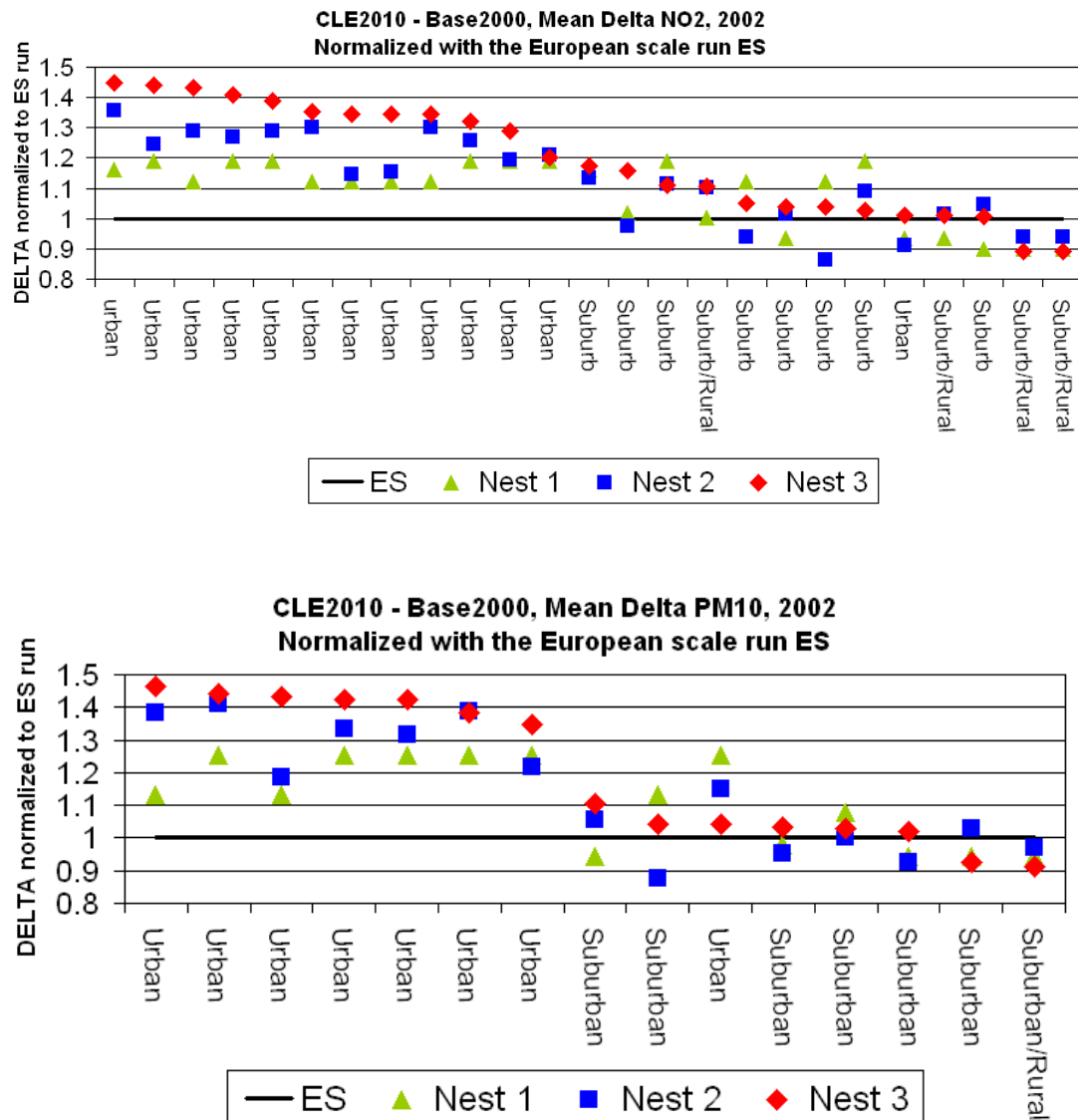


Figure 10 NO₂ and PM₁₀ concentration deltas at 25 NO₂ and 15 PM₁₀ measurement sites characterized as urban, suburban and rural/suburban type stations. The deltas for Nest 1 to 3 are expressed relative to (i.e., divided by) the normalized deltas calculated for the European scale run. CLE 2010 Scenario. For further explanations see text.

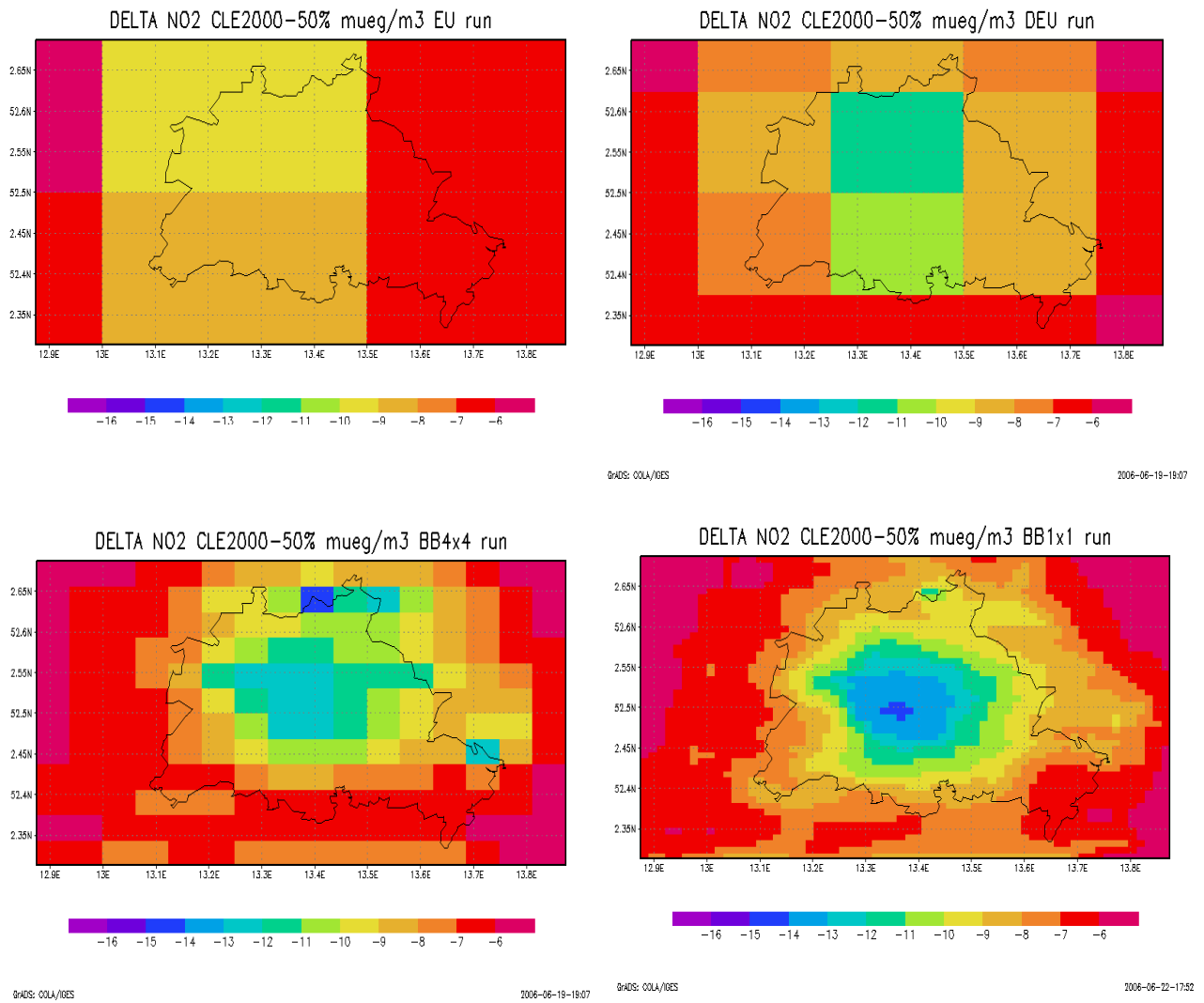


Figure 11 Calculated changes ($\mu\text{g}/\text{m}^3$) in the annual mean NO₂ concentrations from the emission situation 2000 to a uniform -50% emission situation. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1

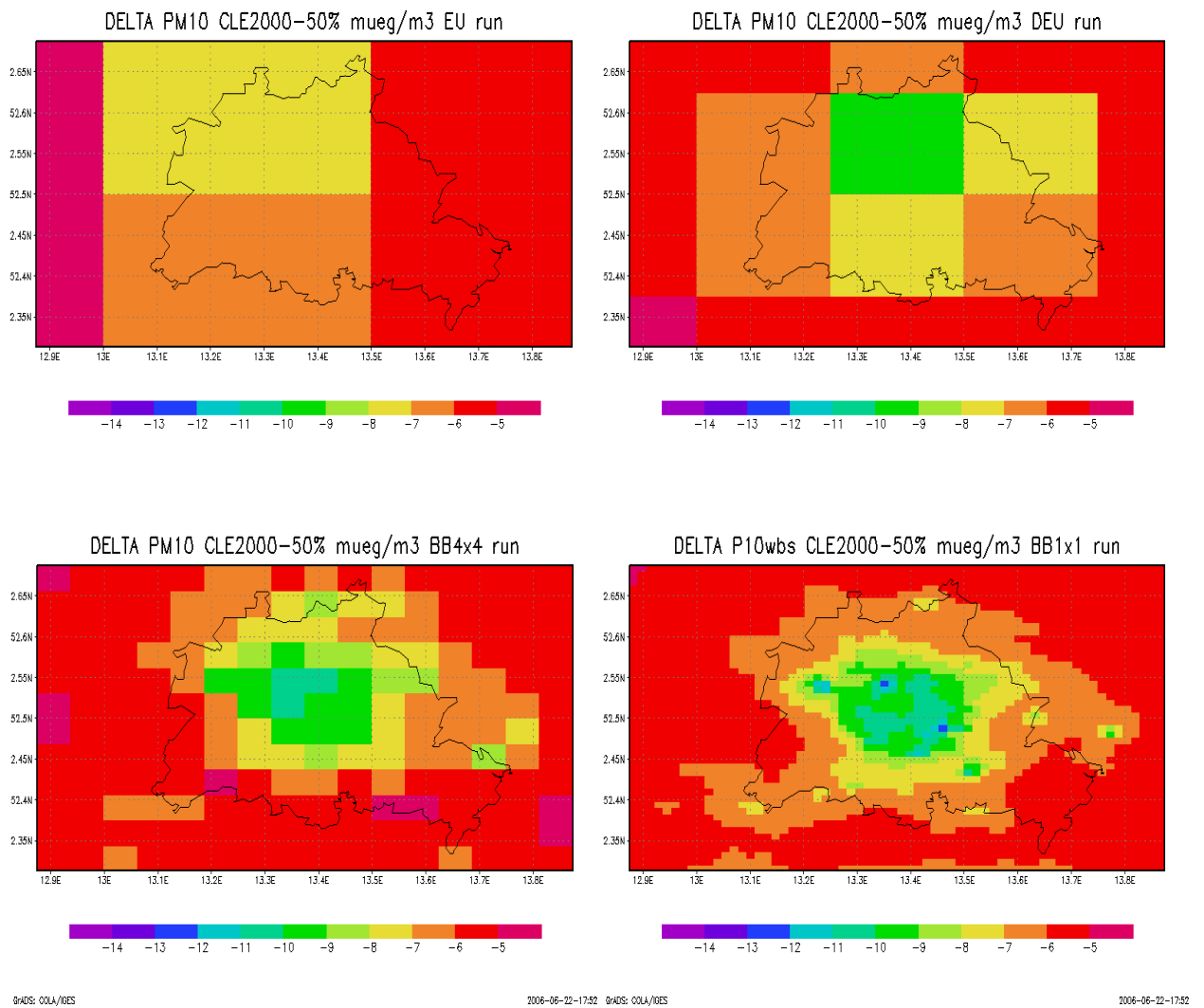


Figure 12 Calculated changes (μg/m³) in the annual mean PM₁₀ concentrations from the emission situation 2000 to a uniform -50% emission situation. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1

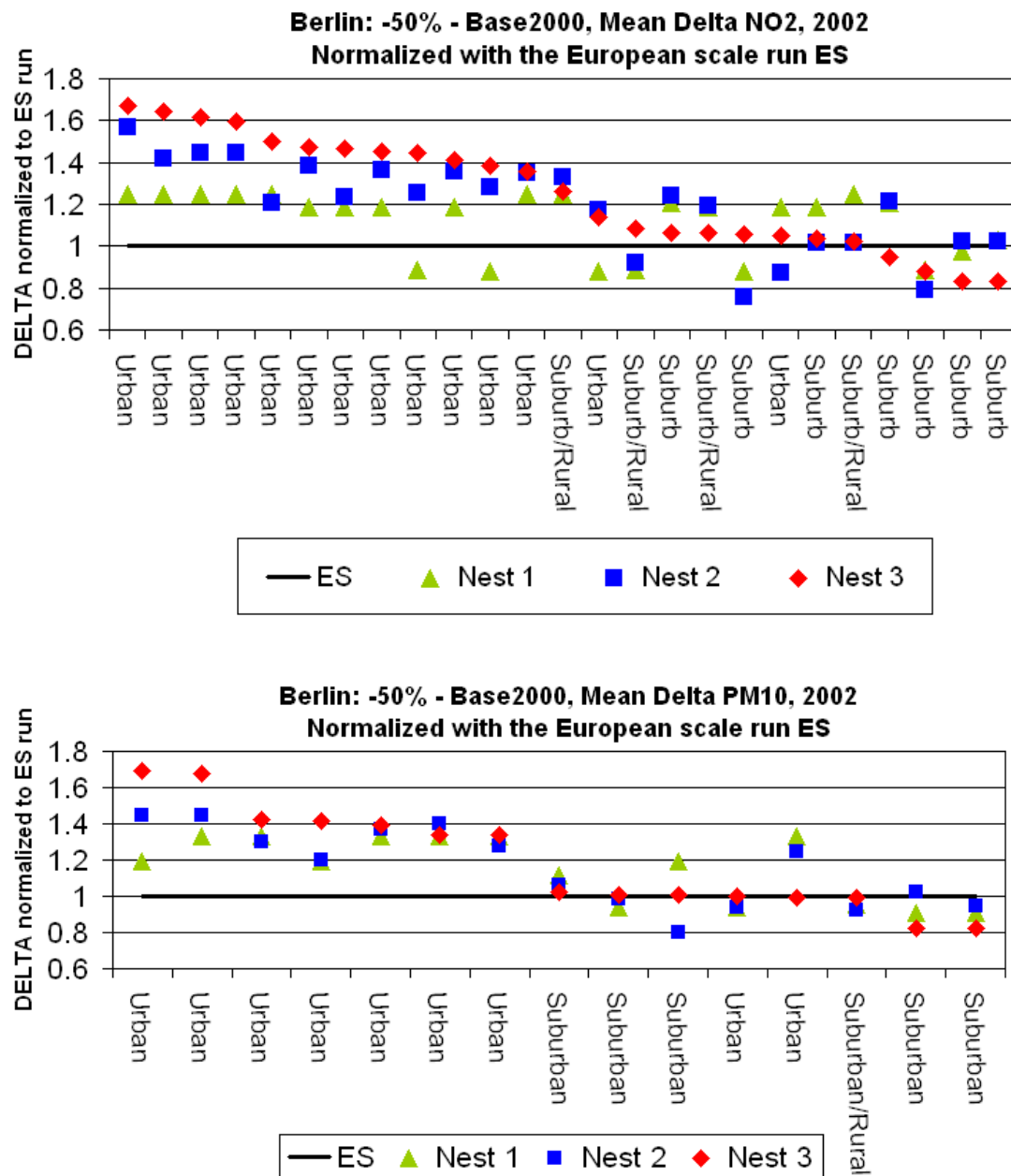


Figure 13 NO₂ and PM₁₀ concentration deltas at 25 NO₂ and 15 PM₁₀ measurement sites characterized as urban, suburban and rural/suburban type stations. The deltas for Nest 1 to 3 are expressed relative to (i.e., divided by) the normalized deltas calculated for the European scale run. Uniform -50% reduction of all emissions. For further explanations see text.

7. Summary and conclusions

Applying the RCG chemical transport model to the greater area of Berlin in four different grid sizes decreasing from 30 km down to 1 km, it turned out that model performance was best for the run with the highest grid resolution. The modelled effectiveness of control measures (CLE2010 scenario and a 50% reduction of all anthropogenic emissions) in an urban area as a function of a horizontal grid resolution showed also, that the urban increment is underestimated by the regional (grid #1) model resolution of 30 km. This implies that the effects of measures will be underestimated in urban areas if they are based on a regional scale model application. In urban areas with a highly inhomogeneous emission pattern even a resolution in the range of 5 km as used in the City-Delta exercise, can be too large for a complete capture of the urban signal.

8. References

- Amann, M., Cabala, R., Cofala, J., Heyes, C., Klimont, Z., Schöpp, W., Tarrason, L., Simpson, D., Wind, P., Jonson, J. (2005)**, The “Current Legislation” and the “Maximum Technically Feasible Reduction” cases for the CAFE baseline emission projections. CAFE Scenario Analysis Report Nr. 2. <http://europa.eu.int/comm/environment/air/cafe/index.htm>
- Amann, M., Bertok, I., Cabala, R., Cofala, J., Heyes, C., Gyarmas, F., Klimont, Z., Schöpp, W., Wagner, F. (2005b)**, Target Setting Approaches for Cost-effective Reductions of Population Exposure to Fine Particulate Matter in Europe. CAFE Scenario Analysis Report Nr. 4. <http://europa.eu.int/comm/environment/air/cafe/index.htm>
- Amann, M., I. Bertok, J. Cofala, F. Gyarmas, C. Heyes, Z. Klimont, 2005**. Baseline Scenarios for the Clean Air for Europe (CAFE) Programme. CAFE Scenario Analysis Report Nr. 1. <http://europa.eu.int/comm/environment/air/cafe/index.htm>
- Cuvelier, K. et al., 2006**, CityDelta: A model inter-comparison study to explore the impact of emission reductions in European cities in 2010. Submitted to Atmos. Environ.
- EMEP (2003a)**, Transboundary acidification, eutrophication and ground level ozone in Europe. Status Report 1/2003, PART I: Unified EMEP model description. EMEP Status Report 2003. ISSN 08606-4520.
- EMEP (2003b)**, Review and revision. Emission data reported to CLTRAP. MSC-W Status Report 2003. EMEP Status Report 2003. ISSN 0804-2446.
- Hass, H., P. Builtjes, D. Simpson and R. Stern (1997)**, Comparison of model results obtained with several European regional air quality models, Atmos. Environ. 31 (1997) 3259-3279.
- Hass, H., van Loon, M., Kessler, C., Matthijssen, J., Sauter, F., Stern, R., Zlatev, R., Langner, J., Fortescu, V., Schaap, M. (2003)**, Aerosol Modeling: Results and Inter-comparison from European Regional-scale Modeling Systems. A contribution to the EUROTRAC-2 subproject GLOREAM. EUROTRAC report 2003
- .

Kerschbaumer, A., Stern, R. und Reimer, E. (2005) Untersuchung des Potentials und der Umsetzbarkeit von Maßnahmen und der damit erzielbaren Minderungen der Feinstaub- und Stickoxidemissionen in Berlin. Bericht für die Senatsverwaltung für Stadtentwicklung Berlin. Freie Universität Berlin. Institut für Meteorologie.

Logan, J. (1998), An analysis of ozonesonde data for the troposphere, recommendations for testing 3-D models and development of a gridded climatology for tropospheric ozone, *J. Geophys. Res.* 104, 16, 1998

Loon van, M. et. al. (2004), Model Intercomparison in the framework of the review of the Unified EMEP. TNO-Report R 2004/282.

Nenes A, Pandis SN, Pilinis C (1998), ISORROPIA, A new thermodynamic equilibrium model for multiphase multicomponent inorganic aerosols, *Aquat.Geoch.*, 4, 123-152

Schell B., I. J. Ackermann, H. Hass, F. S. Binkowski, and A. Ebel, (2001), Modeling the formation of secondary organic aerosol within a comprehensive air quality model system, *J. Geophys. Res.*, 106, 28275-28293.

Stern, R., Yamartino, R., Graff, A. (2003), Dispersion Modelling within the European Community's air quality directives: Long term modelling of O₃, PM₁₀ and NO₂. 26th ITM on Air Pollution Modelling and its Application. May 26-30, 2003, Istanbul, Turkey

Tsyro, S.G. (2005), To what extend can aerosol water explain the discrepancy between model calculated and gravimetric PM₁₀ and PM_{2.5}? *Atmos. Chem. Phys.*, 5, 515-532, 2005

Visscherdijk, A. und Van der Gon, D. (2005), Gridded European anthropogenic emission data for NO_x, SO₂, NMVOC, NH₃, CO, PM₁₀, PM_{2.5} and CH₄ for the year 2000. TNO-report B&O-A R 2005/106.

Binkowski, F. S. and Shankar, U., The Regional Particulate Matter Model, 1. Model description and preliminary results. J. Geophys. Res. 100, D12, 26191-26209 (1995)
Carter, W.; Condensed atmospheric photooxidation mechanisms for isoprene, *Atmos. Environ.* 30 (1996) 4275-4290.

Claiborn et al. (1998). Regional measurements and modeling of windblown agricultural dust: The Columbia Plateau PM₁₀ program. *J.G.R. VOL 103, D16*, 19753-19767 .

Gong, S. L., Barrie, L. A. and Blanchet J.-P. (1997). Modelling sea-salt aerosols in the atmosphere. 1. Model development. *J. Geophys. Res.*, 102, 3805-3818

Hass, H., Builtjes, P. J. H., Simpson, D., and Stern, R. (1997), Comparison of model results obtained with several European regional air quality models, *Atmos. Env.* 31 (1997), 3259-3279.

Hass, H., van Loon, M., Kessler, C., Matthijssen, J., Sauter, F., Stern, R., Zlatev, R., Langner, J., Fortescu, V., Schaap, M. (2003), Aerosol Modeling: Results and Intercomparison from European Regional-scale Modeling Systems. A contribution to the EUROTRAC-2 subproject GLOREAM. EUROTRAC report 2003.

Logan, J. (1998); An analysis of ozonesonde data for the troposphere, recommendations for testing 3-D models and development of a gridded climatology for tropospheric ozone, *J. Geophys. Res.* 104, 16, 1998

Loosmore and Hunt (2000), Dust resuspension without saltation (2000). J. Geophys. Res. Vol 105, D16, 20,663 ff, August 27, 2000

Nenes, A., Pilinis, C., and Pandis, S. N.(1999), Continued Development and Testing of a New Thermodynamic Aerosol Module for Urban and Regional Air Quality Models, *Atmos. Env.* 33 (1999), 1553-1560.

Reimer, E. and Scherer, B. (1992), An operational meteorological diagnostic system for regional air pollution analysis and long-term modelling, in: *Air Pollution Modelling and its Applications IX.*, van Doop, H., ed., Plenum Press 1992.

Roemer, M., Beekmann, M., Bergström, R., Boersen, G., Feldmann, H., Flatøy, F., Honore, C., Langner, J., Jonson, J., Matthijsen, J., Memmesheimer, J., Simpson, D., Smeets, P., Solberg, S., Stern, R., Stevenson, D., Zandveld, P., Zlatev, Z. (2003), Ozone trends according to ten dispersion models. A contribution to the EUROTRAC-2 subproject TOR. *EUROTRAC report 2003*.

Schell, B., I.J. Ackermann, H. Hass, F.S. Binkowski, A. Ebel: Modeling the formation of secondary organic aerosol within a comprehensive air quality modeling system. J. Geophys. Res., 106, 28275 - 28293.

Simpson, D., A. Guenther, C.N. Hewitt, R. Steinbrecher (1995), Biogenic emissions in Europe, 1. estimates and uncertainties, *Journal of Geophysical Research*, vol. 100, No. D11, pp. 22,875-22,890, 1995.

Stern R. (1994), Entwicklung und Anwendung eines dreidimensionalen photochemischen Ausbreitungsmodells, *Meteorologische Abhandlungen Serie A, Band 8, Institut für Meteorologie der FU-Berlin*, 1994.

Stern, R., Yamartino, R., Graff, A.(2003), Dispersion Modelling within the European Community's Air Quality Framework Directive: Long Term Modelling of O₃, PM₁₀ and NO₂. 26th *ITM on Air Pollution Modelling and its Application. May 26-30, 2003, Istanbul, Turkey*

Vautard, R., Builtjes, P. H. J., Thunis, P. , Cuvelier, K., Bedogni, M. Bessagnet, B., Honoré, C., Moussiopoulos, N., Schaap, M. Stern, R. Tarrason, L., Van Loon, M. (2006), Evaluation and intercomparison of Ozone and PM₁₀ simulations by several chemistry-transport models over 4 european cities within the City-Delta project, submitted to *Atmos. Env.*

Walcek, C.J.(2000), Minor flux adjustment near mixing ratio extremes for simplified yet highly accurate monotonic calculation of tracer advection, J. Geophys. Res., 105, D7 (2000), 9335-9348.

Yamartino, R.J., J. Scire, G.R. Carmichael, and Y.S. Chang; The CALGRID mesoscale photochemical grid model-I. Model formulation, *Atmos. Environ.*, 26A (1992), 1493-1512.

9. Figure captions

Figure 1 : RCG modelling domains. Upper left: European scale grid with resolution of 0.25° Lat., 0.5° Lon. Upper right: Nest 1, national scale (Germany) grid with resolution of 0.125° Lat., 0.25° Lon. Lower left: Nest 2, the Federal State (Brandenburg) grid with resolution of 0.03125° Lat., 0.0625° Lon., embedded in Nest 1. Lower right: Nest 3, urban grid Berlin with resolution of 0.0078125° Lat., 0.015625° Lon., embedded in Nest 2 (and Nest 1) and also showing in red the major “ring” motorway around Berlin.	8
Figure 2 : NO _x annual emissions density in t/km ² at four scales for the greater Berlin area. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid Lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1. Note the different scaling for the European grid.	10
Figure 3 Calculated NO ₂ annual mean at four scales for the greater Berlin area. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid Lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1.	12
Figure 4 Calculated PM ₁₀ annual mean at four scales for the greater Berlin area. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid Lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1.	13
Figure 5 Scatter diagram of observed and calculated NO ₂ and PM ₁₀ annual means in the greater Berlin area at four scales, including regression lines and correlation coefficients. Dashed lines indicate the range of +/- 50% of the observations. For further explanations see text.	14
Figure 6 NO ₂ and PM ₁₀ annual mean urban increments in µg/m ³ at NO ₂ and PM ₁₀ measurement locations in the Berlin area, characterized as urban, suburban and rural/suburban type stations. For further explanations see text.	15
Figure 7 PM _{2.5} and SIA (sum of the secondary inorganic aerosols) annual mean urban increments in µg/m ³ at PM ₁₀ measurement locations in the Berlin area, characterized as urban, suburban and rural/suburban type stations. For further explanations see text.	16
Figure 8 Calculated changes (µg/m ³) in the annual mean NO ₂ concentrations from the emission situation 2000 to the CLE emission situation 2010. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1.	18
Figure 9 Calculated changes (µg/m ³) in the annual mean PM ₁₀ concentrations from the emission situation 2000 to the CLE emission situation 2010. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1.	19
Figure 10 NO ₂ and PM ₁₀ concentration deltas at 25 NO ₂ and 15 PM ₁₀ measurement sites characterized as urban, suburban and rural/suburban type stations. The deltas for Nest 1 to 3 are expressed relative to (i.e., divided by) the normalized deltas	

calculated for the European scale run. CLE 2010 Scenario. For further explanations see text.	20
Figure 11 Calculated changes ($\mu\text{g}/\text{m}^3$) in the annual mean NO_2 concentrations from the emission situation 2000 to a uniform -50% emission situation. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1.....	21
Figure 12 Calculated changes ($\mu\text{g}/\text{m}^3$) in the annual mean PM_{10} concentrations from the emission situation 2000 to a uniform -50% emission situation. Upper left: European scale grid, Upper right: Nest 1, national scale (Germany) grid lower left: Nest 2, the Federal State (Brandenburg). Lower right: Nest 3, urban grid Berlin. For grid resolutions, see Fig. 1.....	22
Figure 13 NO_2 and PM_{10} concentration deltas at 25 NO_2 and 15 PM_{10} measurement sites characterized as urban, suburban and rural/suburban type stations. The deltas for Nest 1 to 3 are expressed relative to (i.e., divided by) the normalized deltas calculated for the European scale run. Uniform -50% reduction of all emissions. For further explanations see text.	23