Urban Air Pollution Simulation for Studying the Impact of Traffic Emissions

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Summary Recent investigations has shown that the main source for emissions leading to summer smog is the vehicle traffic. To study the impact of traffic emission on the urban air quality a complex air pollution simulation system is necessary. This paper presents results of the development and application of an air pollution simulation system at GMD FIRST which is aimed to support users in governmental administrations and industry in forecasting, operative decision making as well as short to long-term regional planning. The components of the simulation system are parallelly implemented simulation models for meteorology, transport, and air chemistry, data bases for model input and simulation results, as well as a graphic user interface for spatial data visualization. By means of this system end-users can carry out scenario analyses to study the influence of emission reduction measures such as the building of new roads, the closure of parts of a city for groups of vehicles, speed limits, etc. Results will be presented from two recent applications in the regions of Berlin/Brandenburg and Munich (Germany). The performed scenario analysis were based on statistical input data of traffic emissions. To improve the quality of simulation results and to allow a more detailed assessment of the consequences of traffic control measures and general urban planning issues the traffic emission data should be simulated dynamically. To this aim a new complex model system for the simulation of traffic flow, traffic emissions and air pollution dispersion is under development at GMD FIRST based on the air pollution simulation system which is already in use.

1. INTRODUCTION

Nowadays two major problems of urban areas which are naturally connected with each other are the permanent increase in urban traffic and the problem of air pollution. The growing traffic demand together with an increase of exhaust gas emissions and travel times on the one side, and the likewise growing need for mobility on the other side requires the realization of measures for a better traffic control and planning aiming at shorter travel times and a reduction of air pollution. Urban traffic is actually the main cause for the health-critical concentrations of surface-near ozone which is typical for hot mid-summer periods. The consequences of different traffic control measures on the complex system "urban road traffic" should be known in advance by responsible decision-makers of local authorities so that suitable measures can be selected. For that reason simulation systems for traffic flow, traffic emissions and air pollution dispersion in urban areas are necessary.

In recent years, increasing computing capacity has made it possible to develop numerical models describing the transport and chemical transformation of air pollutants, taking into account complex flow and dispersion characteristics. On that basis simulation systems for air pollution dispersion has been developed and used for scientific investigations at different places. First case studies has been carried out by the system developers. The use of these systems for studying the impact of traffic emissions is very difficult up to now because the modelling and simulation of urban traffic to supply air pollution models with the necessary traffic emission input is only at the beginning.

2. THE DYMOS SYSTEM

At GMD FIRST the DYMOS system (Sydow [1994]) has been developed, a parallelly implemented simulation system to analyze the generation, dispersion, and chemical transformation of 3 kinds of smog:

- winter smog: high concentration of inert (regarding the model domain) pollutants (e.g. SO_2, NO_x, dust, etc.) caused by high pressure weather situations in the winter months.
- summer smog: high concentration of ozone and other photochemical oxidants caused by strong insolation during high pressure weather situations in the summer months.
- antigenous air pollution: high concentration of substances with antigenous effect on the human immune system (bio-polymers such as polypeptides, polysaccharides, nucleic acids, as well as synthetic polymers and a few low-molecular compounds connected with macro-molecules) produced by technological processes and natural sources.

DYMOS consists of the air pollutants transport model REWIMET (Heimann [1985]) and the air-chemistry model CBM-IV (Gery et. al. [1988]).

REWIMET 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.

REWIMET is based on a hydrostatic, divergenceless and dry atmosphere. In contrast to true three-dimensional models calculating the variables at the nodes of a locally fixed spatial grid REWIMET uses the fixed grid structure only horizontally. Vertically, the model is subdivided into 3 layers lying on top of each other. A part of the model variables, namely, the horizontal wind components, the potential temperature, and the air pollutant concentrations, is calculated for each horizontal grid point as box average in all 3 layers. The vertical wind component, the pressure, and the turbulent flux of impulse, heat and air pollutants are determined at the boundaries between the layers.

The model REWIMET is driven by the suprascale stratification, the suprascale horizontal pressure gradient (geostrophic wind), and the surface temperature. The input of the geostrophic wind and surface temperature can be time-dependent. REWIMET considers the orography and the land utilization in the model domain. The transport of several air pollutants can be calculated simultaneously.

CBM-IV is a popular 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. There is no need for the definition of an average molar weight so that this mechanism is mass balanced. Some species are handled explicit because of their special character in the chemical system (for example isoprene which is the most emitted biogenic species). The mechanism involves 34 species and 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.

In order to be able to use a higher vertical resolution of the model domain and to include cloud physics when it seems to be important the atmospheric model GESIMA (Kapitza [1992]) has been implemented in the DYMOS system. GESIMA is a true three-dimensional, non-hydrostatic mesoscale model which realizes the inelastic *Boussinesq* approximations (density variations are considered only in the buoyancy term) and which includes cloud physics. The viscosity properties of air are neglected.

Simulation runs with these complex models REWIMET, CBM-IV and GESIMA have an extensive need for computation time. In order to supply users with results of case studies in acceptable time or to actually allow smog prediction (computation time less than simulation period) the DYMOS system is already parallelized and implemented as message-passing version on parallel computers with Intel i860 and PowerPC processors using tools like PVM. Because the model domain of REWIMET, CBM-IV and GESIMA is represented by a 3D grid the model parallelization is performed by grid partitioning.

3. APPLICATIONS

3.1 Analysis of the Region of Berlin/Brandenburg

By means of DYMOS on behalf of the environmental department of the state government of Berlin and the ministry for environment of the state Brandenburg summer smog analyses were carried out concerning the duration of the measuring campaign FLUMOB (July 1994). Besides of the topographical and meteorological data the available statistical data of traffic emissions in Berlin were pre-processed for model input.

The visualization of the simulation results shows a significant wide-area ozone trail on the lee-side of the urban region resulting from man-made emissions of ozone precursor substances in Berlin. This phenomenon could be confirmed by measurements. The available large amount of data made it possible to extract the initial and boundary values necessary for simulation runs in relatively small model domains from the measurements. Moreover, a comparison of computed values with the values measured in upper layers could be performed for the first time.

By means of the DYMOS system scenario analyses were carried out to study the consequences of possible measures for emission reduction on the production of ozone. The success of a special measure under defined meteorological conditions could be evaluated. In Figure 1 the simulated surface-near ozone concentration in $\mu g/m^3$ of the standard case and scenario 1 on July 25, 1994 at 4 p.m. is presented. Scenario 1 means:

- traffic ban for cars and trucks without emission-reduction technology like controlled catalysts.
- speed limit:
  1. 90 km/h on highways
  2. 80 km/h on normal roads outside of urban areas.
- reduction of the emissions caused by
  1. private households by 5 %
  2. industry by 15 %
  3. point sources (e.g. power plants) by 10 %.

The horizontal extent of the model domain Berlin/ Brandenburg is about 100 km x 100 km. The horizontal grid resolution is 2 km x 2 km. The surface is relatively flat. The meteorological situation of the considered episode is characterized by a long-term high-pressure weather condition with strong solar radiation and high temperatures as well as a large mixing layer.

The comparison between simulation results and measurements shows a relatively good correspondence of the location of the computed and measured ozone trail and its extent. The simulation runs confirm the existence of a significant ozone production mainly caused by the man-made emissions of precursor substances in Berlin. In most cases the maximum of the ozone concentration is reached in some distance from Berlin in the state of Brandenburg.

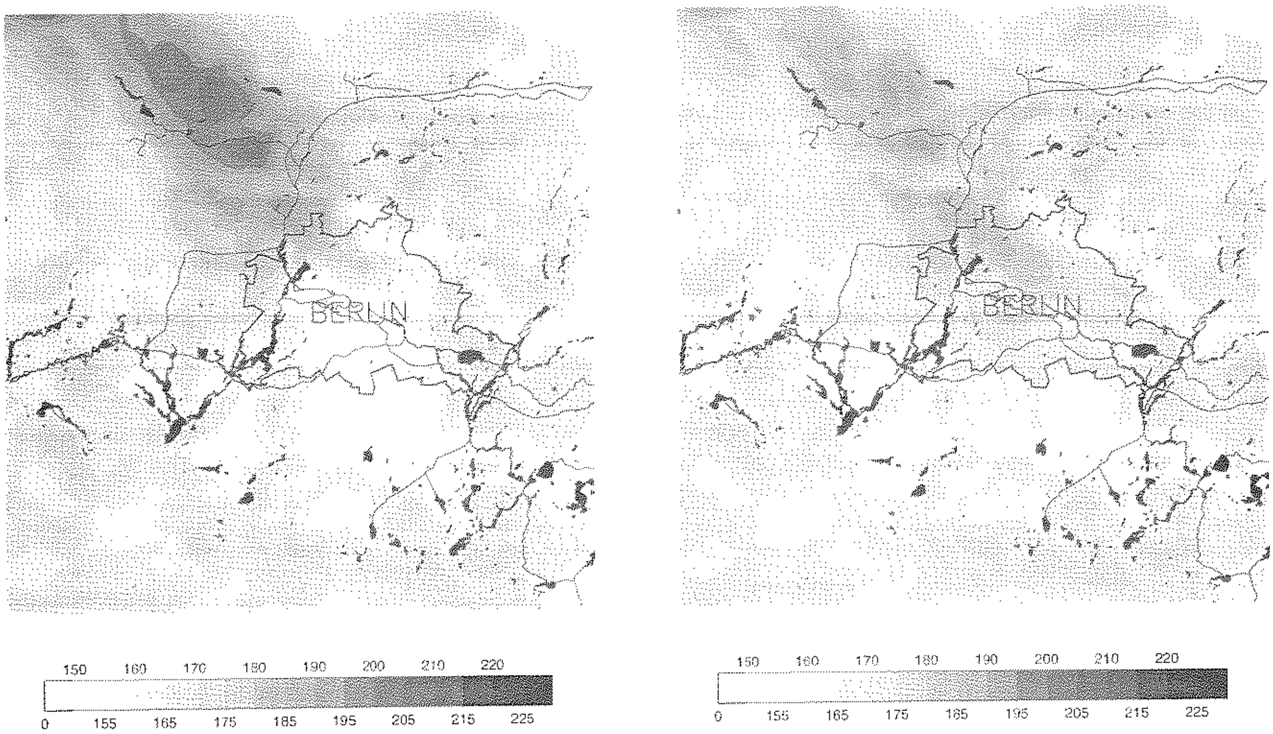

Figure 1: Simulated surface-near ozone concentration in μg/m³ in the region of Berlin/Brandenburg on July 25, 1994 at 4 p.m. (left - standard case, right - scenario 1)

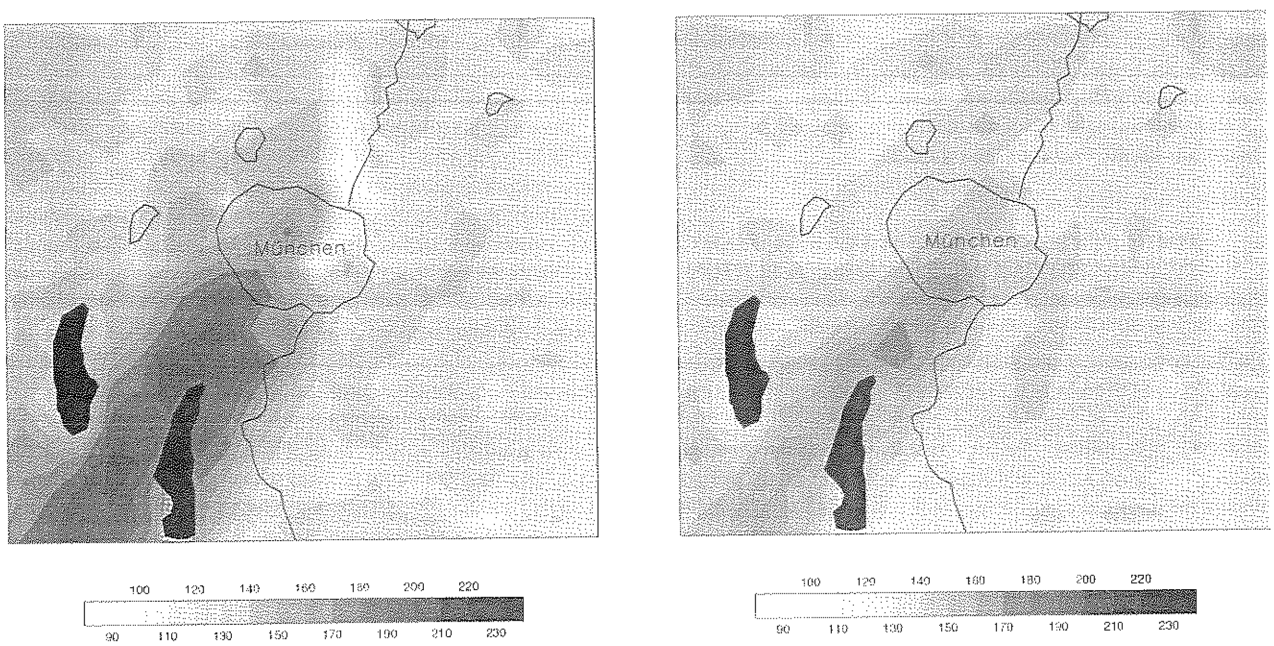

Figure 2: Simulated surface-near ozone concentration in μg/m³ in the region of Munich on a typical mid-summer day in 1994 at 4 p.m. (left - standard case, right - reduction of traffic emissions of 70 %)

3.2 Analysis of the Region of Munich

On behalf of Greenpeace the influence of emissions caused by traffic in Munich on the ozone concentration in the Munich region was analyzed for a typical mid-summer day in 1994. The extent of the model domain of the region of Munich is 150 km x 80 km. Due to the available data the grid resolution is 5 km x 5 km. The surface of the model domain 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, Starnberger See.

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

The ozone and precursor substances concentration of the inflowing air is already quite high which is also characteristic for long-term high-pressure weather conditions in summer. The maximum ozone concentration of the simulations reaches 200 $\mu g/m^3$ and is computed in the trail of air pollutants emitted by sources in munich in a distance of about 20 to 25 km from the city in southwest direction.

The scenario analyses show that insignificant emission-reduction measures (5 %) do not result in a reduced ozone concentration. Quite drastic emission-reduction measures in the field of traffic (50 to 70 %), however, lead to a very significant improvement of the air quality.

4. SIMULATION SYSTEM FOR TRAFFIC FLOW, TRAFFIC EMISSIONS, AND AIR POLLUTION DISPERSION

The analyses carried out with the DYMOS system show that local emission reduction measures separately performed reduce the area of very critical ozone concentration (ozone maxima). To reduce the macroscale background ozone concentration permanently high for summer smog periods drastic measures at least on regional, but better on national or European scale are necessary. These results were also confirmed by the local ozone experiment carried out in the region of Heilbronn in midsummer 1994.

In order to offer decision proposals for traffic control measures that reduces fuel consumption and decreases air pollutants concentrations a simulation system must be able to meet two requirements:

1. to reproduce sufficiently detailed the fuel consumption, production of emissions, and air pollutants dispersion.
2. to include measures with great potentiality for reducing fuel consumption and air pollution in the simulation runs and scenario analyses.

To this aim a simulation system for traffic flow, traffic emissions and air pollution dispersion is under development at GMD FIRST (Sydow [1995]) consisting of the following modules (see Figure 3):

- a traffic flow model considering single vehicles,
- a traffic emission model processing a variety of parameters and vehicle characteristics,
- air pollutants dispersion models calculating transport and chemical transformation,
- a database storing and managing all input and output data,
- a decision support system visualizing data in spatial relations, and deriving decision proposals.

Recent studies has shown that fuel consumption and emissions depend to a large extent on the vehicle speed in process of time and the resulting accelerations. An exact analysis of the accelerating and driving behavior in certain situations (e.g. stop and go at traffic lights) can only be performed by means of traffic flow models which consider single vehicles. Simulation systems with such models do not exist for large urban road networks up to now because the computation of vehicle movement, emission production, and air pollutants dispersion is too time-intensive on conventional computer systems. The use of the proposed simulation system for large networks which can handle the huge amount of input and output data, and should supply users with results of case studies in acceptable time is only promising when implementing it on high-performance parallel computers.

For the operation of the proposed complex model system all necessary information for simulations (vehicle characteristics, road network with traffic lights, topographical data, meteorological data, emission data) and all simulation results are stored in the data base. Based on the traffic demand and on actual traffic conditions the traffic flow model calculates the position of the vehicles in the road network and their actual speed and acceleration values. Based on the output of the traffic flow model the emission model determines fuel consumption and emission values. With these data and with the topographical and meteorological data the air pollution transport and chemistry can be simulated. The decision support system is supplied with the data from the data base and the output from all of the three simulation models, so that the whole knowledge about the simulated process can be represented. By means of data visualization end-users in local authorities and industry get support in decision-making for improving the air quality, and to reduce time delays for the traffic. The impact of possible measures in traffic control can be simulated by varying the parameters in the traffic model (feedback from decision support system to traffic model). Thus scenario analyses and case studies can be carried out.

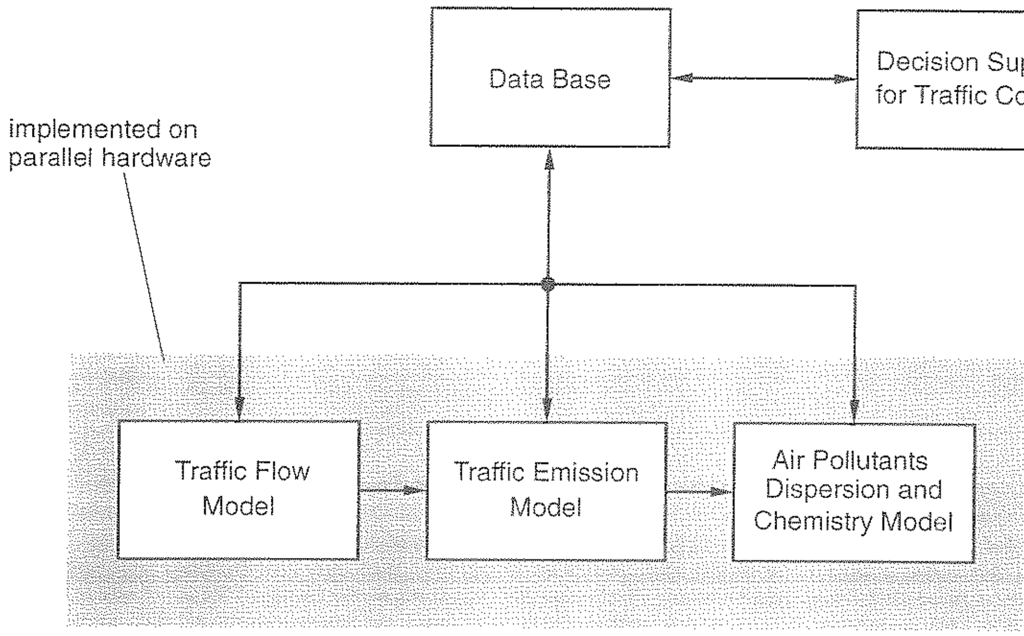

Figure 3: Structure of the simulation system for traffic flow, traffic emissions, and air pollution

5. CONCLUSIONS

At GMD FIRST the DYMOS system has been developed to simulate the transport and chemical conversion of air pollutants in urban areas. By means of DYMOS scenario analyses were carried out for the regions of Berlin/ Brandenburg and Munich to study the impact of traffic emissions on the urban air quality. It was found that drastic measures reducing traffic emissions decrease the area of very critical ozone concentration (ozone maxima). To reduce the macroscale background ozone concentration permanently high for summer smog periods drastic measures at least on regional, but better on national or European scale are necessary. The performed scenario analyses were based on statistical input data of traffic emissions. To improve the simulation results and to allow a more detailed assessment of the consequences of traffic control measures (e.g. closing of parts of the city for individual traffic, control of traffic lights, changes in the number of lanes per direction, building by-passes, construction of new roads, building new subways, etc.) and general urban planning the traffic emission data should be calculated dynamically. To this aim a traffic flow model and a traffic emission model will be coupled with the DYMOS system.

6. REFERENCES

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