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LIMITATIONS OF AIR POLLUTION EPISODES FORECAST DUE TO BOUNDARY-LAYER PARAMETRISATIONS IMPLEMENTED IN MESOSCALE METEOROLOGICAL MODELS

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1. INTRODUCTION

Dispersion models require information on the turbulence characteristics in the planetary boundary layer (PBL). This information is most often extracted from either meteorological measurements or from numerical (prognostic or diagnostic) models, and the requested turbulence parameters are then estimated using a PBL pre-processor.

Traditionally, Monin-Obukhov (M-O) similarity theory is applied when estimating the surface turbulent fluxes and the various vertical profiles of averaged quantities in the surface layer of the PBL (Beljaars and Holtslag 1991; Hanna and Chang 1992; Zilitinkevich et al. 2002b). In this similarity approach several simplifying assumptions are made, among which the requirement of quasi-stationary and horizontally homogeneous flow, and constant (independent of height) turbulent fluxes are the most crucial (Arya 1988). In urban areas and in complex terrain these assumptions are obviously not fulfilled. The theory is particularly questionable in very stable conditions, i.e. under conditions typically prevailing during pollution episodes in winter. In very stable conditions turbulence tends to be sporadic, and wave-turbulence interaction becomes increasingly important as well as drainage effects due to even small terrain slopes (Högström 1996). Moreover, observational data suggest that developed turbulence can exist in the stably stratified surface layer at much larger Richardson numbers than the classical M-O theory predicts (Zilitinkevich, 2002). The M-O theory is nevertheless applied in most models even in these cases, mostly due to lack of other practical formulations (Mahrt 1999).

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In the following study the output from a M-O based meteorological pre-processor, METPRO (Slørdal et al., 2003; van Ulden and Holtslag 1985; Bøhler 1996), is analysed for a particularly stable period in January 2003 in the city of Oslo, Norway. During this period extraordinarily high pollution levels were measured at several sites within the city. A similar pre-processor SURFPRO (Silibello C., 2002; Finardi et al., 1997) is applied to analyse a winter air pollution episode, characterised by strong nighttime stability, in Milan. Since no turbulence measurements exist for these episodes, the sensitivity of the pre-procrssors output on some of the model assumptions are investigated in this study.

2. THE METEOROLOGICAL PRE-PROCESSORS METPRO AND SURFPRO AT VERY STABLE CONDITIONS

The M-O turbulence parameters estimated by the preprocessors are based on either measured meteorological input data or on model output from meteorological circulation models. Typical pre-processor outputs are the friction velocity (u_*), the temperature scale (θ_*) and the Monin-Obukhov length (L):

$$u_* \equiv \left(\overline{u'w'}\right)_0^{1/2} = \left(\tau_0/\rho\right)^{1/2}, \quad \theta_* \equiv -\frac{\left(\overline{\theta' w'}\right)_0}{u_*} = -\frac{H_0}{\rho C_p u_*}, \quad L \equiv -\frac{\left(\overline{u'w'}\right)_0^{3/2}}{\kappa \frac{g}{\theta}\left(\overline{\theta' w'}\right)_0} \equiv \frac{u_*^2}{\kappa \frac{g}{\theta}\theta_*} \qquad (1)$$

Here τ_0 is the surface momentum flux, H_0 is the surface sensible heat flux, ρ is the air density and C_p is the specific heat at constant pressure. Based on an estimate of the surface roughness, z_0, measurements of the wind at one height and the temperature difference between two heights, all made within the surface layer (inertial sub layer), u_*, θ_* and L are computed by an iterative solution of the profile equations for wind speed and temperature. In these expressions κ is the von Karman constant, with a prescribed value of 0.41. The Monin-Obukhov length, L, is a measure of the buoyant stability of the air. Small positive and negative values of L indicate stable and unstable conditions, respectively. The neutral regime is found for large positive or negative values.

In very stable situations, z/L>1, convergence of the above mentioned iterative procedure is not ensured. In this regime, Holtslag (1984) proposed an analytical solution in which, an upper bound is imposed on the surface sensible heat flux through specifying a constant positive limit value for the temperature scale, i.e. $\theta_* = 0.08\,\text{K}$. The analytical solution gives real (physical) values for L as long as its value is greater than a minimum value, L_0, given by $L>L_0 \equiv 5z/\ln(z/z_0)$.

Thus, if the wind speed is measured at z = 25 m and z_0 = 0.5 m, this minimum value of L will be about 32 m. According to Holtslag (1984) lower values of L correspond to very stable conditions, in which there is little or no turbulence. Holtslag (1984) also presents a "practical" solution for $L < L_0$, which is given as

$$L = \left(L_0 \frac{L_n}{2}\right)^{1/2}, \text{ where} \qquad L_n = \kappa\, U(z)^2\, T \Big/ 2g\theta_* \left\{\ln\left(\frac{z}{z_0}\right)\right\}^2 \qquad (2)$$

Equation (2) gives values of L that are continuous at L = L_0 and which results in L = 0 for U(z)=0. Equation (2) is just an interpolation formula. The M-O similarity theory predicts that the turbulence has ceased when $L < L_0$.

In many urban applications a minimum allowed positive value of the Monin-Obukhov length is employed directly. This is a simple way of accounting for the effects of the urban heat island and the increased mechanical turbulence induced by the urban canopy. The minimum values predicted by $L>L_0 \equiv 5z/\ln(z/z_0)$ coincide rather well with tabulated values of minimum L in urban areas of Hanna and Chang (1992).

3. APPLICATION OF METPRO DURING A PEAK POLLUTION EPISODE IN THE CITY OF OSLO

In order to investigate the pre-processors performance under stable conditions, METPRO has been applied, with input data from an urban meteorological measurement station in Oslo (Hovin), to one of the most recent (and most severe) pollution episodes in Oslo. This episode occurred in the second week of January 2003.

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 topographical features of the area contributes to worsen the dispersion conditions, thereby capturing pollutants emitted within the urban air- shed. These effects are of particular importance during the wintertime season.

The meteorological station at Hovin measures the wind at a height of a 25 m mast. The station is located in a park area surrounded by what must be characterised as an urban environment. The surface roughness for momentum for this area has been estimated to be about 0.5 m. On the 7th of January hourly NO_2 values up to about 600 μg/m^3 were observed at monitoring station Alna, the highest NO_2 values ever observed in Oslo. High $PM_{2.5}$ values were observed as well (hourly value of 152 μg/m^3 at Kirkeveien). However, relatively large variability in the concentrations at the different measurement sites within the central city area indicate that sporadic periods of enhanced turbulent mixing occurred at various areas throughout the 3 day pollution episode from the 7th to the 9th of January.

Prior to the episode the measured ground temperatures were low, about -20°C. An area of high pressure prevailed over the north Atlantic on the 3rd of January, and it was transported to the East, arriving at the sea area between UK and Southern Norway on the 7th. On the 6th, relatively warmer air masses were transported at higher altitudes from the northwest; this lead to the formation of a strong inversion 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. The ambient (2m) temperature varied from – 18 to + 1 ºC at the station of Hovin.

The radiosonde vertical temperature profiles for the period 3-10 January measured at 00 UTC at the meteorological station Blindern were analyzed. The main reason for the formation of the long lasting ground based inversion was found to be the advection of warm air above the lowest atmospheric layers. In Figure 1a and 1b time series of the wind speed (measured at 25 m) and the ΔT-value (measured between 25 m and 8 m) at Hovin are shown. In the same plots (see right axis) are the measured NO_2 values at the Løren station presented as well. This is the AQ-station closest to the Hovin meteorological station, located less than a km north of Hovin.

As seen from Figures 1a and 1b the highest NO_2 concentrations at Løren starting on the afternoon of the 6th lasting throughout the 9th are coinciding with relatively low wind speeds and a build up of a strong surface inversion that last for the whole period. The hourly NO_2 concentrations at the Løren station reach slightly above 400 μg/m^3 and as much as 13 hourly values above 200 μg/m^3 are measured during the 7th and 8th. It can be noted from Figure 1b that $\Delta\theta$ maintain its positive value throughout the daytime hours on the 7th, 8th and 9th of January. The term "long lived stable boundary layer" (Zilitinkevich, 2002) therefore seems to describe these conditions better than the traditional term of the "nocturnal boundary layer".

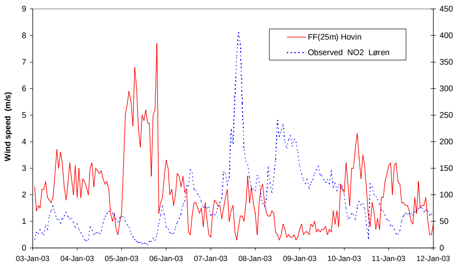

Figure 1a: Time series of hourly values of the observed wind speed (m/s) at Hovin and observed hourly NO_2 concentrations (μg/m^3) at Lørenduring the January 2003 pollution episode.

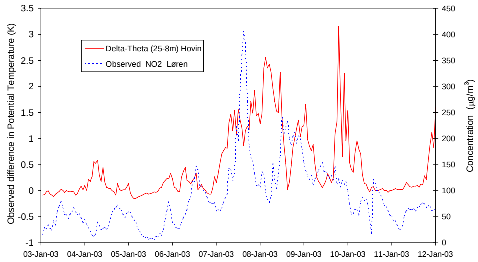

Figure 1b: Time series of hourly values of the observed ΔT (converted to $\Delta\theta$; K) at Hovin and observed hourly NO_2 concentrations (μg/m^3) at Løren during the January 2003 pollution episode.

By applying the observed wind speed and ΔT values at Hovin as input, i.e. the data presented in Figures 1a and 1b, the M-O based meteorological pre-processor METPRO can be applied to estimate various dispersion parameters for this pollution episode. Furthermore, different methods of parameterisation can be compared. In the following the measurement height of the wind speed (z = 25 m) is applied as reference height when estimating the dimensionless value of the stability parameter z/L.

In Figure 2a three estimates of the inverse Monin-Obukhov length are presented. The lower bound on L, applied in METPRO for stable conditions in urban areas, is clearly revealed by the constant maximum value on the 1/L-curve during the entire three day pollution period from the afternoon of the 6th to the end of the 9th, see curve a in Figure 2a. The corresponding minimum value of L is 32 m in this case. When allowing for lower values of L by applying the interpolation formula, Eq.(2), curve b in Figure 2a is computed. A continuous variation of the 1/L-curve is now found with maximum values reaching about 0.40 m^{-1}, implying minimum values of L of about 2.5 m. The sensitivity of applying $\theta_* = 0.08\,K$ in the very stable regime (z/L>1) was investigated by increasing this value to $\theta_* = 0.15\,K$, and then recalculating 1/L without applying a lower limit on L. The resulting 1/L-curve is shown as curve c in Figure 2a. This rather large increase in θ_* leads to somewhat larger peak values of 1/L as compared to the curve b results in Figure 2a. 1/L now reach values of 0.54 m^{-1}, giving minimum values of L as low as 1.9 m. L is thus marginally influenced by the constant chosen for θ_* in the very stable case. Moreover, the turbulent diffusivities estimated from the above M-O parameters remain extremely low, i.e. in the range 0.01 - 0.25 m^2/s, throughout the three-day episode. This is the case even when the lower limit is applied for L.

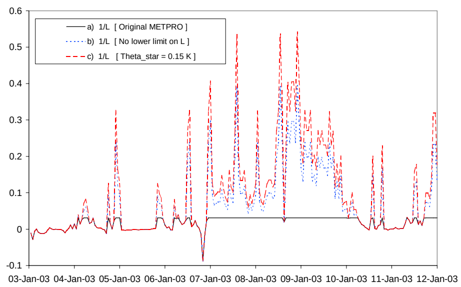

Figure 2a. Values of the inverse M-O length (1/L): a) L estimated from original METPRO, b) with no lower limit on L, c) with no limit on L, but with $\theta_* = 0.15\,K$ instead of $\theta_* = 0.08\,K$ when $z/L > 1$.

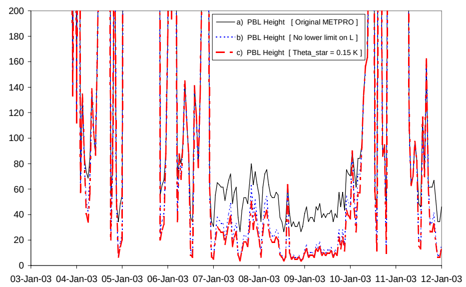

Figure 2b. Estimated values of the PBL height (h): a) L estimated from original METPRO, b) with no lower limit on L, c) with no limit on L, but with $\theta_* = 0.15\,K$ instead of $\theta_* = 0.08\,K$ when $z/L > 1$.

The corresponding effect on the estimated PBL heights of allowing for lower values of L in the very stable regime is shown by curve a – c in Figure 2b. The PBL heights are estimated by use of Zilitinkevich (1972) stable layer parameterisation, i.e. $h = 0.4\sqrt{u_* L/f}$. Very low PBL heights are estimated throughout the three-day pollution episode and therefore only heights below 200 m are shown. Without limitation on L, the PBL height reaches unrealistic values as low as 4 to 5 m, i.e. values much less than the average height of the roughness elements in urban areas. However, when the lower bound on L is applied, PBL heights down to about 25 m (i.e. slightly higher than the average building height in Oslo) are found, indicating that a lower limit on L is indeed needed for urban applications. Furthermore, the results are not very much influenced by the choice of the constant for the temperature scale, θ_*. The period with very low estimated PBL heights coincides rather well with three radio-soundings profiles (7th, 8th and 9th), which exhibit the deep surface based inversion.

4. APPLICATION OF SURFPRO DURING A WINTER POLLUTION EPISODE IN THE CITY OF MILAN

SURFPRO has been applied to a severe pollution episode happened in Milan during December 1998, that has been analysed in Kukkonen et al (2004) in comparison with episodes recorded in other European cities.

Milan city is located in the central part of the Po river basin, in Northern Italy, in a flat area. The atmospheric circulation of the Po valley is characterised by the strong modification of synoptic flow due to the high mountains that surround the valley on three sides. Calm conditions and weak winds occur frequently. The most severe winter episodes are commonly associated with high pressure, weak winds and elevated temperature inversions.

In this work we used meteorological observations from the radiosoundings of the suburban airport of Linate and from the urban surface station of Juvara, where the air quality station is located at the road pavement level, while the corresponding meteorological station is located on a building roof at a height of approximately 30 m.

A period of elevated PM_{10} and NO_2 concentrations is clearly distinguishable from 14 to 19 December 1998 (Figure 3). Exceedancees of UE limits for both pollutants were recorded by all the stations of Milan city air quality network during the episode.

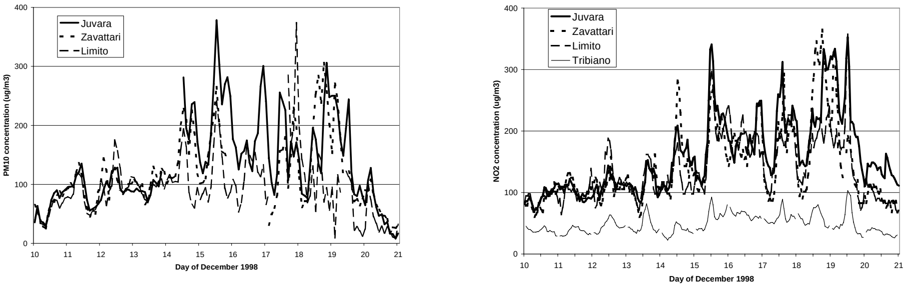

Figure 3: PM10 (left) and NO2 (right) concentrations recorded by some of the stations located in Milan Province during December 1998 episode.

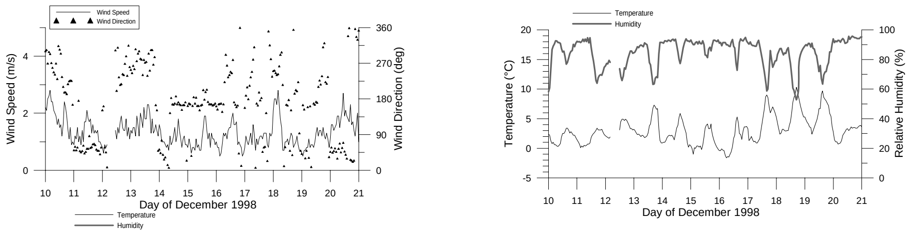

Figure 4: Wind speed and direction (left), temperature and relative humidity (right) observed at the urban station of Juvara during the December 1998 episode.

The synoptic weather conditions were characterised by a high-pressure ridge arriving at the Mediterranean basin on December 13th and remaining quasi-stationary, centred over the western Mediterranean for the whole of the episode duration. The local surface wind speed was low or it was calm. The temperature of the surface layer was rather low for Milan climatology and did not change substantially during the course of the episode (Figure 6). An intense slightly elevated temperature inversion was formed on 13 December that reached its maximum depth and magnitude (with a temperature growth of about 15 °C in the first 1500 metres height) on 15 December and prevailed until 19 December according to radiosonde data at Linate airport. The observed inversions were caused by the advection of warm air aloft carried by the incoming high-pressure ridge.

The M-O based meteorological pre-processor SURFPRO has been applied to estimate turbulence scaling parameters, mixing height and Eulerian dispersion parameters (K_Z) for this pollution episode. A roughness length of 1 metre has been considered to describe urban conditions. In Figure 5 two estimates of the inverse Monin-Obukhov length are presented, with and without the limiting value on L. If applied, this limiting value affects all the periods during which stable conditions were recorded.

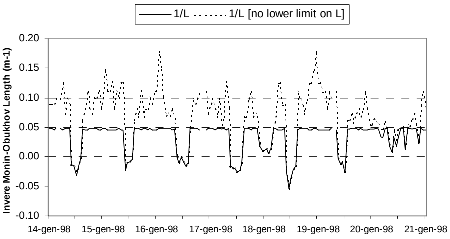

Figure 5a: Estimated values of the inverse M-O length (1/L).

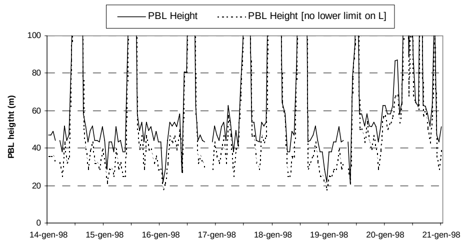

Figure 5b: Estimated values of the PBL height (h) with and without considering a lower limit to MO length (L) - zoom on the first 100 metres.

For the considered application this limit turned on when the wind speed was lower than about 1.8 m/s, a limit that was nearly never exceeded in stable night time conditions. The corresponding effect on the estimated PBL heights is shown in Figure 5.Very low PBL heights are estimated during the whole episode. Daytime values (estimated using a simple encroachment method basen on observed temperature profiles and estimated sensible heat flux) rarely reach 200 metres, while during stable conditions the estimated boundary layer depth is always lower than 50 metres. Values in the range 20-30 metres are obtained without lower limit to the MO lenght.

5. GENERAL DISCUSSION AND CONCLUSIONS

Two meteorological pre-processors (METPRO and SURFPRO), applying traditional Monin-Obukhov similarity theory, have been applied in the parameterisation of dispersion parameters for winter pollution episodes in Oslo and Milan. The boundary layer depths diagnosed for both cities were extremely low during stable conditions. These values roughly varied in the range 25-50 meters. Very low values, rarely > 0.1 m^2s^{-1} , were obtained for the vertical eddy diffusivity.

The episode in Oslo was characterized by very stable atmospheric conditions lasting for several days. Extremely low PBL heights and almost zero turbulent dispersion was predicted during a three-day pollution episode.

By applying a lower (urban) limit to the estimated Monin-Obukhov length, estimated PBL heights lower than the average roughness elements were avoided. Nevertheless, this simple way of urbanizing the scheme did not have a profound impact on the estimated vertical turbulent diffusivities. In reality the turbulent exchange may have been stronger than predicted by the applied M-O theory, at least sporadically in time and space, because of wave – turbulence interactions and drainage effects (Högström 1996). This is also supported by the available air quality measurements that show relatively large variability in concentration levels throughout the 3 day pollution episode.

Instead of using pre-processors of the above type, output from numerical weather prediction models or mesoscale circulation models could be applied. However, lots (if not most) of these models also apply M-O similarity theory in their PBL schemes, and direct extraction of surface fluxes from these models will produce similar results as shown above.

Even though the considered pollution episode in Oslo was quite severe, the meteorological conditions are rather characteristic for pollution episodes in Norwegian, and probably other Nordic, cities. Under such conditions the PBL is termed ”long lived stable boundary layers” by Zilitinkevich (2002) as opposed to the traditional ”nocturnal boundary layer”. Zilitinkevich et al., (2002) propose a practical method for including the effects of internal gravity waves in the description of such long-lived SBLs, thereby enhancing surface layer turbulence. However, in order to apply this method, information on the Brunt-Väisälä frequency in the adjacent layers of the free atmosphere is needed. Observations of the Brunt-Väisälä frequency is normally not available, but estimates of this quantity may be extracted from NWP or mesoscale circulation models. This type of PBL parameterisations together with related expressions on the PBL height (Zilitinkevich et al., 2002a) should be tested further on long-lived episodes, as in Sodeman and Foken (2004).

Acknowledgements

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