A screening model for the calculation of pollutant accumulation in street canyons

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1 Introduction

Pollutant concentrations observed close to the traffic line into under-ventilated streets may be several time higher that the value observed at roof level, which represents the background pollution concentration. At high wind speed, the pollutant exchange between the street and the urban canopy is mainly controlled by a vortex developed inside the street canyon (Berkowitcz, 1997; Rafailidis, 1997). However, at low wind speed (<1m/s), the existence of vortex structure is difficult to accept since the wind speed energy is too weak to drive the vortex (Coppalle, 1999). The street ventilation tends to be controlled by the vertical turbulent diffusion and the mixing at roof level. It is important to assess the pollution at such low wind speed conditions since, in that cases, the pollutant concentration in excess in the street canyon is generally very high. Under such circumstances and for regulatory purposes, the utilisation of a box model is a good compromise between more sophisticated street canyon models (as OSPM, CPM, ADMS, …) and statistical approachs, in which there is no physics. The aim of this work is to develop a simple box model in order to calculate the pollutant in excess inside the street as a function of the traffic emission.

2 Box model description

In a box model, it is assumed pollutants are well mixed inside the street. The figure 1 shows the exchanges which are taken into account and which control the air quality inside the street. Pollutant concentrations are given by the balance between emissions E_c and exchanges,

$$\frac{dC(t)}{dt} = -\frac{(C(t) - C,bcg)}{\tau} - \frac{U_{wind,//}}{L}(C(t) - C,bcg) + Ec(t)$$

where $U_{Wind,//}$ is wind speed parallel to the street axis, L the length of the street, τ is the characteristic time scale of the exchange at roof level. Here, it is assumed that the pollution which is brought into the street by the wind is equal to the background pollution. Under the steady state approximation (Palmgren, 1996), the above relation becomes

$$(C(t) - C,bcg) = \tau_{ech} E_C(t)$$

with $\frac{1}{\tau_{ech}} = \frac{1}{\tau} + \frac{U_{Wind,//}}{L}$

and $E_C(t) = e_C(g/km) 10^3 N_{trafic}(veh/s)/(H\ D)$,

τ_{ech} being the global characteristic exchange time. In reality, the τ time scale is a function of the meteorological conditions. In a recent work (Soulhac, 1998), it has been shown that τ can be determined by the relation

$$\frac{1}{\tau} = \frac{\sigma_w WL}{\sqrt{2\Pi}},$$

where σ_w is the variance of the fluctuations of the vertical wind speed at roof level. We have assumed it is given by the relation σ_w=a1 + a2 $U_{wind,\perp}$, where $U_{wind,\perp}$ is the wind speed component perpendicular to street direction, and a1 and a2 are constants.

The steady state assumption is valid because the characteristic time scale of exchange τ_{ech}, about one minute, is lesser than the characteristic time of emission within the street, about 15 minutes at rush hours. So transfer at roof level is much faster than the traffic emission variations.

The parameters a1 and a2 are determined by a least square fitting minimisation of the error function $\Im(a1,a2)=\sum(C^{mod}-C^{obs})^2$.

The procedure has been applied on NOx long time series observed in Jagtev[#], Berlin[#] (hourly concentrations observed in 1995) and in Rouen (Coppalle, 1999; 15 mn averaged concentrations observed during one month in winter).

3 Results

The street dimensions and the daily traffic within the street are given in table 1. The best values for the coefficient a1 and a1 are also presented for the three data set. We can see the Berlin and Jagtev streets have similar characteristics, they are large and busy. The street in Rouen is not so large, however the traffic on the single lane is so intense it gives often strong pollutant accumulations at the kerb-side. The optimised coefficient a1 and a2 have been obtained taking an average emission rate e equal to 1.5 (g/Km) for all cases.

Table 1 main characteristics of the streets chosen for the box model development, also shown the coefficients a1 and a2, optimised from the Nox data set of each site.

	Berlin 95 Working days	Jagtev 95 Working days	Rouen. Jan.-Feb in 1997
Street width (m) Height(m)	19 26	25 18	11 15
Traffic load(Vh/j)	45000	22000	8080
a1 =	0.47	0.28	0.17
a2 =	0.096	0.13	0.10

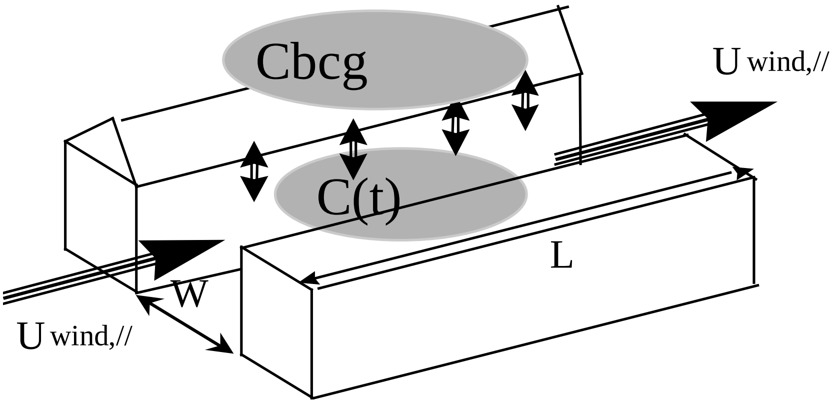

Figure 1 Schematic view of the street and exchanges taken into account in the box model.

The comparison between calculated and observed series is presented in figure 2, in the case of Rouen city. The scatter plots for Jagtev and Berlin are similar and present the same pattern. In figure 2, the complete data set are reported but also the one measured under low wind speed conditions (wind speed measured at roof level). The agreement between calculated and observed values is better for low wind speed. This is also shown in the error distribution diagrams reported on figure 3. One can see the shape of error distribution diagram is symmetrical in relation to the x axis, suggesting there are no particular trend towards overestimation or underestimation. However, the tails of the distribution do not go to zero value, there is a small number of strong errors in the predicted values.

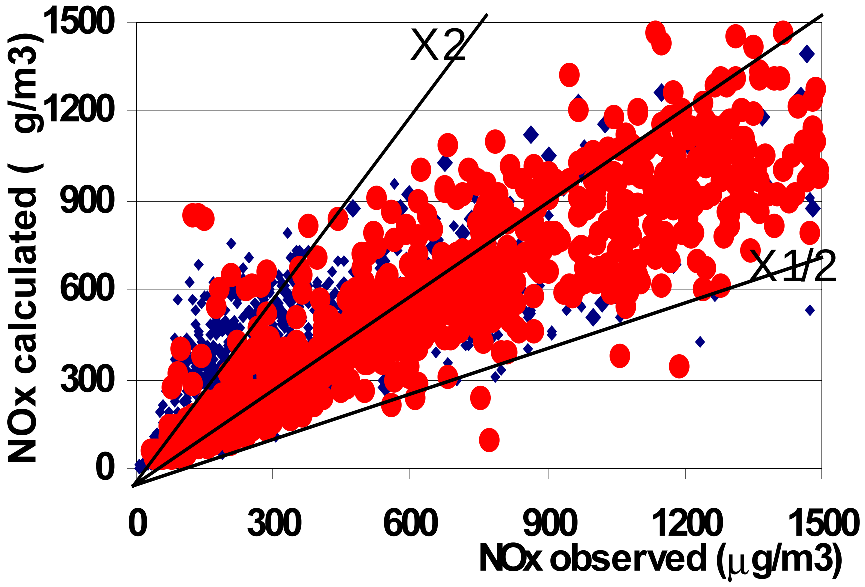

Figure 2 comparison between observed and calculated values of Nox in a street canyon of rouen city. data set are for one month in winter 1998, large symbols for low wind speed (<1m/s).

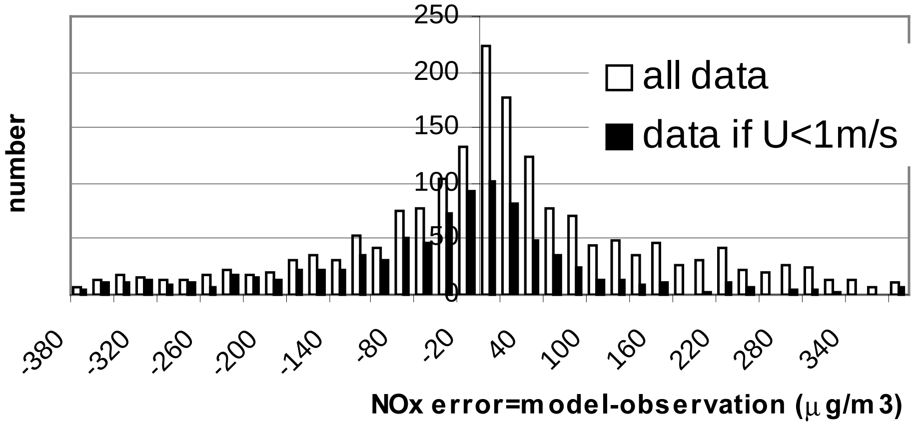

Figure 3 error distribution, plein symbols for data at low wind speed (<1m/s), empty symbols for all data

Another way to assess the model reliability is to use statistical indices, as suggested in the so-called ‘Model Evaluation Kit’ (Olesen, 1994). Some of them have been calculated:

The Fractional bias $FB = \dfrac{(\overline{NOx}^{mod} - \overline{NOx}^{obs})}{(\overline{NOx}^{mod} + \overline{NOx}^{obs})/2}$

The normalised mean square error $NMSE = \dfrac{\overline{(NOx^{mod} - NOx^{obs})^2}}{\overline{NOx}^{mod}\,\overline{NOx}^{obs})}$

The correlation $COR = \dfrac{\overline{(NOx^{mod} - \overline{NOx}^{mod})(NOx^{obs} - \overline{NOx}^{obs})}}{\overline{\sigma}^{mod}\,\overline{\sigma}^{obs})}$

The table 2 gives the statistical index values we calculated.

Table 2 statistical indices calculated with data set of in each site.

Berlin 95 Working days	Jagtev 95 Working days	Rouen. Jan.-Feb in 1997
FB= 1.11 E-02 NMSE= 0.248 COR= 0.740	FB= -1.90 E-03 NMSE= 0.230 COR= 0.839	FB= 3.14E-02 NMSE= 0.167 COR= 0.870

4 Discussions

The previous comparisons between calculated and observed values must not be viewed as a complete validation of the box model since the analisis is performed on the same data as those used to determined the model parameters a1 and a2. However, the comparisons are encouraging for the used of the box model approach, mainly under low wind speed conditions. The comparisons show the relationship σ_w=a1 + a2 $U_{wind,\perp}$ gives a good agreement between predicted and calculated Nox values. The statistical index values in table 2 show model performances which are satisfactory in view of other values reported in the litterature.

However the emission rate e(g/km) is not well know in the present calculations. Without the knowledge of the apportionement between trucks and light vehicles, or between diesel and gazoline cars, it is not possible to calculate the exact value of the emission rate e. So we decided to use a single value e=1.5 g/km for all site. This is a working assumption, and since the concentration within the street is proportional to the emission rate value, this uncertainty has direct effects on the a1 and a2 optimised values. This is the reason it is difficult to compare the values obtained at the three different sites. Therefore from table 1, we can see the range of variation for a1 is much larger than for a2 (respectively equal to 0.17-0.47 and 0.096-0.13). This can be explained by the difference between street traffic loads. With the relation σ_w=a1 + a2 $U_{wind,\perp}$, we take into account the mixing produced by the atmospheric turbulence but also the mixing induced by the traffic inside the street. The parameters a1 is more influenced than a2 by this last effect and its must increase with the traffic intensity.

We have compared σ_w values predicted with the relation σ_w=a1 + a2 $U_{wind,\perp}$ with observed values. For Jagtev and Berlin sites, σ_w was not measured, but for the Rouen case, σ_w was observed on a building located in the surrounding and at 7 meter height above the mean roof level. We have assumed a1 parameter represents the traffic contribution and so only the component a2*$U_{wind,\perp}$ could be compared to observed σ_w value. The plot of observed and calculated values shows a large scatter. However its shape suggests a correlation between the two variables. The linear regression gives the relation $\sigma_{w,model}$ = 0,294* $\sigma_{w,obs}$ with R^2 = 0,587. It is clear the σ_w values are underestimated. There are two explanations for this discrepancy. The separation, between traffic and atmospheric contributions, could not be justified. Moreover in the present work, a constant value of a1 parameter was optimised, so it represents an average of the traffic contribution. Further works are needed to improve the traffic contribution in σ_w calculations. The other explanation is given by the location of the meteorological station. This one is not located exactly at top of the street but higher (7 meters above the mean roof level). Rautach (1995) have shown the turbulence characteristics are not constant within the roughness layer. Above roofs, the σ_w value increases with height.

5 Conclusions

The present box model is well suited for low wind speed conditions and it must be considered as a screening method for regulatory purposes. As an example, it can be used for percentile calculations. For the pollutant exchange at roof level, one must know the variance of the vertical wind speed σ_w. A simple relation between σ_w and the perpendicular wind speed at roof level $U_{wind,\perp}$, $\sigma_w = a1 + a2\ U_{wind,\perp}$, provide good results. However further works are necessary to improve the traffic contribution to the pollutant flux at roof level. One must remember the emission rate of the traffic within the street must be also well know. The box model approach makes it possible to calculate chemistry transformation. The next step will be to take account of the NO/NO2 conversion inside the street.

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