The refinement of a meteorological pre-processor for the urban environment

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Abstract: The meteorological pre-processor used routinely at the Finnish Meteorological Institute (FMI) has been modified in order better to represent urban conditions. We have reevaluated the roughness length, introduced the zero displacement height and divided the surface layer into a roughness sub-layer and an inertial sub-layer. The friction velocity and Monin–Obukhov length are evaluated using an empirically developed, exponential, Reynolds stress profile in the roughness sub-layer. The effect of these modifications has been studied by computing the dispersion parameters used in the urban dispersion modelling system UDM-FMI and comparing the revised parameters with the previous model computations.

Keywords: dispersion, meteorological pre-processor, urban environment.

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1 Introduction and regulatory background

Short-range atmospheric dispersion models require input data on the state of the atmospheric boundary-layer. These models need estimates of at least the mean plume transport velocity, the lateral and vertical components of turbulent energy, the vertical stability parameter and the mixing depth. Not all of these parameters are routinely observed and it is, therefore, necessary to estimate them in terms of the routinely observed variables, using a so called meteorological pre-processor.

The meteorological pre-processor, applied in combination with the regulatory atmospheric dispersion models in Finland (Karppinen *et al.*, 1997), was originally designed for rural areas only. This paper describes the modifications made to the meteorological pre-processor in order to account for urban conditions. The atmospheric surface layer is divided into two parts: a roughness sub-layer of height z^* and an inertial sub-layer. Monin–Obukhov similarity laws are expected to be valid only in the sub-layer (Rotach, 1996). Close to the ground surface, the local Reynolds stress profile is used to recalculate the relevant turbulence parameters.

The key parameter needed to characterize vertical turbulence, the Monin-Obukhov length L, can be assumed to be equal to the depth of the mechanically well mixed layer (e.g. Stull, 1988); this can be identified with the roughness sub-layer. In stable conditions we therefore set the minimum value for L to be equal to z^* so that $L \geq z^* \equiv L_{\min}$.

The influence of these modifications has been analysed by computing the dispersion parameters used in the UDM-FMI dispersion modelling system, and comparing the revised parameters with the previous ‘non-urban’ model computations.

2 Description of the meteorological pre-processor

The meteorological pre-processing model is based on the method developed originally by van Ulden and Holtslag (1985). This method evaluates the turbulent heat and momentum fluxes in the atmospheric boundary-layer (ABL) from synoptic weather observations. The parameterization of the ABL height is based on boundary-layer scaling, utilizing meteorological sounding data. The four main scaling parameters of this method are: the roughness height z_0, the friction velocity u_*, the temperature scale ϑ_* and the boundary-layer height z_i. The friction velocity u_* determines the shear production of turbulent kinetic energy at the surface. According to surface-layer similarity theory, the wind-speed $\bar{U}(z)$ is related to u_* by

$$\bar{U}(z) = \frac{u}{k}\left[\ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right) + \psi_m\left(\frac{z_0}{L}\right)\right] \tag{1}$$

The influence function ψ_m can be evaluated (van Ulden and Holtslag, 1985) from:

$$\psi_m = \left(1 - 16\frac{z}{L}\right)^{1/4} - 1 \text{ for unstable stratification } (L < 0); \tag{2}$$

$$\psi_m = -17\left(1 - \exp\left(-0.29\frac{z}{L}\right)\right) \text{ for stable stratification } (L > 0). \tag{3}$$

The Monin–Obukhov length L is defined by the velocity and temperature scales as

$$L = \frac{T_2 u^2}{kg\theta} \tag{4}$$

where T_2 is the air temperature at the height of 2 m, and k is the von Karman constant. The scaling temperature θ can be written in terms of the turbulent kinematic heat flux at the surface Q_o and the friction velocity, i.e. $\theta = -Q_o / u$.

The mixing height is defined as the mean height to which turbulence extends vertically. In unstable conditions, scalar quantities (e.g. temperature, moisture) are generally well mixed up to this height.

3 The dispersion parameters

The turbulence dispersion parameters in the UDM-FMI dispersion model (Karppinen *et al.*, 1998) are written in terms of the turbulence intensities (Hanna, 1985) as:

$$\sigma_{ty} = i_y f_y x, \quad i_y = \frac{\sigma_v}{\overline{U}(z)}, \quad f_y = \frac{1}{\sqrt{1 + B_y x}}$$
$$\sigma_{tz} = i_z f_z x, \quad i_z = \frac{\sigma_w}{\overline{U}(z)}, \quad f_z = \frac{1}{\sqrt{1 + B_z x}} \tag{5}$$

where i_y and i_z are the lateral and vertical turbulence intensities, f_y and f_z are functions of x, the downwind distance , σ_v and σ_w are the standard deviations of the turbulent velocity fluctuations in the lateral and vertical direction, and $\overline{U}(z)$ is the average wind-speed at height z.

In this paper we investigate only the effect of 'urban' scaling on the parameters σ_v and σ_w, although in the modelling system the parameter B_z also is a function of the roughness length and Monin–Obukhov length (and therefore stability) as follows:

$$\begin{aligned} &B_z = 0 \text{ when } p_q \leq -0.5 \text{ (unstable)} \\ &B_z = 0.0003 + 0.0006 p_q \text{ when } -0.5 < p_q < 2.0 \text{ (neutral)} \\ &B_z = 0.0015 \text{ when } p_q > 2.0 \text{ (stable)} \end{aligned} \tag{6}$$

where the dimensionless stability parameter p_q is calculated from :

$$p_q = \frac{L}{|L|}\left\{\frac{14.6 - 0.167 z_0}{|L|} + \left[1.6 + 0.2\ln(z_0)\right]\left[1 - \exp\left(\frac{-(47.8 + 178.5 z_0)}{|L|}\right)\right]\right\} \tag{7}$$

This equation represents a functional relationship between Monin–Obukhov length L and roughness length z_0 for various Pasquill stability classes (Karppinen *et al.*, 1998). In Equation 5, for unstable situations $B_z = 0$, which means that $f_z \equiv 1$.

The standard deviations of the turbulent velocity fluctuations σ_v and σ_w for point and area sources are evaluated at the average dispersion height H_{eff} as follows. In stable conditions ($L > 0$):

$$\sigma_v = 2.0 u_* \left(1 - \frac{H_{\text{eff}}}{z_i}\right) \text{ and}$$
$$\sigma_w = 1.6 u_* \left(1 - \frac{H_{\text{eff}}}{z_i}\right) \tag{8}$$

and in unstable conditions ($L < 0$),

$$\sigma_v = u_* \sqrt{0.36\left(-\frac{z_i}{kL}\right)^{2/3} + 4.0\left(1 - \frac{H_{\text{eff}}}{z_i}\right)^2} \quad \text{and}$$
$$\sigma_w = u_* \sqrt{1.54\left(-\frac{z_i}{kL}\right)^{2/3}\left(\frac{H_{\text{eff}}}{z_i}\right)^{2/3}\exp\left(-\frac{2H_{\text{eff}}}{z_i}\right) + 2.56\left(1 - \frac{H_{\text{eff}}}{z_i}\right)^2} \tag{9}$$

These equations can be derived from the works of Wratt (1987), Arya (1984) and Caughey *et al.* (1979) as presented by Karppinen *et al.* (1998).

4 Modifications in order to allow for urban conditions

To allow for the influence of urban conditions we have re-evaluated the roughness height z_o and introduced the zero displacement height d, using a computational method discussed by Rotach (1997). The quantities z_o and d were determined for the Helsinki metropolitan area. We have also divided the surface layer into a roughness sub-layer and an inertial sub-layer.

In stable conditions, we have used the height of the roughness sub-layer, z^* as a lower limit for the Monin–Obukhov length L, as L can be interpreted as the depth of the mechanically well mixed layer. It is therefore plausible to assume that the Monin–Obukhov length $L \geq z^* \equiv L_{\min}$, since, by definition, the roughness sub-layer height is the height up to which the urban roughness elements are generating more intense turbulence.

5 Application to the Helsinki metropolitan area

The roughness length and the zero displacement height are evaluated by utilizing an estimate of the proportion of the built-up area: $A_R/A \approx 15\%$. This value is based on the roughness element density and the average building height h of 10 m in the Helsinki metropolitan area (City of Helsinki, 1997). Using these values in the formula of Counihan (1971), estimates can be obtained for the roughness length and displacement height: $z_o \approx d \approx 0.2\ h\left(= 2\text{m}\right)$. These values are similar with the roughness length estimates reported commonly for suburban areas (e.g. Seinfeld and Pandis, 1998). The following computations are based on these estimates for z_o and d.

A more accurate estimate of the displacement height and roughness length, based on measurements from a meteorological mast, yielded similar values for z_o as the above-mentioned. However, based on the mast measurements, the displacement height was re-estimated to be $d \approx 6$ m; this value is better in agreement with corresponding estimates in the literature (e.g. Stull, 1988). This revised value of d would correspond to the proportion $A_R/A \approx 50\%$, which is reasonable, if one takes into account the combined effect of buildings, trees and other obstacles in the area.

Utilizing wind measurements from the Helsinki-Vantaa airport, we can estimate the friction velocity in the inertial sub-layer (Rotach, 1997), yielding $u^{IS} \approx 1.08\ u$, where the friction velocity of the non-urban computations is denoted by u and the superscript IS refers to inertial sub-layer.

The height of the roughness sub-layer can be determined by several methods (e.g. Raupach, 1993). We have adopted the value $z^* = 30$ m, which is in the range from 3 to 5 times the average building height.

Using the exponential Reynolds stress profile, suggested by Rotach (1993), and requiring that $u\left(z\right) = 0.99\ u^{IS}$, we obtain

$$u\left(z'\right) = \sqrt{\overline{u_1' u_3'\left(z'\right)}} = u^{IS}\left(1 - e^{-0.117 z'}\right)^{1/3} \tag{10}$$

where z' is the elevation from the zero displacement level d.

We assume that the turbulent heat flux is constant throughout the roughness sub-layer (Rotach, 1997). The profiles of the Monin–Obukhov length and temperature scale in the roughness sub-layer can now be computed using Equation 4. However, in stable conditions, if the computed Monin–Obukhov length is less than the lower limit of L, we apply the L_{min} value for L, and re-compute the values of the friction velocity and temperature scale.

6 Comparison of dispersion parameters for urban and rural conditions

Figures 1 and 2 show the ratios of the re-evaluated (urban) and original (rural) dispersion parameters. Figures 1 and 2 correspond to unstable, neutral and stable atmospheric stratification respectively. The results are based on meteorologically pre-processed data in the Helsinki Metropolitan Area in 1993. The effective source height is assumed to be low (3 m), compared with the mixing height, as the change in dispersion parameters affects mainly the concentrations near the ground-level.

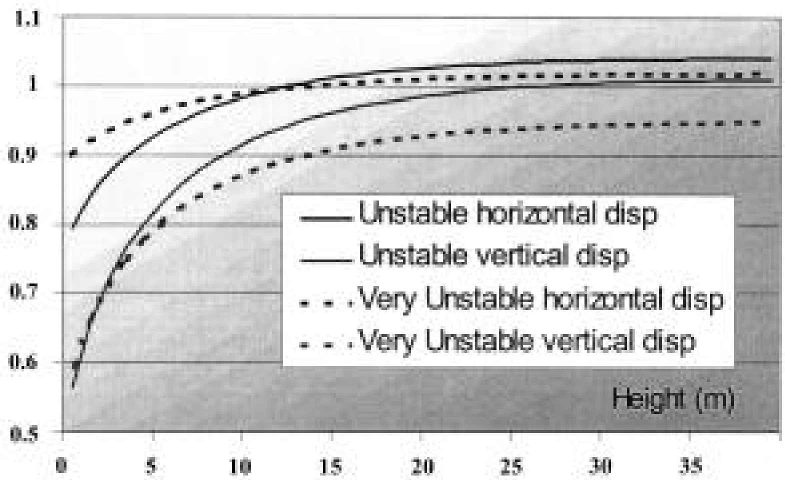

Figure 1 The ratio of urban and rural dispersion parameters in unstable conditions.

In unstable conditions, the urban vertical dispersion parameters are approximately half of the corresponding rural values at an effective dispersion height near the zero-plane displacement. Clearly, the urban roughness elements give rise to enhanced turbulence above the roof-top level and one would therefore expect the urban dispersion parameters to be *larger* within this layer compared with the corresponding non-urban parameters. However, the introduction of the displacement height and the exponentially decreasing Reynolds stress result numerically in clearly smaller values of turbulence parameters in the layer between roof-top level and displacement height. This effect can be seen to be consistent with the generally accepted picture of turbulent flow changing to laminar flow close to a surface. In this case, we can consider the urban roughness sub-layer as a layer within which the spatial average of Reynolds stress increases from zero to its value in the inertial sub-layer (Rotach, 1993).

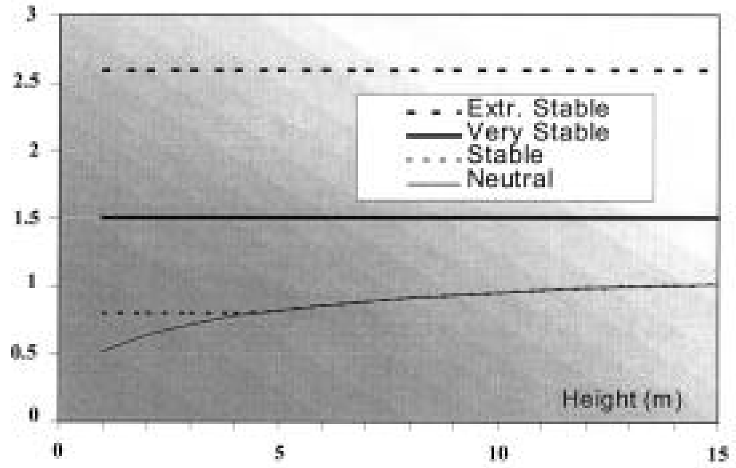

Figure 2 The ratio of urban and rural dispersion parameters in stable and neutral conditions.

In neutral conditions, the variation of the curve is similar, compared with the unstable cases. However, in stable conditions the imposed limit of the Monin–Obukhov length substantially changes the situation. In extremely stable conditions, the urban dispersion parameters exceed the corresponding rural values with a large margin; the key factors influencing this ratio are stability and height of the roughness sub-layer.

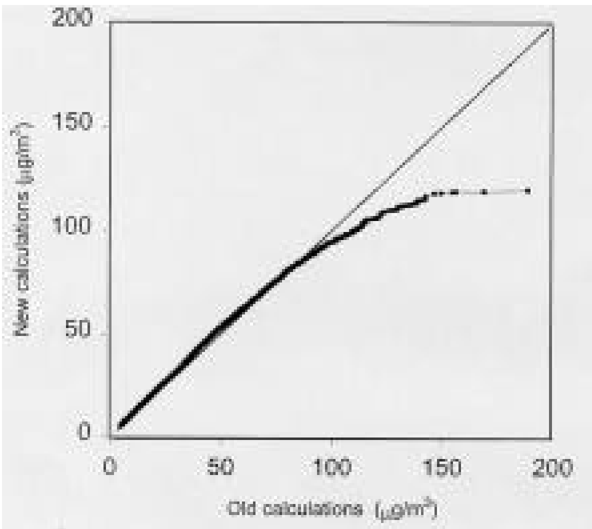

Figure 3 The calculated cumulative NO_2 concentration distributions at the monitoring station of Töölö, Helsinki in 1993.

Figure 3 shows the effect of the modified dispersion parameters on the computed concentration distribution. The highest concentrations, which commonly correspond to extremely stable situations, are lower and more realistic in the new (urban) calculations. The concentrations in the range from 10 to 70 μg/m^3, which typically correspond to neutral or unstable situations, are only marginally higher in the urban calculations. Figure 4 shows that the effect of the model modifications on monthly average concentrations is fairly small.

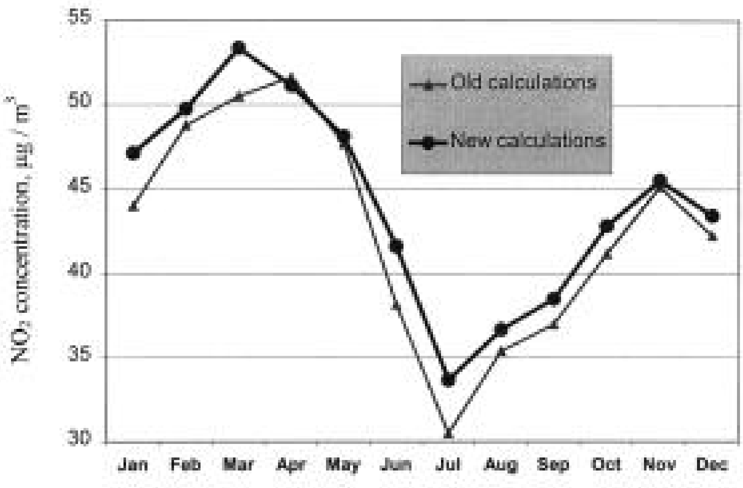

Figure 4 The calculated monthly average NO_2 concentrations at the monitoring station of Töölö, Helsinki 1993.

7 Conclusion

The meteorological pre-processor developed at our institute has been modified in order to represent urban conditions better. We have re-evaluated the roughness length, introduced the zero displacement height and divided the surface layer into a roughness sub-layer and an inertial sub-layer. The friction velocity (Reynolds stress) and Monin–Obukhov length are re-evaluated using an empirically developed exponential Reynolds stress profile in the roughness sub-layer.

The influence of these modifications has been investigated by computing the dispersion parameters used in the UDM-FMI dispersion modelling system, and comparing the revised parameters with the corresponding previous 'non-urban' parameters. These modifications can have a substantial influence on the computed concentrations for the ground-level, or near the ground-level sources (e.g. traffic). The re-evaluated friction velocity and dispersion parameters result in clearly lower concentrations in stable atmospheric stratification and slightly higher concentrations in neutral and unstable atmospheric stratification.

References

Arya, S.P.S. (1984) 'Parametric relations for the atmospheric boundary-layer', *Boundary–Layer Meteorology*, Vol. 30, pp. 57–73.

Counihan, J. (1971) 'Wind tunnel determination of the roughness lengths as a function of the fetch and the roughness density of three-dimensional roughness elements', *Atmospheric Environment,* Vol. 5, pp. 637–642.

Caughey, S.J., Wyngaard, J.C. and Kaimal, J.C. (1979) 'Turbulence in the evolving stable boundary-layer', *J. Atmos. Sci.*, Vol. 36, pp. 1041–1052.

City of Helsinki (1997) 'Statistics of the Helsinki metropolitan area in 1996' (in Finnish), Edita Oy, Statistical Centre, Helsinki.

Hanna, S.R. (1985) 'Air quality modelling over short distances', in Houghton, D.D. (Editor) *Handbook of Applied Meteorology*, Chapter 25, University of Wisconsin, Wisconsin.

Härkönen, J., Valkonen, E., Kukkonen, J., Rantakrans, E., Jalkanen, L. and Lahtinen, K. (1995) 'An operational dispersion model for predicting pollution from a road', *Int. J. Environment and Pollution,* Vol. 5, Nos. 4–6, pp. 602–610.

Karppinen, A., Joffre, S. and Vaajama, P. (1997) 'Boundary-layer parameterization for Finnish regulatory dispersion models', *Int. J. Environment and Pollution,* Vol. 8, Nos. 3–6, pp. 557–564.

Karppinen, A., Kukkonen, J., Nordlund, G., Rantakrans, E. and Valkama, I. (1998) 'A dispersion modelling system for urban air pollution', *Publications on Air Quality 28*. Finnish Meteorological Institute, Helsinki, p. 58.

Rotach, M.W. (1991) 'Turbulence within and above an urban canopy', *ETH Dissertation 9439*, p. 240. Published as ZGS, Heft 45, Verlag GGIETH, Zürich.

Rotach, M.W. (1993) 'Turbulence close to a rough urban surface. Part I: Reynolds Stress', *Boundary–Layer Meteorology*, Vol. 65, pp. 1–28.

Rotach, M.W. (1997) 'Towards a meteorological pre-processor for dispersion models in the urban environment', *Int. J. Environment and Pollution*, Vol. 8, Nos. 3–6, pp. 565.

Seinfeld, J.H. and Pandis, S.N. (1998) *Atmospheric chemistry and physics*, John Wiley & Sons, New York.

Stull, R.B. (1988) *An introduction to boundary-layer meteorology*, Kluwer Academic Publishers, Boston, MA.

van Ulden, A.P. and Holtslag A.A.M. (1985) 'Estimation of atmospheric boundary-layer parameters for diffusion applications', *J. Clim Appl. Meteor.*, Vol. 24, pp. 1196–1207.

Wratt, D.S. (1987) 'An experimental investigation of some methods of estimating turbulence parameters for use in dispersion models', *Atmospheric Environment*, Vol. 21, pp. 2599–2608.