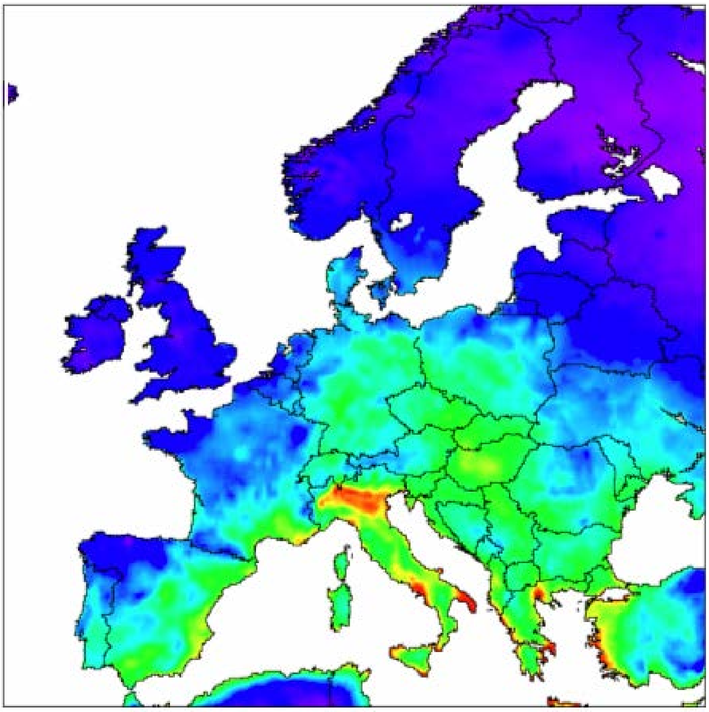
Urban Air quality mapping: new methodologies based on the GMES/COPERNICUS services



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European Topic Centre on Air Pollution and Climate Change Mitigation

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Front page picture:
SOMO35 ozone map for year 2008 (in µg·m^{-3}·d), obtained from an ensemble of analysed model simulations. This map has been produced as part of MACC project (copyright).

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1 Introduction

1.1 General issues

Nowadays, air quality legislation in the European Union, driven by the European Directives (Directive on ambient air quality and cleaner air for Europe (2008/50/CE) and Directive relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air (2004/107/EC)), oblige the Member States (MS) to monitor regulated pollutants, to report on exceedances of limit and target values. The MS have to implement action plans to avoid such non-attainment situations and to inform in those cases about exposure of European citizens to air pollutants harmful for their health.

Limit values currently apply for sulphur dioxide, nitrogen dioxide, PM_{10}, benzene, carbon monoxide and lead while target values are set for ozone (also long term objectives), $PM_{2.5}$, benzo(a)pyrene and heavy metals . The most worrying situations hold for PM_{10} and NO_2 for which annual and shorter term limit values (daily and hourly respectively) are exceeded in many urban places in all the Member States. In those cases, as in any exceedance situation, national authorities have to report on the causes of these exceedances and to assess the geographical areas and the number of inhabitants exposed, in the context of the air quality plans.

Mapping tools are definitively the most appropriate way for evaluating and displaying this kind of indicators. Maps are powerful means to improve communication to the general public and make policy decisions easier with concrete and objective representations of pollution patterns, much more comprehensive than tables and statistics. Moreover, cross-analysis with land cover data or population maps in Geographic Information Systems (GIS) can be elaborated to quantify areas and number of inhabitants exposed, as requested by the Directives. However to derive such maps, “punctual” observation data measured at monitoring sites or within field campaigns are not sufficient. By definition, mapped air pollutant concentration fields must be distributed over grids discretizing the targeted geographical domain with an appropriate resolution. The higher the resolution is, the better air pollution patterns are supposed to be displayed. This “spatialization” process should obviously integrate observations, and other descriptive variables: data related to land cover, road network, population density, eventually modelling results etc. They are combined using either deterministic, geostatistical or statistical tools, or a combination of those approaches.

Obviously mapping systems based on concepts which combine modelling and measurement should offer **the most accurate and the most satisfactory products for decision makers**: observations provide the best estimate of the concentration levels at a given punctual location, and deterministic models are supposed to simulate relevant spatial and temporal distributions of the air pollutant concentration fields. Actually, if the model is mature enough and properly validated, one can expect that the dynamical and chemical processes that drive those distributions in the concentration fields are well simulated for a realistic representation of air pollution patterns.

1.2 Air quality urban maps: technical considerations

Basically, air quality mapping can be derived from two different approaches (see also Schneider et al. 2013):

- Interpolation of observations using more or less complex geostatistical methods (kriging) which are based on the analysis of the temporal and spatial variability of the measurements and the use of ancillary variables to weight the interpolation process;
- Deterministic modelling which solves chemistry-transport equations using input and initial data for emissions, meteorology, boundary conditions.

Kriging-based methodologies have proven to be efficient ways of incorporating different sources of data (monitoring, modelling, geographical databases) into well-resolved informative maps on an annual or short-term basis. Review and application of such approaches can be found in ETC/ACM reports, especially those that refer to the production of *annually interpolated air quality maps of Europe* (http://acm.eionet.europa.eu/databases/interpolated_aq_maps/index_html). Basic principles are reminded in paragraph 3 with appropriate references. To correctly account for concentration gradients and achieve an adequate level of detail for air quality assessment and planning, large effort is usually devoted to the definition of relevant high resolved auxiliary variables that can be combined with measurements.

On the other side, nowadays, one can reasonably consider that chemistry transport models developed and used to simulate atmospheric transport and chemistry at regional scales are relevant to provide reliable estimations of **background air pollutant concentrations**. Those models are generally run over so called “regional” domains covering European, national and sub-national scales with spatial resolution varying from 50km to 10 km.
Several European countries get their own national chemistry-transport model dedicated to policy-support purposes and operational air quality forecasting.

Such models are run operationally to answer policy relevant questions related to the:

- Description of large scale atmospheric pollution patterns and mapping of background concentrations;
- Analysis of transboundary fluxes versus national contribution to episodes;
- Analysis of the impact of emission reduction scenarios;
- Allocation of air pollutant sources;
- Forecasting of air pollution situations.

Therefore those models can provide relevant input data to answer several requests from the Air Quality Directives but might be too coarse in resolution to deal with the:

1. Estimation of population exposure;
2. Prediction of exceedances of the limit and target values.

The most worrying areas considering both issues are urban areas and most of the European cities are so to speak “diluted” in a grid cell of 10km*10km or 15km*15 km resolution. Therefore it is expected that air pollutant concentrations of locally emitted pollutants (like NO_2 and PM) are underestimated over urban areas by deterministic models applied with such resolutions.

“Urban mapping” relates precisely to those issues, and supposes that specific treatment of air quality data (observation and modelling) should be achieved to reproduce more precisely the concentration levels that impact citizens and imply non-attainment limit and target values.

Use of urban maps in the Member States and in general in European cities to report on population exposure and exceedances of limit and target values is very heterogeneous and rather sparse. The

major part of EU countries exclusively use measurement data while some of them have developed skills and competences in urban modelling using kriging approaches or so-called urban models (e.g. ADMS-Urban; Mc Hugh, 1997).

The objective of this study is to evaluate if new material available from recent and current projects could be used to update and improve methodologies and to support local decision makers in getting air pollution maps over their areas of interest, when they have not the resources to develop their own mapping tools.
Presently the development of the GMES[1] Atmosphere services by the European Commission, that should be operationally available in 2014, offers new perspectives in that sense.

1.3 Aim of the present study

Aware about their limitations to deal with local air pollution situations which are the most worrying ones in terms of assessment, the European Environment Agency (EEA) has asked the European Topic Center on Air Pollution and Climate Mitigation (ETC/ACM) to investigate methodologies that could potentially be used to "refine" at the local scale concentration fields provided by regional air quality models. More precisely, the objective is to define and assess approaches that can be easily coupled with Chemical Transport Model (CTM) outputs delivered by the future operational GMES/COPERNICUS services in order to better evaluate air pollution patterns and situations when limit values are exceeded on the urban and local scale . The research projects MACC[2] (2009-2011) and MACC2 (2011-2014), funded by the 7^{th} Framework research program, aim at developing and testing models and tools that will be implemented in the Copernicus services after 2014. Obviously, NO_2 and $PM_{2.5}$ and PM_{10} issues are the main priorities for such work.

The Copernicus services can deliver high quality air pollutant concentration maps at the European scale in a routine way with a resolution that is currently about 25 km, and that should improve to 10 km the coming years (2014). Data provided by the services are freely available and validated but need to be refined to generate actual urban maps over targeted city areas. **The aim of this report is to review and conceive some methodologies that could be implemented to promote the use of the Copernicus/MACC European maps for urban issues in European countries**. To meet this objective we will consider several approaches, some that are based on the current practises developed by the ETC/ACM and others that consider new developments in recent research projects like the EC4MACS[3] project fitted to provide methodological tools to the European Commission. The following issues will be covered in the present report:

- How to use the Copernicus/MACC products within the ETC/ACM methodology for urban mapping;
- How the calculation of "urban increments" according to the EC4MACS methodology (http://www.ec4macs.eu/home/index.html) can help in approving regional chemistry-transport model runs at the urban scale;
- Which high resolution ancillary variables can be used to refine regional air quality model results at the urban scale?

It is important to note that **simulating exeedances of limit values in hot spot areas (near busy roads or industries) is not actually covered by this analysis**. Indeed when exceedances are due to very local sources, only local scale models (statistical, street canyon or similar models) fed by very high resolution input data can provide some relevant insight with the appropriate resolution (EEA, 2011),

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[1] Global Monitoring for Environment and Security (recently re-named to COPERNICUS)
[2] Monitoring Atmospheric Composition and Climate http://www.gmes-atmosphere.eu/
[3] EC4MACS: European Consortium for Modelling of Air Pollution and Climate Strategies (http://www.ec4macs.eu/). This is a Life project which aims at developing modelling tools and databases dedicated to air quality policy support

(Denby, 2011). Those approaches can only be run following a case by case analysis by local experts. Indeed the analysis of the local exceedances of limit and target values can be due to specific activities in the vicinity of the station or to particular site characteristics. Such parameters can only be taken into account with an accurate description of the local environment by competent local experts. However we will refer in this document to some technical guides that address those questions. If respective input data are available one could either implement local models (like street canyon models) or correct urban concentrations (possibly issued from the previous method) with a local increment linked to the traffic contribution or other local sources. This increment is modelled statistically using local measurement data issued from automatic devices or field campaigns (with passive samplers for instance), and other model-external parameters: emissions data, road or site typology, distance between the main source and the measurement site... Those aspects will be shortly discussed in the last part of the report.

Finally the Air Implementation Pilot cities study launched in 2012 by the EEA should be mentioned. This initiative aims at sharing both “successful” and “unsuccessful" experiences, to develop proposals for improved implementation of air regulation that can be shared across European cities. The project started with a sample of 8 cities: Berlin, Dublin, Madrid, Malmö, Milan, Ploiesti, Prague, and Vienna. New mapping methodologies discussed in this report have been applied to display air pollution indicators over those cities. The results are provided in the annexes.

2 The GMES/Copernicus Atmosphere Services

Copernicus-MACC and MACC-II in brief (http://www.gmes-atmosphere.eu/):

The Copernicus program is a European initiative to support the development and the implementation of operational services dedicated to environment and security monitoring. They should provide to the general public, decision makers, research laboratories, industries, consulting companies, data they need or request for knowledge and economy development.
The projects MACC (2009-2011) and MACC-II (2011-2014) relate to the pre-operational phase of the future Copernicus atmospheric Services (2014). Such monitoring services aim at describing and forecasting the atmospheric composition at the global to European scales to inform general public and support policy decision. Services result from a wealth of data from in-situ networks, Earth observations, model results that the "service providers" use to derive operational products: forecasts, maps, and policy-oriented tools. Copernicus should facilitate the development of complementary methods and products that target specific issues or smaller geographical domains than Europe (cities for instance). Input data available from Copernicus services should serve the development of "downstream" services.

In the field of the atmosphere, regional air quality services include the provision of up to 2 days forecasts, daily analysed maps, and re-analysed maps (or assessments) of regulated air pollutants concentration fields (O_3, SO_2, NO_2, PM_{10}, $PM_{2.5}$), throughout the Europe. These products are based on the following characteristics:

- 7 CTMs are run over Europe with a spatial resolution of about 25km. A target resolution of 10km is foreseen for 2014:
  - LOTOS-EUROS (http://www.lotos-euros.nl/) in the Netherlands (Schaap et al, 2008),
  - CHIMERE (http://www.lmd.polytechnique.fr/chimere/) in France (Bessagnet et al, 2004),
  - MOCAGE (http://www.cnrm.meteo.fr/gmgec/spip.php?article87) in France (Peuch et al 1999)
  - EMEP (http://www.emep.int/index_model.html)
  - MATCH (http://www.smhi.se/sgn0106/if/meteorologi/match.htm) in Sweden (Robertson et al, 1999),
  - SILAM (http://silam.fmi.fi/) in Finland (Sofiev et al, 2006),
  - EURAD (http://www.eurad.uni-koeln.de/index_e.html) in Germany
- Analyses refer to the daily calculation of air quality fields assimilating available data in the modelling process. At the time they are used, observation data are not necessarily validated;
- Re-analyses (or assessments) refer to the calculation of air quality fields assimilating observation data once are validated and using re-analysed meteorological fields as input;
- Forecasts, analyses and re-analyses computed by each of the 7 MACC models are combined according to an "ensemble" approach, which results in best estimate;
- Models are fed by a high resolution (7km) emission inventory developed for 2007 and updated for 2010 covering the whole of Europe (http://www.gmes-atmosphere.eu/about/project_structure/input_data/d_emis/).

Analysed and re-analysed air quality maps published by the MACC projects never result from raw simulations. Those are improved implementing data assimilation[4] techniques which "*force the model*

[4] *'Data assimilation' methods [...] are physically consistent. The methods refer to a modelling technique that incorporates monitoring data directly into air quality model calculations during the modelling process itself (see*

to be more consistent with available observations" (EEA, 2011). Therefore a large part of research activities in those projects is devoted to the development of sophisticated data assimilation processes using extensive sets of observation data. Currently, all models assimilate in-situ data from the Airbase database (http://acm.eionet.europa.eu/databases/airbase/). By the end of MACC2, the modelling teams should have developed specific chains to assimilate Earth Observations provided by satellites. Potential benefits have been studied by the ETC/ACM in 2012 (Schneider et al. 2013).
Evaluation of model results against observations is systematically is systematically considered and is a key-point of the Copernicus services provision. In this way, the ability of the MACC individual models and the Ensemble model resulting from a weighted combination of the individual ones, to simulate in a satisfying way air pollutant concentration fields throughout Europe has been confirmed via an in depth evaluation (figure 1).

A specific work-package within MACC2 (called EVA for "Validated assessments") delivers every year re-analysed fields of regulated air pollutant concentrations (http://www.gmes-atmosphere.eu/services/raq/raq_reanalysis/). They allow the calculation of relevant air policy indicators: annual averages, maps of exceedances of the limit and target values, maps of ozone impact indicators (AOT40 for crops and forests, SOMO 35, daily maximum 8-hour mean).

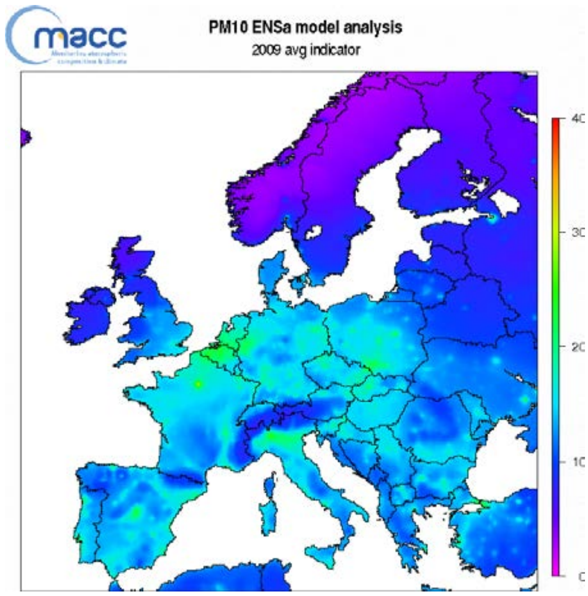

Figure 1. PM10 yearly average for 2009 issued from the MACC re-analysis chain. AIRBASE data are assimilated in simulations run by 7 selected CTMs. The maps display the "ensemble" results

How Copernicus/MACC product are (or should be) used to improve urban mapping

In summary, the current MACC2 project and after 2014 the Copernicus atmosphere services, will allow the delivery at the European and national scales of high quality regulated air pollutant concentrations fields.
They result from a complex modelling chain where 7 CTMs are operationally run assimilating available relevant observation data, and combined together in an "ensemble" model that gathers all models' strengths.

- Copernicus/MACC2 products are relevant for assessing background air pollutant concentrations and their trends, long range transport and natural contributions to countrywide levels, and to better understand the nature of the episodes.

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also Section 5.6.3). It is the measured data that helps guide the model towards an optimal solution, one that is consistent with the physical description provided by the air quality model (EEA, 2011)

- They provide high quality maps of air pollution patterns and validated quantification of highest rural and urban background levels in the various parts of Europe. Their comparison to limit and target values is possible.

But the spatial resolution adopted in the current MACC2 system does not allow catching local pollution situations, especially near busy roads or industrial sites. Further, it does not capture hot spots (e.g. due street canyon effects or traffic congestion areas) in the urban areas.

- This is a limitation of the system, because it means that exceedances of regulated threshold values that occur at these locations cannot be caught. And it is well known that a large number of situations where NO_2 and PM_{10} limit values are exceeded are encountered close to local sources.

Currently, only observations and local modelling coupled with a very high resolution emission inventories (not compatible with the European scale) can accurately deal with this issue. In the Copernicus system, it is considered that this should be covered by local expertise or by the so-called downstream services. Downstream services should develop furthermore when the Copernicus services become operational. In principle, they should bear upon the Copernicus products to create new services suited for specific issues (e.g. health impact) and the local scale.

However some significant improvements that are oh high interest for urban mapping will result from the MACC2 project:

- **The spatial resolution of the models run in MACC2 will increase: a 10 x 10 km^2 spatial resolution over the whole of Europe is expected**. Such a resolution will be relevant for ozone patterns, and will highly increase accuracy of NO_2 and PM concentration fields. It is important to note that this is the same resolution as the one achieved by the ETC/ACM methodologies using kriging and data fusion methodologies;
- **Analysis of the added-value of statistical approaches performed to improve regional simulated fields** accounting for ancillary variables that accurately describe the emission sources drivers (population density, road traffic activity,...) will be considered. Such post-processing methods can help in refining the concentration gradients to achieve more realistic air pollution patterns, which are generally smoothed in maps provided by regional air quality models.

All Copernicus/MACC modelling results (from the individual models and the ensemble one) are freely available on request.

3 Urban maps based on the ETC/ACM methodology

3.1 General description

The ETC/ACM developed an appropriate methodological framework for the routine production of high resolved air quality maps throughout Europe (http://acm.eionet.europa.eu/databases/interpolated_aq_maps/index_html). It allows a systematic assessment of air quality patterns and trends. Therefore, the ETC/ACM delivers every year annual rural and urban maps of ozone (AOT40 for crops and forests, SOMO 35 and 26th highest daily maximum 8-hour mean) and PM_{10} (annual average, 36th highest daily mean) with a spatial resolution of 10 x 10 km^2.

Kriging is a generic term which actually encompasses different techniques. It refers to interpolation techniques that make use of a model of spatial autocorrelation (usually the form of a variogram model) to infer optimal estimates of a variable at a given set of locations. For air quality issues, inter-comparison studies (Malherbe et al, 2009) between kriging variants usually do not show major differences in the results, at least in the domain delimited by the observation points used for kriging.

The mapping methodology developed by the ETC/ACM is based on a 'kriging of the residuals' approach, see for instance Horolek, et al. (2007) for an extensive description, and Horolek et al, (2008), Horolek et al. (2010), Denby et al. (2011). Actually, regression followed by kriging of the residuals is applied using AirBase measurement data supplemented by:

- large scale EMEP[5] modeling results : 50 x 50 km^2 resolution,
- meteorological parameters issued from the Meteorological Archival and Retrieval System (MARS) maintained by ECMWF[6] : 27 km resolution for temperature, wind, solar radiation, precipitations,
- altitude : 200 m x 200 m grid,
- land cover: 100 m x 100 m grid.

Population density (100mx100m grid) is used for the rural/urban maps merging process.
The rural maps are based on observations (measurements) at rural background stations supplemented by EMEP model outputs, meteorological and altitude data. Urban maps are based on observations at urban and suburban background stations supplemented by meteorological data.. Subsequent to that, the rural and urban maps are merged into one combined air quality indicator map using a European-wide population density grid on a 1 x 1 km^2 grid resolution.
It should be noted that the linear regressions and their residual interpolations are currently executed on an aggregated 10x10 km^2 grid resolution, despite some supplementary data being available in a finer grid. That is to keep the calculation demands within reasonable hardware and software limits.

The ETC/ACM has developed extensive experience in applying those methodologies, and this allows the yearly publication of European-wide air quality maps by the EEA. They improved over the last years as described in the ETC reports available on http://acm.eionet.europa.eu/databases/interpolated_aq_maps/index_html (Figure 2). A relevant question is to assess if the availability of the Copernicus products can help in improving furthermore those approaches.

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[5] EMEP is the model used by the Convention on Long Range Transboundary Air Pollution for policy studies http://www.emep.int/index_model.html

[6] European Center for medium-Range Weather Forecasts, www.ecmwf.int

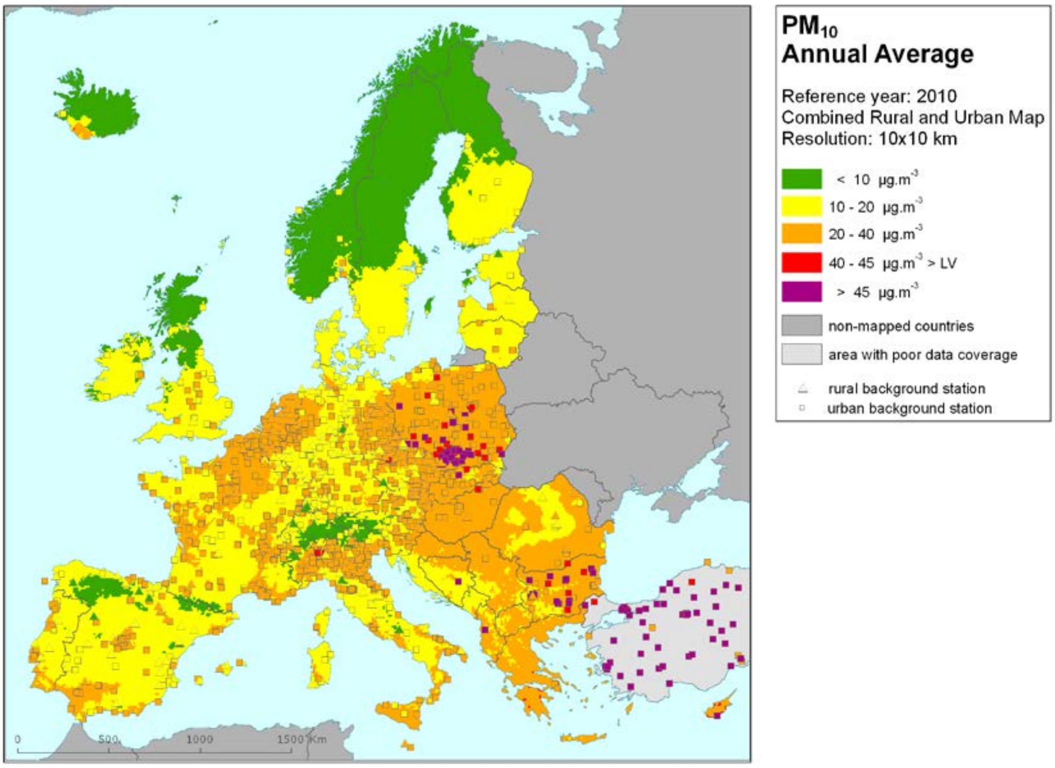

Figure 2. Combined rural and urban concentration map of PM_{10} annual values in µg.m-3 for the year 20010 Source : ETC/ACM

3.2 Use of the GMES products within the current ETC/ACM approach

In the approach so far used by the ETC/ACM and briefly described above, EMEP regional modelling results are a key factor determining the quality of the maps, besides the observation data. . However, until now they have been available with a rather coarse spatial resolution of 50 x 50 km^2. This resolution will improve in the coming years [7](the decision has been taken during the last EMEP Steering body meeting in September 2012), but with the availability of Copernicus results, one can afford to foresee quick improvements.

3.2.1 First approach: substituting EMEP model results with the Copernicus/MACC ensemble

The chemistry transport models are currently run within MACC2 with a 25 km resolution in the worst case (but it drives the ensemble model resolution). But it is confirmed by the evaluation process that

[7] EMEP is running for the convention on Long range Transboundary air Pollution under the so-called EMEP program (Cooperative Porgramme for monitoring and evaluation of the long range transmissions of air pollutants in Europe (www.emep.int). Decisions related to the development of the EMEP model, must be agreed by the EMEP steering body which is formed by representatives of each country (Partie), member of the Convention. Improving EMEP model resolution for policy purposes in support of the Convention work is a decision taken in 2012 :
http://www.unece.org/fileadmin/DAM/env/documents/2012/air/EMEP_36th/n_3_EMEP_note_on_grid_scale__projection_and_reporting.pdf

the Ensemble model provides better results than individual models and in particular better than EMEP which participates to the ensemble.
Therefore, using in the ETC/ACM kriging method with Copernicus/MACC ensemble model results instead of EMEP 50km model results will improve the maps, especially in urban areas for local pollutants like NO_2 and PM. The methodology could be summarised as follows:

1. Download from the Copernicus /MACC service European scale background concentration issued from the **Ensemble raw simulations**. 25km*25 km resolution at least for the current years;
2. Rural maps = kriging observations at rural sites + Copernicus /MACC model results (25km*25km) plus meteorological[8] and site parameters;
3. Urban maps = kriging observations at urban sites + Copernicus /MACC model results + Urban increment (25km*25km) plus meteorological and site parameters;
4. Merging rural and urban maps distributing rural and urban concentration fields according to the population distribution available with a 1km*1km resolution;
5. Aggregating the results over a 10km*10km grid.

The approach will be applied for in-depth comparison with the "classic" ETC/ACM method in 2013 by the ETC/ACM. The comparison will be based on classical model evaluation approaches, using either a set of observations that is not used in the kriging process, or cross-validation principles[9].

3.2.2 Second option: considering the Copernicus /MACC re-analyses

As described in Section 2.2 they are made up of assimilated fields, currently based on in-situ AIRBASE data. Therefore they are "equivalent", in principle, to the kriging maps provided by the ETC/ACM.

It is definitively interesting to compare those re-analyses with the current ETC/ACM high resolved maps, and those derived with the previous approach (3.2.1). Comparison with MACC ensemble model results and perhaps individual models running with a resolution better than 25km will be relevant. This work will be done by the ETC/ACM in 2013.

3.2.3 Third option: use model results corrected over urban areas

The previous approaches are based in the best case when high resolution runs with will be operational in 2014 in Copernicus on a 10 x 10 km^2 model resolution. One can reasonably consider that it is relevant and sufficient to catch **ozone pollution patterns**. A recent study (summer 2012) conducted under the Task Force on Measurement and Modelling of the EMEP program assessed the impact of fine resolution for the simulation of various air pollutants, comparing results of 4 EMEP models runs for the same year (2009). The results are not published[10] yet but they show that for ozone 10 x 10 km^2 resolution is the optimum: ozone results from large scale dynamic processes and long term chemistry and it is shown that the results do not improve significantly with a higher model resolution.

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[8] It should be noted that ECMWF recently (2009) improved the resolution of its regional meteorological models. Therefore, it must be investigated if the resolution of the meteorological variables can be improved as well for maps related to most recent years.
[9] It must be reminded that in 2014, all the models will run with a 10 km resolution (with an emission inventory built up with an equivalent resolution). Thus, significant improvements can be expected. It can be interesting to test the method with individual model runs if some of them are already available with a 10 km x 10 km resolution in 2013.
[10] But they were reported to the 36th session of the EMEP Steering Body meeting (http://www.unece.org/fileadmin/DAM/env/documents/2012/air/EMEP_36th)

For other pollutants like NO_2 and PM which are characterized by a much more “local behaviour” it can be insufficient for simulating emission variability in the urban areas. Recent work realised under the EC4MACS project (see chapter 4.1)provides some solutions for improving this situation, even if they are still inappropriate to reproduce the situation close to busy roads or industrial sites! This point is discussed in the next section.

4 Improving urban concentrations with the EC4MACS approach

4.1 General principle

The EC4MACS project (http://www.ec4macs.eu/) is an EU-LIFE-ENVIRONMENT program, which aims at preparing knowledge base for policy making on air quality and climate change in the European Union. During the period 2006-2012 (end date of the project) EC4MACS established a coherent toolbox of relevant sectoral models that incorporate latest scientific findings in the field of air pollution decision making.
Amongst those tools it derived methodologies to improve the representations of air pollutant concentration fields over urban areas to improve regional model results usually implemented in integrated assessment approaches (EC4MACS, 2012).

The downscaling process implemented in EC4MACCs, allows deriving a simple correction at the city level which reflects the contribution of ground level urban sources. Road traffic, and low residential sources such as domestic stoves are the most significant ones that influence PM and NO_2 concentrations. However the urban correction process is not appropriate to catch exceedances that can occur in the vicinity of busy roads or industrial sites. The correction is applied to concentration fields computed with a low spatial resolution.

The basic idea is summarised by the figure below (Figure 3) and can be described by 4 methodological steps:

1- Run the CTM in a low resolution configuration (50 to 25 km^2) to get the reference regional run.
2- Run the CTM in a high resolution configuration (6-7 km^2) what is relevant to improve the urban background concentrations (but not the local hot-spot levels).
3- Derive the urban increment (for PM and NO_2) of the city areas computing the difference between low and high resolution runs. Annual urban increments are calculated by averaging hourly simulations. This step is justified if one cannot afford to multiply the number of high resolution runs which are computationally expensive. The high resolution run is done with a given model for a given target (reference) year. It is then assumed that the correction can be extrapolated for other years (with emissions not too far from the one of the reference year) and also with other models. This last point is the most difficult, because combining results from different models can weaken the methodology, because of the lack of consistency between various model parameterisations. An obvious issue is the fact that all models do not use the same spatial discretisation grid for simulation, so before transposing one model results on the other, an interpolation step is often necessary and can induce inaccuracies.
4- Apply a co-kriging method to map annual urban increment fields with 1 x 1 km^2 resolution, using population density as a proxy (Figure 4).
5- This increment is considered as a function of emissions. As a first approximation a linear function can be considered.

The urban increment can be systematically applied to air pollutant concentrations calculated with a low resolution model runs on a spatial scale of (6-7 km^2), whatever emission scenario is taken into account (Figure 5).

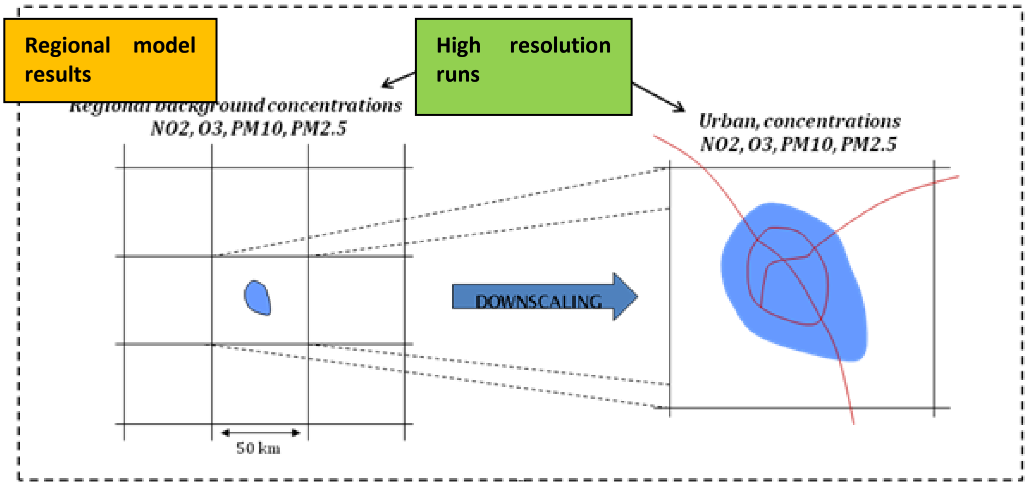

Figure 3. General principle of the downscaling approach within EC4MACS

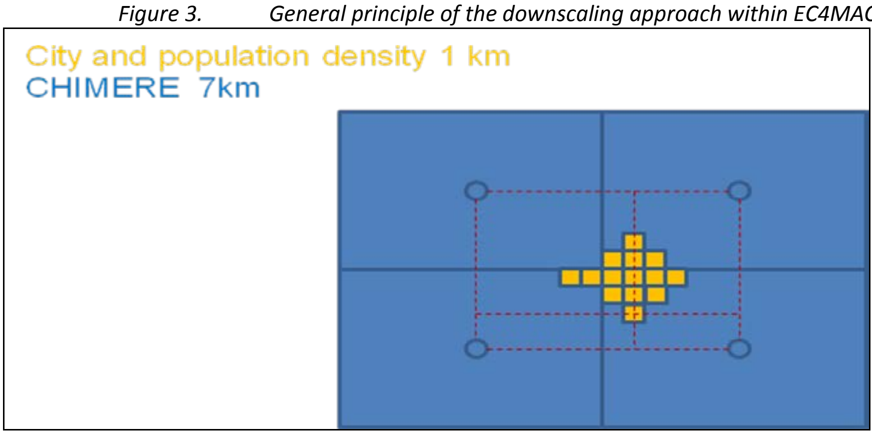

Figure 4. Co-kriging approach to derive 1km air pollutant concentration fields

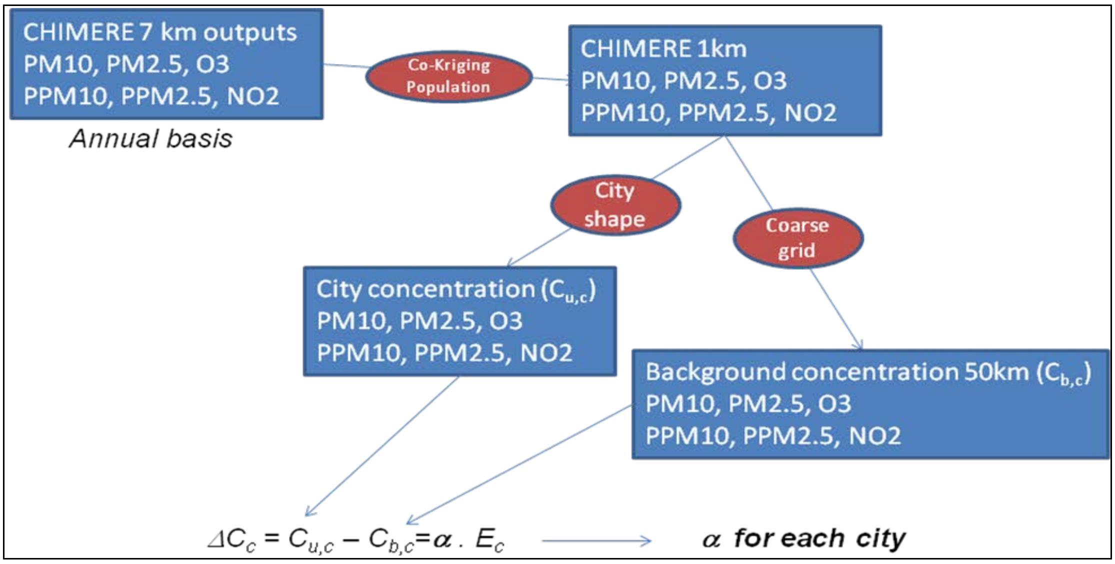

Figure 5. Annual urban increment methodology

4.2 *What has been done with CHIMERE in the EC4MACS project*

Within the EC4MACS project, the CHIMERE model has been run by INERIS[11] with a 50 x 50 km^2 resolution (regional runs) and a 7 x 7 km^2 resolution (high resolution runs) over the whole of Europe for the entire year 2009. Hourly concentrations of ozone, NO_2, PM_{10}, and $PM_{2.5}$ included PM chemical composition, have been calculated, to derive annual averages.

Added value of the downscaling approach can be assessed comparing modelled and observed concentrations for various site typologies (Figure 6). The results are given for the yearly average and are very satisfactory for all types of stations. However the high resolution model results are still less accurate for traffic stations, especially for NO_2. This is not surprising considering that 7 x 7 km^2 is still too coarse to perform simulations for this pollutant very sensitive to local sources.

Sensitive parameters are meteorological fields and the emission inventory.

In EC4MACS, meteorological inputs for the CHIMERE model were issued from the ECMWF Integrated Forecast System (IFS) data (http://www.ecmwf.int/research/ifsdocs). The IFS model has a 0.25 x 0.25°[12] horizontal grid spacing from surface to 0.1 hPa (91 levels). It delivers typical meteorological variables (temperature, wind components, specific humidity, pressure, sensible and latent heat fluxes) that were vertically and horizontally interpolated onto the CHIMERE grid (9 levels). Nevertheless, inaccuracies remain over urban areas. Indeed, IFS provides meteorological variables representative of the regional scale. Urban local effects are not taken into account in the IFS reanalyses[13]. Most of the air pollutant observations are available in the urban sub-layer and the urban canopy and the objective is to calculate pollutant concentrations in those layers.

Unfortunately, meteorological models or reanalysis at such *horizontal* resolution (20 x 20 km^2) cannot reproduce the urban meteorology in the urban canopy and urban sub-layer over such a large domain (the whole of Europe). This has an impact on the vertical diffusion of primary pollutant concentrations (O_3, NO_2 and PM) and their transport close to the ground within the city. This can be partially corrected by data assimilation processes (see below).

Concerning emission data, a huge amount of work has been done to spatially distribute emission totals reported per activity sectors by the EMEP countries (EC4MACS, 2012) Actually, a mix between the high resolution MACC emission inventory (see section 2) and gridded EMEP emissions data had been elaborated by INERIS (EC4MACS, 2012) for more details). A sensitive issue are emissions from residential heating that depend to population density and strongly contribute to PM emissions especially in winter periods.

[11] Institut National de l'Environnement Industriel et des Risques.
[12] This is about 27 x 27 km^2, but this resolution should improve for the most recent and future years.
[13] ECMWF provides operational reanalyses of meteorological fields for past periods. Those results from weather forecasting models run within a data assimilation process (for meteorological variables) to improve estimation

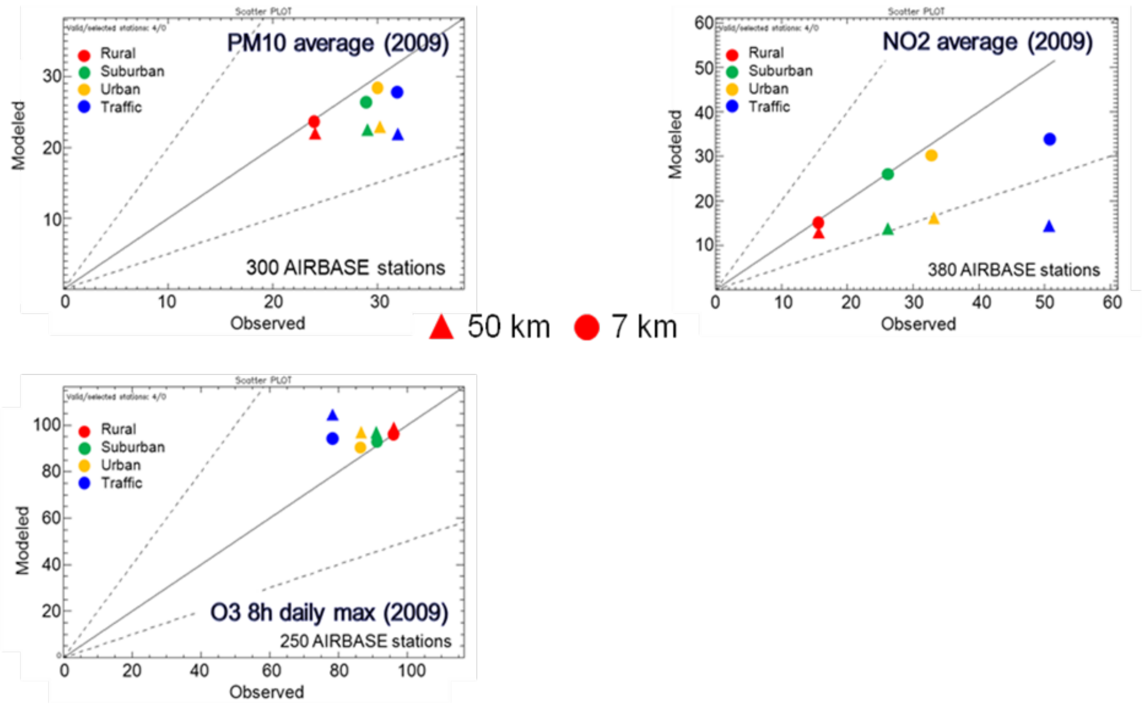

Figure 6. Added value of the high resolution simulation (7km) compare to the coarse simulation (50km) for different types of sites

Considering the spatial variability of the model quality, Figure 7, Figure 8 and Figure 9 show an overall picture of the CHIMERE performances for a 7 x 7 km^2 resolution respectively for NO_2, PM_{10} and $PM_{2.5}$ in 2009.

Clearly, a slight underestimation at backgound sites is displayed for NO_2. For PM_{10} and $PM_{2.5}$ the background concentrations are in good agreement with observations in most of the western part of Europe. In the eastern part of Europe, problems remain in some countries like Poland, Czech Republic, Slovakia and Bulgaria where PM concentrations are strongly underestimated. These problems are probably related to underestimations in emission inventories (coal activities, residential fuel sector burning).

There are several ways to further improve the approach. This should be investigated in the case of extensive use for deriving urban maps, especially to deal with reporting of exceedances of he limit value, or to estimate popualtion exposure. In particular :

- Deriving the methodology from monthly averages rather than annual averages to compute an urban increment which accounts for the seasonal variability. In-depth analysis of the scores show that concentrations during some winter episodes - due to stagnant meteorological conditions - can be significantly underestimated.
- Use model results improved with data assimilation fields rather than raw simulations, especially when the high resolution runs (7 x 7 km^2) are performed. This will improve the quality of the results and should help in compensation of uncertainties in meteorological inputs (that do not catch urban canopy effects).

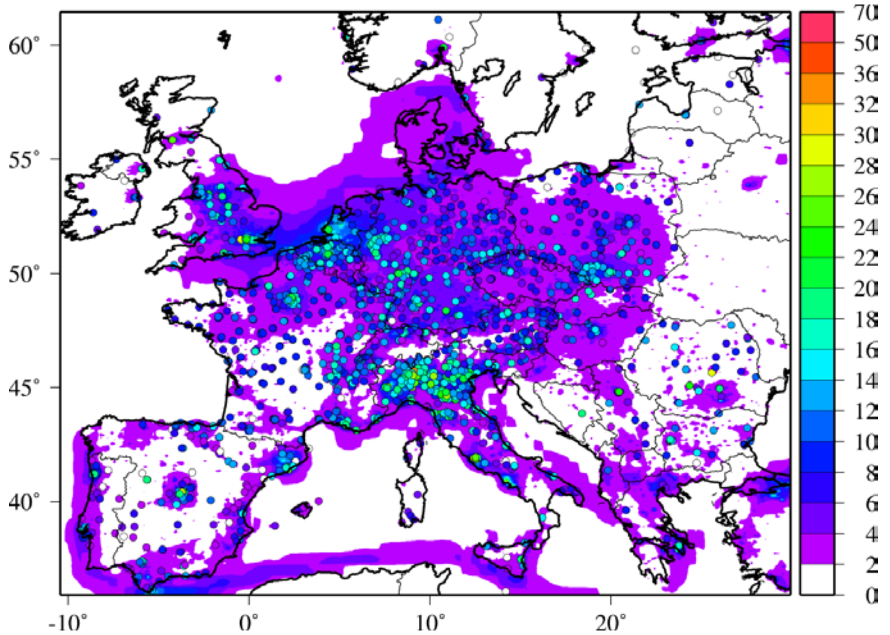

Figure 7. *NO2 concentration annual fields for urban, suburban and rural stations (µg/m³) – Coloured circles are the observations*

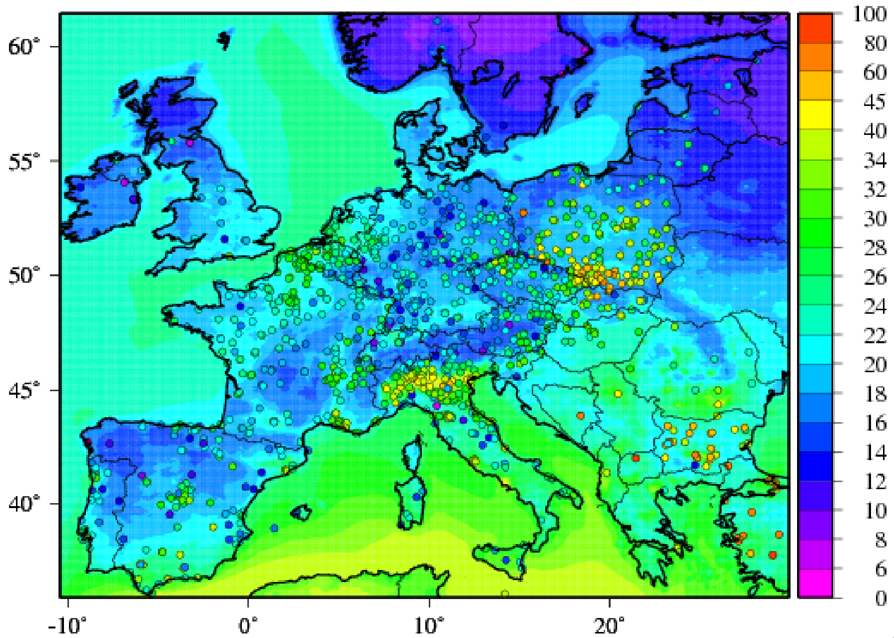

Figure 8. *PM10 concentration annual fields for urban, suburban and rural stations (µg/m³) – Coloured circles are the observations*

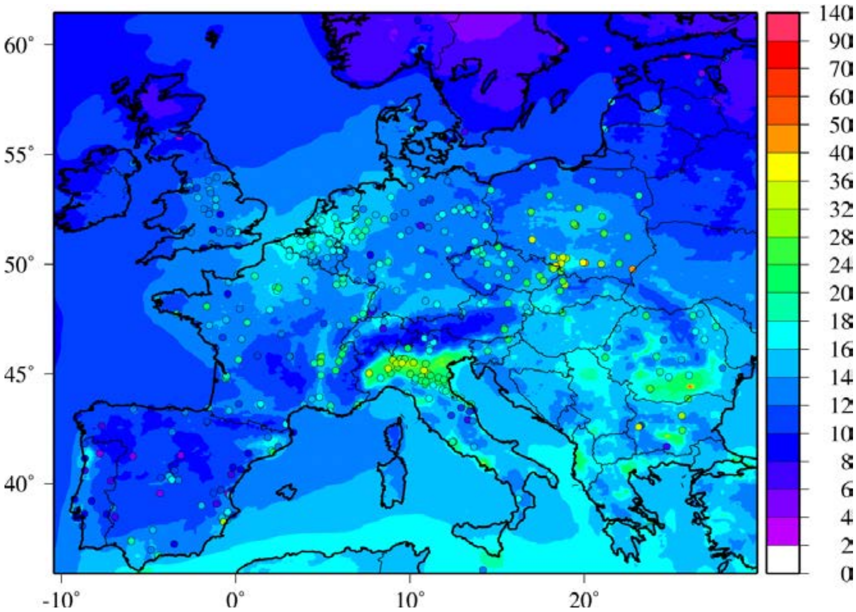

Figure 9. PM2.5 concentration annual fields for urban, suburban and rural stations (µg/m^3) – Coloured circles are the observations

4.3 A new option for improving urban maps?

Considering the urban maps methodologies based on the Copernicus /MACC outputs described in the chapter 3, it is now possible to describe a third option (Section 3.2.3) either based on Copernicus/MACC raw simulation results or re-analyses.

1. Download from the Copernicus /MACC services European scale background concentration fields issued from **Ensemble raw simulations**. 25Km*25 km resolution at least.
2. Evaluate the quality of the simulation and apply the EC4MACS urban increment (computed with CHIMERE for the year 2009) over cities.
3. Rural maps = kriging observations at rural sites plus Copernicus /MACC model results (25km*25km) plus meteorological and site parameters.
4. Urban maps = kriging observations at urban sites plus Copernicus /MACC model results plus Urban increment (25km*25km) plus meteorological and site parameters.
5. Merging rural and urban maps distributing rural and urban concentration fields according to the population distribution available with a 1km*1km resolution.
6. Aggregating the results over a 10km*10km grid and assess the results against urban and suburban stations.

Or :

1. Download from the Copernicus/MACC services European scale background concentration fields issued from **Ensemble re-analyses**. 25Km*25 km resolution at least.
2. Evaluate the quality of the simulation and apply the EC4MACS urban increment (computed with CHIMERE for the year 2009) over cities.
3. Improve spatial distribution of concentrations over the city areas using supplementary data like population maps (1km resolution) -> new kriging over a 1km*1km grid.
4. Assess the capacities of the approach in simulating urban concentrations (by comparing with suburban and urban measurement station results)

The main challenge of this approach is the fact that the regional model results (individual or ensemble) are corrected over cities with high resolution CHIMERE runs (even if finally expressed as a

function of the emissions). Obviously the correction is optimal when the same model is used for coarse and fine resolutions. However, because analysis of the model results shows that generally the models behave the same way, i.e. they underestimate or overestimate levels of the same pollutants and in the same areas (only the intensity changes, an improvement can be expected. It will be quantified in the methods inter-comparison planned within the ETC/ACM 2013 work plan.

This overview should be completed by approaches that are in some cases developed within the Member States for example by the local authorities who map urban concentration fields by applying so-called urban models. Those models are generally based on Gaussian or analytical approaches (see e.g. EEA, 2011 and Denby et al. 2012). Those models strongly depend on the quality of the emission inventories which are crucial input data. Coarse spatial (and temporal) resolution in emissions will not lead to good results concerning the modelled concentrations. And high resolution emission inventories are not so widespread over European cities.

5 Testing High resolution runs

Even if 10 x 10 km^2 air quality model runs are not available yet through the GMES/MACC services, this will most probably be the case in 2014 Once more, this option makes only sense if input data are available with comparable resolution. However this is also planned for the emissions data within the GMES/MACC project.

As an example, and in the framework of the present study INERIS used high resolution results (7km*7km) from the CHIMERE model that were available from the EC4MACS project, to test such an approach. A simple kriging approach (the same kind of those operationally used by the ETC/ACM) has been implemented with high resolved CHIMERE concentration fields used as external drift. For NO_2, the spatial distribution of concentrations is improved over city areas using population maps (1 km x 1 km resolution as supplementary data). This is a rather basic and robust approach. The method could eventually be further improved using the regressions established by the ETC/ACM with meteorological variables and altitude.

The whole of Europe has been simulated this way, but results have been extracted and investigated for the 8 cities taking part in the Air Implementation Pilot undertaken jointly by DG ENV and EEA. Results for NO_2 and PM_{10} are given in annex 1 and 2, respectively. It will be important to submit those results to the cities' air quality managers to get their feedback on the quality and usefulness of those maps. However, the results have been verified against observations from the Airbase database (using a cross-validation process to avoid biases). The time series are given in Annex 3 and look very promising except for small cities like Ploiesti where there are not enough stations for both mapping and evaluation processes.

In conclusion it can be stated that high resolution CTM runs that are planned to be available from the GMES/MACC services (by 2014) will help improving urban mapping processes based on kriging approaches as those promoted by the ETC/ACM.

6 Statistical correction of local scale concentrations near sources

This chapter provides a short analysis of what could be done to improve urban patterns near sources (busy roads, industries) that influence air quality locally and cause exceedances of the limit values. The methods discussed in the previous chapters cannot deal with these situations and a complementary approach is needed. Those situations are the most worrying when it comes to an accurate assessment concerning the attainment of air quality standards set in the AQ Directives. Mapping concentrations over domains including the effect of large air pollutant emission sources like busy roads and industrial sites requests a specific methodology.

Approximating very high air pollutant concentrations in a city in the vicinity of local sources is very challenging. Representing on the same map air pollution (NO_2 and PM) patterns that are representative for different spatial and temporal scales is difficult as well. Since both urban background concentrations and concentration levels near local sources are in different concentration ranges and describe phenomena of very different scales, they cannot be mixed to model the spatial correlation structure of PM and NO_2 concentrations. The analysis provided below aims at illustrating possible solutions to map sub-grid patterns and the inherent difficulties to those methods. At this stage it does not seem possible to define and recommend one common method to European cities. This is mainly because those methods are based on observation and emission input data at a very fine scale, and this data are far from being available everywhere. Mapping exceedances of air quality standards should be carried out under the responsibility of city authorities and only methodological insights are provided here, with illustrations from previous work INERIS has done for French cities.

The methodology we propose needs a relevant set of observation data obtained in the proximity of targeted local sources to improve the information on background concentrations. An example is for instance field campaign data obtained along a road or over an industrial site.

The proposed methodology is based on two steps:

1- Background urban concentrations (calculated using the previous approaches) are estimated at the roadside sampling points and compared to the measured values. The difference between both is viewed as the local contribution of traffic and modelled by a statistical relationship, with NOx or PM emissions as a predictor.
2- The high resolved (less than 1km x 1km) estimation grid is refined along the major roads. In the cells of this refined grid, background concentrations are corrected by an additional term driven by the previously fitted model.

Step 1 needs an extensive set of observations near the targeted sources. For NO_2, data from passive samplers used within field campaigns can be used to complement automatic measurement sets. For PM, the situation is more difficult and still needs to be investigated, because there is no “low cost” measurement method (like passive samplers) which allows running a large number of observation sites.

At the roadside sampling points underestimation by the modelled data compared to the actual measurement data is observed. This gap can be interpreted as a concentration increment due to the local impact of the road (Stedman et al., 2001). For nitrogen dioxide, it turns out to be correlated to NOx emission density within a 1 km radius. So it can be modelled by a linear relationship with parameters obtained by linear regression.

Step 2 consists of improving the concentrations near the major sources. The following method has been evaluated by INERIS to correct NO_2 concentrations along busy roads in several French regions:

The distance over which road emissions influence NO_2 concentrations depends in particular on traffic volume, wind conditions, and the type of environment. In open areas, concentrations are usually found to drop rapidly as distance from the road increases: 50 m away they can be reduced by 50%, reaching background levels at a distance of 100–150 m away from the road. However, this depends also on the road emission strength. In some cases (Le Loch and Fouquet, 2006) areas of impact extending up to 400m from the road can be observed. In the INERIS example, the estimation grid was refined over the whole domain according to a mesh size of 250 m. This choice resulted from a compromise between the spatial scale of traffic-related pollution and the degree of mesh refinement allowed for reasonable computing times.

Then the correction procedure was applied along the roads. Considering the impact distances previously mentioned and to avoid extrapolating the model exaggeratedly, only the small cells intersecting a 200 m wide band on either side of the roads was selected. At the centre of each small cell NO_X emission density within a 1 km radius was calculated with help of the Geographic Information System ArcView. The NO_2 concentration was finally calculated by adding the roadside increment derived from a local statistical model to the estimated background concentration.

An example of the work carried out in France is given below (Figure 10) for the city of Montpellier. INERIS applied the method to detect roads where the limit annual value for NO_2 concentration was exceeded.

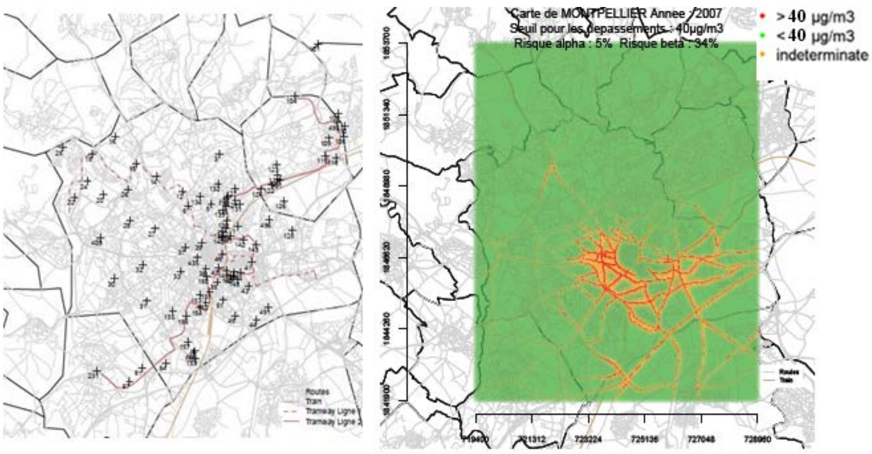

Figure 10. NO_2. Left: sampling points in Montpellier - year 2007 (source of the data: Air Languedoc Roussillon). Right: exceedance of the annual limit value (40 µg/m^3).

As already mentioned, the local mapping example methodology described in this section needs to be further assessed and reviewed before it can be used operationally in other cities. Few keys for further improvement can be given:

- The methodology requires a number of auxiliary variables that should be reviewed to check their availability in the European cities. High resolution emission inventories (city level), and maps of population densities seem essential to correct the background concentration estimates and to fix the local correction. Other variables could be used depending on the city characteristics and the considered pollutant, and this point has to be analysed for each single city case.
- One can expect that the process developed for NO_2 in the previous paragraph must be reconsidered and adapted to deal with PM concentrations because much less measurement data are available (no easy-to-use passive sampler adapted to the measurement of PM levels). PM does not behave as NO_2 in the vicinity of major sources.

7 References

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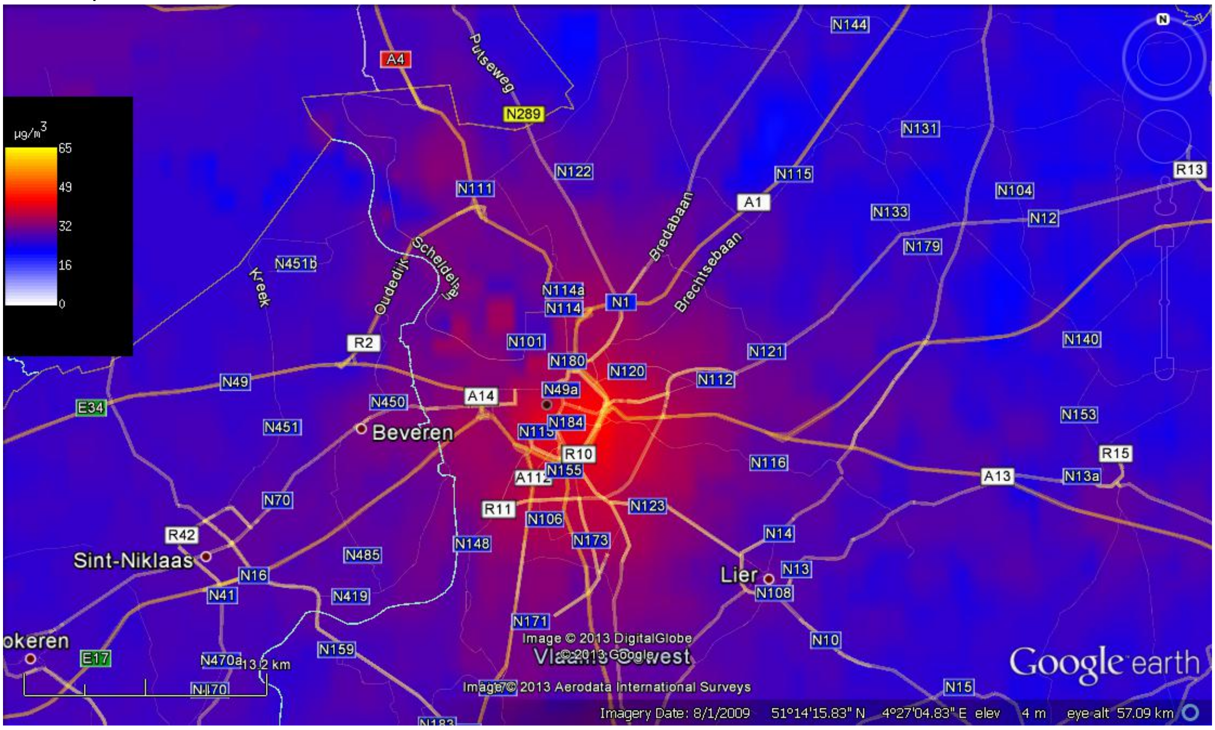
ANNEX 1: NO_2 maps over the pilot cities areas (2009)

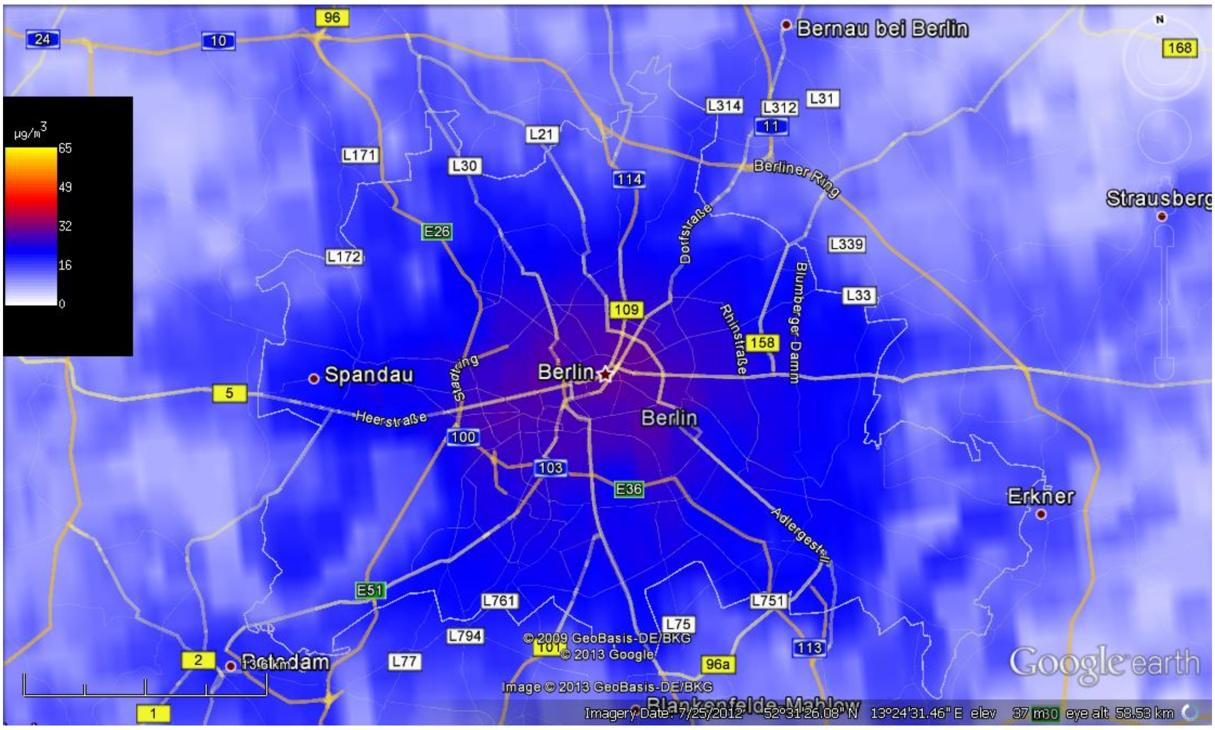
Those results were obtained using kriging methods with CHIMERE high resolution runs (7km) as external drift supplemented in some cases by population density data[14].

Antwerp



[14] Data (inhabitants/km2) taken from the JRC/EEA population database, http://www.eea.europa.eu/data-and-maps/data/population-density-disaggregated-with-corine-land-cover-2000-2

Berlin



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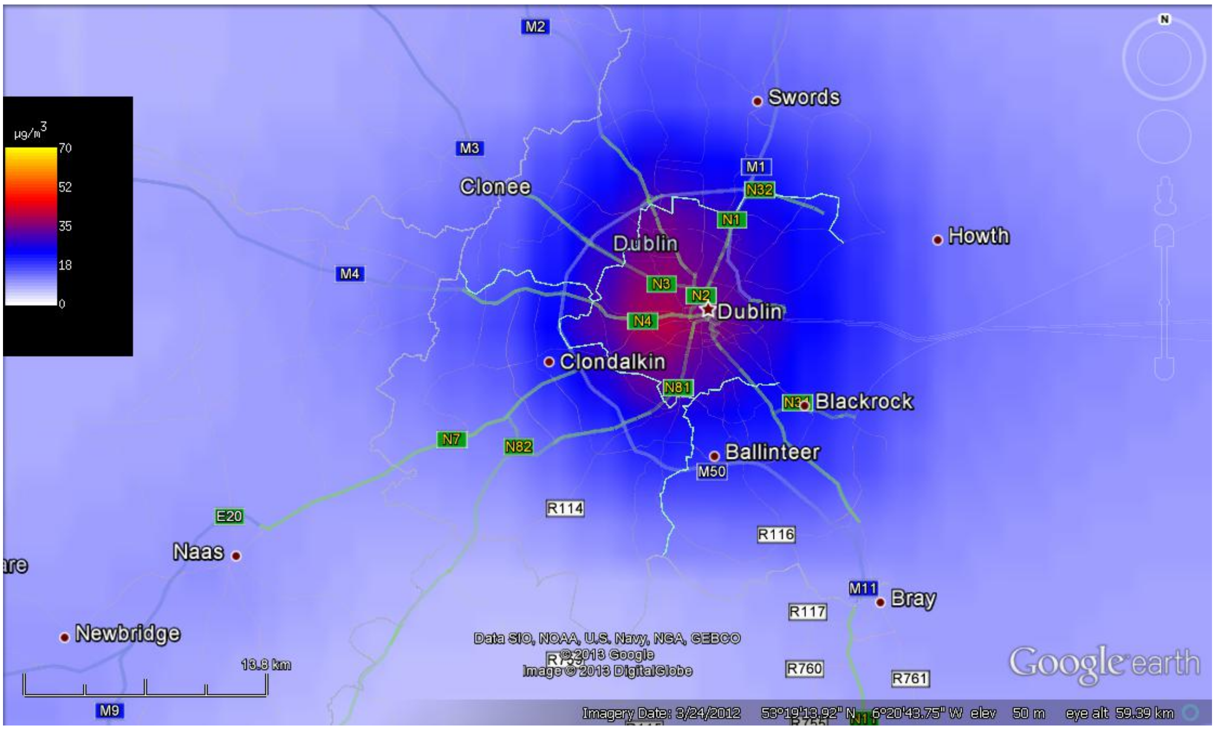

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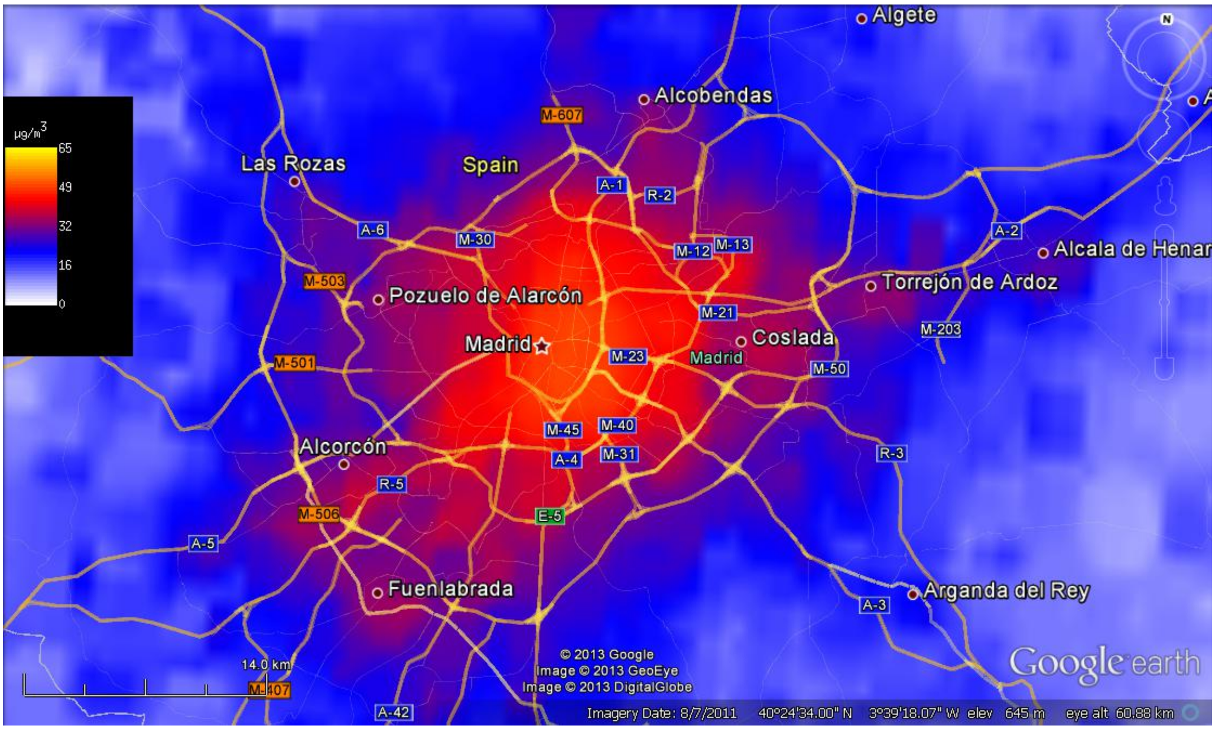

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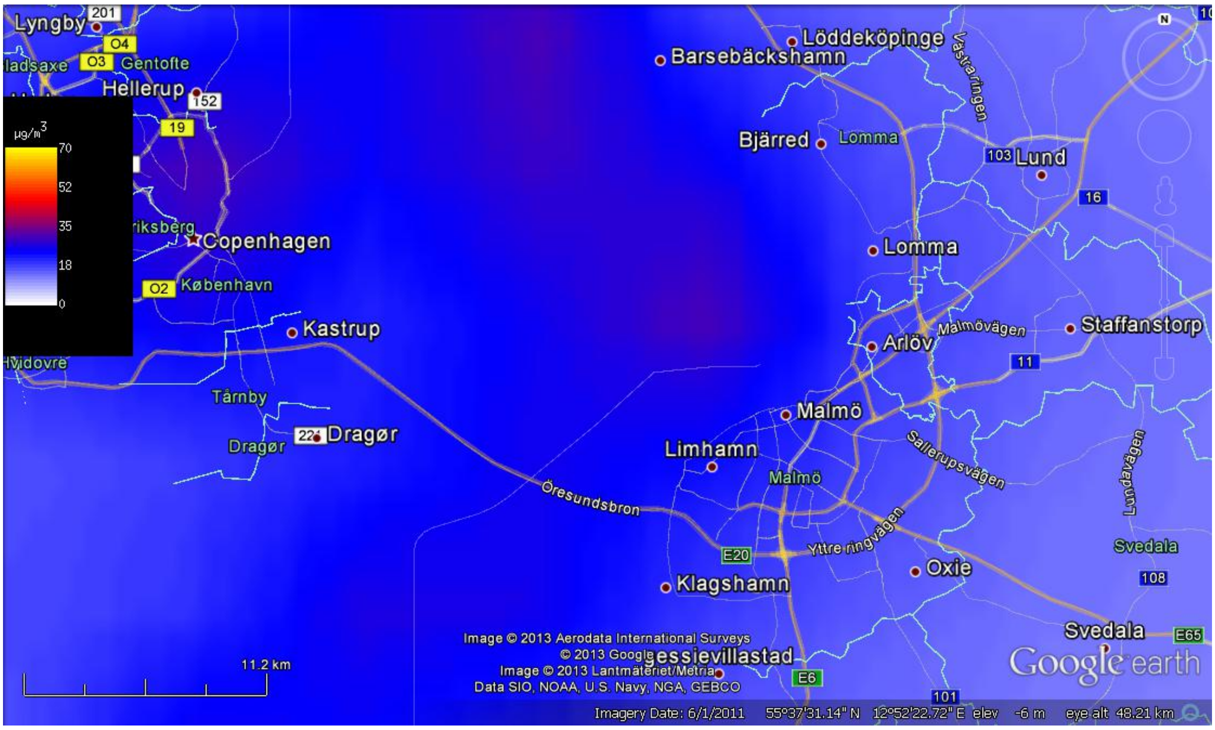

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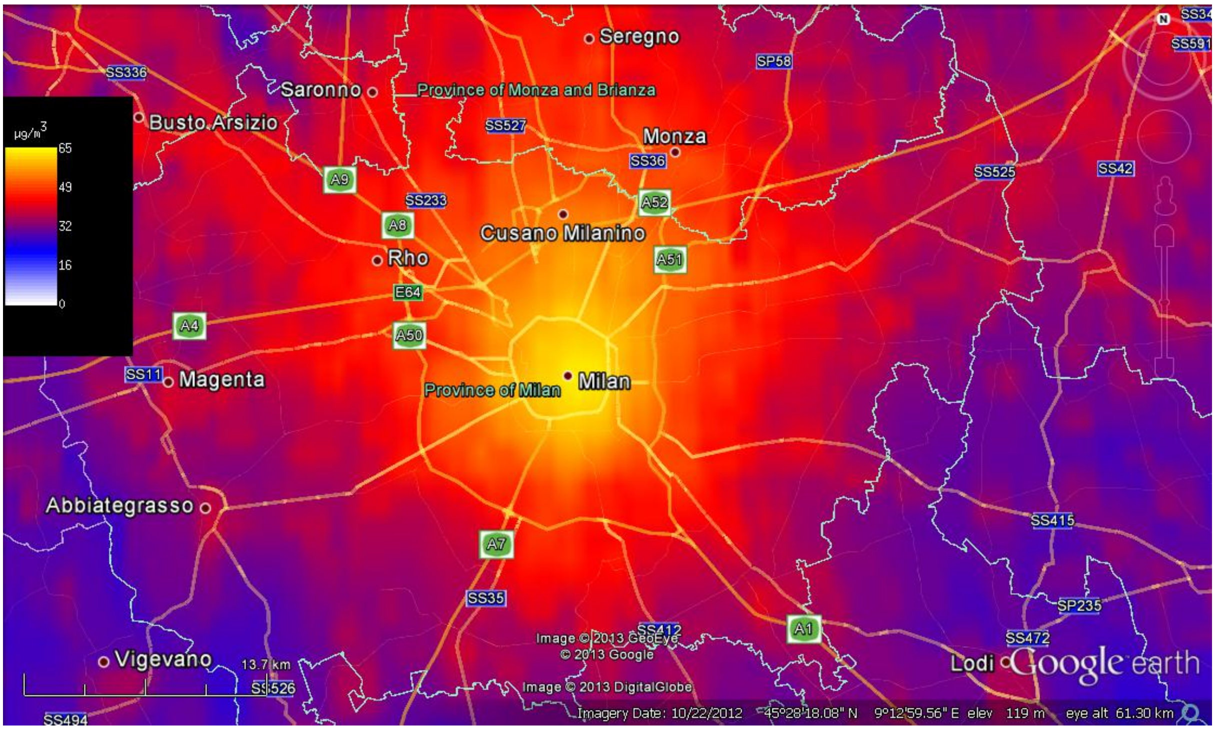

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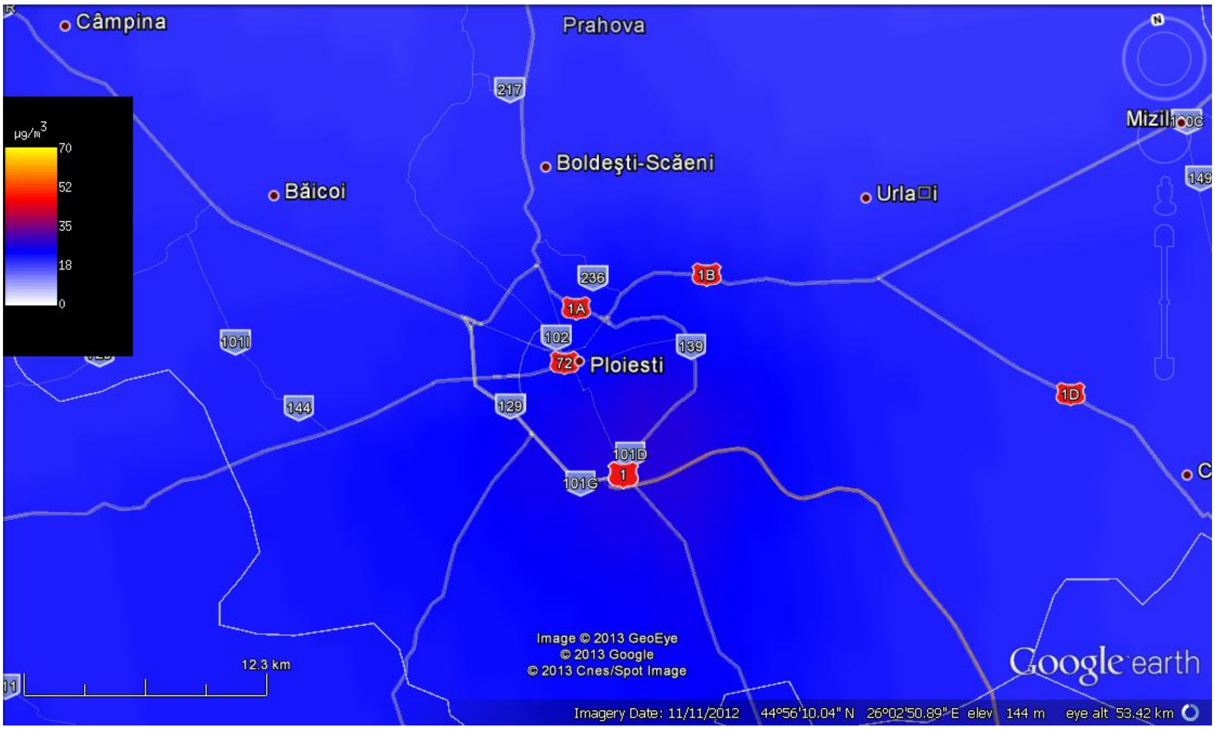

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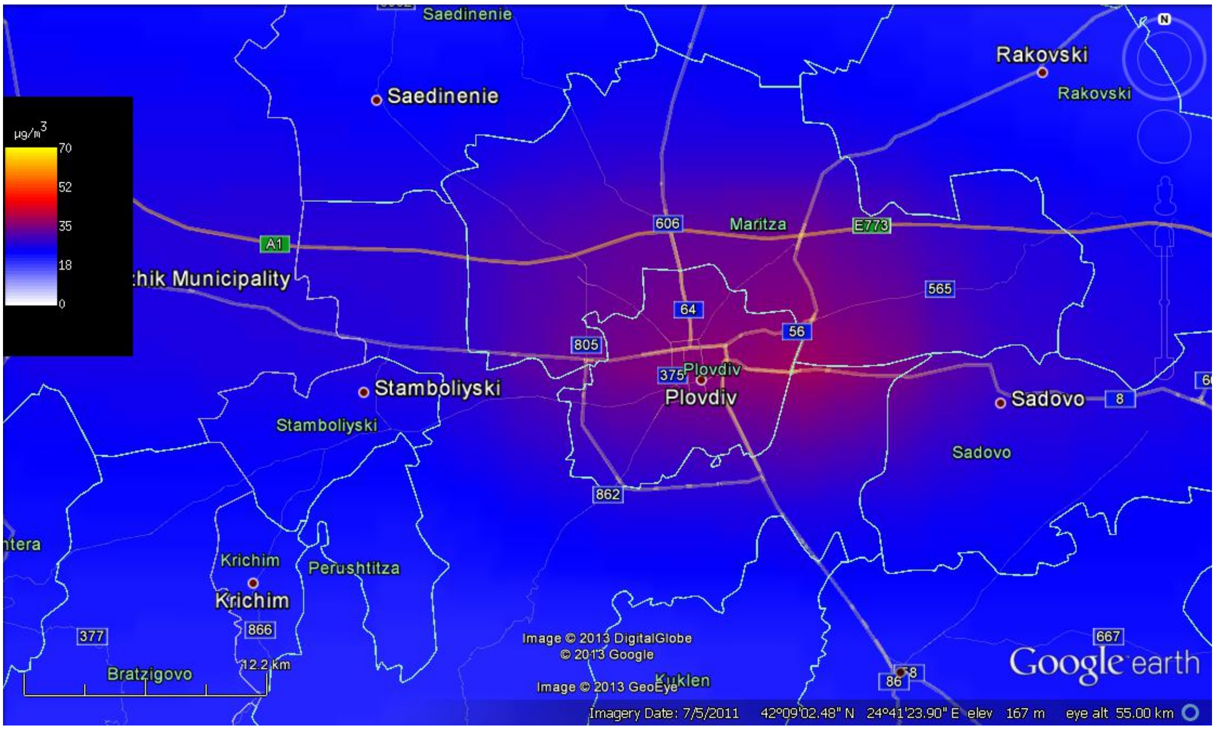
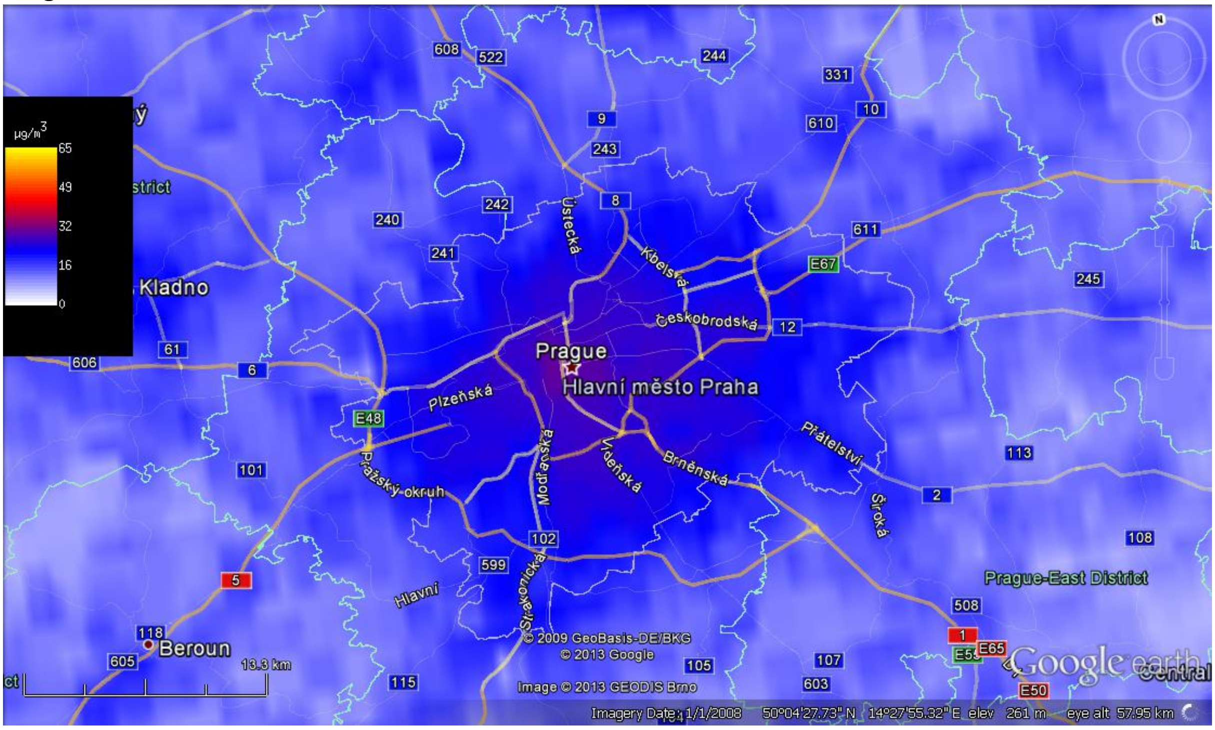


Prague



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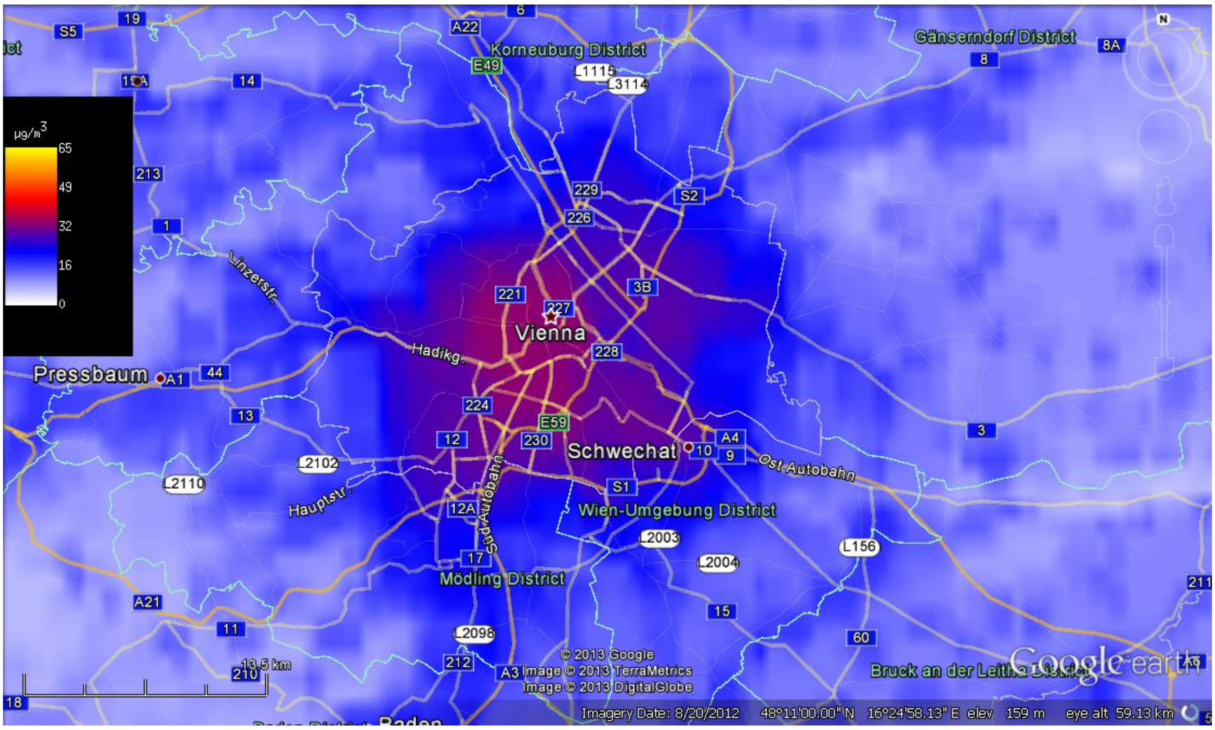
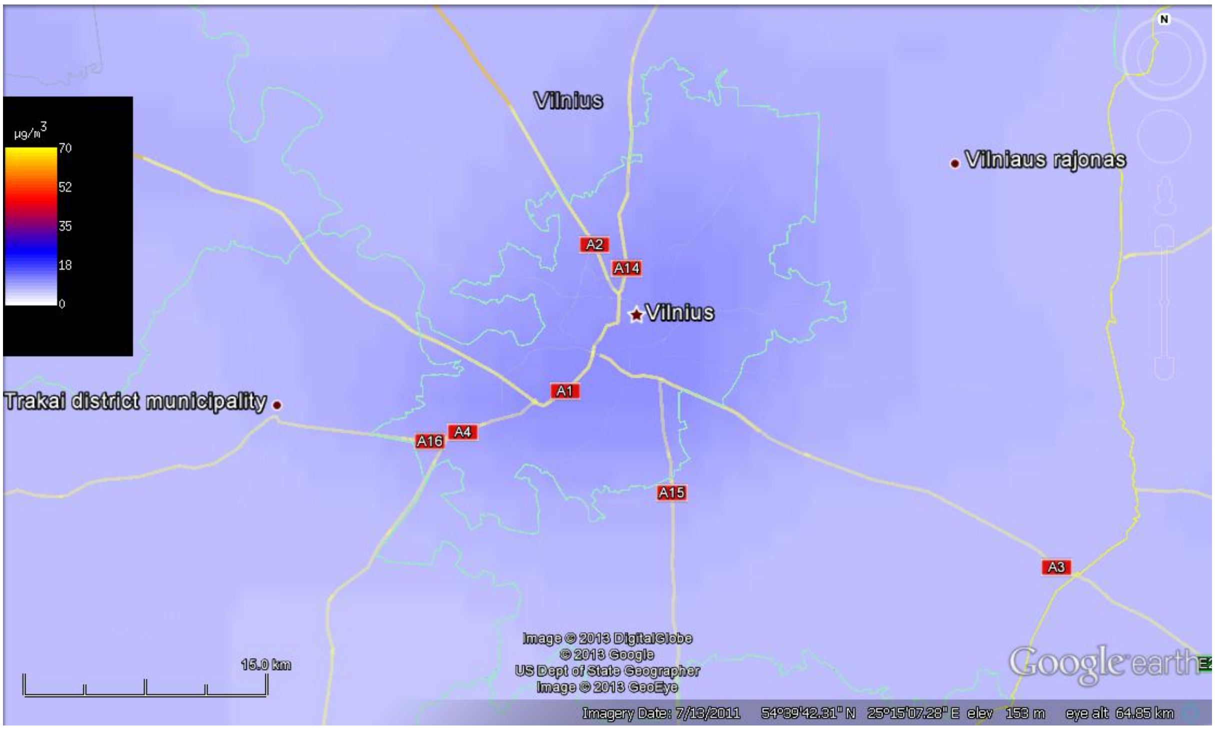


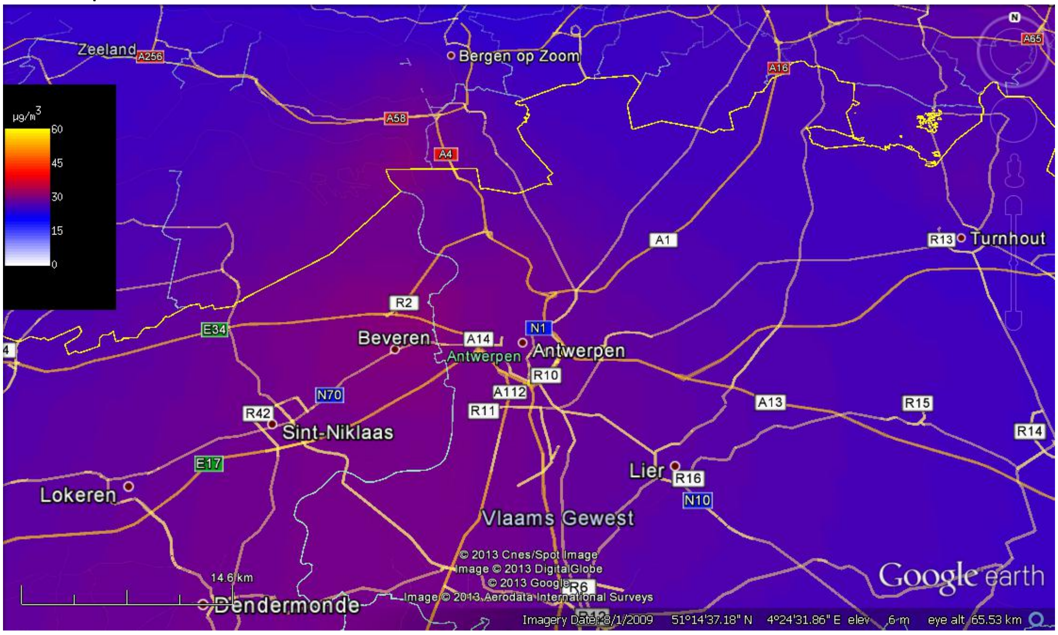
Vilnius



ANNEX 2: PM_{10} maps over the pilot cities areas (2009)

Those results were obtained using kriging methods with CHIMERE high resolution runs (7km) as external drift.

Antwerp



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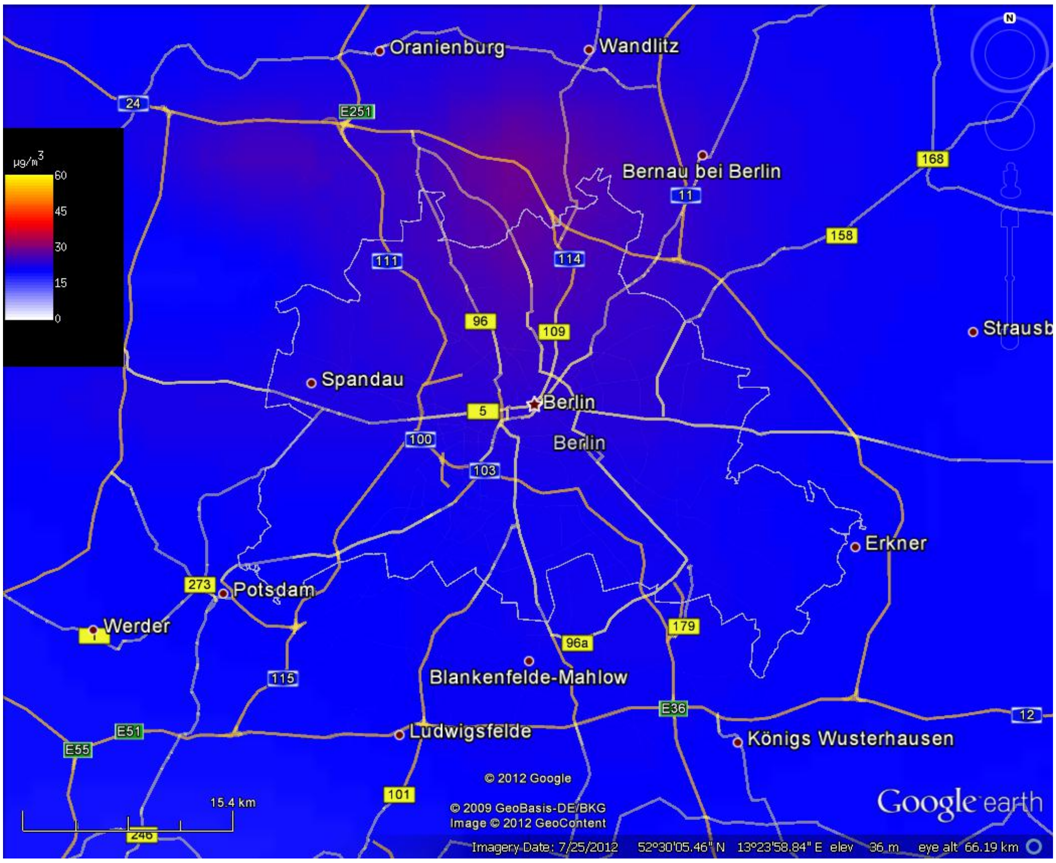

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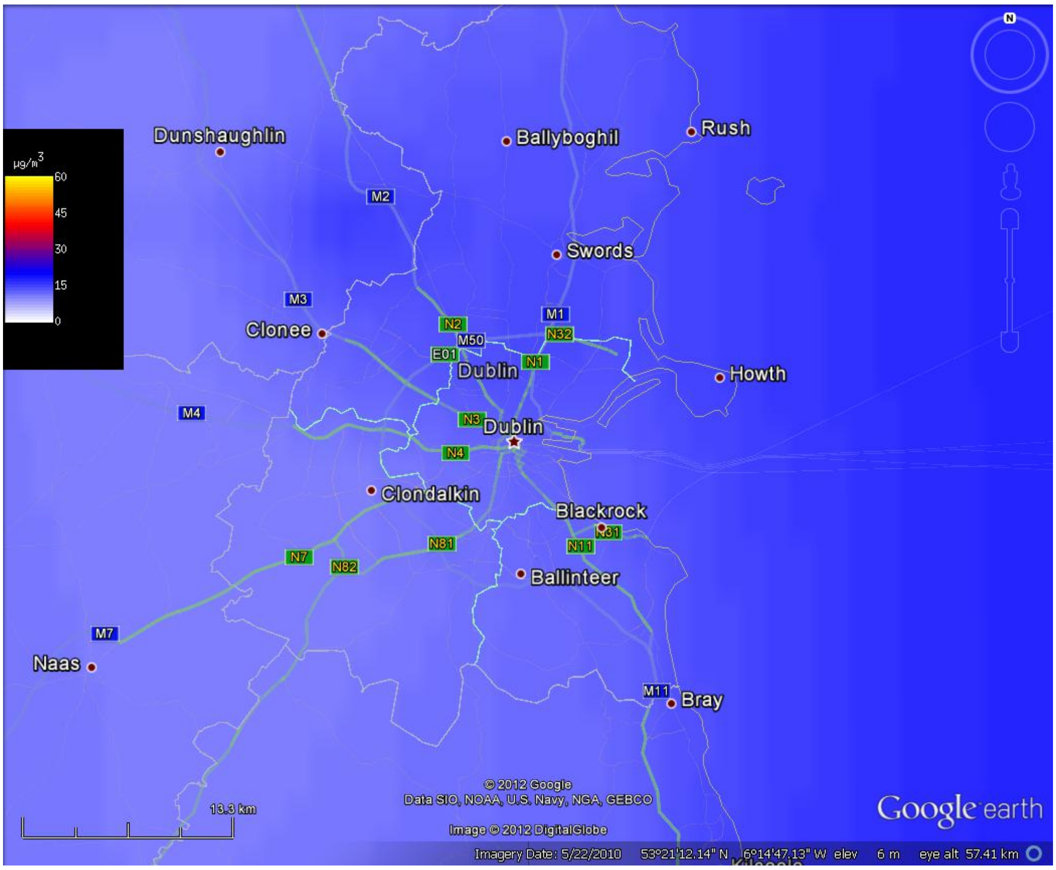
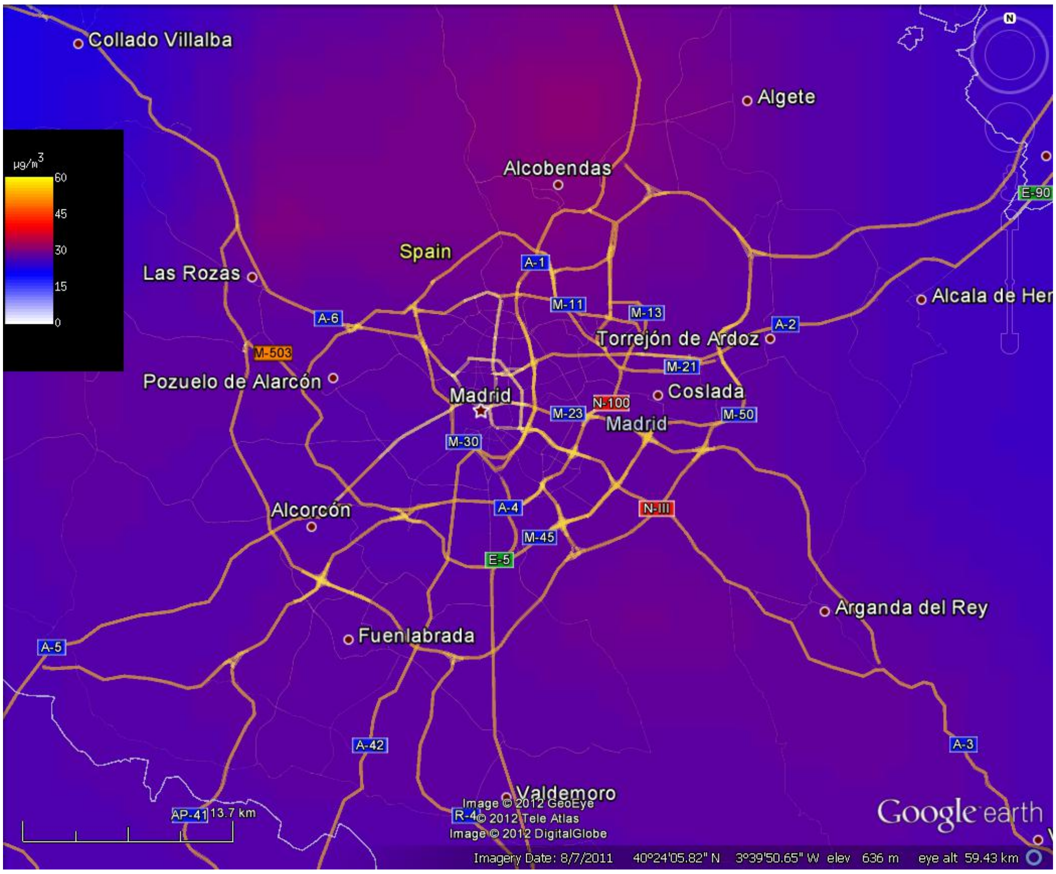
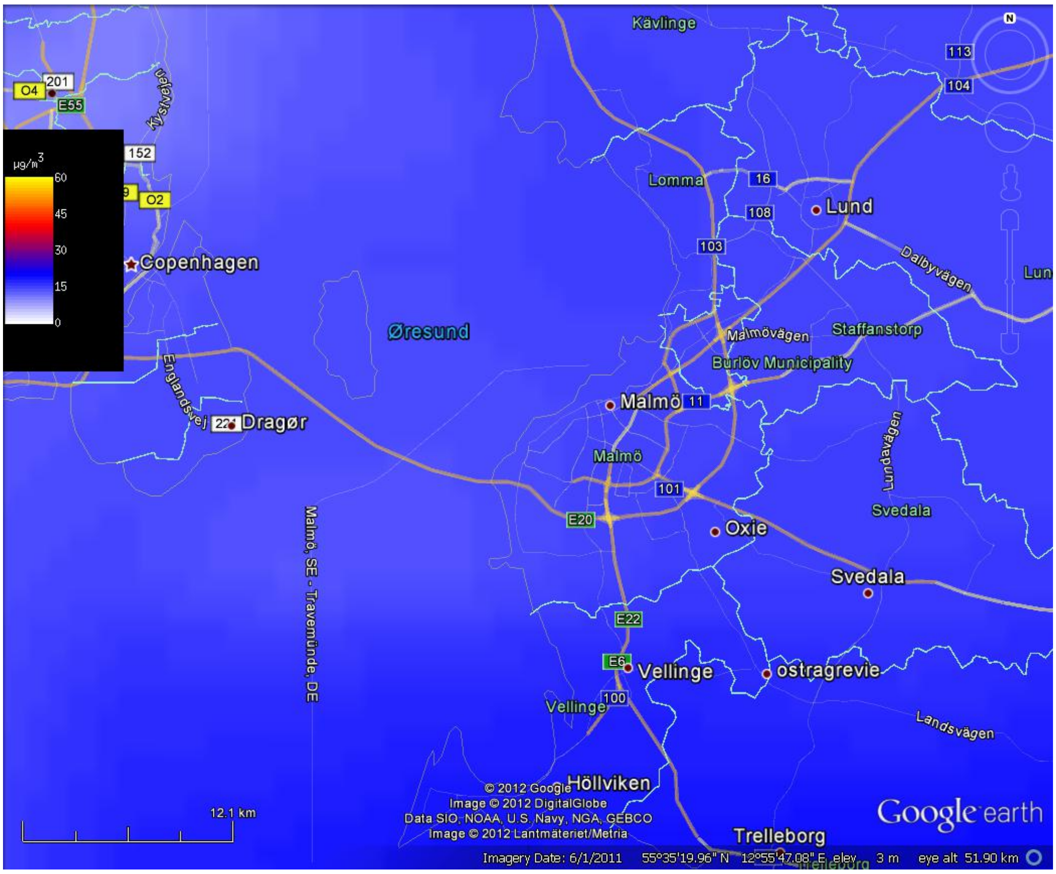


Madrid



Malmö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Øresund
Dragør
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Lund
Staffanstorp
Burlöv Municipality
Malmö
Oxie
Svedala
Vellinge
Höllviken
Trelleborg
12.1 km
© 2012 Google
Image © 2012 DigitalGlobe
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
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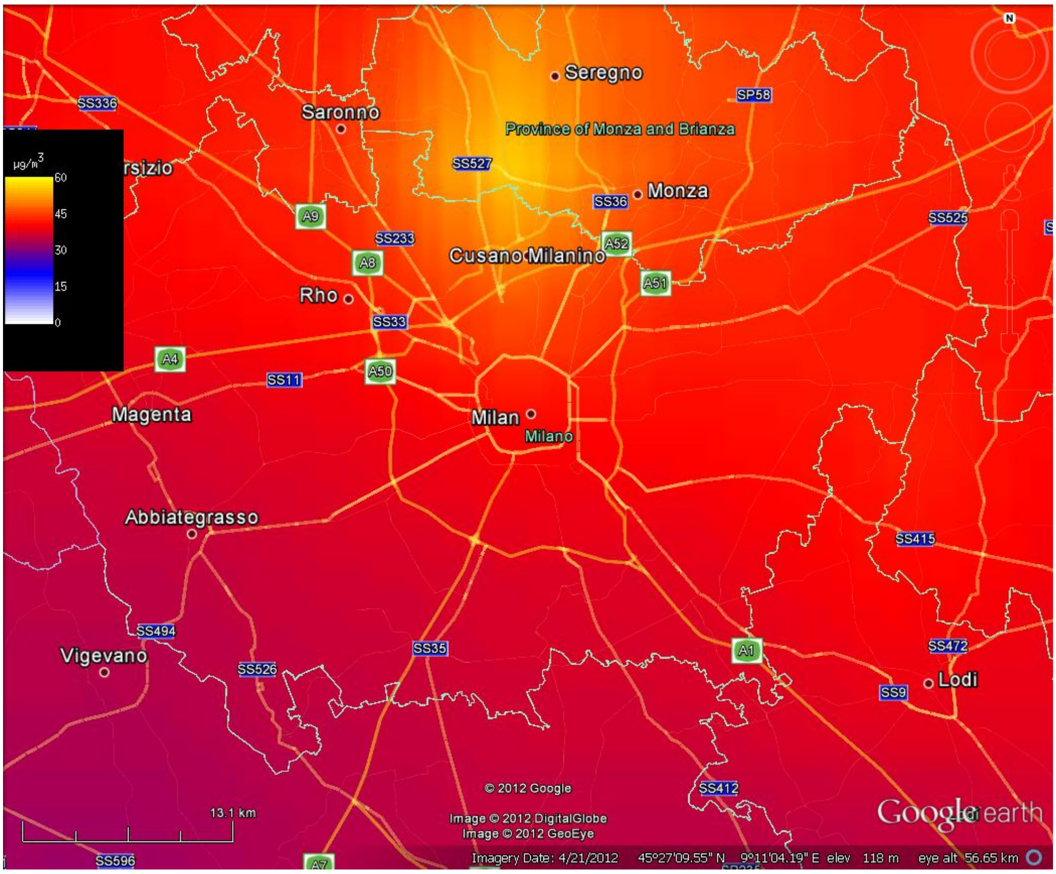
Milan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Monza
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Rho
Magenta
Milan
Milano
Abbiategrasso
Vigevano
Lodi
13.1 km
© 2012 Google
Image © 2012 DigitalGlobe
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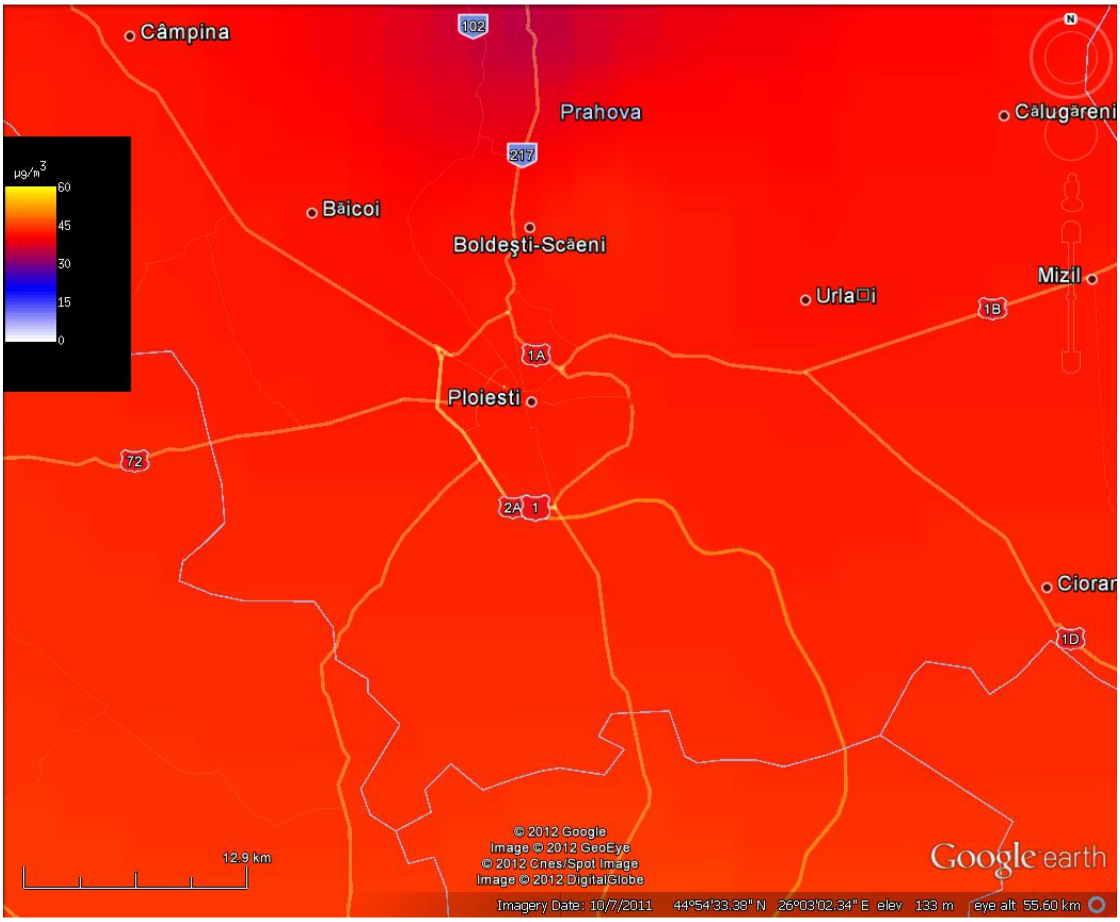
Ploiesti



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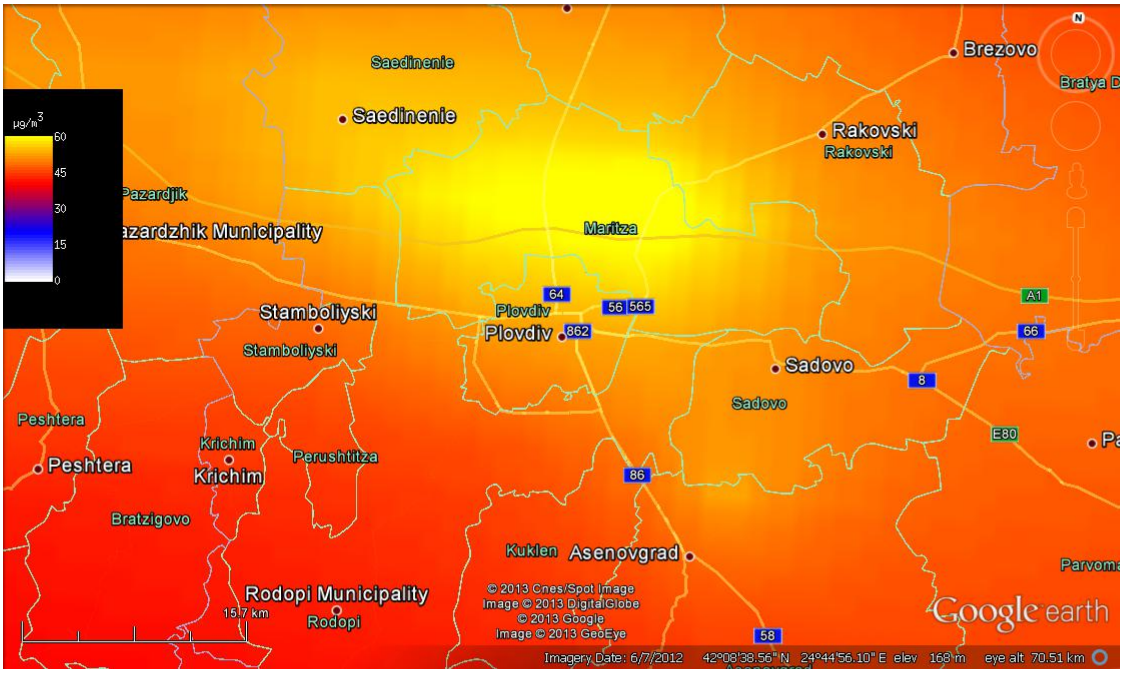

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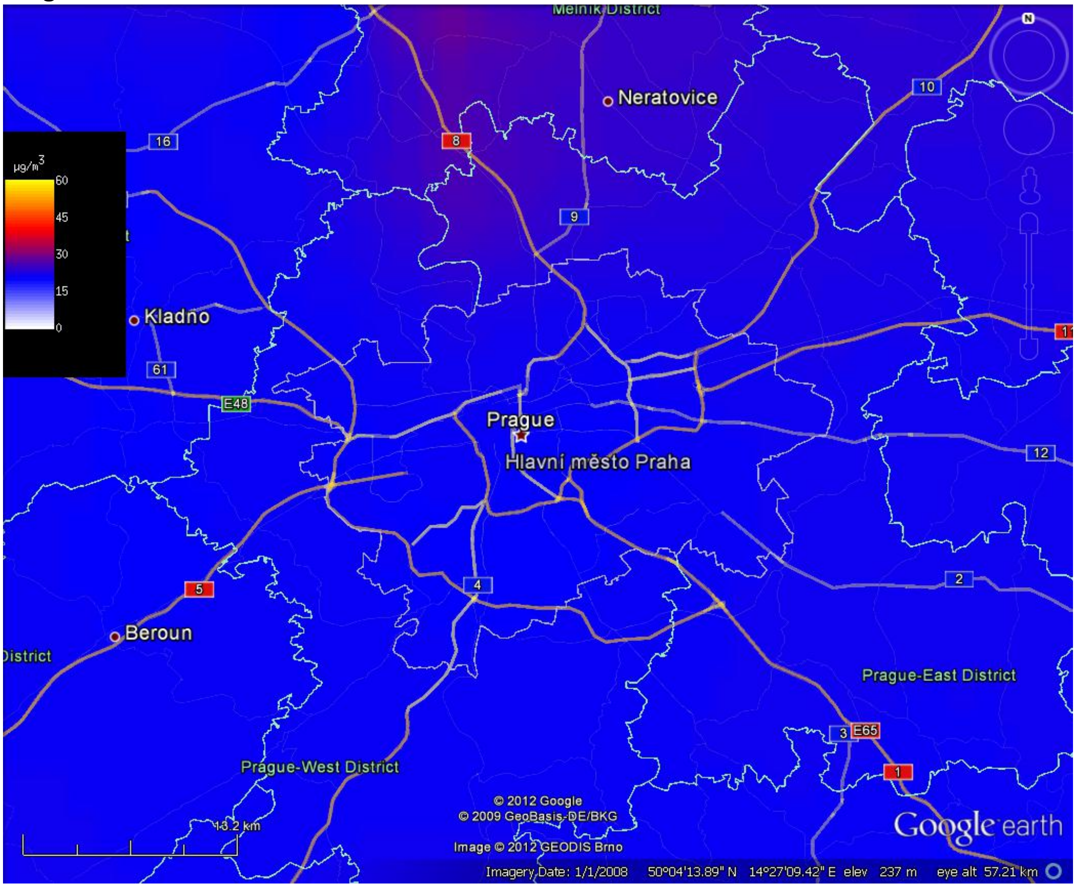
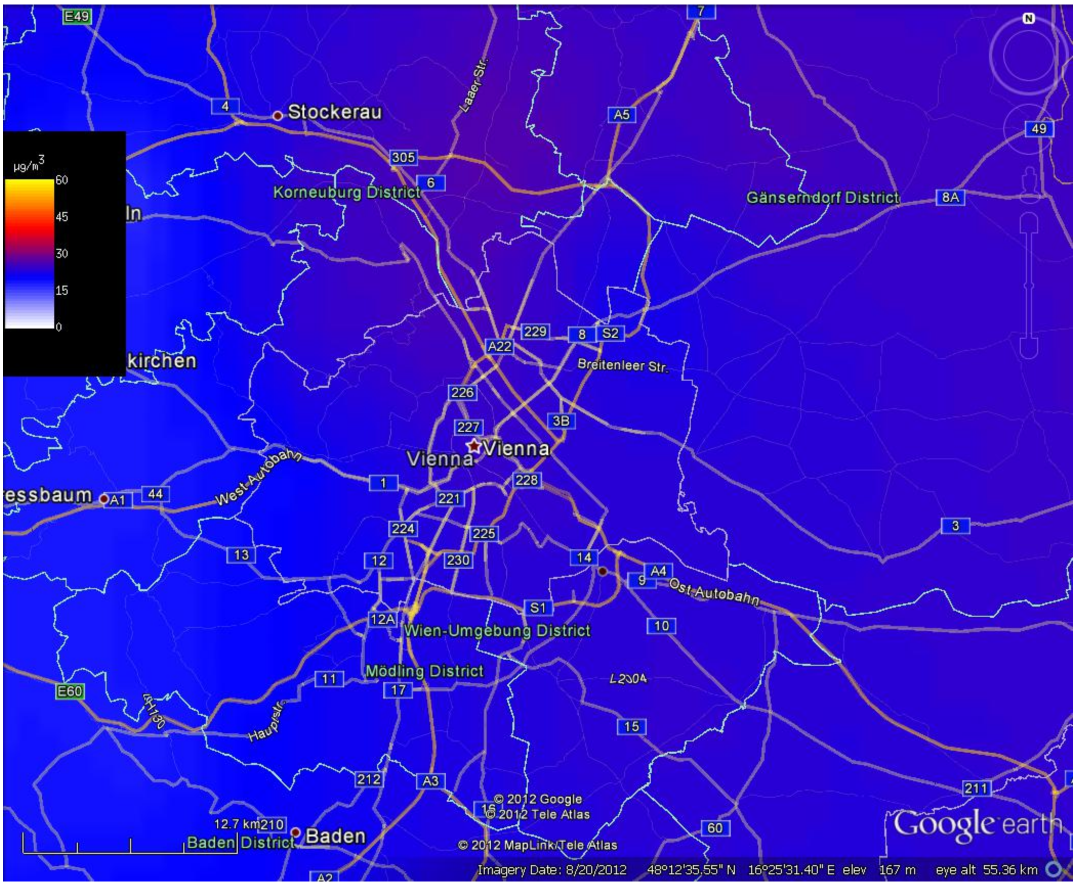
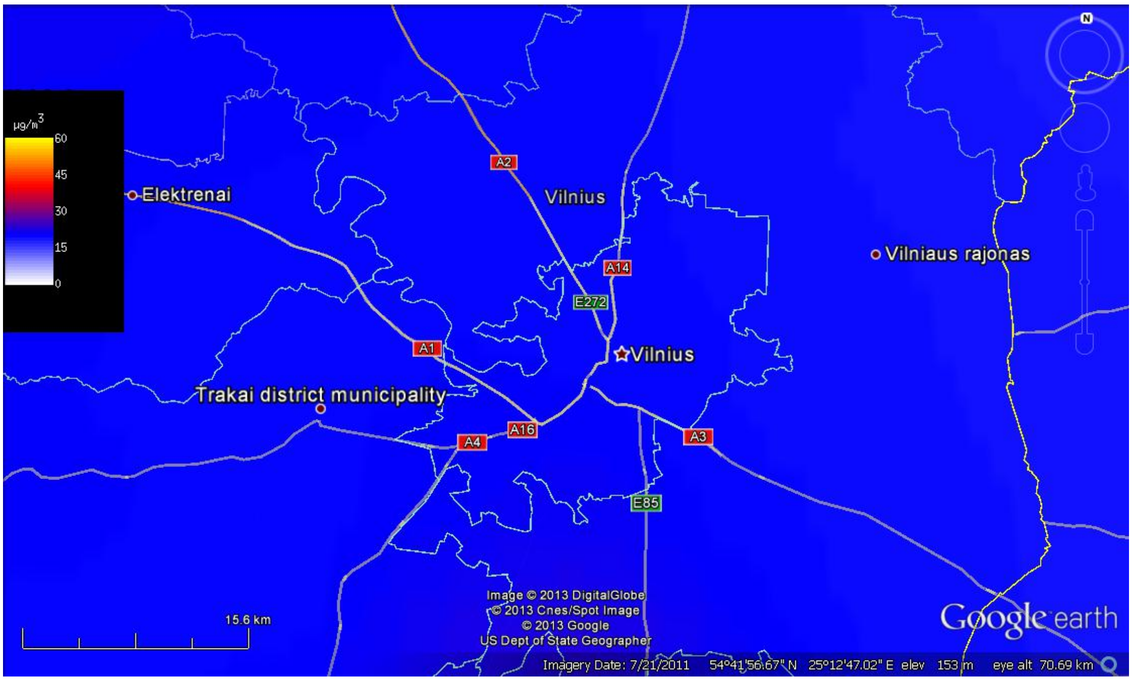


Vienna



Vilnius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A14
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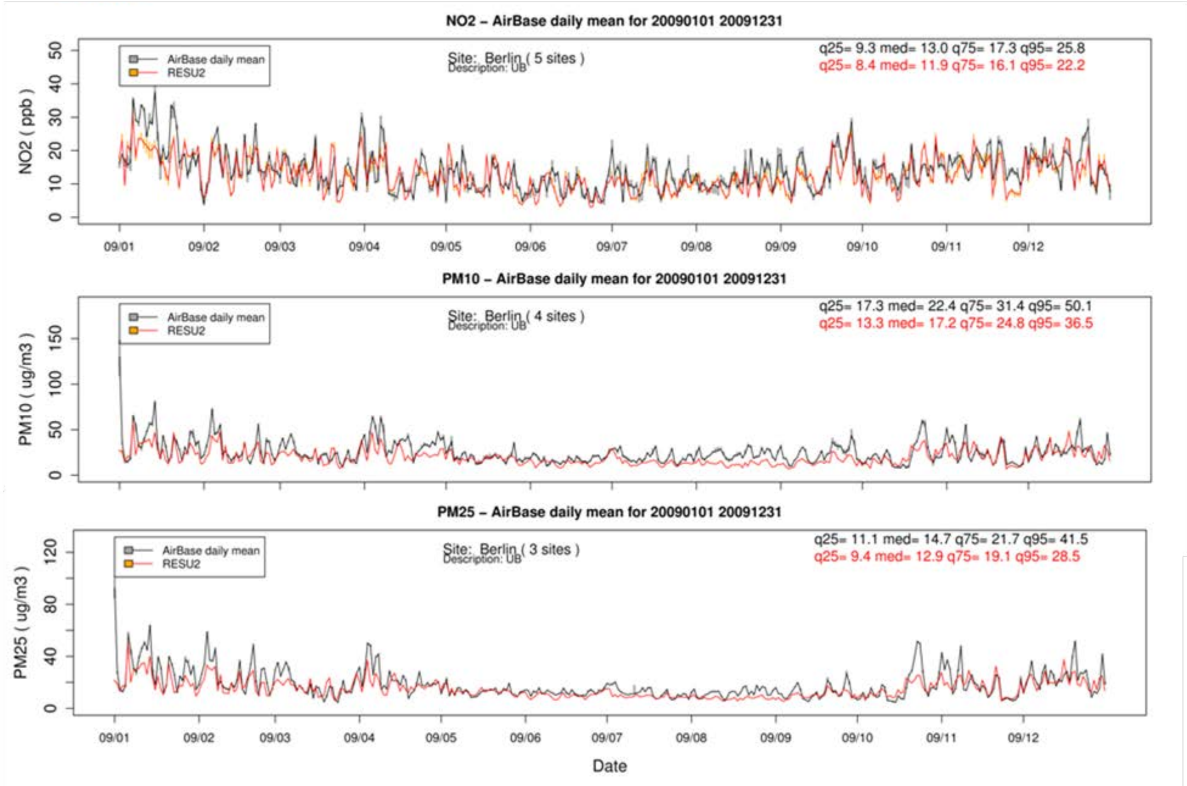
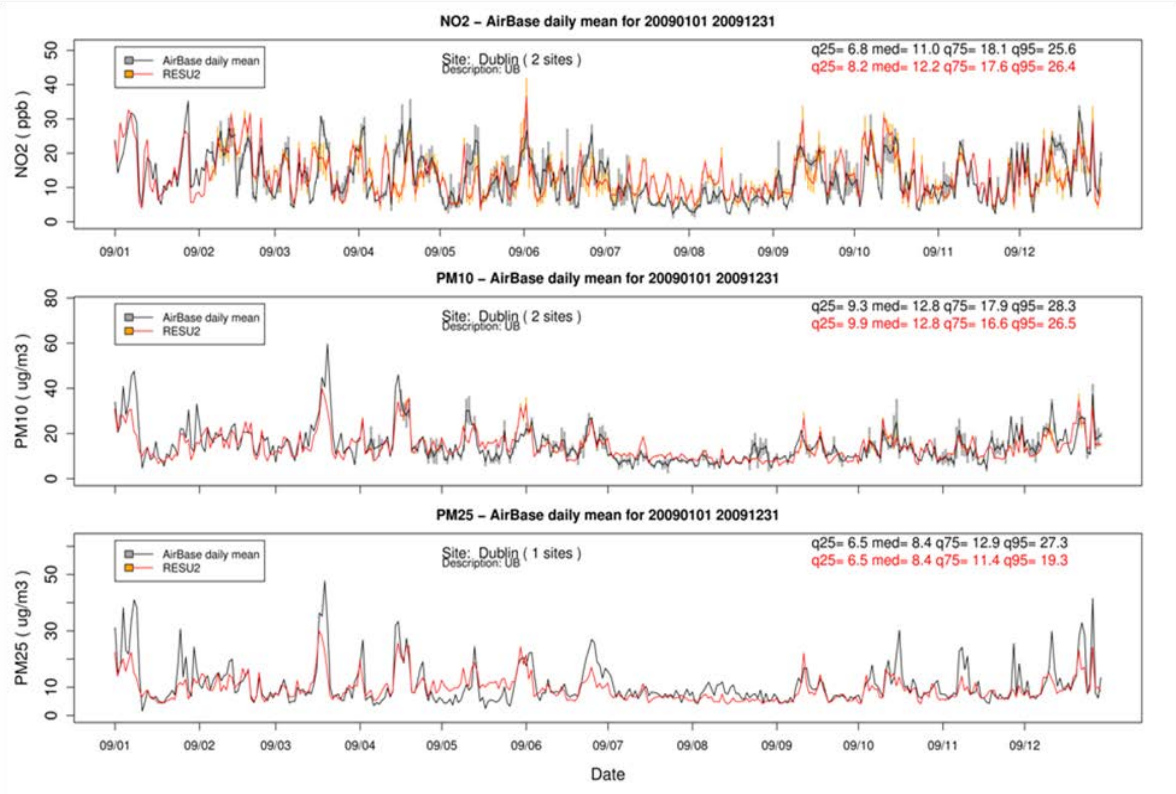
A1
Vilnius
Trakai district municipality
A16
A4
A3
E85
Image © 2013 DigitalGlobe
© 2013 Cnes/Spot Image
© 2013 Google
US Dept of State Geographer
15.6 km
Google earth
Imagery Date: 7/21/2011 54°41'56.67" N 25°12'47.02" E elev 153 m eye alt 70.69 km

Annex 3: times series (AirBase data) to assess the quality of the mapping approach

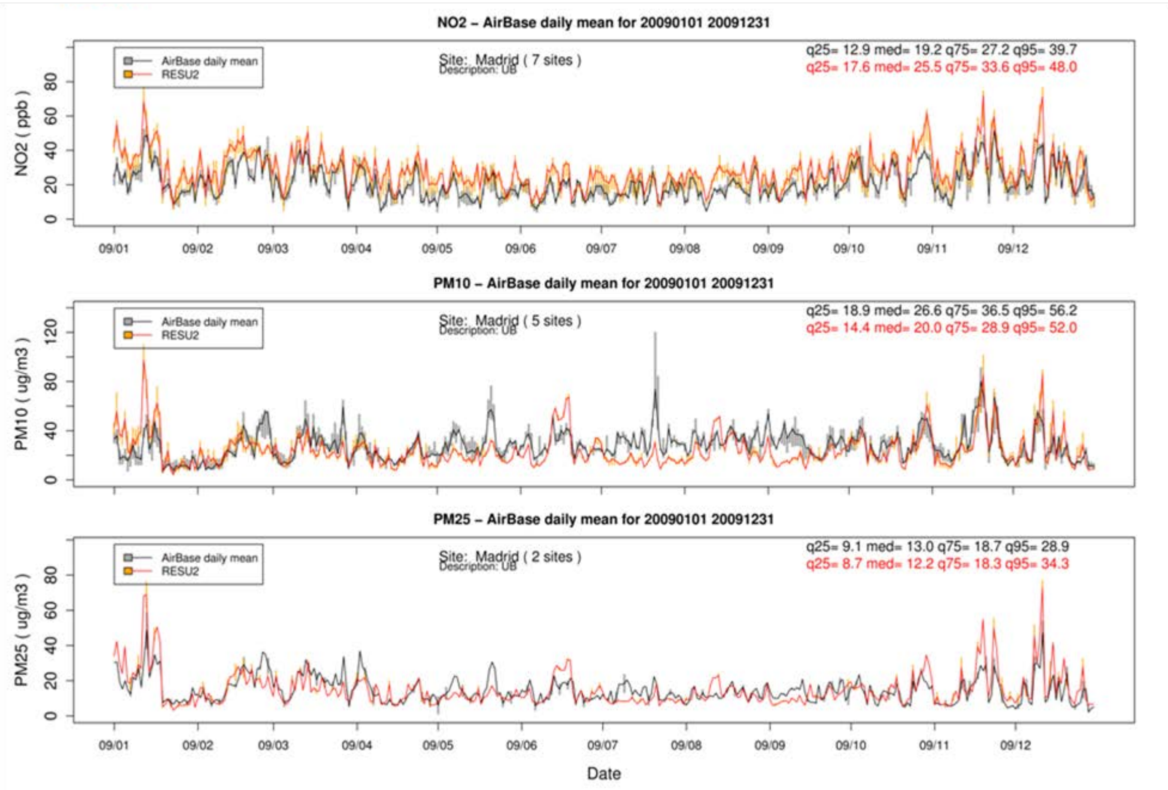
Berlin



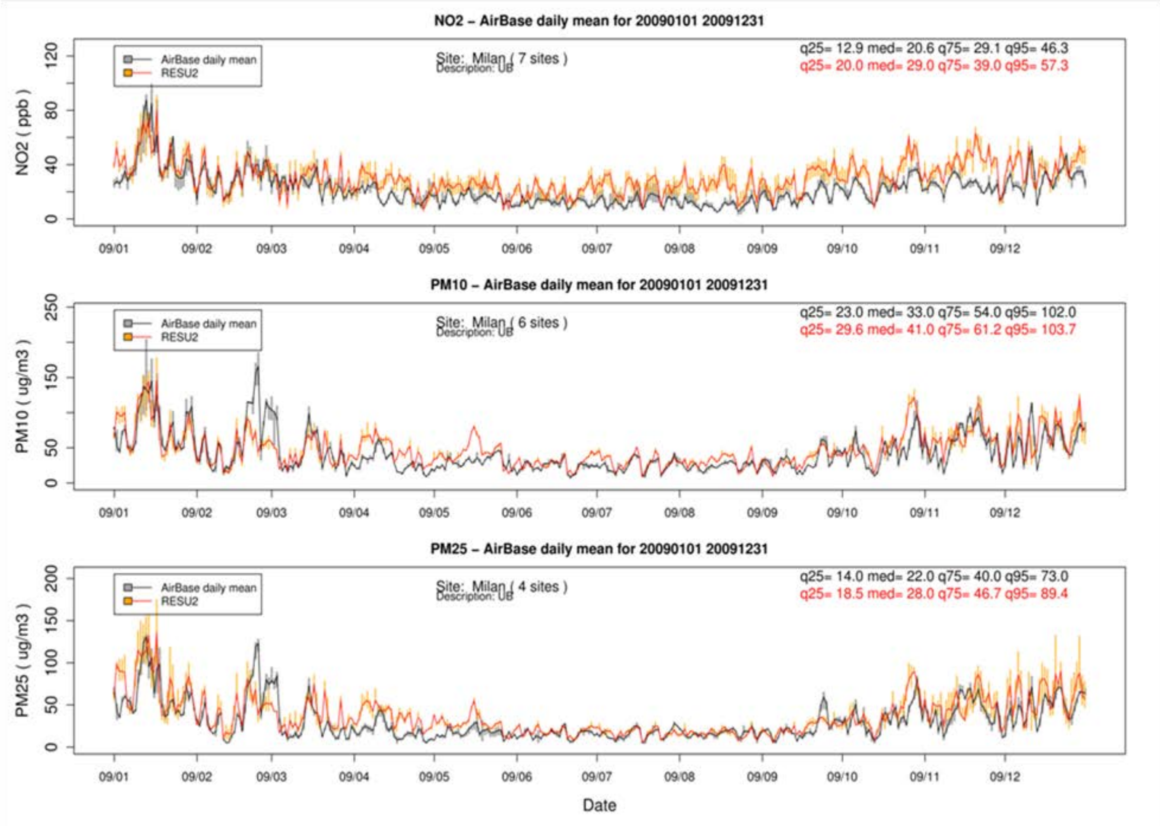
Dublin



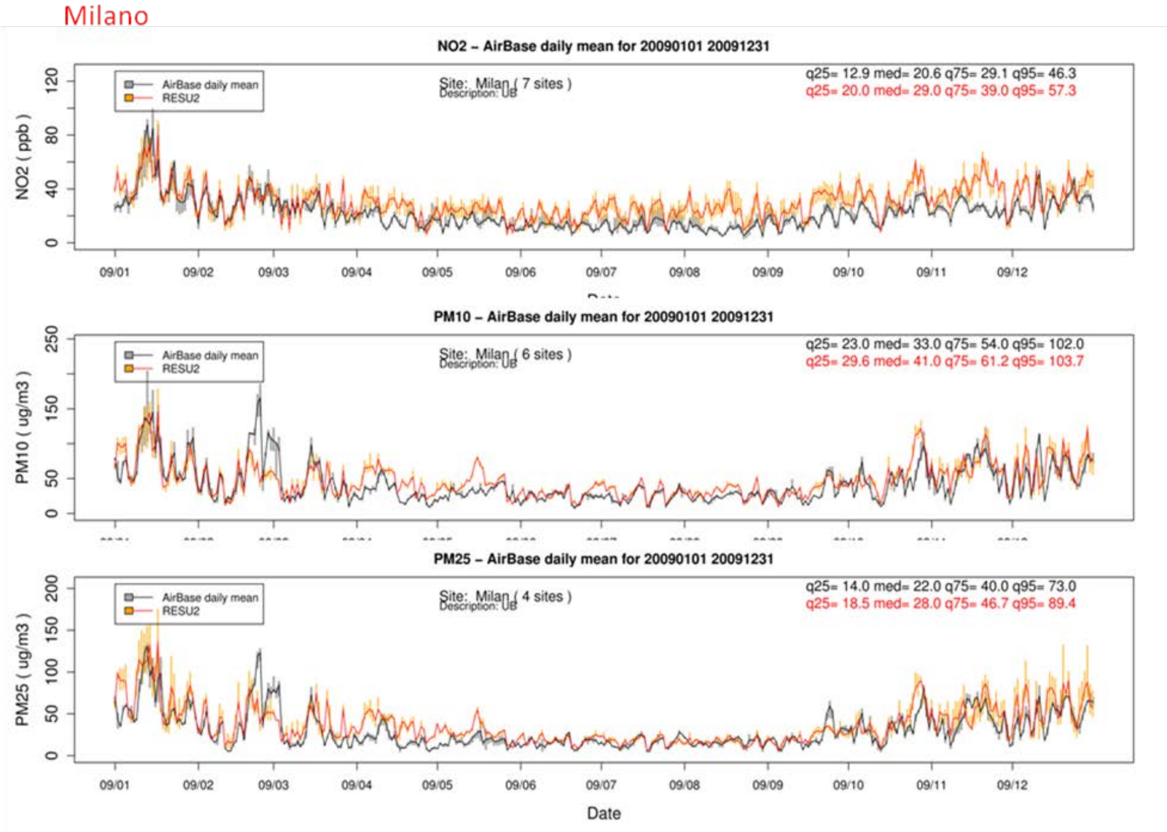
Madrid



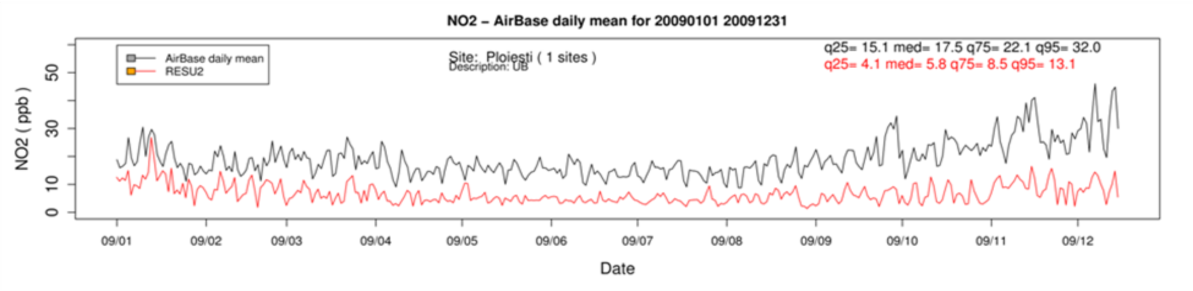
Malmö

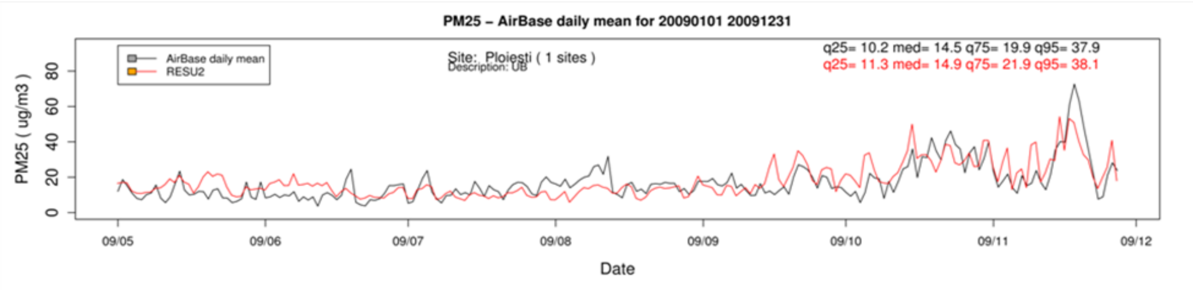


Milano



Ploiesti





Wien