Modelling and forecasting of regional and urban air quality and microclimate

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Existing gaps and requirements of air quality modelling problems for the urban and regional scales are discussed, and a novel strategy and methodology for the integration (off-line and on-line) and downscaling of numerical weather prediction (NWP) and regional/urban air-pollution (RAP/UAP) models, is presented as well as the building of integrated systems for forecasting meteorology and air pollution. Possible realisations of this methodology in the European Union and particularly in Denmark for specific atmospheric pollution problems are discussed. The EU FUMAPEX project is presented including the strategy and recent achievements of the improvement of meteorological forecasts for urban areas, the connection of NWP models to urban air-pollution and population exposure models, and the building of improved urban air-quality information and forecasting systems. The paper outlines the common status of DMI activities on the subject, following the above strategy, in the field of urban and regional scale air pollution modelling and the integration with NWP models, with examples from UAP to RAP modelling for emergency preparedness and ground-level ozone forecasting.

1. INTRODUCTION

Urban and regional air quality modelling studies could be addressing many different environmentally important questions, including the following:

- How does the contribution from a source of air pollution influence the concentration of pollutants at a given site?
- What is the most cost-effective strategy for reducing pollutant concentration below given air quality thresholds?
- How will reduction or addition of a specific air pollutant emission affect the air quality?
- Where should future industrial complexes, freeways etc. be situated in order to minimise their environmental impacts?
- Forecasting: What will the air quality be tomorrow or the day after?

- How can one forecast and in real time implement corresponding abatement measures in order to avoid air pollution episodes in urban and industrial areas?
- Do air pollutants affect meteorological processes and local climate, and if so how?

The solution to the above questions critically depends on: (i) the mapping of emissions, (ii) the Regional (RAP) and Urban Air Pollution (UAP) models (involving detailed Air Chemistry), and (iii) the meteorological models and the quality of meteorological fields in urban areas.

Realisation of such model systems at the modern level requires close integration of meteorological/climate models and their outputs with the air quality forecasting and assessment models. Meteorological data from regional scale numerical weather prediction (NWP) models have been used in most European countries for off-line RAP modelling over the last decade. Classical examples are ground-level ozone, and dispersion and source appointment modelling. However, a possible (on-line) feedback from RAP models back to the NWP models are not included in these model systems.

For urban-scale air quality forecasting the situation was until recently much less promising. UAP models, as a rule, use simple in-situ meteorological measurements which are fed into meteorological pre-processors. Lacking an adequate description of physical phenomena and complex data assimilation and parameterisations of NWP models, these pre-processors do not achieve the potential of NWP models in providing the meteorological fields needed by modern UAP models to improve the urban air quality forecasts. However, during the last decade substantial progress in NWP modelling and in the description of urban atmospheric processes have been achieved. Modern nested NWP models are utilising land-use databases down to 1 km resolution or finer, and are approaching the necessary horizontal and vertical resolution to provide weather forecasts at the urban scale. In combination with the recent scientific developments in the field of urban atmospheric physics and the enhanced availability of high-resolution urban surface characteristics, the capability of the NWP models to provide high-quality urban meteorological data will therefore increase in the coming years.

Historically, air pollution forecasting and numerical weather prediction were developed separately. This was plausible in the previous decades when the resolution of NWP models was too poor for meso-scale and urban air pollution forecasting. Due to powerful supercomputers and modern NWP models approaching meso- and city-scale resolution and using land-use databases with a fine resolution, this situation is changing. As a result the conventional concepts of meso- and urban-scale air pollution forecasting need revision along the lines of integration of meteorological and chemical-transport modelling. For example, a new Environment Canada conception suggests to switch from weather forecast to environment forecast. Certain European projects (e.g. FUMAPEX) already work in this direction and will feed into this Action. In case of FUMAPEX, Urban Air Quality Information and Forecasting Systems (UAQIFS) will include the integration of NWP models with urban air pollution and population exposure models (*Baklanov et al., 2002*).

Despite the increased resolution of existing operational NWP models, urban and non-urban areas mostly contain similar sub-surface, surface, and boundary layer formulation. These do not account for the specific urban dynamics and energetics and their impact on the numerical simulation of the atmospheric boundary layer and its various characteristics (e.g. internal boundary layers, urban heat island effects, precipitation patterns). Besides, the atmospheric chemistry models should be further developed by including heterogenic chemistry and aerosol processes as well as feedback mechanisms. Additionally, NWP models are not primarily developed for air pollution modelling, and their results need to be adapted to urban and mesoscale air quality models, or preferrably meteorological and air pollution models should be as on-line coupled.

2. MAIN ITEMS AND STRATEGY

Proceeding from the above mentioned gaps and requirements of air quality modelling at the urban and regional scales, the main focus of the strategy, developed in the European Union and particularly in Denmark, is the integration (off-line and on-line) of down-scaled NWP and RAP/UAP models, and the building of integrated systems for forecasting meteorology and air pollution.

The paper will outline the common status of European and DMI activities in the field of urban and regional scale air pollution modelling, with examples from UAP to RAP modelling. These examples include descriptions of:

- the recently initiated European FUMAPEX project (Integrated systems for Forecasting Urban Meteorology, Air pollution and Population EXposure), coordinated by DMI. An example will be given of a simulation of a hypothetical accident at the nuclear power plant Barsebäck (in Sweden, close to the Danish capital).

- regional scale ozone forecasts produced at DMI. The purpose of the activity is to inform and warn the public in case of exceedance of EU given critical threshold values.

- an aerosol model recently developed at DMI. The simplicity of this model facilitates implementation in RAP and UAP models. The aerosol model has been implemented in a chemistry transport model and applied to the problem: DiMethyl Sulphide's influence on aerosol formation in the marine boundary layer and the free troposphere.

- nuclear emergency preparedness modelling at DMI based on the regional Danish Emergency Response Model af the Atmosphere (DERMA).

- meteorological drivers for the DMI air pollution models considered, all of which are based on different versions of the operational NWP model DMI-HIRLAM, the DMI version of the High Resolution Limited-Area Model (HIRLAM) which is jointly developed by a number of institutes.

The main objectives of the current ***European FUMAPEX project***: 'Integrated Systems for Forecasting Urban Meteorology, Air Pollution and Population Exposure' (www.fumapex.dmi.dk) are to improve meteorological forecasts for urban areas, advance the connection of numerical weather prediction models to urban air pollution and exposure models, build improved Urban Air Quality Information and Forecasting Systems, and demonstrate their application in cities subject to various European climates.

Additionally, the improvement of urban meteorological forecasts will provide information to city management regarding hazardous or stressing urban climate (e.g. urban runoff and flooding, icing and snow accumulation, high urban winds or gusts, heat or cold stress in growing cities and climate change). Moreover, the availability of reliable urban scale weather forecasts could be of significant support for the emergency management of fires, accidental toxic emissions, potential terrorist actions etc.

In order to achieve the innovative project goal of establishing and implementing an improved new UAQIFS to assist sustainable urban development, the following steps will be achieved:

1. improve predictions of the meteorological fields needed by UAP models by refining the model resolution and developing specific parameterisations of the urban effects to be utilized by NWP models,
2. develop suitable interfaces and meteorological pre-processors from NWP to UAP models,
3. validate the improvements of NWP models and meteorological pre-processors by evaluating their effects on the UAP models verified against urban measurement data,
4. apply the improved meteorological data to UAQIFS, emergency preparedness and population exposure models, and compare and analyse the results, and
5. successfully link meteorologists and NWP modellers with urban air pollution scientists and the 'end-users' of UAQIFS.

The necessary steps are evolving in ten separate, but inter-linked, Work Packages realised by 16 participants and 6 subcontractors. They represent leading NWP centres, research organisations, and organisations responsible for urban air quality, population exposure forecast and control, and local city authorities from ten European countries.

In general, the following urban features influence the atmospheric flow, microclimate, turbulence regime and, correspondingly, the dispersion and deposition of radioactive releases within urban areas:

- Local-scale inhomogeneities, sharp changes of roughness and heat fluxes;
- Wind-velocity reducing effects due to buildings;
- Redistribution of eddies, from large to small, due to buildings;
- Trapping of radiation in street canyons;
- Effects of urban soil structure, diffusivities of heat and water vapour;
- Anthropogenic heat fluxes, implying the formation of the so-called urban heat island (UHI);
- Urban internal boundary layers (IBL) and urban mixing height (MH);
- Effects of pollutants (including aerosols) on the urban meteorology and climate;
- Urban effects on clouds and precipitation.

Accordingly, the following urban effects should be realised in the improved urban-scale NWP models:

- Higher spatial grid resolution and model downscaling;
- Improved physiographic data and land-use classification;
- Calculation of effective urban roughness;
- Calculation of urban heat fluxes;
- Urban canopy sub-model;

- Simulation of the internal boundary layers and mixing height in urban areas;
- Assimilation of urban meteorological measurements in NWP models.

In conclusion, the main problems to be solved are the following:

- Nested high-resolution urban-scale resolving models; coupling atmospheric mesoscale models with heterogeneous chemistry and aerosol models.
- Improvement of the urban boundary layer parameterisation, e.g. turbulent sensible and latent heat fluxes, revised roughness and land use parameters and models.
- Assimilation of surface characteristics based on satellite data as well as urban meteorological measurements in urban scale NWP models.
- A model interface capable of connecting meso-scale meteorological model results with updated urban air quality and atmospheric chemistry models.
- An improved urban meteorology and air pollution model system suitable for any European urban area on the basis of available operational weather forecasts.
- Evaluation and sensitivity studies of these improvements on the meteorological input fields for urban air quality models and of the resulting air quality simulations.
- Testing and implementation of the improved models to urban management and emergency preparedness systems in several European cities.

The recent main achievements at DMI which can be used for air pollution modelling and emergency preparedness are the following:

- high resolution (down to 1.4 km horizontal resolution) numerical modelling of regional meteorological processes,
- use of fields of effective roughness length, satellite-based sea surface temperature and albedo in the DMI-HIRLAM model,
- algorithms of source term determination using inverse methods and adjoint models,
- ensemble modelling of ground-level ozone,
- on-line coupled meteorological and atmospheric pollution modelling,
- new algorithms for the long-lived stable boundary layers in numerical atmospheric models,
- improvements of existing atmospheric chemistry-transport and deposition models,
- development of an aerosol dynamic module and a chemistry-aerosol model,
- chemistry-aerosol modelling of the stratospheric ozone depletion using comprehensive aerosol-physics.

3. DESCRIPTION OF MODEL SYSTEMS AND COMPUTING TECHNOLOGY

In FUMAPEX, the focus is on the integration of updated modelling methods for NWP and UAP in order to build improved Urban Air Quality Information Forecasting Systems (UAQIFS) enhancing the capabilities to successfully describe and predict air pollution episodes in cities of different European regions. It is realised through improvement and integration of systems for forecasting urban meteorology, air pollution, and population exposure based on modern information technologies. The model integration and downscaling scheme for such UAQIFS, suggested in FUMAPEX, in comparison with the previous practice of regulatory models, is demonstrated in Figure 1. Different NWP models (see Figure 1) will be used by different partners of FUMAPEX for the UAQIFS. In this paper we will focus on DMI's contribution to FUMAPEX.

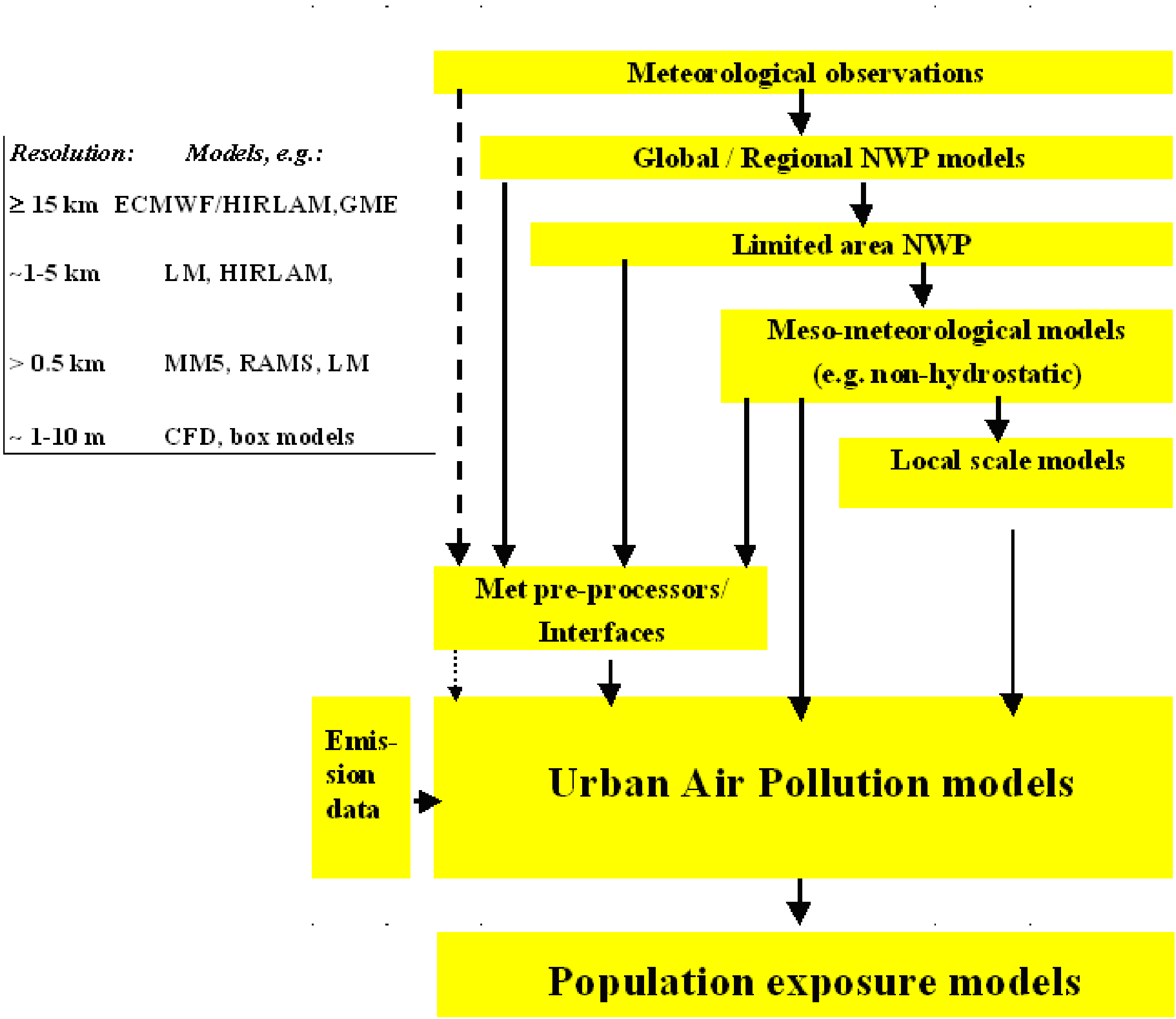
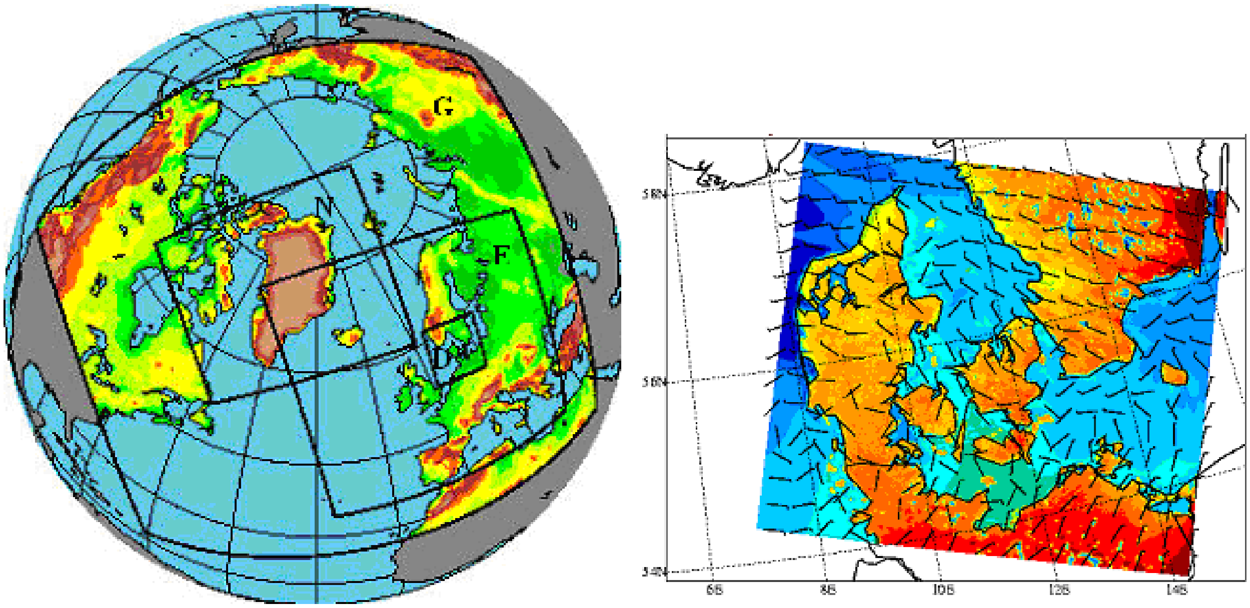


Figure 1. Current regulatory practice (dashed line) and the FUMAPEX suggested (solid lines) way of downscaling and integration of systems of urban meteorology and air quality forecasting for UAQUIFS.

The growth of supercomputer power at DMI (currently a multi-node NEC-SX6 system) and the implementation of grid nesting techniques allowed the DMI NWP system, based on the High Resolution Limited-Area Model (HIRLAM) (*Undin, 2002; Sass, 2002*), to approach the resolution of the city-scale (*Sattler, 1999; Baklanov et al., 2002*). The Danish operational NWP system consists of several nested models named DMI-HIRLAM 'G', 'N', 'E' and 'D', where the high resolution model 'D', covering an area around Denmark, uses a 4.6 km horizontal grid obtaining boundary values from the large scale model 'E' (Figure 2a). During summer periods the last two years, DMI has run operationally an experimental version of DMI-HIRLAM over the Zealand island, including the Copenhagen metropolitan area, with a horizontal resolution of 1.4 km (Figure 2b). The current vertical discretization of the operational DMI-HIRLAM is given by 40 vertical levels later this year to be changed to 60 levels.



a b

Figure 2. DMI-HIRLAM NWP system nested domains: a) the four operational versions (G, N, E, D), b) experimental city-scale (1.4 km resolution) version (I) for the Danish territory.

The DMI atmospheric pollution models utilise three-dimensional forecast or analysis meteorological data from DMI-HIRLAM or ECMWF model systems. Therefore, as the first step towards integration (off-line coupling), interfaces were developed for reading of meteorological fields in suitable formats and computing grids, and calculation of additional meteorological characteristics important for the dispersion models.

In general, for the simulation of the coupling between meteorology, heterogeneous chemistry and aerosols, and their effects on climate systems at different scales, it is necessary to build an integrated atmosphere-chemistry-aerosol modelling system with the following elements (Figure 3):

- an emission module including aerosols and gas compounds,
- an atmospheric heterogeneous chemistry model,
- a multi-component aerosol dynamic model,

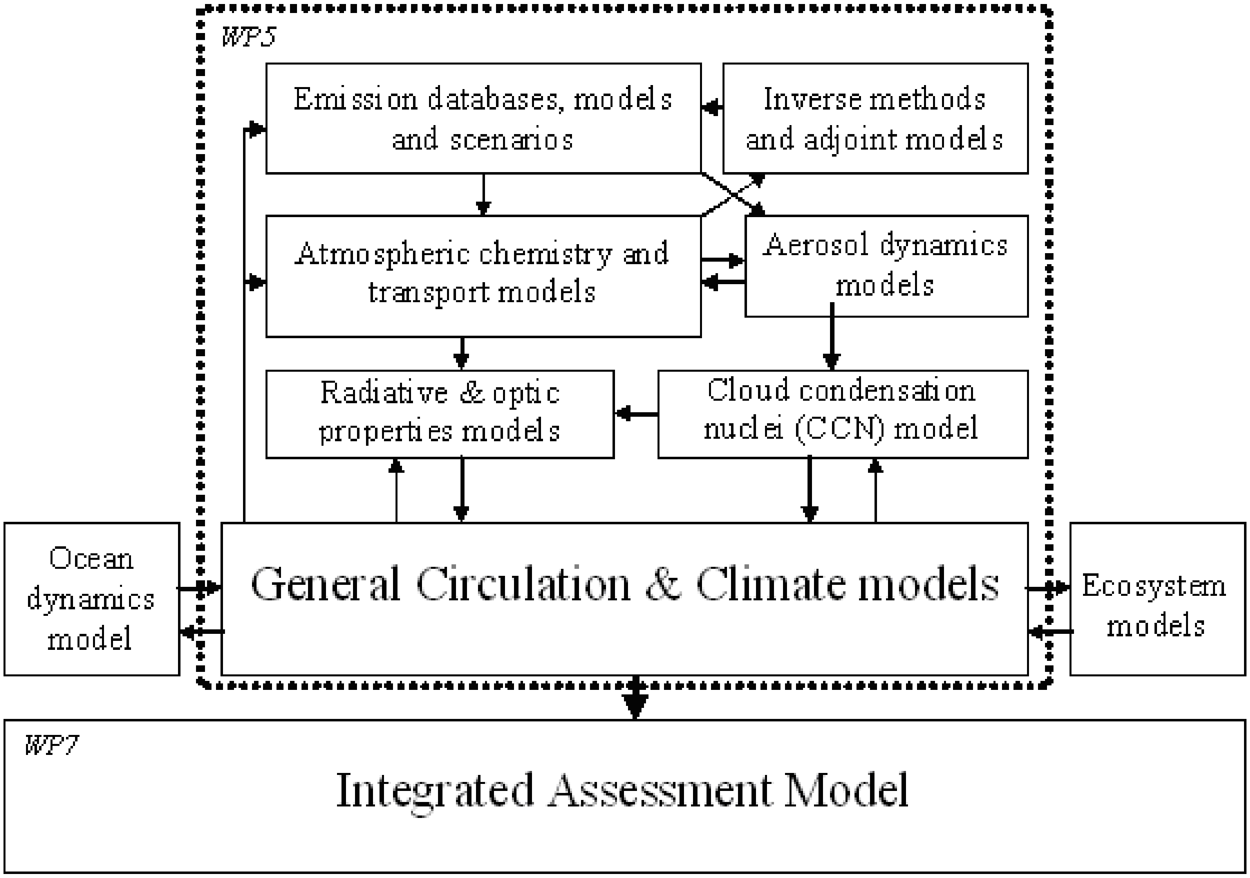


Figure 3. The integrated system structure for studies of environmental weather modelling and climate forcing of atmospheric pollutants.

- an atmospheric dynamics/general circulation model,
- a module for scavenging of different size multi-compound aerosols,
- a CCN module integrated with the aerosol model, and
- a radiative forcing module for the climate model system.

Following this strategy a Chemistry-Aerosol-Cloud (CAC) model system has been developed. The structure of the CAC model is presented in Figure 4. It includes the three-dimensional atmospheric chemical transport model MOON (Multi-trajectOry Ordinary-differential-equation Numerical-box) (*Gross, 2000*), a particle size-dependent deposition module (*Baklanov and Sørensen, 2001*), and the modal aerosol model (*Gross and Baklanov, 2003*). Depending on the study items, different meteorological data sets, i.e. NWP model data (such as DMI-HIRLAM) or climate model data, can be used as meteorological driver for the CAC model.

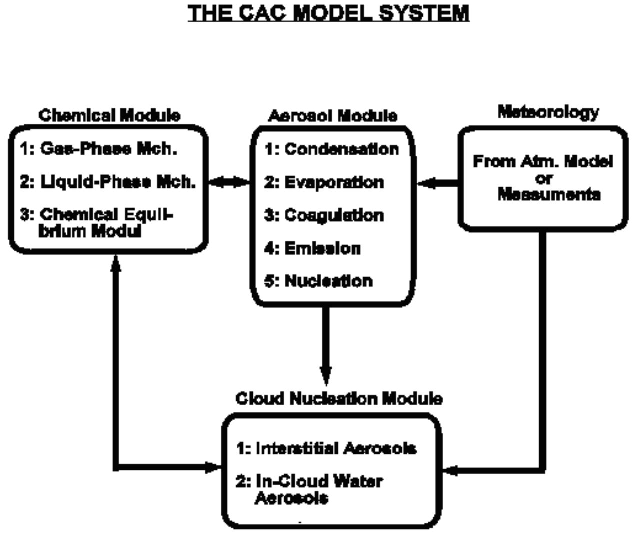


Figure 4. Schematic illustration of the Chemistry-Aerosol-Cloud (CAC) model system, being developed at DMI.

The MOON model is incorporated in the DACFOS model system for operational ozone forecasting (*Kiilsholm, 2000; Gross, 2000*) at DMI. The model includes the following elements: (i) Lumped atmospheric chemical mechanism: RACM (Regional Atmospheric Chemistry Mechanism) with 77 species and 237 reactions (*Stockwell et al., 1997*); (ii) Photolysis calculated using the TUV model; (iii) Chemistry solved using the SMVGEAR solver (*Jacobson, 1998*); (iv) Dry and wet deposition; (v) Emission from the EMEP database; (vi) Exchange mechanism between the ABL and the free troposphere; (vii) Horizontal and vertical diffusion.

With the perspective to develop an integrated mesoscale air pollution forecast system, a version of HIRLAM, has been implemented with advection and diffusion of passive tracers (*Chenevez et al., 2002, 2003*). The resulting model is called DMI-HIRLAM-TRACER (in the following shortened as TRACER). A first step towards a fully integrated air pollution model consists in simulating the transport of passive tracers using a well suited advection scheme involving acceptable computing costs. Indeed, the treatment of transport is of high importance for air pollution models, in which the advection scheme has to comply with positivity, monotonicity, mass conservation and low numerical diffusion properties.

Recently, the Danish nuclear emergency preparedness decision-support system, the Accident Reporting and Guidance Operational System (ARGOS) (*Hoe et al., 2002*), has been extended with the capability of real-time calculation of regional-scale atmospheric dispersion of radioactive material from accidental releases. This is effectuated through on-line interfacing with the Danish Emergency Response Model of the Atmosphere (DERMA) (*Sørensen, 1998; Sørensen et al., 1998, Baklanov and Sørensen, 2001*), which is run at DMI. DERMA is a three-dimensional Lagrangian long-range dispersion model using a puff diffusion parameterisation, particle-size dependent deposition parameterisations and radioactive decay. In general, the DERMA model can be used with different sources of NWP data, including the DMI-HIRLAM and ECMWF NWP models with different resolution. For local-scale modelling of atmospheric dispersion, ARGOS utilises the Local-Scale Model Chain (LSMC) (*Mikkelsen et al., 1997*), which makes use of high-resolution DMI-HIRLAM numerical weather-prediction model data provided by DMI four times a day under operator surveillance covering Denmark and surroundings. Figure 5 depicts the overall integrated system consisting of DMI-HIRLAM, DERMA and ARGOS.

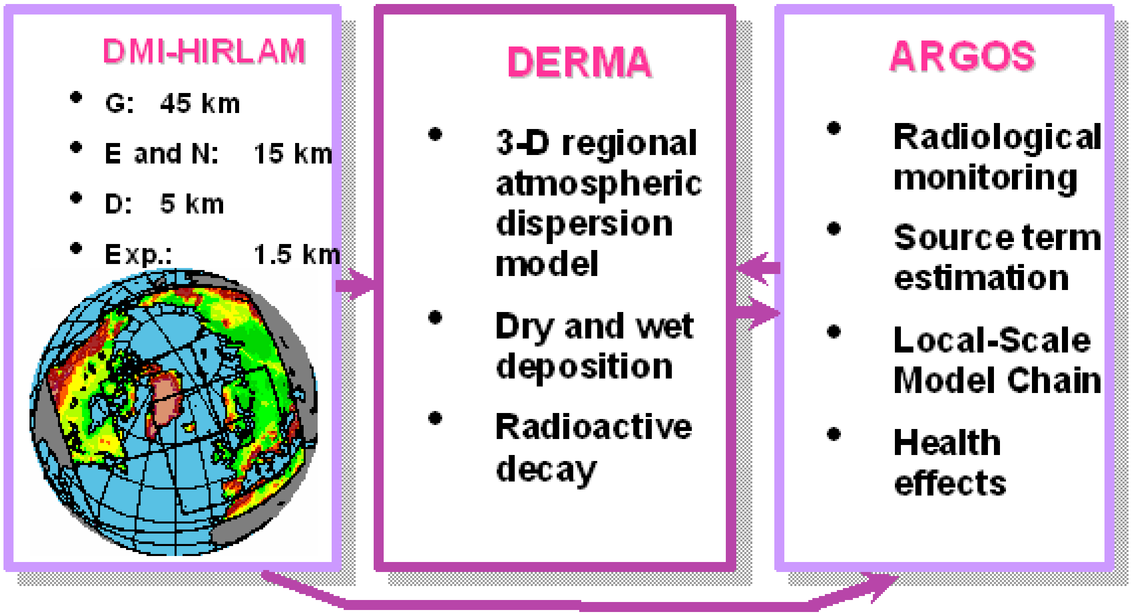


Figure 5. The DMI-HIRLAM numerical weather prediction model versions, the DERMA regional atmospheric dispersion model, the ARGOS real-time on-line nuclear decision support system, and links between

In addition to the above-mentioned direct simulation models, methods for the inverse problems and risk assessment modelling using long-term dispersion modelling, inverse methods and adjoint models are developed. Algorithms for source term estimation and vulnerability studies, which are based on sensitivity theory and inverse modeling are suggested (*Penenko and Baklanov, 2001*). A first simple attempt to apply inverse modelling using the DERMA model is realised and employed for the estimation of an unknown source corresponding to a hypothetical release of a biological warfare agent carried out by a terror organisation.

One of the ways to diminish the uncertainties of air pollution forecasts by numerical deterministic models is the use of the ensemble methods. In recent years, such methods have been developed and applied to e.g. nuclear emergency preparedness (see e.g., *Monache and Stull, 2003; Galmarini et al., 2003).* In additional to the above mentioned DMI models, ensemble versions of the DERMA and MOON systems, based on the ensemble of several models or model runs using different meteorological fields and model parameters, are tested at DMI for nuclear emergency preparedness and ground-level ozone forecasting.

The considered numerical models, especially integrated models, require powerful computer facilities. Operational high resolution forecast of meteorological fields and atmospheric pollution in urban areas is possible only on modern supercomputers.

The structure of the NEC SX-6 multi-node supercomputing system at DMI used for atmospheric modelling is presented in Figure 6. The most computer-resource consuming operational models at DMI, DMI-HIRLAM and MOON, runs on the NEC SX-6 supercomputer. Less computationally expensive models, e.g., the DERMA model, can be running on powerful scalar servers or on the NEC SX-6. The computing scheme of the DMI-HIRLAM operational system is presented in Figure 7.

4. MODEL VALIDATION AND EXAMPLES OF FORECASTING RESULTS

For the meteorological forecast and as a meteorological driver for local- and urban scale air pollution models, DMI has in recent years run an experimental version of DMI-HIRLAM over Denmark including the Copenhagen metropolitan area with a horizontal resolution of 1.4 km. This involves 1-km resolution physiographic data with implications for the surface parameters, e.g. surface fluxes, roughness length and albedo. The enhanced high-resolution NWP forecasting is provided to demonstrate the improved dispersion forecasting capabilities of the ARGOS nuclear decision-support system for the city of Copenhagen (Baklanov et al., 2003). Figure 8 presents two examples of urban-scale forecasted wind fields at 10-meter height and of 2-meter air temperature for the Zealand island and the Copenhagen metropolitan area by the experimental version of DMI-HIRLAM with the horizontal resolution of 1.4 km. The results show that the high resolution model can considerably better simulate the local-scale features and circulations, e.g., effects of the coast areas on the wind fields and other meteorological parameters important for air pollution forecasts.

The DERMA model has been verified against the European ETEX experiment involving a passive tracer and the accidental Algeciras release of ^{137}Cs (*Sørensen, 1998; Baklanov and Sørensen, 2001; Baklanov, 1999*). Comparisons of simulations by the DERMA model versus ETEX gave very good results. 28 institutions from most European countries, USA, Canada and Japan contributed to the real-time model evaluation. Based on analyses from the first experiment, the DERMA model was emphasised as being very successful (*Graziani et al., 1998*). Figure 9 depicts the results of the DERMA model verification for the ETEX-1 experiment (hourly-average concentration measured at Risø, Denmark) and for the Algeciras release (daily-average concentration measured at JRC, Ispra, Italy).

As an example of the use of adjoint modelling, consider the DERMA simulations for a hypothetical bio-terror action in the Copenhagen area. Figure 10 on the left map presents the inhalation dose after a hypothetical release of 100 g Anthrax spores as calculated by DERMA (the stars correspond to 'measurement' stations). Assuming that the source is unknown and

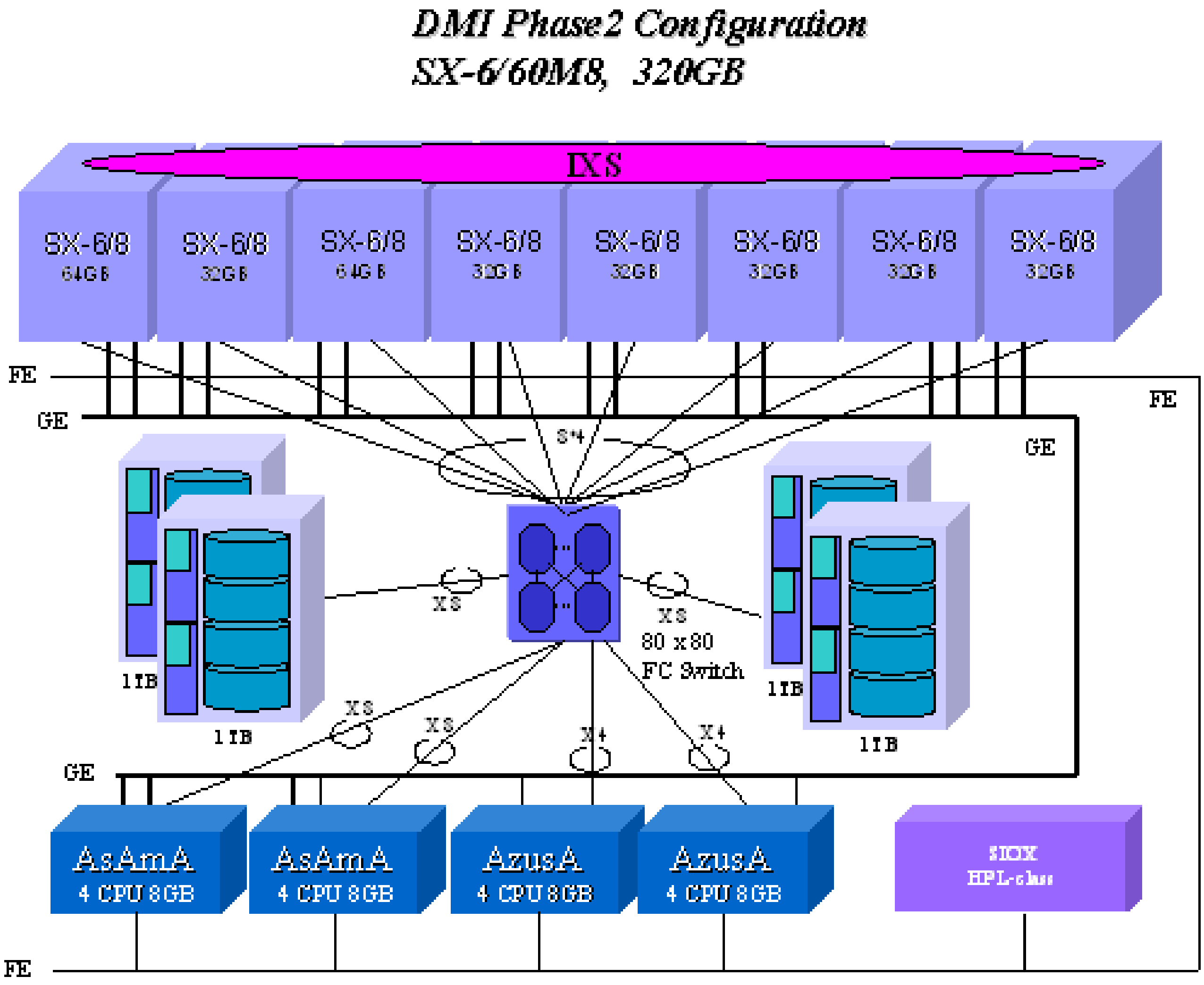


Figure 6. Structure of the DMI NEC SX6 multi-node supercomputing system for atmospheric modelling.

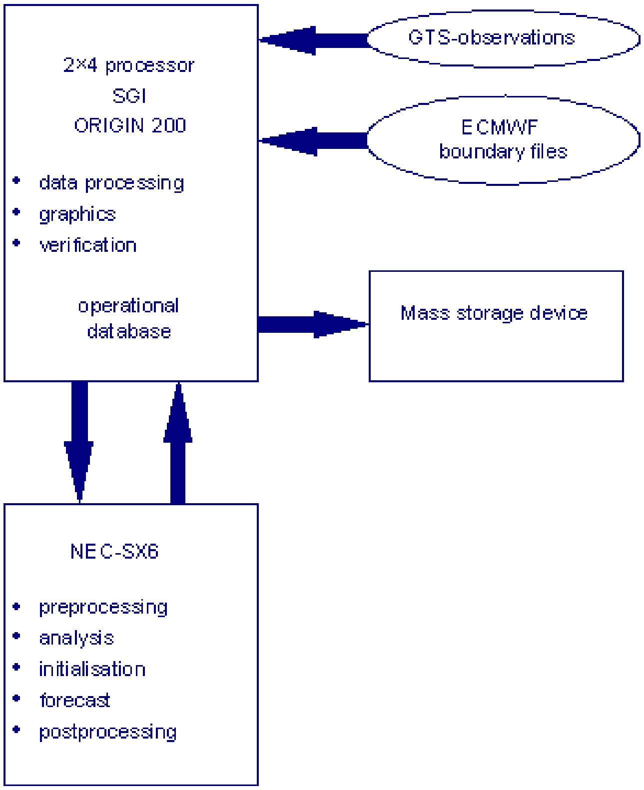


Figure 7. Computing scheme of the DMI-HIRLAM operational system running on DMI supercomputing system.

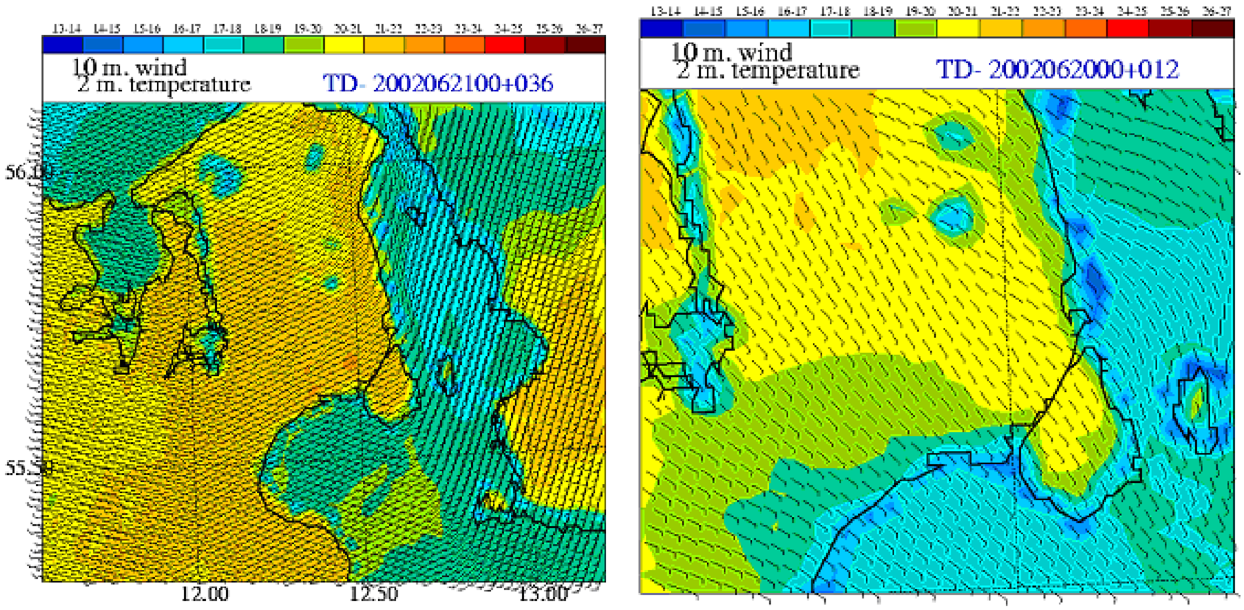


Figure 8. An example of forecasted wind fields at 10-meter height and of 2-meter air temperature for the Copenhagen metropolitan area by the experimental version of DMI-HIRLAM with horizontal resolution of 1.4 km.

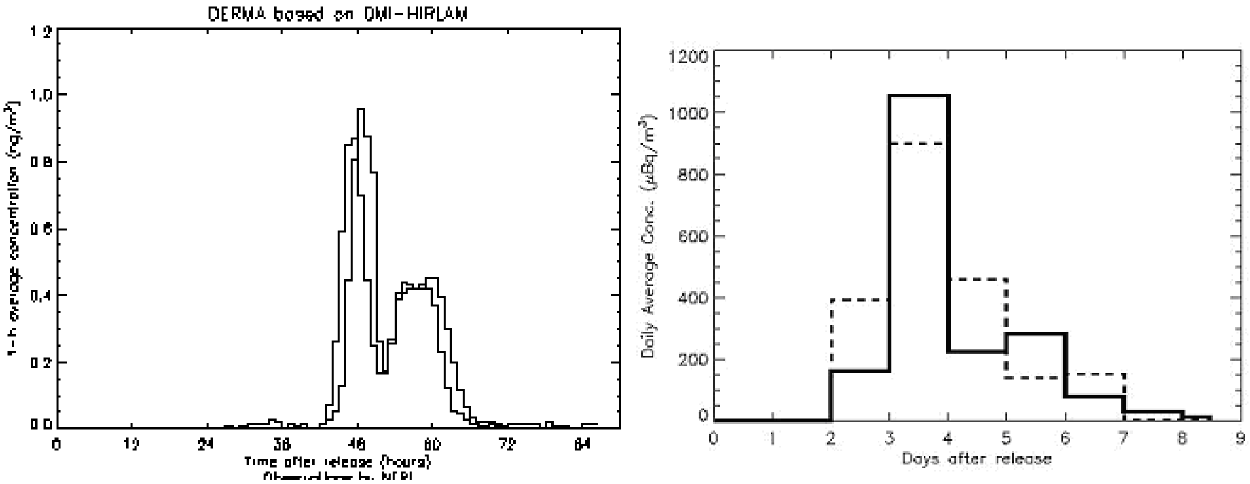


Figure 9. Results of the DERMA model verification for (left) the ETEX-1 European experiment (hourly-average concentration measured at Riso, Denmark) and (right) for the Algeciras ^{137}Cs release (daily-average concentration measured at JRC, Ispra, Italy).

that we have available concentration measurements from the indicated locations, the right figure shows the corresponding sensitivity function for the determination of the source by the inverse (adjoint) DERMA model. As we can see from the figure, the maximum value of the sensitivity function, which gives the likely source position, is situated very close to the source location. This test gives a preliminary conformation of the applicability of the model. Depending on the quality of the measurement data one should, however, in general expect to find several local maxima of the sensitivity function end thereby several potential candidates of the source.

For ground-level ozone forecasting DMI uses several model systems based on backward and forward long-range Lagrangian transport modelling. They include the DACFOS model system for operational ozone forecasting (*Kiilsholm, 2000*), the Kalman filter model (*Chenevez and Jensen, 2001*) and the MOON air chemistry model, based on the RACM2 mechanism, (Gross, 2000). In additional to the above mentioned methods, a new ozone forecasting system, based on an ensemble of models and model runs using different meteorological fields and model parameters, is currently developed and validated at DMI. The operational ozone forecasting system of DMI produces 48 hour forecasts every day from 00, 06, 12 and 18 UTC for 32 location in Europe, 11 of these location are Danish. For each forecast the model is run for six days time interval.

Lets consider a verification and a comparison of the currently operational ozone forecasting system DACFOS/MOON and the proposed ensemble system for the Keldsnor monitoring station, Denmark. Figure 11 depicts the scatter plots for the forecasted vs. observed concentrations of surface ozone for Copenhagen for June 2000 (left) and August 2001 (right) by the DACFOS/MOON model (top) and ensemble forecast (bottom). Corresponding June 2000 and August 2001 statistics for the DACFOS/MOON model forecasts and the Ensemble forecasts vs. measured surface ozone data are presented in Table 1. Both the figure and the table demonstrate a significant improvement of the ozone forecast quality using the ensemble forecast method.

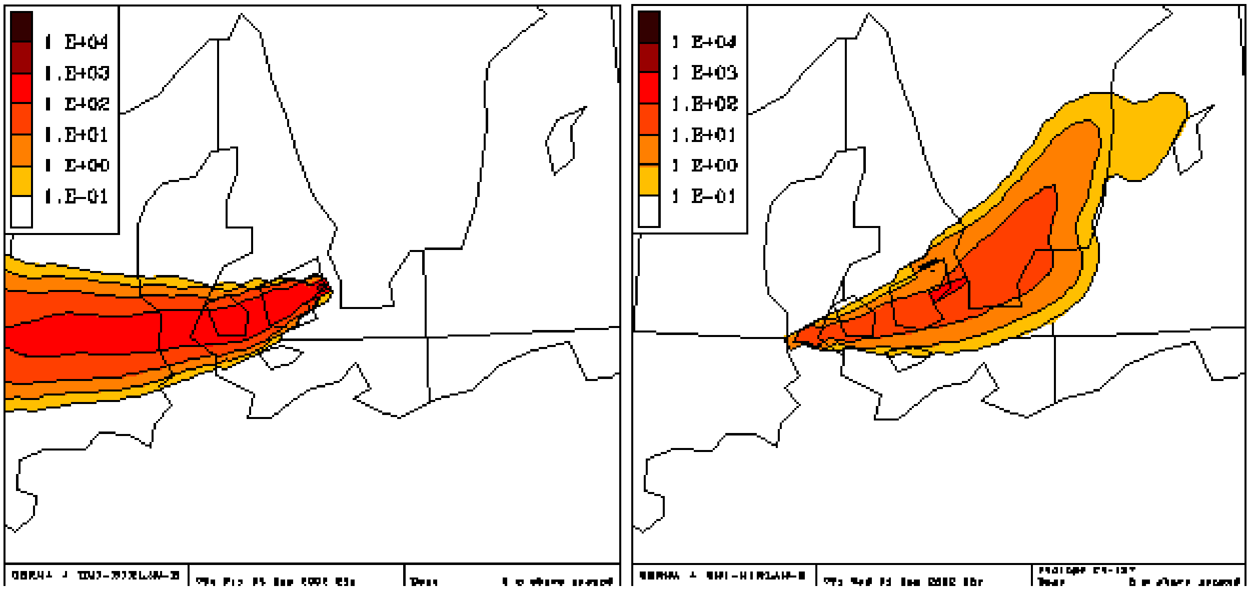


Figure 10. DERMA simulations related with a hypothetical bio-terror action for the Copenhagen area. Left figure: Inhalation dose after a hypothetical release of 100 g Anthrax spores calculated by direct simulation (stars depict measurement stations). Right figure: Determination of the source by inverse (adjoint) modelling based on measured data.

Table 1. Statistics for the DACFOS/MOON model forecasts and the Ensemble Forecasts vs. measured surface ozone data for the Keldsnor station, Denmark. *Italics:* statistics — DACFOS/MOON forecasts, **bold**: statistics — ensemble forecasts

	June 2000				August 2001			
	All Forecast		*Max. Ozone*		*All Forecasts*		*Max. Ozone*	
	Obs.	MOON model	Obs.	MOON model	Obs.	MOON model	Obs.	MOON model
$<[O3]>$ (ppbV)	43.35	42.17 *48.20*	47.68	45.83 *52.57*	37.61	36.71 *41.45*	44.37	42.28 *47.60*
St. Dev. (ppbV)	12.67	10.52 *11.52*	14.70	12.05 *11.67*	10.51	8.57 *10.14*	11.35	9.67 *9.84*
Corr.	1.00	0.95 *0.73*	1.00	0.79 *0.78*	1.00	0.86 *0.48*	1.00	0.90 *0.59*
Bias (ppbV)	0.00	-1.36 *4.84*	0.00	-2.12 *4.85*	0.00	-0.94 3.90	0.00	-2.16 *3.40*
RMSE (ppbV)	0.00	4.66 *10.26*	0.00	5.14 *10.41*	0.00	5.39 *11.23*	0.00	5.54 *10.33*

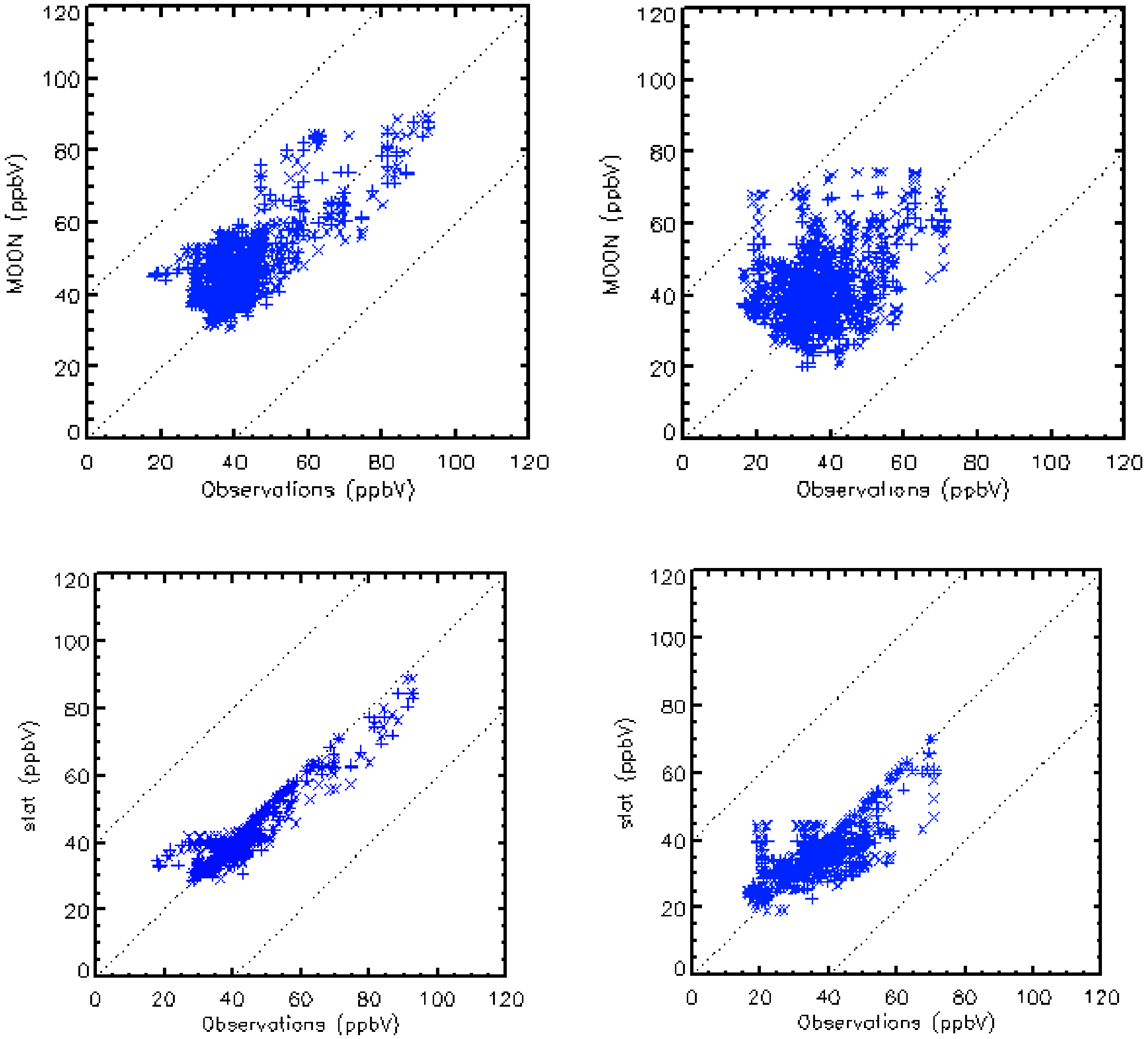


Figure 11. Scatter plots for the forecasted vs. observed concentrations of ground-level ozone for Copenhagen for June 2000 (left) and August 2001 (right) by the MOON model (top) and ensemble forecast (bottom).

5. CONCLUSIONS AND FUTURE DIRECTIONS

Proceeding from the analysed gaps and requirements of air quality modelling for the urban and regional scales, a suggestion is made for an improved main strategy and novel methodology of the integration (off-line and on-line) and downscaling of NWP and RAP/UAP models, and the building of integrated systems for forecasting meteorology and air pollution,. The realisation of this methodology in the European Union and particularly in Denmark for specific atmospheric pollution problems is discussed.

The FUMAPEX project strategy and recent achievements of the improvement of meteorological forecasts for urban areas, the connection of numerical weather prediction (NWP) models to urban air-pollution and population dose and exposure models, the building of improved urban air-quality information and forecasting systems are presented.

Following the above strategy, the paper outlines the common status of DMI activities in the field of urban and regional scale air pollution modelling and the integration of air pollution models with NWP models. Examples are given from UAP to RAP modelling, e.g.:

- improved meteorological forecasts for urban areas, the connection of city-scale NWP models to emergency preparedness models. Examples of simulations related with a hypothetical bio-terror action for the Copenhagen metropolitan area is considered.

- regional scale ozone forecasts produced at DMI. The purpose of the activity is to inform and warn the public in cases of exceedances of critical limit values.

- an aerosol model recently developed at DMI. The simplicity of the model facilitates the implementation in RAP and UAP models. The aerosol model has been implemented in the chemistry transport model and applied to the problem of DiMethyl Sulphide's influence on aerosol formation in the marine boundary layer and in the free troposphere.

- nuclear emergency preparedness at DMI based on the DERMA long-range transport model in the direct and inverse modes.

In our view the main perspective for the future directions of the Regional and Urban Forecasting of Air Pollution includes the following:

1. Forecasts of atmospheric aerosols. Many research groups have started actively to model aerosol dynamics on the global, regional and local scale. High resolution forecast of aerosols on the regional or local scales is more problematic due to the demand on very powerful computers. At present the best solution to this problem is the modal description of the aerosol physics.

2. Data assimilation in forecasting of air pollutants. Data assimilation is widely used for meteorological forecasts, but existing attempts of data assimilation for air pollutants has been used for case studies only, not in the forecast mode. At present this topic is a hot subject of research in USA.

3. Ensemble forecasts of air pollution. Ensemble forecasts is used by ECWMF and certain other national meteorological centres for meteorological forecasting. It has not been applied to air pollution in forecasts mode, but a few examples of ensemble simulations have been made showing promising results.

4. Integrated (on-line coupled) forecasting models. This item is still quite far from the complete solution, especially for studies of feedbacks of air pollution on meteorological processes and climate forcing of atmospheric pollutants.

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