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Evaluation of an Emission Inventory and Air Pollution in the Metropolitan Area of Buenos Aires

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1. Introduction

Air is a vital resource, so its quality must fall within a tightly bound range. This quality is the level needed to protect public health. In addition, the quality must be able to support other life, notably diverse and sustainable ecosystems. The atmosphere is an extremely complex system in which numerous physical and chemical processes occur simultaneously. Ambient measurements give us only a snapshot of atmospheric conditions at a particular time and location. Such measurements are often difficult to interpret without a clear conceptual model of atmospheric processes. Moreover, measurements alone cannot be used directly by policymakers to establish an effective strategy for solving air quality problems. An understanding of individual atmospheric processes (chemistry, transport, removal, etc.) does not imply an understanding of the system as a whole. Mathematical models provide the necessary framework for integration of our understanding of individual atmospheric processes and study of their interactions. A combination of state-of-the-science measurements with state-of-the-science models is the best approach for making real progress toward understanding the atmospheric environment. Over the past four decades, there has been a significant increase in the number of locations where air quality data have been obtained. Also, there has been a substantial improvement in the technique for modelling the different physical and chemical processes occurring in the atmosphere. Despite this progress, currently available observations are still spatially and temporally sparse and the predictions of current generation of air quality models are still uncertain. Consequently, observations and model outputs should be combined to create high-resolution spatial-temporal maps of air quality. However, at present air quality observations and model results are generally used separately.

Urban air pollution is still on rise at many cities worldwide, or has experienced only small improvements. Some causes of urban air pollution problems are the amount and density of air pollutant sources, particularly vehicles, residences and industries. Because of the complexity of urban systems, air quality management in these areas is still a serious problem.

Emission inventories are important tools to describe the emission situation and eventually to manage air quality. An emission inventory is a list of the amount of pollutants from

different sources entering the air in a given time period and a particular geographical area. It usually includes information on the amount of the pollutants released from major industrial sources, and averages figures for the emissions from smaller sources throughout the area. The information included in an emission inventory helps to identify the sources and in the development of abatement strategies. Ball & Radcliffe (1979) have identified several applications for urban air pollution emission inventories. Their information is useful to elaborate a map showing the geographic distribution of emissions. This map can be an important aid in land use planning by identifying parts of the region that are likely to be subject to high levels of pollution, and the location of pollution sources in relation to sensitive areas. Emission inventories can point out the major sources whose control can lead to a considerable reduction of pollution in the area. They can be used in conjunction with an atmospheric dispersion model, to estimate air pollutant concentrations at ground level and/or assess trends in air quality. They can also help in the design of air quality monitoring networks, by indicating, for example, where the highest concentrations of pollution are likely to be found, or which areas are the most representative.

The method used to develop an emission inventory does have some elements of error, but other two alternatives are expensive and subject to their own errors. The first alternative would be to monitor continually every major source in the area. The second alternative would be to monitor continually the pollutants in ambient air at many points and apply appropriate dispersion equations to calculate the emissions. In practice, the most informative system would be a combination of all three, knowledgeably applied. Air pollution emission inventories have been developed for several urban areas (Andrade et al., 2010; Ariztegui et al., 2004; Beaton et al., 1992; Borrego et al., 2003; Butler et al., 2008; D'Avignon et al., 2010; Gurjar et al., 2008; Kim, 1996; Miller et al., 2006; Mohan et al., 2007; Nishikawa & Kannari, 2010; Saija & Romano, 2002; Sallés et al., 1996; Seika et al., 1996; Sturm et al., 1999; Tsilingiridis et al., 2002; Wang et al., 2010; Zárate et al., 2007). Particularly, a few years ago, the first versions of an urban emission inventory (year 2000) for the city of Buenos Aires (Mazzeo & Venegas, 2003) and for area sources located in the Metropolitan Area of Buenos Aires (year 2005) (Pineda Rojas et al., 2007) have been prepared.

An emission inventory is an essential tool in the management of local air quality, particularly when its information is used in conjunction with atmospheric dispersion models.

A model is a simplified representation of real conditions. It contains assumptions and sometimes also some experimentally derived constants. Operational decisions based on predictions of a model should be made therefore when the underlying assumptions are met and when the model is being applied within the range of values for which the model has been tested. Atmospheric dispersion models provide a link between the source emissions and ambient concentrations. The heart of the matter is to estimate the concentration of a pollutant at a particular receptor point by calculating from basic information about the source of the pollutant, the meteorological conditions and the surface characteristics. Atmospheric dispersion models help us to understand the way air pollutants behave in the environment and are a useful tool in the urban air quality management system. There are many reasons for using atmospheric dispersion models, such as working out which sources are responsible for what proportion of concentration at any receptor; estimating population exposure on a higher spatial or temporal resolution than is practicable by measurement; targeting emission reductions on the highest contributors; and predicting concentration changes over time. Urban atmospheric dispersion models range from simple empirical

models to complex three-dimensional urban air-shed models. Sometimes, available input data make application of complex numerical tools not possible, and simple urban background pollution models become an acceptable alternative giving as good results as computations with more sophisticated models (Berkowicz, 2000; Hanna et al., 2002). Some examples of urban scale dispersion modelling systems developed during last decades are the UAM model (Morris & Myers, 1990), the DAUMOD model (Mazzeo & Venegas, 1991; 2010); the Danish OML model (Olesen, 1995), the UK-ADMS Urban model (Carruthers et al., 1994; CERC, 2003; McHugh et al., 1997) and the UDM-FMI (Karppinen et al., 2000) model. Dispersion models for the urban scale estimate urban background concentrations.

This chapter presents a summary of the development and results of a high spatial and temporal resolution version of the emission inventory of carbon monoxide (CO) and nitrogen oxides (NO_x) for the Metropolitan Area of Buenos Aires (MABA), including area source emissions (motor vehicles, aircrafts, residential heating systems, commercial combustion and small industries). The spatial distributions of CO and NO_x annual emission rates from area sources within the Metropolitan Area of Buenos Aires are shown with a spatial resolution of 1 × 1 km. The urban atmospheric dispersion model DAUMOD is applied to evaluate the air quality in the MABA due to the contribution of area source emissions in the urban area. Estimations of horizontal distributions of CO and nitrogen dioxide (NO₂) background concentrations in the MABA are presented.

2. Description of the Metropolitan Area of Buenos Aires

The Metropolitan Area of Buenos Aires (MABA) is considered the third megacity in Latin America, following Mexico City (Mexico) and Sao Paulo (Brazil). It is integrated by the city of Buenos Aires (CBA) and the Greater Buenos Aires (GBA). The city of Buenos Aires (Lat. 34°35'S – Long. 58°26'W), capital of Argentina, is located on the west coast of de la Plata River. The city has an extension of 203km² and 2891082 inhabitants (Instituto Nacional de Estadística y Censos [INDEC], 2010). The city of Buenos Aires is surrounded by the Greater Buenos Aires. This area is compound by 24 districts. It has an extension of 3627km² and 9910282 inhabitants (INDEC, 2010). The area of the MABA is 0.14% of the territory of Argentina and its population is approximately 32% of the population of the country. Fig. 1 shows the different districts of the Metropolitan Area of Buenos Aires and the grid net considered in calculations.

The terrain is flat with height differences lesser than 30 m. The de la Plata River is a shallow estuary, which covers 35000 km² approximately. The estuary is 320 km long, and its width varies between 38 km and 230 km in the upper and lower regions, respectively. In front of the CBA, the width of the river is about 42 km. The mean water temperature in the river varies from 12°C in winter to 24°C in summer.

The de la Plata River plain has a temperate climate. In summer (December to February), the city of Buenos Aires is warm and moist, with a mean temperature of 24°C. During autumn and spring atmospheric conditions are variable, with fluctuating temperatures. The winter months (June to August) are temperate and moist, with a mean temperature of 12°C. The annual mean temperature in the city is 18°C, and between 15-16°C in its surroundings. In the MABA, frosts occur between June and August, and snowfalls are very rare. The annual precipitation varies between 900 mm and 1600 mm, influenced by winds that advect humidity from the Atlantic Ocean. Rains are heavier on March. Winds are generally of low intensity. Strong winds are more frequent between September and March, when the greatest

storm frequency is observed. The annual frequency of winds blowing clean air from the river towards the urban area is 58%, and that of calm conditions is 3%. Cases of wind direction persistence may last more than 6 hours at any wind direction sector (Mazzeo & Venegas, 2004).

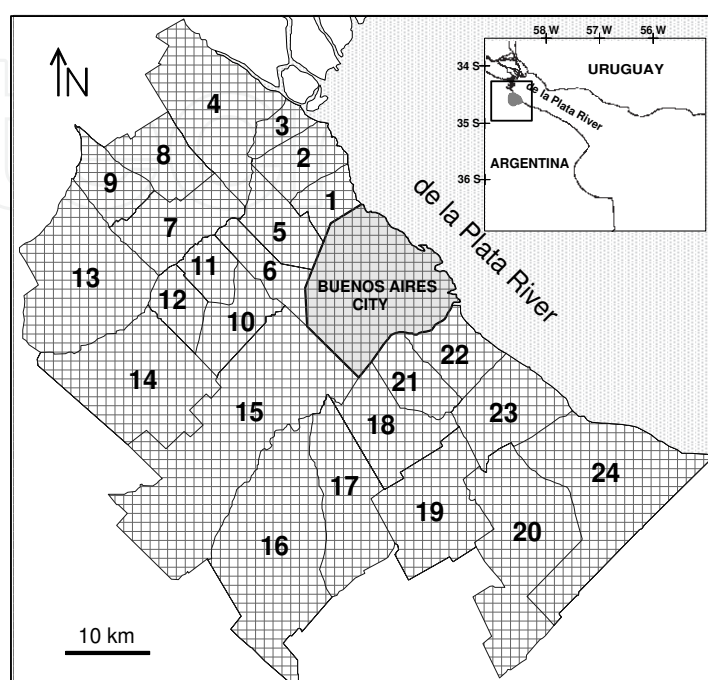


Fig. 1. Map of the Metropolitan Area of Buenos Aires, including the city of Buenos Aires and the Greater Buenos Aires. Districts of the Greater Buenos Aires (*inhabitants*): 1: Vicente López (270929); 2: San Isidro (291608); 3: San Fernando (163462); 4: Tigre (380709); 5: Gral. San Martín (422830); 6: Tres de Febrero (343774); 7: San Miguel (281120); 8: Malvinas Argentinas (321833); 9: José C. Paz (263094); 10: Morón (319934); 11: Hurlingham (176505); 12: Ituzaingó (168419); 13: Moreno (462242); 14: Merlo (524207); 15: La Matanza (1772130); 16: Ezeiza (160219); 17: Esteban Echeverría (298814); 18: Lomas de Zamora (613192); 19: Almirante Brown (555731); 20: Florencio Varela (423992); 21: Lanús (453500); 22: Avellaneda (340985); 23: Quilmes (580829); 24: Berazategui (320224). Grid cell side: 1km.

Mazzeo & Venegas (2008, 2010) and Venegas & Mazzeo (2006a, 2010a) proposed and applied methodologies to design different air quality monitoring networks for the city of Buenos Aires. At present, air pollutant concentrations are registered at the first three air quality monitoring stations of the network in the city (Venegas & Mazzeo, 2010b). The air quality in the city of Buenos Aires has been the subject of several studies carried out during the last years using different methodologies: analysis of data obtained from some measurement surveys of pollutants in urban air (Arkouli et al., 2010; Bocca et al., 2006; Bogo et al., 1999, 2001, 2003; Mazzeo & Venegas, 2002, 2004; Mazzeo et al., 2005; Venegas & Mazzeo, 2000, 2003; Vogt et al., 2007) and application of atmospheric dispersion models (Mazzeo & Venegas, 2010; Mazzeo et al., 2010; Venegas & Mazzeo, 2005, 2006b, 2010a). In the Greater Buenos Aires, very few air quality measurements have been made (Fagundez et al., 2001; Japan International Cooperation Agency-Secretaría de Desarrollo Sustentable y Política Ambiental [JICA-SAyDS], 2002).

3. Brief description of pollutants considered in this chapter

The pollutants considered in this chapter are carbon monoxide (CO) and nitrogen oxides (NO_x). Carbon monoxide is generated primarily by incomplete combustion of carbonaceous fuels in automobile engines and is a colourless and odourless gas. It is a very stable compound having a lifetime of two to four months in the atmosphere. There are studies (e.g. Harte et al., 1991), which show that high concentrations of CO can cause physiological and pathological changes and ultimately death of human. Carbon monoxide is a poisonous inhalant that deprives the body tissues of necessary oxygen. It is toxic because haemoglobin absorbs CO more readily than oxygen. With the bloodstream carrying less oxygen, brain functions is affected and heart rate increases in an attempt to offset the oxygen deficit. In very high doses it is fatal due to cerebral and cardiac hypoxia.

The stable gaseous oxides of nitrogen include nitrous oxide (N₂O), nitric oxide (NO), nitrogen trioxides (N₂O₃), nitrogen dioxide (NO₂) and nitrogen pentoxide (N₂O₅). An unstable NO₃, also exist. The nitrogen oxides present in the atmosphere in any significant amount are N₂O, NO and NO₂. N₂O is an inert gas with anaesthetic characteristics. Its atmospheric concentrations are considerably below the threshold concentration for biological effects, but it may be a significant contributor to global warming. NO is a colourless gas and at its air concentrations its biological toxicity in terms of human health is insignificant. However, NO is a precursor to the formation of NO₂ and is an active compound in photochemical smog formation as well. NO₂ is a reddish brown gas and is quite visible in sufficient amounts. The toxicological and epidemiological effects of NO₂ on human being are not completely known (WHO, 2006a). NO₂ may penetrate to the pulmonary region increasing susceptibility to respiratory pathogens.

4. The emission inventory for the MABA

4.1 Inventory technique

To develop an emission inventory for an area, one must: a) determine the type of air pollutants of concern, such as CO and NO_x; b) list the types of sources for the area, such as motor vehicles, aircrafts, residential, commercial and industrial combustions; c) examine the literature to find valid emission factors for each pollutant of concern; d) through an actual count, or means of some estimating technique, determine the number and size of specific sources in the area; and e) multiply the corresponding numbers from c) and d) to obtain the total emissions for each activity and then sum the similar emissions to obtain the total for the area. Valid emission factors for each source of pollution are the key to an emission inventory. Emission factors are then applied to the activity data in order to estimate the likely emissions:

$$\text{Emission} = \text{Activity level} \times \text{Emission factor} \quad (1)$$

This chapter focuses on area source emissions of CO and NO_x in the Metropolitan Area of Buenos Aires. The following source categories are considered:

- Mobile sources: road traffic and aircrafts
- Fixed sources: residential, commercial and small industries activities.

Point source emissions could not be included because, at present, there is not available sufficient data on the large industries located in the MABA. Information on the actual point source emissions is only available in a limited number of cases. There is also a lack of

homogeneity among the amount and quality of basic information available for each district of the MABA. The existence of multiple local Administrations in the region is the main reason for such heterogeneity. Furthermore, it should be noted that the city of Buenos Aires is a city-state and the 24 districts of the Greater Buenos Aires are part of the Province of Buenos Aires. CBA and GBA have different Governments.

4.2 Emissions from mobile sources

Main mobile sources in the Metropolitan Area of Buenos Aires have been divided into the following groups:

- Road traffic: passenger cars (including taxis), buses (including coaches) and heavy-duty vehicles.
- Air traffic: aircraft’s landing-take-off (LTO) cycles at the domestic airport located in the city of Buenos Aires and at the international airport located in the Greater Buenos Aires.

4.2.1 Road traffic emissions

There are usually about three million vehicles circulating in the MABA during working days. The city of Buenos Aires and its surroundings concentrate approximately 43% of private cars, 60% of taxis, 50% of urban and interurban buses and 29% of cargo transportation of Argentina. As mentioned above, the methodological approach to estimate the emission rates from road traffic is based on the multiplication of activity data by emission factors. The first step involves the determination of an estimate of vehicle activity. Five traffic parameters are considered: volume, composition, vehicle velocity, vehicle age and travel distance in each grid cell. All traffic data have been obtained from the National Secretary of Transportation, the Buenos Aires City Government and the Secretary of Transportation of the Province of Buenos Aires. Available information includes mean daily traffic flow at several locations as well as traffic flow and composition measured at different hours of the day on different streets, routes, avenues and highways in the MABA. Most private cars are petrol-driven and taxis burn natural gas. All the buses and heavy duty vehicles are considered to run on diesel. The approximately age of the vehicle fleet is illustrated in Fig.2.

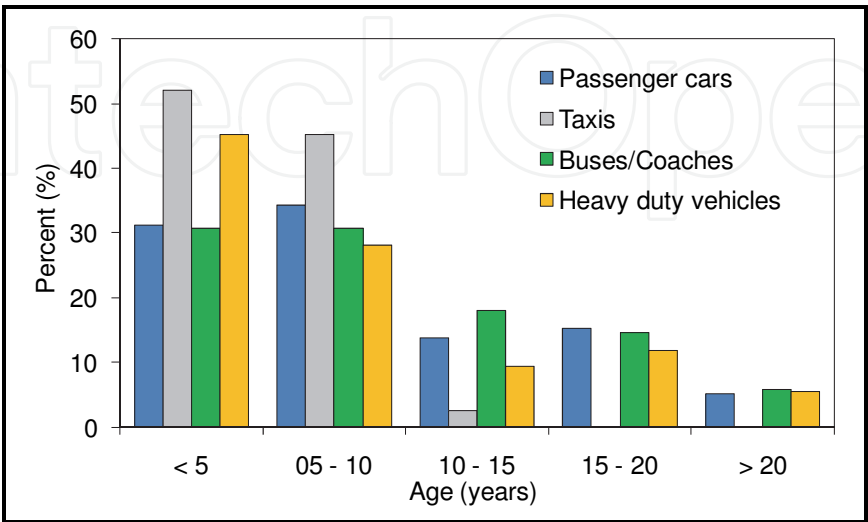


Fig. 2. Distribution of the age of each vehicle category.

The road network of the Metropolitan Area of Buenos Aires is assumed to be integrated by: highways, routes, avenues, main streets and streets. These specifications are quite useful since they generally correspond to particular traffic density levels and fleet compositions. Statistical shapes for traffic rates and average speed on these road types are then applicable to the CBA and the GBA. Based on measurements at several sites, the following vehicle fleet compositions are considered for the entire domain: a) highways: 89.7% (passenger cars) and 10.3% (buses and heavy duty vehicles); b) routes, avenues and main streets: 95.0% (passenger cars) and 5.0% (buses and heavy duty vehicles); and c) streets: 99.0% (passenger cars) and 1.0% (buses and heavy duty vehicles). As it is difficult to define a law to estimate a spatial vehicle speed evolution along a road, an average vehicle speed has been set for each road type (highways, routes, avenues, main streets, streets). The second step involves selecting emission factors. The emission factors used for mobile sources are based on measurements of in-service emissions in Buenos Aires (Rideout et al. 2005) and on the European Environment Agency's Atmospheric Emission inventory Guidebook (COPERT method) (European Environment Agency, 2001). Results for the city of Buenos Aires and for the Greater Buenos Aires are described below.

In the city of Buenos Aires passenger cars employ the following fuels: 78.9% gasoline; 16.0% diesel and 5.1% compressed natural gas (CNG). Traffic flow data in the city are available at different sites located in highways, avenues and streets (Gobierno de la Ciudad de Buenos Aires, [GCBA], 2006). In the interest of completeness, where there are no traffic flow data available for a particular road street, a local mean flow is assigned according to the traffic map elaborated by the Secretary of Transport for the city of Buenos Aires (see detail in Fig. 3). Using this information, population density distribution and representative traffic flow measured at different points of the city, the vehicle kilometres travelled in each grid cell are estimated.

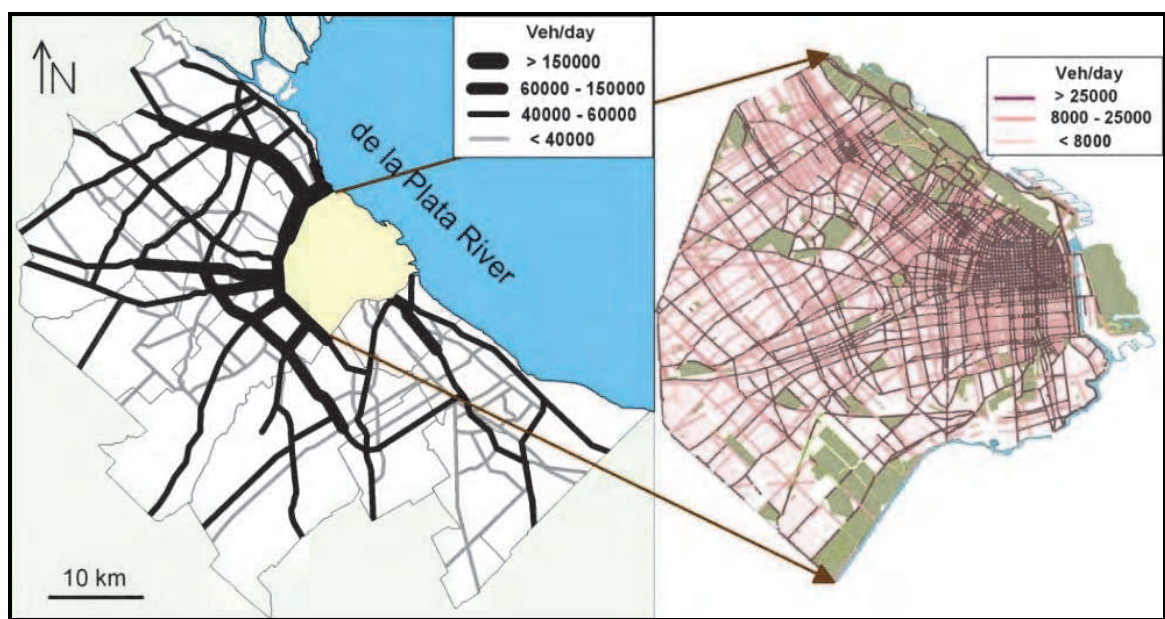


Fig. 3. Traffic flow map in the MABA and the city of Buenos Aires (detail).

Examples of traffic profile registered at different locations within the CBA are shown in Fig. 4 (left). The average vehicle speed considered for the different roads within the city of

Buenos Aires is: 80km/h (highways); 35km/h (avenues); and 15km/h (streets). The representative emission factors for CO and NO_x considered for the vehicles in the CBA are included in Table 1.

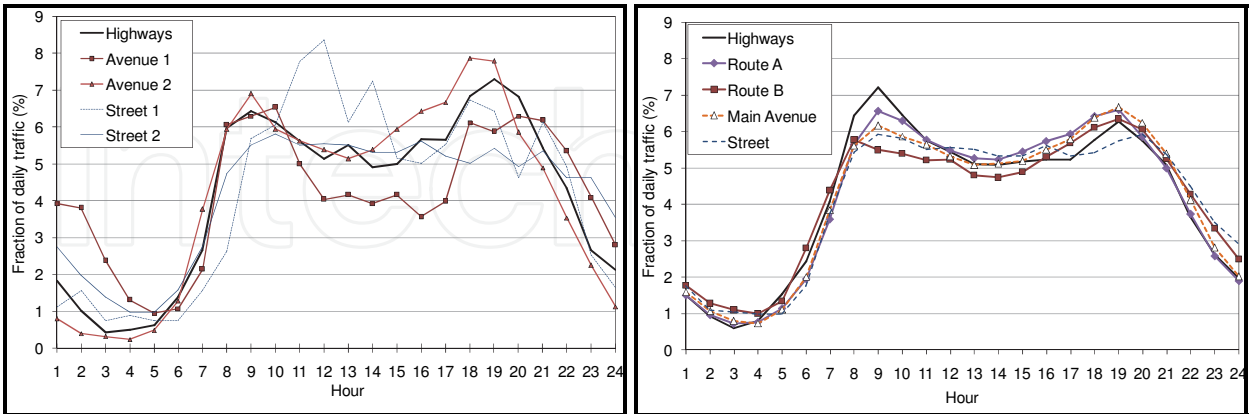


Fig. 4. Hourly traffic profiles at different sites registered within the CBA (left) and the GBA (right).

City of Buenos Aires							
Vehicle type	Fuel	Highways		Avenues		Streets	
		F (CO)	F (NO _x)	F (CO)	F (NO _x)	F (CO)	F (NO _x)
Passenger cars	Gasoline	12.0	2.8	18.7	1.8	38.0	1.5
	Diesel	0.5	0.8	0.6	1.0	1.0	1.1
	CNG	8.0	2.6	2.0	2.1	7.0	2.0
Buses	Diesel	2.2	3.0	5.5	5.0	8.0	14.7
Heavy Duty Vehicles	Diesel	1.8	3.6	2.5	6.1	6.0	10.0
Greater Buenos Aires							
Vehicle type	Fuel	Highways		Routes and Avenues		Streets	
		F (CO)	F (NO _x)	F (CO)	F (NO _x)	F (CO)	F (NO _x)
Passenger cars	Gasoline	10.0	3.4	16.7	1.9	38.0	1.5
	Diesel	0.4	0.8	0.5	0.9	1.0	1.1
	CNG	8.0	2.8	2.0	2.2	7.0	2.0
Buses	Diesel	2.0	5.6	5.0	6.7	8.0	14.7
Heavy Duty Vehicles	Diesel	1.5	4.0	2.0	6.0	6.0	10.0

Table 1. Emission factors (F) (g veh⁻¹ km⁻¹) for CO and NO_x.

In the Greater Buenos Aires, passenger cars employ the following fuels: 66.1% gasoline; 15.6% diesel and 18.3% CNG. Traffic flow data in the GBA are available at different sites in highways, routes and avenues. Even when data are given for a specific road, they are usually measured within a particular duration of time and in discrete locations. Since information is not available everywhere along a given road, both spatial and temporal assumptions have been made in order to obtain the characteristics for the whole road and so

finally to describe emissions over the entire region in a daily evolution. In order to elaborate a map of the traffic flow in the main roads of the GBA, vehicle rates (R) are extrapolated anywhere along every main road. These estimations are based mostly on empirical assumptions. In the GBA, highways and most major roads are roughly either radial or semi-circular. This feature facilitates the direct setting of roads on a polar reference frame. From available data, it may be assumed that radial road traffic rates decrease with distance (x) to the border of the city of Buenos Aires. An empirical exponential law is used to describe this typical star-form network behaviour (Sallés et al, 1996). The traffic rate ($R(x)$) at a given distance from the border of the city of Buenos Aires is estimated by:

$$R(x) = R(0) \exp [-\alpha x] \tag{2}$$

where $R(0)$ is a reference value (traffic rate at the border of the CBA) and α is an empirical coefficient. The values of α have been obtained by fitting to traffic flow measurements registered at several points in highways and routes. Fig. 5 shows the values of $R(0)$ and α for each sector considered in calculations.

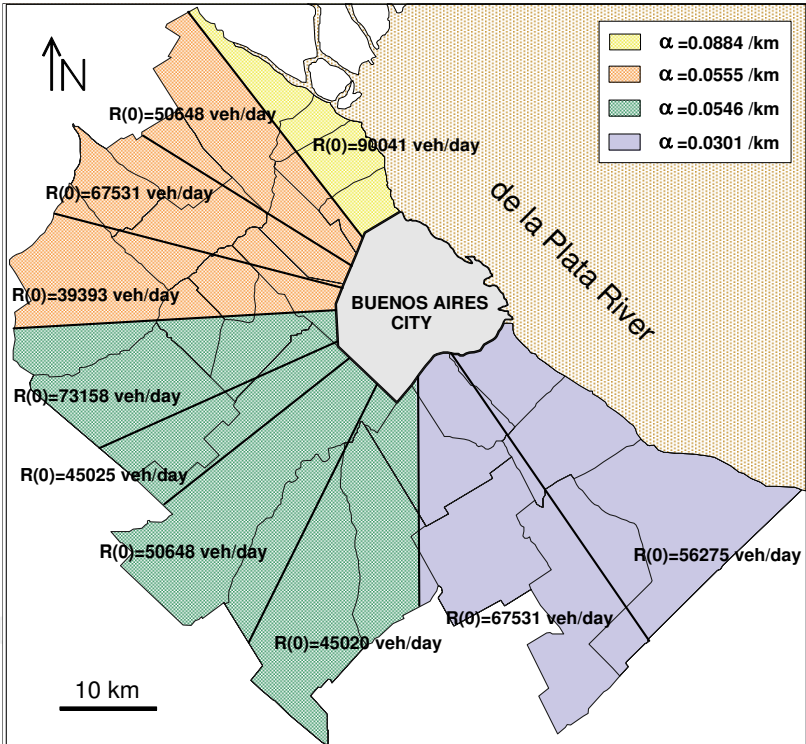


Fig. 5. Values of $R(0)$ and α for each sector, considered in Equation (2) to estimate the traffic flow along the highways and main roads in the GBA.

Available data suggest that semi-circular road traffic rates remain constant along the main roads, within each sector. The traffic map for the Greater Buenos Aires showing the obtained mean daily traffic flow in highways, routes, avenues and main streets is included in Fig. 3. These vehicle flux data are further used to account for vehicle distribution in the streets of the urban area in the GBA. The extrapolation assumption includes both the traffic in the main roadways and the spread traffic in streets and is based on a flux balance criterion between ingoing and outgoing vehicles in each grid cell. Hourly variation of traffic

rate is obtained applying hourly typical traffic rate profiles. Representative traffic profiles at different roadways within the GBA are shown in Fig. 4. The average vehicle speed considered for the different roads within the Greater Buenos Aires is: 100km/h (highways); 40km/h (routes and avenues); and 15km/h (streets). The representative emission factors for CO and NO_x considered for the vehicles in the GBA are presented in Table 1.

CO and NO_x emissions from buses in the MABA are obtained from the emission factors, the total distance travelled by each bus within each grid cell, the bus service frequency and the mean speed of the vehicles in each grid cell. Finally, CO and NO_x emissions from road traffic are estimated for each grid cell over the entire region in a daily evolution.

4.2.2 Air traffic emissions

Aircraft emissions have been estimated using the “alternative simple methodology” proposed by Romano et al. (1999). The aircraft operations of interest that may affect ground level pollutant concentrations are defined as the landing and takeoff (LTO) cycle. The cycle begins when the aircraft approaches to the airport on its descent from the cruising altitude, lands and taxis to the gate. It continues as the aircraft taxis back out to the runway for subsequent takeoff and climb-out as it heads back to the cruising altitude. For all forms of commercial aircrafts, the time spent in each of the LTO modes is reckoned at 19 min for idling and taxiing out, 42 sec for take-off, 2.2 min for climb-out and; at the other end of the cycle, 4 min for approach to landing and 7 min for taxiing and idling (Romano et al. 1999). Fuel consumption and CO and NO_x emission factors for each operation mode depend on engine type (European Environment Agency, 2001; Romano et al., 1999; US.EPA, 1995). Emissions from aircrafts are calculated considering the modes related to the departure and arrival parts of the LTO cycle separately. For example, the total emission for an aircraft type during its departure is calculated multiplying the emission rates by the amount of time in each mode of the departure part of the LTO cycle, and then summing results from the considered modes. The aircraft type that operates at the domestic airport is mainly Boeing B-737, as it is used in domestic and regional flights. At the international airport the airlines operate the following aircraft types: Boeing B-737, B-747, B-757, B-767, B-777 and Airbus A319, A320, A321, A340. Fig. 6 shows the hourly distribution of the mean daily frequency of departures and arrivals at each airport, respectively. The daily evolution of aircraft emissions is added to the area source emissions estimated for the grid cells where each airport is located.

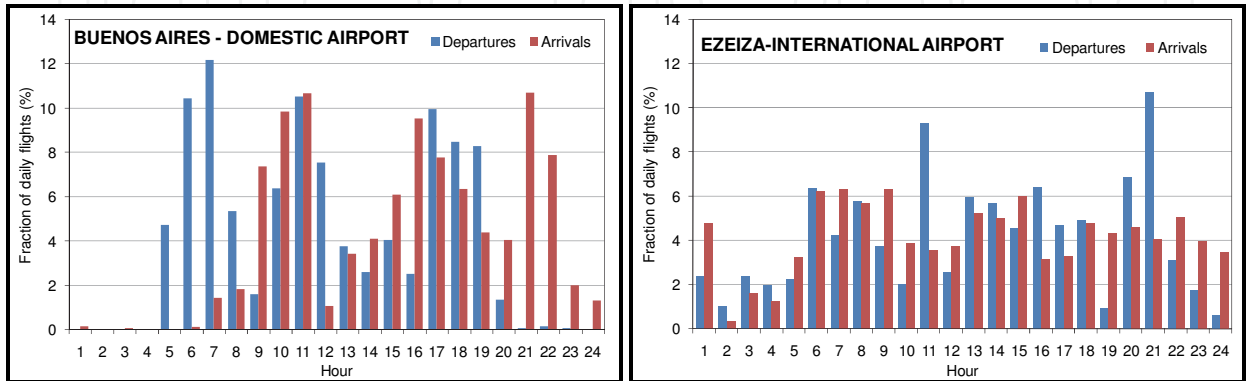


Fig. 6. Hourly distribution of the fraction (%) of mean daily departures and arrivals at the domestic and the international airports.

4.3 Emissions from fixed sources

The small size fixed sources (residential, commercial and small industries combustion activities) are considered as area sources. These sources consume natural gas for heating, cooking and other activities. The monthly natural gas consumed by residential houses was spatially distributed considering population density. Then, using the CO and NO_x emission factors for natural gas combustion for domestic heating units given in US.EPA (1995) residential emission rates at each grid cell are estimated. Considering monthly natural gas consumed by commercial activity, its spatial distribution in the MABA and the emission factors (US.EPA, 1995), CO and NO_x emission rates for this activity are computed for each grid cell. Finally, considering the monthly natural gas consumed by small industries, their spatial distribution in the MABA and the emission factors (US.EPA, 1995), CO and NO_x emission rates of this activity were estimated for each grid cell. Natural gas consumption and a typical diurnal variation of the consumption for each activity have been provided by the National Gas Administration (ENARGAS).

4.4 Carbon monoxide and nitrogen oxides emissions in the Metropolitan Area of Buenos Aires.

Annual area source emission rates estimated for the city of Buenos Aires (CBA) are 324.7 Gg-CO yr⁻¹ and 22.9 Gg-NO_x yr⁻¹ and for the Greater Buenos Aires (GBA) are 294.6 Gg-CO yr⁻¹ and 43.9 Gg-NO_x yr⁻¹. Therefore, for the Metropolitan Area of Buenos Aires (MABA) annual area source emissions result 619.3 Gg-CO yr⁻¹ and 66.8 Gg-NO_x yr⁻¹. Fig. 7 shows the percentage distribution of the annual emission of carbon monoxide and nitrogen oxides by source category in the MABA. Road traffic accounts for 99.4% of CO and 80.6% of NO_x annual area source emissions in the MABA.

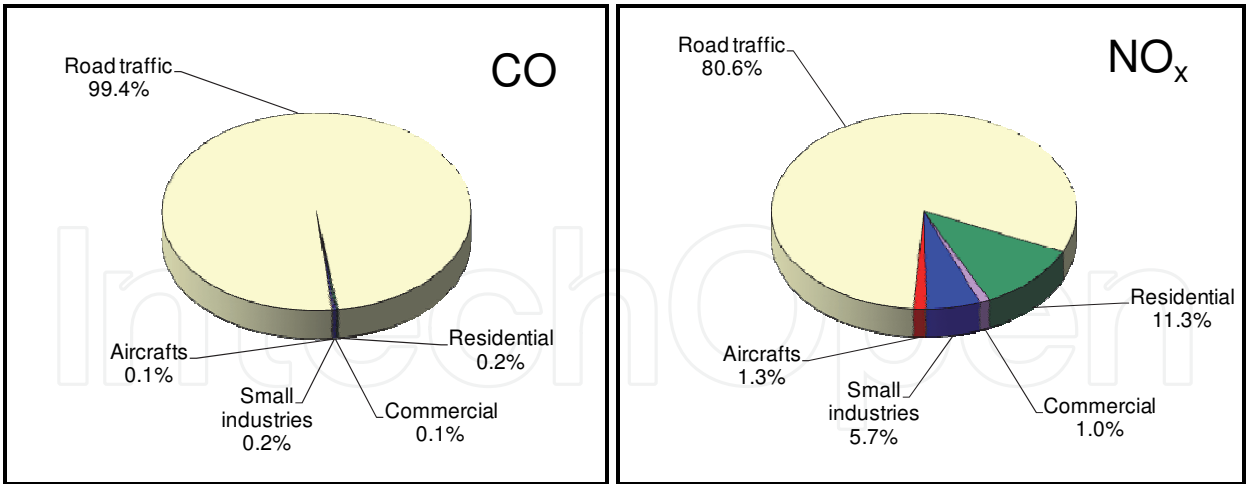


Fig. 7. Estimated annual area source emission of CO and NO_x by source category in the MABA.

The spatial distributions of CO and NO_x annual emission rates (in ton km⁻² yr⁻¹) from area sources within the MABA are shown in Fig. 8. The intensity of emissions varies considerably across the urban area. There is a wide range in CO and NO_x emissions between different grid cells depending on the density of road transportation sources in each grid cell. It is clear that high emission rates per unit area can be found in downtown of the city of Buenos Aires.

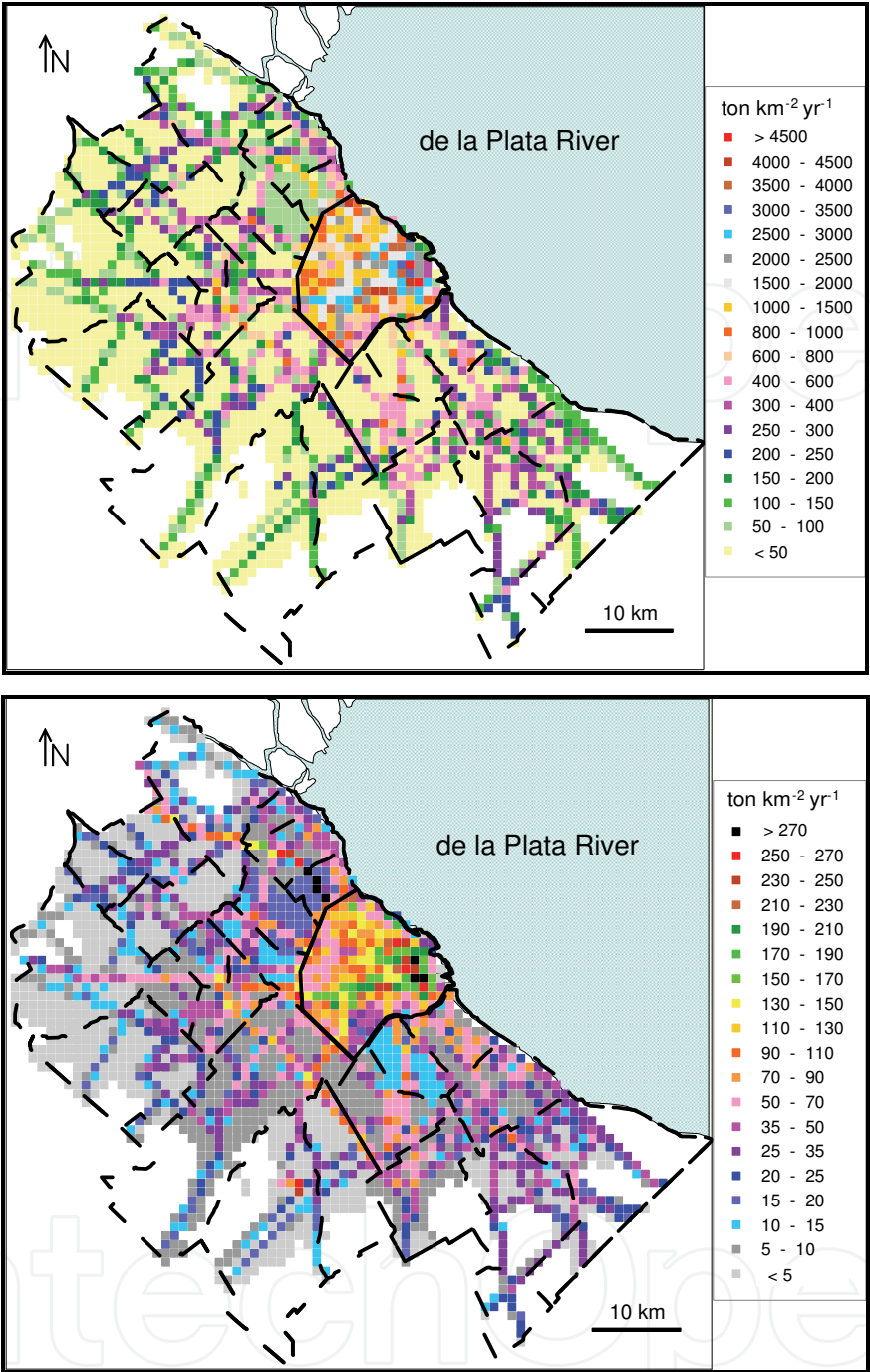


Fig. 8. Annual emission rates ($\text{ton km}^{-2} \text{yr}^{-1}$) of CO (top) and NO_x (bottom) from area sources in the MABA. Grid resolution is $1 \times 1 \text{ km}$.

4.5 Uncertainty assessment

Uncertainty is a statistical term that is used to represent the degree of accuracy and precision of data. It often expresses the range of possible values of a parameter or a measurement around a preferred value. Various approaches for representing uncertainty in the context of different domains are widely described (Azondèkon & Martel, 1999; Draper, 1995). Emission inventories are based on assumptions that are needed to be made and statistical data. Real measurements are available for a few emission sources and/or for certain time

periods only. Therefore, uncertainty estimations are of importance and should always be foreseen (Sturm, 2003). However, it is not easy to assess uncertainty at the level of aggregated datasets. Information related to emissions and their uncertainties that originates from a few measurements has to be applied for a large number of sources. As the latter may differ strongly, even within the same category, the uncertainty increases as the emission inventory becomes more detailed. On a more aggregated level, averaging helps to improve the uncertainty situation (Sturm, 2003). There are different studies (Frey & Li, 2003; Frey & Zheng, 2002; Regan et al., 2003; Romano et al, 2004) done in differentiating and quantifying the contributions from uncertainty and natural variability to emission data. The reliability of the information provided by emission inventories is strongly biased by a wide range of causes. Particularly, when the emissions are estimated through emission factors the following points have to be taken into account: a) uncertainty related to the choice of the indicators, b) uncertainty related to the quantitative value of the indicators, c) uncertainty related to emission factors and d) uncertainty related to the structure of emission estimate models. In the MABA, the use of traffic flow values registered at several sites on different days to compute the average vehicle fleet in each road type, results in a mean error of approximately 20-30%. The uncertainty estimation of the average vehicle speed for different road types is found to be near 20%. These uncertainties may introduce an error in the selection of emission factors of about 20%. Other uncertainties may come from the spatial grid resolution. The estimation of travel distance along each road type in each grid cell has an error of 10-15%. The uncertainty of the spatial distribution of population density, commercial activity and small industries in each grid cell of the urban area is about 40%. In general, the error in the estimation of the emissions of carbon monoxide and nitrogen oxides in the MABA are expected to be around 40%.

5. Air pollutant concentration estimations

5.1 Brief description of the urban atmospheric dispersion model used

Urban background concentrations of CO and NO₂ in the Metropolitan Area of Buenos Aires have been estimated applying the urban atmospheric dispersion model DAUMOD(v.2) to the area sources described above. This model has been developed and introduced in former papers (Mazzeo & Venegas, 1991, 2010; Venegas & Mazzeo, 2002; 2006b). However, a brief description of its main considerations and assumptions is included below.

The DAUMOD model (Mazzeo & Venegas, 1991) is an urban atmospheric dispersion model valid for steady-state conditions. It is assumed that effluents are emitted continuously from the surface. The x-axis is in the direction of the mean wind and the z-axis is vertical. At a given distance, the vertical extension of the plume of contaminants is given by $h(x)$. Concentration at $h(x)$ is negligible and there is no transport of mass through the upper limit of the plume. The variation of $h(x)$ is parameterised in the model by potential functions given by (Mazzeo & Venegas, 1991),

$$\frac{h}{z_0} = a \left(\frac{x}{z_0} \right)^b \quad (3)$$

where z_0 is the surface roughness length and coefficients a and b depend on atmospheric stability (Mazzeo & Venegas, 2010). Other basic assumption included in the model is that

background air pollutant concentration $[C(x,z)]$ can be expressed by the following polynomial form:

$$C(x,z) = C(x,0) \sum_{j=0}^6 A_j \left(\frac{z}{h} \right)^j \quad (4)$$

Coefficients A_j ($j=0,\dots,6$) depend on surface roughness and atmospheric stability (Mazzeo & Venegas, 2010) and have been computed by fitting Equation (4) to the results given by the following expression (Pasquill & Smith, 1983):

$$C(x,z) = C(x,0) \exp \left[-4.605 \left(\frac{z}{z_m} \right)^s \right] \quad (5)$$

where s is a shape factor which depends on atmospheric stability and surface roughness (Gryning et al., 1987) and z_m is the height at which concentration is $0.01C(x,0)$. The height z_m is usually considered to be the upper limit of the plume, so it is assumed $h = z_m$. Considering different atmospheric stability conditions, the coefficients (A_0, A_1, \dots, A_6) of the polynomial of grade 6 are obtained for each fitting. There are excellent fittings of polynomial forms (given by Equation (4)) to values obtained from Equation (5), with coefficients of determination of ≈ 1.0 (the reader can find details of these results in Mazzeo & Venegas, 1991).

In an urban area, a horizontal distribution of area sources with strength varying according to a typical square grid pattern may be assumed. Each grid square has a uniform source strength Q_i ($i = 0, 1, 2, \dots, N$) expressed as mass per unit area per unit time. According to the DAUMOD model $C(x,z)$ can be estimated by:

$$C(x,z) = \frac{a \left[Q_0 x^b + \sum_{i=1}^N (Q_i - Q_{i-1})(x - x_i)^b \right]}{\left(|A_1| k_v z_0^b u_* \right)} \sum_{j=0}^6 A_j \left(\frac{z}{h} \right)^j \quad (6)$$

where k_v is the von Kármán's constant and u_* is the friction velocity.

A constant wind direction is required for application of Equations (6). It has been noted from the applications of Equation (6) that estimated concentration at any receptor is mainly originated from the emission in the grid square in which the receptor is located. This is because area source distributions in a city are generally quite smooth and, the contribution of upstream grid squares (from Equation (6)) rapidly reduces with distance to the receptor. The simplification of assuming that the uniform area source strength Q_i only varies with x (in the wind direction), suppose to consider a "narrow plume" hypothesis. This assumption has also been included in other simple urban dispersion models (Arya, 1999; Gifford, 1970; Gifford & Hanna, 1973). The spatial resolution of the model calculations is given by the resolution of the area source emission inventory.

The performance of DAUMOD model in estimating concentrations has been evaluated comparing estimated and observed concentration data from several cities. Results for Bremen (Germany), Frankfurt (Germany) and Nashville (USA) have been reported in

Mazzeo & Venegas (1991) and for Copenhagen (Denmark) can be found in Venegas & Mazzeo (2002). The comparison of DAUMOD estimations of background air pollutant concentrations with observations in the city of Buenos Aires can be found in Venegas & Mazzeo (2006b). Results show that the performance of the model in estimating short-term concentrations (hourly and daily) is good and it improves when estimating long averaging time values (monthly and annual). Several applications of different versions of DAUMOD to Buenos Aires have been reported in former papers (Mazzeo & Venegas, 2004, 2008, 2010; Mazzeo et al., 2010; Pineda Rojas & Venegas, 2008, 2009, 2010; Venegas & Mazzeo, 2005, 2006a; 2006b).

At present, photochemical transformations involving NO, NO₂ and O₃ are not included in DAUMOD model. However, DAUMOD(v.2) estimates concentrations of NO₂ on the basis of an empirical relationship between NO₂ and NO_x (Derwent & Middleton, 1996; Dixon et al., 2001; Middleton et al., 2008). The concentration of NO₂ is calculated using the polynomial expression (CERC, 2003; Derwent & Middleton, 1996):

$$[\text{NO}_2] = 2.166 - [\text{NO}_x] (1.236 - 3.348 B + 1.933 B^2 - 0.326 B^3)$$

where $B = \log_{10}([\text{NO}_x])$ and $[\text{NO}_x]$ is hourly-averaged concentration in ppb.

An application of DAUMOD(v.2) to estimate the influence of NO_x emitted from area sources in the Metropolitan Area of Buenos Aires on the air quality of the city of Buenos Aires have been reported in Venegas & Mazzeo (2007).

5.2 Application of DAUMOD model to area source emissions in the Metropolitan Area of Buenos Aires

The DAUMOD(v.2) model is applied to area source emissions in the MABA, to estimate hourly ground level background concentrations of CO and NO₂ in the area. Calculations are performed considering three years of hourly meteorological information registered at the weather stations of the Argentine Meteorological Office located at the domestic airport (in the city of Buenos Aires) and at the international airport (in the Greater Buenos Aires, 30 km southwest the city of Buenos Aires). The spatial resolution used in calculations is 1x1 km.

One consideration to take into account is that this modelling approach does not produce 3-dimensional wind fields, so land-sea breezes are not modelled. Breeze circulations over the wide estuary of the river could bring pollutants back to the receptor area. However, the frequency of atmospheric recirculation events over the city is small: 8% in summer, 7% in autumn, 5% in winter and 7% in spring (Venegas & Mazzeo 1999). In this way, it is expected that this modelling limitation will not significantly affect the results.

5.2.1 Concentrations of CO in the MABA

Three years of hourly and running 8-h average ground level CO concentrations are estimated for the entire MABA. As expected, estimated CO concentration values are higher in the city of Buenos Aires than in the Greater Buenos Aires.

Hourly CO concentrations are all below the air quality standard value of 35ppm (Res. 198/06 city of Buenos Aires and Res. 242/97 Province of Buenos Aires). The highest hourly concentration value resulted 25.7ppm and appeared at downtown of the city of Buenos Aires. In order to illustrate the spatial distribution of CO concentration in the MABA, Fig. 9 shows the computed hourly CO concentrations at rush hour in the evening (20:00), averaged over the three years.

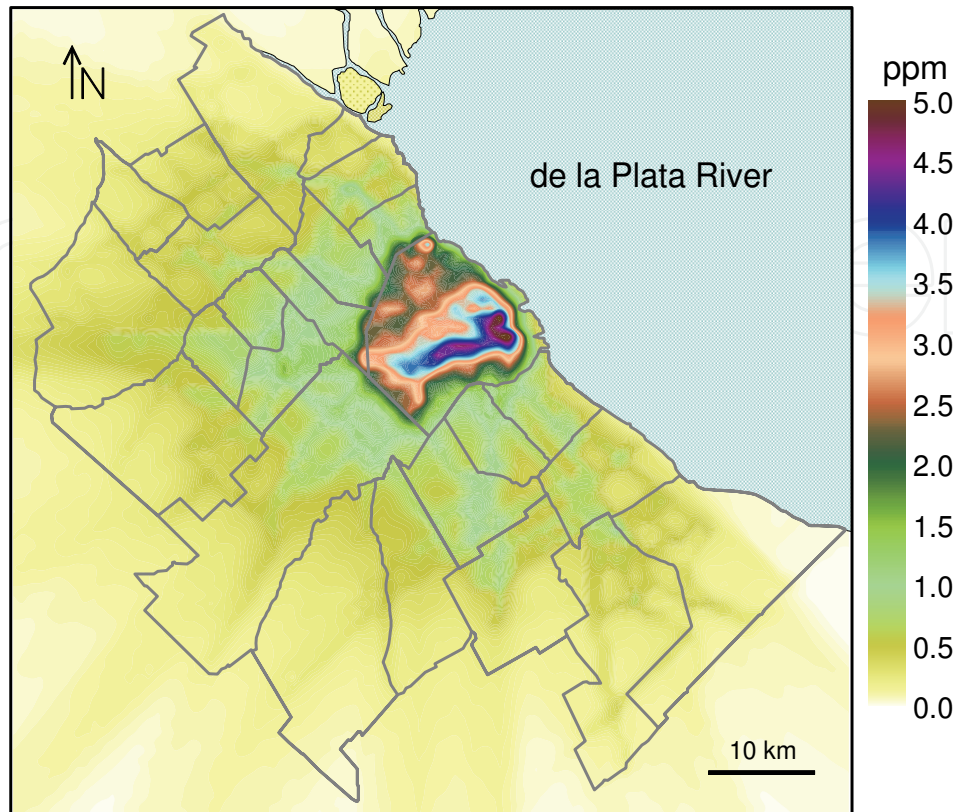


Fig. 9. Mean hourly ground level CO concentrations for rush hour in the evening (20:00)

Also, as an example, the spatial distribution of mean (three years average) running 8-h average ground level CO concentrations in the MABA for the period 08:00-16:00 is shown in Fig. 10. The highest running 8-h average CO concentration (C_{8h}) estimated for the three years is 16.1ppm. This value is greater than the air quality standard value (9ppm) established for the MABA. However, as can be seen in Fig. 11, the highest mean annual frequency of $C_{8h} > 9\text{ppm}$ at one grid cell reaches 118 cases and appears in the downtown area of the CBA. This value represents the 1.3% of the annual cases of running 8-h average concentrations. Therefore, the air quality regulation for the CBA (Res. 198/06) is accomplished as it requires that 98th percentile of annual cases (considering three years) should be below 9ppm. The analysis of the situations with $C_{8h} > 9\text{ppm}$ reveals that 41% of these cases affect areas of 1km² (Fig.12). Only in 10% of the cases the extension of the affected areas is between 16-35 km².

Fig. 13 shows the frequency distribution of the running 8-h average CO concentrations greater than 9ppm obtained during the three years according to the end hour of the 8-h period. Most exceedances are associated to high emission values during the evening (when most people returns home) and nocturnal atmospheric conditions (low wind speed, neutral or stable atmospheric stability). Monthly distribution of the estimated running 8-h average CO concentrations greater than 9ppm is included in Fig.14. These situations are more frequent between May and August, during late autumn and winter.

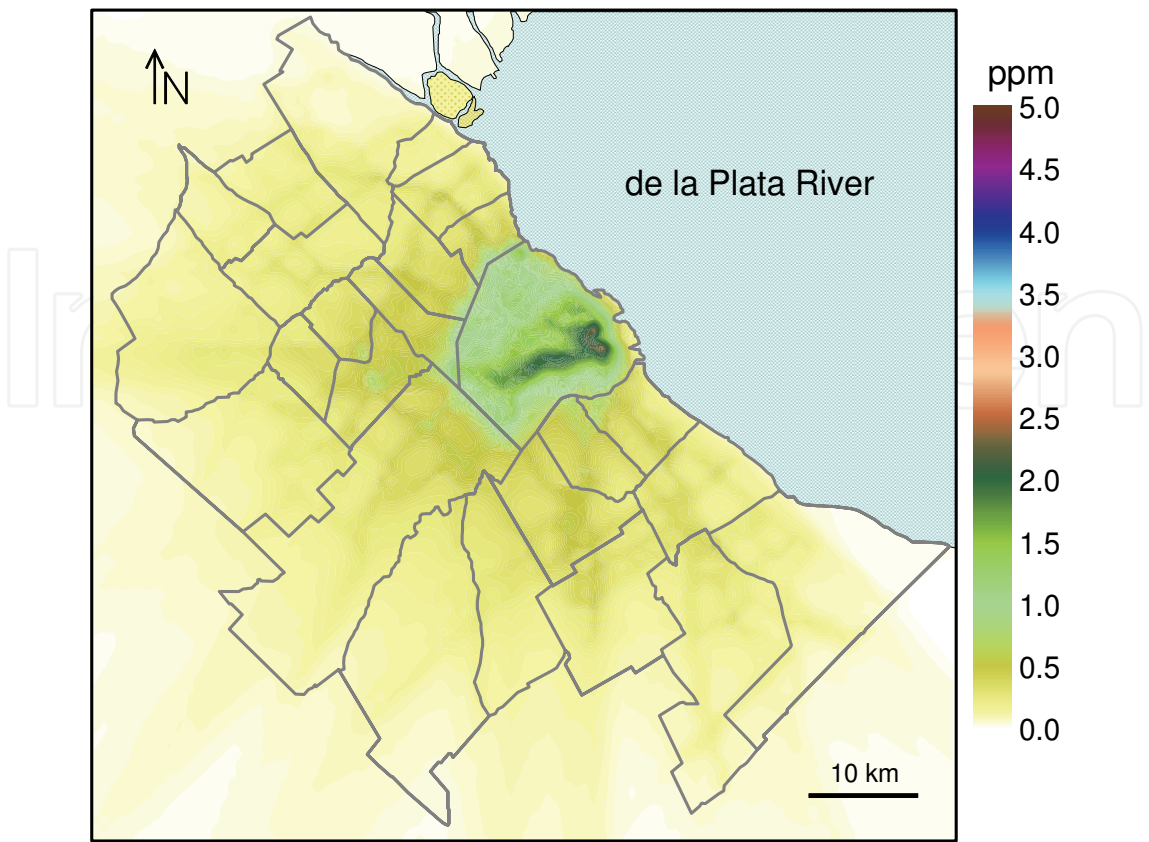


Fig. 10. Estimated mean running 8-h average ground level CO concentrations (period: 08:00-16:00)

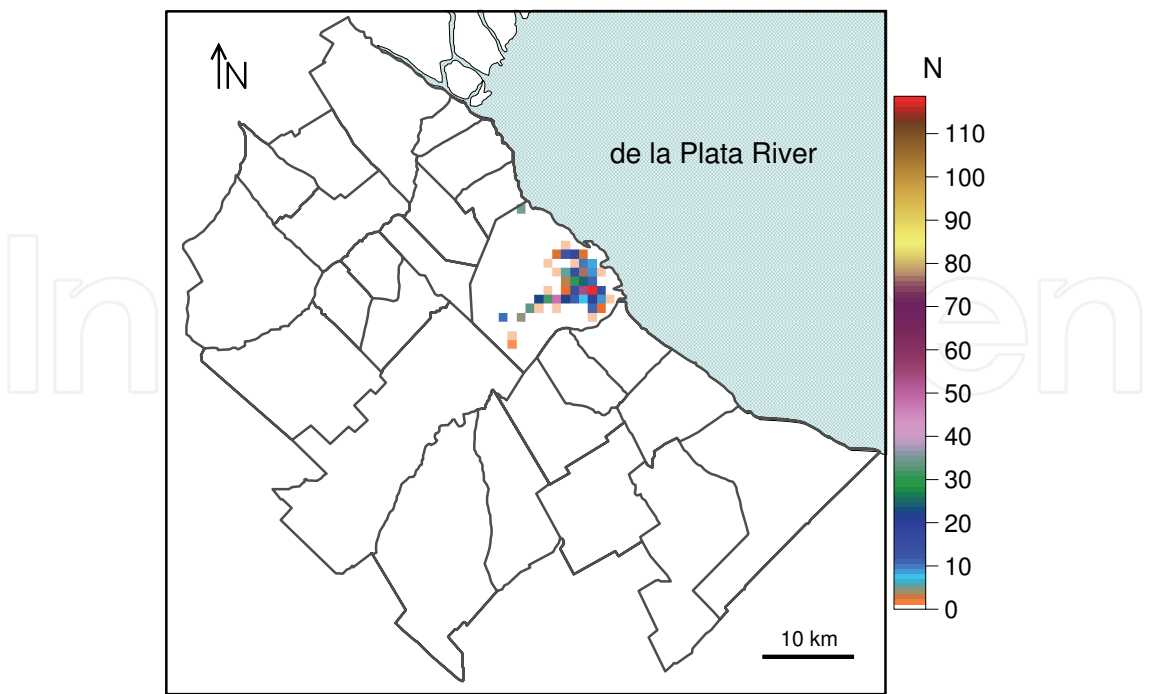


Fig. 11. Annual mean number of cases with running 8-h average CO concentration greater than 9ppm.

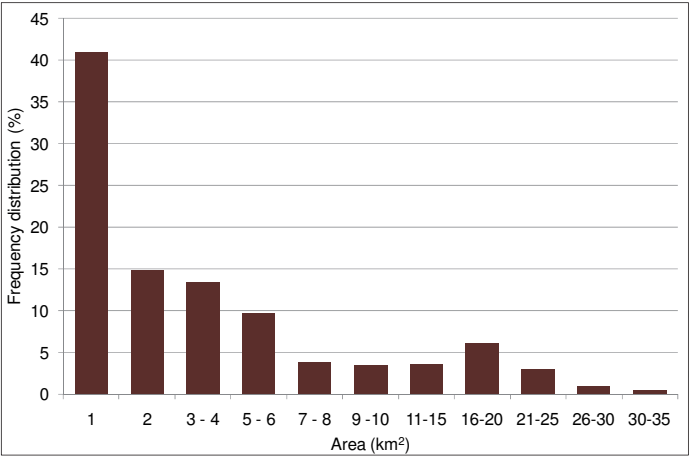


Fig. 12. Frequency distribution of the affected area (km²) of the situations with running 8-h average CO concentration greater than 9ppm.

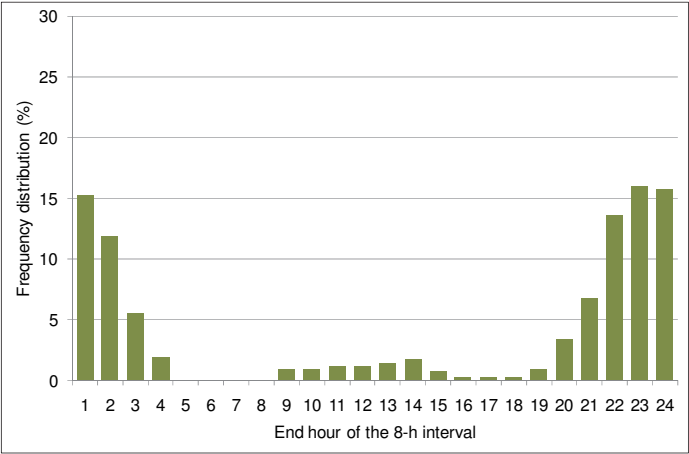


Fig. 13. Daily distribution of estimated running 8-h average CO concentrations greater than 9ppm.

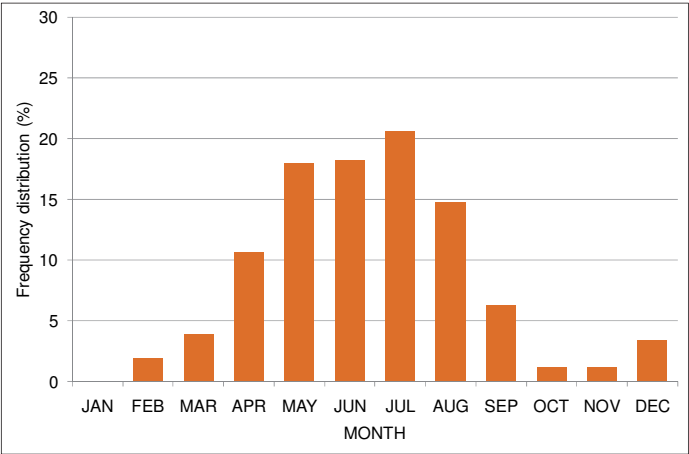


Fig. 14. Monthly distribution of estimated running 8-h average CO concentrations greater than 9ppm.

5.2.2 Concentrations of NO₂ in the MABA

Three years of hourly NO₂ ground level concentrations are estimated for the whole MABA. The higher NO₂ concentration values are obtained at downtown of the city of Buenos Aires and along the highways of the Metropolitan Area of Buenos Aires. The highest hourly NO₂ concentration estimated in the three years period is 184ppb, at downtown. Hourly concentrations are below the air quality standard (200ppb) for the city of Buenos Aires (Res. 198/06, city of Buenos Aires) and for the Greater Buenos Aires (Res.242/97, Province of Buenos Aires). The spatial distribution of the mean hourly NO₂ concentrations for the rush hour in the evening is shown in Fig. 15. These results are the hourly values obtained for 20:00 averaged over the three years.

The spatial distribution of annual mean NO₂ concentrations in the MABA is included in Fig. 16. The concentration distribution pattern shows a large spatial variability across the urban area. Different areas with high concentration values can be identified, as highways, areas with dense traffic and close to the airports. NO₂ annual concentration may reach 28ppb downtown. All values are below the air quality standard (53ppb) for the CBA (Res. 198/06, city of Buenos Aires) and for the GBA (Res. 242/97, Province of Buenos Aires).

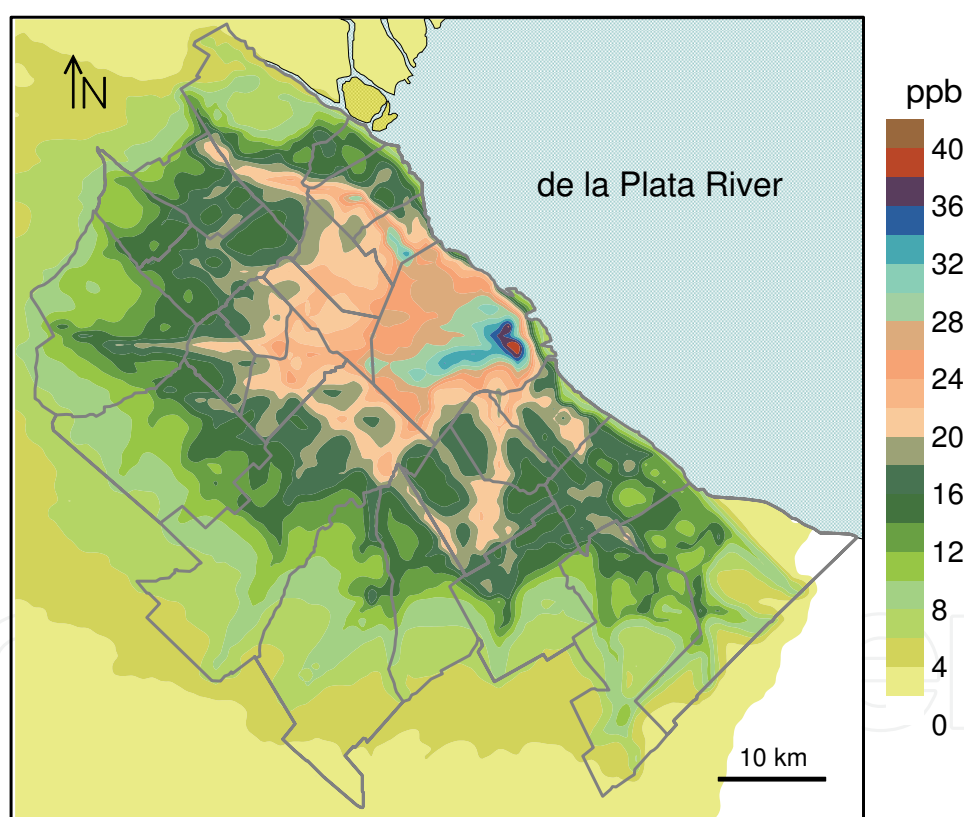


Fig. 15. Mean hourly ground level NO₂ concentrations for rush hour in the evening (20:00)

As mentioned above, model results indicate that NO₂ hourly background concentrations may exceed the air quality guideline proposed by the World Health Organisation (100ppb) (WHO, 2006b) at some places in the MABA. The mean annual number of hourly NO₂ concentrations that exceed 100ppb at each grid cell is shown in Fig. 17. Most exceedances occur in the city of Buenos Aires, where they may reach a maximum of 50 cases per year at one grid cell located downtown. In the Greater Buenos Aires, hourly NO₂ concentrations

greater than 100ppb have been obtained in the Northern and Southern highways. These highways constitute two main entrances to the CBA. Also, exceedances are obtained close to the international airport located in the GBA, approximately 30km southwest the CBA.

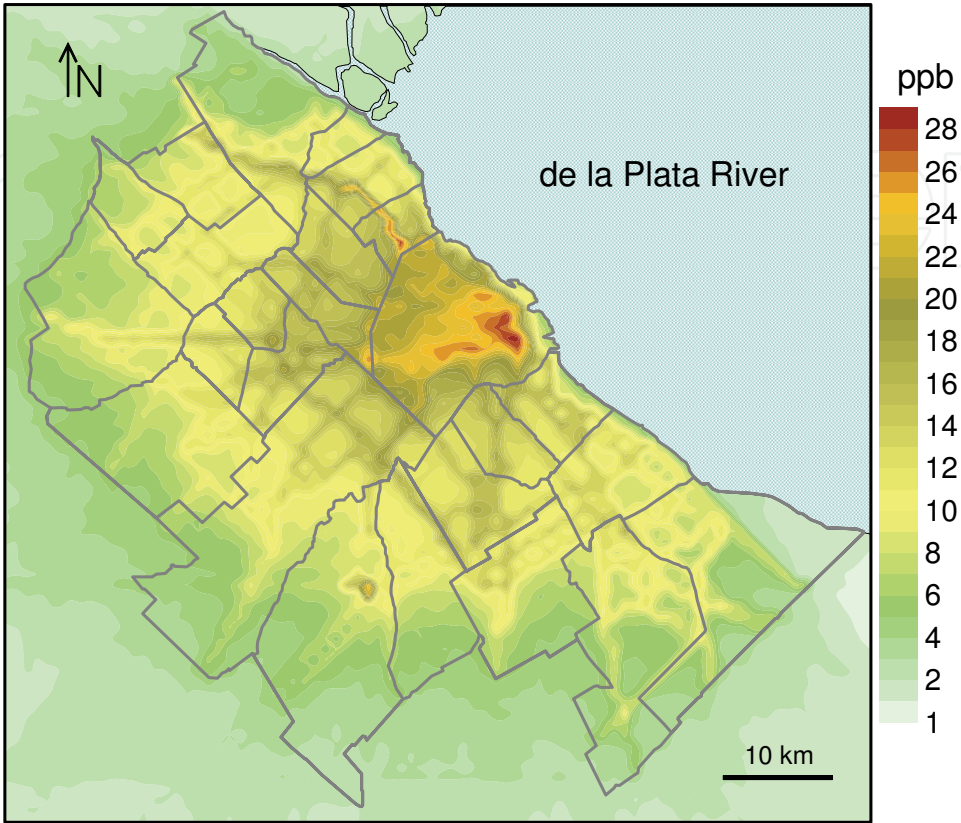


Fig. 16. Annual mean ground level NO₂ concentrations.

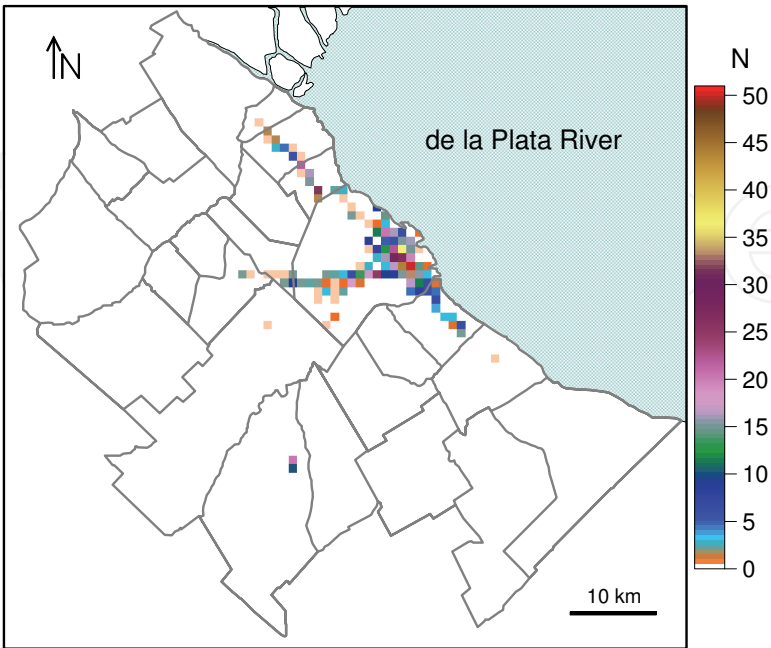


Fig. 17. Annual mean number of hourly NO₂ concentrations greater than 100ppb.

The analysis of the situations with hourly NO₂ concentrations greater than 100ppb obtained in the three years, reveals that the extension of the affected area is 1km² in 29% of the cases but it may reach a maximum of 43km² (1%) (Fig. 18). As shown in Fig. 19, high values of hourly NO₂ concentrations are obtained mainly during rush hours in the morning (07:00 to 09:00) and the evening (18:00 to 22:00). The frequency of values greater than 100ppb is higher in the evening/night than in the morning. High vehicle emissions and reduced atmospheric dispersion conditions are responsible for this result. Situations with hourly NO₂ concentrations greater than 100ppb in the MABA are more frequent from May to August (Fig. 20).

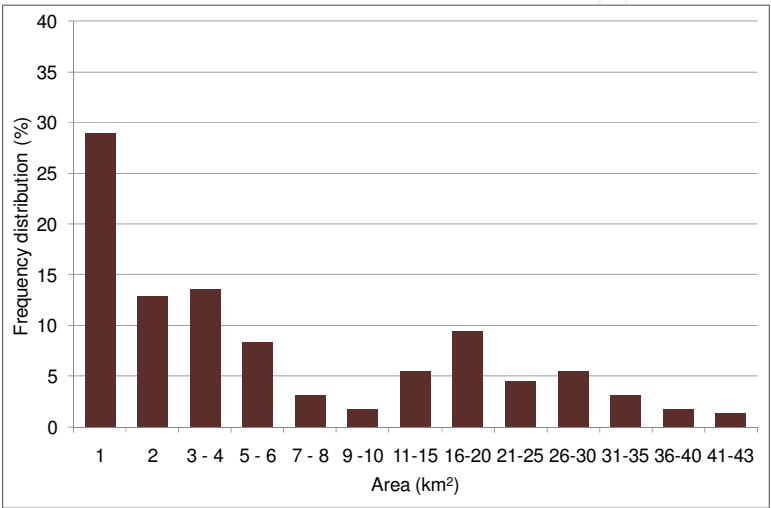


Fig. 18. Frequency distribution of affected areas (km²) with hourly NO₂ concentrations greater than 100ppb.

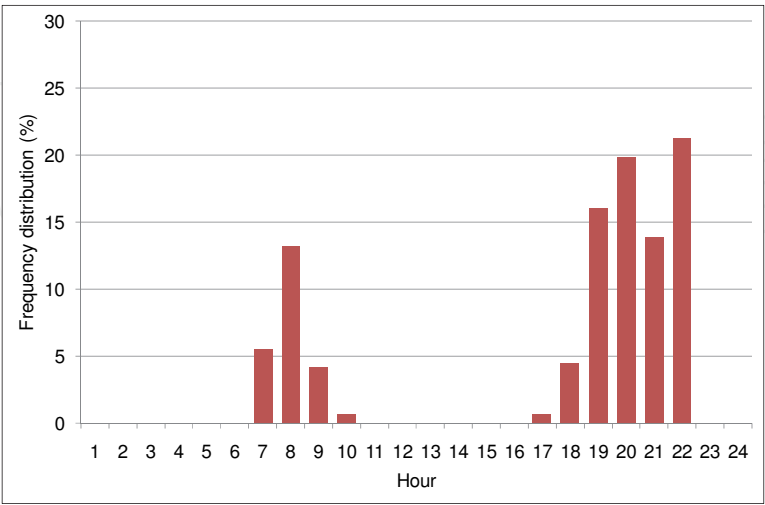


Fig. 19. Daily distribution of hourly NO₂ concentrations greater than 100ppb.

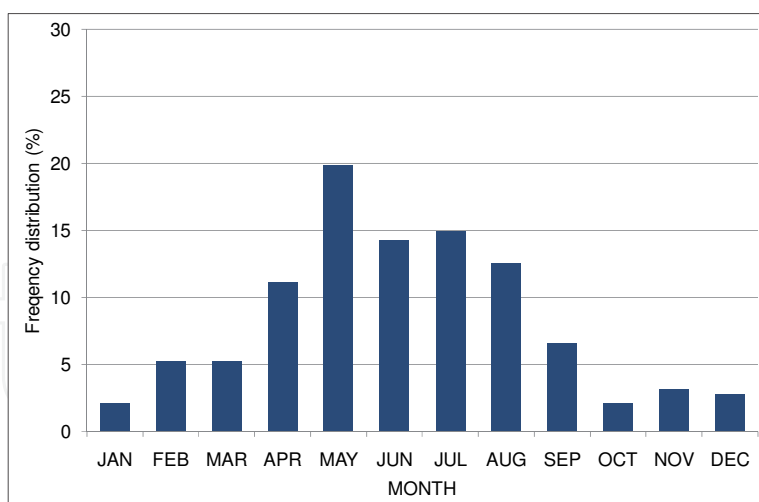


Fig. 20. Monthly distribution of hourly NO_2 concentrations greater than 100ppb.

6. Summary

This chapter presents the results of a high spatial and temporal resolution version of the area source emission inventory of carbon monoxide (CO) and nitrogen oxides (NO_x), and the evaluation of the air quality in the Metropolitan Area of Buenos Aires (MABA). The inventory includes mobile sources (passenger cars/taxis, buses and aircrafts) and fixed sources (emissions arising from residential, commercial and industrial buildings). Its main originality is that it deals as much as possible with distinctive on-road traffic features in order to describe more accurately the emission distribution at a scale comparable to that of the air quality models. The emission inventory for the Metropolitan Area of Buenos Aires can be characterised by the presence of an important contribution of CO and NO_x emitted from mobile sources. Mobile sources contribute with 99.4% of CO and 80.6% of NO_x annual emissions of area sources in the MABA. Annual area source emission rates estimated for the city of Buenos Aires are 324.7 Gg-CO yr^{-1} and 22.9 Gg- NO_x yr^{-1} and for the Greater Buenos Aires are 294.6 Gg-CO yr^{-1} and 43.9 Gg- NO_x yr^{-1} . Therefore, for the MABA annual area source emissions result 619.3 Gg-CO yr^{-1} and 66.8 Gg- NO_x yr^{-1} . Spatial distributions of carbon monoxide and nitrogen oxides emissions show an appreciable variation across the MABA. The urban atmospheric dispersion model DAUMOD is applied to evaluate the air quality in the MABA due to the contribution of area source emissions in the urban area. Estimations of horizontal distributions of CO and nitrogen dioxide (NO_2) background concentrations in the MABA are presented. Air quality regulations established for CO and NO_x in the MABA are accomplished. The analysis of running 8-h average CO concentrations greater than 9ppm reveals that 41% of these cases affect areas of 1km². Only in 10% of these cases the affected areas show extensions between 16-35 km². Model results indicate that NO_2 hourly background concentrations may exceed the air quality guideline proposed by the World Health Organisation at some places in the MABA. Most exceedances occur in the city of Buenos Aires, where they may reach a maximum of 50 cases per year at one grid cell located downtown. In the Greater Buenos Aires, hourly NO_2 concentrations greater than the air quality guideline have been obtained in the Northern and Southern highways. The analysis of the situations with hourly NO_2 concentrations greater than the air quality guideline reveals that the extension of the affected area is 1km² in 29% of the cases but it may reach a maximum of 43km² (1%).

7. Acknowledgements

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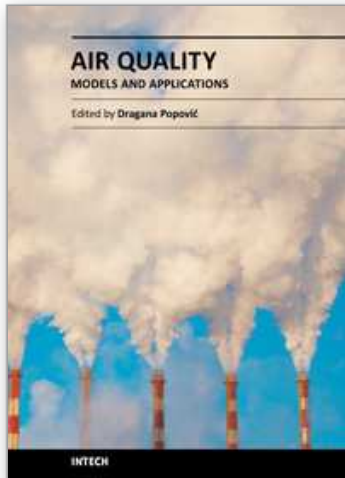
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