Intercomparison of Atmospheric Dispersion Models Applied To An Urban Street Canyon Of Irregular Geometry

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ABSTRACT

The NOx concentrations measured at the sampling site of Cordoba Avenue, Buenos Aires City, characterised by an irregular geometry on both sides of the street, are used to intercompare results of five urban street canyon dispersion models, STREET, OSPM, AEOLIUSF, STREET-BOX and SEUS. Three different wind directions with respect to the street axis are considered, i.e., leeward, windward and parallel. Additionally, two wind speed classes are considered, above and below 2 m s^{-1}. In order to evaluate the models performance, observed and calculated concentrations are compared using different statistical measures, i.e., mean values, bias, mean square error and fractional error. In general, all models estimate better leeward conditions and wind speeds above 2 m s^{-1}, with SEUSproviding the overall best result.

Keywords: Atmospheric dispersion models; Intercomparison of results; Urban street canyon with irregular geometry

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INTRODUCTION

The main sources of environmental air pollution in urban areas are vehicles. Air quality in urban street canyons is deteriorated, often failing to meet environmental standards due to reduced atmospheric ventilation. These aspects, coupled with the fact that the emission of pollutants occurs near the ground level~~,~~ very close to the receptors, can cause adverse impacts on human health (Gehrsitz, 2017, Khreis, 2017).

The most distinctive feature of airflow within an urban canyon is the formation of an internal vortex, which determines that the wind direction at street level is opposite to that of the air flow above the buildings. The presence of a vortex within the urban canyon was detected by Albrecht (1933) and later verified by Georgii et al. (1967). The air flow within canyons can be described by their aspect ratio (Hosker, 1985; Hussain and Lee, 1980; Oke, 1988; Mei et al., 2016). This flow is also affected by the mechanical turbulence induced by the movement of the vehicles (Eskridge and Rao 1986, Kastner-Klein et al., 2003, Mazzeo and Venegas, 2005, 2011, Mazzeo et al., 2007, Thaker et al., 2016), or created by the roughness elements within the canyon (trees, balconies, moldings) (Hoydysh and Dabberdt, 1994 and Theurer, 1999). On the other hand, the shape and intensity of the vortices can also be affected by the atmospheric stability and other thermal effects induced by the differential heating of the walls and the street (Kwak et al., 2014; Sini et al., 1996, Tan et al., 2015, Vallati et al., 2016).

The study of air pollutants dispersion in urban street canyons, for research or regulatory purposes, is carried out using atmospheric dispersion models that relate the emission and ventilation conditions to the levels of air pollutants concentration.

There are few atmospheric dispersion models that allow routine evaluations of vehicle emissions impact on air quality in urban street canyons. Among these, the most common models are parametric and semi-empirical, for example: STREET (Johnson et al., 1973), OSPM (Hertel and Berkowicz, 1989a), AEOLIUSF (Buckland, 1998) and STREET BOX (Mensink and Lewyckyj, 2001). STREET and STREET–BOX are mainly variations of "box" models, while OSPM and AEOLIUSF are based on concepts introduced by Yamartino and Wiegand (1986) in the Canyon Plume Box Model (CPBM).

OSPM makes use of a simplified parameterisation of atmospheric flow and dispersion conditions in a street canyon. This parameterisation has been deduced from extensive analysis of experimental data and model tests (Berkowicz et al., 1997). AEOLIUSF is based on similar concepts and techniques to those of OSPM. Nevertheless, there are some discrepancies between the estimations of both models due to differences in coding, parameterisation and data pre-processing techniques (Vardoulakis et al., 2007). STREET takes into account the initial mixing of the pollutants and the traffic induced turbulence. In this model, the concentration is inversely proportional to the wind speed at roof level. Finally, STREET-BOX involves a uniform concentration distribution over the street, with the box dimensioned by the length and width of the street and the height of the surrounding built-up area.

The recently developed Semi-Empirical Urban Street (SEUS) model (Venegas et al., 2014), has the advantage of easy implementation requiring limited input data, and includes new empirical parameterisations of wind-related and traffic-induced turbulence in urban street canyons. The objective of this study is the intercomparison of results of four widely used urban street canyon models, namely AEOLIUSF, OSPM, STREET, and STREET-BOX, with the recently developed SEUS, employing hourly NOx concentrations measured at the air quality monitoring station of Cordoba Avenue, Buenos Aires City, historical traffic information, routine meteorological data and modelled urban background concentrations.

BRIEF DESCRIPTION OF MODELS

STREET model (Johnson et al., 1973) was empirically derived using measurements of pollutants concentrations of an urban canyon in San Jose, California. This model assumes that air pollutant concentrations within an urban canyon results from contributions due to the emissions generated by vehicles circulating in the street, or "local" concentration, and "background" concentration resulting from the impact of other emission sources located outside the urban canyon. This model calculates the concentration of inert pollutants in air on both sides of the street (leeward and windward).

The Operational Street Pollution Model (OSPM) (Hertel and Berkowicz, 1989a, 1989b; Berkowicz et al., 1997; Berkowicz, 2000) is based on similar principles of CPBM. The total concentration (C_s) results from the direct contribution of vehicle emissions (C_d) (which is calculated by means of a plume model), added to the contribution of re-circulating pollutants (C_r) within the urban canyon using a box model, and to the background concentration (C_b) of emissions from sources outside the urban canyon, so that $C_s=C_d + C_r + C_b$.

AEOLIUS model emerges as a computational program developed by Buckland (1998), considering the concepts and techniques previously presented by Hertel and Berkowicz (1989a, 1989b) and used in the development OSPM, and has two versions. A simple version (AEOLIUSQ or AEOLIUS Screen) in which the user inputs emission intensity (Q) and the model calculates the concentrations only for wind directions perpendicular and parallel to the axis of the urban canyon, in order to determine the "most critical scenario". Another "full" version (AEOLIUSF) calculates the concentration for any wind direction and requires hourly input information (meteorological data and traffic flow). Although, in general, AEOLIUS is based on the same formulation as OSPM, some differences can be found between both model calculations due to differences in programming codes, parameterizations and input data pre-processing.

STREET BOX (Mensink and Lewyckyj, 2001; Mensink et al., 2002) is a one-dimensional and analytical model that assumes a uniform distribution of pollutants concentration in an urban canyon. Pollutants concentration is determined by the balance between the temporal variations of horizontally transported mass, vertically dispersed and emitted from vehicles, and assumes no recirculation of air flow within the canyon. Turbulent diffusive flux is described using the Prandtl-Taylor hypothesis (Garrat, 1997), so it is assumed that vertical exchange of pollutants occurs on a characteristic length scale given by a typical mixing length associated with turbulent vortices coming from the urban canyon top, intensifying the mass and momentum exchange.

SEUS is an urban-air atmospheric dispersion model developed by Venegas et al. (2014) that calculates pollutant concentrations (C) within street urban canyons as:

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

where E is the emission rate per unit length, u_s the dispersive velocity scale, W is the urban canyon width, C_b is the urban background concentration.

Assuming that air speed fluctuations caused by vehicles circulation contribute to air pollutants dilution within an urban canyon in an additive form to those resulting from the atmospheric processes determined by the wind, it is possible to define a dispersive velocity scale (Kastner-Klein et al., 2001, 2003):

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

where $\sigma_u^2 = aU^2$ is the wind speed variance, $\sigma_v^2 = bv^2$ is the traffic induced velocity variance, U is the ambient wind speed, v is the traffic velocity, and a and b are dimensionless empirical parameters.

Parameter a is the proportionality coefficient between the wind speed variance and wind speed at the urban canyon top. This parameter depends, among other factors, on street geometry, wind direction and the position of the air quality monitoring station (Kastner-Klein et al, 2003, Mazzeo and Venegas, 2010; 2011).

Parameter b depends on the vehicles flow conditions and determines the proportionality between traffic induced velocity variance and traffic flow speed. For windward conditions the term bv^2 is considered null because pollutants emitted within the urban canyon are transported and dispersed mainly by the main vortex generated within the urban canyon and the traffic-induced turbulence contribution can be considered negligible.

In order to determine parameters a and b, data from air quality measurement campaigns in four urban canyons were employed: GöttingerStrasse (Hannover, Germany), Schildhornstrasse (Berlin, Germany), Jagtvej (Copenhagen, Denmark) and Hornsgatan (Stockholm, Sweden). Since these canyons have different orientations with respect to the North and the position of the air quality sensors within them is different in each case, the ambient wind direction (WD) cannot be used as a common indicator of leeward or windward conditions in the four urban canyons. Therefore, a generic parameter θ (in degrees) is defined with the purpose of having a common indicator of the air flow conditions within street canyons with different orientations, as follows (Mazzeo and Venegas, 2011):

$$\theta = WD - ST \qquad \text{when } WD \geq ST \tag{3}$$

$$\theta = WD + 360^o - ST \qquad \text{when } WD < ST$$

where *ST* is the angle between the North and the street axis to the right of the receptor (when facing the street, looking towards the opposite path) (see Fig. 1).

The data of the four canyons are used to calculate parameters *a* and *b*, and the results were combined in order to derive the following general expressions:

$$a = 0.002745\ exp[0.452317 - 1.9803\ sen(0.005557\pi\theta)] \quad (4)$$

$$b = 2.88642*10^{-06}\ (n_v)^{-0.930771} \quad (5)$$

where n_v is the traffic density expressed in km.

DATA

Córdoba Avenue is oriented in the East-West direction, has an average width of 30 m, five lanes, and a traffic flow of approximately 38000 vehicles day^{-1}. The average building height is different on both sides of the avenue, so that in contrast with most of the European canyons it has the particularity of being very irregular and asymmetric (see Fig. 2 for an outline). The average height of the buildings is 40 m in the southern margin of the avenue, varying between 10 m and 80 m, while in the northern side is smaller (average height 10 m) and more uniform. The air quality monitoring station is located on the southern side, almost at the corner of Rodríguez Peña street, so that *ST* = 90 °.

The hourly meteorological data employed are the observations at Aeroparque Aero meteorological station of the National Meteorological Service (approximately 5 km to the northwest of the air quality monitoring station). NOx background concentrations –*Cb*- were estimated using the DAUMOD urban dispersion model (Mazzeo and Venegas, 1991; Venegas and Mazzeo, 2006). Emission data used in DAUMOD were obtained from an emission inventory carried out for the Buenos Aires Metropolitan Area (Venegas et al., 2011). Traffic flow data, vehicular traffic composition and vehicles speed were obtained from different Buenos Aires City Government reports (GCBA, 2006; GCBA-ACOM, 2006). The study covers the period June to December 2009 since it is the only one with available data. Despite the fact that a 7-month period may seem relatively short, it is representative since it contains sufficient wind data for the study. Data from a single street canyon have been used because it is the only one in Buenos Aires City with available air quality measurements.

RESULTS

The five models are used to calculate hourly NOx concentrations and the results are compared with the measurements of the air quality monitoring station of Cordoba Avenue, operated by the Buenos Aires City Government. In order to evaluate the models performance, three different wind directions, relative to the street orientation, are considered: leeward ($22.5° < \theta \leq 157.5°$), windward ($202.5° < \theta \leq 337.5°$) and parallel to the street axis ($157.5° < \theta \leq 202.5°$ and $337.5° < \theta \leq 22.5°$). Fig. 3 shows the quantile-quantile plot of observed vs calculated NOx concentrations with the five models for all wind direction conditions, i.e., leeward, windward, parallel as well as the three wind conditions together, hereinafter identified as whole data set.

Considering the whole data set, the lowest NOx concentrations are slightly overestimated by all models, but over 100 ppb STREET and STREET-BOX considerably underestimate the observations. AEOLIUSF, OSPM and SEUS overestimate the observations up to 200 ppb while higher values are underestimated, but not as much as STREET and STREET-BOX. In the case of the whole data set and leeward conditions, SEUS fits more closely to the 1:1 line, and together with AEOLIUSF and OSPM are the models that in general reproduce better the observed values. In the particular case of leeward conditions, STREET and STREET-BOX display a significant underestimation of the observations throughout the quantile distribution. The worst performance of all models is under windward conditions, in particular AEOLIUSF and OSPM for the lowest concentrations and STREET for the highest concentrations. Under parallel wind conditions, AEOLIUSF and OSPM show a similar behaviour to windward conditions, in which the lowest values are overestimated. STREET and STREET-BOX fit well the observations (particularly STREET) up to 150 ppb, while highest concentrations are underestimated by all models.

Different statistical measures are employed in order to complement the interpretation of results and the intercomparison of the models performance (Chang and Hanna, 2004). The bias is the mean difference between observed (C_o) and calculated (C_e) values, defined as: $(\overline{C_o - C_e})$; the normalized mean square error (NMSE) is defined as: $\left(\frac{\overline{(C_o - C_e)^2}}{\overline{C_o}\,\overline{C_e}}\right)$; the fractional bias (FB) is defined as: $\left(\frac{(\overline{C_o} - \overline{C_e})}{0.5(\overline{C_o} + \overline{C_e})}\right)$ and indicates whether the model underestimates (FB>0) or overestimates (FB<0) the observations; and the data fraction (FA2) indicates the percentage of cases satisfying the condition $0.5 \leq C_e/C_o \leq 2$. In these definitions the overbar means arithmetic average. A “perfect" model should have bias, NMSE and FB equal to zero and FA2 equal to one.

The analysis of the statistical measures is done for the four wind direction conditions and Table 1 presents the results. SEUS shows the best performance of the four statistical measures for leeward conditions. Under windward and parallel conditions STREET has the minimum Bias and

SEUS the second best Bias, while STREET-BOX has the minimum Bias for the whole data set. SEUS has the best NMSE for the four wind direction conditions and the best FA2 in all but parallel wind condition in which is the second best.

The dispersion of pollutants within street canyons is influenced by turbulent processes which strongly depend on wind speed. Therefore, the models performance is also analyzed considering weak winds ($U \leq 2$ ms^{-1}) and strong winds ($U > 2$ ms^{-1}), and Table 2 presents the results of the four statistical measures.

The models show a better performance for wind speeds greater than 2 ms^{-1}. OSPM and SEUS show similar and satisfactory statistical values for both wind speed classes. Considering all wind speeds, SEUS gives the best statistical indicators in comparison to the other models (Table 2 shows the highest FA2 and the lowest FB, NMSE and BIAS).

Fig. 4 shows the pollution roses of observed NOx concentrations (ppb) at Cordoba Avenue air quality monitoring station, and calculated NOx concentrations with the five models. In general, SEUS and OSPM concentrations depart less from observed values in comparison to the other models. All models overestimate the observations in the North-East quadrant, particularly AEOLIUSF, and underestimate the observations in the South-West quadrant, in particular STREET and STREET-BOX. In the case of leeward and parallel wind conditions SEUS, OSPM and AEOLIUSF pollution roses resemble very well the observed one, especially in the wind sectors between South-West and South-East, while the other two models calculate smaller concentrations than SEUS. Under windward conditions all models overestimate the observations and the STREET pollution rose is the closest to the observed one, followed by SEUS. In general, all models perform better under leeward conditions, in comparison to windward and parallel conditions.

Fig. 5 shows the daily mean variation of observed and calculated NOx concentrations composed in two groups of models, i.e., the average of STREET and STREET BOX and the average of SEUS, OSPM and AEOLIUSF, because of their similar results. In general, STREET and STREET BOX represent better the observed mean daily variation, while the other group slightly overestimates the observations particularly during rush hours. At late night all models display a relatively small underestimation of the observations. In the case of SEUS, uncertainties in traffic flow input data may explain the departures between observed and calculated mean values. The concentrations calculated with SEUS include the background concentration *Cb* obtained with DAUMOD. According to Venegas and Mazzeo (2002), DAUMOD slightly underestimates low values and overestimates high values of hourly mean concentrations. Therefore, the averaged SEUS hourly concentrations may result greater than the average hourly observations (as at rush-hour in the evening), whereas at night they are lower than the observations.

DISCUSSION AND CONCLUSIONS

Most of the investigated models have been used in a number of studies for several years in different urban street canyons. Their strength and weaknesses are quite well established, as well as sensitivity analysis. For example in Plantin en Moretuslei, a street in the city of Antwerp (Belgium), Mensink et. al (2006) found that the OSPM hardly shows any difference between leeward and windward side of the street, whereas STREET does. OSPM and STREET BOX underestimate the highest percentiles, probably due to the lack of accurate background concentrations. Ganguly and Broderick (2011) compare observed data from a street canyon in Dublin, Ireland, with results from STREET and OSPM and obtain a better correlation with the last one. This model was applied in Runeberg Street (Helsinki, Finland) with reasonable accuracy using modeled urban background and pre-processed meteorological values as model input (Kukkonen et al., 2003). Vardoulakis et al. (2002) studied the sensitivity of OSPM in busy street canyons in Paris and identify large uncertainties only in vehicle emission factors. Venegas and

Mazzeo (2012) applied STREET, STREET-BOX, AEOLIUS and OSPM in Göttinger Strässe (Hannover, Germany). STREET improves results by proposing a different value of the empirical constant k = 12.1 (originally k = 7). STREET-BOX gives acceptable results for leeward and intermediate wind direction conditions. The results obtained with OSPM and AEOILUSF are the ones with minimum difference with respect to the observed values in Göttinger Strässe. Vardoulakis, et al. (2007) apply OSPM and AEOLIUS Full in two busy low-rise canyons in Birmingham and London and find underestimation of the annual mean concentrations in most cases, and variable performance depending on location, time of the day, day of the week and prevailing wind conditions.

In general, SEUS, AEOLIUSF and OSPM are the models that represent better the observations in the present study. This is probably due to the fact that these models incorporate the parameterization of: a) the direct contribution of vehicular emissions and the indirect contribution due to pollutant recirculation within the canyon; and (b) the influence of vehicle-induced turbulence on pollutant dispersion within the urban canyon (Mensink et al, 2006; Ganguly and Broderik, 2011; Venegas and Mazzeo, 2011). Cordoba Avenue canyon has a different average building height on both sides of the street, in contrast with the European canyons whose results were discussed in the previous paragraphs. Therefore, SEUS, AEOLIUSF and OSPM would be the more suitable models for urban canyons with irregular and asymmetric geometry. The best overall performance is obtained with SEUS according to the results of the statistical indicators FA2, FB, NMSE and BIAS. The advantage of SEUS is that it requires a small amount of input data and, given its simplicity, can be easily implemented in a spreadsheet to provide a first estimation of air quality within an urban canyon.

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Figure Captions

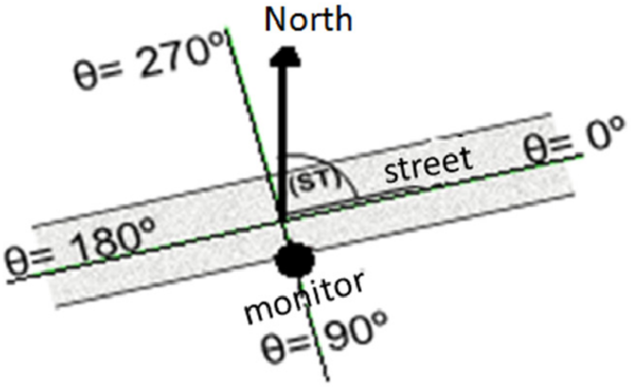
Fig. 1. Definition of parameter θ

Fig. 2. Outline of Cordoba Avenue urban canyon. Black dot indicates the sampler location.

Fig. 3. Quantile-quantile representation of observed and calculated NOx concentrations with STREET, OSPM, AEOLIUSF, STREET BOX and SEUS, for different wind conditions.

Fig. 4. Pollution rose of observed NOx concentrations (ppb) at Cordoba Avenue sampling site, and calculated with STREET, OSPM, AEOLIUSF, STREET BOX and SEUS models. The dotted black line represents the urban street canyon orientation.

Fig. 5. Daily mean variation of observed NOx concentrations (ppb) at Córdoba Avenue air quality station and calculated by two groups of models, the average of STREET BOX and STREET, and the average of SEUS, OSPM and AEOLIUSF.



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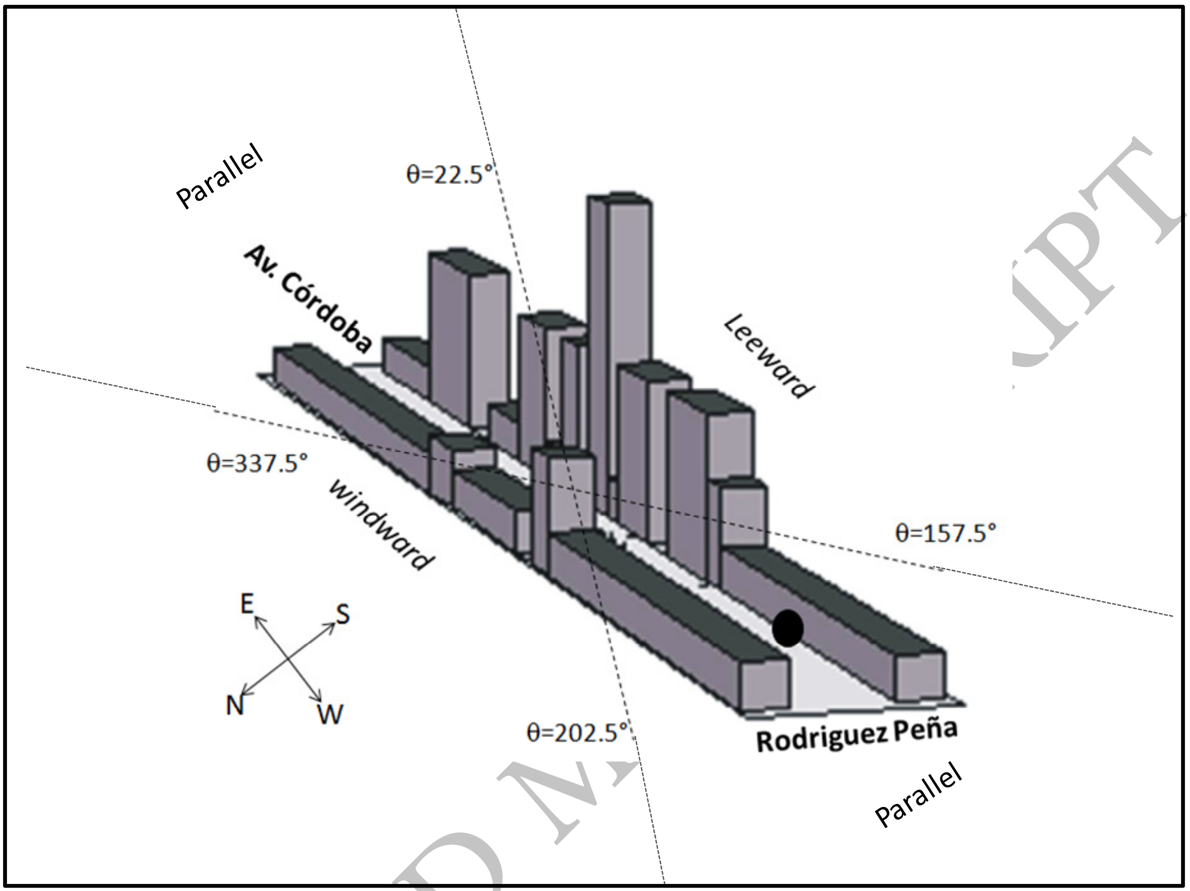
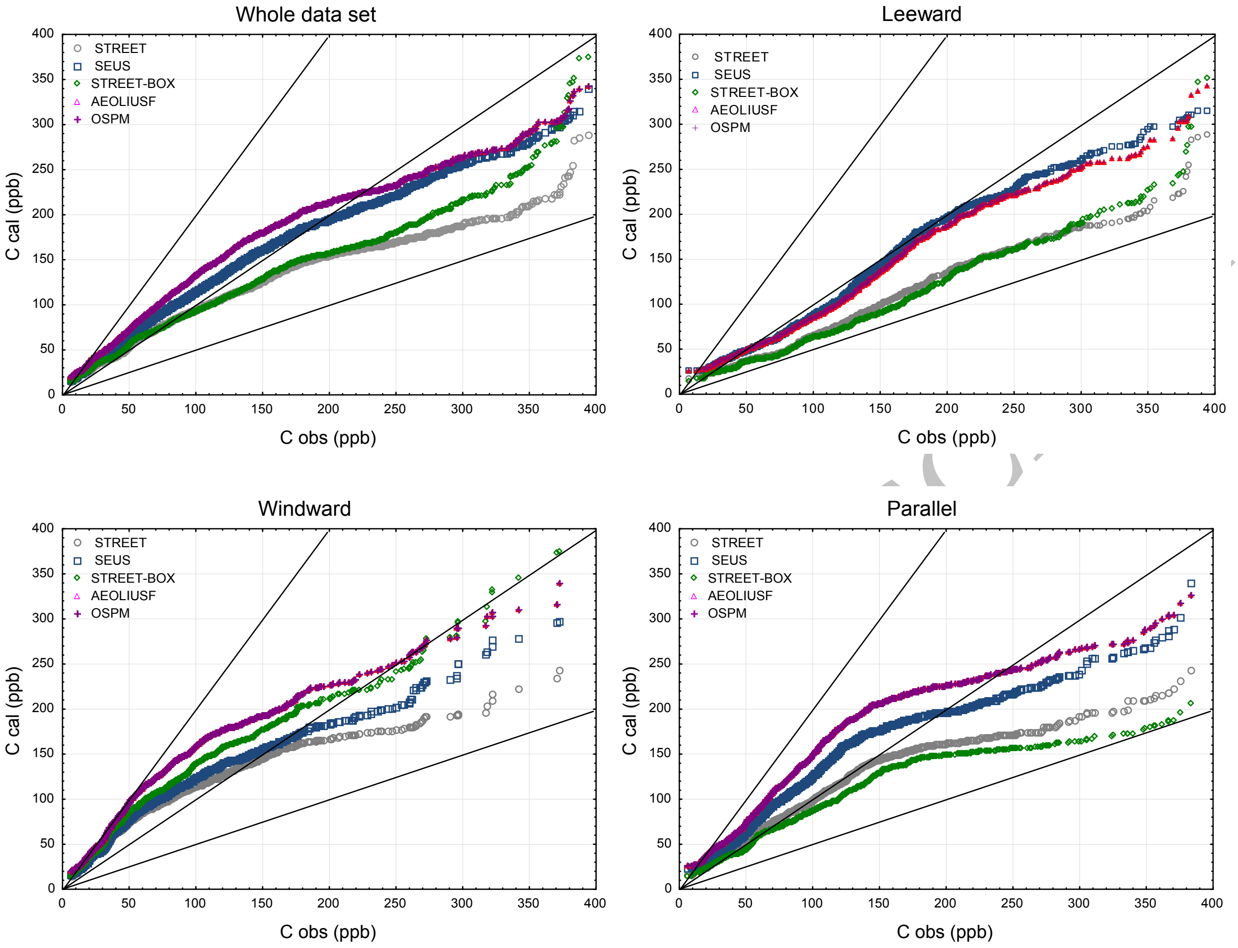


Fig. 2: Outline of Cordoba Avenue urban canyon. Black dot indicates the sampler location.



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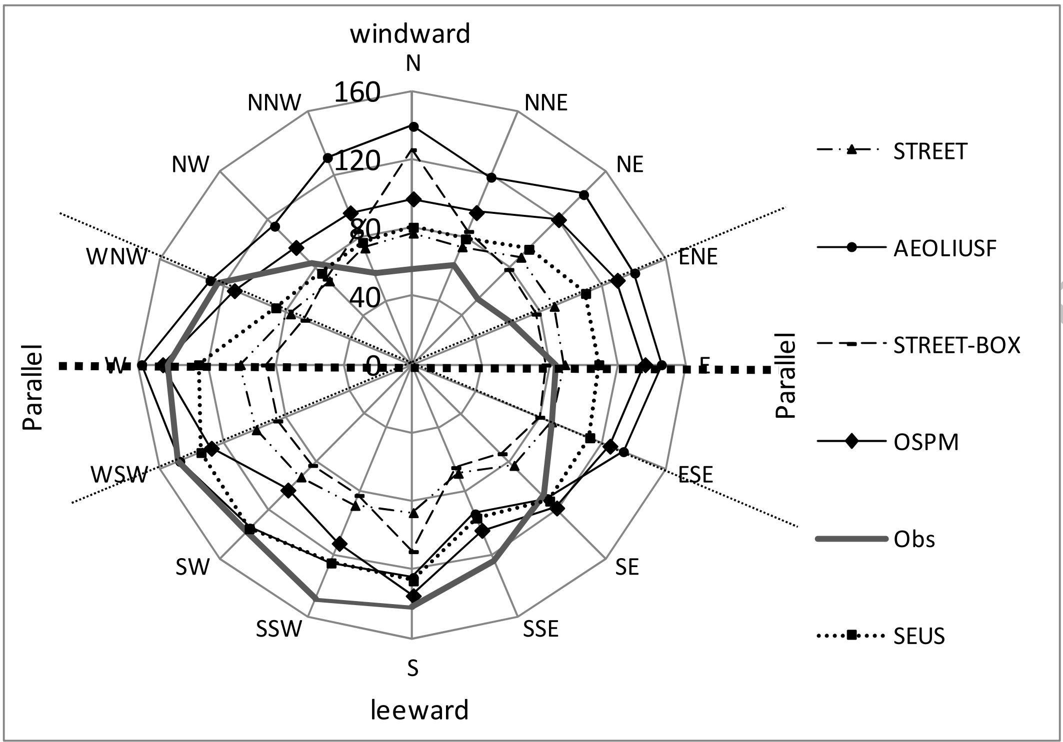

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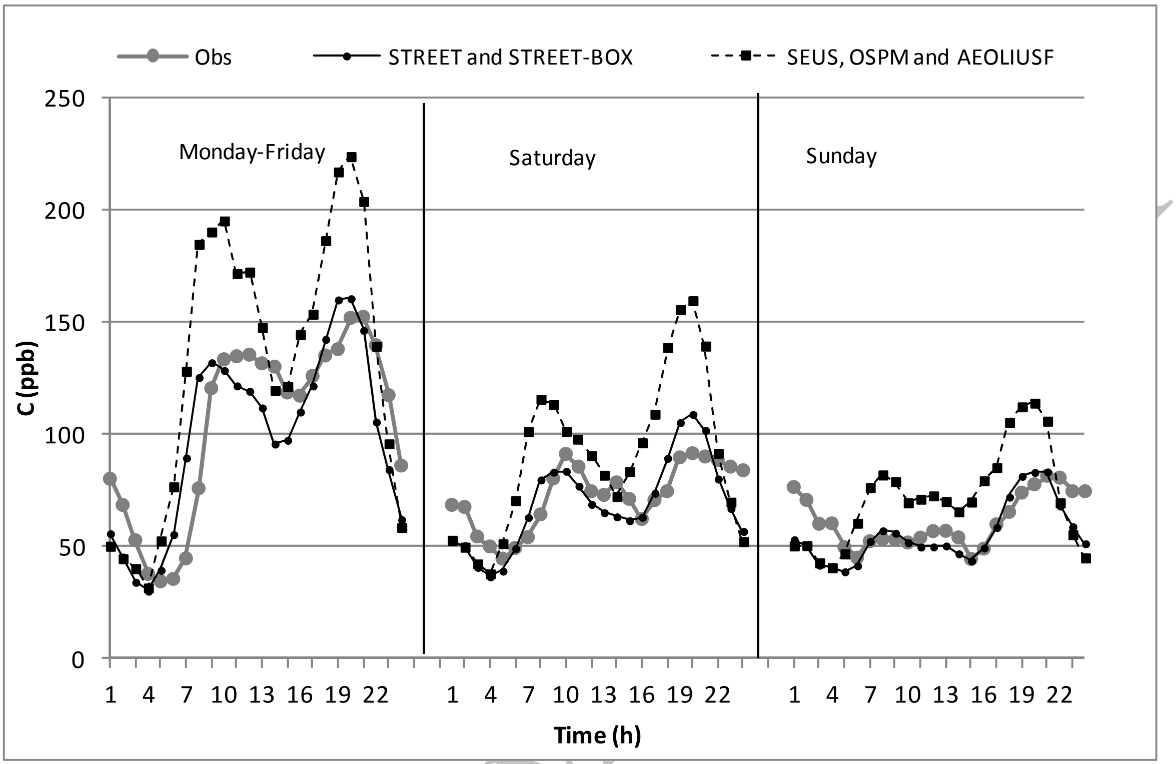

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Table 1. Statistical evaluation of STREET, OSPM, AEOLIUSF, STREET BOX and SEUS, for each wind condition, including Bias; Normalized Mean Square Error (NMSE); Factor 2 (FA2) and Fractional Bias (FB). Dark (light) gray shaded rectangles highlight the best (second best) statistical values.

Table 2: Statistical evaluation of STREET, OSPM, AEOLIUSF, STREET BOX and SEUS, for low wind speeds (U≤2 ms^{-1}) and high wind speed (U>2 ms^{-1}), including Bias; Normalized Mean Square Error (NMSE); Factor 2 (FA2) and Fractional Bias (FB). N is the number of cases. Dark (light) gray shaded rectangles highlight the best (second best) statistical values.

Table 1: Statistical evaluation of STREET, OSPM, AEOLIUSF, STREET BOX and SEUS, for each wind condition, including Bias; Normalized Mean Square Error (NMSE); Factor 2 (FA2) and Fractional Bias (FB). Dark (light) gray shaded rectangles highlight the best (second best) statistical values.

Model	Bias (ppb)	NMSE	FA2	FB
All (N=4353)				
STREET	9.65	0.46	0.687	0.109
OSPM	-21.97	0.40	0.681	-0.211
AEOLIUSF	-37.00	0.52	0.595	-0.331
STREET BOX	8.54	0.56	0.644	0.096
SEUS	-10.32	0.34	0.726	-0.105
Leeward (N=1234)				
STREET	44.32	0.45	0.685	0.408
OSPM	13.00	0.21	0.839	0.105
AEOLIUSF	9.10	0.23	0.81	0.072
STREET BOX	47.51	0.51	0.656	0.444
SEUS	8.69	0.18	0.860	0.069
Windward (N=1725)				
STREET	-12.44	0.54	0.63	-0.177
OSPM	-37.20	0.68	0.554	-0.449
AEOLIUSF	-64.11	1.01	0.408	-0.666
STREET BOX	-25.54	0.72	0.57	-0.332
SEUS	-17.59	0.54	0.63	-0.241
Parallel (N=1394)				
STREET	5.81	0.39	0.752	0.063
OSPM	-34.09	0.41	0.699	-0.302
AEOLIUSF	-44.29	0.46	0.634	-0.375
STREET BOX	16.23	0.49	0.723	0.185
SEUS	-16.20	0.35	0.741	-0.156

Table 2: Statistical evaluation of STREET, OSPM, AEOLIUSF, STREET BOX and SEUS, for low wind speeds ($U \leq 2$ ms^{-1}) and high wind speed ($U > 2$ ms^{-1}), including Bias; Normalized Mean Square Error (NMSE); Factor 2 (FA2) and Fractional Bias (FB). N is the number of cases. Dark (light) gray shaded rectangles highlight the best (second best) statistical values.

MODELS	**STREET**		**OSPM**		**AEOLIUSF**		**STREET BOX**		**SEUS**	
U (m.s^{-1})	U>2	≤2	>2	≤2	>2	≤2	>2	≤2	>2	≤2
N	3902	451	3902	451	3901	451	3902	451	3898	451
Bias (ppb)	8.19	22.29	-22.38	-18.45	-38.58	-23.37	7.08	21.19	-10.14	-5.86
NMSE	0.45	0.45	0.39	0.44	0.53	0.44	0.54	0.59	0.31	0.37
FA2	0.691	0.654	0.685	0.65	0.589	0.647	0.65	0.588	0.735	0.696
FB	0.096	0.188	-0.223	-0.133	-0.356	-0.165	0.083	0.178	-0.108	-0.04