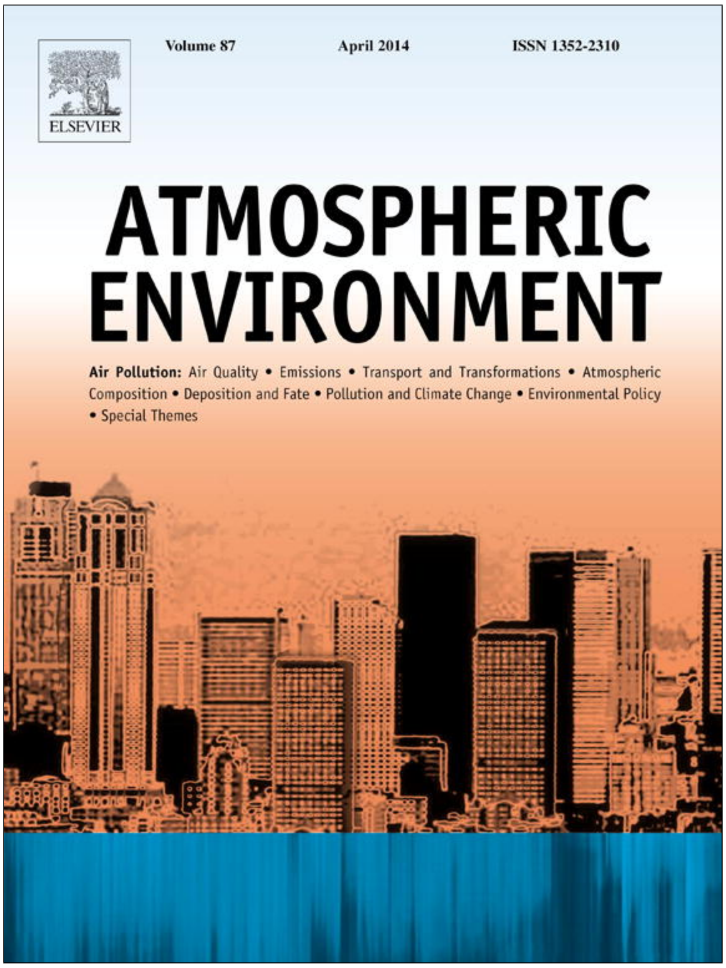
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A simple model for calculating air pollution within street canyons

Laura E. Venegas*, Nicolás A. Mazzeo, Mariana C. Dezzutti

National Scientific and Technological Research Council (CONICET), Avellaneda Regional Faculty, National Technological University, Av. Ramón Franco 5050, 1874 Buenos Aires, Argentina

HIGHLIGHTS

- This paper presents the Semi-Empirical Urban Street (SEUS) model.
- SEUS is a simple model to estimate air pollutant concentrations in street canyons.
- The performance of SEUS is evaluated in a street canyon in the city of Buenos Aires.
- Estimated and observed NO_x and NO_2 hourly concentrations show good agreement.
- SEUS model has been reasonable accurate, in spite of its simplicity.

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ABSTRACT

This paper introduces the Semi-Empirical Urban Street (SEUS) model. SEUS is a simple mathematical model based on the scaling of air pollution concentration inside street canyons employing the emission rate, the width of the canyon, the dispersive velocity scale and the background concentration. Dispersive velocity scale depends on turbulent motions related to wind and traffic. The parameterisations of these turbulent motions include two dimensionless empirical parameters. Functional forms of these parameters have been obtained from full scale data measured in street canyons at four European cities. The sensitivity of SEUS model is studied analytically. Results show that relative errors in the evaluation of the two dimensionless empirical parameters have less influence on model uncertainties than uncertainties in other input variables. The model estimates NO_2 concentrations using a simple photochemistry scheme. SEUS is applied to estimate NO_x and NO_2 hourly concentrations in an irregular and busy street canyon in the city of Buenos Aires. The statistical evaluation of results shows that there is a good agreement between estimated and observed hourly concentrations (e.g. fractional bias are −10.3% for NO_x and +7.8% for NO_2). The agreement between the estimated and observed values has also been analysed in terms of its dependence on wind speed and direction. The model shows a better performance for wind speeds >2 m s^{-1} than for lower wind speeds and for leeward situations than for others. No significant discrepancies have been found between the results of the proposed model and that of a widely used operational dispersion model (OSPM), both using the same input information.

1. Introduction

Trafficked streets are air pollution spots in the urban areas. An urban street canyon is characterised by the presence of buildings on both sides of the street. Naturally, the pollutant levels in the urban streets are strongly affected by emissions taking place inside the street itself. However, the concentration level and the distribution of air pollution inside the street are governed by surrounding physical conditions. The physical conditions heavily affect the wind speed and especially the wind direction inside the street (Britter and Hanna, 2003; Oke, 1996). The classical example is the street vortex flow that governs the pollutant distribution inside the street canyon. When wind flows are close to perpendicular to the street canyon a spiral or helical type flow develops within the canyon. Within the vortex flow relatively clean air from rooftop height is drawn down at the windward face of the street, across the road at street level, in the reverse of the wind direction at rooftop, bringing pollutants in the road to leeward face of the canyon (Britter and Hanna, 2003). The concentration inside the urban street canyon can be considered as the result of two contributions, one from emissions from local traffic in the street itself and one from background pollution entering the street canyon from above roof level.

* Corresponding author.
E-mail addresses: lvenegas@fibertel.com.ar, lvenegas@fra.utn.edu.ar (L. E. Venegas), nmazzeo@fra.utn.edu.ar (N.A. Mazzeo), ymariana@gmail.com (M. C. Dezzutti).

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Several dispersion models have been specially developed for or simply used in street canyons applications. They can be useful in air quality and traffic management, urban planning, interpretation of monitoring data, pollution forecasting, population exposure, etc. (e.g. Ganguly and Broderick, 2010; Holmes and Morawska, 2006; Jensen et al., 2009; Kukkonen et al., 2003; Vardoulakis et al., 2003; Wang and Xie, 2009). Air quality models can be divided into two main categories: parametric and numerical models. Among the first group, mathematical techniques can be simple parameterisations such as the STREET (Johnson et al., 1973) and the STREET-BOX (Mensink and Lewyckyj, 2001) models or more developed models as the Canyon Plume-Box Model (CPBM) (Yamartino and Wiegand, 1986), the Assessing the Environment Of Locations In Urban Streets (AEOLIUS) model (Buckland and Middleton, 1999), the Danish Operational Street Pollution Model (OSPM) (Berkowicz, 2000; Berkowicz et al., 2008), the Semi-Empirical Parameterized Street Canyon Model (SEP-SCAM) (Papathanassiou et al., 2008) and the parametric relations in the street network approach (Soulhac et al., 2013). In the second group, numerical approaches include computational fluid dynamics (CFD) (Eichhorn, 1996; Murena et al., 2009; Parra et al., 2010; Schatzmann and Leitl, 2011; Solazzo et al., 2011; Stern and Yamartino, 2001) and large-eddy simulations (LES) (Li et al., 2012; Moonen et al., 2013; Zhang et al., 2011). Simple models require smaller amount of input information and computational resources than more advanced simulation techniques. Nevertheless, they do not take into account certain characteristics, such as dispersion processes related to the configuration of buildings in urban intersections, the shape of building roofs, etc. On the other hand, numerical models produce detailed modelling outputs in terms of flow and turbulence and can be used to study the air flow structure inside the street canyon.

This paper introduces the Semi-Empirical Urban Street (SEUS) model which includes new empirical parameterisations of wind related and traffic-induced turbulences in street canyons. SEUS is a simple parameterised model to estimate inert air pollutants and nitrogen dioxide (NO_2) concentrations using chemical processes in street canyons. The sensitivity of SEUS estimations is studied using the propagation of errors methodology. SEUS is applied to compute nitrogen oxides (NO_x) and NO_2 hourly concentrations in a street canyon in the city of Buenos Aires using historical traffic information, routine meteorological data and modelled urban background concentrations. Statistical evaluation of model results is done comparing estimated hourly concentrations with observational data and with results of a widely used operational street canyon model.

2. The SEUS model

2.1. Model description

The Semi-Empirical Urban Street (SEUS) model is based on the scaling of air pollution concentration (C) inside urban street canyons given by the following expression:

$$C = E\,u_s^{-1}W^{-1} + C_b \tag{1}$$

where E is the emission rate per length, W is the width of the canyon, C_b is the background concentration and u_s is the dispersive velocity scale given by Kastner-Klein et al. (2003):

$$u_s = \left(\sigma_u^2 + \sigma_v^2\right)^{1/2} = \left(aU^2 + bV^2\right)^{1/2} \tag{2}$$

where $\sigma_u^2 = aU^2$ is the wind speed variance, $\sigma_v^2 = bV^2$ is the traffic-induced velocity variance, U (m s^{-1}) is the ambient wind speed, V (m s^{-1}) is the traffic velocity, a and b are dimensionless empirical parameters. Parameter a depends, among other factors, on street geometry, wind direction and sampling position. The height of the buildings is implicitly included in Eq. (1) through parameter a as part of the street geometry. Parameter b depends on traffic flow conditions. Turbulent motions mechanically generated by traffic become an important factor for the dilution of pollutants in streets under low wind speed conditions. Empirical expressions for a and b have been derived using full-scale experimental data from four street canyons (Mazzeo and Venegas, 2010, 2011; Mazzeo et al., 2012). Available information used to obtain functional forms for a and b includes hourly air pollutant concentrations and traffic flow data registered at the following street canyons (www2.dmu.dk/AtmosphericEnvironment/trapos/datadoc.htm): Göttinger Strasse (Hannover, Germany), Schildhornstrasse (Berlin, Germany), Jagtvej (Copenhagen, Denmark) and Hornsgatan (Stockholm, Sweden) along with wind speed and direction data registered nearby. One year of hourly information was available for each street canyon. As the street canyons have different orientations, it is necessary to introduce a new parameter (θ) to refer the results of the four street canyons to a common value relative to the street orientation, the wind direction (WD) and the position of the monitoring station within the street. Parameter θ (Fig. 1) is defined as

$$\theta = \begin{cases} \mathrm{WD} - \mathrm{ST} & \text{for WD} \geq \mathrm{ST} \\ \mathrm{WD} + 360^\circ - \mathrm{ST} & \text{for WD} < \mathrm{ST} \end{cases} \tag{3}$$

where ST is the angle between the north and the street axis towards the right side of the monitoring location (facing the street). The value of θ is expressed in degrees. In this way, if wind blows perpendicular to the street axis, the leeward situation verifies $\theta = 90^\circ$ and the windward situation $\theta = 270^\circ$, in any street canyon.

In the evaluation of parameters a and b, full-scale data have been grouped into 16 wind sectors of 22.5° centred in $\theta = 0^\circ$, 22.5°, 45.0°, 67.5°, 90.0°, 112.5°, 135.0°, 157.5°, 180.0°, 202.5°, 225.0°, 247.5°, 270.0°, 292.5°, 315.0° and 337.5°. The values of a and b obtained for each street canyon applying statistical methods to experimental data are presented in Mazzeo and Venegas (2005, 2010, 2011).

The variation of a (averaged over the four street canyons) with θ is presented in Fig. 2. The fitting curve (coefficient of determination, $R^2 = 0.951$) is given by

$$a = 0.002745 \exp[0.452317 - 1.9803 \sin(1.01821\pi\theta/180^\circ)] \tag{4}$$

valid for $0^\circ \leq \theta < 360^\circ$.

The variations of b with traffic density (n_v) and θ for the four street canyons have been studied in Mazzeo and Venegas (2011). The traffic density is n_v (km^{-1}) $= N_t/V$ where N_t (h^{-1}) is the total number of vehicles passing the street per time unit given by

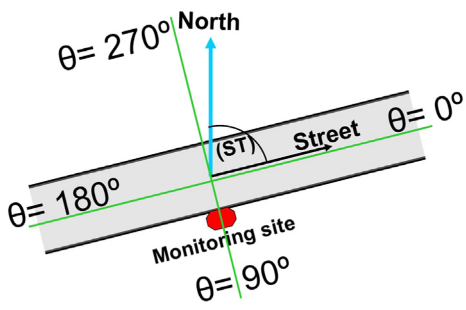

Fig. 1. Definition of parameter θ.

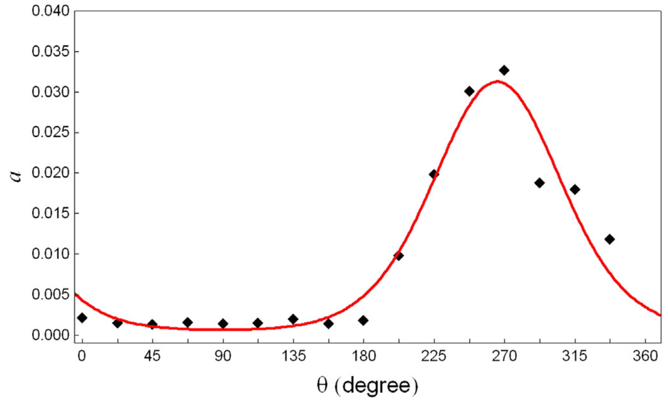

Fig. 2. Variation of a with θ.

$N_t = N_p + N_h$, N_p (h^{-1}) is the number of small vehicles per hour (passenger cars and light duty vehicles), N_h (h^{-1}) is the number of large vehicles per hour (heavy duty vehicles, buses and trucks) and V is calculated as V (km h^{-1}) $= (N_p V_p + N_h V_h)/(N_p + N_h)$ where V_p (km h^{-1}) is the velocity of small vehicles and V_h (km h^{-1}) is that of large vehicles.

Considering the cases with $0° \le \theta \le 180°$, b increases with traffic density but it does not show a clear dependence on θ. In order to obtain the empirical expression of b as a function of n_v, the values of b have to be sorted on n_v into the following bins: <10, 10–20, 20–33, 33–45, 45–55, 75–85 and >120 km^{-1} because the number of cases of b is not uniformly distributed with traffic density (Mazzeo and Venegas, 2011; Mazzeo et al., 2012). Fig. 3 shows the variation of b (averaged for each bin) with traffic density and the best fitting curve ($R^2 = 0.925$) given by

$$b = 2.88642\mathrm{E}-06\ (n_v)^{0.930771} \quad (5)$$

valid for $0° \le \theta \le 180°$, the unit of the numerical coefficient 2.88642E-06 ($km^{0.930771}$) results from the fitting methodology and it is such that dimensionless value of b is obtained for n_v expressed in km^{-1} (Mazzeo et al., 2012). Traffic induced turbulence ($\sigma_v^2 = bV^2$) is estimated using Eq. (5) and V taking into account traffic composition, but the different contributions generated by vehicles of different sizes are not explicitly identified. Mazzeo et al. (2012) used this expression and three other parameterisations of traffic-produced turbulence proposed by other authors into the scaling of air pollutants inside a street canyon to estimate hourly nitrogen oxides (NO_x) concentrations at ground-level for leeward conditions

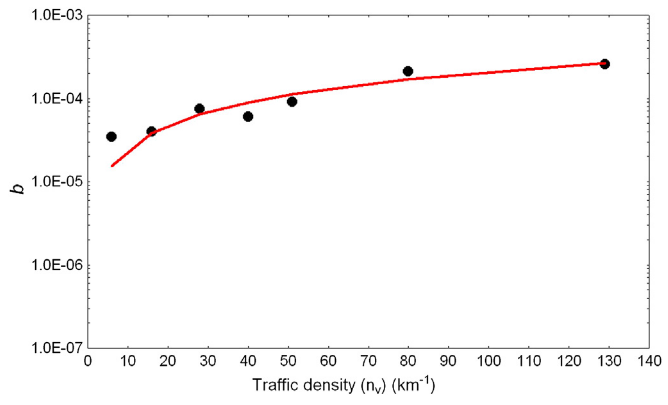

Fig. 3. Variation of b with traffic density.

Table 1
Range of the weighting factor K [Eq. (7)] of the parameters included in Eq. (6), for different intervals of θ.

θ	[0°–45°]	(45°–90°]	(90°–135°]	(135°–180°]	(180°–360°)
U	0.006–0.99	0.003–0.99	0.004–0.99	0.006–0.99	1.0
V	0.001–0.99	0.004–0.99	0.003–0.99	0.001–0.99	–
a	0.003–0.50	0.0015–0.50	0.002–0.50	0.003–0.50	0.50
b	0.0005–0.50	0.002–0.50	0.0015–0.50	0.0005–0.50	–

and compared results with observations. The results obtained using b given by Eq. (5) were as good as obtained considering other parameterisations (which account for the differences in turbulence generated by vehicles of different size).

If $180° < \theta < 360°$ and $U > 2$ m s^{-1}, the receptor receives the recirculating part of the pollutants in the street and in these cases the contribution of traffic-induced turbulence to the dilution of pollutants can be neglected, so $b = 0$. However, for meteorological conditions with $180° < \theta < 360°$ and low wind speeds ($U \le 2$ m s^{-1}) b is evaluated using Eq. (5).

Eqs. (1)–(5) constitute SEUS model for inert pollutants. In summary, the application of SEUS model to estimate inert pollutant concentrations requires the following input information: street canyon dimensions, traffic flow and composition in the street, air pollutant emissions, ambient wind speed and direction, and background concentration contribution from sources outside the street.

2.2. Sensitivity analysis of the basic expression of SEUS

Combining Eqs. (1) and (2), the basic expression of SEUS is given by

$$C = E\left(aU^2 + bV^2\right)^{-1/2} W^{-1} + C_b \quad (6)$$

The sensitivity of estimated concentrations to variations in the magnitude of each parameter included in Eq. (6) is studied using the propagation of errors methodology. Because of the simple form of Eq. (6), it is possible to examine its sensitivity analytically, by means of the partial derivate of the calculated concentration (C) with respect to each parameter p (Hilst, 1970). In this way, the sensitivity of model estimations $|\delta C/C|$ to variations in the magnitude of each parameter ($p = E, W, U, V, a, b, C_b$) is given by $|\delta C/C| = K|\delta p/p|$. The form of the weighting factor (K) for each parameter can be obtained from:

$$\left|\frac{\delta C}{C}\right| = \left|\frac{\delta E}{E}\right| + \left|\frac{\delta W}{W}\right| + \left|\frac{aU^2}{aU^2+bV^2}\right| \cdot \left|\frac{\delta U}{U}\right| + \left|\frac{bV^2}{aU^2+bV^2}\right| \cdot \left|\frac{\delta V}{V}\right| + \left|\frac{aU^2}{2(aU^2+bV^2)}\right| \cdot \left|\frac{\delta a}{a}\right| + \left|\frac{bV^2}{2(aU^2+bV^2)}\right| \cdot \left|\frac{\delta b}{b}\right| + \left|\frac{\delta C_b}{C_b}\right| \quad (7)$$

As expected, relative variations in E, W and C_b produce similar relative variations in C as $K = 1.0$ for these variables. For the other parameters (U, V, a, b) K varies with θ. The ranges of the weighting factor of the relative variation of these variables for different intervals of θ are included in Table 1. For $180° < \theta < 360°$, $K = 1$ for $\delta U/U$ and $K = 0.5$ for $\delta a/a$. For $0° \le \theta \le 180°$, relative variations $\delta U/U$ and $\delta V/V$ produce less equal relative variations in C because $0.001 \le K \le 0.99$. Eq. (7) shows that the relative variations in a and b have smaller influence on δ_C/C than the variation of other variables because $\delta a/a$ and $\delta b/b$ are multiplied by $K = 0.5\ [aU^2/(aU^2 + bV^2)]$ and $K = 0.5\ [bV^2/(aU^2 + bV^2)]$, respectively. The evaluation of these weighting factors (Table 1) shows that relative variations in a and b have the smallest influence on δ_C/C as for these parameters $0.0005 \leq K \leq 0.50$.

2.3. Chemical processes in the street canyon

Due to the relatively short time scales involved, only fast chemical reactions can have a significant influence on air composition in a street canyon. For nitrogen oxides, it is therefore sufficient to include only the basic reactions involving nitrogen monoxide (NO), nitrogen dioxide (NO_2), oxygen (O_2) and ozone (O_3). SEUS includes the same simplified chemistry as in the OSPM model (Berkowicz et al., 1997). For practical purposes, the three basic reactions between the mentioned species are:

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{8a}$$

$$NO_2 + h\upsilon \rightarrow NO + O^{\bullet} \tag{8b}$$

$$O^{\bullet} + O_2 + M \rightarrow O_3 + M \tag{8c}$$

where M (usually N_2 or O_2) represents a molecule that absorbs the excess vibrational energy and thereby stabilises the O_3 molecule formed, $h\upsilon$ represents the energy of a photon and O• is the active mono-atomic oxygen. The reaction between the oxygen radical (O• and the molecular oxygen (O_2) is so fast that for all practical purposes the reaction system can be restricted to reactions (8a) and (8b). Taking into account the chemical transformations and the exchange of street canyon air with the ambient air, under steady-state conditions, the total concentration of NO_2 in the street is calculated by Berkowicz et al. (1997):

$$[NO_2] = 0.5\left[B - \left(B^2 - 4C\right)^{1/2}\right] \tag{9}$$

with

$$B = [NO_x] + J/k + 1/(k\tau) + [NO_2]_v + [NO_2]_b + [O_3]_b$$

$$C = [NO_x]([NO_2]_v + [NO_2]_b + [O_3]_b) + ([NO_2]_v + [NO_2]_b)/(k\tau)$$

$[NO_x]$ is the total concentration of NO_x in the street; $[NO_2]_b$ and $[O_3]_b$ refer to background concentrations of NO_2 and O_3, respectively; $[NO_2]_v$ ($= f\ [NO_x]_v$) is the contribution from the direct emission in the street, f is the fraction of NO_x directly emitted as NO_2 and $[NO_x]_v$ is calculated by the first term in Eq. (6) ($[NO_x] = [NO_x]_v + [NO_x]_b$); k ($ppb^{-1}\ s^{-1}$) = 5.38E-02 exp($-1430/T^{-1}$) is the reaction coefficient of Eq. (8a) which is a function of air temperature, T (K); J is the photo-dissociation coefficient that depends on global radiation, q ($W\ m^{-2}$), and is given by $J\ (s^{-1}) = 8.0E\text{-}04\ \exp(-10/q) + (7.4E\text{-}06)q$ if $q \geq 1.0\ W\ m^{-2}$, otherwise $J = 0$; $\tau = H/\sigma_{wt}$, refers to pollutants residence time in the street and is calculated as the ratio between the depth of the street canyon (given by the average building height, H) and the turbulent exchange velocity $\sigma_{wt} = [0.01U^2 + 0.4\sigma_v^2]^{1/2}$.

In case of modelling NO_2 concentrations, the fraction of NO_x directly emitted as NO_2, air temperature and global radiation, and background concentrations of NO_x, NO_2 and O_3 are required in addition to the input information already mentioned for inert species.

2.4. Study of the behaviour of SEUS with ambient wind

The variation of air pollutant concentrations with ambient wind conditions, estimated by SEUS in a hypothetical street canyon orientated east–west is summarised in Fig. 4. The model is run considering that the street canyon is 20 m wide with buildings of 20 m height and the receptor is located on the southern side of the street. Computations are made for a constant traffic flow consisting of 900 light and 100 heavy vehicles per hour, travelling at a speed of 40 km h^{-1}. The emission rate is set to 1000 ppb $m^2\ s^{-1}$. The background concentration is $C_b = 0$ ppb and chemical reactions are not taken into account.

Fig. 4 shows that SEUS clearly reproduces higher concentrations on leeward conditions than on windward conditions. The difference between them decreases for lower wind speeds. In calms, the turbulence created by traffic, determines the dispersion conditions.

This example serves as an illustration of the model behaviour only.

3. Results and discussion

3.1. Site and data

SEUS model has been applied to estimate NO_x and NO_2 hourly concentrations in a street canyon of Córdoba Avenue (Buenos Aires). This street canyon is busy, irregular and asymmetric (Fig. 5). Córdoba Ave. has five lanes, is 30 m wide and is orientated east to west. Buildings on the northern side of the avenue are low (~10 m) and quite regular. On the southern side, buildings are much taller and of different heights (10 m–80 m). Traffic flow in the avenue is approximately 38000 veh day^{-1} with a mean fraction of large vehicles (buses and trucks) of 5%. Average traffic speed is about 30 km h^{-1}. Fig. 6 illustrates the diurnal variation of hourly average traffic flow for working days. Information on traffic flow, average road traffic speed and vehicle fleet composition has been obtained from several reports elaborated by local authorities (GCBA, 2006; GCBA-ACOM, 2006). Unfortunately there is no actual information on traffic flow for the period of study. Model estimations are compared with measurements obtained from a monitoring station at the southern side of the canyon near 10 m east from the intersection with R. Peña St. Traffic flow in Córdoba Ave. is more than three times greater than the traffic flow in the crossing street and it can be expected to be the main responsible for observed air pollutant concentrations at the monitoring site. The monitoring station is located at a kerbside site in a commercial area with buildings destined to business activities and residence. It integrates the air quality monitoring network of the city and belongs to the Environmental Protection Agency of the city of Buenos Aires. At this site, continuous air quality measurements cover CO, NO, NO_x, NO_2,

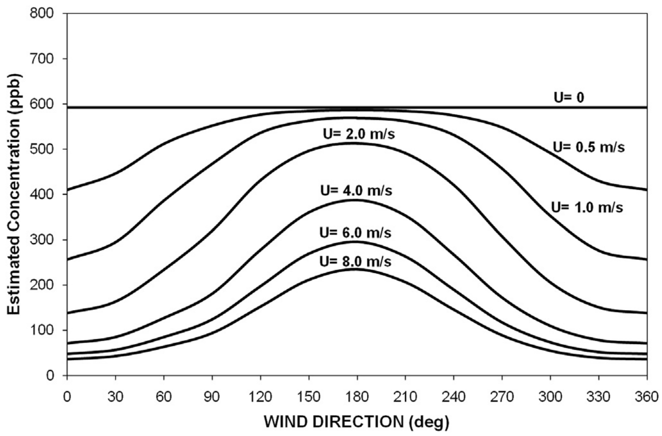

Fig. 4. Variation of estimated concentration with ambient wind direction and speed (U) at a south side receptor in an east-west oriented street canyon.

Fig. 5. Picture of a 3D perspective of the monitoring site location (●) in Córdoba Ave., Buenos Aires. (Picture: Google Earth).

SO_2 and PM10. The measuring height is 2.5 m and the distance from the building walls is 5 m. The concentration of nitrogen oxides was analysed by a chemiluminescence monitor. The accuracy of the monitor was better than 5% at a concentration of 200 ppb for NO. The precision was 1% and the linearity was +/−1% full scale.

SEUS is run using the hourly meteorological information registered at the meteorological station of the National Meteorological Service in the domestic airport located in the city, near the coast about 3.5 km NNE of the monitoring site. Due to lack of available information on ambient wind at the monitoring site wind speed and direction registered at the domestic airport have been considered as ambient wind conditions (Mazzeo and Venegas, 2012). It is recommended to include observed background concentrations in calculations. However, in the city of Buenos Aires there is not a continuous air quality monitoring station representative of urban background concentrations. Several experimental campaigns (Bogo et al., 1999, 2001; Mazzeo et al., 2005) reported low levels of ozone concentration in Buenos Aires. Model calculations are done assuming a value of 23ppb for background ozone concentration based on the background ozone concentration obtained during an experimental campaign and discussed in Mazzeo et al. (2005). On the other hand, background concentrations of NO_x and NO_2 considered in calculations have hourly variations. Modelled hourly background concentrations of NO_x and NO_2 are estimated applying the DAUMOD urban atmospheric dispersion model (Pineda Rojas and Venegas, 2013; Venegas and Mazzeo, 2006) in the Metropolitan Area of Buenos Aires considering an hourly emission inventory with a grid resolution of 1 km^2 (Venegas et al., 2011). In order to avoid double-counting of emissions at the

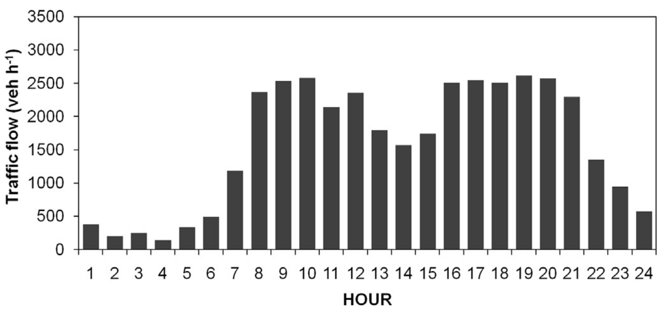

Fig. 6. Diurnal variation of hourly average traffic flow for working days.

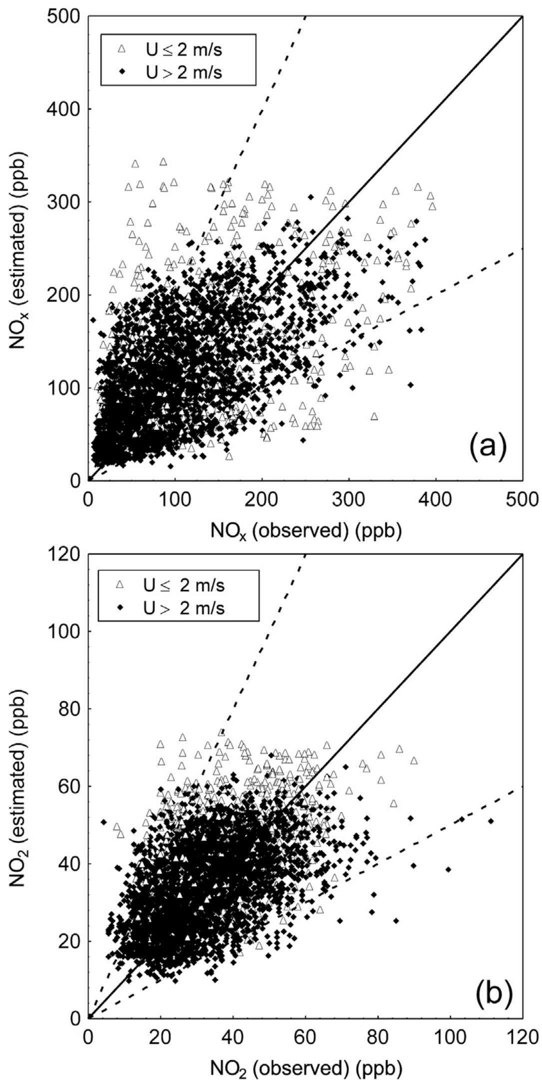

Fig. 7. Comparison between estimated and observed NO_x (a) and NO_2 (b) hourly concentrations (ppb) categorised into two wind speed (U) classes. Lines showing an agreement between estimations and data by a factor of two are also indicated.

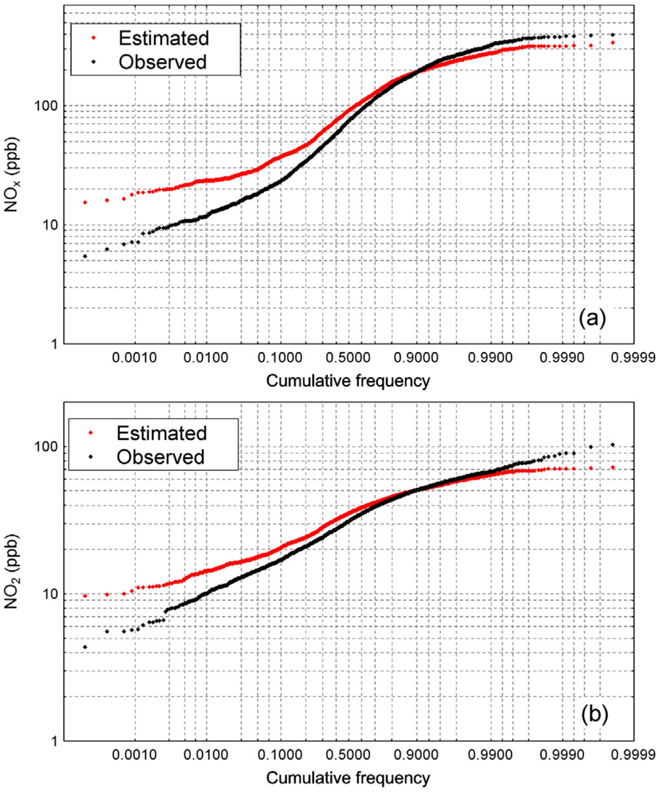

Fig. 8. Estimated and observed cumulative frequency distributions of NO_x (a) and NO_2 (b) hourly concentrations.

receptor, hourly variations of NO_x and NO_2 background concentrations at the receptor grid are obtained averaging the values at the surrounding grids. The direct emission of NO_2 is considered 10% of NO_x (Pineda Rojas and Venegas, 2013).

3.2. Comparison of model results with observations

Seven month of measured hourly concentrations of nitrogen oxides (NO_x) and nitrogen dioxide (NO_2) are available. The comparisons of estimated and observed hourly concentrations of NO_x and NO_2 are presented in Fig. 7. The data have been categorised into two ambient wind speed (U) classes, $U > 2$ m s^{-1} and $U \leq 2$ m s^{-1}. The scatter of observed and estimated data points is wider for low wind speed ($U \leq 2$ m s^{-1}) conditions compared with the cases with higher wind speeds ($U > 2$ m s^{-1}), for both NO_x and NO_2. The internal variation of data points in both scatter plots is substantial. However, for both pollutants, a great portion of data points is located inside the "factor of two" lines.

According to the scatter plots (Fig. 7) the model underestimates the highest concentration values of both pollutants. However, it is also of interest to find out whether the model can generate a concentration distribution that is similar to the observed, especially at the upper percentiles. Fig. 8a–b show comparisons of estimated and observed hourly concentration distributions for NO_x and NO_2, respectively. Notice that in these plots estimated and observed concentrations for the same percentile may not correspond to the same case nor occur under the same conditions. For both pollutants, Fig. 8 illustrates the overestimation of model results at low concentrations, a good agreement at high percentiles and the underestimation of extremely high values. This is of particular interest for hourly NO_2 concentrations because in several countries air quality regulations for NO_2 usually involve the value of the pth percentile (for example, the 98th percentile in the National Ambient Air Quality Standards for the US and in the Environmental Law for the city of Buenos Aires in Argentina, or the 18 permitted exceedences each year-equivalent to the 99.8th percentile- in the EU).

The overestimation of low values suggests an overestimation of background concentrations (C_b). Estimated NO_x and NO_2 hourly concentrations at the lower 10th-percentile range in Fig. 8a–b are sensitive to C_b. In this range, C_b contributed with more than 50% of the estimated concentration in 96% of the NO_x and in 98% of the NO_2 hourly values.

The evaluation of the agreement between SEUS estimations and observations is done considering all data and also regarding: a) wind speed: $U > 2$ m s^{-1} and $U \leq 2$ m s^{-1} (including calms), and b) wind direction: leeward ($22.5° < \theta \leq 157.5°$), windward ($202.5° < \theta \leq 337.5°$) and parallel ($337.5° < \theta \leq 360.0°$; $0.0° < \theta \leq 22.5°$; $157.5° < \theta \leq 202.5°$) situations. Table 2 summarises the statistical evaluation of model performance including the number of values (N), the mean and sigma of estimated (C_e) and

Table 2
Summary of estimated and observed hourly concentrations for NO_x and NO_2 and their agreement. (N: number of cases; NMSE: normalised mean square error; R: correlation coefficient; FA2: fraction of modelled values between a factor 2 of observations; FB: fractional bias).

	All data	$U > 2$ m s^{-1}	$U \leq 2$ m s^{-1}	Leeward	Windward	Parallel
N	4488	3893	595	1229	1725	1390
Results for NO_x						
$Mean_{obs}$ (ppb)	93.7	88.7	126.4	130.7	64.2	95.3
$Mean_{est}$ (ppb)	103.8	99.1	134.8	122.1	81.8	112.0
$Sigma_{obs}$ (ppb)	70.2	66.1	85.7	76.1	53.9	64.4
$Sigma_{est}$ (ppb)	61.1	56.4	78.6	69.0	47.3	57.6
NMSE	0.34	0.31	0.43	0.18	0.54	0.34
R	0.631	0.659	0.467	0.732	0.509	0.548
FA2	0.727	0.735	0.674	0.861	0.630	0.742
FB	−0.103	−0.111	−0.065	0.067	−0.241	−0.161
Results for NO_2						
$Mean_{obs}$ (ppb)	32.8	31.9	38.7	36.1	29.5	33.5
$Mean_{est}$ (ppb)	35.5	34.0	44.9	37.9	31.8	36.6
$Sigma_{obs}$ (ppb)	13.2	12.8	14.2	12.8	13.3	12.5
$Sigma_{est}$ (ppb)	11.6	10.6	12.9	12.3	10.3	10.7
NMSE	0.14	0.13	0.15	0.11	0.16	0.13
R	0.512	0.506	0.409	0.542	0.488	0.458
FA2	0.913	0.919	0.874	0.945	0.881	0.934
FB	−0.078	−0.064	−0.148	−0.048	−0.075	−0.087

observed (C_o) values, and the following measures (Chang and Hanna, 2004):

- Normalised Mean Square Error

$$\mathrm{NMSE} = \overline{(C_o - C_e)^2} \Big/ \left(\overline{C_o}\,\overline{C_e}\right)$$

- Correlation coefficient

$$R = \overline{\left(C_o - \overline{C_o}\right)\left(C_e - \overline{C_e}\right)} \Big/ \left(\sigma_{C_e}\,\sigma_{C_o}\right)$$

- Fraction of estimations within a factor of two of the observations (FA2)

$$0.5 \le C_e/C_o \le 2.0$$

- Fractional bias

$$\mathrm{FB} = 2\left(\overline{C_o} - \overline{C_e}\right) \Big/ \left(\overline{C_o} + \overline{C_e}\right)$$

A perfect model would have $R = 1.0$; FA2 = 1.0; NMSE = 0.0 and FB = 0.0. Chang and Hanna (2004) based on extensive experience with evaluating many models with many field data sets, summarised typical magnitudes of the above performance measures of model acceptance criteria. They concluded that 'acceptable' performing models have the following typical performance measures: FA2 > 0.5, −0.3 < FB < 0.3 and NMSE < 1.5. However, these are not firm guidelines and it is necessary to consider all performance measures in making a decision concerning model acceptance.

Considering all data, 72.7% of NO_x and 91.3% of NO_2 estimated values are between a factor of two of observations. The FB values for the scatter plots of NO_x and NO_2 are −10.3% and −7.8%, respectively. The NMSE values are 34% and 14% for NO_x and NO_2 estimations, respectively. These results show an acceptable performance of SEUS in estimating hourly concentrations of both pollutants in this irregular street canyon, when using routine meteorological information and modelled background concentrations.

Regarding wind speed, the statistics included in Table 2 show a better model performance for $U > 2$ m s^{-1} than for lower ambient wind speeds. For NO_x, the NMSE values are 43% and 31%, the R values are 0.467 and 0.659 and the FB values −6.5% and −11.1% for the estimations obtained for low wind speed ($U \le 2$ m s^{-1}) and for $U > 2$ m s^{-1}, respectively. On the other hand, for NO_2 the NMSE values are 13% and 15%, the R values are 0.506 and 0.409 and the FB values are −6.4% and −14.8% for the scatter plots corresponding to the higher wind speed conditions and lower wind speed conditions, respectively. For lower wind speed cases, model estimations of both pollutants show larger relative errors and weaker correlations compared with the results for higher wind speed.

The analysis of SEUS results regarding the wind direction reveals that the best performance of the model is obtained for leeward cases. In these conditions, 86.1% of NO_x and 94.5% of NO_2 estimations are between a factor of two the observations. The FB values are +6.7% and −4.8%, the NMSE are 18% and 11% and the R values are 0.732 and 0.542, for NO_x and NO_2 estimations, respectively. For both pollutants, the values of NMSE and FB are low.

On the other hand, the model overestimates the hourly concentrations of both pollutants under windward conditions, with FB values of −24.1% for NO_x and −7.5% for NO_2.

The observed and estimated pollution roses for NO_x and NO_2 are shown in Fig. 9a–b, respectively. The pollution roses for NO_x show a clear dependence of concentrations on wind direction. The street canyon effect, i.e. higher leeward than windward concentrations, is

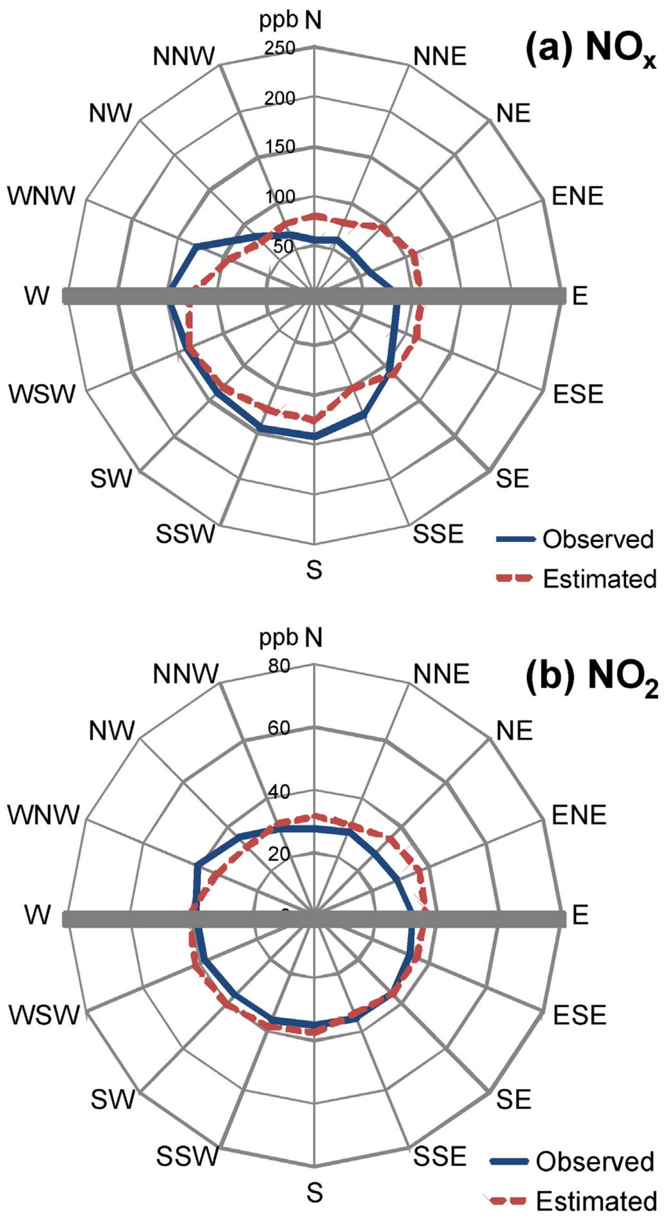

Fig. 9. Comparison between observed and estimated air pollution roses for NO_x (a) and NO_2 (b). The heavy straight line indicates the street canyon orientation. The monitoring site is on the southern side of the street.

clearly reproduced by SEUS, although the observed leeward/windward concentration ratio is higher than the modelled ratio for the perpendicular wind condition. Discrepancies between estimated and observed mean concentration values are more pronounced for wind directions from the sector N − ESE. Building heights in the street canyons of the European cities, on which the model development has been based, are more regular than in Buenos Aires. The existence of irregular building heights and asymmetries in the street canyon where the model is applied may enhance discrepancies between estimations and observations.

The pollution roses for NO_2 show a little variation of mean concentrations with wind direction. This variation can be explained by the fact that NO_2 is mainly a secondary pollutant. In general, the patterns of estimated and observed pollution roses are quite similar. Discrepancies between both pollution roses are more pronounced for wind direction WNW, NE and ENE.

Additionally, traffic emissions in the crossing street may impact particularly on NO_x concentrations and contribute to the higher observed mean concentration for westerly wind direction shown in Fig. 9a. In this direction, the estimated averaged NO_x concentration is 14% less than that observed. The impact of the emissions in the crossing street on NO_2 concentrations registered at the monitoring site is expected to be small due to the secondary nature of this air pollutant (as can be seen in Fig. 9b). The better match between observed and estimated pollution roses for NO_2 than for NO_x is reflected in the lower fractional bias (FB) for NO_2 than for NO_x (Table 2).

The comparison of daily variations of hourly mean estimated and observed concentrations for NO_x and NO_2 are presented in Fig. 10a–b. Diurnal variations are plotted for Mondays to Fridays, Saturdays and Sundays. In general, the shape of diurnal and weekly variations is well reproduced. Uncertainties in traffic flow input data may explain the departures between estimated and observed mean values. Mean hourly concentrations are overestimated at rush-hour in the evening and underestimated during the night. However, from the averaged values shown in Fig. 10 it is not possible to infer any conclusion on model performance in estimating hourly concentrations. This is because hourly concentrations observed at the same hour during the period of study, show a wider spread than hourly estimations for that hour. Therefore, the average of hourly estimations can be greater than the average of hourly observations (as at rush-hour in the evening) whereas for those hours the highest estimated hourly concentration is lower than the observed one (upper percentiles in Fig. 8). On the other hand, at night the model underestimates the averaged values (Fig. 10) but the lowest hourly estimation is greater than the lowest observed value (lower percentiles in Fig. 8).

3.3. Comparison between SEUS and OSPM performances in Córdoba Ave

The performance of SEUS in Córdoba Ave. is compared with that of the well-known widely used Windows-based version of OSPM.

Table 3
Summary of OSPM estimated and observed NO_x and NO_2 hourly concentrations and their agreement (N: number of cases; NMSE: normalised mean square error; R: correlation coefficient; FA2: fraction of modelled values between a factor 2 of observations; FB: fractional bias).

$N = 4488$	Mean (ppb)	Sigma (ppb)	NMSE	R	FA2	FB
NO_x_obs	93.7	70.2	–	–	–	–
NO_{x_OSPM}	116.5	65.6	0.42	0.565	0.677	−0.217
NO_2_obs	32.8	13.2	–	–	–	–
NO_{2_OSPM}	38.4	12.2	0.16	0.486	0.886	−0.157

OSPM is applied to estimate NO_x and NO_2 hourly concentrations in Córdoba Ave. for the same period using the same input information (except for the detailed street configuration) as in SEUS application. The statistical measures to evaluate the performance of OSPM for all data are summarised in Table 3. These values and the obtained for the proposed model (first column of Table 2) show good agreement between the estimations of both models and observations. Also, their performances are quite similar with NMSE of 0.34 (SEUS) and 0.42 (OSPM) for NO_x, and 0.14 (SEUS) and 0.16 (OSPM) for NO_2.

Moreover, Fig. 11a–b show the excellent agreement between SEUS and OSPM estimated NO_x and NO_2 hourly concentrations at street level in Córdoba Ave. The statistical evaluation of SEUS estimations when compared to OSPM results is summarised in Table 4. With NMSE of 0.04 for NO_x and 0.01 for NO_2, there has been no significant discrepancy between the results of both models when using the same input information.

4. Conclusions

This paper describes the simple mathematical street canyon model SEUS which includes empirical expressions for the parameterisation of turbulent motions related to wind and traffic recently obtained from full-scale data. The parameter included in the parameterisation of wind-induced dispersive motions is expressed as a function of wind direction, street orientation and sampling

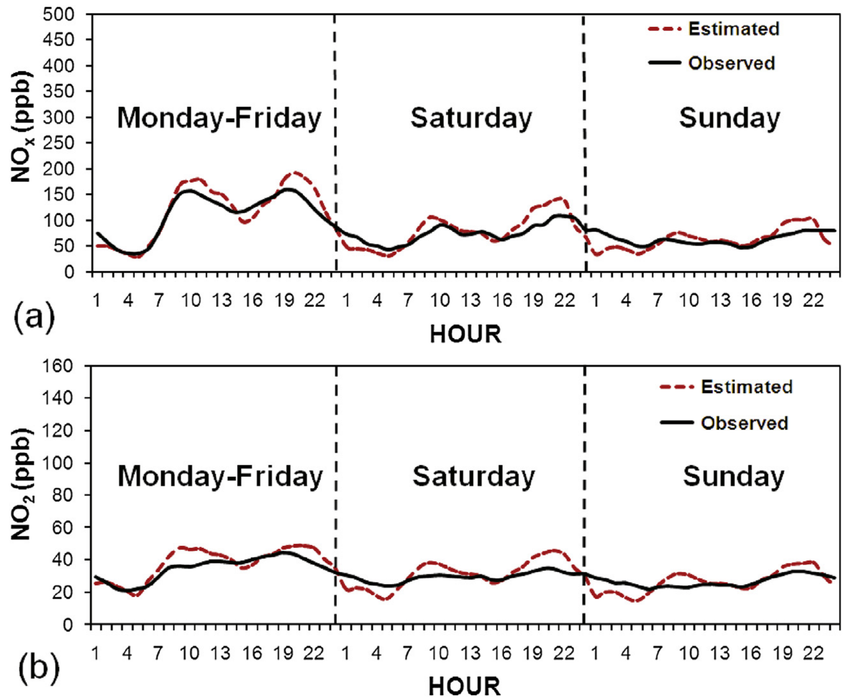

Fig. 10. Average diurnal variation of estimated and observed NO_x (a) and NO_2 (b) concentrations in Córdoba Ave. (Buenos Aires).

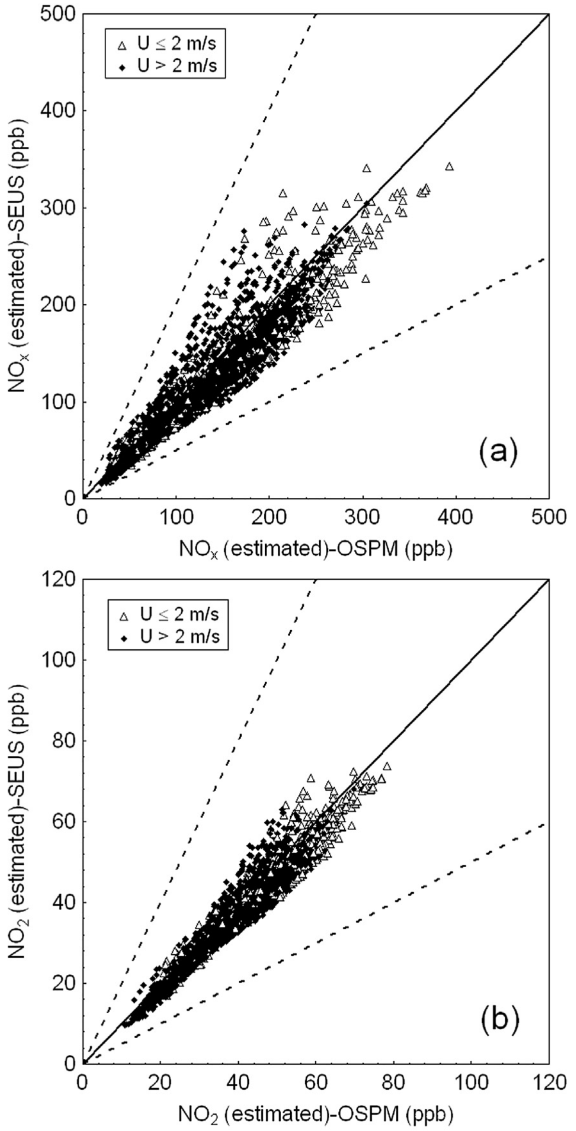

Fig. 11. Comparison between SEUS and OSPM estimated NO_x (a) and NO_2 (b) hourly concentrations in Córdoba Ave. (Buenos Aires).

location within the street. The parameter included in the parameterisation of traffic-induced turbulence is expressed in function of traffic density (traffic flow and composition and traffic velocity). The sensitivity analysis of SEUS model indicates that the uncertainties in the evaluation of the two empirical parameters have less influence on model uncertainties than that of the uncertainties in the other input variables.

Table 4
Summary of SEUS and OSPM estimations of NO_x and NO_2 hourly concentrations and their agreement. (*N*: number of cases; NMSE: normalised mean square error; *R*: correlation coefficient; FA2: fraction of modelled values between a factor 2 of observations; FB: fractional bias).

$N = 4488$	Mean (ppb)	Sigma (ppb)	NMSE	*R*	FA2	FB
$NO_{x\text{–}OSPM}$	116.5	65.6	–	–	–	–
$NO_{x\text{–}SEUS}$	103.8	61.1	0.04	0.958	1.00	0.115
$NO_{2\text{–}OSPM}$	38.4	12.2	–	–	–	–
$NO_{2\text{–}SEUS}$	35.5	11.6	0.01	0.972	1.00	0.079

SEUS can be applied to estimate ground-level concentrations inside street canyons for any non-reacting pollutant if data concerning traffic emissions and urban background concentrations are known. It can also estimate NO_2 concentrations as it takes into account a simple photochemistry between NO, NO_2 and O_3.

SEUS has been applied to estimate NO_x and NO_2 hourly concentrations in an irregular street canyon in the city of Buenos Aires using historical traffic information, routine meteorological data and modelled urban background concentrations. The results have been compared with observations obtained from the station of the Environmental Protection Agency of the city of Buenos Aires in this canyon. For both pollutants, the statistical evaluation shows a good agreement between estimated and observed hourly concentrations. SEUS model has been reasonably accurate, in spite of its simplicity. Furthermore, the performances of SEUS and OSPM models in Córdoba Ave. using the same input data are very similar.

SEUS requires a relative small amount of input information and due to its simplicity it can be easily implemented on a standard spreadsheet which can be used to obtain a first estimation of the air quality at a ground-level receptor inside a street canyon. It could become a useful screening tool in air quality applications, if successful evaluations in a wide variety of urban street canyons are accomplished. Future research will aim at validations of the proposed model for more air quality data obtained in different street canyons.

In air quality assessment at street level, when relevant monitoring data are not available, it is recommended that more than one model should be used to avoid excessive reliance on a specific code.

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