# Applying the DYMOS System in Conurbations

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**Abstract** During hot mid-summer periods health-critical concentrations of surface-near ozone can be found in many urban and industrial areas around the world. In Germany, federal authorities are commited to take steps to protect the population if certain limits have been reached, for example to ask the public to stay inside closed rooms. In order to support governmental administrations and industry responsible for air pollution management, complex air pollution simulation systems are necessary. DYMOS is a parallelly implemented air pollution simulation system for mesoscale applications, consisting of different meteorological models, an air-chemistry model, a database, and a graphic user-interface. Using the DYMOS system, various case studies regarding summer smog in urban areas have been carried out or are in preparation (e.g. in the regions of Berlin, Munich, Budapest, Gdansk, Athens, Sao Paulo). On the behalf of the Senate of Berlin and the Ministry of Environmental Protection of Brandenburg, a measuring campaign in 1994 of ozone and ozone precursor substances was accompanied by computer simulations with a subset of the DYMOS system, that is the simulation system REGOZON. Commissioned by Greenpeace, the influence of emissions caused by traffic in Munich on the ozone concentration in the larger Munich region was analysed for a typical mid-summer day using the DYMOS system. Some of the results are presented here in this paper, in particular a scenario analysis for the region Berlin-Brandenburg and a scenario analysis for the larger Munich region.

## 1. INTRODUCTION

During hot mid-summer periods, health-critical concentrations of surface-near ozone arise particularly in urban and industrial areas. In Germany, official concentration limits has been introduced by the German government in 1995. If these limits are reached, federal authorities are commited to take steps protecting the population. However, to date they only have asked the public to stay inside their houses or to reduce private traffic.

The processes leading to high ozone concentrations are very complex. Mixing from stratospheric levels to the ground can lead to high surface-near ozone concentrations as well as the production of ozone from anthropogenic and natural ozone precursor substances, nitrogen oxides (NOx) and volatile organic compounds (VOC), even in considerable distances from the emissions sources. As it is in the interest of local and federal authorities to assess the effectiveness of precautionary steps preventing critical ozone concentrations, complex air pollution simulation systems are necessary. Although Eulerian dispersion models are less suitable for general prognostic systems, they nevertheless can be used to support environmental agencies in their smog management and long-term planning.

## 2. THE DYMOS/REGOZON SYSTEM

DYMOS (Sydow [1994]) is a parallelly implemented air pollution simulation system for mesoscale applications, developed, implemented and extensively tested at GMD FIRST during the last 5 years. The aim of DYMOS is to (i) support governmental administrations and industry in operative decision making as well as long-term planning, (ii) to serve as a scientific basis for national or international negotiations, and (iii) to provide smog information for the public. DYMOS may be applied to winter smog (high concentrations of inert pollutants), summer smog (high concentrations of ozone and other photochemical oxidants), antigenous air pollution (high concentrations of substances with antigenous effects on the human immune system), or to the spread of single components (e.g. heavy metals, benzol, radioactive substances).

As the presented results in this paper have been obtained with the sub-system REGOZON, we will restrain our description to this more elementary version (DYMOS consists of different meteorological models of different complexity, and only one of these models have been implemented in the sub-system REGOZON). The simulation system REGOZON consists of the meteorological (Eulerian) model REWIMET, the air-chemistry model CBM-IV for the calculation of photochemical oxidants, a database for model input and simulation results and a graphic user-interface for spatial data visualization.

REWIMET (Heimann [1985]) is a mesoscale atmospheric model which is officially distributed by the German Engineer Association VDI. Mesoscale models describe processes (e.g. thunderstorms, cloud clusters, low-level jets) occurring over a horizontal extension of about 20 to 200 km and therefore provide the foundation for simulations covering urban areas. Based on the assumption of a hydrostatic, incompressible and dry atmosphere, REWIMET is driven by the suprascale stratification, the suprascale horizontal pressure gradient (geostrophic wind), and the surface temperature. Furthermore, the input of topographical data (surface elevation, land use) and some emission data (industry, private households, traffic) is necessary. The input values of the geostrophic wind can be given time-dependent, and the transport of several air pollutants can be calculated simultaneously.

In contrast to true three-dimensional models, REWIMET uses a fixed grid structure only horizontally. Vertically, the model is subdivided into three layers lying on top of each other (such an approach is justified by the very flat terrain of the model region - the largest difference in the altitude of grid points is about 120 m - and the well mixed boundary layer of up to 3500 m (at noon) during the simulated time period). The first layer (surface layer) follows the ground level and has a fixed vertical thickness of 50 m. It is turbulent mixed and its physical behaviour is strongly coupled with the surface characteristics. Emissions from traffic, from households and from industrial sources with low emission heights are introduced into the surface layer. The second layer (mixed layer) reaches from the upper level of the surface layer to the upper level of the atmospheric boundary layer. It is also turbulently mixed and shows the characteristic diurnal variation of the thickness of the atmospheric boundary layer. Emissions from higher emission sources, for example high stacks from power stations, enter the mixed layer. The third layer (temporary layer) is located above the mixed layer. It is assumed to be free of turbulence. Since the atmospheric boundary layer can expand to the suprascale inversion, it is possible for the temporary layer to disappear. It will be recreated when the atmospheric boundary layer sinks. No substances are emitted in this layer but it transports the suprascale background concentrations of ozone and ozone precursor substances above the atmospheric boundary layer.

CBM-IV (Gery et al. [1988]) is a well-known and sufficiently tested reaction scheme describing the most important chemical processes in the gas phase chemistry for the production of ozone and other photooxidants. It is officially distributed by the Environmental Protection Agency of the United States. CBM-IV is a condensed version of the original CBM. Carbon atoms with similar bonding are treated similarly, however, some species are handled explicitly because of their special character in the chemical system (for example isoprene which is the most emitted biogenic species). The mechanism involves 34 species, 82 reactions, and contains 9 primary organic compounds. To profit from the features of the CBM-VI, detailed information of the hydrocarbon mixture is necessary.

Simulation runs based on the models REWIMET and CBM-VI have an extensive need for computation time. In order to supply users with the results of case studies in acceptable time or to actually allow smog prediction (computation time less than simulation period) the DYMOS system has been implemented on parallel computers as message-passing version. Due to the model inherent structure, the model parallelization has been performed by grid partitioning.

## 3. APPLICATIONS

### 3.1 A Scenario Analysis of a Summer Period in 1994 in the (larger) Region of Berlin-Brandenburg

On the behalf of the Senate of Berlin and the Ministry of Environmental Protection of Brandenburg, the measuring campaign FLUMOB (July 23 - July 27, 1994) of ozone and ozone precursor substances in the region Berlin-Brandenburg was accompanied by computer simulations with the REGOZON system (Mieth et al. [1995]).

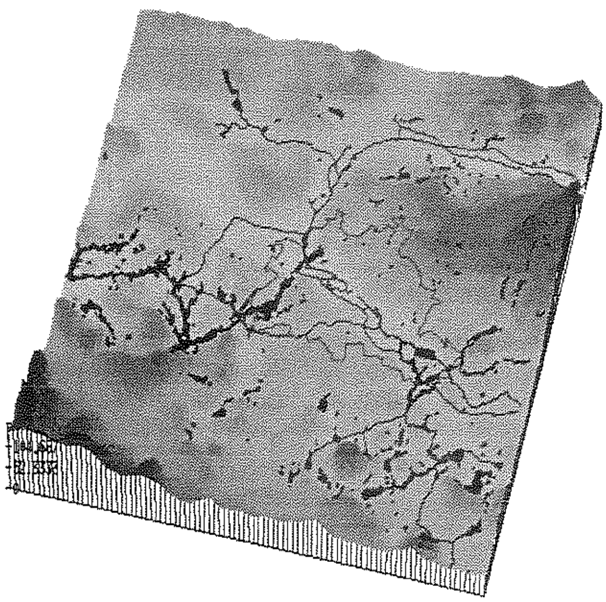

**Figure 1:** Orography of the model domain Berlin-Brandenburg

The extension of the model region Berlin-Brandenburg is about 100 km x 100 km, which were resolved to a grid size of 2 km x 2 km. The surface of the region is relatively flat (the orography of the model region is shown in Figure 1). One of the main characteristics of this area is that a densely populated city (Berlin) with high emissions is embedded in a sparsely populated area (Brandenburg) with low emission levels. Such a situation is expected to display clearly the effects of anthropogenic emissions, even more since the measuring campaign took place during a high-pressure period (for example the 25th of July was characterized by a moderate wind from the south east, temperatures up to 35°C and a mixing height of up to 3500 m in the afternoon).

The measuring campaign provided a large set of data. Since two aircrafts were utilized, data in higher levels of the mixed layer could be obtained. Mobile measuring stations on the ground determined the ozone concentrations in the up wind and lee side of the city. Additionally, a relatively good set of data for initializing the model and for updating the inflow boundary conditions was available. The emissions in this region are documented in a data base which has recently been improved concerning the diurnal variation of the traffic emissions (an overview over the classification of the total emissions of $NO_x$ and VOC's during the summer is presented in Table 1). The diurnal variations of the background ozone concentration and the concentration of background precursor substances were calculated with a chemical box model (coarse nesting). This box model uses averaged meteorological values from the model domain as time-dependent input parameters. Its initialization was carried out with the earliest available measurements at the up wind side of Berlin. Under the assumption that there are no strong sources of ozone precursor substances close to the model boundaries and that the wind direction is not significantly changing during the simulation period, this method yields in general good results for the background concentrations of the inflowing air.

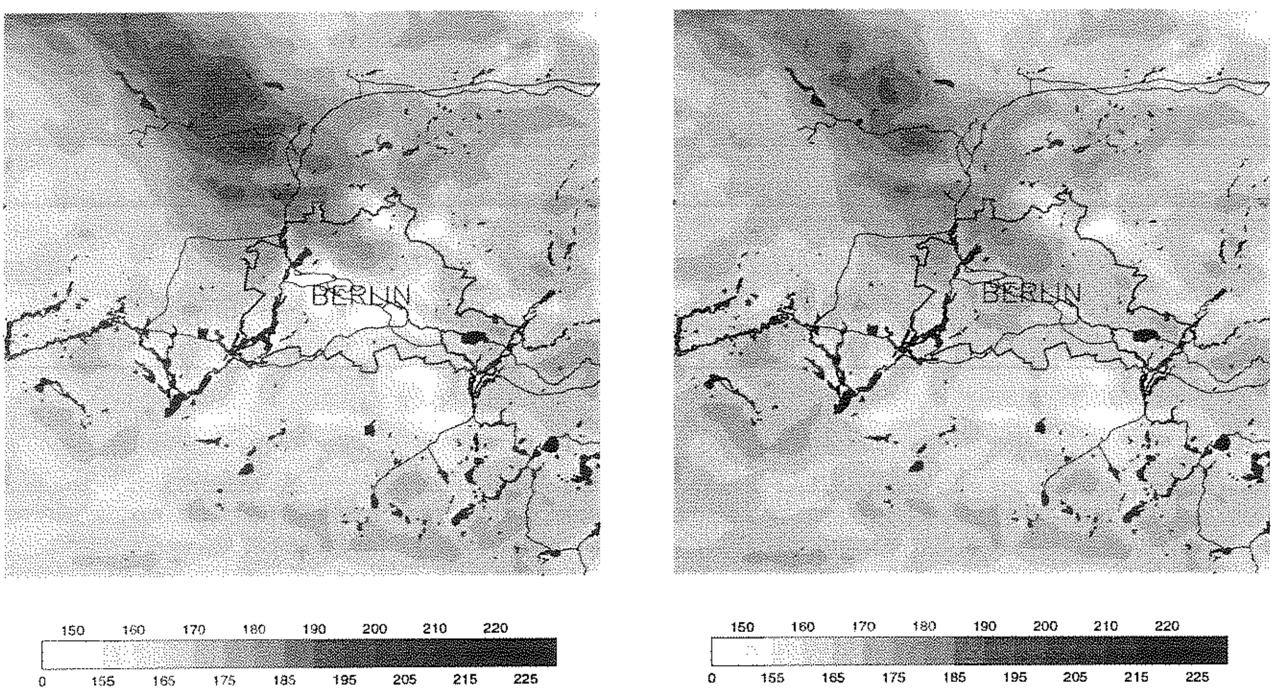


**Figure 2:** Simulated surface-near ozone concentration in $\mu g/m^3$ in Berlin/Brandenburg on July 25, 1994 (afternoon)
Left: standard case, Right: scenario simulation

The simulation system were implemented on a parallel computer (Parsytec PowerGC) with 16 nodes in order to decrease execution time. Moreover, changes in the chemical reactions and new deposition velocities were computed only every 8th transport time step.

Defining two days out of the campaign week, (July 25 and July 27, 1997) as reference states, scenario analyses were carried out by GMD FIRST to study the effects of more or less realistic emission-reduction steps on the production of ozone. In any discussion concerning the reduction or avoidance of high ozone levels it has first to be realized that vehicular traffic accounts for more than 70% of the $NO_x$ emissions and more than 55% of the overall VOC emission in the model area. Taking further into account the predominant role of $NO_x$ control and the slightly less important role of VOC control under the given emission conditions it follows that effective ozone control strategies have to concern mainly the traffic.

For that reason the following emission reductions steps were assumed:

- traffic ban for cars and trucks without emission-reduction technology like controlled catalysts

- speed limit on highways (90 km/h) and on country roads outside urban areas (80 km/h)
- reduction of the emissions caused by private households (5 %), industry (15 %), and point sources, e.g. power plants (10 %)

**Table 1:** Distribution of the emissions into different emission classes (in percentage of the total emission during the summer)

| | VOC | $NO_x$ |
|---|---|---|
| industry (emissions from high stacks) | 1,2 % | 27,1 % |
| industry (low emission height) | 31,3 % | 1,5 % |
| moving traffic (including aircrafts) | 32,8 % | 70,9 % |
| standing traffic (evaporation) | 23,9 % | - |
| households | 10,8 % | 0,5 % |

Figure 2 presents the simulated surface-near ozone concentration [$\mu g/m^3$] in the model area Berlin-Brandenburg on July 25, 1994. The left figure shows the computed "regular" ozone concentration, and the right figure displays the simulated ozone concentration under the scenario assumptions. Both visualizations of the simulation results show a significant wide-area ozone trail on the lee-side of the urban region. This establishes a significant contribution of anthropogenic emissions to the ozone production in the model domain. The maximal concentration of ozone is actually reached in some distance outside Berlin. Comparing the results of the scenario simulation with the orginal reference case, a noticeable decrease of the ozone concentration in the plume of the city of up to 15 $\mu g/m^3$ can be observed under the assumed scenario conditions.

### 3.2 Analysis of the (larger) Munich Region

Commissioned by Greenpeace, the influence of emissions caused by traffic in Munich on the ozone concentration in the larger Munich region was analyzed for a typical mid-summer day in 1994 (Mieth [1994]). The extent of this model domain is 150 km x 80 km, and the surface of the region around Munich is formed by the Alpine foothills steeply ascending south of Munich, by the river valleys of Isar and Inn, and the big lakes Chiemsee, Ammersee, and Starnberger See. Due to the available data the grid resolution were set to 5 km x 5 km.

The selection of meteorological data should be representative for weather conditions with high ozone concentrations. Climatological investigations show that in the case of north east to north wind, high ozone concentrations have been registered, whereas west and south wind is connected with low ozone values. Representing the standard case, a day in July was chosen characterized by strong and relatively long-term solar radiation. High-pressure weather conditions with maximal temperatures of 30 °C, clear sky, a relatively light geostrophic wind from the north east, and a surface-near inversion in the morning defined the meteorological situation. These assumptions can be considered as typical for a summer smog period in the model domain Munich.

Due to the assumed high-pressure weather conditions, the concentration of ozone and its precursor substances was already quite high. For that reason it can be no surprise that the (simulated) maximum ozone concentration in the model domain reaches 200 $\mu g/m^3$. Again, the maximum concentration is obtained outside the city, that is within a distance of about 20 to 25 km in southwest direction.

Corresponding scenario analyses have shown that insignificant emission-reduction steps (5 %) do not result in a reduced ozone concentration. Only quite drastic emission-reduction steps concerning the traffic (50 to 70 %) lead to a very significant improvement of the air quality (see Figure 3).

## 4. CONCLUSIONS

Two applications of the air pollution system DYMOS in conurbations were presented here in this paper, namely in the region Berlin-Brandenburg and in the larger Munich region. The computed simulations indicate that a more or less drastic reduction of traffic emissions can decrease the size of regions with high, that is health-critical, ozone concentrations. However, as further investigation not presented here in this paper have shown that the efficiency of emission reductions depend strongly on the given meteorological conditions, the obtained results can not be generalized. As the peak ozone values in the region Brandenburg are due to the high amount of precursor substances released within the city Berlin, any emission reduction step have to concern mainly densly populated areas. However, in order to reduce the macroscale background ozone concentration on a permanent base, regional but better national or European wide steps are necessary.

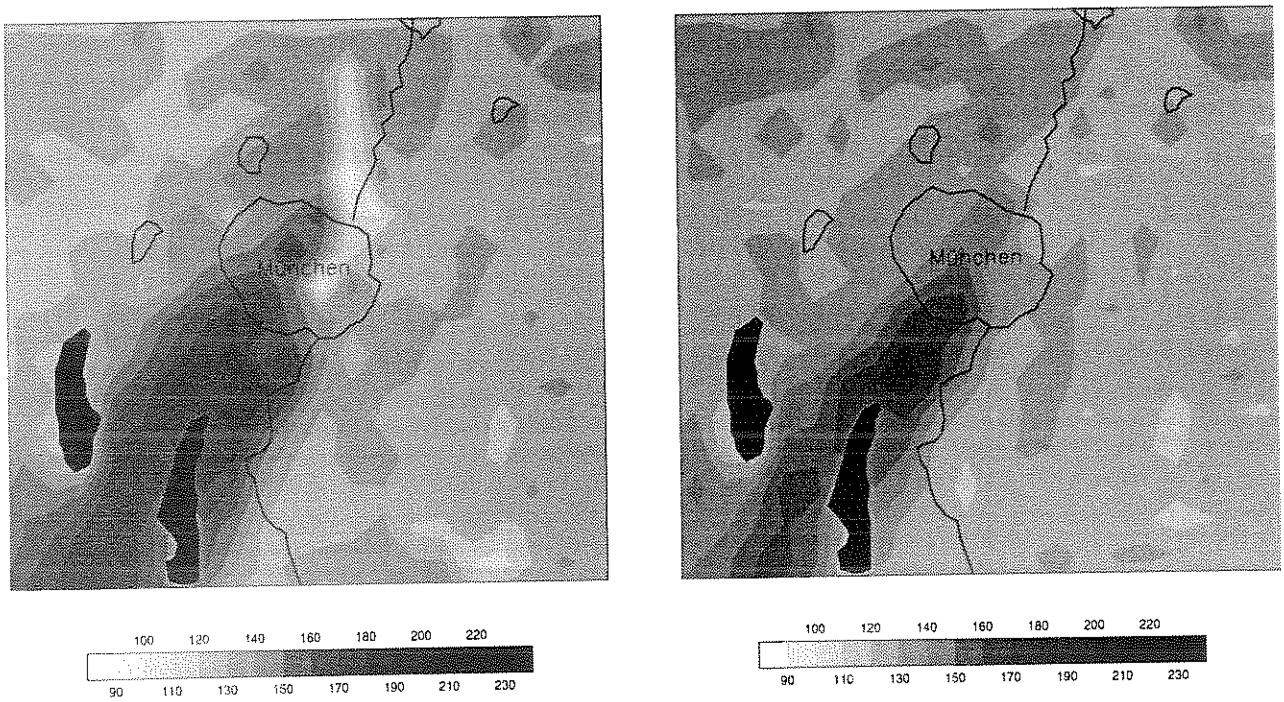


**Figure 3:** Simulated surface-near ozone concentration in $\mu g/m^3$ in the region of Munich on a typical mid-summer day in 1994 (afternoon) Left: standard case, Right: scenario simulation

## 5. REFERENCES

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