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SCALE INTERACTIONS IN LOCAL, URBAN AND REGIONAL AIR QUALITY MODELLING

C. Mensink, K. De Ridder, F. Deutsch, F. Lefebre and K. Van de Vel

VITO - Centre for Integrated Environmental Studies
Boeretang 200, B-2400 Mol, Belgium
clemens.mensink@vito.be

ABSTRACT

Air quality modeling can help us to improve our understanding of scale interactions related to meteorology, transport, emissions, formation and removal and other processes taking place at local urban and regional scales. For the local scale we use a coupling of a street canyon model and the Gaussian dispersion model to study the interactions of emissions and concentrations in urban streets and surrounding urban neighborhoods. For the urban scale, the AURORA model has been applied successfully in assessments of urban air quality in the entire cities or urbanized areas like the Ruhr area in Germany. The model can calculate ozone and PM_{10} concentrations for various land use scenario's revealing the impact of urban sprawl and the use of green areas. For the regional scale, the EUROS model is used to study the urban and regional scale interactions that are important in simulating concentrations of ozone, $PM_{2.5}$ and PM_{10}.

Key Words: Air Quality Modelling, Scale Interactions, Urban Air Pollution, Street Canyons, Particulate Matter.

1. INTRODUCTION

In Northwest Europe more than 80% of the population is living in cities or towns. Clean air is essential to this urban life. However, more than 70% of large European cities fail to meet air quality standards set by the World Health Organisation. It is obvious that people in urban areas are increasingly concerned about this, especially since the growing awareness of the possible health impacts of exposure to air pollution. Urban air quality is strongly related to other important elements that determine the quality of the urban environment, like accessibility and opportunities for economic activities, social interaction and recreation (green areas, open space). Air quality management is therefore a difficult and interdisciplinary task which often goes beyond the limits of the urban scale.

Scale interactions can also be found back in the physical context. Local emissions sources form traffic or industrial activities have a major impact on the urban air quality. Cities have a significant impact on urban and regional air quality up to 10-100 km because of their particular surface characteristics and because of high emissions of several pollutants. Atmospheric circulation created by the city itself (e.g. as an urban heat island) directly affect the dispersion of these pollutants. On the other hand it is known that the majority of Europe's total urban population is exposed to high levels of ozone concentrations and particulate matter. These concentration levels are in many cases largely determined by regional scale processes.

The objective of this contribution is to show how we can improve our understanding of some of these scale interactions by studying the local emission control measures on pollutant concentrations in and around urban areas. Important questions that will be addressed are:

- How are the local urban concentrations affected by traffic emission reductions in surrounding street canyons and high ways?
- How does urban air quality benefit from green spaces and open spaces in the city?
- To what extend are PM concentrations in urban areas determined by regional processes?

2. METHODOLOGY

Over the past decade, we developed several modelling tools to assess air quality at various scales, ranging from the local scale to the continental scale with urban and regional scales in between. The models were developed, improved and implemented to estimate environmental risks and perform various assessment studies for the Flemish, Belgian and European administrations, as well as for industrial companies.

2.1 Local scale modeling

Gaussian models are widely accepted as tools for local air quality assessment. They are used in assessing the environmental impact of certain private or public initiatives. For regulatory purposes, environmental impact studies and more specific impact studies in Flanders, the IFDM model is used (Cosemans et al., 1997).

In order to study the interactions of emissions and concentrations in a specific urban street on one hand and the emissions and concentrations in the surrounding urban neighborhood on the other hand, a novel approach has been developed consisting in the coupling of a street canyon model (OSPM, Berkowicz, 1998) and the Gaussian IFDM model (Mensink and Cosemans, 2005). OSPM computes the contribution of the traffic emissions inside a particular street, whereas IFDM computes the background contributions, including the concentration levels caused by the surrounding streets, industrial stacks and domestic heating within a domain with a 20-30 km radius. Both models are interacting and have been integrated into an advanced computer program.

2.2 Urban scale modeling

On an urban scale the AURORA model (Mensink *et al.*, 2001) is used as an urban air quality management tool that can provide reliable answers to policy makers and traffic planners. This urban air quality management system has been designed for urban and regional policy support and reflects the state-of-the-art in air quality modelling, using fast and advanced numerical techniques. The model input consists of terrain data (orography, land use, road networks, remote sensing), meteorological fields and detailed emission data. Meteorological input data are provided with a resolution up to a few hundred meters by a separate meteorological model (ARPS). The emission input data are resulting from a detailed inventory and acquisition of existing emission data in combination with emission modelling (Mensink *et al.*, 2000). In this way the emissions are described as a function of space, time and temperature.

The AURORA model was successfully applied for assessment of urban air quality in the cities of Antwerp and Ghent in Belgium, and furthermore in Budapest in Hungary and in the Ruhr area in Germany. It also contributed to the EU 5th framework projects DECADE (http://www.cle.de/umwelt/decade/edecade.htm) and BUGS (Benefit of Urban Green Spaces) (http://www.vito.be/bugs/) (De Ridder *et al.*, 2004).

2.3 Regional scale modelling

On the regional scale the operational Eulerian air quality model EUROS was extended with two special modular algorithms for atmospheric particles. The first module is the Caltech Atmospheric Chemistry Mechanism (CACM, Griffin et al., 2002), being the first mechanism in describing the formation of precursors of secondary organic aerosols in the atmosphere in a mechanistic way. The second module is the Model of Aerosol Dynamics, Reaction, Ionization and Dissolution (MADRID 2, Zhang et al., 2004), which treats the formation of secondary aerosols through equilibrium calculations between the gas phase and the aerosol phase for inorganic (ISORROPIA) and hydrophilic and hydrophobic organic compounds (AEC-SOA-module). Also dynamic processes (e.g. nucleation) are included in MADRID 2. The chemical composition is expressed in terms of 7 components: ammonium, nitrate, sulphate, primary inorganic compounds, elementary carbon, primary organic compounds and secondary organic compounds (SOA).

The Caltech Atmospheric Chemistry Mechanisms (CACM) comprises 361 reactions among 122 components. CACM contains besides the complete ozone chemistry also the reactions of various generations of organic compounds during which semi-volatile reaction products are formed which can equilibrate into the solid phase. 42 of these condensable products are treated in CACM, all of them reaction products of anthropogenic and natural organic compounds, e.g. terpenes. Various routines of EUROS (e.g. VOC-split, background concentrations) were adjusted to CACM.

3. RESULTS

3.1 Local scale modeling

The coupled system OSPM/IFDM was applied to a city quarter in Ghent, Belgium. For this exercise, traffic emissions were obtained dynamically from the traffic simulation model Paramics. The dynamic emission allocation is derived by VITO from emissions measurements (Mensink et al., 2005) and is used to calculate for each time step and for each car, the emission of 5 pollutants (PM, CO, NO_x, VOC and CO_2) depending on the car's category, speed and acceleration. Figure 1 shows the yearly averaged $PM_{2.5}$ concentrations for 2003. Results show that the background contribution from a nearby highway exit is dominant in streets where low traffic is observed, but even in cases of moderate traffic, the local background concentration is substantial.

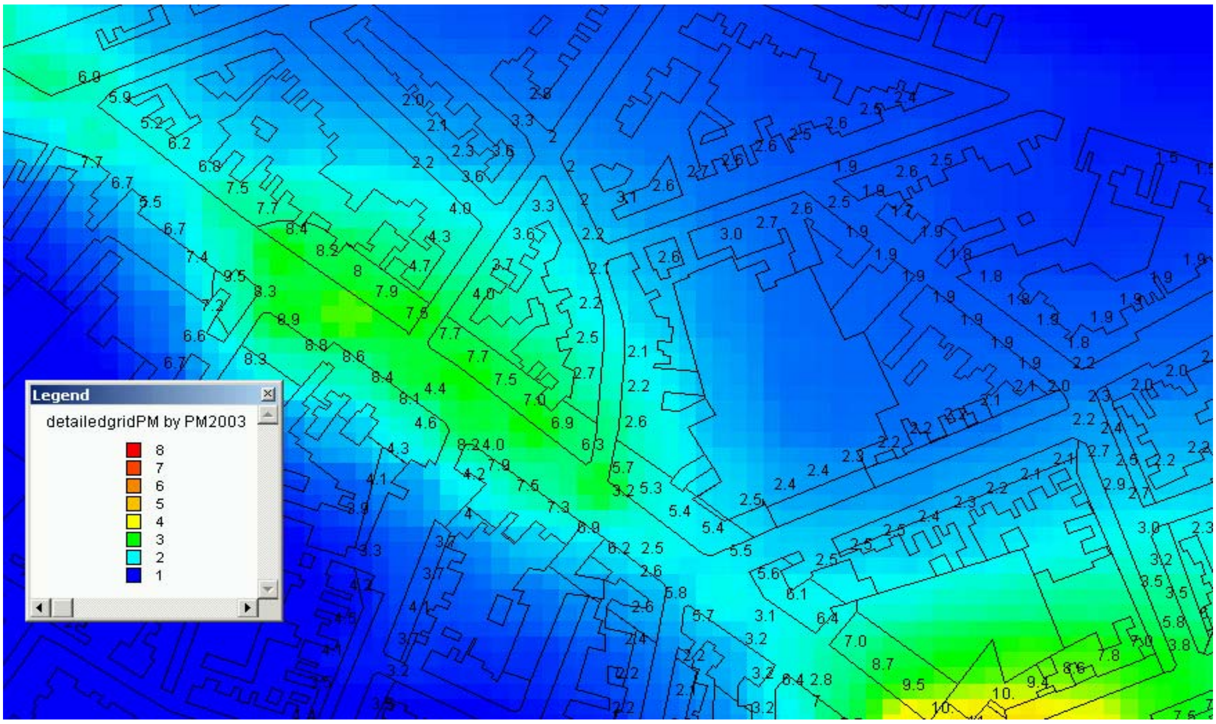

Figure 1. Predicted concentrations of $PM_{2.5}$ (2003) in the city quarter of Gentbrugge. Numbers show the $PM_{2.5}$ concentrations inside street canyons. Colours show the $PM_{2.5}$ concentrations outside street canyons.

3.2 Urban scale modeling

Application of the AURORA model to the German Ruhr area reveals that the re-distribution of green areas have a considerable impact. This was studied by comparing two different urban sprawl scenario's representing different developments in jobs,

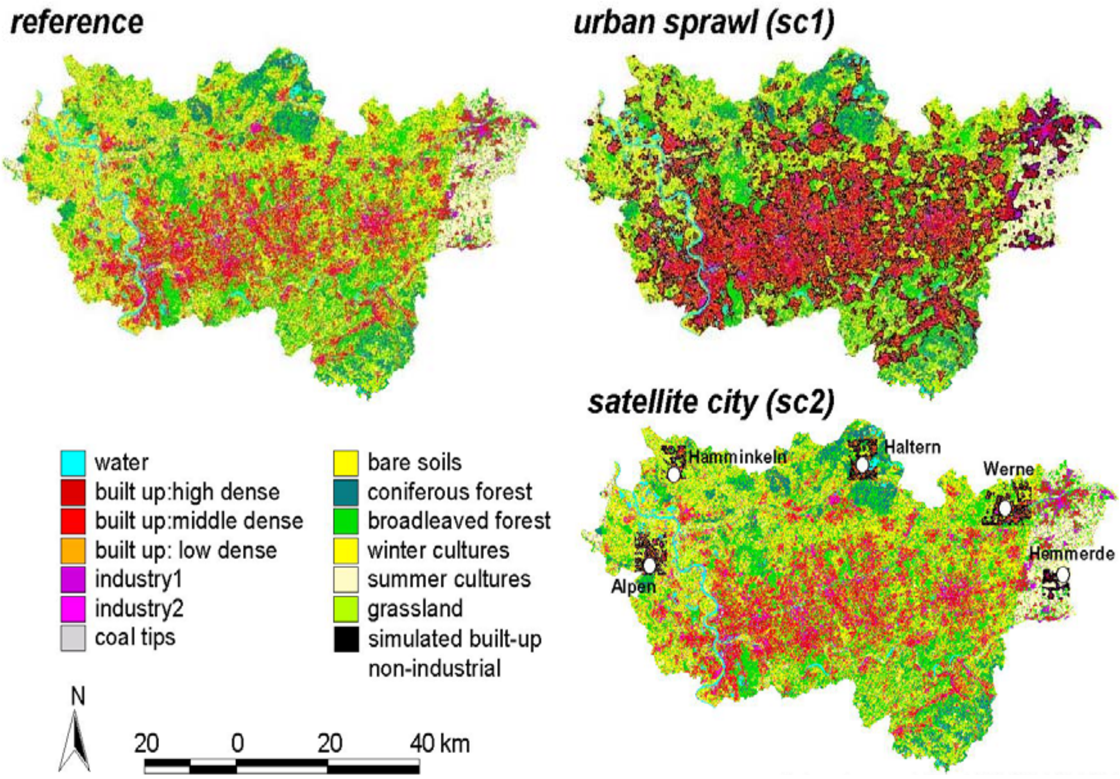

Figure 2. Land use categories of the reference state and the two scenarios urban sprawl (1) and satellite city (2). The red band extending in the east-west direction in the central portion of the domain corresponds with the urbanised areas.

mobility and land use. Figure 2 shows the land use categories of the reference state and two scenarios: a urban sprawl scenario (1) in which no controlled urban development is simulated and a satellite city scenario (2) in which the urban development is controlled by creating 5 concentrated urban development areas. The main result here is that, for the urban-sprawl situation, the urbanised area in the study domain increases by almost 75 %, hence land consumption is rather drastic. For the satellite-city scenario, urban land use changes are much lower, around 9 %. The resulting updated maps of the area were used as input for the traffic and atmospheric dispersion simulations, which showed that total traffic kilometres and associated emissions increased by up to almost 17 %. As a consequence, the domain-average pollutant concentrations also increased, though by a smaller amount.

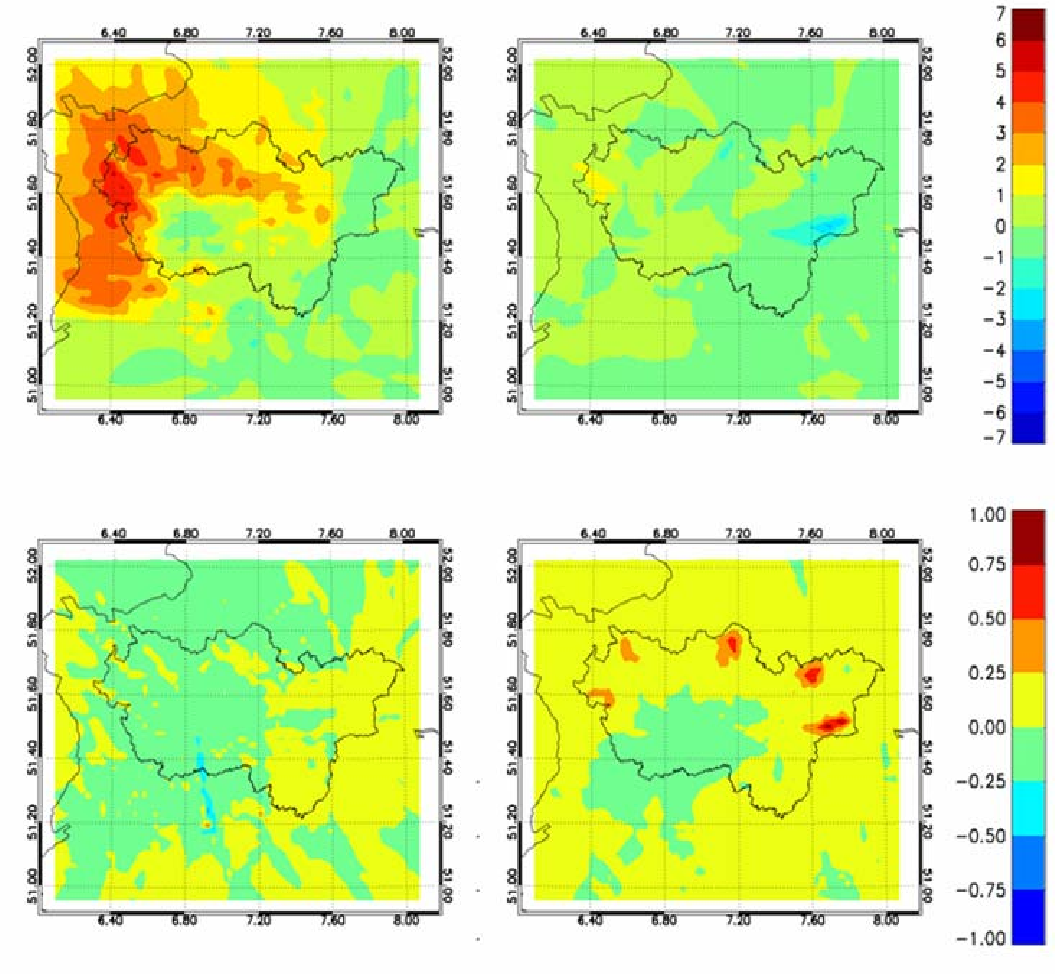

Figure 3. Concentration change (in µg m^{-3}) of ozone (upper panels) and PM_{10} (lower panels) for scenario 1 (left panels) and scenario 2 (right panels). Positive values indicate an increase of the considered scenario compared to the reference situation.

For a three-week simulation period, 1-20 May 2000, the simulated change of ground-level ozone and of primary particulate matter is shown in Figure 3. With respect to ozone, the largest changes are seen to occur for the urban-sprawl scenario. Owing to the dominating south-easterly wind direction during this episode, an increased ozone plume is simulated north-west of the agglomeration. The titration effect, on the other hand, slightly depresses ozone concentrations in the central portion of the domain, i.e., where the highest population densities occur. As a result, the average exposure to ozone pollutants (calculated as the average of the concentrations, spatially weighted with population density) remained almost unchanged – they increased by 0.3 % – between the reference case and the urban-sprawl scenario. Also in the satellite-city scenario the changes are minimal (decrease by 0.45 %), despite the increased domain-average emissions.

With respect to fine particulate matter, the effect of the scenarios is perhaps not so clear (Figure **3**3). Whereas the satellite-city scenario clearly exhibits local spots of (a very modest) increase of this pollutant, the concentration patterns in the urban-sprawl case appear almost unaltered. A detailed analysis shows that there is a slight overall increase of domain-average concentration. However, the effects on human exposure to this pollutant are not so straightforward: whereas one would intuitively associate increased emissions and the ensuing increased domain-average concentrations with increased human exposure values, the contrary is seen to occur. Indeed, a detailed analysis shows that the urban-sprawl scenario results in an exposure *reduction* of 5.7 %, and a reduction of 1.4 % for the satellite-city case. The dominant driver of these exposure changes appears to be the movement of people from locations with high to locations with lower particulate matter concentrations. Stated otherwise, the global exposure decreases when a portion of the population moves from the relatively polluted conurbation to less-polluted areas.

3.3 Regional scale modelling

The EUROS model has been applied to urban areas in the Flanders in order to study the formation and chemical composition of aerosols in an urban and regional context. The chemical composition of the aerosol showed a strong dependence on the season.

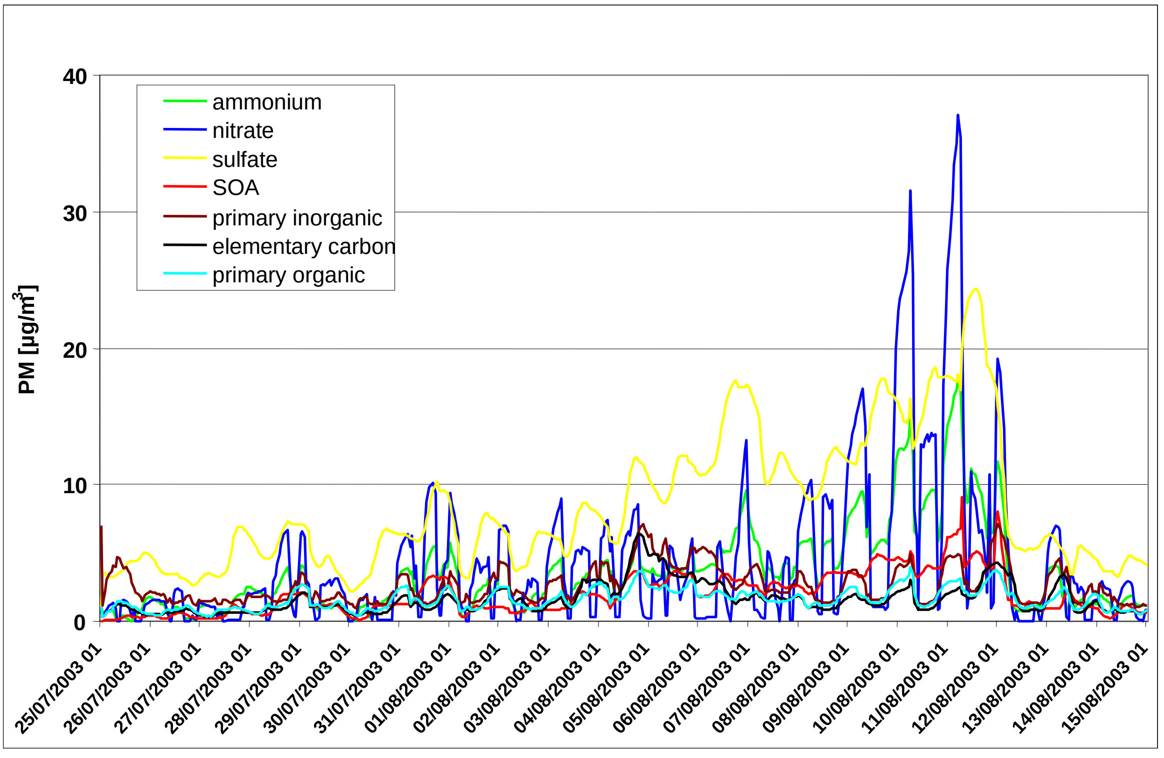

Figure 4. Composition of $PM_{2.5}$ during summer time conditions in 2003 in an urban monitoring station in Flanders (Borgerhout).

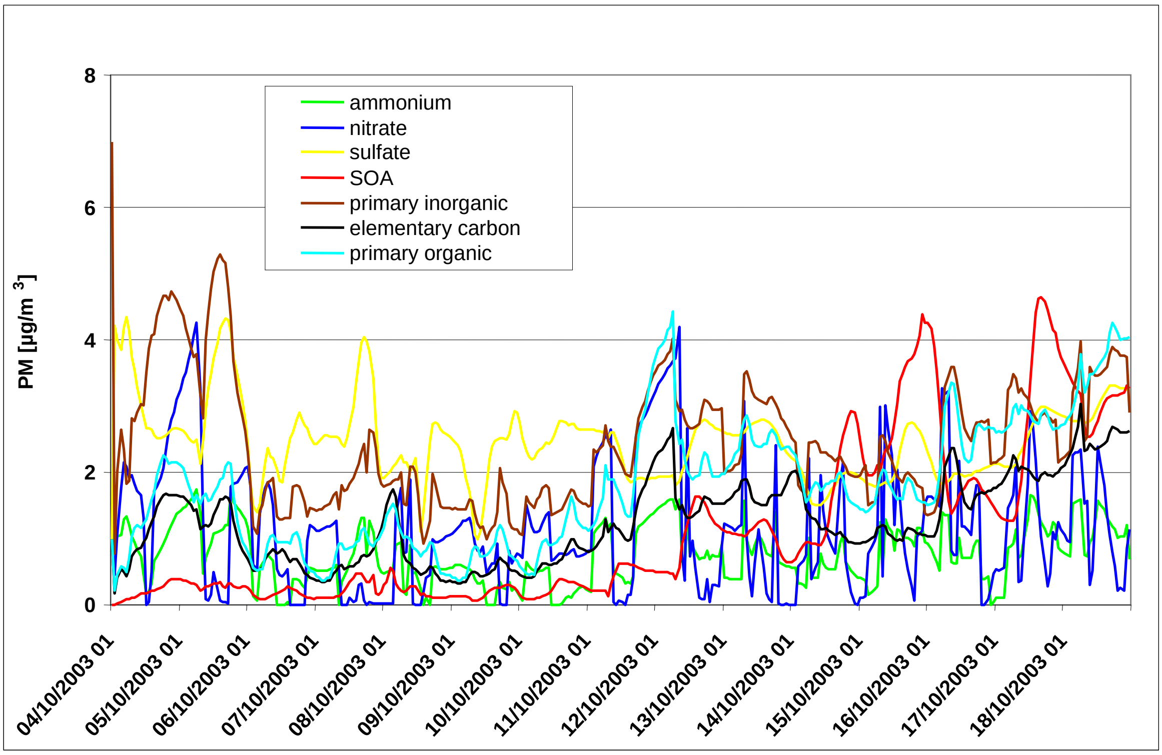

Figure 5. Composition of $PM_{2.5}$ during autumn time conditions in 2003 in an urban monitoring station in Flanders (Borgerhout).

Figure 4 shows the contributions to the composition of $PM_{2.5}$ during summer conditions in an urban monitoring station in Flanders (Borgerhout). Figure 5 shows the aerosol composition of $PM_{2.5}$ in autumn time conditions for this station.

High aerosol concentrations during the summer were mainly due to high concentrations of the secondary components nitrate, ammonium and SOA in the fraction $PM_{2,5}$, thus showing a dominant regional contribution. This shows again the importance of taking scale interactions into account. During the autumn and winter, lower concentrations of secondary aerosol were modeled and hence local or urban contributions of e.g. primary PM components were found to be more important.

4. CONCLUSIONS

A novel approach was demonstrated based on the coupling of the street canyon model OSPM and the Gaussian model IFDM. OSPM calculates the contribution of the traffic emissions inside a particular street canyon, whereas IFDM computes the background contributions, including the concentration levels caused by the surrounding streets, industrial stacks and domestic heating. The combined modelling tool can be applied to study these scale interactions within a domain with a 20-30 km radius. Both models are interacting and have been integrated into an advanced computer program.

On an urban scale, urban sprawl and satellite-city scenarios were studied using spatial modelling techniques, traffic simulations and the air quality model AURORA. Despite the global concentration increases that were calculated by the model, an analysis of human exposure to atmospheric pollution revealed that both scenarios considered here lead to *lower* rather than higher exposure values. While not contesting the evident advantages of compact or polycentric cities with respect to a host of sustainability indicators, like e.g. land consumption, these results indicate that compact/polycentric cities may also induce adverse effects, which should be taken into account by policy makers when making choices regarding urban development scenarios.

The fine particulate matter version of the EUROS-model showed to be suited to determine the most important contributions to aerosol concentrations, including the percentage of secondary aerosols. It can be used to define sources and formation mechanisms of particulate matter and can be an important policy-supporting instrument for drawing up and evaluating reduction scenario's for fine particulate matter.

The chemical composition of the aerosol showed a strong dependence on the season. High aerosol concentrations during the summer were mainly due to high concentrations of the secondary components nitrate, ammonium and SOA in the size fraction $PM_{2,5}$. These secondary compounds are transported from outside the urban area that is considered (regional contribution). During other seasons, secondary components were less abundant in this size fraction, although SOA still contributed significantly to the total aerosol mass. For these cases local or urban contributions of e.g. primary PM components were found to be more important.

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