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Dispersion conditions in the stable boundary layer as described by the MM5-model.

A case study of a pollution episode in Oslo, Norway.

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DISPERSION CONDITIONS IN THE STABLE BOUNDARY LAYER AS DESCRIBED BY THE MM5-MODEL – A CASE STUDY OF A POLLUTION EPISODE IN OSLO, NORWAY

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ABSTRACT

As part of the ongoing EU-funded FUMAPEX project, the Urban Air Quality Information and Forecasting Systems (UAQIFS) presently applied in Oslo, Norway, is being considered for possible improvements. In this presentation preliminary results from the FUMAPEX project are discussed. Special attention is devoted to the numerical weather prediction model's (MM5) ability to describe the local circulation in cases of "long lived" stable conditions. A pollution episode, with weak winds and a strong ground based temperature inversion is examined.

1 INTRODUCTION

High levels of PM_{10}, $PM_{2.5}$ and NO_2 are observed every winter in Norwegian cities during stable conditions with ground based temperature inversions, weak winds and little vertical mixing. In order to reduce or prevent critical concentration levels, abatement measures (such as traffic restrictions) should be planned at least one or two days in advance, based on proper air quality forecasts. In Oslo, Norway, an Urban Air Quality Information and Forecasting Systems (UAQIFS) of this type has already been in operational use for several years. This forecasting system was selected for further development in the ongoing EU-funded FUMAPEX project, which is ending October 2005.

The city of Oslo is located at the northern end of the Oslo fjord, surrounded by several hills up to 600 m height and with three main valleys emanating from the city basin, the largest to the northeast, one to the north and one to the northwest. During low wind conditions, with strong ground based or slightly elevated inversions, the pot-formed topography of the area contributes to worsen the dispersion conditions, thereby capturing pollutants emitted within the urban air shed. Our experience so far with the applied meteorological model (MM5) is that predicted ground based inversions are too strong and too frequent, and that very low wind speeds are difficult to achieve. This is also the case with the forecast for the selected episode in the present study.

In addition to inherent uncertainties in the applied emission inventories and in the dispersion model itself, the quality of the air pollution forecast critically depends on the meteorological input data. The air quality model is designed to handle pollutants which are emitted close to the ground, i.e. from road traffic and house heating, and is therefore particularly sensitive to the wind speed, wind direction and the turbulence characteristics predicted in the lower part of the PBL. Factors that are assumed to influence the description of the PBL in the NWP model, namely choice of PBL parameterisation scheme, vertical model resolution, model design and forecast length, are therefore investigated.

2 METHODOLOGY

The presently applied UAQIFS in Oslo is an offline model system consisting of the mesoscale (non-hydrostatic) meteorological model MM5 and the urban scale air quality model AirQUIS. These two models are coupled through a meteorological pre-processor interface program.

The applied operational NWP system combines the HIRLAM model (Undén, 2002), which produces boundary values with 10 km resolution (HIRLAM10), and version 3.4 of the non-hydrostatic Fifth-Generation Penn State/NCAR Mesoscale Model, (MM5, 2005). The operational MM5 configuration consists of an outer 3 km horizontal resolution grid and an inner mesh with 1km horizontal resolution, covering a quite large area around Oslo. Initial and six hourly boundary values are interpolated from HIRLAM10. The MM5 horizontal grids have 76 x 61 grid points, and both integration areas have 17 vertical layers (8 below 1000m). 48 hours forecasts are made daily with this system and the last 24 hours of the prognosis period are utilized as input to the air quality model. Thus, when presenting model results for several days, these are in reality separate 24-hour sequences that have been added up to a continuous time series. The MM5 model has several different choices for parameterisations of the diabatic processes. The physic options presently in operational use are: a first order turbulence closure scheme, i.e. the MRF-scheme (Hong and Pan, 1996), a 5-layer soil model, a cloud interactive radiation scheme, and explicit moist physics including ice phase but with no parameterisation of cumulus and shallow convection. Topography and 16 land use classes are collected from the U.S. Geological Survey. At the latitude of Oslo (60° north) these data have a horizontal resolution of 0.5 km x 0.9 km, thus enabling the use of 1 km resolution.

The air quality forecast is made by the PC-based Air Quality Information System, (AirQUIS, 2004). AirQUIS combines functionalities for emission inventories and numerical dispersion modelling. The dispersion model within AirQUIS is a Eulerian grid model with use of embedded sub grid line and point source Gaussian models for near source treatment (Slørdal et al., 2003). The model calculates urban background concentration levels, and near source concentrations from road traffic and individual stacks. For the Oslo application AirQUIS is applied on the 1 km resolution grid of the finest MM5 grid, and Air Quality forecasts are made for NO_2, PM_{10}, and $PM_{2.5}$. Presently the horizontal model domain of AirQUIS is required to be defined as a subset of the 1 km^2 MM5 model domain, with identical fields of topography and land use classification in order to avoid use of horizontal interpolation. Vertically MM5 apply a terrain following (σ) coordinate defined from an idealized hydrostatic pressure-distribution. In AirQUIS a similar, but not identical, terrain following Cartesian height-σ coordinate is applied (Slørdal et al., 2003). However, since the two models are applying identical fields of topography, the model layers can be defined approximately at the same physical heights, thus avoiding vertical interpolation. In the operational version of the UAQIFS the following meteorological parameters are transferred from MM5 to AirQUIS:

- Three-dimensional fields of temperature and horizontal wind.
- Two-dimensional fields of precipitation, relative humidity, cloud cover, ground temperature and dew-point temperature.

Note that the vertical velocity applied in AirQUIS is recalculated based on the gridded horizontal wind field from MM5 and an additional physical requirement of mass continuity.

In the present forecast version the meteorological input required by AirQUIS are just extracted from MM5 as if these were observed values available in the model grid system. The dispersion parameters for the air quality forecast are then calculated using traditional Monin-Obukhov similarity theory following the methods of van Ulden and Holtslag (1985). Important quantities like the PBL (or mixing) height, the vertical profile functions in the surface layer, and the vertical eddy diffusivity $K_{z,}$ are estimated. However, instead of estimating the dispersion parameters in the interface program, these quantities could instead have been extracted directly from MM5. Consequently, as part of the present study, the effects of direct application in AirQUIS of the MM5 calculated eddy diffusivities (for heat) have been investigated.

3 RESULTS AND DISCUSSION

The pollution episode in study occurred in January 2003. On the 7^{th} of January hourly NO_2 values up to about 600 $\mu g/m^3$ were observed. High $PM_{2.5}$ values were observed as well (hourly value of 152 $\mu g/m^3$). Moreover, throughout a 3-day period from the 7^{th} to the 10^{th} of January rather high concentration levels were maintained during nighttime as well. Prior to the episode the measured ground temperatures were low, about -20°C. On the synoptic scale an area of high pressure prevailed over the north Atlantic on the 3^{rd} of January, and was transported to the East, arriving in the area between UK and Southern Norway on the 7^{th}. As a result of this, relatively warmer air masses were transported over the Oslo area at higher altitudes from the northwest on the 6^{th}. On a local scale this relative warm air formed a strong inversion layer over the entire city of Oslo that lasted from the 7th to the 10th of January. The ground surface was covered with snow or ice during the course of the episode.

In Figure 1a and 1b time series are presented of the observed and MM5 calculated wind speed (profile-adjusted to 10 m) and vertical temperature gradient (measured between 25 m and 8 m, and calculated between 21 and 7 m), respectively, at the urban meteorological station Hovin. In the same plots (right axis) are the measured NO_2 values at a nearby urban street station (Løren) presented. As seen from Figures 1a and 1b the highest NO_2 concentrations at Løren, starting on the afternoon of the 6th and lasting throughout the 9th, reaching slightly above 400 μg/m^3 in the early afternoon of the 7th, are coinciding with the occurrence of low observed wind speeds and a strong surface inversion. The predicted values, on the other hand, reveal that MM5 overestimates the wind speed close to the surface. Moreover, the predicted inversion strength is comparable to the measurements during the pollution episode, but is much too high both before and after this period. The net effect on the air quality forecast is shown in Figure 2a.

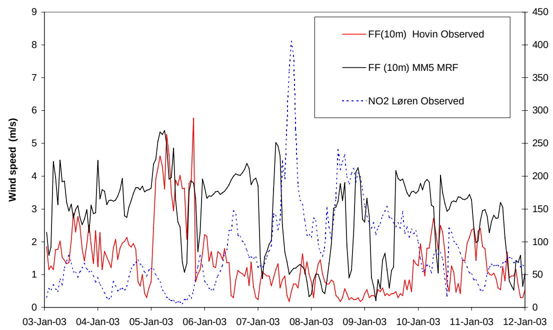

Figure 1a: Time series of hourly values of the observed wind speed (left axis; m/s) at Hovin and observed hourly NO_2 concentrations (right axis; μg/m^3) at Løren during the episode.

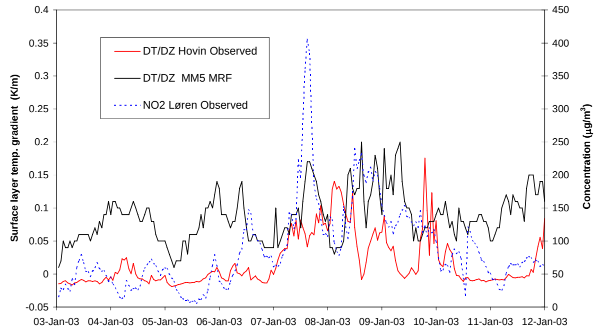

Figure 1b: Time series of hourly values of the observed temp. gradient (left axis; K/m) at Hovin and observed hourly NO_2 concentrations (right axis; μg/m^3) at Løren during the episode.

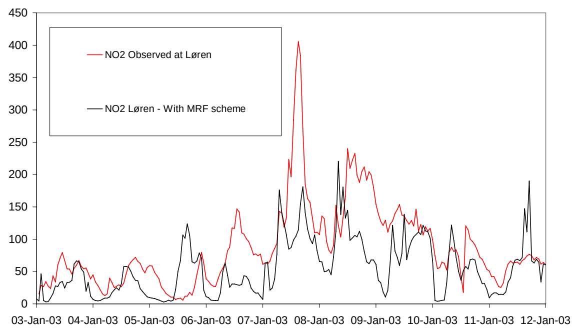

Figure 2a: Time series of hourly values of the observed and predicted NO_2 concentration (μg/m^3) at Løren during the episode. The MRF PBL-scheme is applied in MM5.

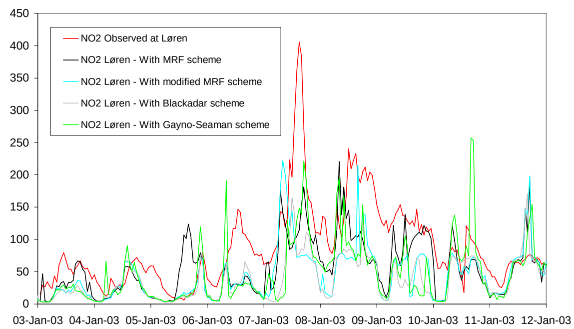

Figure 2b: Time series of hourly values of observed and predicted NO_2 concentrations (μg/m^3) at Løren during the episode. Model results are shown for 4 different predictions with different PBL-schemes applied in MM5. See text below for description.

As seen from Figure 2a the overestimation of the surface layer stability in MM5 is counteracted by the over-predicted wind speed, resulting in a relatively correct NO_2 forecasts both before and after the pollution episode. However, during the 7th and 8th, when the highest concentration levels are observed, the model predictions are far too low. This is also the case for all of the other measurement sites within the city area. Furthermore, the observed NO_2 levels show a continuous increase in nighttime concentration levels from the 7th to the night of the 9th when the concentration never get below 110 μg/m^3. This nighttime build-up is also seen at several of the measurement sites within the central city area and is a clear indication of local stagnation and/or recirculation of pollutants.

In the present study the selected pollution period has been recalculated with various choices of turbulence closure schemes that are available in the MM5 package. The schemes that have been tested in addition to the MRF scheme are: a modified version of the MRF scheme (Sorteberg, 2001), the Blackadar scheme (Zang and Anthes, 1982), and the Gayno-Seaman scheme (Ballard et al., 1991). According to the MM5 documentation all of these schemes are appropriate for high-resolution simulations. However, only the Gayno-Seaman scheme applies higher order closure, with prognostic calculation of TKE. For stable conditions, which are prevailing during the pollution episode under study, all the other schemes are local K-theory schemes based on different variants of traditional Monin-Obukhov similarity theory. Examples of the resulting NO_2 forecasts are presented for the Løren station in Figure 2b. As seen from this figure the various turbulence schemes clearly have an impact on the calculated NO_2 levels. In spite of this, none of the schemes lead to a clear improvement in forecasting the highest concentration levels or the nighttime pollution build-up during the 3-day episode. A detailed study of the calculated surface wind and temperature stratification show that all of the turbulence schemes predict results that are rather similar. All of the schemes predict near zero turbulent exchange between the two lowermost model layers, which in turn means near zero turbulent exchange of the surface-emitted pollutants. When, despite of this, the pollution forecast does not reach the observed levels or the pollution build-up, the most likely reason is that the pollutants are advected out of the city area too fast by the model system. This supposition is corroborated by trajectory calculations, showing that particles emitted within the central city area are transported out of the city in a few hours. Both the overestimation of the wind speeds and the vertical temperature gradient indicate that the upper warm air is advected too efficiently in the lowermost model layers all down to the city basin. Examination of vertical cross sections confirms that the observed dynamics with warm air floating on top of the cold stagnant air fails to be described by the model. In addition, the 1 km resolution is still too coarse to properly resolve small scale topographic and/or land use features that locally influence the flow patterns and are responsible for the high nighttime concentrations of pollutants during these stable conditions.

The above results are based on consecutive periods of the last 24 hours of daily-performed 48 hours forecasts. Tests where the first 24 hours of the prognosis period is applied instead show no improvement in the systematic overestimation of surface wind speed and stability. These features are therefore not gradually evolving during the prognosis period.

The air quality forecasts have also been recalculated with direct application of the MM5 estimated 3-dimensional fields of eddy diffusivities for heat. However, even though this clearly represents a more consistent coupling of AirQUIS and MM5, only marginal changes were found in the calculated concentration fields for this stable period. It is nevertheless recommended to make use of the diffusivities, since stronger impacts are to be expected during unstable conditions.

Moreover, test simulations in which the number of vertical levels below 1000 m where doubled (from 8 to 16) in both MM5 and AirQUIS, did not lead to any significant improvement on the results. The thickness of the three lowermost levels was kept identical in these simulations in order to avoid differences in initial dilution of the emissions.

4 CONCLUSIONS

The choice of parameterization schemes, forecast lengths and vertical resolutions are shown to have limited potential to explain the model's failure in describing the circulation responsible for the high pollution levels observed. The advection of heat and momentum from the elevated areas north of the city basin is too efficient along the lowermost model layers. Thus the predicted surface wind speeds are overestimated, and the ventilation of pollutants is efficient in spite of the strong surface inversion. Moreover, small-scale surface based recirculation, which seems to exist in the central city area, is not properly resolved with the present model resolution.

5 ACKNOWLEDGEMENTS

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