A REAL-TIME OPERATIONAL FORECAST MODEL FOR METEOROLOGY AND AIR QUALITY DURING PEAK AIR POLLUTION EPISODES IN OSLO, NORWAY

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Abstract. A real-time operational forecast model for meteorology and air quality for Oslo, Norway is presented. The model system consists of an operational meteorological forecasts model and an air quality model. A non-hydrostatic model operated on two different domains with 1 and 3 km horizontal resolution is nested within the routine meteorological forecast model, which is run for North West Europe with 10 km horizontal resolution. The meteorological data are applied to an air quality model of Oslo with a 1 km grid and sub-grid treatment of line and point sources. Results from 22 days during the winter season 1999–2000 are presented and discussed. Prediction of wind speed and directions and relative humidity are clearly improved by increasing the horizontal resolution of the meteorological model. Temperature inversion strengths are however considerably overestimated. The predictions of PM_{10} corresponds best with measurements on winter days with wet or frozen surfaces in the city. On dry days, especially during spring time with a large deposit of accumulated dust on the roadside, the model under predicts the PM_{10} concentrations considerably. It is in particular recommended to improve the description of the PM_{10} source strength in order to enhance the precision in the air quality forecasts.

Keywords: air quality and meteorological model, forecast models, urban air quality, wintertime

1. Introduction

High levels of PM_{10} and NO_2 are observed every winter in Norwegian cities during temperature inversions with weak winds and little vertical mixing. High levels of PM_{10} also occur during dry weather conditions in particular during spring, when large amounts of particulate matter have accumulated along the roads due to wintertime road maintenance and usage of studded tires. Important measures to reduce the effects of wintertime air pollution are to issue forecasts and to employ traffic restrictions on days when high concentrations are expected. In order to support the air quality forecasts, a real-time operational forecast model has been developed. The meteorological part of the model is based on the MM5-model (Grell *et al.*, 1994) operated with 1 km horizontal resolution and nested within the operational forecast model of the Norwegian Meteorological Institute. The meteorological forecast

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data are further employed by the air quality modeling system developed at the Norwegian Institute for Air Research (AirQUIS, see Slørdal and Tønnesen, 1999), which predicts the air pollution levels. During the winter 1999–2000 the forecast model was run operationally for 22 cases favorable to high levels of air pollution in Oslo. The results of the simulations are presented and discussed in this paper. The forecast results were distributed automatically at about 07:30 in the morning to the local authorities with a forecast valid for the next day. Traffic restrictions were applied during one of the cases. A more detailed discussion of the model results during the day with traffic restrictions is also given.

2. Meteorological Forecast for the City of Oslo

The operational runs with MM5 were based on initial and boundary fields from HIRLAM (High Resolution Limited Area Model, Källén, 1996) started at 00 UTC and run for a 48 h prognosis with 10 km horizontal resolution covering North West Europe and adjacent seas. The MM5 was nested within the HIRLAM 10 km model (henceforth denoted H10) employing firstly one domain with 3 km horizontal resolution and secondly 1 km horizontal resolution over the Oslo area (see Figure 1). MM5 was operated on the second day of the HIRLAM prognosis (+ 24 to + 48 prognosis). The reason for this was simply the need to save computer time and the fact that the local authorities mainly needed the quantitative air quality forecast for the second day in order to prepare for daily forecasts or possible traffic restrictions.

Table I presents a statistical overview of the results for 22 cases during the period November 1 1999 to April 30 2000 for the two stations Blindern and Valle Hovin close to the center of Oslo (see Fig. 1). The bias of the wind speed is 0.51 $m.s^{-1}$ at Valle Hovin while the bias is close to zero at Blindern. The BIAS, MAE and STDE are all reduced significantly compared with the H10. The scatter plot presented in Figure 2 also clearly shows an improvement in the wind speed forecast when shifting from H10 to MM5. Furthermore, the difference in predicted and observed wind direction is less than 20 degrees in about 30% of the cases for MM5 and 10% for H10. About 50% of the wind direction data from MM5 are within 40 degrees of the observed direction. The respective number for H10 is 25%. We can conclude that the forecasted wind speed and direction are improved by shifting from H10 to MM5 1 km. We expect a large part of the improvements to be due to increasing the horizontal resolution, since the topography around Oslo has a large impact on the local winds. Small scale circulation patterns with a horizontal scale of just a few kilometers develop in the Oslo region and therefore cannot be captured by H10. In addition, the two models employ different numerical solvers and physical packages (see Grell *et al.*, 1994 and Källén 1996 for details about the models). H10 employs a semi-lagrangian solver for the momentum equations, while MM5 uses an explicit method except for the acoustic waves which are solved by an implicit method. Both models have been run with 1. order PBL-schemes.

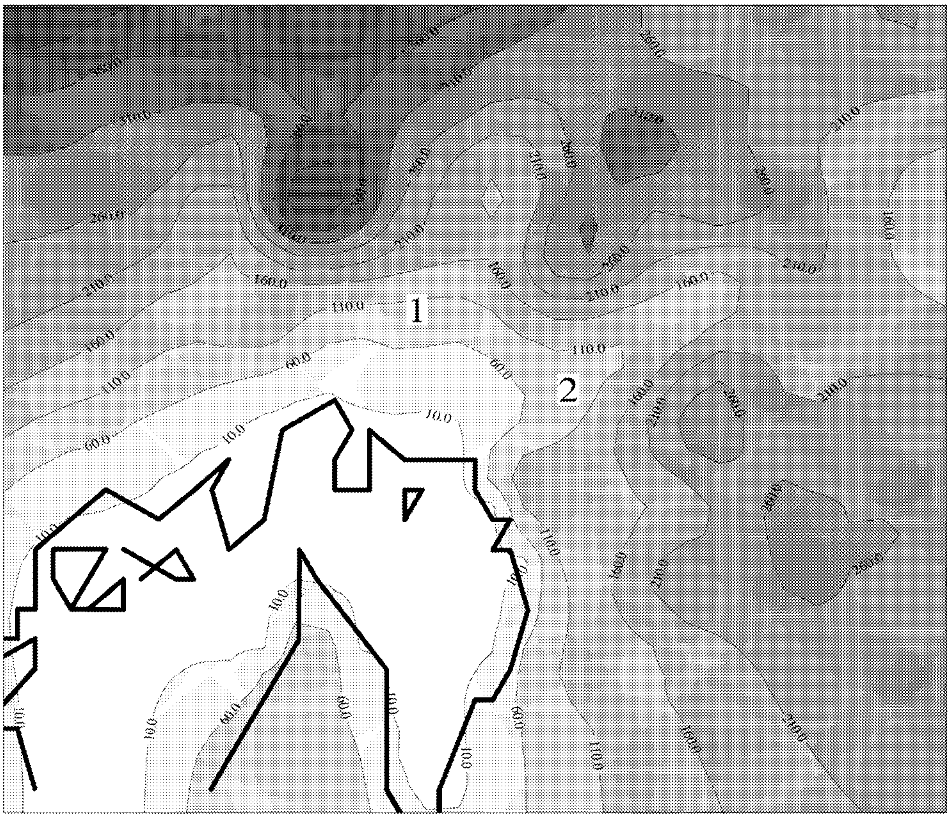

Figure 1. Inner modeling domain for MM5 (1 km horizontal resolution). Blindern is located at 1 and Valle Hovin is located at 2. Domain size is 31 * 31 km.

However, how important differences in formulation of the numerical solutions and the physical processes could be for the differences in the results has not been studied yet. Such a study would ideally require the set up of H10 on a 1 km horizontal grid, but since H10 is a hydrostatic model it is not recommended to apply this model at 1 km horizontal scale in complex terrain.

The temperature is however systematically underestimated in MM5 with a BIAS of –4.46 °C at the 2 m level at Valle Hovin and –4.39 °C at Blindern. We also note that a large part of this underestimation arises from too low temperatures in the HIRLAM model. However, at 25 m height at Valle Hovin the BIAS is reduced to –1.62 °C. Therefore, the near surface inversion strength is too strong in MM5. However, the daily cycles of near surface temperatures are qualitatively realistic (see also Figure 8 as an example). The standard deviation in the temperature is reduced for the 1 km compared to the 10 km horizontal resolution. Relative humidity is on average overestimated, but also for this component the predictions are improved by changing from 10 to 1 km resolution. In particular the daily cycle of relative humidity is considerably more realistic in MM5 compared to H10 (see

TABLE I

Results from 22 days of forecasted (+ 24 to + 48) wind speed (W), temperature (T) and relative humidity (RH) for HIRLAM with 10 km horizontal resolution (H10) and MM5 with 1 km horizontal resolution. The temperature and wind speed measured at 25 m are compared with the model output at 23 m (MM5) and 30 m (H10) for every 3 h

Station	Parameters	Mean error (BIAS)		Mean absolute error (MAE)		Standard deviation (STDE)	
		H10	MM5	H10	MM5	H10	MM5
Valle Hovin	W25 m	1.71	0.51	2.11	1.17	1.92	1.32
Blindern	W10 m	0.73	–0.08	1.21	0.95	1.34	1.22
Valle Hovin	RH2 m	15.63	13.06	17.42	15.21	17.77	13.47
Blindern	RH2 m	11.36	5.67	15.32	12.17	17.42	15.15
Valle Hovin	T25 m		–1.62		3.04		3.20
Valle Hovin	T2 m	–3.34	–4.46	4.34	4.71	4.01	3.16
Blindern	T2 m	–3.67	–4.39	4.48	4.80	3.86	3.46

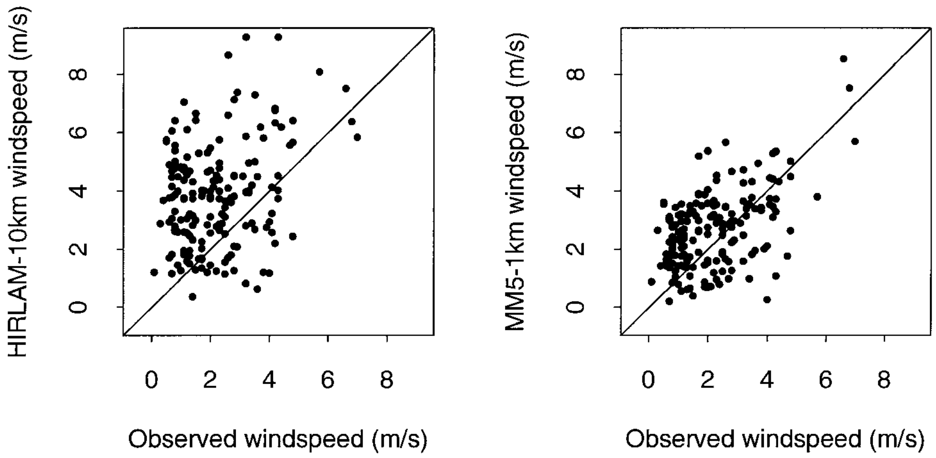

Figure 2. Observed and modeled wind speeds at Valle Hovin for 22 days during the winter 1999–2000.

Figure 9 as an example). Our analysis of the meteorological forecasts with 1 km horizontal resolution clearly indicates an improvement compared with the forecasts based on 10 km horizontal resolution.

3. Air Quality Forecast for the City of Oslo

The meteorological data are utilized to run an air quality modeling system called AirQUIS (Air QUality Information System) developed by the Norwegian Institute of Air Research (NILU) in cooperation with NORGIT Senteret A/S in Norway. The core features of the system are an air quality model and an emission inventory database and emission model. Additional features are linkage to a measurement database, statistical and graphical tools etc. The air quality model in AirQUIS consists of a combined eulerian/lagrangian dispersion model called EPISODE (Larssen *et al.*, 1994). Exposure calculations are also performed based on population distributions. The latter are improved by performing sub-grid scale calculations based on individual treatment of line-sources and building points within each Norwegian city.

The emission inventory database in AirQUIS typically consists of a set of area-, point- and line-sources. Area-sources are associated with emissions from domestic heating sources, or from traffic on smaller roads, distributed in a grid, point sources with emissions from industry or industrial activities, and line sources with emissions from larger individual roads. The exact position of the road, together with information about road width, steepness, speed limit, amount of daily traffic and vehicle composition, is stored in the database for each road. The AirQUIS database also contains daily and weekly traffic patterns for each road type, in addition to emission factors dependent on compound and vehicle type (gasoline-or diesel-driven cars, buses, trucks etc.). Emission of particles (PM_{10} and $PM_{2.5}$) is calculated dependent on the vehicle composition and traffic speed. The direct particle emissions from the exhaust gases, and small particles from road dust ($PM_{2.5}$) are calculated separately. The coarse fraction ($PM_{10} - PM_{2,5}$) is then calculated dependent on the fraction of vehicles using studded tires, taking into account the degree of dryness on the roads based on the meteorological information and the contribution from re-suspension of particles (Tønnesen, 2000).

The AirQUIS/EPISODE model uses a positive definite 4th order Bott scheme (Bott, 1993) for the horizontal transport of air pollutants. Vertically a simple upwind scheme is used (Grønskei *et al.*, 1993; Larssen *et al.*, 1994). Only the horizontal wind fields from Hirlam10 and MM5 are used directly. The vertical part of the wind field is generated internally in the AirQUIS/EPISODE model by integrating the horizontal divergence vertically. In this way the model operates locally using a 3D divergence free wind field for the transport.

The air quality forecasting system has first of all been set up to predict PM_{10} levels since the local authorities are more concerned about this component than

TABLE II

Statistical parameters for PM_{10} 24 h average values

Parameter	Unit	Kirkeveien	Furuset
N		21	20
Observed average	$\mu g\ m^{-3}$	57,2	56,9
Predicted average	$\mu g\ m^{-3}$	36,3	70,7
BIAS		0,37	–0,24
$\sigma_{observed}$	$\mu g\ m^{-3}$	26,8	23,2
$\sigma_{predicted}$	$\mu g\ m^{-3}$	11,3	33,4
Observed maximum	$\mu g\ m^{-3}$	126,8	127.5
Predicted maximum	$\mu g\ m^{-3}$	61,6	125,2
RMSE	$\mu g\ m^{-3}$	37,9	47,2

other chemical species. Additionally, any restriction on traffic would be based on 24 h average PM_{10} values rather than shorter term (hourly) values. Our evaluation of the air quality forecasts are therefore based on 24 h average PM_{10} values during the 22 episodes for which the whole model system was operated. Table II presents a few statistical parameters for the 24 h average PM_{10} values at the two stations Kirkeveien and Furuset. Kirkeveien is situated close to a main road in the outer part of the city center. Furuset is situated close to a highway east of the city.

The observed average concentrations are similar at the two stations, however the model underpredicts the PM_{10} values at Kirkeveien (37%) while an overprediction (24%) is seen at Furuset. The standard deviation in the model data (σ_p) is smaller than the observed value (σ_o) at Kirkeveien while the opposite is the case at Furuset. Similarly the root mean square error (RMSE) is larger at Furuset than at Kirkeveien. A further examination of the 22 cases is given in Figures 3 and 4. During the first four episodes (from 10 November 1999 to 2 December 1999) the conditions were rather dry in the city, i.e. there was little or no water, ice or snow on the roads. Similar dry conditions also prevailed from 23 to 31 March 2000. At Kirkeveien the model clearly underpredicts the 24 h PM_{10} concentrations during these dry periods. However, for the episodes from 16 December 1999 to 14 of March 2000 the modeled and the observed values compare quite well. In this period the surface was covered or partly covered by snow and ice and hence the source for road dust was suppressed. Apparently, the predictions at Kirkeveien coincide much better with the observations on days with wet surfaces. We believe this is linked to the description of the source strength of PM_{10} from the surface on dry days. In particular, the re-suspension of dust deposited at the roadside is difficult to describe accurately in the model. At Furuset the differences between the modeled and observed value are less systematic and local conditions close to the station are likely to be of more importance. Additionally, more detailed studies (not

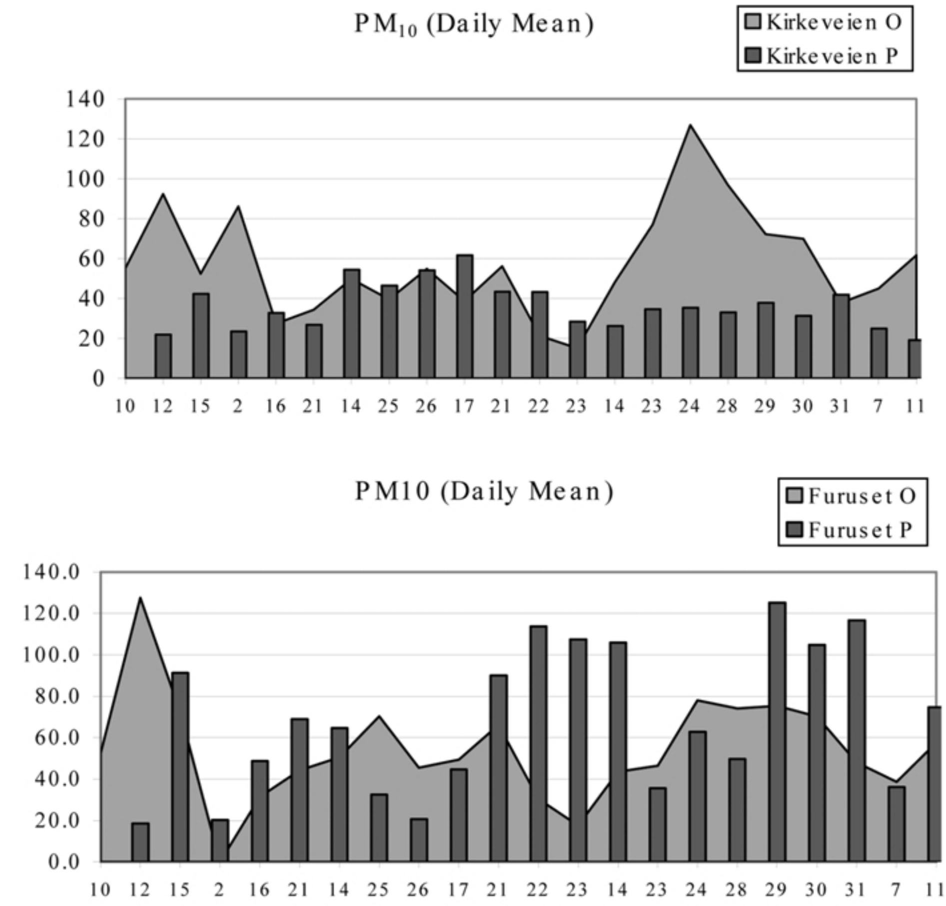

Figure 3. 24 h average PM_{10} values (in μg m^{-3}) for 22 cases at the stations Kirkeveien (upper panel) and Furuset (lower panel). The data starts 10 November 1999 and ends 11 April 2000. The continuous line represents the measurements (O). The model predictions (P) are given by the bars.

shown here) of the predicted wind direction indicate that the differences between observed and predicted PM_{10} concentrations can often be explained by the fact that the predicted wind is an average for a 1 km * 1 km area and therefore could deviate from the local wind direction close to the measuring stations (see also next section).

4. Results from a Day with High PM_{10} Concentrations and Traffic Restrictions

30 March 2000 the speed limits on the main roads in Oslo were reduced from 80 to 60 km h^{-1} aiming at reducing the PM_{10} levels during this day (see Bedre byluft,

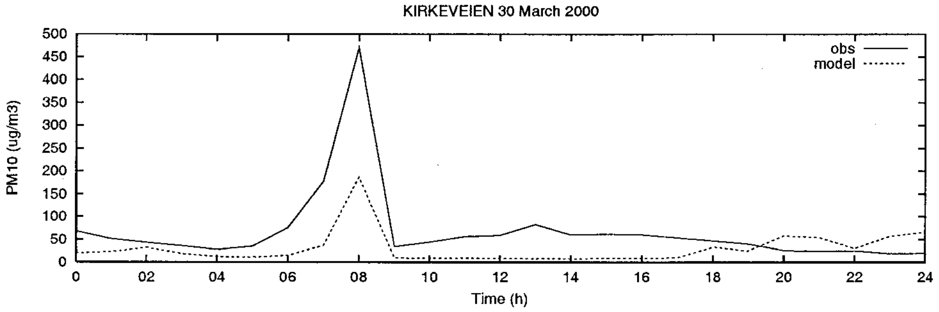

Figure 4. Hourly observed and modeled PM_{10} 30 March 2000 at Kirkeveien.

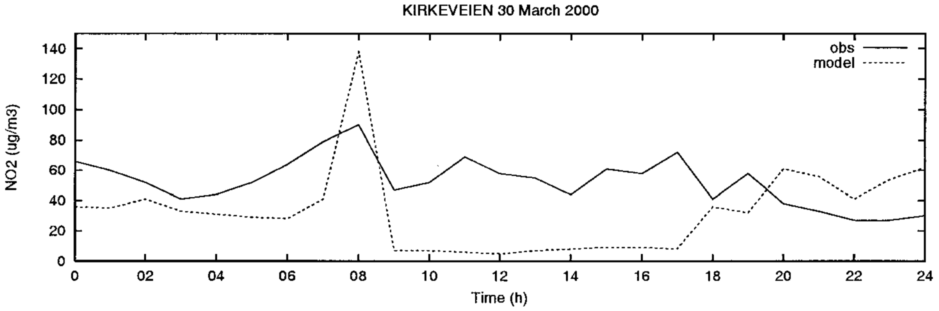

Figure 5. Hourly observed and modeled NO_2 30 March 2000 at Kirkeveien.

2000, for an evaluation of the effects of the traffic restrictions). The restriction followed after several days with high levels of PM_{10}. Figure 4 shows the observed PM_{10} levels for the station Kirkeveien during 30 March 2000. The station Kirkeveien is situated about 3 m on the southern side of a busy road with two lanes in each direction. There are buildings on each side of the road. The highest values were observed in the morning rush hours with a maximum value of nearly 500 μg m^{-3} at 0800 local time (LC). Note that the afternoon peak value was considerably lower. The corresponding NO_2 values from the same site are given in Figure 5. The NO_2 levels varied less than PM_{10}, but peak values linked to the morning and afternoon rush hours were observed. The weather conditions were dry and sunny as explained below, which would allow for some photochemical activity during daytime.

4.1. METEOROLOGICAL SIMULATIONS

A high pressure system was situated over southern Norway and the Oslo region on 30 March 2000. This gave rise to dry and sunny conditions together with weak winds. Inversions prevailed during nighttime while a well mixed PBL was established over land during daytime. Local circulation systems developed with kata-

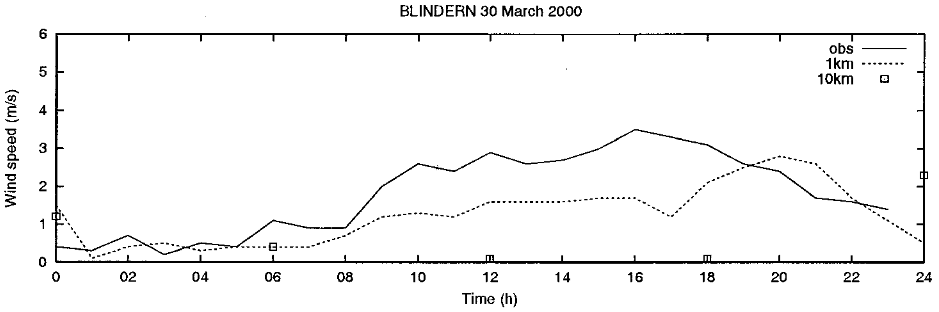

Figure 6. Observed (obs) and modeled (1 km = MM5 and 10 km = H10) wind speed at Blindern 30 March 2000.

batic winds from the hillsides toward the fjord during night (see Figure 1 for a description of the topographical features) and a sea breeze during daytime directed up the hillsides. Figures 6–9 show the meteorological observations and model simulations for Blindern, a meteorological station situated approximately 1 km north of the air quality station Kirkeveien. The model results are for the forecasting period + 24 to + 48 h. Wind speeds of 1 m.s^{-1} or less were recorded from midnight until 0800 LT (Figure 6). The wind direction was mostly from NE to NW veering toward E and SE (Figure 7). After 0900 LT winds were stronger (2–3 m.s^{-1}) and from S and SW. The wind did not veer back to north before 2300 LT. At that time wind speeds were lower again. MM5 predicted the wind speed and direction well during nighttime and in the morning. The shift in wind direction around 0800 LT was also well described, but the wind speeds were too low during daytime. The H10 predicted the same wind direction (W and SW) during the whole day, while wind speeds were very low (close to calm during daytime). MM5 was able to generate a local sea breeze (not shown) during daytime and thereby enhanced the wind speeds compared to the 10 km run. As we see, the shift from katabatic flow in the morning to a local sea breeze at 0800 to 0900 LT was well picked up by MM5. However, the afternoon katabatic flow was established around 1800 LT about 4–5 h too early. Sensitivity studies have shown that this was partly due to an overestimation of the snow cover in the surrounding hills. This forces the onset of the katabatic winds to be predicted too early. A model simulation including an improved snow cover (not shown) delayed the onset of the katabatic winds for about two hours.

The MM5 predicted temperature coincided very well with the observed temperature at Blindern. The larger scale H10 underestimates the temperature especially during daytime. Both models gave too high a figure for relative humidity in the night and the morning. At noon MM5 predicts a realistic relative humidity, but the onset of the increase came too early. At 1800 LT considerably higher humidity values were found in MM5 compared with the observations. This could be linked to the early onset of the katabatic winds in MM5. Vertical mixing is weak in the katabatic flow, hence the surface evaporation could moisten the air close to the

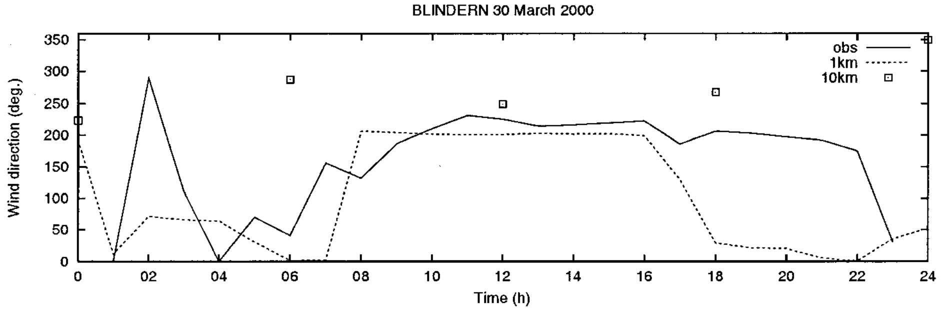

Figure 7. Observed (obs) and modeled (1 km = MM5 and 10 km = H10) wind direction at Blindern 30 March 2000.

surface more rapidly. Late in the day (at 2200 LT), when the local katabatic winds again were observed at Blindern the models corresponded much better with the observations.

4.2. PM_{10} AND NO_2 SIMULATIONS

The high PM_{10} values at 0700 and 0800 LT (see Figure 4) coincided with the peak emissions in the morning and with the shift from local drainage flow to the local sea breeze. At this time the winds were very weak and turned nearly 180 degrees. The nighttime inversion still persisted at this time. No PM_{10} peak value was observed during the evening rush hours (1600 to 1700 LT) since the wind and thereby the turbulent mixing was stronger at this time. The model predicts the diurnal behavior in the PM_{10} values qualitatively well, although the values were underestimated nearly for all hours. This was also the trend for the 22 daily averages presented in Figure 3 for Kirkeveien during days with dry and snow free conditions. It is quite likely that this is linked to the PM_{10} emission strength which is difficult to estimate correctly as it depends on the magnitude of the accumulated storage of particles along the roads, the dryness of the surface, the particle size distribution of the storage, the efficiency of the wind in picking up dust, local road maintenance and cleaning routines etc. In addition, the local turbulence and wind fields at Kirkeveien were not measured and may have deviated somewhat from the 1 km spatial averages obtained from MM5.

From Figure 5 we observe that NO_2 varied much less during the day. The rush hour maximum was only twice as high as the nighttime minimum. As for PM_{10} the peak was measured at 0800 LT. An afternoon peak at 1700 LT was also recorded. The model underestimated the NO_2 levels somewhat the first night, while a slight overestimation was seen the second night. The timing of the morning peak was correct although too large a value was modeled. During daytime the model strongly underestimated the NO_2 levels. Since NO_2 is coupled to the atmospheric chemical activity and the available ozone the behavior is more difficult to interpret since in particular no ozone measurements were available. Although the AirQUIS model employs a simplified chemical scheme for NO_2 the strong underestimation during daytime can probably not be explained by discrepancies in the chemistry only. We observe that both modeled PM_{10} and NO_2 were modeled at very low levels from 0900 to 1700 LT. Studies of the variability of the concentrations as a function of the MM5 wind directions (not shown) showed a large sensitivity to the wind direction. Since Kirkeveien is situated in a street canyon small shifts in the wind direction may give rise to large differences in the calculated concentrations at one side of the road.

5. Summary and Conclusions

A real-time operational forecast model for meteorology and air quality for Oslo, Norway, has been presented. The model was operated for the +24 to +48 forecasting period for 22 cases with high levels of air pollution in the Oslo region during the winter season 1999–2000. Results from the forecast model have been evaluated by use of two meteorological and air quality measuring sites. At one of the air quality sites the 24 h PM_{10} average was well simulated during days with snow cover and wet or icy roads. The highest PM_{10} values on dry days were however underestimated. This is probably linked to rather large uncertainties in the PM_{10} source strength during dry days. Also uncertainties in the predicted wind directions are important. At the second site an over prediction of PM_{10} was revealed. A larger random variability of the difference in observed and measured values was found which may indicate that local conditions are more important at this site. An improvement in the forecasted wind speed and direction and relative humidity was achieved by using the MM5 model with 1 km instead of the HIRLAM model with 10 km horizontal resolution. The strength of the temperature inversion was however overestimated near the ground by MM5 and a larger negative bias in the 2 m temperature was found compared with the 10 km model. However, the random error in the temperature predictions was reduced when the horizontal resolution was increased. An episode with high PM_{10} values during 30 March 2000 was further investigated. A realistic picture of the shift between nighttime katabatic winds and daytime see breeze was found. However, MM5 predicted the onset of evening katabatic flows too early. A clear linkage of the strength and timing of the cold drainage flows to the snow cover was found. The Air Quality Model gave a qualitatively realistic picture of the PM_{10} values, but the levels were generally underestimated. Less satisfactory correspondence was found for NO_2 on this particular day.

Further improvements of the temperature and inversion predictions of the HIRLAM and the MM5 model during wintertime are recommended. These studies should include improvements of the parameterization of the vertical eddy diffusion and improved descriptions of the surface characteristics such as snow cover, soil

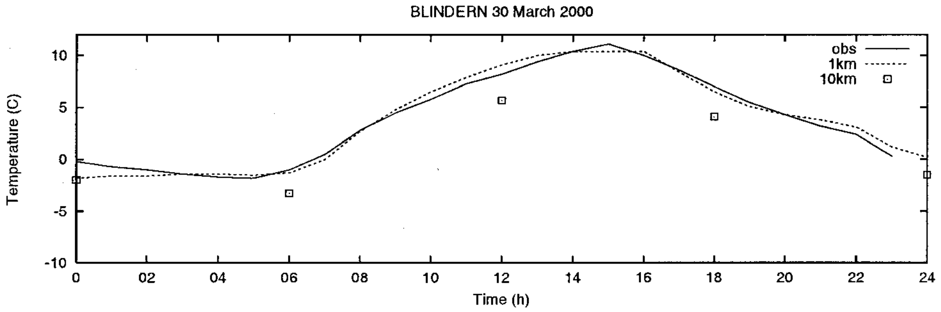

Figure 8. Observed (obs) and modeled (1 km = MM5 and 10 km = H10) temperature at Blindern 30 March 2000.

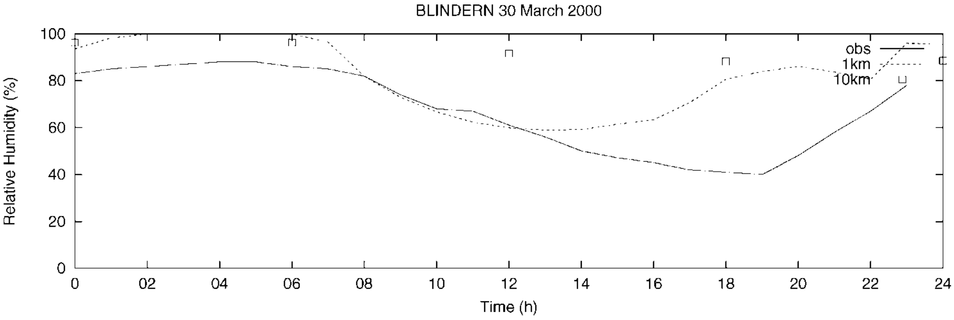

Figure 9. Observed (obs) and modeled (1 km = MM5 and 10 km = H10) relative humidity at Blindern 30 March 2000.

temperatures and soil humidity. There is also a clear need for an improved description of the PM_{10} sources especially on days when surfaces are dry. Attention should also be given to the linkage of the local dispersion modeling to the modeled wind speed and direction. More attention could also be given to the NO_2 chemistry and the selection of background ozone values.

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