Megapoli Scientific Report 10-19

Exposure Maps for Selected Megacities

MEGAPOLI Deliverable D4.5

Joana Soares, Ari Karppinen, Bruce Denby, Sandro Finardi, Jaakko Kukkonen, Massimo Cassiani, Paolo Radice, Matthew Williams

Left: PM2.5 yearly average concentrations (µg/m3) for the Greater London (provided by CERC), year 2001.

Right: Annual PM2.5 exposure scaled to 1km² grid cell (µg s/m³) for the Po Valley region, 2005.

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Abstract

We present exposure model results for two different MEGAPOLI case studies: Greater London (United Kingdom) and Po Valley region (Italy). The choice of these two cases was based on the availability of concentration and population gridded data. The methodology described and implemented here illustrates the use of two different methods for exposure assessment for the study areas, i.e. long term exposure at home residences. The two studies presented are compared just to have an idea of the order of magnitude of the values for population averaged concentrations, since these two studies were conducted for different years. The population averaged concentrations obtained from the high resolution exposure study for the Greater London is 24.5 \( \mu g/m^3 \) for PM\textsubscript{10} and 42.4 \( \mu g/m^3 \) for NO\textsubscript{2}. When comparing with the regional scale resolution assessment, the difference in population weighted concentration estimates (and exposures) are 1.5-2 times higher in the high resolution study. For this particular domain, only one grid cell form EMEP calculations and a completely different reference year was considered in the regional scale resolution study, which is already enough to explain the differences. For the Po Valley region case, the values obtained by these two different modeling studies for PM\textsubscript{10} are much closer to each other: according to the higher resolution exposure study the population averaged concentrations for PM\textsubscript{10} are 27.1 \( \mu g/m^3 \), while the values range between 16.5-19.3 \( \mu g/m^3 \) in the regional modeling based study. The results for Po Valley are much more comparable since the years studied are much closer, so at least the emissions will be more similar, and the gridding for Po Valley study for the regional scale calculations is much more representative for the whole area than in the Greater London case study.
1. Introduction

Assessment of human exposure to air pollution is an essential part of environmental risk studies and can be estimated by mathematical modeling. The mathematical modeling is based on deterministic simulation of environmental processes and the assessment of exposure usually requires application of integrated model chains starting from estimation of emissions, atmospheric dispersion and transformation of air pollutants. The exposure model then combines ambient air concentrations of pollutants and population activity data to calculate human personal exposure concentrations or simply ambient air concentrations and population distribution to obtain a proxy for the population exposure.

The latter approach was used to determine the exposure to different atmospheric pollutants for two different case studies: Greater London (United Kingdom) and Po Valley region (Italy). The choice of these two cases was based on the availability of concentration and population gridded data. In the following sections modelling tools and data will be described, followed by the results and discussion of the outcome.

2. Data and modelling tools

2.1 Exposure modelling

To estimate the overall exposure of the population to a certain pollutant, the exposure is modelled by combining concentration and population in a certain period of time. The following equation shows how the exposure (E) is computed for this study:

\[ E = n \times t \times C \quad (\text{ug.s/m}^3) \]

Where \( n \) is the number of people per grid cell, \( t \) is the time period [s] and \( C \) is concentration [\( \mu \text{g/m}^3 \)] for the pollutant. The final results will be shown as annual average exposures.
2.2 Population and concentration data

2.2.1 Study case 1: Greater London

Human exposure to PM\textsubscript{2.5} for the Greater London was estimated for the year 2001. The population and concentration data was provided by Cambridge Environmental Research Consultants (CERC). Both data sets were provided in a regular grid of points with a resolution of 1 km for population data and 50 m for concentration data. These data were available for the Greater London as yearly averages.

![Population for the Greater London](image)

*Figure 1: Population for the Greater London based on data provided by CERC.*

Population data is based upon a number of spatially resolved datasets for the Greater London. These datasets are derived from an inter-censual data source that can provide estimates for the population
To estimate the concentrations CERC utilized the dispersion model ADMS-Urban (CERC, 2001), computing the concentrations for different pollutants such as NO₂ and fine and coarse PM, the compounds of interest for the research undertaken in MEGAPOLI. The base year for the computations is 2001. ADMS-Urban is driven by off-line meteorology and specific parameters to describe the modeling area and dispersion characteristics, e.g. surface roughness and wind speed.

The meteorological parameters were obtained from a measurement site situated in Heathrow, for the year 2001, with hourly resolution. The ADMS meteorological pre-processor, written by the Met Office, uses these data to calculate the parameters required by the program.

The model includes a semi-empirical photochemical model known as the Generic Reaction Set (Venkatram et al. 1994) to describe the reactions involving nitrogen, ozone and volatile organic compounds.

The traffic emissions for the dispersion computations are calculated by using traffic flows from the London Atmospheric Emission Inventory (LAEI, Mattai and Hutchinson, 2008) combined with the fleet composition data provided by NETCEN and the latest set of emission factors from the UK Emissions Factor Database (UKEFD). All other non-traffic related emissions (NO₂, PM₂.₅ and PM₁₀) have been taken from the LAEI, including domestic and industrial sources. Background concentrations are based on the measurements obtained at different rural stations surrounding London city.

Modelling was carried out with concentrations calculated over a regular grid of points, with additional points located along major roads, where the concentration gradients are steepest. The predicted concentrations have been verified against measurements at various measurement sites, AURN network, in London city for the year 2001 (CERC, 2006).
2.2.2 Study case 2: Po Valley

The data for the Po Valley Region was provided by the National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Italy. For this case study concentrations were available for several different years (not for 2001). We have chosen the year 2005 for the estimation of exposure for PM$_{2.5}$ and PM$_{10}$ in the Po Valley region. Yearly average gridded data in terms of concentration was obtained with a spatial resolution of 4 km and the population data obtained from the municipal census with 1 km resolution.

The simulations for the concentrations were carried out with the Atmospheric Modelling System (AMS), which is part of the Italian Integrated Assessment Modelling System for supporting the International Negotiation Process on Air Pollution and assessing Air Quality Policies at national/local level (MINNI) (Zanini et al., 2005).

Figure 2: PM$_{2.5}$ yearly average concentrations (µg/m$^3$) for the Greater London (provided by CERC), year 2001.
Figure 3: Population distribution for the Po Valley Region (provided by ENEA).

The main components of AMS are: the meteorological model RAMS (Cotton et al., 2003) and the Local Analysis and Prediction System (LAPS) (McGinley et al., 1991), for simulating the meteorology, and the emission processor EMMA and the air quality model FARM (Gariazzo et al., 2007), for simulating the atmospheric chemistry. The aerosol dynamics and chemistry is described by AERO3 module (Binkowski and Roselle, 2003).

The anthropogenic emissions used for simulations were derived from the diffuse emissions inventory at provincial level (APAT, 2000, 2005), while the simulation at high spatial resolution over north of Italy is based on a version of the same inventory scaled down to municipalities using a set of proxies.
2.3 Data handling

Some of the data obtained was pre-processed for the exposure calculations. Due to the different resolution of the two databases, population data was interpolated to the same grid resolution as concentration data since population data is varying less in terms of magnitude than concentrations.

In the case of Greater London data, The Aikman’s interpolation was the method used for the population interpolation to the same resolution as the concentration data. This method is a smooth bivariate interpolant suitable for scattered data. Exposure results were plotted with a GIS-based program, MapInfo v8.5.

3 Results

3.1 Greater London

The human exposure was determined for PM$_{2.5}$, PM$_{10}$ and NO$_2$ for the year 2001. The total population for the Greater London is 8.5 million inhabitants. The computational domain for the Greater London is divided in 1297474 grid squares for PM$_{2.5}$ and 986400 grid squares for PM$_{10}$ and NO$_2$ of 50 m spatial resolution. Therefore PM$_{2.5}$ exposure calculations include the whole population and PM$_{10}$ and NO$_2$ exposure calculation include only 8 million inhabitants.

The exposure maps are presented both as exposure values scaled with the size of the grid cell (a) to
obtain maps which are readily comparable to studies done with different grid sizes and also as absolute values corresponding to each grid cell (b).

**Figure 5a:** Annual PM2.5 exposure scaled to 1km$^2$ grid cell ($\mu$g.s/m$^3$) for the Greater London, year 2001.
Figure 6a: Annual PM$_{10}$ exposure scaled to 1km$^2$ grid cell ($\mu$g.s/m$^3$) for the Gr. London, year 2001

Figure 6b: Annual PM$_{10}$ exposure ($\mu$g.s/m$^3$) for the Greater London, year 2001
The annual average exposure to PM$_{2.5}$ for 2001 averaged over all grid squares is $3.5 \times 10^9 \ \mu g \cdot s/m^3$.
6.3*10^9 \mu g*s/m^3 for PM_{10} and 1.1*10^{10} \mu g*s/m^3 for NO_2. The highest exposure values obtained for the Greater London area grid cells are 3.9*10^{10} \mu g*s/m^3 for PM_{2.5}, 6.5*10^{10} \mu g*s/m^3 for PM_{10} and 1.0*10^{11} \mu g*s/m^3 for NO_2. The total exposure for the Greater London is 4.5*10^{15} \mu g*s/m^3 for PM_{2.5}, 6.3*10^{15} \mu g*s/m^3 for PM_{10} and 1.1*10^{16} \mu g*s/m^3 for NO_2. The exposure values are relatively higher in the center of the Greater London, decreasing three orders of magnitude for all the pollutants, when focusing on areas closer to the limits of the domain.

### 3.2 Po Valley

The human exposure was determined for PM_{2.5}, and PM_{10} for the year 2005. The number of inhabitants of the Po valley region is of about 20 millions, that grows to 29 millions over the area covered by concentration fields that includes surrounding coastal and mountain regions. The Po Valley region has been devided in 13678 square grids of 4 km spatial resolution.

![Figure 5. Annual PM_{2.5} exposure scaled to 1km^2 grid cell (\mu g.s/m^3) for the Po Valley region, 2005.](image)
For the Po Valley area, the annual average exposures for PM$_{2.5}$ and PM$_{10}$, for the year 2005 averaged over all grid squares, were 1.6*10$^{12}$ μg.s/m$^3$ and 1.8*10$^{12}$ μg.s/m$^3$, respectively. The exposure is higher for the grid cells (4*4 km$^2$) including the urban centers of the region, clearly seen in the population map described by Figure 3, reaching 5.9*10$^{14}$ μg.s/m$^3$ and 6.7*10$^{14}$ μg.s/m$^3$ for PM$_{2.5}$ and PM$_{10}$, respectively (note the scaling with the grid cell size). Additionally, higher exposures are seen for the grids cells over the Alps, at the north of the Po Valley Region. The difference from urban to rural areas can be as high as 3 orders of magnitude. The total exposure for all the Po Valley grid squares is 2.2*10$^{16}$ μg.s/m$^3$ for PM$_{2.5}$ and 2.4*10$^{16}$ μg.s/m$^3$ for PM$_{10}$.

The presence of areas with zero exposure value can be attributed to the procedure adopted to obtain gridded population from municipal census data. Within every municipality population has been distributed over the target grid using CORINE land cover 2000 "urban" classes space statistics as proxy. The procedure produced cells with 0% urbanisation where no inhabitants have been allo-
cated. This result is a partial artefact (areas over 1 square kilometre with no inhabitants are frequent over the mountains but not over the plains) that can indirectly take into account the commuting of population towards urban centres during daytime working hours.

4. Sub-grid variability in regional scale air quality models and its implication for exposure assessment: application to the MEGAPOLI megacities

In the MEGAPOLI Deliverable 4.4 a methodology for calculating the impact of sub-grid variability on exposure calculations was described and applied to all of Europe. In this second part we apply the methodology and extract the results from the MEGAPOLI megacities of London, Paris, the Po Valley and the Rhine Ruhr region. The 50 x 50 km\(^2\) EMEP model data for 2006 are also applied here. The indicators of annual mean NO\(_2\), annual mean PM\(_{10}\) and SOMO35 are assessed. Grids which cover 25\% or more of the defined regions were included in the assessment. The results are presented in Tables 1-5 for all of Europe and for the individual megacity areas.

For London only one 50 x 50 km\(^2\) grid covers the London area and so the results are based on the parameterisation of that grid only. Po Valley is the largest region, including 56 grid points and the Rhine Ruhr and Paris include 7–8 grid points. The results for the four megacities (Tables 2-5) follow a similar pattern to the overall assessment of Europe (Table 1).

Table 1. Results of the application of the covariance parameterisation to 50 km EMEP grid data for all of Europe. Shown are the average model concentration over the whole domain, the population weighted (pw) concentration derived from the model calculations, the pw concentration after the application of the parameterised covariance correction factor and the total covariance correction factor (or fractional difference between the model and parameterised pw concentrations).

<table>
<thead>
<tr>
<th>Compound</th>
<th>Average model concentration</th>
<th>pw model concentration</th>
<th>Parameterised pw model concentration</th>
<th>Total covariance correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO(_2)</td>
<td>4.8 (\mu)g/m(^3)</td>
<td>10.0 (\mu)g/m(^3)</td>
<td>13.8 (\mu)g/m(^3)</td>
<td>+0.38</td>
</tr>
<tr>
<td>PM(_{10})</td>
<td>8.7 (\mu)g/m(^3)</td>
<td>11.3 (\mu)g/m(^3)</td>
<td>12.9 (\mu)g/m(^3)</td>
<td>+0.14</td>
</tr>
<tr>
<td>SOMO35</td>
<td>6239 (\mu)g/m(^3).h</td>
<td>6999 (\mu)g/m(^3).h</td>
<td>4881 (\mu)g/m(^3).h</td>
<td>-0.30</td>
</tr>
</tbody>
</table>
Table 2. As in Table 1 but data extracted for the megacity region of London (1 grid point).

<table>
<thead>
<tr>
<th>Compound</th>
<th>Average model concentration</th>
<th>pw model concentration</th>
<th>Parameterised pw model concentration</th>
<th>Total covariance correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO₂</td>
<td>25.3 μg/m³</td>
<td>25.3 μg/m³</td>
<td>32.8 μg/m³</td>
<td>+ 0.30</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>11.5 μg/m³</td>
<td>11.5 μg/m³</td>
<td>12.5 μg/m³</td>
<td>+ 0.09</td>
</tr>
<tr>
<td>SOMO35</td>
<td>3198 μg/m³.h</td>
<td>3198 μg/m³.h</td>
<td>2501 μg/m³.h</td>
<td>- 0.22</td>
</tr>
</tbody>
</table>

Table 3. As in Table 1 but data extracted for the megacity region of Paris (7 grid points).

<table>
<thead>
<tr>
<th>Compound</th>
<th>Average model concentration</th>
<th>pw model concentration</th>
<th>Parameterised pw model concentration</th>
<th>Total covariance correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO₂</td>
<td>14.7 μg/m³</td>
<td>28.3 μg/m³</td>
<td>40.0 μg/m³</td>
<td>+ 0.42</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>12.3 μg/m³</td>
<td>15.8 μg/m³</td>
<td>17.6 μg/m³</td>
<td>+ 0.12</td>
</tr>
<tr>
<td>SOMO35</td>
<td>6090 μg/m³.h</td>
<td>4885 μg/m³.h</td>
<td>3438 μg/m³.h</td>
<td>- 0.30</td>
</tr>
</tbody>
</table>

Table 4. As in Table 1 but data extracted for the megacity region of the Po Valley (56 grid points).

<table>
<thead>
<tr>
<th>Compound</th>
<th>Average model concentration</th>
<th>pw model concentration</th>
<th>Parameterised pw model concentration</th>
<th>Total covariance correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO₂</td>
<td>8.7 μg/m³</td>
<td>13.4 μg/m³</td>
<td>19.8 μg/m³</td>
<td>+ 0.42</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>13.2 μg/m³</td>
<td>16.5 μg/m³</td>
<td>19.3 μg/m³</td>
<td>+ 0.17</td>
</tr>
<tr>
<td>SOMO35</td>
<td>12437 μg/m³.h</td>
<td>12766 μg/m³.h</td>
<td>8606 μg/m³.h</td>
<td>- 0.33</td>
</tr>
</tbody>
</table>

Table 5. As in Table 1 but data extracted for the megacity region of the Rhine Ruhr region (8 grid points).

<table>
<thead>
<tr>
<th>Compound</th>
<th>Average model concentration</th>
<th>pw model concentration</th>
<th>Parameterised pw model concentration</th>
<th>Total covariance correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO₂</td>
<td>18.0 μg/m³</td>
<td>19.28 μg/m³</td>
<td>23.6 μg/m³</td>
<td>+ 0.23</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>12.4 μg/m³</td>
<td>12.8 μg/m³</td>
<td>13.67 μg/m³</td>
<td>+ 0.07</td>
</tr>
<tr>
<td>SOMO35</td>
<td>5651 μg/m³.h</td>
<td>5569 μg/m³.h</td>
<td>4675 μg/m³.h</td>
<td>- 0.16</td>
</tr>
</tbody>
</table>
5. Discussion and conclusion

Analyzing the results obtained it is clear that exposure is very strongly spatially correlated with the population data. This is expected since emissions and concentrations are highest, in particular traffic-related emissions, where the population density is highest. This is most clearly visible in the Greater London case study. The Po Valley study shows a similar correlation between the population density distribution and the exposure results but we also see a strong influence of the topography of the terrain. The Alps in the northern part of the domain create a specific situation in terms of dispersion of the pollutants, trapping the pollution within the valleys closer to the mountains and increasing the exposure to pollutants.

The methodology described and implemented here provides the basic exposure assessment for the study areas, i.e. long term exposure at home residences. While the spatial resolution of our assessment is at least satisfactory (see MEGAPOLI D4.4 for detailed discussions), the temporal resolution is very poor. This may lead to severe underestimation of especially exposure related to traffic (see...
MEGAPOLI D4.4). Local, detailed activity data would be needed to assess properly the uncertainty related to the rough temporal resolution. For assessing short term exposures it would be crucial to have better temporal resolution. On the other hand, assessing long term exposures to ambient air ‘properly’ you should take into account the time activity and hence have a model temporal resolution to reflect that. Even so, the time activity data would always be aggregated (i.e. week day and weekend diurnal averages) and the model results would actually not be needed for every hour but should reflect the diurnal and weekly cycles. For estimating these cycles, information about micro-environments and how these impact on the ambient concentration is needed. Minimum information needed would be a work/home address disaggregation and the linkage between homes and workplaces. Some information on this is already reported for London in an ETC report (http://air-climate.eionet.europa.eu/reports/ETCACC_TP_2009_17_AQ_health_urban), while for Po Valley we were not yet able to identify any similar data.

This modelling analysis has also a number of other inherent limitations and uncertainties. There are uncertainties concerning the emission and population inventories and regarding the dispersion modelling. Since the models and inventories here utilized were different, the detailed uncertainties related to these will also be different. In general, population inventories are not compiled very frequently, census is typically only carried out every 10 years, and in cities like London the spatial distributions of population can be very dynamic, significant changes in the population densities can occur even in a 1 year timeframe. There are always large uncertainties with emission inventories (typically +-50%) and the temporal and spatial resolution of these inventories might not be compatible with the spatial and temporal resolution of the dispersion model. Also the dispersion models utilized in this study have different requirements in terms of input data and the intrinsic physical processes that must be solved mathematically differently since their simulation domain is quite different: local/urban scale for Greater London and regional scale for the Po Valley.

The two studies presented in sections 3 and 4 can be compared just to have an idea of the order of magnitude of the values for population averaged concentrations, since these two studies were
conducted for different years. The population averaged concentrations obtained from the exposure study for the Greater London is 24.5 $\mu$g/m$^3$ for PM10, and 42.4 $\mu$g/m$^3$ for NO2. When comparing with the study by Bruce and Cassiani, the values for the latter study are much smaller, but for this particular domain, only one grid cell form EMEP calculations and a different reference year are considered, which is already enough to explain the differences. For the Po Valley region case, the values obtained by these two different modelling studies for PM$_{10}$ are much closer to each other: according to the higher resolution exposure study the population averaged concentrations for PM$_{10}$ are 27.1 ug/m$^3$, while the values range between 16.5-19.3 ug/m$^3$ in the EMEP modelling based study. The results for Po Valley are much more comparable since the years studied are much closer, so at least the emissions will be more similar, and the number of grid cells used for the Po Valley study by Bruce and Cassiani is much more representative.

**Acknowledgements**

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http://megapoli.dmi.dk/publ/MEGAPOLI_sr09-03.pdf

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Megacities: Emissions, urban, regional and Global Atmospheric POLLution and climate effects, and Integrated tools for assessment and mitigation

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WP7: Integrated tools and implementation
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WP8: Mitigation, policy options and impact assessment
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WP9: Dissemination and Coordination
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