Requirements and problems for UBL parameterisation under calm conditions

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1 Introduction

High levels of PM_{10} and NO_2 are every winter observed 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. A forecasting system for the air quality in the major Norwegian cities has been developed in order to inform the public on a daily basis about the air quality and to issue warnings when peak pollution episodes are expected. In Oslo traffic restrictions may also be enforced if PM_{10} values above a certain threshold level are forecasted.

The air quality modelling system has been set up for the four Norwegian cities Oslo, Bergen, Trondheim and Drammen (see Berge et al., 2000, Berge et al., 2001). The model has been run operationally from 1 of November 2000 until 1 of May 2001). The meteorological part of the model is based on the MM5-model (Grell et al., 1994) operated with 1 km and 3 km horizontal resolution and the HIRLAM10 model (Källén, 1996) operated with 10 km horizontal resolution. The inner (1 km resolution) MM5 domain is shown in Fig. 11. The meteorological forecast data of the smallest domain with 1 km resolution are employed by the AirQUIS air quality modelling system developed at the Norwegian Institute for Air Research (Slørdal, 2001), which predicts the levels of NO_2, $PM_{2.5}$ and PM_{10}.

During the winter season 1999/2000 22 cases with calm winds and high concentrations of PM_{10} or NO_2 where analysed. The predictions from MM5 showed a clear improvement of the wind speed, wind direction and relative humidity predictions compared to the larger scale HIRLAM10 model. However, surface temperatures where underestimated and near surface inversions where too strong. Figure 2 shows a comparison of the modelled and measured temperature differences between 8 and 25 meters (left panel) and 2 and 8 meters (right panel). The temperature difference of 8 and 25 meters are measured directly by one sensor while the difference of 2 and 25 meters are based on the difference of two sensors at these two levels. From the two figures an overestimation of the inversion strength by the model is clearly seen.

Both wind speed, wind direction and vertical stability are considered as key input parameters from the meteorological model to the air quality model. Our experience so far is that the largest difficulties are encountered in the vertical stability predictions. We will therefore concentrate our discussion on this issue. We have separated our presentation into two parts. The first part covers results from mid-winter inversions where the inversion is not broken down during daytime. Peak episodes of NO_2 tend to occur during these cases and hourly values up to 200-300 $\mu g/m^3$ have been recorded in Oslo. Maximum hourly PM_{10} values are typically 100 $\mu g/m^3$ while the daily average is somewhat lower. During mid-winter the surface in the city is mostly covered by ice, snow or water. Occasionally, however, the streets dry up and then large amounts of particles (mainly from street wear caused by studded tyres) are re-suspended especially from the heavy-duty vehicles. If these periods coincide with unfavourable dispersion conditions, peak pollution episodes of PM_{10} may occur particularly in areas close to the main roads.

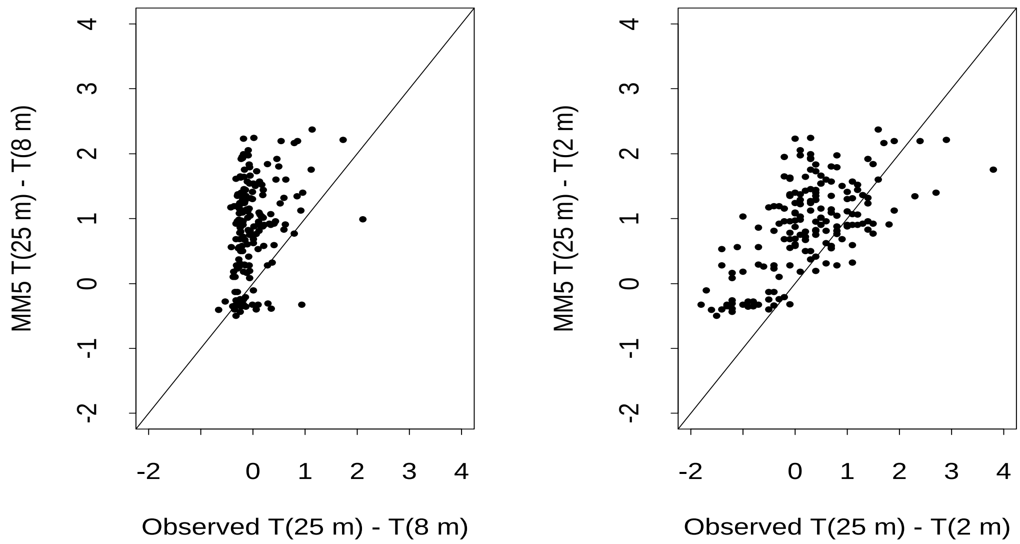


Fig.1 Observed and calculated temperature difference between 8 and 25 meters (left) and 2 and 25 meters (right). Results are based on 22 winter days in Oslo with calm winds.

The second part covers spring time peak PM_{10} episodes. At this time of the year there is a substantial deposit of particulate matter along the roadsides, which represents an important source of PM_{10} if the weather is dry. Hourly PM_{10} values as high as 400-500 $\mu g/m^3$ have been recorded. The daily averages of PM_{10} could in the spring reach above 100 $\mu g/m^3$. The solar heating during daytime generates local thermal wind systems, which as will be demonstrated in the following sections, are important for the local dispersion of the air pollutants. For the spring period we have also performed sensitivity simulations with different PBL-parameterisations in order to better understand the link between the PBL-parameterisations and the resulting vertical stability profiles.

2 Methodology

2.1 PBL-parameterisation in MM5

2.1.1 The MRF scheme.

In the routine runs of MM5 we have applied the so-called MRF PBL-parameterisation scheme as described by Hong and Pan (1996). Several details of the scheme can also be found in Sorteberg (2001). Here we summarise the most important equations employed in MM5. The scheme is first order and the eddy diffusivities for momentum (K_m) and heat (K_h) in the planetary boundary layer are calculated by:

$$K_m = K_{m,0} + \frac{ku_* z}{\phi_m(\frac{z_0}{L})} \quad (1)$$

$$K_h = K_{h,0} + \frac{ku_* z}{\Pr\, \phi_h(\frac{z_0}{L})} \quad (2)$$

$K_{m,0} = K_{h,0} = 0.001\Delta z$ where Δz is the thickness between two model layers, ϕ_m and ϕ_h are the non-dimensional wind shear and temperature gradients, z_0 is the roughness length, z the height above the ground, k is von Karmans constant and u_* is the friction velocity given by u_{*0} multiplied by a profile function. Pr is calculated from

$$\Pr = (\frac{\phi_h}{\phi_m} + bk\frac{0.1h}{h}) \quad (3)$$

where b=7.8 and h is the PBL-height. Furthermore, during stable conditions it is assumed that

$$\phi_h = \phi_m = (1 + 5\frac{0.1h}{L}) \quad (4)$$

A key parameter in the MRF-scheme is the PBL-height h. During stable conditions h is defined to be between the first layer where $Ri_b > Ri_c$ and the layer underneath, where Ri_b is the bulk Richardson number and Ri_c is the critical Richardson number (Sortberg, 2001).

2.1.2 Modified version of the MRF scheme.

As mentioned in the previous section and discussed in detail by Sorteberg (2001) the MRF scheme tends to overestimate the inversion strength in the PBL near the surface. Sorteberg (2001) therefore reformulates the scheme in order to allow for more vertical mixing near the surface during stable conditions, and thereby reduces the inversion strength somewhat by following Beljaars and Viterbo (1998). In addition a lower limit of 50 m is set on the PBL-height. The reason for this is that the original MRF scheme may under very stable conditions set h equal to the height of the lowest layer. With the lowest level at 7.5 m as in our case this may lead to unrealistically low PBL heights with consequently very low vertical mixing.

In our sensitivity studies we have also employed a 2.5 level Mellor-Yamada closure scheme due to Burk and Thompson (1989) henceforth denoted the BT-scheme. Unfortunately, the BT-scheme can only be coupled to a simpler (two layer) soil model in MM5 than the 5 layer soil model applied to the MRF-scheme. This, indeed, introduces an uncertainty when the PBL-schemes are compared.

2.2 Parameterisations of dispersion parameters in the AirQUIS – system

The dispersion calculations are performed in an off-line mode. Parameters are extracted from MM5 as if they are measurements.

The variables that are extracted from MM5 are:

- The wind field
- The temperature
- For stability considerations: The temperature difference between the two lowermost heights in MM5 (~21.4 m and 7.1 m above ground).
- Relative humidity
- Precipitation
- The surface roughness (z_0)

Combining the above data with the Monin-Obukhov theory, the stability parameters u_* (the friction velocity), θ_* (the temperature scale for turbulent heat transfer), and L (the Obukhov length), can be calculated iteratively by applying the profile method (Nieuwstadt, 1978; Berkowicz and Prahm, 1982 a; van Ulden and Holtslag, 1985; Bøhler, 1996).

2.2.1 Dispersion parameters applied in the Eulerian grid model

The grid-model of the AirQUIS-system makes use of K-theory in the treatment of the vertical turbulent diffusion process. The applied vertical eddy diffusion coefficient, K_{zz}, is divided in the two following expressions:

$$K_{zz} = K^* + K_0(u_*, \Delta z_1), \tag{9}$$

where K^* is a standard parameterisation depending on the stability conditions, and K_0 is an additional site-specific term which has been found necessary in stable, low wind situations. It is also possible to extract the vertical diffusivity of heat directly from MM5, i.e. Eq. 2 above, and this will be tested in the near future.

In unstable conditions K^* is parameterised according to the empirical expression of Lamb and Duran (1977). Under neutral conditions the eddy diffusivity of Shir (1973) is applied:

$$K^* = \kappa u_* z \exp(-\frac{8fz}{u_*}) \tag{10}$$

while the expression of Businger and Arya (1974) is applied under stable conditions:

$$K^* = \frac{\kappa u_*}{0.74 + 4.7(z/L)} \exp(-\frac{8fz}{u_*}) \tag{11}$$

The values of u_*, and L is calculated by the AirQUIS meteorological pre-processor MEPDIM (Bøhler, 1996). $\kappa = 0.4$ is the von Karman constant, and f is the Coriolis parameter.

As mentioned above these expressions have been found to give unrealistic low values for K^* during stable low-wind conditions in Norwegian cities during winter time situations. In order to avoid this problem the empirical term $K_0(u_*, \Delta z_1)$ has been added to the equation of K_{zz}. This term is defined as:

$$K_0(u_*, \Delta z_1) = (2 \cdot \Delta z_1)^2 / 3600 \quad \text{for } u_* > 0.2 \text{ m/s.}$$

$$K_0(u_*, \Delta z_1) = \Delta z_1^2 / 3600 \qquad \text{for } u_* < 0.1 \text{ m/s.} \tag{12}$$

with a linear variation of K_0 for values of u_* in between 0.1 m/s and 0.2 m/s. In the expression above Δz_1 is the thickness of the lowermost layer of the dispersion model. This particular choice of K_0 is based on a scale analysis where it is assumed that the minimum values of K_{zz} should be large enough, during a one hour period, to mix an air-column of thickness Δz_1 and $2 \cdot \Delta z_1$, when u_* is less than 0.1 m/s and larger than 0.2 m/s, respectively. With a value of Δz_1 equal to 20 m, this gives a K_0 value of 0.1 m^2/s, which is a very low value.

2.2.3 Dispersion parameters applied in the line and point source models

For receptor points close to important line and point sources, simple Gaussian type formulas are applied in combination with the Eulerian grid model to estimate the contribution to the near-field of the individual sources. The dispersion parameters, σ_y and σ_z, describing the lateral and the vertical spread of the plume, are functional dependent on the turbulence parameters σ_v and σ_w. Since these parameters are not calculated in MM5, they have been parameterised according to the formulas of Gryning et al. (1987). For stable conditions the following expressions are applied:

$$\sigma_v(z) = u_* \left[2 \left(1 - \frac{z}{h} \right) \right]^{1/2} \qquad \text{and} \qquad \sigma_w(z) = u_* \left[1.7 \left(1 - \frac{z}{h} \right)^{3/2} \right]^{1/2} \tag{13}$$

where the boundary layer height h, is given by $h = 0.4 \left(\frac{u_* L}{f} \right)^{1/2}$. Further descriptions on the AirQUIS system can be found in Walker (1997), Walker et al. (1999) and Slørdal (2001).

3 Model results for the period 7. – 20. January 2001

Wind speed and direction was measured at Hovin (situated in the lower part of the main valley to the north/east of the city centre; indicated as station 2 in Figure 11.) In Figure 2 time series of the measured and MM5-forecasted wind speeds are presented. Even though there are discrepancies, the overall impression is that the model reproduces the measured signal quite well. Also the calculated wind direction (not shown) agrees well with the observations.

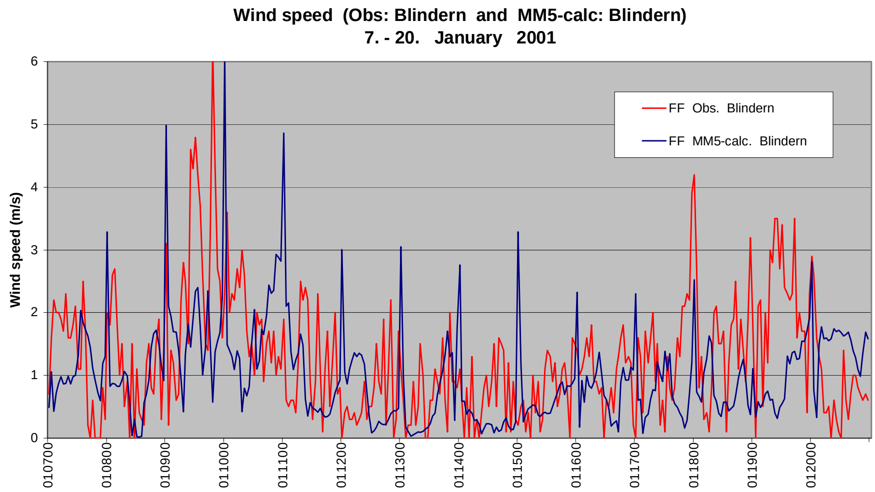


Figure 2: Observed and calculated wind speed at Hovin

At Hovin direct measurements of the temperature difference between 25 m and 8 m above ground is made. In Figure 3 the calculated temperature difference between the two lowermost layers in MM5 (i.e. between about 21.4 m and 7.1 m) is shown together with the measured ΔT value. As seen in Figure 3 the calculated temperature difference is strongly biased towards the stable regime.

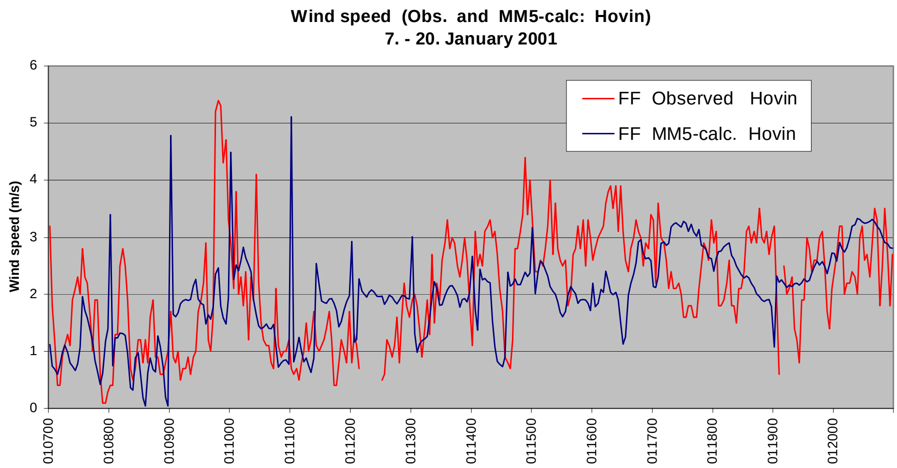


Figure 3: Observed and calculated temperature difference at Hovin

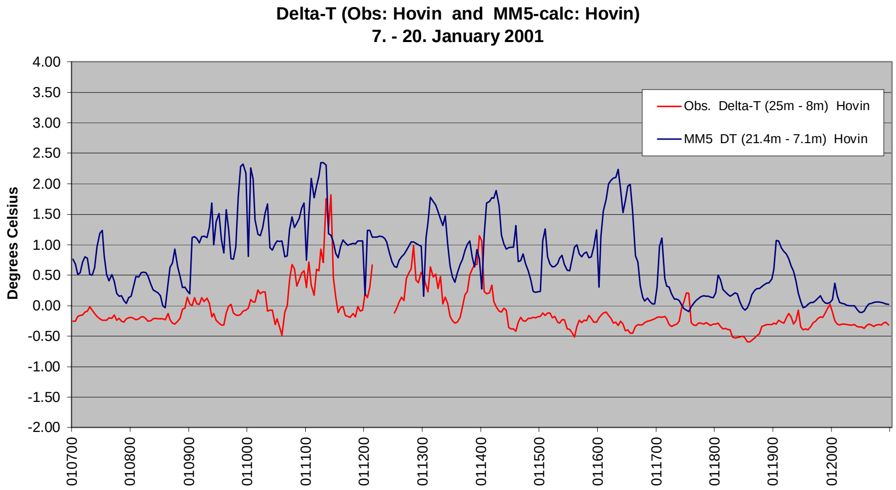


Figure 4: Observed and calculated wind speed at Blindern.

In Figure 4 the measured and MM5-calculated wind speed are presented for the station Blindern. This station is situated in the northern part of the central city area; indicated as station 1 in Figure 1. For most of the period the observed wind speed agrees fairly well with the calculated values. Note that the observed wind speeds at Blindern are considerably lower than the Hovin values for the period 12. – 17. January, even though the distance between these two stations is just about 5 km. The temperature difference is not measured at Blindern, but MM5 predicts an even stronger ground based inversion at Blindern than at Hovin. In the central city area, south of Blindern, air quality measurements have been made at an urban background station and at a street station. At both of these stations MM5 indicated an inversion strength comparable to the ΔT-values calculated at Hovin.

In addition to the two air quality stations in the central city area, measurements of NO_2 and PM_{10} was also made at Bjorvika, which is situated in the eastern harbour area of the city. As a consequence of the relatively warm fjord-water, the strong ground based inversion is not found in the MM5 results for this area.

4 AirQUIS calculated air quality

Below a comparison of modelled and measured NO_2- and PM_{10}-results are presented for the various air quality stations in Oslo. Measurements of PM_{10} are made at the street station Kirkeveien (central city area), and at the two urban background stations Nordahl Brunsgt. (central city area) and Bjorvika (eastern harbour area). NO_2-measurements have only been made at Kirkeveien and Bjorvika. Observed and calculated hourly NO_2-values are shown in Figure 5 for the Kirkeveien station. The general impression is that the model over-predicts the concentration levels severely. In Figure 6 the NO_2-results for the Bjorvika station are presented. The measuring period started not until the 12 of January at this station. Even though there is a tendency of over-estimation at this station as well, the overall agreement is much better here than at Kirkeveien.

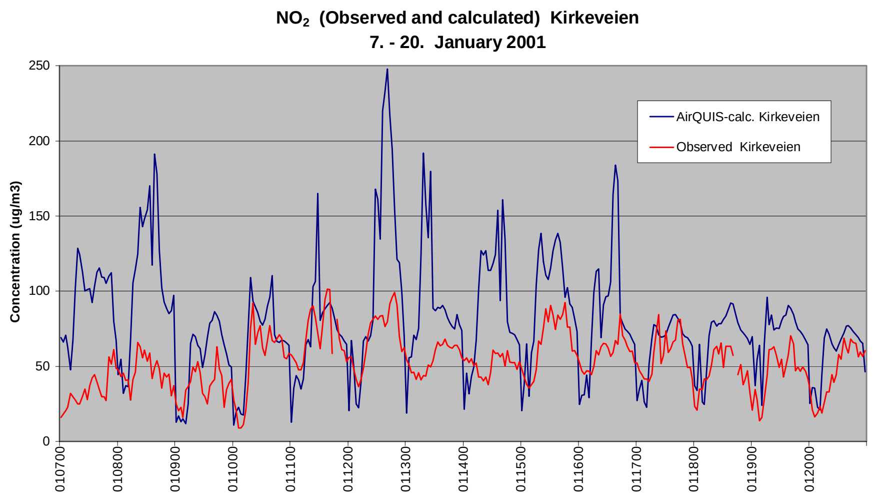


Figure 5: Observed and AirQUIS-calculated NO_2 concentrations at Kirkeveien

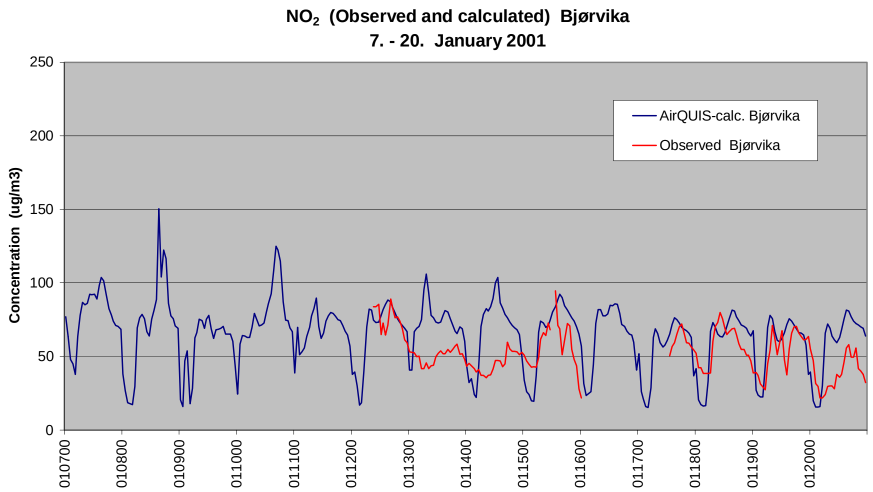


Figure 6: Observed and AirQUIS-calculated NO_2 concentration at Bjorvika

Comparisons between measured and calculated hourly PM_{10} concentrations for the stations Kirkeveien, Nordahl Brunsgt and Bjorvika are shown in Figure 7 – Figure 9. Again the predicted concentrations are far above the measured values at Kirkeveien and more in line with the measurements at Bjorvika. At the urban background station Nordahl Brunsgt the over-prediction is clearly evident as well.

Based on the comparison of the observed and MM5-predicted wind speed and ΔT values, presented in Section 3 it seems clear that an important reason for the over-prediction of the NO_2 and PM_{10} levels at Kirkeveien and Nordahl Brunsgt, is associated with the over-estimation of the strength of the surface inversion over the city. In the harbour area the heat reservoir of the Oslo-fjord lowers the ground level stability in the MM5-calculations, and thereby reducing the over-prediction for the Bjorvika station. Errors in the MM5-calculated wind speed and wind direction also contribute to the misfit between the measured and calculated air quality levels, but these parameters are not so clearly biased as the ground level temperature gradient. Earlier model calculations with the AirQUIS-system, applying the same emission inventory as in the present forecast study, have not revealed the same systematic overestimation at the central city air quality stations (Slørdal, 2001). In these earlier calculations the measured temperature difference at Hovin has been applied homogeneously for the whole city area.

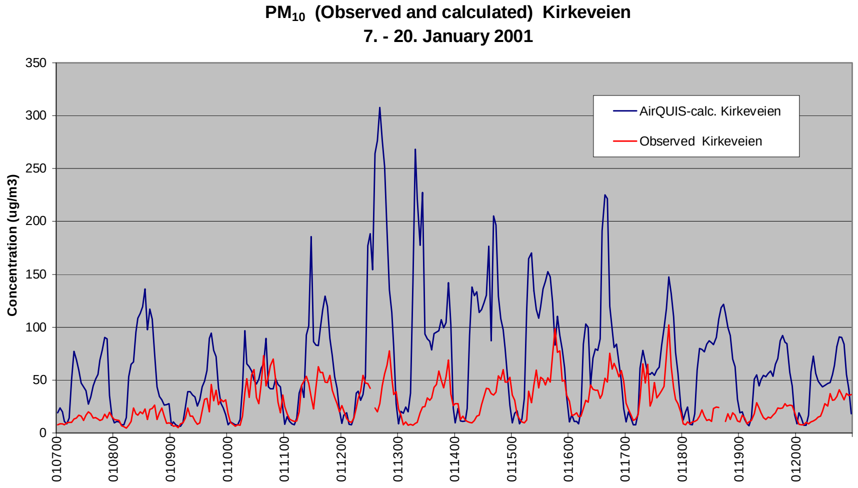


Figure 7: Observed and AirQUIS-calculated PM_{10} concentration at Kirkeveien

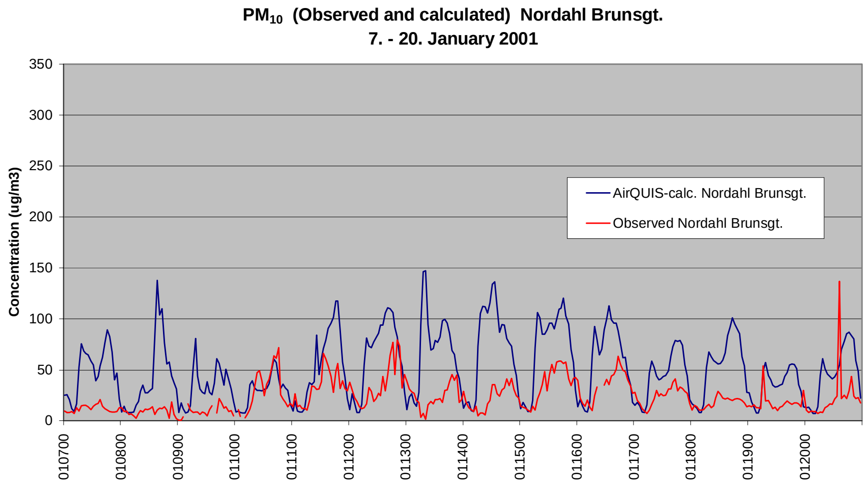


Figure 8: Observed and AirQUIS-calculated PM_{10} concentration at Nordahl Brunsgt.

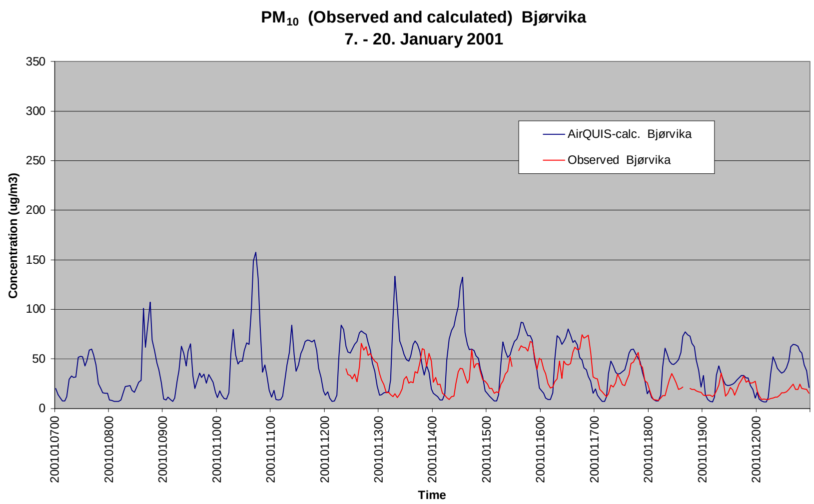


Figure 9: Observed and AirQUIS-calculated PM_{10} concentration at Nordahl Brunsgt.

5 Results from 24 March 2000, a peak PM_{10} episode

In the following section we have studied in more detail a particular episode of the 24 March 2000, where the highest PM_{10} values during the spring 2000 where measured. More details about this case can be found in Ettema (2001). Figure 10 shows the measured concentration. A strong peak in the PM_{10} values is encountered in the morning rush hour at 08.00 (local time). A smaller peak is seen at 20.00 2-3 hours later than the afternoon rush. The measured wind direction at Hovin showed a shift from easterly to south southwesterly wind direction in the morning. This represent the shift from the nighttime katabatic flow to a sea breeze generated by the heating of the hills around the Oslo fjord. At the time of the wind shift an inversion exists (see Figure 12) and the air is stagnant in the city. This coincides with the morning rush hour that enables the large deposit of particulate matter at the roadsides to be brought into the city air. The peak value in the late evening coincides with the shift back to katabatic flow and the build up of the inversion. Since this occurs 2-3 hours later than the rush hour, the PM_{10} values cannot reach as high as in the morning.

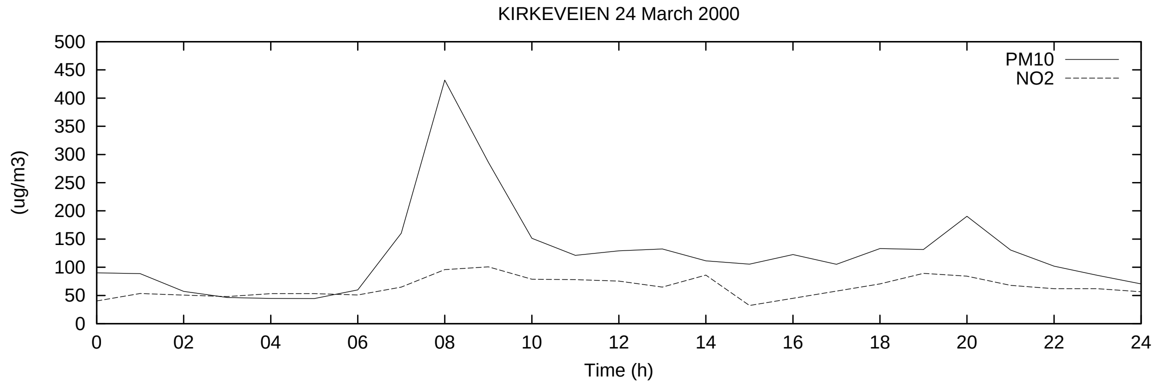


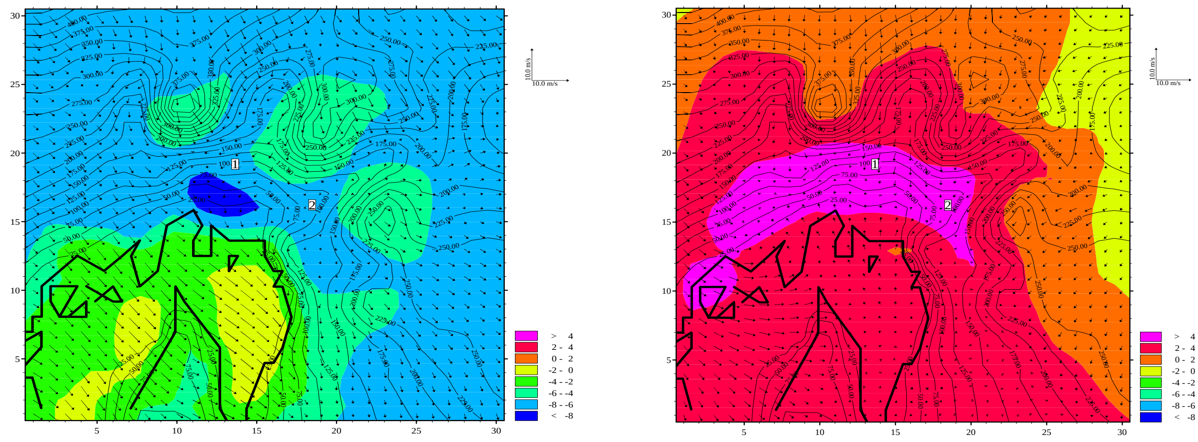
Fig. 10. PM_{10} and NO_2 measured at Kirkeveien station during 24 March 2000.

Temperature, wind speed and wind direction estimated by MM5, are presented in Figure 12. Weak northerly or variable winds are encountered in the city centre in the morning (08.00 local time (06 UTC)). During mid-day a weak southerly sea breeze is found close to the fjord south west of Hovin (station number 2). However, the sea breeze does not reach all the way up to the station. HIRLAM10 yields a northerly flow in the Oslo region during all the day. The offset of the sea breeze in MM5 is encountered too early. In Figure 12 the vertical profiles in the lowest 200 m from the model simulations are presented. The vertical profiles are given for the MRF parameterisation (section 2.1.1), the modified MRF (section 2.1.2) and the BT-scheme (section 2.1.2). The MRF run is started on a +24 hours HIRLAM10 run and a +00 HIRLAM10 analysis. The two other runs are both initiated on the +00 data. We see that the +24 initial field is somewhat colder than the +00 analysis. The observations indicate no inversion during midnight at the start of the simulation. After 6 hours we observe that an inversion of about 1.5 degrees from 25 to 8 meters has build up. The BT-scheme yields a much weaker inversion than the MRF scheme. The modified MRF scheme gives the best inversion strength at 08.00, however this scheme also has the largest deviation in the temperature. At noon the MRF-schemes correspond closely to the observation. The higher order BT-scheme is however too cold. Note that the difference between the MRF scheme and the modified MRF scheme is very small during daytime with near neutral or weakly unstable conditions as expected from the formulations given in Section 2. At 20.00 (18 UTC) the cooling is rapid in all four model simulations while the observations show that the cooling starts later. Similar features of a too early onset of the night time cooling has been described by Berge et al. (2001). In this particular case we find little improvement by employing different PBL-parameterisation schemes. Studies by Ettema (2001) have shown that in this case the temperature fields is to a large degree dominated by a too strong cold air inflow from the larger scale HIRLAM10 model. Also, the temperature fields are very sensitive to the snow cover and thereby also the quality of the snow cover input data. Considerable uncertainties are also linked to the treatment of the surface energy balance. Other case studies by Sorteberg (2001) have however shown improved description of the inversion strength by modifying the MRF-scheme.

6 Concluding remarks

We have presented results from modelling of Urban Air Quality by use of meteorological data from an NWP-model, MM5. Focus has been given to the link between the estimated concentrations and the near surface modelled vertical stability since MM5 tends to overestimate the inversion strength. A clear link between overestimated inversion strength and overestimated air concentrations are found. Our studies so far indicate that the low near surface temperatures could be due to several factors. A systematic underestimation of the near surface temperature in the larger scale HIRLAM10 clearly affects the simulations in the city. Unrealistic representation of snow cover and parameterisation of snow and surface effects in MM5 is another important factor. The PBL-parameterisation employed gives too little vertical mixing and downward transport of heat during stable cases. Improved parameterisations can compensate for this. However, a proper description of the urban canopy with its turbulent mixing, heat island effects etc. is yet not available in our model. A future goal is to include these urban effects and thereby improve the modelling capability of the Urban Boundary Layer.

Fig. 11. Results from MM5 inner domain (1km horizontal resolution) for 06 and 12 UTC 24.03.2000. Meteorological stations are indicated with the black dots. (1 – Blindern, 2 – Hovin), below.



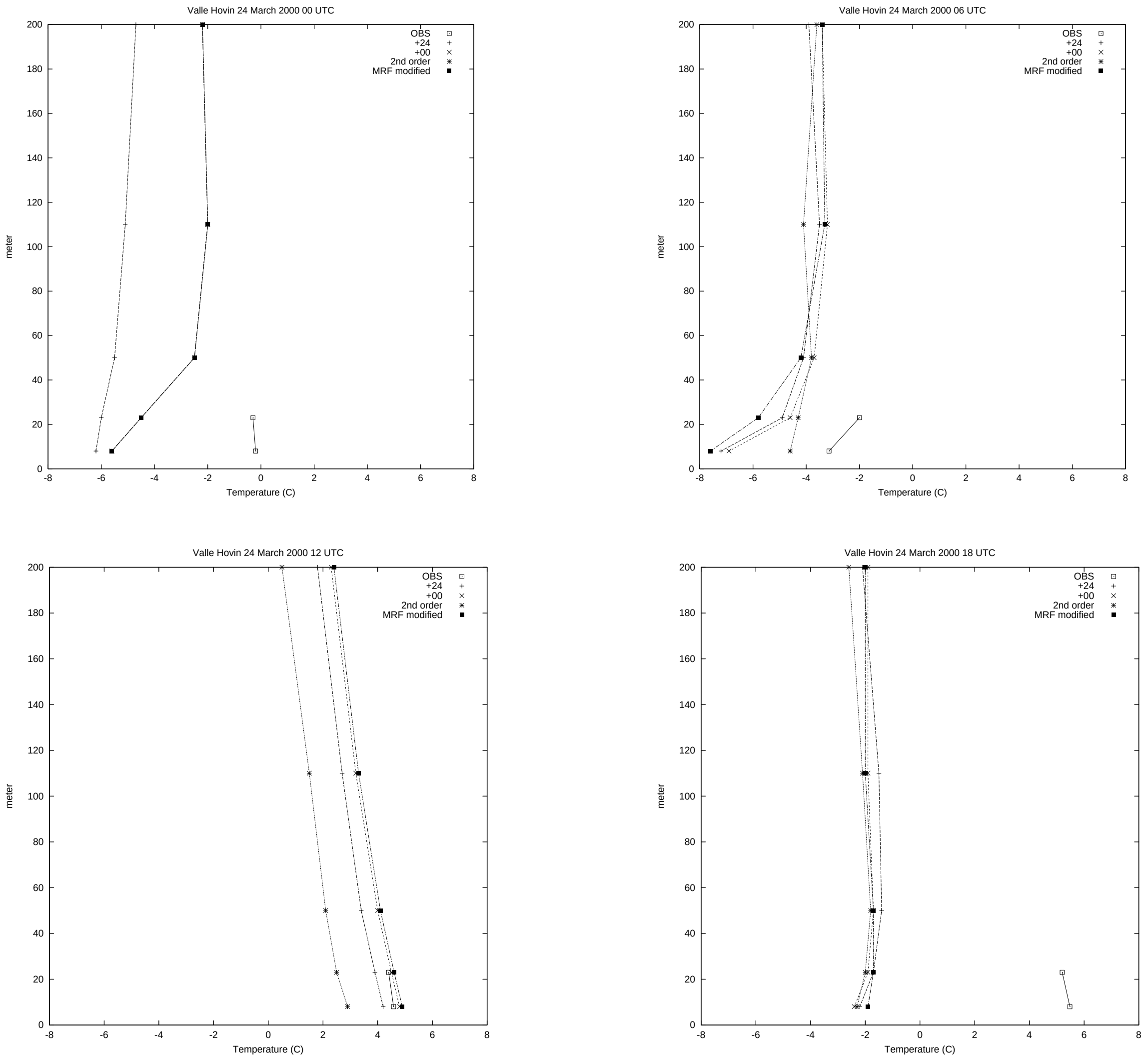


Fig. 12. Vertical profiles of temperature during 24.03.2000 at 00, 06, 12 and 18 UTC for MRF (+24 and +00), MRF modified and BT-scheme.

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