Atmospheric Models as Key Elements for Environmental Analysis

A. Sydow, T. Aßelmeyer, T. Lux, P. Mieth, S. Unger
GMD Research Institute for Computer Architecture and Software Technology (GMD FIRST)
Kekuléstr. 7, D-12489 Berlin, Germany

Abstract The paper describes exemplary applications of atmospheric models as key elements for environmental analysis. Today atmospheric models are frequently used for air quality analysis in meso-scale applications. The meso-scale deals with a range of 20 to 500 km which includes phenomena like tropical cyclones, sea breeze flows, urban heat islands, mountain lee waves, local storms, etc. Typical applications are urban and industrial regions, metropolitan areas, coastal regions, etc. Future activities in the field of atmospheric modelling are related to the topics down-scaling and up-scaling. Down-scaling means that phenomena with a smaller dimension (in time and space) will be studied as currently under investigation. Examples for down-scaling in the field of atmospheric modeling are integrating micro-scale models, using finer data resolutions by remote sensing, etc. Up-scaling, on the other hand, is used here in sense that phenomena will be studied with a larger dimension. This implies, that models of different scales will be integrated to more global models used for continental domains or global change analysis. Some perspectives of environmental research using atmospheric models will be presented.

1. INTRODUCTION

Atmospheric modelling and air pollution analysis have been widely used during the past decades among the scientific community. Due to the tremendous increase of the computer power, realistic complex 3D models which define the state-of-the-art in atmospheric modelling can run in a reasonable time. The usage of such models is no longer restricted to the researchers themselves, but has been extended to include operational use by engineering companies and authorities. The application scale ranges from micro-scale emergency management to global climate research. Numerical weather forecast has become a standard tool as well as model-based air pollution analysis including chemical effects.

2. REMOTE SENSING FOR ATMOSPHERIC MODELLING

High quality satellite images in different spectral channels provide lots of information. Methods for data analyzing, failure correction and data management have rapidly improved in recent years. Measuring devices have been developed which are capable of providing instantaneously vertical concentration profiles as well as profiles of meteorological quantities which are very useful as inputs of atmospheric models. All together, improved models, remote sensing techniques for data acquisitions and high-performance computers are opening up qualitatively new perspectives (Herlin [1998], Mieth and Sydow [1997]).

Atmospheric models require a considerable amount of input data that represent information about the application area (Digital Elevation Models - DEM - and land use), about model initialization (meteorological inputs, initial concentrations, emissions), and about model parameterization (for instance surface characteristics). The currently used information sources suffer from several drawbacks, depending on the nature of the data. Using earth observation (EO) data will bring several benefits:

- **Site information data:** Atmospheric models require the knowledge of the orography (DEM) and land use (LU) at model scale. Required LU information is a percentage of the different LU classes at each grid point. Besides orographical effects, the land use characteristics form an important driving force for the development of local or even regional wind systems. The most important influence of different land use effects is given by its specific thermal response and its surface roughness. Strong land use driven features in meso-scale models are, e.g., sea breeze and urban heat islands. Different atmospheric models usually consider slightly different land use classifications because they are often designed for a special purpose, or the model developer had a certain model application domain in his mind. In general, a model adaptation to a new model domain needs certainly some corrections in the land use parameter sets. A normal user is usually in favour of using a fixed classification. The selection of the significant land use types by using EO data is an important step towards an objective land use classification procedure that might differ from place to place. Additionally, the land use can be very much the same but the surface characteristics can vary considerably. This can hardly be detected by conventional methods, but to a certain extent by EO data usage. Considering air pollution modelling, the land use and vegetation determination parameterize important interactions between the pollutants and the ground. For example, surface uptake processes are directly influenced by the kind of soil and/or vegetation. Additionally, biogenic emissions are a very important source of volatile organic compounds (VOC), which belong to the ozone precursor substances. These emissions can reach comparable values as anthropogenic VOC emissions. However, up to now, this emission estimation is very poor because of lack of appropriate vegetation maps. Recently, wind field models, dry deposition models and biogenic emission models often rely on the same input data set. If the converted EO data allow a more precise determination of the vegetation, this leads to a new quality in air pollution modelling and model results. For example, an independent vegetation map can be built covering only species that have a contribution to the biogenic emissions.

- **Model initialization, boundary conditions and synoptic data:** When running in operational mode, an air quality forecast requires the accurate knowledge of the following input data: data concerning meteorological conditions (wind fields, humidity, cloud cover, radiation intercepted by clouds, initial temperature, turbulence, other meteorological fluxes), data concerning the air pollution situation, and an emission inventory. Both initial values over the simulation domain and boundaries conditions at the limits of the domain have to be known. Two kinds of boundaries have to be distinguished: artificial boundaries due to the size restricted domain and physical boundaries at the surface. The use of EO data will greatly enhance the quality of some of these data.

- **Model parameterization data:** the various phenomena involved in air pollution modelling are parameterized by physical quantities, such as surface characteristics: temperature diffusivity, emissivity, aerodynamic roughness length, etc. These data are very often considered as depending only on the land use classes. However, they undergo both spatial (different values for the same land use classes in different sites) and temporal (seasonal changes due to the vegetation cycle) variations. The effects of the constancy hypothesis still remain to be studied. Dedicated research work has to be done by users of models, in order to (i) evaluate the models' sensitivity to the variability of these parameters and (ii) to investigate the methodologies and the appropriate sensors likely to deliver a better spatio-temporal parameter estimation.

Although often not very difficult from a scientific point of view, data preparation serving as input for atmospheric modelling by means of satellite images are still not well developed. But these techniques can be very efficient for the preparation of input data and for the adaptation to a new model domain. The use of satellite images offers the possibility to make the input data more dynamic using current maps and taking into account the seasonal change of the vegetation pattern.

Additionally, there is a variety of model parameters which can be determined in a more objective manner by means of satellite images. Meteorological input quantities which are often only sparsely available from surface observations can be detected with a high spatial resolution, and not to forget the new opportunities in model evaluation procedures.

3. NESTING OF ATMOSPHERIC MODELS

Current attempts to apply atmospheric chemistry models for air-pollution policy in Europe have been severely limited by the lack of availability of appropriate modelling tools. The EU and UNECE have so far mainly relied upon the long-term (6-12 month) EMEP Lagrangian models with 150 km grid sizes which cover all of Europe (Amann et al. [1999], MSC-W [1998], Simpson [1993]). This includes the UN/ECE 2nd Sulphur Protocol, 2nd NOx Protocol (currently in negotiation), EU Strategy on Acidification and Ozone Strategy, the National Emissions Ceilings Directive and the Ozone Daughter Directive. For the EU Auto/Oil work this Lagrangian model work has been supplemented with 3-D modelling studies for urban areas. The long-term modelling capability is required by policy makers for many reasons (see below), but the 150 km grid size is obviously a major weakness of such simulations, especially if estimates of human exposure are required for health-related assessment.

In contrast, the urban 3-D modelling used had the major weakness that only a few days of simulation were possible, thus restricting the statistical validity of the models, and making it impossible to derive useful results for all pollutants from the same simulation. Of course, long-term modelling with simple models has been ongoing for decades, involving for example gaussian plume studies for non-reactive pollutants, box chemical models. Recently a hybrid ozone model for fast long-term simulations has been developed (Moussiopoulos et al. [1996]). However, all of these systems have strong limitations in terms of physical or chemical realism.

To overcome these difficulties, several research projects has been initiated aiming at the nesting of models with different scales. The advantages of the nested model use are:

- The upper-scale model provides the lower-scale model with boundary values allowing long-term simulations.
- The lower-scale model provides the upper-scale model with sub-grid variability and allows a better parameterization within the upper-scale model.
- Nesting makes it possible to estimate the relative effect of local measures versus national or continental measures on conurbation areas with very different climates and air pollution problems.

Research in the field of model nesting brings together experts from the fields of long-term policy-related modelling, research-oriented meso-scale modelling, parallel computing, chemical mechanism development, and measurements, to produce a tool of use to policy makers and scientific study. The nested model approach will significantly improve the ability of new tools to handle coupled regional-local issues, helping to separate and define the air quality problems which require continental measures and those where local measures are more effective. In the case of ozone, EU or UN/ECE agreements aimed at reducing rural ozone levels may lead to higher ozone in urban areas - such effects need to be quantified over the long-term. Non-linear problems such as ozone formation or aerosol chemistry can be addressed at the appropriate scales. Routine long-term 3-D modelling on the city-scale is a new step to pollution control, but it is essential to a multi-pollutant approach for a number of reasons:

- Many health effects are thought to be associated with long-term exposure to pollutants rather than (or as well as) short-term episodes.
- For any one pollutant a large number of meteorological conditions may give rise to elevated concentrations. For some pollutants, especially ozone, it is not even enough to examine days of high pollution in current conditions and work out control strategies based upon these. Areas with low ozone in emission conditions in the 1990's may experience higher ozone after NOx emissions are reduced in the years to come. The most important example of such negative effects is likely to be urban areas, so that population exposure to long-term ozone levels may increase in some areas.
- Each pollutant has its own emission and formation characteristics. The meteorological conditions conducive to high particulate concentrations are usually different from those giving high ozone.
- Pollution episodes occur on different days in different parts of Europe. Furthermore, on some days pollution levels in urban areas may be dominated by inflow from the regional scale, on other days local emissions and production processes may dominate, and on many days pollution levels experienced in urban areas will be a mix of local and regional pollutants.

4. GLOBAL WARMING AND HAZARDS

In recent years the discussion about global warming and natural hazards has given an increased urgency to climate modeling. Climate models span the range from simple Energy Balance Models to more sophisticated Statistical Dynamic Models to the very complex General Circulation Models (GCM) of the atmosphere and ocean. GCMs are generally regarded as the most powerful tools available. The basic purpose of the GCM is to move parcels of air (or water if considering the ocean) around on a time-scale of a few minutes.

Applying GCMs, climate change processes can be investigated more realistically. The El Niño Southern Oscillation (ENSO) has been studied using a coupled atmosphere-ocean general circulation model (CGCM) developed at University of California Los Angeles (Yu et al. [1999]). ENSO is the most important interannual fluctuation of the coupled ocean-atmosphere climate system. Cycles of warm (El Niño) and cold (La Niña) ENSO events occur irregularly in the tropical Pacific Ocean and are known to have significant impacts on global weather patterns.

GCMs are also able to provide basic knowledge about the increase of greenhouse gases in the atmosphere, the corresponding global warming, and the impact of these effect on the weather and the occurrence of extreme temperature and precipitation conditions. Nevertheless, strong efforts are necessary to improve the climate models in order to get reliable results about such complex interactions like global warming, rising of sea-level (Titus and Narayanan [1995]), more frequent natural hazards (storms, floods, etc.).

The study of long-term records of weather data has provided valuable insight into the appearance of extreme temperatures. These processes can hardly be simulated numerically, since they are especially sensitive to abnormal air flow. Therefore the National Oceanic and Atmospheric Administration (NOAA) of the U.S.A. developed a purely statistical model providing probability data about daily maximum and minimum temperatures. The model uses three parameters which are available from meteorological measurements and calculations: the mean value of the temperature, the daily variation and the its correlation between consecutive days. Based on these three values, the model computes the duration and the maximum of extreme temperatures.

Besides the total amount of precipitation, the appearance of flooding rain is of great interest, because it causes not only considerable damage, but also danger to life. The appearance of precipitation mainly depends on the relative humidity of the air. As a result of computer simulations it is known, that the distribution of the relative air humidity will not change due to global warming. Nevertheless, the absolute amount of water vapor in the atmosphere increases due to global warming, since the capacity to store humidity increases with temperature. Therefore due to global warming, the frequency of precipitation will not increase but the amount of precipitation. This means that the probability of flooding rain increases.

Earlier studies about the relation between global warming and tropical storms led to the conclusion that the frequency and strength of storms increases. Recent investigations with climate models showed that this relation is not so simple. The generation of tropical storms depends on a variety of different factors such as sea surface temperature, vertical temperature distribution within the atmosphere, instabilities of air flow, wind velocity variation due to height above ground, etc. The problem is so complex, that no general predictions are possible based on simulations with current climate models, e.g., because the models do not have the spatial resolution for simulating the core of the storm.

All these problems show that there is a strong demand for an improvement of climate modelling as well as extensive observations and measurements of climate and weather data in order to get reliable predictions of the effects of global warming and in order to assess the results of different prevention strategies.

5. REFERENCES

Amann, M., et al., Cost-Effective Control of Acidification and Ground-Level Ozone, Seventh Interim Report to the European Commission, DG-XI, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 1999.

Herlin, I., I. Cohen and D. Bereziat, Wind Estimation by Image Processing for Air Pollution Modelling, Systems Analysis Modelling Simulation, 32/1-2, 57-66, 1998

Mieth, P. and A. Sydow, Data acquisition for atmospheric modelling and air pollution analysis - New perspectives by remote sensing, Proc. International Symposium on Informatics for the Environments, 10 - 12 September 1997, Strasbourg, France

Moussiopoulos, N., P. Sahm, S. Papalexiou and T. Voegele, Nested grid simulations of air pollutant transport and transformation in Thessaloniki, Greece, In: Caussade, B.; Power, H. and Brebbia, C. A. (eds.), Air pollution IV: monitoring, simulation and control., Billerica, MA, Computational Mechanics Publications, 717-724, 1996.

MSC-W, Transboundary acidifying air pollution in Europe. MSC-W Status report 1998 - Part I, Meteorological Synthesizing Centre - West, Norwegian Meteorological Institute, Oslo, Norway.

Simpson, D., Photochemical model calculations over Europe for two extended summer periods: 1985 and 1989. Model results and comparison with observations, *Atmos. Environ.*, 27A, 921-942, 1993.

Titus, J.G. and V.K. Narayanan, The Probability of Sea-Level Rise, U.S. EPA, 1995.

Yu, J.-Y., C.R. Mechoso and C.-C. Ma, El Niño Simulation and Prediction using a Coupled Atmosphere-Ocean General Circulation Model, Proc. 1999 International Conference on Mission Earth, January 17 - 20, 1999, San Francisco, California, USA