UNDERSTANDING THE ORIGINS AND FATE OF AIR POLLUTION IN BOGOTA, COLOMBIA

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Imagine all the people
Living life in peace...

John Lennon
(1940-1980)

To mamá Elvia,
mamá Teresa, papá Saúl,
Elsita, Dorita and Fabio

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Abstract

Bogota has more than 8 million inhabitants and is the 5^{th} biggest urban agglomeration in Latin America. It has more than one million vehicles and a large number of small industries. High levels of air pollutants are thus detected. The purpose of this work consists in applying air quality modelling tools to the region of Bogota, aiming to acquire a deeper understanding of the factors that originate air pollution in the city, and of the way pollutants are dispersed and chemically transported. Furthermore, the knowledge gained is used to propose and evaluate air pollution abatement strategies. In the first part of this thesis, two versions of the traffic emission inventory are generated, one using standard CORINAIR traffic emission factors and the other using bulk real-world traffic emission factors. Both emission inventories are compared and evaluated with the help of numerical simulations. The emission inventory calculated using bulk real-world traffic emission factors generates simulated concentrations closer to the observed values. Thus, an innovative technique consisting in the combination of measurements and modelling to estimate and evaluate traffic emissions is proposed in this part of the study. In the second part, mesoscale meteorological and air quality models are applied to the city. The wind pattern developed over the complex topography of the region and the development of the plume of pollutants are simulated with success. In the third part of this work, the air quality model is used to study the plume of pollution in terms of the governing chemical regimes and the individual and combined effects of the main sources of emission. Traffic is the major contributor to the plume of pollutants in Bogota. Three feasible emission scenarios which are addressed to the mitigation of emissions from heavy traffic are evaluated with the model. Whereas reductions are attained for primary pollutants and aerosols (whose simulation is presented in the forth part of this work), levels of Ozone increase with these scenarios. The air quality model indicates that strategies directed to mitigate air pollution might have contradictory effects depending on the pollutant to be tackled. Air quality modelling proved to be a very useful tool for evaluating emission scenarios in advance and prioritizing actions to mitigate pollution in Bogota.

Keywords: Bogota, Urban air pollution, Air quality management, Emission inventory, Real-world emissions, Complex topography, Photochemical modelling, PM_{10} simulation.

Résumé

Avec plus de 8 millions d'habitants, un million de véhicules et une quantité importante de petites industries, Bogota est la cinquième plus grande ville d'Amérique Latine. Ce travail a pour objectif l'utilisation de modèles de qualité de l'air sur la région de Bogota afin de mieux comprendre les facteurs qui génèrent la pollution atmosphérique ainsi que ceux qui influencent la dispersion et la transformation chimique des polluants sur la région. Enfin, ces nouvelles connaissances sont utilisées pour proposer des stratégies d'abattement de la pollution et pour évaluer leur efficacité. Dans la première partie de cette thèse, deux cadastres des émissions dues au trafic sont générés, l'un à partir des facteurs d'émission standards proposés par CORINAIR, et l'autre à partir de facteurs d'émission estimés grâce à des mesures réalisées dans les rues de Bogota. Les deux cadastres sont comparés et évalués à l'aide de simulations numériques. Le cadastre calculé à partir des facteurs d'émission provenant des mesures permet d'obtenir les concentrations simulées les plus proches des valeurs observées. Ainsi, cette partie du travail a permis de montrer l'efficacité d'une nouvelle technique consistant à combiner des résultats de mesures et de modélisation pour estimer et évaluer les émissions provenant du trafic. La deuxième partie de cette thèse est dédiée à l'application de modèles météorologiques et de qualité de l'air sur la région. Ces modèles ont simulés avec succès l'évolution des champs de vent et des panaches de pollution qui se développent sur la topographie complexe entourant la ville. Dans la troisième partie de ce travail, le modèle de qualité de l'air est utilisé pour étudier les facteurs qui contribuent à la formation des panaches de polluants aussi bien en termes de régimes chimiques que des contributions individuelles et combinées des principales sources d'émissions. Le trafic routier apparaît comme la source majeure contribuant à la formation du panache de polluants. L'efficacité de trois scénarios réalistes concernant la réduction des émissions du trafic lourd est évaluée à l'aide du modèle. Dans les simulations des trois scénarios, les concentrations de polluants primaires et d'aérosols (la simulation de ces derniers est présentée dans la quatrième partie de cette thèse) diminuent, alors que les concentrations d'ozone augmentent. Le modèle de qualité de l'air met en évidence que les stratégies d'abattement des émissions peuvent avoir des effets contradictoires sur les niveaux des différents polluants atmosphériques. La modélisation de la qualité de l'air s'avère être un outil adéquat pour évaluer l'efficacité des scénarios d'abattement des émissions et pour définir les priorités permettant le contrôle de la qualité de l'air à Bogota.

Mots clés: Bogota, pollution de l'air, gestion de la qualité de l'air, cadastre d'émission, topographie complexe, modélisation photochimique, aérosols.

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Chapter 1

Introduction. Large cities, air pollution and tools for air quality assessment.

1.1 Urbanization and urban air pollution

According to the United Nations (UN, 2006), 49% of mankind (3.2 billion) were urban dwellers in 2005, as compared to a 13% in 1900. The process of urbanization appears to be both a cause and a consequence of global change (Mayer, 1999; Gurjar and Lelieveld, 2005), and there is a clear connection between high levels of urbanization and high rates of economic growth. People are attracted by the economic opening-up offered by cities, more employment and education opportunities, access to comfort and to sophisticated infrastructure (the majority of megacities are internationally well connected). Other reasons for migration to cities are the search of better political conditions, to protect from violence, after natural disasters or to skip poverty.

The process of urbanization has been especially important in less developed countries,[1] where governments do not have a strong presence in rural

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[1] The terms 'less developed countries' or 'developing countries' are used along this study to refer to countries with a relatively low standard of living, an undeveloped industrial base and a moderate to low Human Development Index (UNDP, 1990). The definition of 'standard of living' may be debated if one takes into account other aspects apart from material goods. Standard of living is defined here as the quality and quantity of goods and

areas and people migrate to the cities in search of a better quality of life. In developing regions, urban population is about 7 times larger than in 1950 (fig. 1.1). In this year, there were only two megacities (with a population $\geq$ 10 million), New York and Tokyo with 12.4 and 11.3 million people respectively. At present there are around 25 megacities, most of them belonging to developing countries or to countries with economies in transition (Gurjar and Lelieveld, 2005; UNEP, 2006). Table 1.1 shows a list of the main megacities in the world and its population.

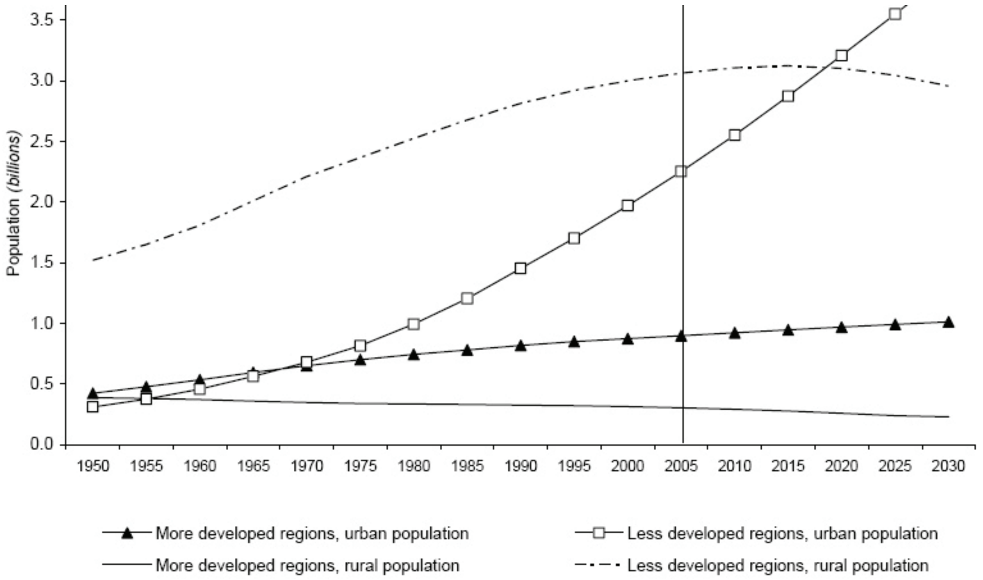

Figure 1.1: Urban and rural population of more developed regions and less developed regions, 1950-2030. Source: UN (2006). The urban population of less developed regions has increased almost exponentially in the last 50 years.

High levels of economical activities in large cities imply high energy consumption, which is mainly dependent on the combustion of fossil fuels. This generates emissions of huge amounts of polluting substances into the atmosphere. Although air pollution is only one of the environmental hazards

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services available to people and the way they are distributed within a population. In these countries, there is low per capita income, widespread poverty, and low capital formation. The term ‘developing countries’ does not convey for the author a notion of inferiority when compared to ‘developed countries’.

Table 1.1: Megacitites of the world and their air quality data. Years of data are 1999 and 2000. All data reported correspond to the mean annual concentration in µg m^{-3}, except for O_3 which corresponds to the maximum annual 1-h concentration, in µg m^{-3}. Coverage is not complete since not all cities have monitoring systems. Source: Baldasano et al. (2003).

City	Popul.[a]	O_3	TSP[b]	PM_{10}	SO_2	NO_2
Tokyo, JP	33.4		49		18	68
Seoul, KR	23.1		84		44	60
Mexico, MX	22.0	546	201	52	46	55
New York, US	21.8	272		24	26	70
Bombay, IN	21.1		240		33	39
Delhi, IN	20.8		415		24	41
Sao Paulo, BR	20.3	403	53		18	47
Shanghai, CN	18.6		246		53	73
Los Angeles, US	17.9	225		39	9	66
Jakarta, ID	16.9		271			
Osaka, JP	16.6		43		19	63
Cairo, EG	15.8				69	
Calcutta, IN	15.4		375		49	34
Manila, PH	15.2				32	
Karachi, PK	14.6					
Dacca, BD	13.6					
Buenos Aires, AR	13.5		185			20
Moscow, RU	13.4		100			80
Beijing, CN	12.4		377		90	122
Rio de Janeiro, BR	12.2		60		50	40
WHO standard[c]			90	20	50	40

[a] Population expressed in millions, 2005. The city refers to urban agglomerations. Source: www.citypopulation.de.

[b] TSP = Total suspended particles.

[c] WHO standard for PM_{10} was issued in 2005, all the rest in 2000 (WHO, 2000, 2005).

alongside water contamination, hazardous wastes, noise and others, it is currently the most politically controversial environmental concern of large cities. It affects every resident, it is seen by every resident, and is caused by nearly every resident (Mage et al., 1996; Mayer, 1999). Studying the human health effects of air pollution has been challenging, because it is difficult to isolate from other factors that also influence health such as smoking, diet, etc. However, it is clear that exposure to elevated concentrations of ambient air pollutants cause adverse human health effects (increased mortality, morbidity, deficits in pulmonary function and cardiovascular and neurobehavioural effects), but the critical question has been how severely is health affected. The World Health Organization (WHO, 2005) has estimated that urban air pollution causes the premature death of more than 2 million people in developing countries per year, and millions of cases of respiratory illness are associated to air pollution in big cities. Other environmental impacts from air pollution, as reported by the World Bank (Kojima and Lovei, 2001), include damages to buildings and structures, agricultural crops, vegetation and forests, reduced visibility and increasing greenhouse gas emissions (fig. 1.2).

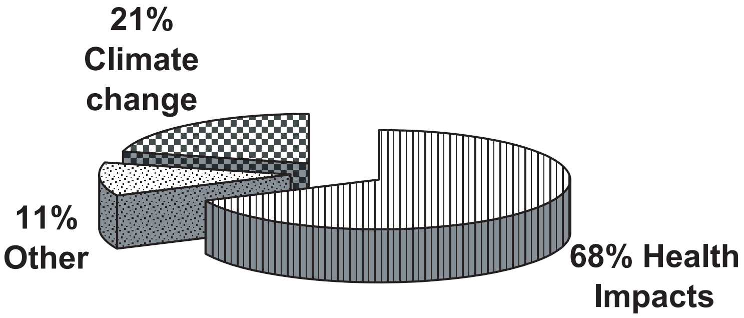

Figure 1.2: Composition of environmental damages from fuel combustion in six developing country cities, 1993. The cities are: Bangkok (Thailand), Krakow (Poland), Manila (Philippines), Bombay (India), Santiago (Chile) and Shanghai (China). Source: Kojima and Lovei (2001).

A number of local (Molina and Molina, 2002; Vivanco and Andrade, 2006) and global studies (Mage et al., 1996; Mayer, 1999; Moussiopoulos, 2003) show that on-road traffic is a major source of air pollution in large cities. It is expected that with the process of urbanization more people will drive more vehicles over greater distances and for longer time, increasing emissions. The crucial problem of vehicle emissions, which occur near the ground level and in densely populated areas, is that they cause greater human exposure to harmful pollutants in the immediate locality than do emissions from sources such as power plants that are situated at elevated levels and often further away from dense population centers (Kojima and Lovei, 2001). They are a major source of four of the six principal air pollutants (CO, NO_x, Volatile Organic Compounds and Lead), and contribute to the total suspended particle (TSP) concentrations. Besides, in cities where a substantial portion of the motor vehicle fleet is diesel-powered, such as Bangkok, Manila and Seoul (Mage et al., 1996), there are additional problems of black smoke, SO_2 and greater particulate emissions.

Emissions of air pollutants by motor traffic not only depend on traffic density but also on different factors such as driving habits, state of maintenance of the vehicle, technology, ratio of automobiles to trucks, quality of the fuel, etc. As far as traffic is concerned, developed countries present the trend of decreasing emissions of air pollutants, whereas less developed countries show the opposite trend (Mayer, 1999). According to UNEP (2006), this happens because much attention is directed to the regional and global consequences of fuel combustion in rich countries, executing some control over the factors mentioned above. In developing countries, the local environmental problems associated with energy use for transport remain a paramount matter of concern. Pollution abatement in the transport sector is therefore likely to become increasingly important in urban air quality management strategies in the coming years, as suggested by institutions such as the World Bank (Kojima and Lovei, 2001) and the World Health Organization (Mage et al., 1996).

1.2 The case of Bogota

Bogota, the capital of Colombia, is the 5^{th} largest city in Latin America (table 1.2) and the 32^{th} in the world. As other cities, it also undergoes important immigration problems and growth. For example, an average annual population growth of 2.7 % was estimated during the last decade for the city (Gutiérrez et al., 2001). Nowadays, it has more than 8 million inhabitants, and it is classified as a lower-middle income city (Baldasano et al., 2003).[2]

Table 1.2: Supercities in Latin America and their air quality data. Years of data are 1999 and 2000. All data reported correspond to the mean annual concentration in µg m^{-3} except for the second O_3 column (see note b). Source: Baldasano et al. (2003).

City	Popul.[a]	O_3	O_3 [b]	TSP[c]	PM_{10}	SO_2	NO_2
Mexico city, MX	22.0	72	546	201	52	46	55
Sao Paulo, BR	23.1		403	53		18	47
Buenos Aires, AR	13.5			185			20
Rio de Janeiro, BR	12.2			139			
Bogota, CO	8.4	38	348		58	40	39
Lima, PE	8.2			176		39	92
Santiago, CL	5.9	31	351		77	12	51
Belo Horizonte, BR	5.7						
Caracas, VE	4.8			53		33	57
Guadalajara, MX	4.4			61	26	71	
WHO standard[d]				90	20	50	40

[a] Population expressed in millions, 2005. The city refers to urban agglomerations. Source: www.citypopulation.de. According to the World Bank (2006), about 75% of the Latin American population lives in urban agglomerations.
[b] Maximum 1-h concentration.
[c] TSP = Total suspended particles.
[d] WHO standard for PM_{10} was issued in 2005, all the rest in 2000 (WHO, 2000, 2005). WHO guidelines are designed to offer guidance in reducing the health impacts of air pollution.

Topographical aspects

Examining the topographical situation of a city is crucial in order to better understand its atmospheric interactions. The Andean mountain chain is divided into three ranges in the south part of Colombia. Bogota, located at 4.6°N and 74.1°W, lies in a plateau situated in the eastern Andean range (fig.

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[2] The World Bank establishes a classification of Economies by Gross National Income (GNI): (i) high income, \$ 9 266 or more; (ii) upper middle income, \$ 2 996 - \$ 9 265; (iii) lower middle income, \$ 756 - \$ 2 995; (iv) low income, \$ 755 or less. Economies are divided according to the 2000 GNI per capita (Baldasano et al., 2003). The National Department of Statistics from Colombia (DANE, 2006) reports that around 10 % of the dwellings in Bogota have at least one of the basic human needs unsatisfied.

1.3). The plateau is about 40 km wide and 100 km long, aligned from the southwest to the northeast, with an average elevation of 2600 meters above sea level (masl). Mountainous complex terrain borders the plateau in three sides: two ridges are parallel to the plateau axis, at its eastern and northwestern borders, reaching about 4200 and 3600 masl respectively (fig. 1.4), whereas it is partially closed at its northern side. It is open at its southern border to the southwest, descending gently to the *Magadalena Valley* (less than 500 masl), that separates two of the main Andean chains crossing the country. Additionally, at its eastern side, the mountain range descends steeply towards the *The Eastern Plains*.

Figure 1.3: Geographical localization of Colombia and Bogota. Source: http://www.worldatlas.com/.

Levels of pollution

Comparing levels of pollution between cities is difficult because the records of such levels may be affected by the amount of measurements available and the place where they are taken. In their report about air quality data from large cities, Baldasano et al. (2003) compare mean annual 1-h concentrations of different pollutants for a number of cities. Some of these results are presented in tables 1.1 and 1.2. It can be observed that the WHO air quality

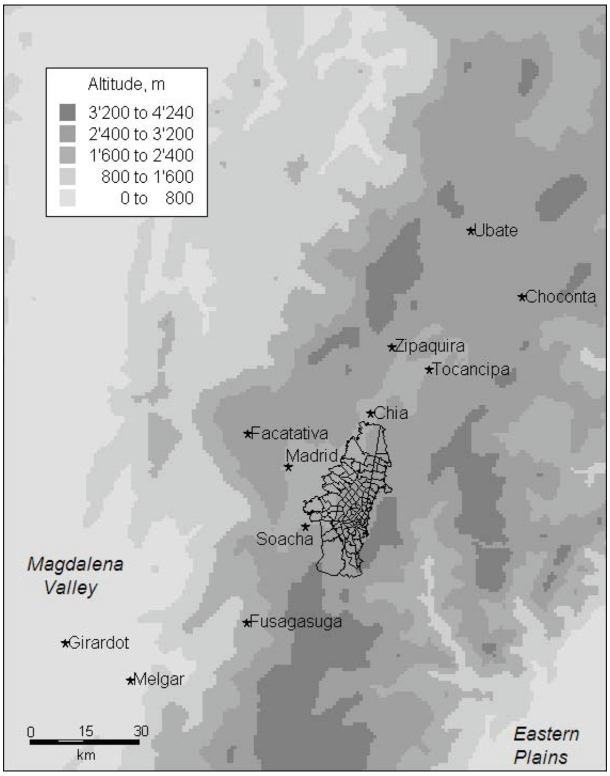

Figure 1.4: Topography of the region around Bogota. The black lines delimit the city and its main zones. Other towns in the region are presented for reference.

guidelines (WHO, 2005) are exceeded for a number of cities. In Bogota, O_3 and PM_{10} are the most critical pollutants. The hourly O_3 standard and 24-h PM10 standard stipulated by the local environmental agency are also frequently exceeded.[3] For example, in 2001 those standards were exceeded 281 times out of 49 913 hourly measurements for O_3 (7 monitoring stations) and 510 times out of 98 612 hourly measurements for PM_{10} (14 monitoring stations). The maximum values attained during the same year were 393 µg m^{-3} (1-h) for O_3 and 225 µg m^{-3} (24-h average) for PM_{10}.[4] Although there is no regulation for other pollutants like toluene, benzene and formaldehyde,

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[3] Departamento Técnico Administrativo del Medio Ambiente (DAMA), attached to the Major's office. Since 1997 it counts with a monitoring network which has 9 measuring stations spread around the city.

[4] DAMA standards are 163 µg m^{-3} (1-h) for O_3 and 170 µg m^{-3} (24-h) for PM_{10}, DAMA (2006), resolution # 391/01.

some data had been collected during the years 1998, 1999 and 2000 for these pollutants. Unexpectedly high values were found in some measuring stations in the city (UNIANDES/EPFL, 2001).

Bogota currently takes part of the Clean Air Initiative for Latin American cities created by the World Bank (2006). This initiative includes also Buenos Aires, Lima, Mexico city, Rio de Janeiro, Sao Paulo and Santiago de Chile. It facilitates the creation and exchange of programs conceived to improve air quality in Latin America.

1.3 Atmospheric Interactions

Emitted air pollutants are dispersed and diluted in the atmosphere. Chemical reactions producing photochemical O_3 or secondary aerosols occur frequently during the transport process. Dispersion and dilution of air pollutants are strongly influenced by meteorological conditions, especially by the wind and the atmospheric stability. Topographical siting and urban structures have a great effect on these meteorological parameters. Chemical reactions also depend on ambient weather conditions because they are influenced by short-wave radiation, air temperature and air humidity.

Chemical reactions and dispersion processes affect ambient air pollution levels, causing concentrations of different substances which vary with time and space (Mayer, 1999). Fig. 1.5 illustrates this process. Levels of pollutants found at a given place depend thus on how much emissions are released, chemical reactions, specific meteorological conditions and the background levels of such pollutants.

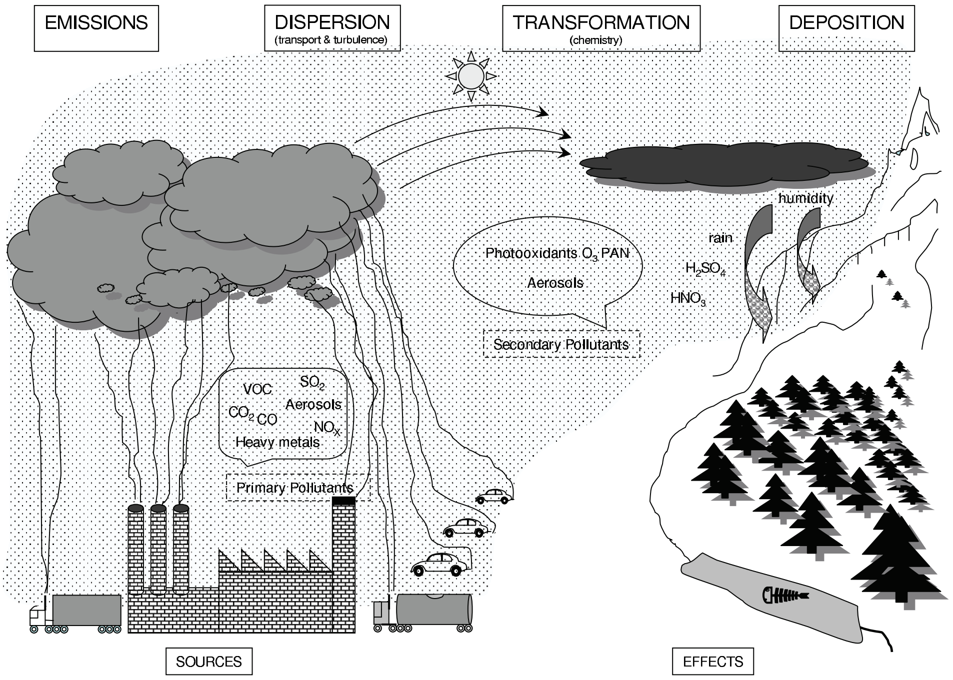

Figure 1.5: Atmospheric interactions of pollutants. Source: modified after Clappier, A. (1999). Levels of air pollution found at a given place depend on specific emission conditions, general meteorological conditions and the background air pollution (Mayer, 1999).

1.4 Scientific questions to be solved in the frame of this work

At this point we can state that: (i) Bogota undergoes high levels of air pollution; (ii) those levels are to a certain extent linked to the atmospheric processes taking place, which are complex, depend on many factors and thus are not easy to understand; and (iii) we want to tackle the air pollution problem in the city. The first step to attack the problem consists in fully understanding the processes taking place. The following questions can hence be formulated for this purpose:

- **How much emissions are released to the atmosphere in Bogota?**: What are the contributions of each one of the emitting sources? Are standard bottom-up methodologies to calculate emission inventories reliable enough in the case of Bogota? What can we expect if we apply a top-down methodology to verify results? How is the spatial and temporal distribution of such emissions?

- **How does the plume of pollutants generated by Bogota behave?** This question is very broad and probably several studies of this kind will be necessary to fully reply it. In the frame of this work, the question is addressed to those specific meteorological conditions which occasion particularly high levels of both primary and secondary pollutants in town. The first dry season of the year (late December, January, February and beginning of March) has been identified as a period in which high levels of pollutants are presented in the city (UNIANDES/EPFL, 2001). In this work, the development of Bogota's plume of pollutants is studied for these specific circumstances. This question defines the size of the plume, its intensity, and its spatial and temporal evolution.

- **Do emissions released outside the city have an effect on it?** What kind of interactions exist between emissions from the city and from outside, taking into account that some industrial corridors are located outside the city, not far from it?

- **What kind of abatement strategies can be recommended?** On which source should we act first? What impact might certain abatement strategies have?

1.5 Accessible tools: Approaches to Air Quality assessment

This section describes some of the tools which will be used along this work to solve the questions presented in the previous section. The results through the application of these tools in the case of Bogota, and the proposition of new combined tools represent the main scientific contributions of this work.

- **The Emission Inventory:** Emission inventories are important tools to describe the emission situation and eventually to manage air quality. They provide comprehensive information on emission sources and emission fluxes in the area under consideration. Different methodologies can be applied to establish an emission inventory. While an inquiry for single sources (based on in site information on emissions and activity data) is defined as bottom-up methodology, a use of statistic data results in a top-down estimation. Bottom-up approaches are connected to big efforts in data collection, therefore this approach is restricted to a certain amount of emitters. On the other hand, top-down approaches are often not detailed enough for urban emission inventories. The big effort for bottom-up methodologies and the inaccuracy of top-down approaches are limitations of both methods. Therefore, a combination of both methods can be used for urban emission estimates (Friedrich and Reis, 2004).

- **Modelling:** The European Directives on air quality (EU Directive 96/62/CE) recognize the importance of modelling as a tool in the definition of high pollutant concentration areas that are not in compliance with air-quality objectives. According to Borrego et al. (2003), the use of numerical models to estimate pollutants concentrations at mesoscale or local scale, can be an important contribution to the identification of sensitive urban areas in terms of air quality and evaluation of human exposure to different pollutants. With the use of air pollution modelling, it is possible to relate air emissions to air quality (Friedrich and

Reis, 2004). Additionally, modelling might be the only tool capable of adequately reproducing the complex phenomena taking place in the atmosphere, allowing, once validated, to obtain rapid responses to predesigned emission scenarios.

- **The monitoring networks**: Models have to be validated through the comparison of its results with measurements. The more measurements exist, the better we can emit concepts on the accuracy of the models. Bogota counts with a monitoring network administrated by DAMA, with 9 measuring stations spread around the city (14 in 2002). Some of them measure only meteorological parameters, and some measure both meteorological parameters and air quality levels. Additionally, we count on meteorological data generated by the departmental monitoring network of CAR,[5] and by the national monitoring network of IDEAM.[6]
- **Measuring campaign**: Sometimes the monitoring networks are not located at places where we foresee important impacts of the plume of pollutants. Measuring campaigns allow to obtain such information at the desired place for a short period of time, but long enough to obtain crucial information (weeks or a few months). During a measuring campaign, it is possible to catch "pollution episodes", which correspond to a series of days in which concentrations of pollutants were particularly high. This is the case of the measuring campaign which took place in the region of Bogota during February and March, 2002. It was coordinated by LPAS and logistically supported by UNIANDES.[7] The

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[5] Data from 2 monitoring stations of CAR (Coorporación Autónoma Regional de Cundinamarca, CAR (2006)) was furnished under the frame of this work. CAR is the environmental regulation authority at state level. Bogota is also the capital of the department of Cundinamarca in Colombia.

[6] Data from 4 monitoring stations of IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia, IDEAM (2006)) was furnished under the frame of this work. One of them correspond to the international Airport El Dorado, located at the western border of Bogota.

[7] The Air and Soil Pollution Laboratory (LPAS) from the Swiss Federal Institute of Technology (EPFL), and la Universidad de los Andes in Bogota (UNIANDES) are the scientific partners in the cooperation project that conceived this work.

information obtained during this campaign was very valuable for this work.

1.6 This Work

Chapter 2 of this work is devoted to the aspects related to the Emission Inventory of Bogota and the region. Two versions of the Emission Inventory are generated for the city. In the first version, known standard traffic emission factors are used. In the second, bulk traffic emission factors calculated particularly for the city, using in-situ measurements and inverse modelling techniques at street level, are used. Both emission inventories are compared and evaluated with the help of an air quality model. **Chapter 3** introduces the reader to the meteorological and air quality numerical simulations in the region around Bogota, at mesoscale level. The "episode" approach is chosen, that means, the formation of the pollution plume during a typical photochemical 2-day episode is investigated. This approach helps to acquire a deep understanding of the dynamics of the atmosphere in the zone of study and open a new possibility to manage air quality in Bogota through a scientifically-based approach. In **chapter 4** some emission scenarios are formulated and evaluated in order to identify the critical agents causing high levels of pollution in Bogota. In the last part, some feasible emission scenarios are proposed and evaluated using modelling tools. Finally, **chapter 5** presents results regarding the simulation of aerosols for the region.

All chapters are presented in the form of scientific articles. **Chapter 2** has been submitted to *Atmospheric Environment*, **Chapter 3** and **Chapter 4** have been submitted to the *Journal of Environmental Management.* All of them are currently under review.

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Chapter 2

Combined techniques to estimate and evaluate emission inventories: The Bogota case.

Abstract

Two versions of the Emission Inventory (EI) are generated for the city of Bogota, Colombia. In the first version (EI-1), CORINAIR traffic emission factors (EFs) are used. In the second (EI-2), bulk traffic EFs calculated for the city, using in-situ measurements and inverse modelling techniques at street level, are used. EI-2 traffic emissions are 5, 4 and 3 times bigger than the corresponding values in EI-1, for CO, PM_{10} and NMVOCs respectively. The main goal of this study consists in evaluating the two versions of the EI when introduced into a mesoscale air quality model. The AOT (Accumulated exposure Over a Threshold) index is calculated for comparison between observed and simulated concentrations of primary pollutants. Simulated concentrations using EI-2 are closer to the observed values. This comparison allows us to extract some conclusions of the methodology used to calculate the EFs. Local factors like the driving behavior, the altitude, vehicle technology and an aged fleet cannot be totally included and corrected in the standard methodologies, and seem to be more important than obtaining very detailed and precise information on the classification of the fleet or driving speeds. Under financially limited and fast changing situations, as in the case of many developing countries, a simple methodology to estimate bulk traffic EFs and to evaluate the EI, is of utmost importance. The use of combined techniques such as in-situ measurements to estimate bulk traffic EFs, and further evaluation of the inventories with numerical models, proved to be a useful tool for this purpose.

2.1 Introduction

Urban agglomerations are major sources of regional and global atmospheric pollution. This case is especially severe in cities of developing countries, where population, traffic, industrialization and energy use increase as people continue to migrate to the cities (Mage et al., 1996). Consequently, it is urgent to develop an air quality management policy and to establish strategies of atmospheric pollution prevention and control for such cities. Main limitations are, however, that either environmental authorities are not always effective, or air pollution mitigation may not be an immediate priority for the city (Mayer, 1999). Even if it is, there may be a strong lack of information and knowledge. Bogota, capital of Colombia, is to some extent a representative case of the latter condition. By 2001, it had reached 6.6 million inhabitants inside the urban perimeter (Skinner, 2004) and about 8.0 million taking into account the suburbs. It is the 5^{th} biggest city in Latin America with nearly one million vehicles circulating every day, among which 50 000 are diesel-powered heavy vehicles. Bogota (4.6°N and 74.1°W) lies in a plateau placed in one of the three Andean mountain ranges crossing the country. The plateau is about 40 km wide and 100 km long, and aligned from the southwest to the northeast. It has an average elevation of 2600 masl, while mountainous complex terrain borders the plateau (fig. 2.1(a)).

Bogota has an air quality monitoring network administrated by the DAMA (Departamento Técnico Administrativo del Medio Ambiente). Since 1997, it has been registered that the air quality standards of PM_{10} (170 µg m^{-3}, 24-h average), O_3 (83 ppb, hourly average) and NO_2 (168 ppb, hourly average) are frequently exceeded. For example, in 2001 those standards were exceeded 281 times out of 49 913 hourly measurements for O_3 (7 monitoring stations) and 510 times out of 98 612 hourly measurements for PM_{10} (14 monitoring stations). The maximum values attained during the same year were 393 µg m^{-3} (1-h) for O_3 and 225 µg m^{-3} (24-h average) for PM_{10}. The center and southwest parts of the city are highly polluted zones (fig. 2.1(b)): MMA and Cazuca stations indicate the most frequent exceedances for O_3, Merck and Sony stations for PM_{10}, and Nacional and MMA for NO_2 (DAMA, 2006).

Aiming to improve air quality in Bogota, the research project entitled *Develop-*

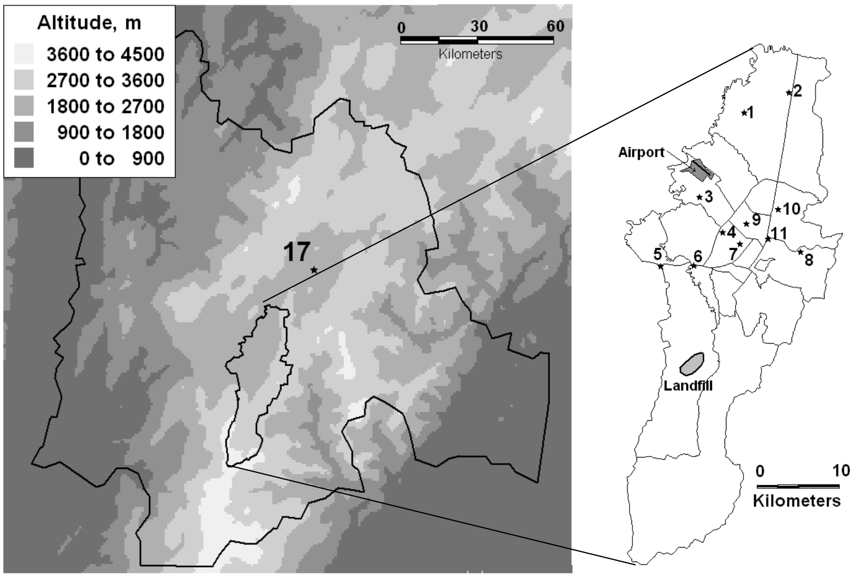

Figure 2.1: Domain chosen for the emission inventory and simulations. (a) Topography of the domain of study (212 km x 212 km, lower left corner 3.9°N and 75.0°W) and city of Bogota. Cundinamarca department and Bogota's urban perimeter are delimited in thick black. Monitoring station number 17 (Duque) is also shown. (b) Bogota's urban perimeter, street network and measuring stations: 1. Corpas, 2. Escuela, 3. Fontibón, 4. Merck, 5. Cazucá, 6. Sony, 7. Cade, 8. Monserrate, 9. Nacional, 10. Santo Tomás, 11. MMA.

ment of an air quality management system for Bogota was conceived. This project comprises the development of a set of tools which will facilitate the understanding and management of the air pollution problem in the city. Uncertainty regarding the response of pollutant concentrations to reductions of emissions, has made of modelling an essential tool to test abatement strategies (Vivanco and Andrade, 2006; Martilli et al., 2003); hence meteorological modelling in combination with air quality simulations is part of the set of tools to be developed. The modelling in turn will depend on an optimal spatially and temporally distributed emission inventory (EI). The goal of the project is to quantify emissions and to evaluate their implications on air quality, by applying a combined meteorological-photochemical air pollution model to the case of Bogota. The ultimate purpose is to implement efficient pollution control plans, following a careful cost benefit analysis. A series of articles is currently being prepared in order to present the main contributions of this case study. Up to now, a comprehensive spatially and temporally resolved EI did not exist for Bogota, neither have up to date photochemical models been applied to the region. The present paper is devoted to the presentation and evaluation of the EI for Bogota, 2002 being chosen as the base year. Problems encountered while completing the EI are presented, as well as the solutions adopted. This is of paramount importance because the lack of information and knowledge on emissions is a frequent situation when working on air pollution case studies in developing countries (e.g. Gurjar et al. (2004); Wang et al. (2005); Vivanco and Andrade (2006)). Consequently, finding adequate solutions to quantify emissions in a rapidly changing environment is often a major challenge for such countries.

Detailed EIs of air pollutants from human activities and natural sources are a first essential step towards understanding, controlling and mitigating air pollution; since the composition of the atmosphere is directly related to the emission fluxes (Taghavi et al., 2005). Two main methodologies can be applied when building an EI (Friedrich and Reis, 2004), namely bottom-up (based on in site information on emissions and activity data, it implies a big effort in data collection and it relies on emission models), and top-down (independent estimates of emissions based for example on analysis of statistical data, which are often not detailed enough for modelling purposes). Many authors (Friedrich and Reis (2004); Vivanco and Andrade (2006); Parrish (2006) among others) recommend a combination of both methodologies; when their estimates agree, EIs are then considered to be more reliable.

Within the framework of this project a bottom-up approach is used to build our EI. The emission model AIREMIS (ACRI, 2000), which is based on CORINAIR methodologies (EEA, 1999), is used for this purpose. Two main types of data are needed: activity data (for example data on on-road vehicle sources like the average trip length, number of vehicles circulating per hour and per road, their average speed, etc.) and emission rate data, that is, emission factors (EFs). The first group of information represents a challenge in the case of Bogota because often the required data are not available.

For the second group of information, in the case of Europe for example, large databases of EFs exist, like those proposed by CORINAIR. Nevertheless, there is still an important uncertainty regarding precise real-world emissions. We focus our interest on on-road traffic because this source is among the main contributors to air pollution at urban sites (Rappenglück et al., 2000; Na et al., 2003; Vivanco and Andrade, 2006; Parrish, 2006). The project BAB II (Karlsruhe **B**undes**A**uto**B**ahn campaign (Germany), Corsmeier et al. (2005)), shows an example of the differences that can be found between model-calculated and real-world on-road traffic EFs. CO and NO_x emissions are underestimated by the emission model by about 23% and 17% respectively. For NMHC, the underestimation depends on the chemical species, but it can go up to a factor of about 20 times. The accuracy of mobile emission estimates have been questioned by many studies (Wang et al., 2005; Vivanco and Andrade, 2006; Parrish, 2006), suggesting the need of verification of the inventories and EFs. Traffic EFs depend to a large degree on the driving conditions and therefore can vary depending on the location (Berkowicz et al., 2006). This is particularly relevant for Bogota, where traffic jams are frequent, roads are often in a poor state of repair, and travel times are long (Skinner, 2004). There have been many attempts to estimate better real-world mobile emissions in developing countries using different approaches, for example, in India and China (Gurjar et al., 2004; Wang et al., 2005) laboratory measurements were done using local driving conditions and motor vehicles. Mexico has worked on direct measurement of exhaust emissions using remote sensing techniques (Schifter et al., 2003) and mobile laboratory in chase techniques (Zavala et al., 2006), while some other studies have been done to validate the EI through comparison with observations such as the study made in Sao Paulo by Vivanco and Andrade (2006). Some other methodologies like the application of street canyon models compared to measurements have been applied (e.g Olcese et al. (2001); Berkowicz et al. (2006)). The general conclusion of these studies is that model-calculated traffic emissions are underestimated and further research is needed to bring modelled and real-world traffic emissions in closer agreement.

In this paper, two estimations of the Bogota's EI are presented and compared. In a first step CORINAIR traffic EFs are used for the calculation of the EI (in the following this EI will be labelled *EI-1*). An evaluation of the traffic EFs for Bogota was conducted afterwards, via a top-down methodology which combines measurements inside a street canyon (SC) and the inverse use of a dispersion model. In this study, total on-road vehicle emissions are calculated by replacing CORINAIR EFs by those obtained in our evaluation process, so as to obtain a second version of the EI (in the following this EI will be labelled *EI-2*). Both EIs are tested using a state-of-the-art Air Quality Model (AQM) as tool of comparison. The AQM is applied to the particular case of a photochemical episode which took place in Bogota during 6 and 7 March 2002 (and for which a measuring campaign was conducted). The simulated concentrations obtained using both versions of the EI are compared with measurements.

Section 2.2 of this paper presents the relevant information on activity data for each source of emission and the description of how the EI is built. In the case of traffic, a brief description of the methodology used for the calculation of Bogota's traffic EFs is presented (section 2.2.2). In the last part of section 2.2, results of the two versions of the EI are included. The evaluation and comparison of the EIs using the AQM is presented in section 2.3. Section 2.4 includes the analysis and discussion of results once the EIs have been evaluated.

2.2 Emission inventory data

The methodology for the preparation of the EI includes three steps, considering that it will be used as input data of the AQM: definition of the temporal and spatial resolution of the inventory, source classification and calculation of emissions, and incorporation of the time dependent source data into the grid defined for modelling. A temporal resolution of one hour is used, and calculations are done for a given working day in March. As for the spatial resolution, the EI is calculated for the Cundinamarca state (fig. 2.1(a)), which is included inside the grid used for modelling (212 km by 212 km with 4-km square cells). Emission calculations are first individually done by source for Cundinamarca and afterwards adjusted to the 4 x 4-km cells.

Four main sources are considered for the calculations: production and services (P&S), air traffic, biogenic (section 2.2.1), and on-road traffic (section 2.2.2). For the former, two sets of EFs are used: CORINAIR EFs (section 2.2.2) and Bogota's own EFs (section 2.2.2). Emission estimations are done for NO_x, CO, NMVOCs, CO_2, SO_2, CH_4, and PM_{10}. AIREMIS is used for calculations and spatial aggregations. Section 2.2.3 presents results for both EIs.

2.2.1 Input data other than traffic

Production and Services (P&S)

These sources are divided in point sources (industries and commercial establishments) and area sources (fuel commercialization and Bogota's landfill). DAMA furnished emission data inside the urban perimeter for 4 818 point sources (table 2.1 and fig. 2.2), product of a detailed industrial EI carried out during 2001, using the AP-42 series EFs proposed by the EPA methodology (DAMA/INAMCO, 2001; EPA, 2004). From the 4 818 sources, 3 194 are georeferenced. The remaining do not have an official address in agreement with DAMA's street network database. From the 3 194 sources, 106 contribute with 95% of the total emissions (except NMVOC), so in this inventory they are considered as point sources inside the urban perimeter, and their emissions are input to AIREMIS (as furnished by DAMA). The remaining 4 712 sources (4818 – 106) are grouped as area sources by district (Bogota's urban area is divided into 19 districts, fig. 2.3). Most of the 106 point sources are situated in the Puente Aranda district, the most important industrial center in Bogota.

Table 2.1: Percentual distribution by economical activity in Bogota and Cundinamarca*

Economical activity	Bogota	Cundinamarca
Food and drink production	14.8	28.9
Textile industry	2.5	3.2
Shoe production	4.3	NA
Chemical industry	4.1	16.5
Plastic and rubber industry	4.7	7.6
Metallurgy and metal products	1.6	13.3
Furniture manufacture	6.8	12.9
Non-metallic minerals extraction and production	0.1	15.8
Manufacture of paper, cardboard and derivatives	NA	1.8
Hotels, bars	25.1	NA
Miscellaneous**	36.0	NA

*sources: DAMA/INAMCO (2001); DANE (2004). **Miscellaneous comprises dry cleaning, printing, engineering services, etc. NA=Not available.

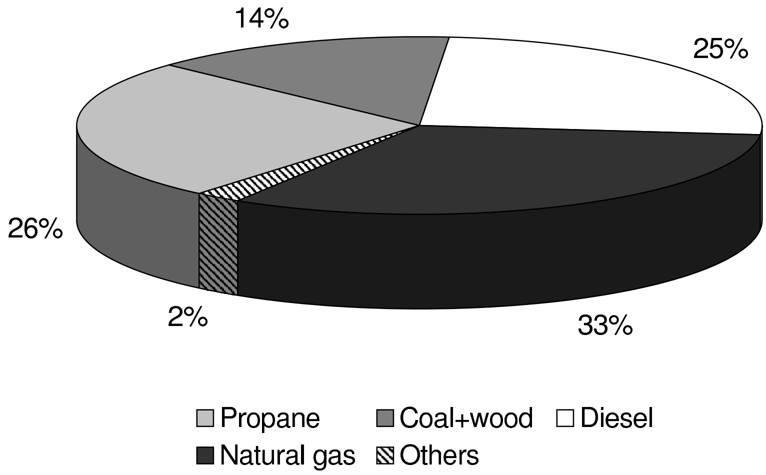

Figure 2.2: Fuel usage for the 4818 records of point sources in Bogota. Other fuels are: crude oil, fuel oil, burned oil and gasoline. Source: DAMA/INAMCO (2001). Although 59% of the industries are using propane and natural gas, a high percentage (16%) uses coal, wood and other fuels of low quality.

To cover the spatial resolution of the inventory described in this study, industries located outside the urban perimeter but inside Cundinamarca department are taken into account. A total number of 260 point sources, comprising two important industrial centers in the region (northern and western industrial corridors, fig. 2.3), are used as input data. The existing information for these industries is very poor, an official detailed database does not exist (only by economical activity, table 2.1), and information concerning fuel usage or temporal distribution is even more scarce. Either CORINAIR EFs or direct measurements of emissions, when available, are used for the calculations. For example, 91 of the 260 sources, correspond to brick factories. Existing emission measurements from a representative number of them are used as average input emission data for all of them, because EFs for some of the fuels used, such as crude oil, biomass, tires, etc., do not exist. When possible, local characteristics of the fuels are used, as for example in the case of composition of the coal used.

EPA's methodologies and EFs (EPA, 2004) are used for the calculation of

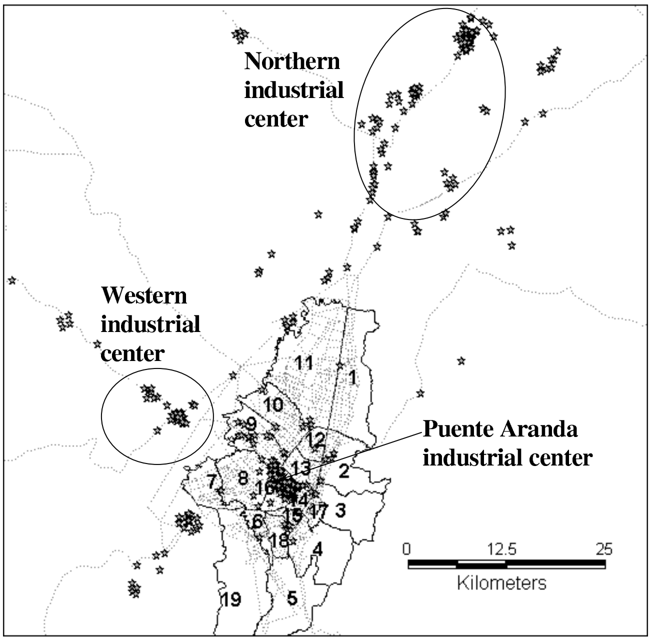

Figure 2.3: Spatial distribution of the main point industrial sources around the region of Bogota. Three main industrial zones are shown: center of the city (Puente Aranda district), and the northern and western industrial corridors. The administrative division of Bogota by localities is also depicted: 1. Usaquén, 2. Chapinero, 3. Santafé, 4. San Cristóbal, 5. Usme, 6. Tunjuelito, 7. Bosa, 8. Kennedy, 9. Fontibón, 10. Engativá, 11. Suba, 12. Barrios Unidos, 13. Teusaquillo, 14. Mártires, 15. Antonio Nariño, 16. Puente Aranda, 17. Candelaria, 18. Rafael Uribe, 19. Ciudad Bolívar.

emissions coming from the commercialization of fuel (NMVOC emissions due to handling and selling gasoline) and the landfill (CH_4, CO_2 and NMVOCs). Both are considered as area sources. For the first one, 19 area sources inside Bogota's urban perimeter (by district), and one area source for the rest of the Cundinamarca department. As for the landfill, one area source comprising the whole extension of it (fig. 2.1(b)).

Air traffic

The airport in Bogota is located inside the city (fig. 2.1). Emissions are calculated based on the georeferencing of the landing strip and the airport area, the air fleet composition, the total number of air operations per year and the temporal variations of them. EFs are those proposed by the MEET methodology (ACRI, 2000).

Results appear as both linear (over the landing strip, while taking off and landing) and area (over the surface of the airport, while moving or parking) emissions, and are calculated at the ground level. Pollutants taken into account are: CO, NMVOC, NO_x and SO_2. The total number of air operations during the year 2000 was 165 497 (AEROCIVIL, 2002), value used as input for AIREMIS. Monthly, daily and hourly coefficients are applied to obtain the temporal distribution of the air operations (UNIANDES/EPFL, 2002).

Biogenic sources

The biogenic EI is important for modelling, because biogenic VOCs can contribute significantly to the formation of ozone (Stockwell et al., 1997; Rappenglück et al., 2000). Land use data (U.S. Geological Survey, 2002) grouped in three main types of biogenic sources (foliar forest, grasslands and other kinds of similar vegetation, and soils) is used for the calculation. The two first groups concern emissions of Isoprenoids, Terpenes and other VOCs, whereas the last one concerns Methane emissions. Although biogenic EFs are inherent to the existing vegetal species at a given place and time, those from CORINAIR (EEA, 1999) are used for this study, due to the lack of documentation in the geographical distribution of the vegetal species of the region and their EFs. Typical hourly values of temperature and Photosynthetically Active Radiation (PAR), for a day in the first dry season of the year, are used to compute these emissions.

2.2.2 Input data for traffic

Classic methodology: CORINAIR EFs (EI-1)

Traffic emissions are calculated using three main groups of activity data: the georeferenced street network, the fleet composition, and temporal and spatial variations of circulation and parking of this fleet. A traffic model is applied to the city (Reymond, 2002) to obtain the number of vehicles (and their average speed) circulating per segment of the street network between 1800LT and 1900LT of a given working day (this hour stands for the input information required by AIREMIS). The linear emission per segment is calculated based on CORINAIR velocity-dependent EFs according to the composition of the fleet and the type of road (highway, peripheral or urban). The emissions are computed hour per hour, using hourly coefficients which are given as input to the model for each type of road.

Total traffic emissions are calculated by adding emissions from two different sources, namely exhaust emissions and evaporative emissions. Exhaust emissions are at the same time divided into the thermally stabilized engine operation (hot engine) and the warming-up phase (cold start). Gasoline evaporation includes diurnal emissions, hot soak emissions and running losses. For both diurnal and hot soak emissions, GIS-based data of the economical distribution of the city, that is, the location of commercial, industrial and residential districts is used, in order to generate the corresponding area sources of emissions. Hourly temperatures expected for a given average day of the first dry season of the year (January, February and beginning of March) are also taken into account for this calculation.

Concerning the fleet circulating in Bogota, an official, complete and updated database does not exist. Bogota has a total of 989 366 vehicles (684 428 registered in the city and 304 938 registered outside the urban perimeter but with their owners having an address in Bogota, according to the state of the fleet in 2002, UNIANDES/EPFL (2002)). 6% are equipped with diesel. This corresponds to buses, trucks and a few light duty vehicles and passenger cars (1%), whereas the remaining 94% corresponds to gasoline passenger cars, light duty vehicles, minibuses, microbuses and vans. The database containing the information of the composition of the fleet by type and fuel has only 565 613 entries. We apply the percentages of repartition from this database to the total number of vehicles (Tables 2.2 and 2.3). Splitting by classes (according to the engine capacity) is also required as input data for each type of vehicle. 382 547 entries possess this information in the existing database, so input percentages to AIREMIS are based on information from these records.

The hourly coefficients of traffic circulation (fig. 2.4) per type of road are computed based on existing vehicle counts (UNIANDES/EPFL, 2002). The coefficient for the hour between 1800LT and 1900LT, the same hour for which the traffic model is run, has a value of 1. The amount of vehicles circulating per hour is calculated by multiplying such coefficients by the traffic model results. Calculations for all

Table 2.2: Composition of Bogota's fleet (% by year of production, state in 2002) for Gasoline passenger cars (GPC).

Production year	%
< 1972	4.66
1972-1977	7.90
1978-1980	5.49
1981-1985	9.91
1986-1992	15.82
1993-1996	20.97
1997-2000	12.07
$\geqslant 2001$	3.30
Total	**80.12**

See table 2.3 for the rest of the fleet distribution

the vehicles were done using an average trajectory length of 25 km, which is the value reported by the *Ministry of Transport* (UNIANDES/EPFL, 2002).

Estimation of Bogota's traffic EFs (EI-2)

On-road traffic is the most important factor contributing to urban pollution in Latin American supercities. It is therefore of great importance to have reliable traffic EIs. We apply a simple and cost-effective methodology to obtain real-world EFs for Bogota. A brief description of the methodology, which is based in the work made by Palmgren et al. (1999) and Olcese et al. (2001), is presented here (details can be found in Manzi et al. (2003)). A new traffic EI is thus computed by replacing CORINAIR EFs by those obtained for Bogota.

The methodology used to obtain Bogota's EFs consists in the inverse application of a dispersion model within a street canyon (SC) with a high traffic circulation, assuming that it is representative of the general driving conditions and fleet circulating in the city. This methodology allows estimation of hot emissions within the SC, and it is based on the premise that the street contribution to pollution (C_s, [g m^{-3}]) is the product of the local street traffic emissions submitted to a given dispersion, which is dependant on meteorological factors and the geometry of the SC:

Table 2.3: Composition of Bogota's fleet (% by year of production, state in 2002) for Gasoline light duty vehicles (GLDV), diesel passenger cars (DPC), diesel light duty vehicles (DLDV), heavy duty vehicles-trucks (HDV-T) and heavy duty vehicles-buses (HDV-B).

Production year	GLDV	DPC	DLDV	HDV-T	HDV-B
< 1972	1.47	0.02	0.00	0.98	0.40
1972-1991	5.76	0.29	0.01	1.30	1.15
1992-1996	4.05	0.25	0.01	0.34	0.52
1997-2000	2.32	0.38	0.02	0.10	0.10
$\geqslant 2001$	0.19	0.07	0.01	0.01	0.14
Totals	**13.80**	**1.01**	**0.04**	**2.72**	**2.31**

For GPC see table 2.2. 55% of the total fleet is 10 years old or more at the moment of consulting the database. From the total fleet, 6% run with diesel, 94% with gasoline.

$$C_s = D \cdot Q_s \tag{2.1}$$

where D is the dispersion factor [s m^{-2}] and Q_s is the emission rate of pollutant in the street [g m^{-1} s^{-1}], which varies with the daily traffic. In order to evaluate D, the model STREET is used (Johnson et al., 1973; Berkowicz et al., 1997). It is empirically derived based on pollution measurements in a number of SCs and describes two formulations for C_s (C_w and C_l, for the windward and leeward sides of the street). The formulation for C_l can be found elsewhere (Berkowicz et al., 1997; Olcese et al., 2001); C_w is expressed as:

$$C_w = C_s = \frac{kQ_s}{w(u+0.5)} \frac{H-z}{H} = D \cdot Q_s \tag{2.2}$$

where H is the depth of the SC [m], w is its width [m], u the wind speed at roof level [m s^{-1}], z the receptor height [m], and k a nondimensional empirical constant. Releasing known amounts of passive tracer so that a line source inside the SC is simulated, and measuring its concentrations, k is obtained. Equation 2.2 can afterwards be inverted to calculate Q_s for the pollutants of interest, if their concentrations are also measured.

Q_s can be expressed as the total number of vehicles circulating per hour (t_F) times an average emission rate per mobile source q, [g m^{-1} veh^{-1}]. Moreover, for

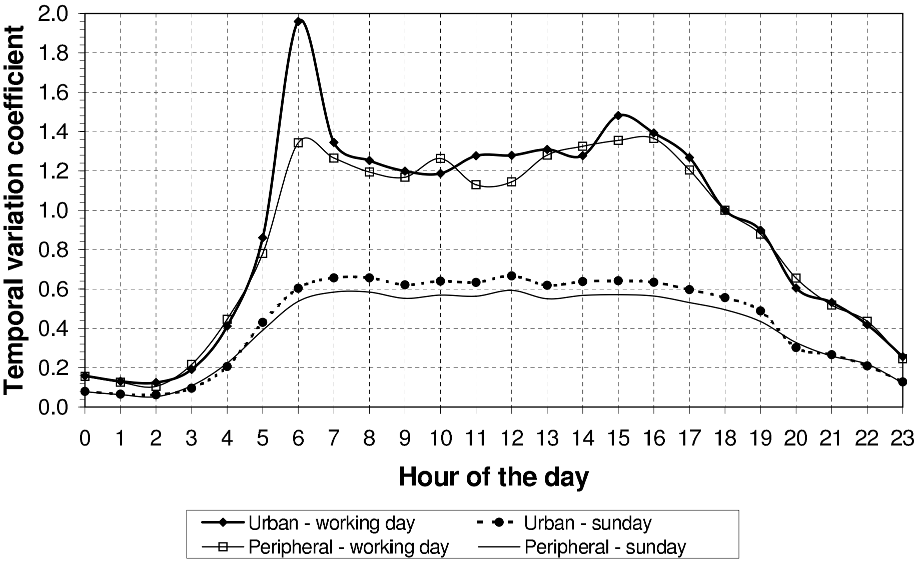

Figure 2.4: Hourly coefficients of traffic distribution, per type of road. A value of 1.0 is attributed between 1800LT and 1900LT to both types of roads, peripheral and urban (highway not used in this study), for a working day. The rest of the coefficients are assigned based on the existing traffic counts in the city.

two different types of vehicles (heavy and light):

$$Q_s = t_F \cdot q = t_{FL} \cdot q_L + t_{FH} \cdot q_H \tag{2.3}$$

where t_{FL} and t_{FH} represent the hourly traffic counts for light and heavy vehicles (as mentioned before, light and heavy vehicles use mainly gasoline and diesel as fuel respectively). q_L and q_H correspond to the average emission per mobile source [g m^{-1}veh^{-1}] for each vehicle category. Whenever hourly car counts are available, equation 2.3 is formulated. All the possible pairs of linearly independent equations are solved, in order to calculate separately q_L and q_H, which correspond to the desired EFs in our study. The average values obtained are presented in table 2.4.

These EFs are replaced in AIREMIS as velocity-independent, equal average values for every type of vehicle, separating only into two main types (light and heavy vehicles). A discussion on these results is presented in section 2.4.2.

Table 2.4: Traffic emission factors (q) found for Bogota, for light and heavy vehicles* [g km^{-1} veh^{-1}]

Pollutant	Light	Heavy	Weighted average
CO	8.27±1.96	385.2±142.3	15.47±2.84
NO_X	0.11±0.02	18.9±0.37	0.41±0.09
PM_{10}	0.27	2.38	0.35±0.08
NMVOC	5.58		

*source: Manzi et al. (2003). Light vehicles include passenger cars and light duty vehicles; heavy duty vehicles include trucks and buses. The average EF obtained ± the standard deviation is presented in this table.

2.2.3 Results of the Emission Inventories

Table 2.5 presents the results of the EI by source for Bogota, and its percentages of contribution to total emissions in Cundinamarca. Two columns are presented for traffic, using CORINAIR (EI-1) and Bogota's (EI-2) EFs. This table shows how total traffic emissions increase 5, 4 and 3 times for CO, PM_{10} and NMVOCs respectively after applying Bogota's EFs. A further discussion of these results will be presented in section 2.4.

Table 2.5: Total emissions by source for the urban perimeter of Bogota [ton day^{-1}]*

	On-road traffic		P&S	Air Traffic	Biogenic
Pollutant	EI-1	EI-2			
CO	165.0 (73)	838.8 (64)	21.9 (41)	6.7 (100)	-
NO_x	39.0 (64)	37.4 (64)	3.8 (17)	7.6 (100)	-
PM_{10}	1.0 (70)	4.5 (65)	8.1 (78)	-	-
NMVOC	42.6 (83)	130.4 (68)	12.1 (78)	3.2 (100)	0.03 (0.4)
SO_2	6.3 (69)		14.0 (1)	0.4 (100)	-
CH_4	1.4 (77)		132.7 (100)	-	-
CO_2	5 133.4 (70)		1 095.9 (22)	-	-

* Numbers in parenthesis are the percentage of contribution of Bogota's emissions to total emissions over the studied domain. P&S= Production and Services.

2.3 Evaluation of the Emission Inventories over a specific case study

In order to assess the two versions of the EI, an AQM at the mesoscale level is applied. The goal is to compare the concentrations of CO, NO_x, NMVOCs and Ozone generated by the AQM for both EIs (EI-1 and EI-2). The AQM is applied to the 2-day photochemical episode during the dry season in 2002 (March 6 and 7). This test case represents a typical photochemical pollution situation often found during the dry seasons in the plateau of Bogota (see section 2.3.2), and it is chosen because we rely on data from a measuring campaign which took place in the region for this period, allowing a better validation of the model. Simulated and observed concentrations are compared to evaluate the proximity of both EIs to measurements. Sections 2.3.1 and 2.3.2 present a brief description of the AQM and the meteorological situation in the region respectively. Results of running the AQM for the two emission scenarios (EI-1 and EI-2) are presented in section 2.3.3.

2.3.1 Model description

The models TAPOM (Transport and Air POllution Model, Martilli et al. (2003)) and FVM (Finite Volume Model, Clappier et al. (1996)), developed at LPAS (EPFL), are used for this study. They are three dimensional Eulerian models using terrain following grid and finite volume discretization. The transport and photochemistry model TAPOM includes the RACM lumped species mechanism (Stockwell et al., 1997), the Gong and Cho (1993) chemical solver for the gaseous phase, the ISORROPIA module for inorganic aerosols (Nenens et al., 1998), the passive transport of organic aerosols, and the solar radiation module TUV developed by Madronich (1998) to calculate the photolysis rate constants. Meteorological input data for TAPOM is obtained from the model FVM, whose borders can be forced using wind and temperature fields from large scale model results. FVM includes an urban turbulence module (Martilli et al., 2002, 2003) which specifically simulates the effects of urban areas on the meteorology. For both meteorological and air quality simulations, we use a domain of 212 km by 212 km (fig. 2.1), with 4-km square cells and the city of Bogota in the middle. A pre-run of one day with the same emissions and wind fields is conducted for all the simulations, in order to provide more realistic initial conditions.

2.3.2 Meteorological situation in the zone of study during the episode

The episode chosen corresponds to a period of the year in which the general climatic conditions in the colombian Andes are dry and hot. During late December, January, February and early March, the intertropical convergence zone (ITCZ) is located at a latitude of about 2°N, thus global scale winds (The Trade winds) come from the NE to the region of study. The influence of these winds is mainly seen over Bogota's plateau during the mornings, hence pollutants are pushed to the southwest of the city. As the sun heats up the ground throughout the day, a thermal wind predominates, air masses go up from the valleys and are pushed towards the East and Northeast, so pollutants are recirculated back over the city again. This meteorological behavior is representative of the first dry season of the year in the region, and it is of main interest since pollutants are brought back over the city towards the end of the morning, increasing exposition levels. The validation of meteorological and air quality simulations has been done using both data from Bogota's monitoring network and from the measuring campaign. It will be presented in separate articles which are currently being prepared.

2.3.3 Comparison of simulated and observed surface concentrations

A first comparison with primary pollutants is conducted. CO and NO_x are little influenced by the chemistry on the temporal scale of the order of a few hours (even if NO and NO_2 are reactive, the total $NO_x = NO + NO_2$ is little influenced by the chemistry). They are mainly influenced by dispersion and thus their concentrations are good indicators to evaluate the EI. Predicted daily CO concentrations using CORINAIR traffic EFs (EI-1) are much lower than the observed values and than those predicted with Bogota's traffic EFs (EI-2) (fig. 2.5). Nightly peaks of CO are not well reproduced by the simulations, probably due to an inadequate distribution of the nightly wind field. For NO_x (fig. 2.6), both simulations give similar results, since total NO_x traffic emissions do not differ much between both inventories (around 4 %, see table 2.5), nevertheless, morning and nightly maximum concentrations are over-predicted at Nacional station. The hour of the morning peak, which is related to traffic, is generated by the model at 0900LT, and it is in good agreement with observations.

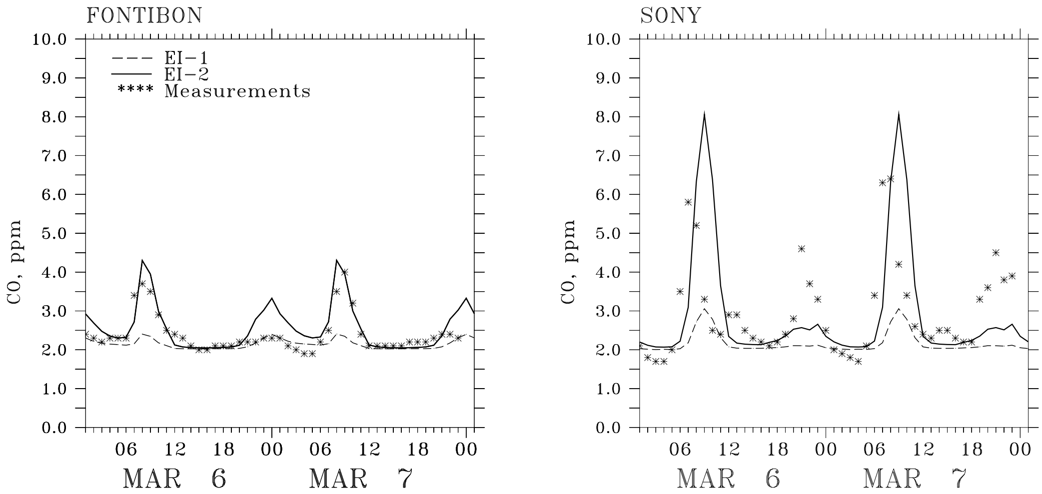

Figure 2.5: Time series of observed (stars) and simulated CO concentrations in ppm using two versions of the emission inventory: EI-1 (dashed line) and EI-2 (solid line), 6 and 7 March 2002, for Fontibon and Sony measuring stations.

In order to better evaluate results, the index AOT$_{min}$ is calculated (Accumulated exposure Over a Threshold, is the surface under the curve of pollutant concentration time series above a certain threshold, in this case the threshold is the minimal concentration found for each curve), for both emission scenarios and observations, and for all the measuring stations. The difference in percentage between the AOT$_{min}$ values obtained for the simulations and those obtained for the observations is computed for each station and afterwards averaged (table 2.6). The simulation labelled EI-2 is closer to observations, especially for CO, presenting an average percentual difference of 33%, whereas simulation EI-1 presents 85%. For NO$_x$, percentual differences with respect to observations are smaller for EI-2, although not so different from EI-1 results. This indicates a clear underestimation of CO emissions in EI-1, whereas for NO$_x$ both EI-1 and EI-2 generate similar results.

The model also shows how simulated concentrations of NMVOCs (fig. 2.7) are

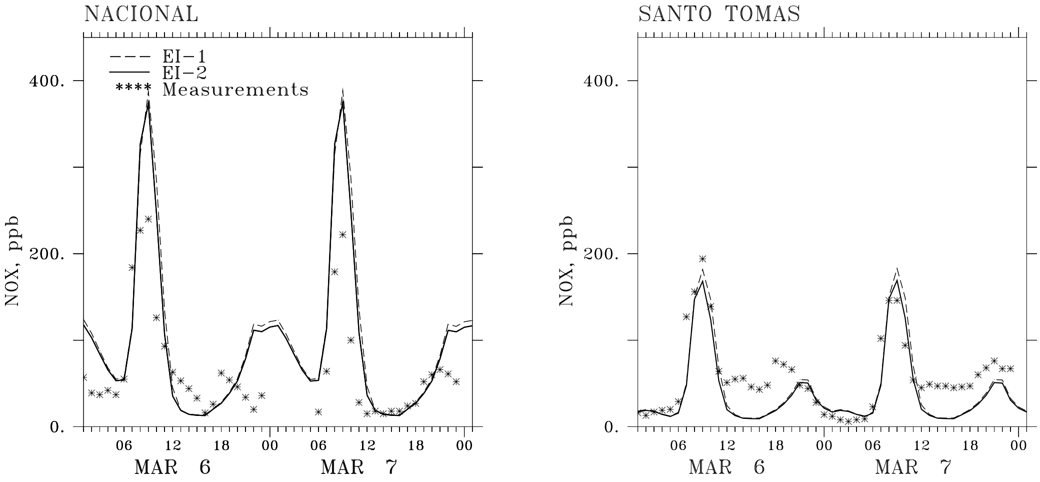

Figure 2.6: Time series of observed (stars) and simulated NO_x concentrations in ppb using two versions of the emission inventory: EI-1 (dashed line) and EI-2 (solid line), 6 and 7 March 2002, for Nacional and Santo Tomas measuring stations.

Table 2.6: Percentual difference between the AOT_{min} values computed for the two simulations (EI-1 and EI-2) and the observations. AOT values are calculated over the 2-day pollution episode (6 and 7 March 2002).

Pollutant	EI-1	EI-2
CO	85	33
NO_x	76	72

much higher when using Bogota's EFs. Since there are no NMVOC measurements available, we proceed to examine Ozone concentrations (fig. 2.8) as an indirect way to evaluate the impact of a change in the NMVOCs input emission data, although Ozone chemistry is strongly non-linear and concentrations depend on many other factors such as solar radiation and wind. On 6 March, the maximum measured O_3 value is 149 ppb, attained at Nacional station, downtown Bogota. With both EIs, the model reproduces an O_3 maximum in the city center (87 and 107 ppb for EI-1 and EI-2 respectively, at Nacional station), showing a better agreement for EI-2. On March 7, the maximum measured O_3 value is attained at Monserrate station, towards the eastern part of the city (see fig. 2.1), with 120 ppb (not shown), whereas the model simulates a maximum in downtown, as the day before. This difference allows us to conclude that the meteorological conditions of the second

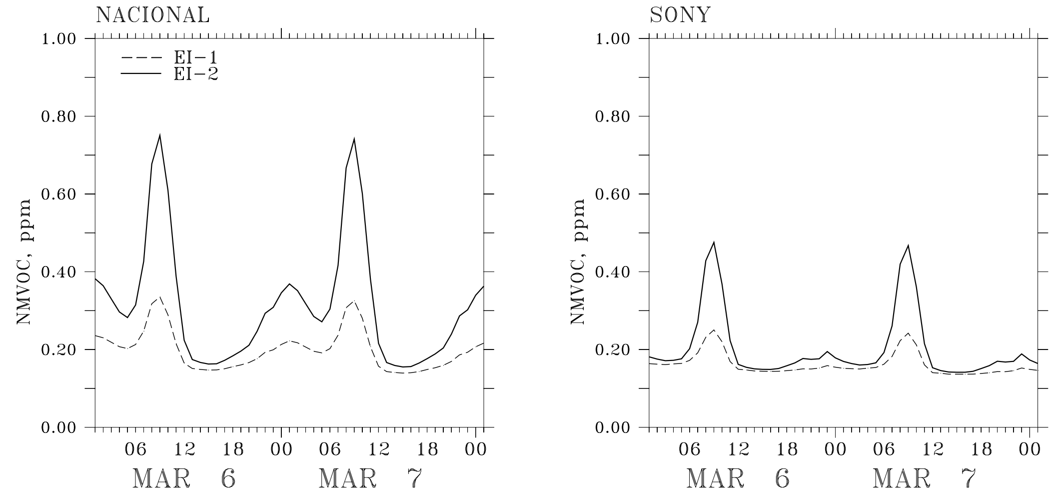

Figure 2.7: Time series of simulated NMVOCs concentrations in ppm using two versions of the emission inventory: EI-1 (dashed line) and EI-2 (solid line), 6 and 7 March 2002, for Nacional and Sony stations.

day are not accurately reproduced by the model. Therefore, even if EI-1 simulated O_3 values are closer to measurements in Nacional and Merck stations for the second day of simulation, we consider that the calculation using EI-2 simulates better the O_3 production.

2.4 Discussion and implications of the emission inventory results

Once both EIs have been evaluated and EI-2 is found to be more realistic, further conclusions are extracted based on it (section 2.4.1). Afterwards, some limitations of the methodology are outlined (section 2.4.2).

2.4.1 Distribution of emissions by source and by region

The most important contribution of CO, NMVOC, CO_2 and NO_x in Bogota is attributed to traffic (fig. 2.9). A similar relative source strength is found for other Latin-American cities such as Santiago and Mexico city (CONAMA, 2000; SMA,

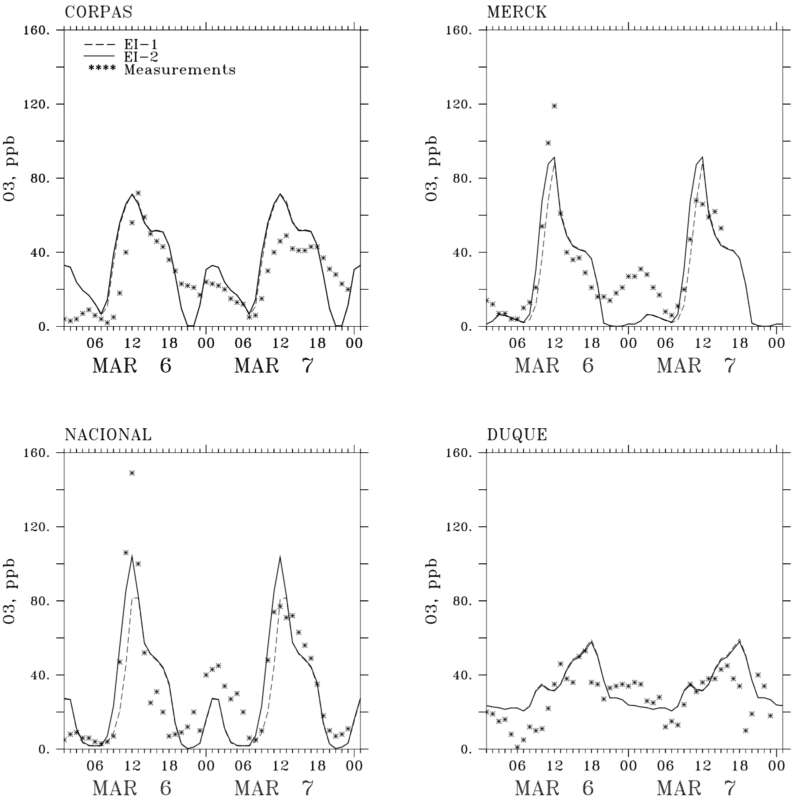

Figure 2.8: Time series of observed (stars) and simulated O_3 concentrations in ppb using two versions of the emission inventory: EI-1 (dashed line) and EI-2 (solid line), 6 and 7 March 2002, for Corpas, Merck, Nacional and Duque stations.

2004), especially for CO and NO_x. Fig. 2.10 shows the repartition of the on-road traffic emissions for light and heavy vehicles. For PM_{10}, NO_x, CO and SO_2, the 99, 96, 84 and 65% of the total traffic emission, respectively, correspond to heavy vehicles (buses and trucks). This result is of main importance when considering that only 5% of the total fleet corresponds to heavy vehicles, using diesel as fuel. This small proportion of the fleet accounts for a large part of the air pollution in Bogota, and sheds light on where the environmental authorities should address their efforts. A similar situation is found in other cities like Sao Paulo (Colon et al., 2001; Vivanco and Andrade, 2006) and Mexico (Zavala et al., 2006), where only a small portion of the fleet is responsible of a large part of the total traffic emissions. Moreover, although the methodology described in this study is developed to determine emissions for only two vehicle classes (light and heavy), it would be very interesting to apply it (with more specific traffic counts) aiming to obtain emissions for different light vehicle categories, since, as in the case of Mexico City (Zavala et al., 2006), some particular gasoline powered light vehicle categories might account for a large percentage of the emissions.

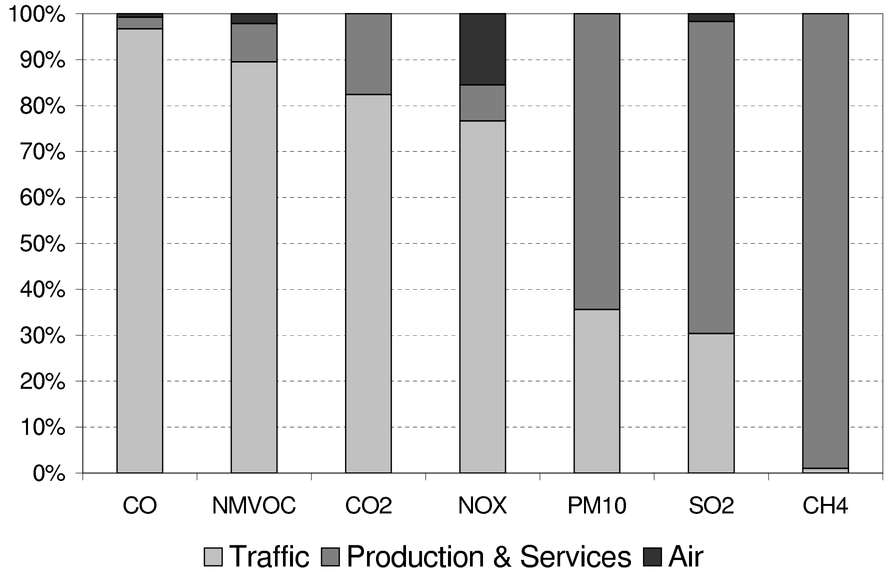

Figure 2.9: Distribution of the emissions by source and pollutant in Bogota's urban perimeter. Biogenic emissions are mainly found outside the urban perimeter (not shown here).

Total NO_x traffic emissions for EI-1 and EI-2 do not differ significantly. Nevertheless, a very important proportion of the emission (96 %) is attributed to heavy duty vehicles in EI-2. This high proportion may be partially attributed to the effects of altitude, as it has been shown by Bishop et al. (2001). However, NO_x is one of the species that is most influenced by the driving mode (Zavala et al., 2006), and the methodology described in this paper attempts to represent the average driving mode of a typical street in Bogota. It would be interesting to explore results of the application of the same methodology presented in this study, but for a street characterized by a different driving mode.

Fixed sources contribute mainly with PM_{10} and SO_2. Concerning PM_{10}, some sources were not taken into account in this EI, like construction, natural sources or resuspension and therefore this conclusion is not definitive. Further research is needed regarding PM_{10}.

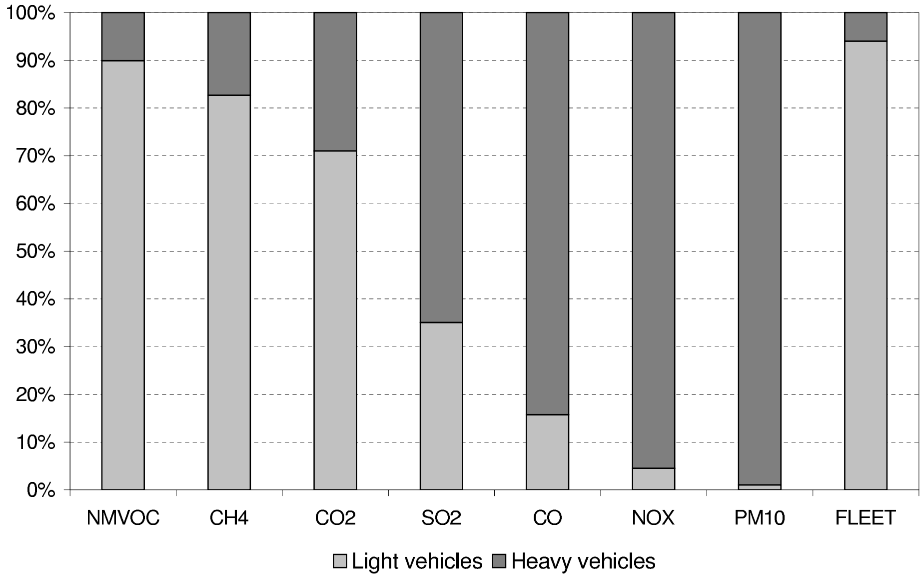

Figure 2.10: Distribution of the on-road vehicle emissions in Bogota by type of vehicle and by pollutant.The last bar indicates the repartition of the fleet.

The spatial distribution of emissions (fig. 2.11 and table 2.7) indicates that downtown Bogota (cell ID's X21, Y20, Y21, Z20, Z21 and Z22) contributes with significant emissions of CO, PM_{10}, NMVOC and NO_x. Those emissions are mainly related to traffic, and to a less extent to one of the main industrial centers in the city, located in Puente Aranda district (fig. 2.3). The cell where the landfill is located (cell ID X17) contributes by far with the highest amount of CH_4 in the domain (this pollutant is not significant in the process of ozone production, but it is of interest for other reasons such as global warming and climate change). The cell where the airport is located (cell ID X23) indicates a significant contribution of NO_x. 16% of the NO_x emissions in the city is coming from air sources. This result is important because it indicates that the proximity of the airport to the city may have important repercussions over air pollution, namely on the production of ozone. Another significant contribution of NO_x is seen in the western industrial corridor of the region. This NO_x is brought over the city contributing to the production of ozone (see section 2.3.2). The northern industrial corridor (cell ID's

AB30, AC29, AE35) points out important emissions of PM_{10}, NO_x, CH_4, SO_2 and CO_2. This region is characterized among others by a number of brick manufactures operating with fuels like coal, crude oil, fuel oil, etc, and thus, generating important contributions to emissions.

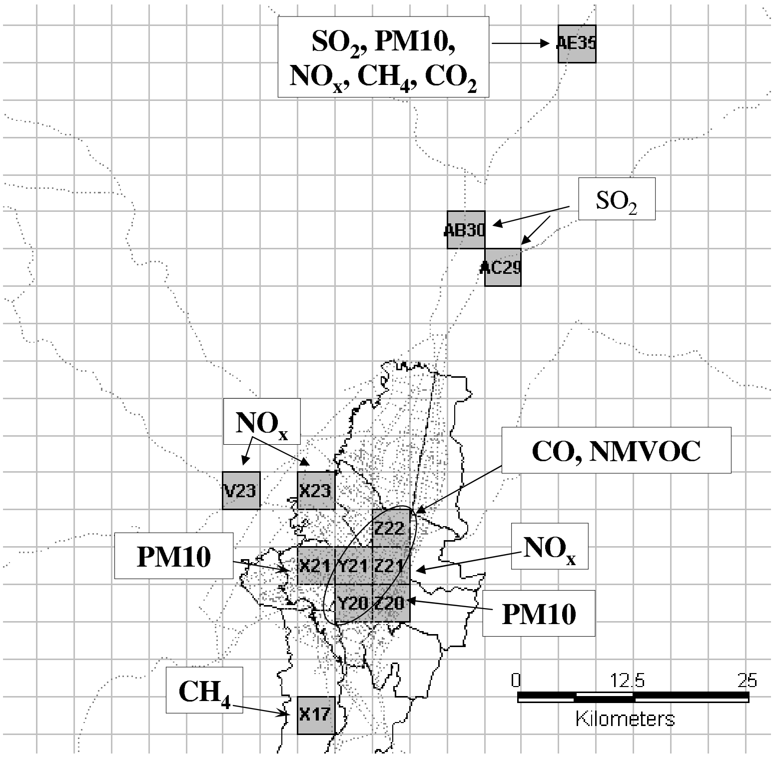

Figure 2.11: Spatial distribution of the emissions in the region of Bogota. The most polluted cells in the domain of study are presented. The city center presents high levels of emissions for all the pollutants. Refer to table 2.7 for data about emissions in these cells.

2.4.2 Limitations of the methodology and discussion

The major shortcoming of the bottom-up methodology used to build our EI is the difficulty to obtain all the necessary input data. The incomplete data make difficult to conduct a full evaluation of uncertainties. We can state that uncertainties in our EI come from three sources: first, the quality of the input data we have collected. Second, the extrapolation based on the existing information to fill in the remaining data gaps. Third, some aspects of the methodology itself and AIREMIS

Table 2.7: Most polluted cells in the domain of study and their emissions

Pollutant	Cell ID and emission, ton day^{-1} cell^{-1}			
CO	*Z21*	*Z22*	*Y21*	*Y20*
	89.6	72.7	69.0	65.9
NO_x	*X23*	*Z21*	*AE35*	*V23*
	7.2	4.2	4.1	4.0
PM_{10}	*Y21*	*X21*	*AE35*	*Z20*
	2.7	1.9	1.6	1.1
NMVOC	*Z21*	*Z22*	*Y21*	*Y20*
	13.5	11.9	10.6	9.7
CH_4	*X17*	*AB30*	*AE35*	*Z21*
	132.2	0.3	0.2	0.1
CO_2	*AB30*	*AE35*	*Y21*	*Z21*
	1997.8	1476.7	663.8	534.0

For each pollutant, the first line indicates the cell ID (the location of each cell is shown in fig. 2.11.) and the second its emission.

procedure, as it has been developed and applied by European countries and is not necessarily optimized for other countries.

In the second approach used for this study, bulk EFs are obtained for light and heavy vehicles regardless of a more complex composition of the fleet, and of variations in the driving speed (obtained EFs are assumed to be an average of the average driving speed measured inside the SC, 30 km h^{-1}). Results from the previous section allow us to conclude that the inventory including Bogota's own on-road traffic EFs is more realistic (closer to measurements) than the one obtained using CORINAIR EFs. This means that at the present, for a city like Bogota, focusing efforts in obtaining EFs representative of the actual state of maintenance of the vehicle fleet, local driving patterns and effects due to the altitude, is more important than obtaining especially detailed and precise information of the fleet classification and its circulation speeds. The later should be conceived as to facilitate the identification of the biggest contributors. Although more research is needed in order to improve these EFs, (for example, measurements could be conducted in more than one SC, for different driving speeds, more vehicle categories), the aggregated value of this methodology consists in its simplicity, relative low cost, the representation of real-word driving conditions at the altitude of Bogota, and the fact that it takes into account a large number of vehicles. On the other hand, a direct and quick evaluation of some abatement scenarios, which would need new on-road EFs, is not as simple as it is via a bottom-up methodology. Both methodologies are thus complementary.

An additional limitation of this methodology stands for the fact that the EI is evaluated on only one pollution event. We use this event because we rely on more data for validating its simulation and because it is particularly interesting since there is a recirculation of pollutants over the city due to a change in the wind direction, which is a common situation during the first dry season of the year. Nevertheless, conclusions remain only partial until simulating several pollution episodes or even applying long-term simulations.

Despite the limitations, a first version of Bogota's EI is accomplished, enhancing the knowledge about the spatial and temporal distribution of emissions in the region. The EI allows to identify the relative contribution of each source to pollution in the region, which will in turn help to recognize where efforts should be focused in order to improve the quality of the EI. Our results indicate that special attention should be given to heavy vehicles in Bogota, because they contribute crucially to air pollution in the city. Moreover, further investigations on emissions of this type of vehicles in Bogota are needed.

2.5 Summary and outlook

Two versions of the emission inventory for Bogota have been established. First, calculations were done using CORINAIR on-road traffic EFs. Second, real-world EFs for Bogota were used for the calculation. These real-world EFs have been obtained by means of in-situ measurements and inverse modelling. A numerical model was used to evaluate the emission inventories, and emissions of CO, PM_{10} and NMVOC's were found to be underestimated when using CORINAIR traffic EFs.

A comprehensive understanding of emissions is available for the first time in the region, pointing that on-road traffic sources represent a significant contribution of the EI. Though further investigation is required to fulfill the gaps in the missing information before emitting definitive conclusions, our results suggest that in particular heavy vehicles play a key role in the air pollution of the city, indicating where environmental authorities should focus their efforts.

The lack of complete databases and real-world EFs in many countries, represent a foremost limitation when building an EI. It is paradoxical that this lack of information is mainly found in countries contributing enormously to global emissions (Gurjar et al. (2004); Wang et al. (2005); Vivanco and Andrade (2006) and many others), making uncertain the emission estimations. Improving the quality of data as to fulfill the requirements of the existing methodologies such as CORINAIR, is perhaps a very expensive and time-consuming task for such countries. In the case of Bogota, using a simple methodology to estimate bulk real-world on-road traffic EFs, we succeed in obtaining an EI which in turn generates pollutant concentrations (via the AQM) closer to observations for this specific case. Factors such as the stop-and-go driving behavior, the altitude, an aged fleet and the state of maintenance of the fleet, seem to be more important than obtaining very detailed information on the repartition of the fleet or driving speeds, for emission calculation purposes; at least as a first stage in the calculation. Consequently, under financially limited situations, a simpler methodology to estimate bulk traffic EFs might be of utmost importance. Moreover, the traffic situation is constantly changing in developing countries, and thus emissions. Efforts on improving methodologies able to quantify such changes periodically are crucial for those countries. The use of combined techniques such as measurements inside a street canyon to estimate traffic EFs, and further evaluation of the inventories with numerical models, proved to be a useful tool for this purpose. Nevertheless, the analysis presented here should be considered only as a first step towards a full evaluation of the EI. Further research is needed running the AQM for a longer period of time in order to draw final conclusions, as well as exploring the possibility to better couple both bottom-up and top-down techniques in order to optimize the evaluation of abatement scenarios.

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Chapter 3

A study of the photochemical plume formed in Bogota using numerical simulations.

Abstract

Air pollution in Bogota is a challenging case study due to high levels of emissions in a region of complex Andean topography. Aiming to understand the formation of the pollution plume during a typical photochemical 2-day episode, which took place in March 2002, meteorological and air quality mesoscale modelling tools are applied for the first time to the city. The influence of the global scale Trade Winds is investigated, as well as the local thermal winds developed due to the orographic features. This study examines the interaction between these two types of winds as to understand the atmospheric circulation pattern that takes place during this period of the year in the region. Convergence fronts are identified and the consequences over the formation of the plume of pollutants are analyzed. The plume is mainly developed over the city core and sharp ozone peaks cross the central part of the city. The models successfully simulate such phenomena, showing good agreement with measurements. They help to understand the dynamics of the atmosphere in the zone of study and open a new possibility to manage air quality in Bogota through a scientifically-based approach.

3.1 Introduction

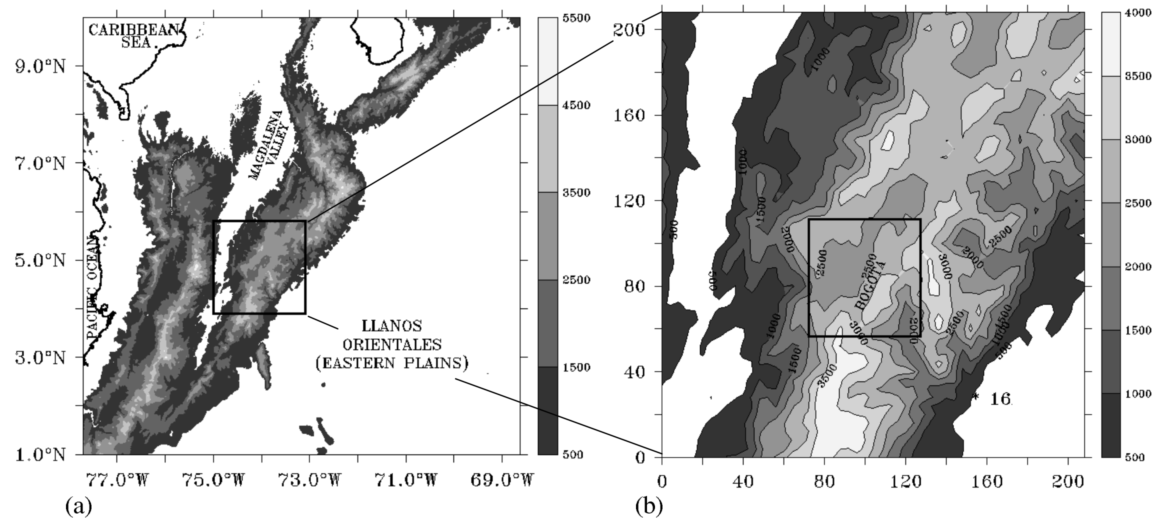
Bogota, the capital of Colombia, is the 5^{th} supercity in Latin America, with 6.6 millions of inhabitants inside the urban perimeter by 2001 (Skinner, 2004), and 8.0 millions taking into account the suburbs. It is a dynamic metropolitan area, and as many other urban zones, significant amounts of gaseous pollutants and particulate matter are released to the atmosphere. Critical concentrations of pollutants are often found in the city, exceeding the air quality standards for PM_{10} (170 µ/m^3, 24-h average), NO_2 (168 ppb, hourly average) and O_3 (83 ppb, hourly average)(DAMA, 2006).

High levels of Ozone indicate that photochemical smog episodes take place. These are widespread phenomena in urban regions worldwide where increased labels of volatile organic compounds (VOC's) and nitrogen oxides (NO_x) may be found from various anthropogenic sources. For example, in 2001 the hourly standard of O_3 was exceeded 281 times out of a total of 49 913 hourly measurements in the city of Bogota (7 monitoring stations), with maximum values around 200 ppb (DAMA, 2006). A scientifically-based air pollution control legislation requires to determine the amount of emission reduction needed, in order to control and mitigate such episodes. Adopting pollution control measures is a very expensive work, and the expected results may not necessarily be as efficient as believed, because the processes involved in the formation of photochemical episodes are very complex and highly non-linear (Martilli (2001); Berkowitz et al. (2005); Yang et al. (2005) and many others). Therefore, in order to better define high pollutant concentration areas and to test in advance different scenarios of abatement strategies and pollution control measures, air quality models are widely used (Borrego et al., 2003; Martilli et al., 2003; Wang and Ostoja-Starzewski, 2004; Rappenglück et al., 2005; Tong et al., 2005; Calori et al., 2006). The research project *Development and Implementation of an Air Quality Model for Bogota* (EPFL, 2002) aims to study such aspects locally, for the particular case of a big city like Bogota located on a complex terrain, and to generate a tool that can be used for air quality management, able to test abatement strategies for the city. This project includes the generation of a spatially and temporally distributed emission inventory, as well as meteorological and air quality simulations. The goal of the project was first of all to understand the air pollution problem in Bogota, the relative contribution of each emission source and the features affecting the meteorology for such complex terrain and thus air quality. Subsequently, to propose and test different abatement strategies for the city. A series of articles is currently being prepared in order to present the main contributions of this case study.

The present contribution is devoted to the results of the application of modelling tools (meteorological and air quality simulations) to the region, investigating the influence of the topography and the urban island over air quality. Data from a specific pollution episode which took place during 6 and 7 March 2002 is used to validate results from the models. Although the simulation of one episode is presented here and care must be taken when generalizing conclusions, this study represents a first step in understanding air pollution in the region and contributes to the comprehension of the meteorological phenomena taking place in the high mountain ranges of the Andes and big cities located in altitude. Section 3.2 and 3.3 of this paper present the description of the models and of the measurements respectively. Results of meteorological and air quality simulations are presented in sections 3.4 and 3.5. Section 3.6 sums up the main results and discuss them. Below, some main aspects of the topography and the climate in the region are presented.

3.1.1 Topography of the region

Bogota lies in a plateau situated in one of the three Andean mountain ranges crossing the country (fig. 3.1). It is located at 4.6°N and 74.1°W. The plateau is about 40 km wide and 100 km long, aligned from the southwest to the northeast. It has an average elevation of 2600 masl. A mountainous complex terrain borders the plateau on three sides. Two ridges are parallel to the plateau axis, on its eastern and northwestern borders, reaching about 4200 and 3600 masl respectively. Further to the east, there is a very steep and narrow descent which leads to “Los llanos orientales” (the Eastern Plains, between 0 and 500 masl). The plateau is partially closed at its northern side. It is open on its southern border to the southwest, descending gently to the central Magadalena valley (less than 500 masl), which separates two of the main Andean chains.



(a) (b)

Figure 3.1: Topography of the Colombian Andean region and domains of simulation. (a) First meteorological domain simulated (1008 km x 1008 km, resolution of 24 km). The Andes are divided into three chains when they enter the country. The central black square indicates the domain in: (b) the eastern Andean chain where Bogota's plateau is located, and domain of the meteorological simulation (212 km x 212 km, resolution of 4 km). The central black square in (b) shows the domain used for the air quality simulations (55 km x 55 km, resolution of 1 km), and the localization of the city. Measuring station 16 (Vanguardia) is also shown in this image, towards the south-eastern part of the domain. See fig. 3.2 for other measuring stations.

3.1.2 Main features of the climate in the region

Since Colombia is crossed by the Equator, it is influenced by the Intertropical Convergence Zone (ITCZ), and therefore by the Trade Winds, circulating towards the ITCZ. During January, February and early March, the ITCZ is around 2°N of latitude, thus most of the country undergoes a dry season with global-scale winds coming from the NE (the Trade Winds). Late March, April, October and November, correspond to periods of time in which the ITCZ goes across the region, first from south to north (late March and April) and then in the opposite sense (October and November) (Pabón et. al., 2001). Therefore, Bogota's basin climate is conformed by two dry and two wet seasons throughout the year, with the rainy seasons corresponding to the passage of the ITCZ. During the first dry season, period of the year chosen to conduct the simulations presented in this paper, it is common to have, on one hand, winds coming from the NE, especially in the mornings. On the other hand, this time of the year is also characterized by days with clear sky conditions, and thus high solar radiation and temperatures (daytime temperatures increasing from 6 to 25°C, for an altitude of 2600 masl) are reached. In such days, the orographic features strongly influence the wind patterns and the local climate in the region.

3.2 Models description and set-up

3.2.1 Meteorological model

The model used in this study (called FVM, Finite Volume Model) is a three dimensional Eulerian meteorological model, which uses a terrain following grid with finite volume discretization (Clappier et al., 1996). It was mainly developed at the Air and Soil Pollution Laboratory (LPAS) of EPFL. The borders can be individually forced for wind and temperatures by large scale model results. It provides an urban turbulence module which specifically simulates the effects of urban areas on the meteorology, representing the city as a series of parallelepiped of concrete. This model has been described in detail by Martilli (2001); Martilli et al. (2002).

Two different grids are simulated with FVM. The first one covers an area of 1008 km x 1008 km (fig. 3.1(a)), whereas the second one is 212 km x 212 km (fig. 3.1(b)). Horizontally, the grids have a resolution of 24 km and 4 km respectively, in both x and y directions. Nesting procedures are applied from the coarser grid to the smaller one, so that results of wind and temperature from the 1008-km grid are used as initial and boundary conditions for the 212-km grid. Vertically, the grids extend up to 11 000 m and are divided into unequal layers increasing their size progressively with a stretching ratio of 1.2. The layer thicknesses near the ground and at the top are 20 and 1500 m respectively.

Land use data, necessary as input information for the simulations, are obtained from the U.S. Geological Survey (2002). Parameters for each grid cell are obtained by performing a weighted average according to the fraction of the various land use types. Rural area's soil is considered of two types: sandy-clay-loam, with a moisture saturation factor of 40%, for altitudes bigger than 2000 masl, and silty-clay-loam, with a moisture saturation factor of 60% for altitudes below 2000 masl. This consideration is based on the fact that soils at low altitudes have a thicker tropical vegetation canopy and thus are more humid. As for the urban land use, downtown Bogota has high-rise buildings being closely packed. The density is lower in the surroundings. Two types of urban classes are considered: Downtown and surroundings, with average building heights of 15 and 7 m respectively. A pre-run of one day is performed for all the meteorological simulations, in order to provide more realistic initial conditions.

3.2.2 Air quality model

TAPOM (Transport and Air POllution Model, Martilli et al. (2003); Junier et al. (2005)), developed at LPAS, is a transport and photochemistry three dimensional Eulerian model. It uses a terrain following grid with finite volume discretization. It includes the RACM lumped species mechanism (Stockwell et al., 1997), the Gong and Cho (1993) chemical solver for the gaseous phase, the ISORROPIA module for inorganic aerosols (Nenens et al., 1998), passive transport of organic aerosols, the transport algorithm developed by Collela and Woodward (1984), and Clappier (1998), as well as the solar radiation module TUV developed by Madronich (1998) to calculate the photolysis rate constants.

A grid of 55 km x 55 km (fig. 3.1(b)) with a resolution of 1-km in both x and y directions is run with TAPOM. Vertically, the grid extends up to 7300 m, and is divided into unequal layers with stretching factors of 1.2 and 1.6 (for the lower and upper layers of the grid respectively). The layer thicknesses near the ground and at the top are 15 and 1900 m respectively. Meteorological data from the mesoscale simulation with FVM are interpolated and used as input to the air quality simulation. A pre-run of one day is performed in order to provide more realistic initial conditions.

3.3 Measurements description

Model results are compared to the available measurements in the region (fig. 3.2) for the same days of the episode evaluated. Bogota counts with a monitoring network administrated by the local environmental regulation agency (DAMA, 2006), currently with 9 measuring stations spread around the city. In 2002, 10 monitoring stations are in service: Corpas, Escuela, Fontibón, Merck, Cazucá, Sony, Cade, Nacional, Santo Tomás and MMA. Some of them measure only meteorological parameters, and some measure both meteorological parameters and air quality levels, with a time resolution of 10 minutes. Hourly averages are obtained out of these data. The stations report data at an average elevation of 8 m above the ground.

Data from two more meteorological monitoring stations (Cogua and Tisquesusa) are furnished by the Departmental regulation agency (CAR, 2006). They supply information about the meteorological behavior in Bogota's plateau. Moreover, meteorological data from three additional stations administrated by the Institute of Hidrology, Meteorology and Environmental studies (IDEAM, 2006) (Dorado, Mosquera and Vanguardia) serve to enhance the available information to validate the model in the domain of interest. Whereas Mosquera is located on Bogota's plateau, Vanguardia is situated at the border between the Eastern Plains and the mountain range (fig. 3.1), with an altitude of 423 masl. Dorado station corresponds to Bogota's international airport. This station reports sounding balloon vertical profiles of temperature, wind speed and wind direction once per day (at 0700LT). Both CAR and IDEAM surface temperatures and wind are taken at an average elevation of 2 and 10 m above the ground respectively. The time resolution of the reported data is one hour.

3.4 Meteorological simulations and results

3.4.1 Boundary and initial conditions (simulations over the large domain)

The model is first applied to a 1008 km x 1008 km grid, aiming to generate adequate boundary and initial conditions for our mesoscale domain. This grid contains

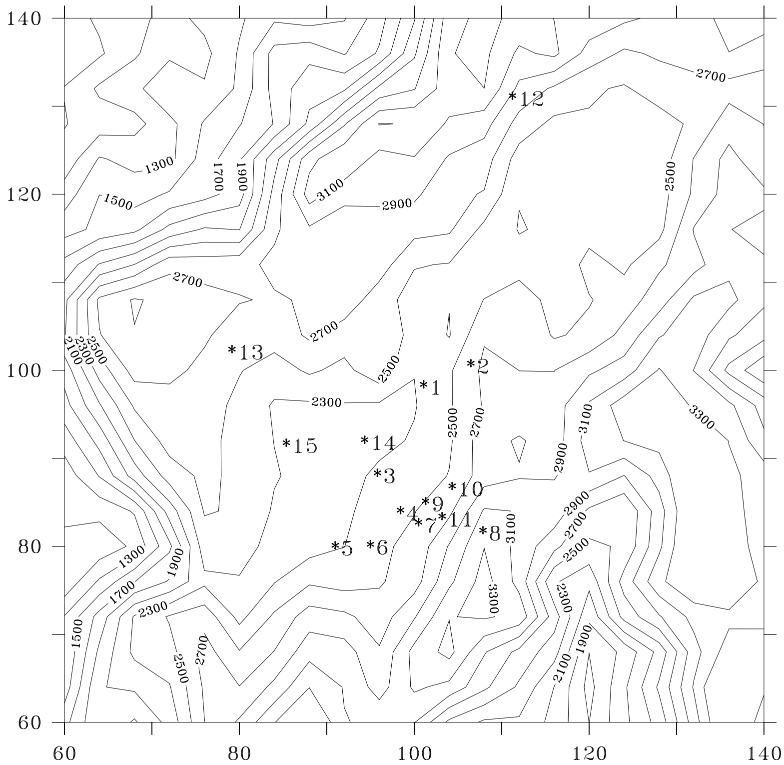


Figure 3.2: Localization of the Measuring stations: 1. Corpas, 2. Escuela, 3. Fontibon, 4. Merck, 5. Cazuca, 6. Sony, 7. Cade, 8. Monserrate, 9. Nacional, 10. Santo Tomás, 11. MMA, 12. Cogua, 13. Tisquesusa, 14. Dorado, 15. Mosquera. See fig. 1 for localization of station 16, Vanguardia. Stations 1 and 2 are placed in the northern part of Bogota. Stations 3,4,7,9,10 and 11 are in the center and western part of the city, and 5 and 6 in the southern part. The city's western border is given by El Dorado Airport (station 14). Stations 12,13 and 15 correspond to small towns near Bogota. Station 8 is placed on the top of one of the eastern hills bordering the plateau (Monserrate), at 3210 masl, and it was set during the measuring campaign held under the frame of this study.

the three colombian andean mountain chains, as well as the Magdalena valley and the Eastern plains (fig. 3.1(a)). This simulation uses 6-hourly data from the NCEP/NCAR (2006) reanalysis dataset for its initial and boundary conditions. The examination of NCEP wind data gives us some features of the global wind pattern in the region. In early March, when the episode of our interest takes place, the Trade Winds come from the northeast and enter the country, crossing it until converging with the southern Trade Winds (towards the ITCZ, around 2 °N). When they enter the country, they undergo a perturbation at the surface level due to the Andean chains. Data from NCEP show slope winds and deviations due to this topography, which is seen in average as a single thick chain reaching maximum altitudes of around 1300 masl (NCEP's resolution is 1°latitude-longitude). In general, this wind pattern remains through the entire episode treated. Preliminary tests made with different resolutions of the grid indicate the importance of fairly reproducing the three mountain chains and the valleys in the first simulation, e.g. keeping a relatively high resolution, since the dynamics in the Magdalena valley play an important role in the atmospheric circulations of Bogota's plateau.

A resolution of 24 km in both x and y directions is thus used for the simulation of the 1008 km x 1008 km grid. The perturbation of the Trade Winds coming from the Northeast, occasioned when they hit the Andean mountain ranges, is well seen in this simulation (fig. 3.3), as well as some local effects. At 0700 local time (LT) (fig. 3.3(a)), when the sun has not yet heated enough the surface, air masses are pushed down the slopes still forming nightly mountain-valley breezes. In the case of the eastern mountain range where Bogota is located, air masses are going both in the direction of the Magdalena valley and the eastern plains.

Due to the sun-heating effect, at 1200LT (fig. 3.3(b)), air masses are partly pushed up the slopes and partly channelled through the valleys in the direction of the point where the three mountain chains are joined, in the south of the country. Bogota's plateau experiences the effect of winds blowing from the Magdalena valley. Due to the same effect of mountain-valley breezes, some air masses go up from the Eastern Plains side towards the plateau, generating thus an important convergence front, on the top of the eastern mountain range. The Eastern Plains show a wind direction which is the result of the perturbation caused when the NE Trade Winds hit the Andean mountains plus the local effect of the thermal breeze. At 1700LT (fig. 3.3(c)), the effect of the sun-heating is stronger, the wind is channelled through the Magdalena valley but slope winds going up to the plateau are also important. During nighttime (2300LT, fig. 3.3(d)), the local effects of the air masses going down the slopes are seen again, in the direction of the Magdalena Valley and the Eastern Plains. Around 0300LT of the second day (March 7), the global-scale effect gains importance again. A very similar behavior of the wind patterns between the two days of the episode is simulated by the model (not shown).

To sum up, the global pattern of the Northeastern Trade Winds is seen at this

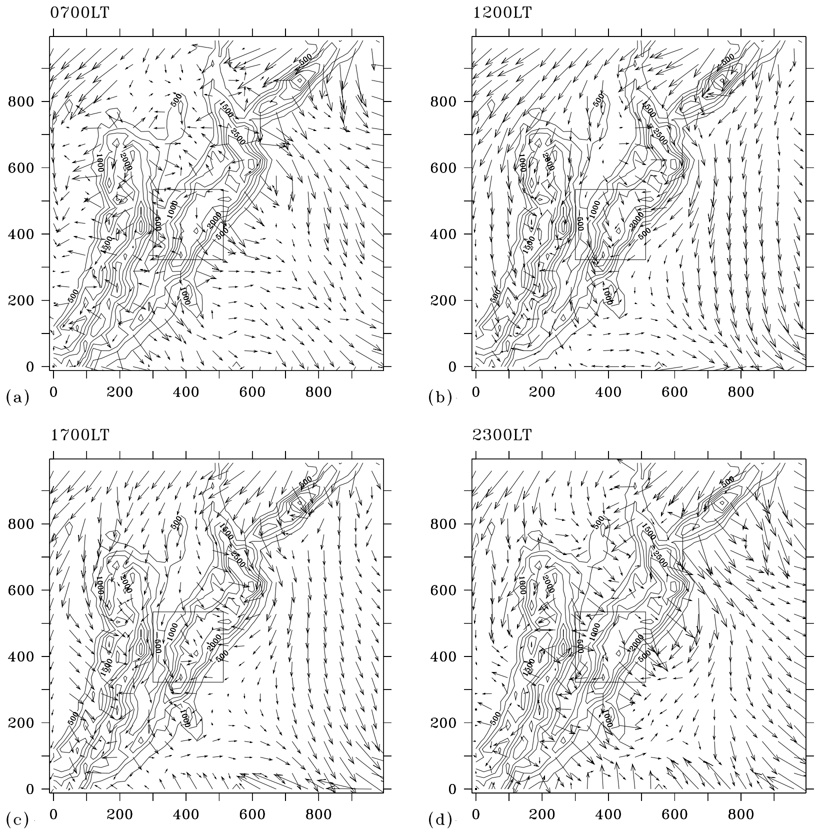


Figure 3.3: FVM wind field simulation at ground level for the domain of 1008 km x 1008 km with a resolution of 24 km x 24 km, 6 March 2002. Geographical coordinates of the lower left corner: 77.7°W, 1.0°N. Maximum wind speed shown: 18.8 m s^{-1}. The mesoscale domain (212 km x 212 km) is depicted in the center. (a) 0700LT, (b) 1200LT, (c) 1700LT, (d) 2300LT.

resolution throughout the entire episode of our interest. Some local effects such as slope winds generated from both sides of the mountain strongly affect the wind pattern over the plateau. The slope wind coming from the Magdalena valley towards the plateau strengthens as the day advances. A better resolution is needed in order to catch the complex effects of the hills surrounding the plateau and the convergence front formed on the top of the mountains.

3.4.2 Mesoscale simulation (over the small domain)

The domain presented in fig. 3.1(b) (212 km x 212 km) is chosen for the mesoscale meteorological simulations of the episode. Bogota's plateau is located approximatively in the center of the domain, and it also encompasses part of the Magdalena valley and the steep descent to the Eastern Plains (Llanos Orientales, see fig. 3.1(a)).

Wind fields at ground level

In the morning, the wind blows to Bogota's plateau from the northeast. At 0900LT (fig. 3.4(a)), some air masses still descend the slopes and some others start to climb them up due to the effect of the sun. By 1100LT (fig. 3.4(b)), the sun has warmed up the ground, and the thermal wind is developed in the region. Air masses come up from the Magdalena valley and they enter the plateau from the southern side of its axis. Some other air masses reach the plateau from the northwest, coming also from the Magdalena valley, but they go up first to 3600 masl (the northwestern hilly border of the plateau) and then by inertia they go down until converging with the air masses coming from the southwest. At 1400LT (fig. 3.4(c)), the wind strengthens and the thermal regime is fully developed. Air masses coming from the Magdalena Valley enter the plateau and go on partly eastwards, to climb its eastern mountainous border; and partly northwards, channelled through the axis of the plateau. Two main convergence fronts can be perceived at this time: air masses coming from the Magdalena valley, entering from the southwest and the northwest, find each other over the plateau, as explained for the situation at 1100LT. Another convergence front, of paramount importance for air quality, is the one formed just behind the eastern mountains bordering the plateau. Slope winds climbing from the Eastern Plains side go up to 4200 masl and meet up the air masses which originally come from the Magdalena valley and have crossed the plateau. This flow pattern does not change much throughout the afternoon. At 1900LT, the solar heating has ceased and the land surface cools down. During the night, (fig. 3.4(d)), the wind gradually weakens and the night slope wind is developed. Air masses come down to the plateau from the eastern mountain border and continue further down through the southern exit to the Magdalena Valley. Around 0300LT of the second day (March 7), the northeastern wind is predominant again. A very similar behavior of the wind patterns between the two days of the episode is simulated by the model.

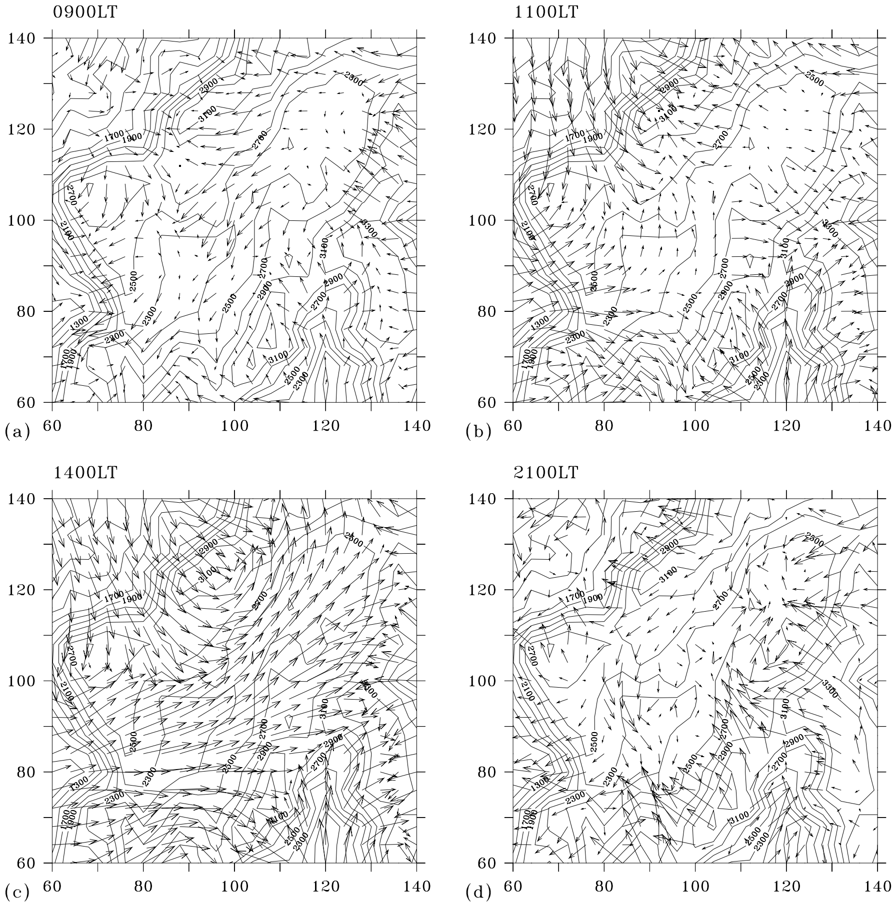


Figure 3.4: FVM wind field simulation at ground level for the domain of 212 km x 212 km, 6 March 2002. Here a zoom of the domain presented in fig. 3.1(b) is shown for better visualization. Maximum wind speed shown: 6.9 m s^{-1}. (a) 0900LT, (b) 1100LT, (c) 1400LT, (d) 2100LT.

The measurements taken during the episode corroborate this wind pattern. All the measuring stations (fig. 3.2) show systematically daily and nightly maximum wind speed values (fig. 3.5), which correspond with the full development of the slope winds. Minimum wind speed values are observed between 0500LT and 0600LT, and at 1800LT, when a change in the wind direction takes place (fig. 3.6). The first change of wind direction corresponds to the change in predominance from the nightly slope wind to the northeastern wind, as explained above. The model reproduces this change a bit too early (0300LT). The second change in wind direction is accurately reproduced by the model, corresponding to the cooling of the ground and the development of the nightly slope wind.

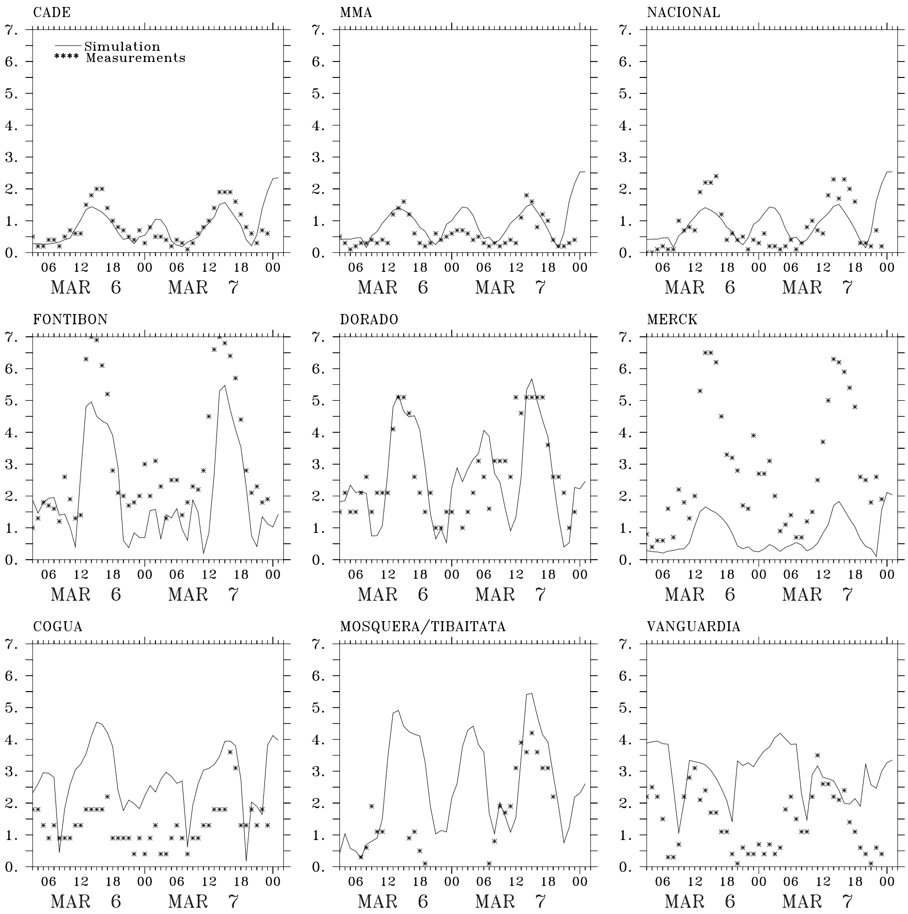


Figure 3.5: Simulated (solid line) and observed (stars) wind speed (m s^{-1}) time series at ground level for different stations, 6 and 7 March, 2002

The morning observations at all the stations in town (Cade, MMA, Nacional, Fontibon, Dorado and Merck, fig. 3.6), show a wind blowing from the north, for the two days of the episode. This pattern changes around midday, a sudden increase in the wind speed is observed in the same stations, and the wind starts blowing eastwards (about 270°), until 1800/1900LT. It indicates that a strong thermal wind is formed over the plateau, blowing up to the eastern ridge. Mosquera/Tibaitá station corroborates this direction. The model reproduces correctly

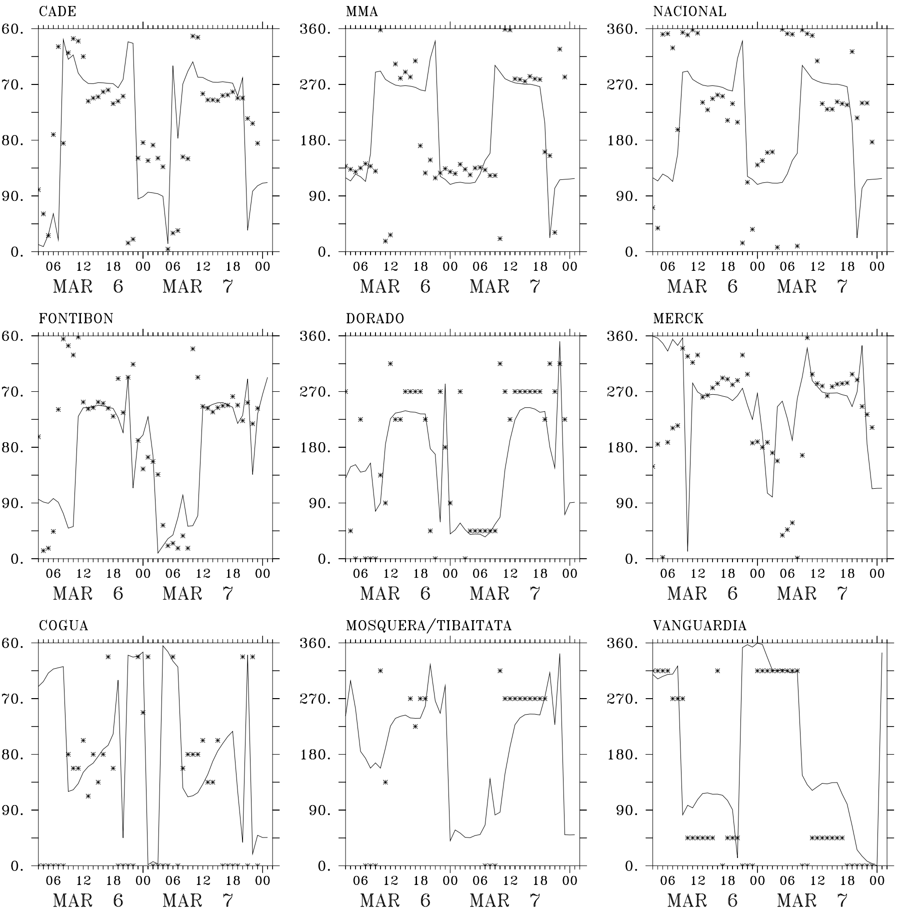


Figure 3.6: Simulated (solid line) and observed (stars) wind direction (°) time series at ground level for different stations, 6 and 7 March, 2002.

the morning and afternoon pattern for most of the stations. The wind direction in Cogua station is an indicative of the thermal predominance in this part of the domain, with air masses blowing northwards during the day, in both observations and the simulation. This station is placed at the feet of the northwestern mountain ridge bordering the plateau (fig. 3.2).

Different kinds of measuring stations can be identified when regarding the wind speed data. Low wind speeds (maximum 3 m s^{-1}) are found in stations like CADE, MMA and Nacional, which are located downtown Bogota (fig. 3.2). These stations undergo the effect of the city and its buildings. Some other stations such as Fontibon, Dorado and Merck are also in the city but not in the packed center (different building morphology), so maximum wind speed values are between 5 and 7 m s^{-1}. The model reproduces well wind speeds for Fontibon and Dorado stations, whereas for Merck they are under-predicted. The explanation for this lays on the resolution used, since Merck is in the cell where the building morphology changes. Cogua, Mosquera/Tibaitatá and Vanguardia, are stations located outside Bogota. Maximum wind speed values go up to 4 m s^{-1} and the model predicts them fairly well. Nocturnal wind speeds are over-predicted for Vanguardia station which might also be attributed to the resolution used. A sudden increase of the wind speed is seen at the end of the second day of simulation, which is not registered by observations. This result is produced by the increase of the wind in the NCEP/NCAR reanalysis boundary conditions.

Temperatures

In general, FVM captures correctly the trends and magnitude of the temperature variations. The model predicts well the time of the day when temperatures start increasing due to the sunrise (around 0600LT), as well as the time of the maximum value (between 1200LT and 1300LT, fig. 3.7). On the other hand, it underestimates nocturnal temperatures in urban stations such as Merck and Fontibon. One possible explanation stems from the fact that the NCEP/NCAR nightly temperatures are also underestimated at ground level, contributing to cool down the borders of the domain, and thus the simulated temperatures. The vertical profile of temperature at 0700LT (fig. 3.8) shows for both observations and the simulation that there is a thermal inversion at this hour of the day. The model indicates lower values of temperature when compared to observations, which is in agreement with the low nocturnal temperatures simulated. Although we do not have more vertical measurements during the day, the model indicates that as the sun heats the ground, temperatures increase and the thermal inversion disappears.

In conclusion, the episode chosen represents a common situation found in the region during the first dry season of the year. Low temperatures at night generate a thermal inversion in the early morning, which is later broken as the sun heats the ground and daily temperatures rise. The wind follows the northeasterly synoptic flow in the morning. As the sun heats the ground, a thermal breeze is developed, which strengthens and penetrates further in the plateau. Two main convergence

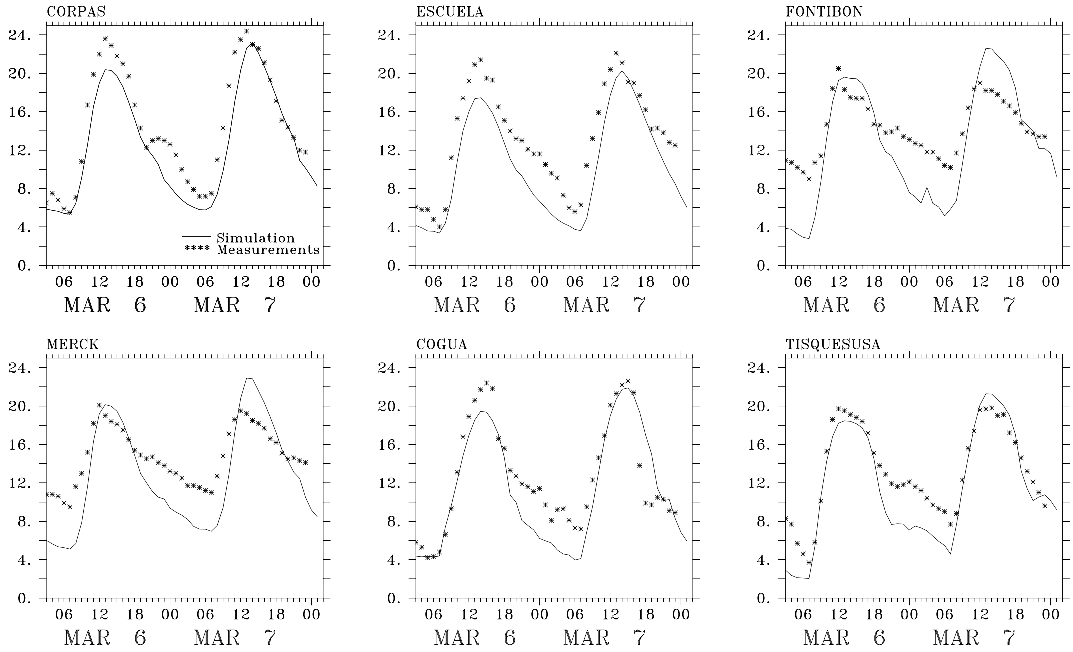


Figure 3.7: Simulated (solid line) and observed (stars) air temperature (°C) time series at ground level for different stations, 6 and 7 March, 2002

zones are created, one of them formed not far from the core of the city and thus of paramount importance for air quality purposes.

3.5 Air quality simulation and results

A detailed emission inventory was previously developed for the region (Zárate et al., 2006a). It is calculated for a given full-working day during March, with a temporal resolution of one hour and a spatial resolution of 4 km x 4 km. It is afterwards interpolated to the cells of the domain of 55 km x 55 km. Non methane volatile organic compounds (NMVOC) emissions are speciated and grouped for each source of emission according to the groups of chemical species proposed by Stockwell et al. (1997) in their RACM lumped species mechanism (table 3.1). The same percentages of repartition are applied every hour to the total NMVOC emissions; except for biogenic emissions, whose speciation depends on solar radiation and temperature and thus change with the hour of the day. This speciation is

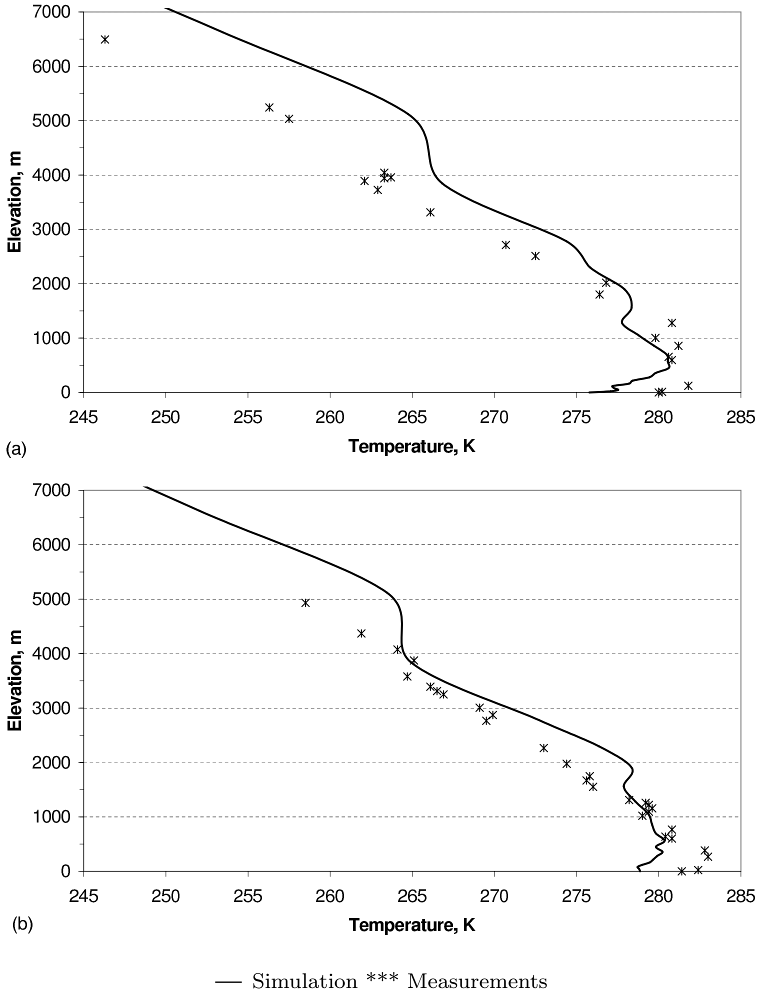


Figure 3.8: Simulated (solid line) and observed (stars) vertical profiles of temperature at 0700LT, El Dorado Airport(see fig. 3.2 for localization of the station). (a) 6 March 2002 (b) 7 March 2002. The Y axis represents the elevation in meters above the point of measurement.

taken as reported by Velasco (2003) for the Mexico city region, for Isoprene, Terpenes and other VOCs (OVOC). In order to adapt these data to the requirements of RACM, Terpenes are split as proposed in the CORINAIR methodology (EEA, 2006). The list of compounds proposed by Guenther et al. (1994) is used to split the OVOC, assigning equal percentages of distribution to each compound and then grouping into the RACM categories.

Initial and boundary conditions are primarily set at the same values, and a pre-run of one day with the same emissions and wind fields is conducted, in order to provide more realistic initial conditions for the simulation. Measurements taken from stations located outside Bogota are used as input data for initial and boundary conditions when possible. In the case of NMVOCs, standard suburban concentrations are taken (Seinfeld and Pandis, 1998). The same chemical-species distribution used for the emissions is used to generate the split of the initial and boundary conditions of NMVOCs.

Table 3.1: Speciation of NMVOCs per source and group of chemical species (Mass %), as input data for the air quality model TAPOM

Species	LVG	LVD	HDVD	P&S	FC	A	L	B
ETH	1.13	0.52	0.04	8.67	0	1.20	0	2.14
HC3	13.07	4.83	3.01	21.57	1.77	8.42	5.58	7.12
HC5	9.66	0.00	0.14	3.97	20.82	17.75	0.00	6.51
HC8	6.82	32.57	40.31	7.36	70.72	4.26	9.00	15.32
ETE	9.03	7.04	9.63	12.70	0.00	20.28	0.00	2.14
OLT	9.61	6.70	3.88	8.57	0.81	4.23	0.13	8.09
OLI	4.51	1.80	5.72	2.15	1.56	3.30	9.34	0.00
TOL	18.57	5.15	0.49	22.41	2.42	3.91	36.38	0.00
XYL	18.61	5.28	5.09	2.66	0.00	1.55	39.56	0.00
CSL	0.00	0.00	0.00	3.05	0.00	0.33	0.00	0.00
HCHO	1.85	14.47	11.57	1.95	0.00	18.51	0.00	0.00
ALD	7.08	19.11	20.12	2.69	1.91	14.36	0.00	4.19
KET	0.05	2.53	0.00	2.25	0.00	1.90	0.00	3.76
ISO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	24.71
API	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.24
LIM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.78

LVG: Light vehicles running with gasoline, LVD: Light vehicles running with Diesel, HDVD: Heavy duty vehicles running with diesel, P&S: Production and services, PD: Fuel commercialization, A: Air traffic, L: Bogota's landfill, B: Biogenic. Chemical species: ETH:Ethane, HC3:Alkanes, alcohols, esters and alkynes with HO rate constant less than $3.4x10^{-12}$ cm^3/s, HC5:Alkanes, alcohols, esters and alkynes with HO rate constant between $3.4x10^{-12}$ and $6.8x10^{-12}$ cm^3/s, HC8:Alkanes, alcohols, esters and alkynes with HO rate constant greater than $6.8x10^{-12}$ cm^3/s. ETE:Ethene, OLT:Terminal alkenes, OLI:Internal alkenes, TOL:Toluene and less reactive aromatics, XYL:Xylene and more reactive aromatics, CSL:Cresol and other hydroxy substituted aromatics, HCHO:Formaldehyde, ALD:Acetaldehyde and higher aldehydes, KET:Ketones, ISO:Isoprene, API:α-pinene and other cyclic terpenes with one double bound, LIM:d-limonene and other cyclic diene-terpenes. For details on each one of the chemical species see Stockwell et al. (1997). The same split was used hourly for every source, except for biogenic emissions. Values presented here correspond to the split over the daily totals.

3.5.1 Primary pollutants

Both simulated and measured concentrations of CO and NO_x (Fig. 3.9) show an important morning peak between 0700LT and 0900LT. This peak is related to high emissions from traffic circulation in the morning rush hour and a low mixing height. The intensities of the peaks of both CO and NO_x are in good agreement with observations (except from Escuela station), nevertheless, the background concentration of CO appears to be a problem in stations like Cazuca and Merck. Based on observations, this value is set at 2 ppm for the simulations. Fontibon and Merck are stations which are not far one from each other (fig. 3.2), placed on a highly polluted zone of the city. However, observations show important differences in their baselines, and this is not reproduced by the model. As for Cazuca, the opposite case is observed, the simulation under-predicts all the measured values in the order of 2 ppm. These differences could be explained either by a continuous source of emission which has not been taken into account in the simulations (for example a chimney located close to the measuring point), or by a problem in the calibration of the measuring stations.

Important nightly peaks of CO and NO_x (around 2100LT), appear both in the simulation and measurements. This peak is also related to traffic and it is sometimes overestimated by the model, which might be attributed to an underestimation of the nightly wind speed (it is the case for example for Fontibon station), and/or to an overestimation of the traffic circulating at this hour. A second nightly peak appears around 0300LT, which corresponds to the time in which the simulation changes the circulation pattern from nightly slope wind to the northeastern global pattern.

3.5.2 Secondary pollutants: Ozone

Spatial distribution

Primary pollutants are mainly emitted by the city (located in fig. 3.10 where stations Merck, Nacional and Corpas are depicted). The spatial distribution of ozone is generated depending on the primary pollutant concentrations and the meteorological conditions. For this episode, pollutants are pushed in the mornings by a

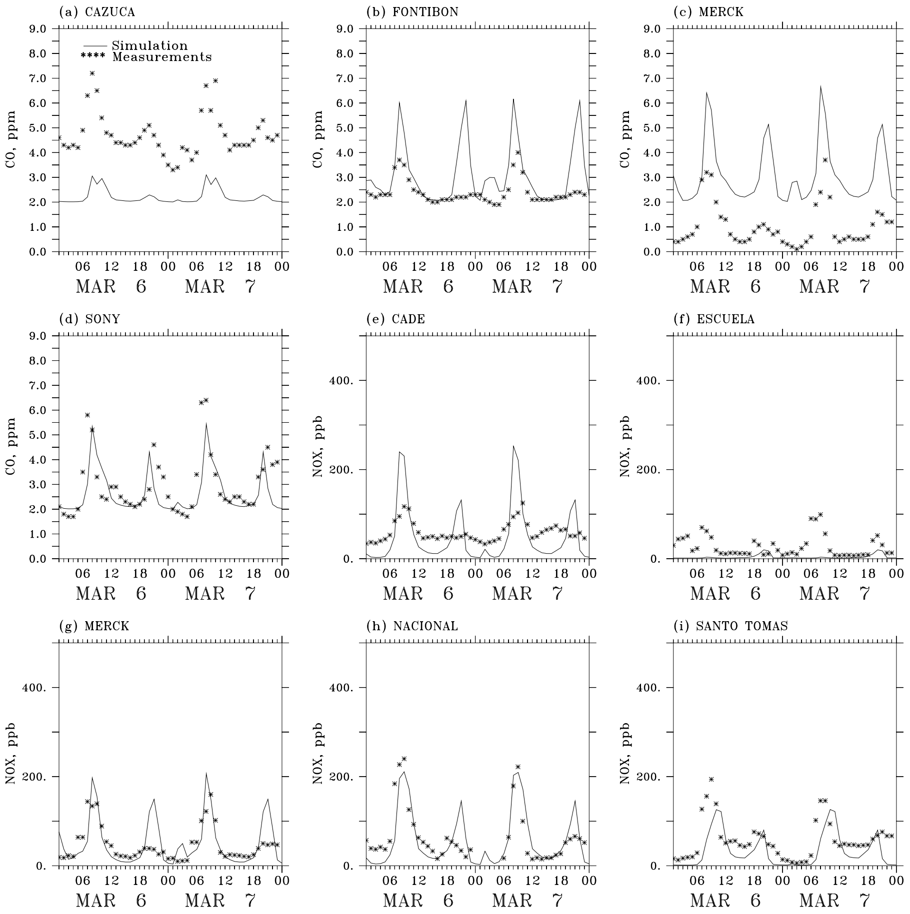


Figure 3.9: Simulated (solid line) and observed (stars) CO and NO_x (ppb) time series for different stations

wind coming from the northeast, while ozone is being formed (fig. 3.10(a)). Around 1100LT the wind pattern changes and pollutants are transported eastwards, which in turn occasions a plume of ozone with its maximum values at midday, fully developed over the city (fig. 3.10(b)). Two O_3 maxima are computed at this time of the day, 170 and 135 ppb, for the northeastern and southeastern parts of the city respectively. After midday, thanks to the wind that penetrates the plateau from the southwest (the Magdalena valley), which is afterwards channelled through it, the plume continues to move in the northeast direction (fig. 3.4(c)). At 1600LT maximum ozone values have dropped to 80-85 ppb (fig. 3.10(d)) and the plume has taken a preferential northerly direction. The plume cannot advance forward to the east because of the converge wind front (fig. 3.4(c)) generated by the air masses going up the mountains from the Eastern Plains (from los Llanos Orientales). These results indicate that the plume of pollutants is pushed southwards in the early morning, while the synoptical conditions predominate. When the thermal wind is developed, pollutants are then transported eastwards, crossing again the central part of the city. This happens at the same time of maximal solar radiations, thus important peaks of ozone are generated in town.

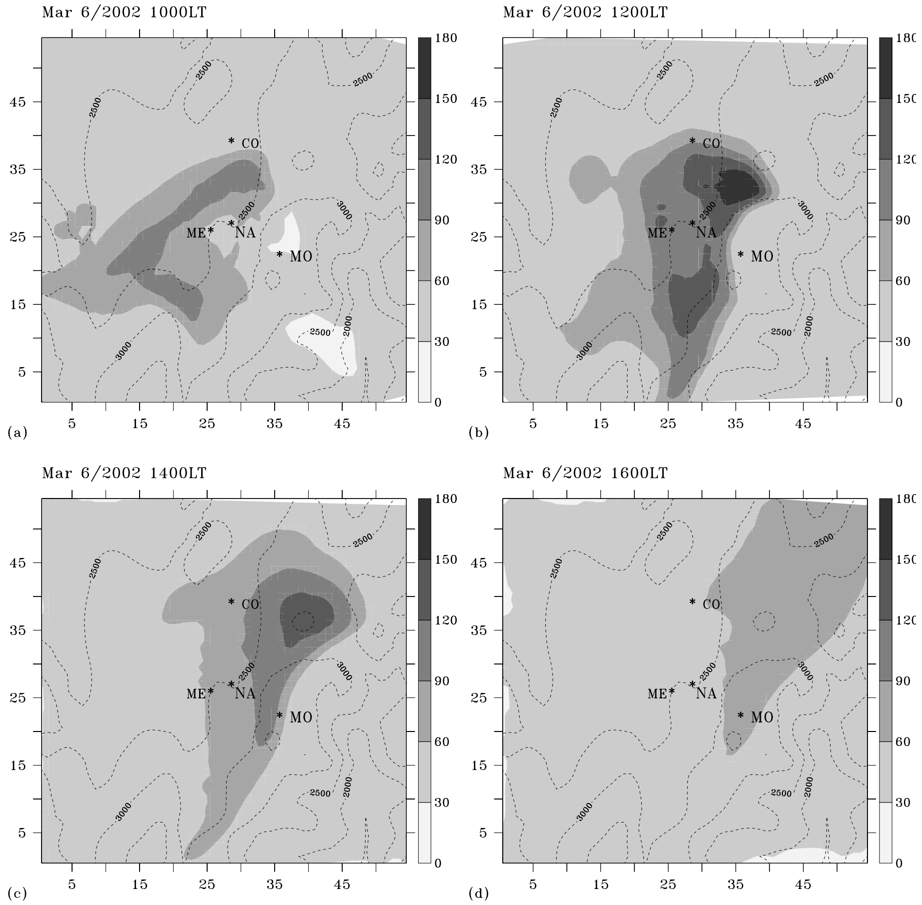


Figure 3.10: Map of Ozone concentrations (ppb) simulated by TAPOM in the domain used for the air quality simulations (55km x 55 km), 6 March 2002. Measuring stations: CO: Corpas, ME: Merck, NA: Nacional, MO: Monserrate

Comparison with measurements

The O_3 measurements corroborate the presence of the plume over the city, with high peaks in Merck (119 ppb), Nacional (149 ppb) and Corpas (72 ppb) stations for 6 March, and lower values for 7 March. This might imply that the city plume remains mainly in the city center on 6 March, but is slightly moved towards the East on 7 March. The simulation shows high O_3 levels at the same stations as the observations do on 6 March (fig. 3.11), indicating a good reproduction of the plume position. The model underestimates the maximum intensity of the peak at Nacional station (of about 40 ppb), however, this station appears between the two cores of the plume presented at midday (fig. 3.10), with maximum values of 135 and 177 ppb respectively. As for Corpas, a station located in the northern part of the city and away from the main emissions of primary pollutants, both measurements and the simulation (maximum values of 72 ppb and 90 ppb respectively, at 1300LT) confirm the fact that pollutants are being transported in the eastern/northeastern direction after 1100LT.

Monserrate represents a good urban airmass fingerprint, even if there are no measurements on March 6. It shows an observed maximum of 106 ppb for March 7. The model predicts a maximum as well for this station, but less intense and in delay. This might be due to a slight underestimation of the wind speed for this specific day, so the simulated plume of pollutants reaches Monserrate in late with respect to measurements. This also explains why measured O_3 peaks are lower on this day in town as compared to the simulated values. The wind transports pollutants towards the east faster than on 6 March.

Observations in Merck and Nacional show a night peak of ozone reaching values between 40 and 50ppb, which is well reproduced by the model. This peak is attributed to the change in the easterly slope wind, bringing downwards to the plateau air masses containing the remaining ozone formed during the day.

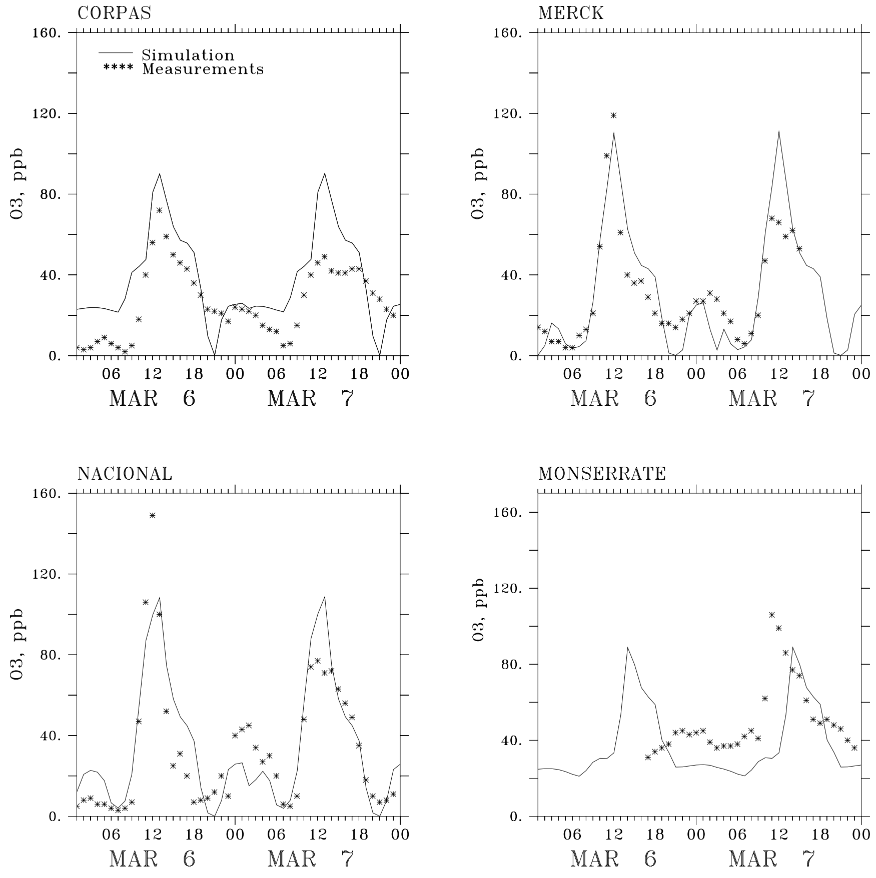


Figure 3.11: Simulated (solid line) and observed (stars) Ozone (ppb) time series for different stations

3.6 Discussion

The meteorological model FVM creates a complex flow pattern with several convergence zones over the region of interest. For this particular episode, an important influence of the global scale winds is perceived in the morning hours, approximately between 0300LT and 1000LT, which pushes primary pollutants southwards of Bogota's plateau. As temperature increases throughout the day, thermal winds become predominant. Due to the complexity of the orography, we can speak of thermal winds developed at two different scales: (i) those generated by the surrounding mountains of the plateau (fig. 3.4) and (ii) circulations generated at a national scale, due to the three Andean chains crossing the country. Air masses penetrate the plateau from the Magdalena valley thanks to this pattern. Pollutants are hence mainly carried further to the east, but also go on towards the north due to the phenomenon explained in (i). A converge front is developed when these air masses encounter others coming also from the Magdalena valley but penetrating the plateau from the northwest. Another convergence front, more important for air quality, is generated further the eastern border of the plateau when the western air masses encounter winds coming from los Llanos Orientales. In order to reproduce adequately the phenomena taking place over the plateau, it is necessary to use a grid which covers at least the main features of the orography: the Magdalena valley, the Eastern Plains and the mountains bordering the plateau.

Simulations made with TAPOM show a plume of pollutants for this particular episode, with high photochemical activity. This plume is mainly developed over the city area for 6 March, and not entirely for 7 March, but probably more towards the east of the city. Due to the eastern converge front, pollutants remain trapped not far from the city, and they come back down to it at night, thanks to the change in the circulation pattern. Little knowledge about VOCs in the ambient air of the city is available so far. This information would allow to better understand the processes of O_3 production taking place in the region.

The urban area has an important impact over the air circulations in the plateau, decreasing the simulated wind speeds at daytime. Observations are in agreement with this statement. The decrease of the wind speed generated by the city contributes partially to a development of the plume over it. The model over-predicts the decrease in the wind speed generated by the urban island on 7 March, generating an Ozone peak in Monserrate which is in late in comparison to observations (fig. 3.11). Monserrate site is under urban influence in the afternoon for this episode.

The episode presented in this study describes a circulation pattern which is typical of the main dry season in the region. We believe that understanding the flow pattern for specific episodes is a first essential step before starting long-run simulations, which in turn will allow the generalization of conclusions for all the year. As photochemical study, this particular kind of circulation is of extreme importance since the O_3 precursors are partly pushed to the southwest, outside the city; to be pushed again to the northeast later on, at the moment of major solar radiation. This consequently causes the photochemical plume to be developed over the city, crossing the measuring sites, with sharp peaks of ozone up to 170-180 ppb.

3.7 Conclusions and outlook

The modelling approach of simulating a photochemical episode using a nested mesoscale meteorological model and an air quality model has been applied to the study case of air pollution in Bogota with success. This is a challenging application due to the combination of complex terrain features and a very dense urban agglomeration. The models helped to better understand the phenomena taking place for this episode, by correctly reproducing the effects of the Magdalena valley over Bogota's plateau, the mountain-valley breezes and the urban heat island. This study represents the first air quality modelling contribution to the region of Bogota.

Finally, it must be stressed that in order to verify our results, it would be very useful to have data about the real VOC concentrations. Additionally, although the most favorable conditions to generate photochemical pollution were chosen, in order to extend conclusions aiming to apply abatement strategies, further research is necessary concerning the different meteorological cases presented throughout the year in Bogota.

Acknowledgements

The work described herein was supported by the SDC (Swiss Agency for Development and Cooperation) and by DAMA (Departamento Técnico Administrativo de Bogota). We are also grateful to IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia) and CAR (Coorporación Autónoma Regional de Cundinamarca) for providing some of the meteorological data. We would like particularly to thank professor Diego Echeverry from UNIANDES, Dr. Eugenio Giraldo, Dr. Petra Seibert and Mr. Robinsson Rodriguez for their precious collaboration and support.

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Chapter 4

Origins of the pollution plume in Bogota and design of abatement strategies based on air quality simulations for different emission scenarios.

Abstract

In this study, modelling tools are used to characterize the plume of pollution formed in Bogota during a typical photochemical episode which took place during March 2002. A better understanding of the origins of the plume leads to the identification of optimal abatement strategies to mitigate air pollution. First, the ozone-precursor relationship is determined by establishing the chemical regimes governing during this episode. Second, different hypothetical emission scenarios designed to identify the critical aspects causing high levels of pollution in Bogota are formulated. A factor separation technique is applied in order to evaluate the relative contribution of each one of the sources investigated. This approach shows that Bogota's traffic is the main contributor to pollution in the region. Moreover, in this episode emissions before 0900 local time (LT) are responsible of the major peaks of pollutants formed during the day. A better knowledge of the processes involved during the episode facilitates the proposition of emission abatement strategies and the understanding of their responses in terms of pollution levels. In the last part of this study some feasible emission scenarios are proposed and evaluated. Primary pollutants decrease linearly with the emission reduction, whereas it is not the same case for Ozone, which shows a more complex response.

4.1 Introduction

Photochemical pollution is one of the main air quality problems that the city of Bogota must face. A complete characterization of the plume of pollutants is necessary in order to allow environmental regulators to apply the most efficient measures of pollution control. Due to the complexity of the non-linear chemical reactions taking place, numerical models represent a powerful tool for this purpose. In this context, the research project *Development and Implementation of an Air Quality Model for Bogota* (EPFL, 2002) was created in order to investigate the air pollution problem in Bogota. In the first phase of this project, a detailed emission inventory for the city and its surroundings (Zárate et al., 2006a) was generated. In the second phase, numerical simulations of a typical photochemical episode (6 and 7 March 2002) were performed and validated (Zárate et al., 2006b). We studied the meteorology as well as the transport and chemical reactions of the pollutants emitted for this particular episode. The agglomeration of Bogota has more than 8 million inhabitants and is located on a plateau at 2600 masl. Bogota is a challenging case-study in terms of air quality, characterized by high levels of anthropogenic emissions released in a region with complex topography and air circulation patterns.

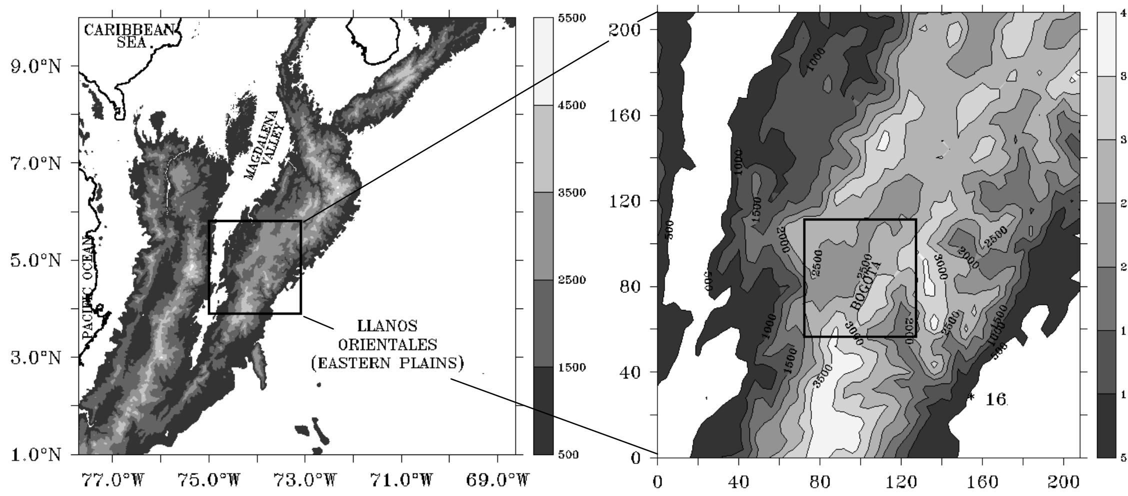
The design of abatement strategies requires a deep understanding of the critical aspects leading to high levels of pollution in the specific location where such strategies are to be applied. One way to initiate this understanding consists in the numerical simulation of hypothetical emission scenarios over a given episode of pollution (Grossi et al., 2000; Palacios et al., 2002; Oanh and Zhang, 2004). In this paper, we first make a sensitivity study to evaluate the evolution of the photochemical regimes as defined by Sillman (1999), namely NO_x-sensitive and VOC-sensitive regimes. The characterization of the plume in terms of the relationship between ozone and its main precursors allows to achieve a deeper knowledge of the non-linear processes taking place, and sheds light over the generation of possible abatement strategies. Some key factors playing a crucial role in the problem are identified out of this analysis. Secondly, a hypothetical set of emission scenarios is designed and applied to this specific pollution episode, aiming to quantify the relative importance of such factors. The factor separation (FS) technique proposed by Stein and Alpert (1993) is used, as to obtain the relative contributions and interactions of the processes which are being investigated. In the last part of the study, some feasible abatement strategies are proposed and evaluated for the same pollution episode. The examination of such strategies over a well characterized episode facilitates the comprehension of the responses obtained when they are applied.

4.2 Models description and set-up

The models FVM-TAPOM are used in this study. FVM (Finite Volume Model, Clappier et al. (1996)) performs the meteorological simulations whereas TAPOM (Transport and Air POllution Model, Martilli et al. (2003); Junier et al. (2005)) performs the photochemical dispersion simulations. Both models were mainly developed at the Air and Soil Pollution Laboratory (LPAS) of EPFL. They are three dimensional Eulerian models, and use a terrain following grid with finite volume discretization. FVM borders can be individually forced for wind and temperatures by large scale model results. It provides an urban turbulence module which specifically simulates the effects of urban areas on the meteorology, representing the city as a series of parallelepiped of concrete. This model has been described in detail by Martilli (2001); Martilli et al. (2002a).

The chemical model TAPOM includes the RACM lumped species mechanism (Stockwell et al., 1997), the Gong and Cho (1993) chemical solver for the gaseous phase, the ISORROPIA module for inorganic aerosols (Nenens et al., 1998), passive transport of organic aerosols, the transport algorithm developed by Collela and Woodward (1984) and Clappier (1998), as well as the solar radiation module TUV developed by Madronich (1998) to calculate the photolysis rate constants. The RACM chemical mechanism includes a total of 237 chemical reactions, in which 17 stable inorganic species, 4 inorganic intermediates, 32 stable organic species (4 of these of biogenic origin), and 24 organic intermediates, are involved.

Two different grids are simulated with FVM. The first one covers an area of 1008 km x 1008 km and the second one is 212 km x 212 km (fig. 4.1). Horizontally, the grids have a resolution of 24 km and 4 km respectively, in both x and y directions. 6-hourly wind and temperature data from the NCEP/NCAR (2006) reanalysis dataset supply the initial and boundary conditions for the 1008-km domain. Results of wind and temperature from this grid simulation are used as initial and boundary conditions for the 212-km grid. Vertically, the grids extend up to 11 000 m above the ground level and are divided into 23 unequal layers increasing their thickness progressively with a stretching ratio of 1.2. The layer thicknesses near the ground and at the top are 20 and 1500 m respectively. The goal of this nested simulation is to assure that all the details of the complex topography of the Andean mountains in Colombia, and the regional and local effects of the at-



(a) (b)

Figure 4.1: Topography of the Colombian Andean region and domains of simulation. (a) First meteorological domain simulated (1008 km x 1008 km, resolution of 24 km). The Andes are divided into 3 chains in the southern part of Colombia and they go across the country. The central black square indicates: (b) the domain of the mesoscale meteorological simulation (212 km x 212 km, resolution of 4 km). This domain is composed by a section of the Eastern Andean chain, where Bogota's plateau is located. This chain is bordered by the Magdalena valley on the west and by the Eastern Plains on the east. Parts of these valleys are included in the domain. The central black square in (b) shows the domain used for the air quality simulations (55 km x 55 km, resolution of 1 km), and the localization of the city.

A grid of 55 km x 55 km (fig. 4.1(b)) with a resolution of 1-km in both x and y directions is used for the air quality simulations with TAPOM. Vertically, the grid extends up to 7300 m above the ground level, and is divided into 12 unequal layers with stretching factors of 1.2 and 1.6 (for the lower and upper layers of the grid respectively). Meteorological data from the FVM mesoscale simulation is interpolated to the air quality simulation grid, and used as input for TAPOM.

For TAPOM, initial and boundary concentrations are primarily set at the same values. Measurements taken from background stations are used when possible, and a pre-run of one day with the same emissions and wind fields is conducted, in order to provide more realistic initial conditions for the simulation.

The emission inventory that is used for this study takes into account the following main sources of emissions: on-road and air traffic, production and services, fuel commercialization, landfill and biogenic (Zárate et al., 2006a). Linear, punctual and area emissions from these sources are adapted to the 55 km x 55 km domain. The emission inventory is built for a full working day in the region of interest with hourly resolution.

4.3 Description of the pollution event: Base case

Bogota's basin climate is conformed by two dry and two wet seasons along the year, with each one of the rainy seasons corresponding to the passage of the Intertropical Convergence Zone (ITCZ), first from south to north and after in the opposite sense (Pabón et. al., 2001). During the first months of the year, the ITCZ is around 2°N, and thus Bogota (4°N) undergoes the first dry season of the year, characterized by days with clear sky conditions and high solar radiation and temperatures. Besides, due to the localization of the ITCZ, the global scale Trade Winds, coming from the NE, influence the wind pattern over the region. 6 and 7 March 2002 are chosen for simulation not only because these days present the features described above, but also because more observations are available thanks to a measuring campaign which took place during February/March 2002 in the region. Data from this measuring campaign have been used to perform the validation of both meteorological and air quality simulations. Detailed results from this validation have been presented in a previous contribution (Zárate et al., 2006b).

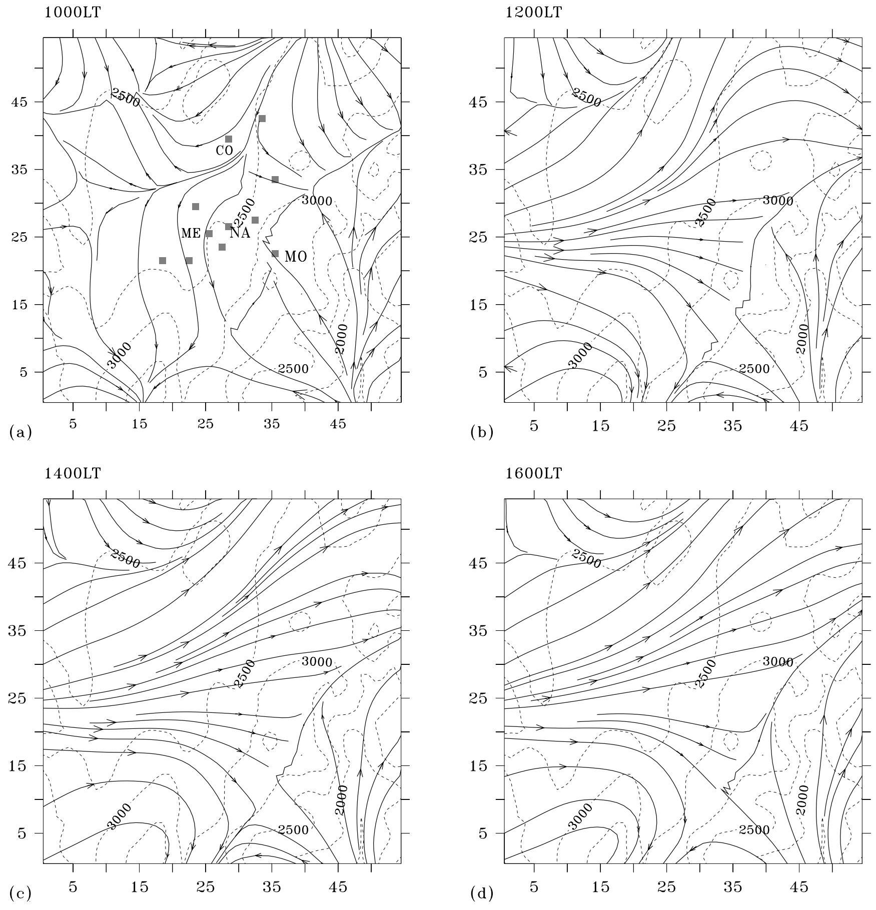


Figure 4.2: Main wind pattern observed in the region as simulated by FVM for the 6 March 2002. (a) 1000LT, (b) 1200LT, (c) 1400LT, (d) 1600LT. The measuring stations presented as grey squares in (a) help to identify the size and location of the city (names not shown apart from Nacional (NA) and Merck (ME) which are located in the central part of the city, Corpas (CO) in its northern end and Monserrate (MO) on the top of one of the eastern mountains bordering the plateau.

In general, the models FVM-TAPOM reproduce well the observations obtained for this episode. The observed daily wind pattern is very similar for both 6 and 7 March. For the purposes of this paper, we focus only on 6 March. From one side, Bogota's plateau is influenced by the NE Trade Winds, especially between 0500 local time (LT) and 1000LT. A prevailing NE wind direction is observed over the plateau at the ground level (fig. 4.2(a)), with maximum intensities of 3-4 m s^{-1}. Important amounts of pollutant emissions are released to the atmosphere during the same block of hours, because it corresponds to the morning traffic rush hour. Therefore, pollutants are pushed towards the SW part of the city (fig. 4.3(a)).

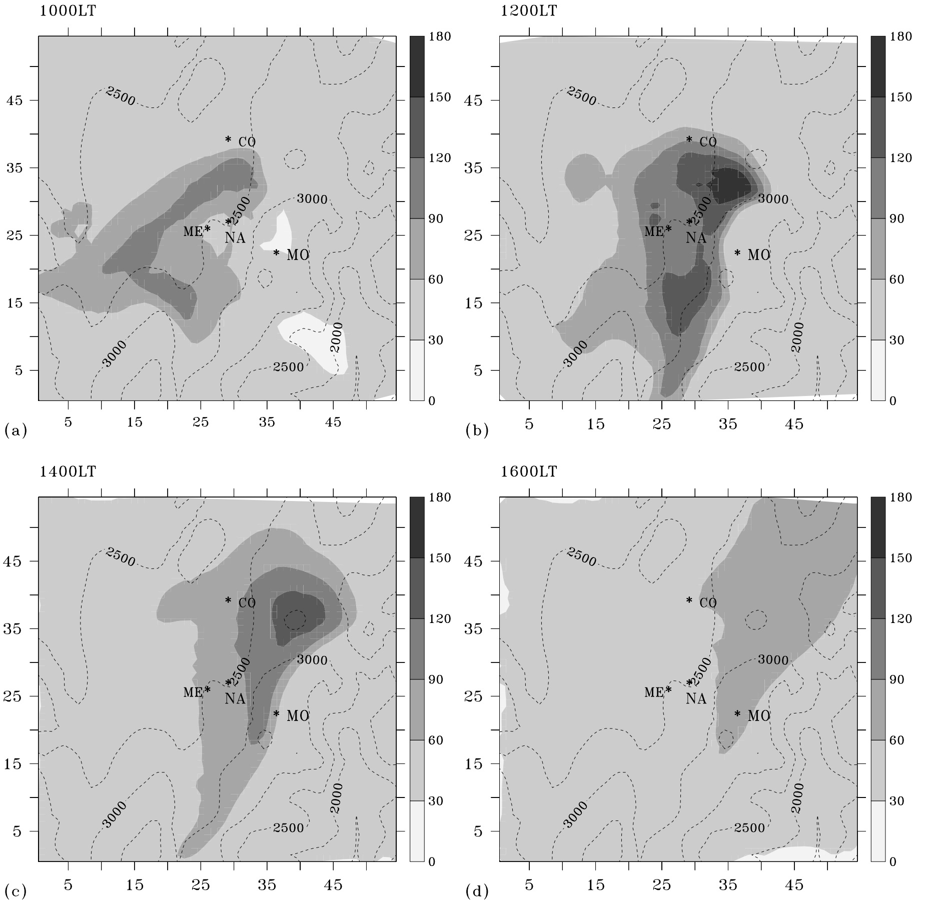


Figure 4.3: Map of Ozone concentrations (ppb) simulated by TAPOM, base case, 6 March 2002. (a) 1000LT, (b)1200LT, (c) 1400LT, (d) 1600LT. Some measuring stations are presented to facilitate the location of the city: Nacional (NA) and Merck (ME) are located in the central part of the city, Corpas (CO) in its northern border and Monserrate (MO) on the top of one of the eastern mountains bordering the plateau. For simulated and observed Ozone time series of these stations, refer to Zárate et al. (2006b).

Since clear-sky conditions and high solar radiations prevail, as the sun heats the ground slope winds start gaining importance. Thus, the wind direction changes after 1000LT, and air masses ascending from the Magdalena valley penetrate the plateau from the west and continue going up the mountains which border the plateau towards the E, SE and NE directions, reaching maximum ground intensities of 6-7 m s^{-1} around midday (fig. 4.2(b)). Due to this wind pattern, pollutants are pushed again over the city (fig. 4.3(b)). The western wind direction remains throughout the afternoon (fig. 4.2(c) and (d)), until 2000LT (not shown), hour from which the direction of the slope wind changes, and air masses descend the slopes. This nightly wind remains until the Trade Winds regain importance in the early morning of the following day.

The slope wind phenomenon also appears from the eastern side of the mountain range, that is, air masses blow from the Eastern Plains up to higher peaks of the mountain range, reaching the other side of the mountains which border the plateau at its eastern side. In consequence, air masses blowing from the Magadalena valley and from the Eastern Plains converge over the eastern border of Bogota's plateau, not far from the city (fig. 4.2(c) and (d)). This convergence front avoids the plume of pollutants to move further to the east, remaining "trapped" by the convergence front and only moving slightly northwards (fig. 4.3(c) and (d)). In this way, the nightly wind brings some of this pollution back over the city.

The maximum O_3 peak (which is a good tracer for the pollution plume of the city in this case) is attained at midday with 177 ppb (fig. 4.3(b)). It is formed towards the northeastern part of the city. A second plume of pollutants is observed in the southeastern part of the city, which is formed when the wind direction changes and western air masses arrive to the plateau. The maximum O_3 peak of this secondary plume reaches 139 ppb, also at midday (fig. 4.3(b)).

Succinctly, the photochemical plume of Bogota is mainly developed over the city. Downtown measuring stations like Merck and Nacional exemplify this behavior with sharp peaks of ozone up to 170-180 ppb. Monserrate and Corpas stations confirm that the plume is mainly transported eastwards, and to a less extent, northwards (time series are not shown, see Zárate et al. (2006b) for further details).

4.4 Quantification of pollutants response to hypothetical emission scenarios

In this section some hypothetical changes to anthropogenic emissions with respect to the base case (described in the previous section) are introduced. The repercussions that such changes might have over the mixing ratios of CO, NO_x, VOC and O_3 are evaluated. First, the region is characterized in terms of the governing chemical regimes (section 4.4.1). Critical geographical spots and hours during the day can be identified out of this analysis. Second, total emissions are split into predefined groups in order to quantify the individual impact of each group and the interactions between them (section 4.4.2). The temporal and spatial distribution of emissions and the impact of the main emission sources, are the features in which the selection of groups is based.

4.4.1 Sensitivity of Ozone production to reductions in its precursor's emissions

Sillman (1999) states that the relationship between O_3 and its two main precursors (NO_x= NO + NO_2 and VOC) can be understood as a fundamental split into NO_x-sensitive and VOC-sensitive chemical regimes, which is difficult to determine when specific pollution events take place. There are several techniques used to identify the transition between the two chemical regimes (Sillman, 1999; Martilli et al., 2002b; Couach et al., 2004; Oanh and Zhang, 2004). A straightforward way to distinguish NO_x and VOC sensitive conditions, consists in alternatively applying moderate reductions (20-50%) to the total NO_x and VOC emissions and then evaluating the model response to those reductions in terms of O_3 concentrations. Therefore, if 20 or 50% reduction in VOC emission is more effective in reducing O_3 than the same percent reduction in NO_x, the governing chemical regime is VOC-sensitive. Another way of distinguishing the chemical regimes consists in the calculation of indicators such as the H_2O_2/HNO_3, O_3/NO_y and O_3/NO_z ratios ($NO_z = NO_y - NO_x$). VOC-sensitive conditions correspond to values below 0.3, 7 and 9 for each one of these ratios respectively.

In this study, we choose to reduce anthropogenic VOC and NO_x emissions by

35 % in the domain. Two new simulations are generated keeping the same initial and boundary conditions, and O_3 results from both are compared. If O_3[35% less VOC]-O_3[35% less NO_x] < 0, it is more efficient to decrease VOC in order to tackle the O_3 problem, so we can state that we are in a VOC-limited chemical regime. If it is > 0, it is more efficient to decrease NO_x, thus we are in the NO_x-limited chemical regime. Fig. 4.4 presents the daily evolution of the chemical regimes for the region of Bogota, for this particular episode. Downtown Bogota is VOC-limited in the morning (fig. 4.4(a) and (b)). At 1200LT, hour of the O_3 maximum (fig. 4.4(c)), the VOC-limited regime has contracted and moved with the city plume towards the east. At 1400LT (fig. 4.4(d)), the remaining plume has changed entirely to a NO_x-limited regime. The following statements can be withdrawn from this analysis:

- Two main VOC-limited regions are identified at 0900LT (fig. 4.4(a)): a big region found over the city core, and a smaller one situated outside the city, towards its northwestern part (in the following, this zone will be defined as the NW zone). The former appears over an important industrial corridor, with high NO_x emissions. "Titration zones" in which O_3 is destroyed by freshly emitted NO, are identified inside the same regions at this hour of the day. The destruction of O_3 occurs at nighttime in places with high NO_x emissions (in this case, downtown and the NW zone). The effects of titration are perceived until 0900LT, that is, O_3 values from the base case simulation remain lower than the background until this hour of the day.

- The city plume shows two regions with maximum values when the wind direction changes (around 1000LT) and starts blowing towards the east, carrying back the pollution from the early morning over the city (see section 4.3). One region is located towards the NE and the other towards the SE. At 1000LT (fig. 4.4(b)), both plumes are in the VOC-sensitive regime. Later on, only the portion of the plume going NE remains VOC-sensitive (fig. 4.4(c)), so that the SE maximum O_3 is in the NO_x-sensitive regime. The places where both NE and SE O_3 maximums appear are considered also as critical spots functioning under different chemical regimes (fig. 4.5).

- The H_2O_2/HNO_3 ratio <0.3 has been found to be a robust indicator to de-

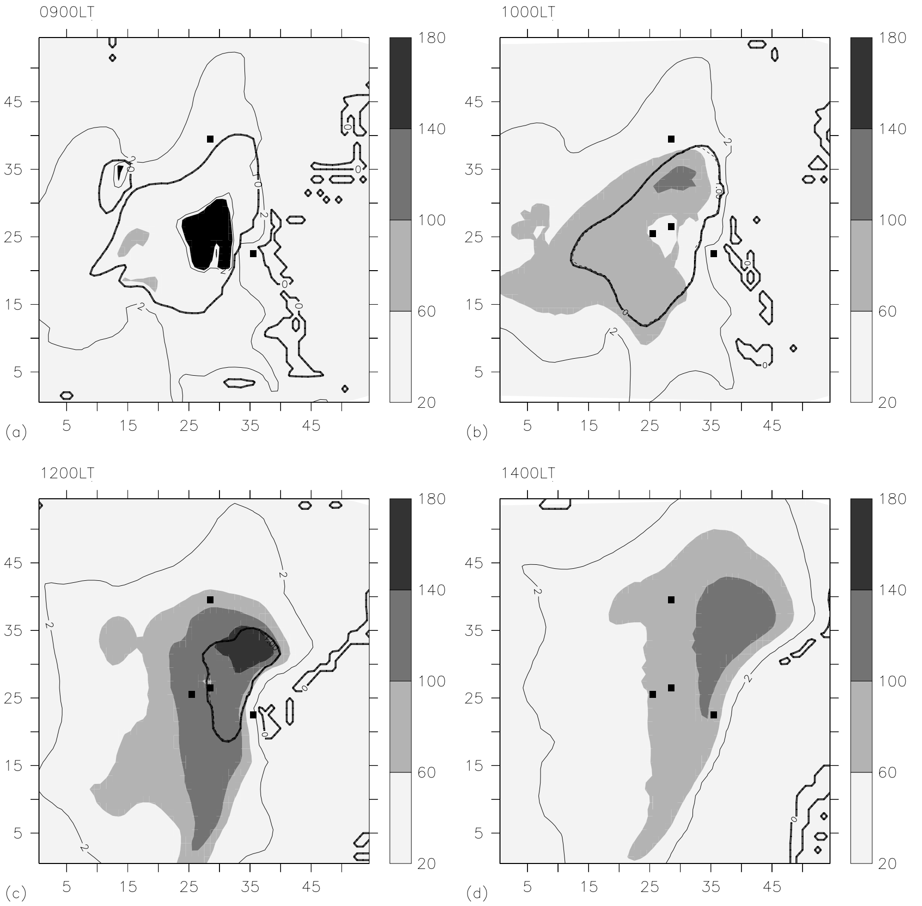


Figure 4.4: Evolution of the chemical regimes in the region of Bogota for 6 March 2002. Bogota's O_3 plume is presented in all the figures (Ozone concentrations in ppb are included in the scale to the right of each figure), and it is delimited by the isoline of 2 ppb. The thick black line included in (a), (b) and (c) represents the limit between VOC-sensitive (inside) and NO_x-sensitive (outside) regimes. The VOC-sensitive zone shrinks and moves eastwards until 1300LT. At 1400LT (d), all the region is in the NO_x-sensitive regime. In (a), titration zones are shown in black. They indicate simulated O_3 concentrations smaller than the background value (30 ppb), confirming the nightly O_3 destruction. The black squares symbolize some measuring stations (see fig. 4.3).

fine a VOC-sensitive regime (Jeanneret et al., 2001; Chen and Chang, 2006). The contour line of 0.3 defined by this indicator overlaps almost entirely (not shown) the VOC-sensitive zones presented in fig. 4.4. The values reached at the places of the maximum NE and SE O_3 peaks are 0.1 and 0.31 in that order (at 1200LT). These values corroborate the VOC-sensitive and NO_x-sensitive nature of the NE and SE plumes respectively. However, the result obtained for the SE plume indicates that a small swift in the original conditions could easily favor a VOC-sensitive regime in this portion of the plume. Other indicators like O_3/NO_y and O_3/NO_z ratios behave similarly, that is, values far below 7 and 9 for the NE plume, and close to 7 and 9 in the SE (not shown).

- The maximum O_3 increase predicted by the simulation in which 35% of NO_x emissions are reduced, with respect to the base case, is of 55 ppb and it takes place in the city center (at 1000LT). The maximum O_3 peak in the domain is increased by 25 ppb with this emission reduction. In the same way, the maximum O_3 decrease predicted by the simulation in which 35% of VOC emissions are reduced, with respect to the base case, is of 47 ppb and it takes place in the northeastern part of the city (1100LT), in the core of the city plume. The maximum O_3 peak in the domain is reduced by 27 ppb. Additionally, the maximum reduction attained in the city center is about 20 ppb (1100LT).

Four critical spots of Bogota's pollution plume (fig. 4.5), which react differently to changes in emissions, have been identified out of this analysis: The NW region is separated from the main emissions in town, and is characterized by high NO_x emissions. The NE and SE regions correspond to two different parts of the city plume, with important O_3 peak values at midday but functioning under different chemical regimes. Finally, the city center (represented by the letter C), with constant high levels of emissions.

4.4.2 Interactions and contributions of different emissions to the pollution plume and to Ozone formation

The factor separation (FS) technique proposed by Stein and Alpert (1993) is used in this part of the study. It quantifies the relative contribution of predefined factors, individually and in mutual interaction (i.e. Thunis and Cuvelier (2000); Grossi et al. (2000); Tao et al. (2005); Carvalho et al. (2006)). Without isolating the

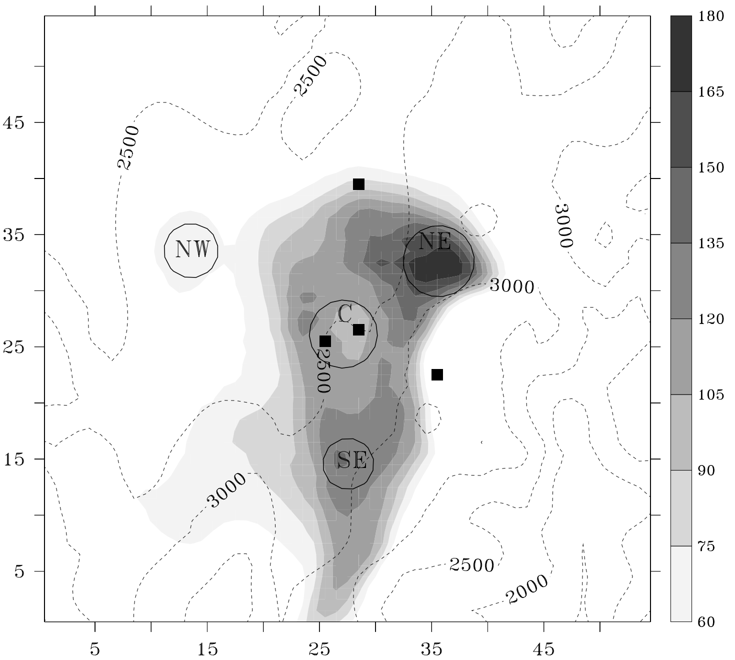


Figure 4.5: Definition of critical zones of pollution in the region: NW=Northwest, NE=Northeast, C=Center of the city, SE=Southeast. The map of simulated O_3 concentrations (ppb) for the base case, 6 March 2002, 1200LT is also presented. Note that two O_3 maximums appear at this time of the day, in the NE and SE regions. The black squares illustrate some of the measuring stations (see fig. 4.3).

contributions from the different factors, ambiguous or deceptive results might be expected, due to the nonlinearity of the processes involved. This technique requires 2^n simulations, where n is the number of factors to be studied. Hence, to estimate the relative impact of factors A and B, 4 simulations are required: including none of the factors, only with factor A, only with factor B, and including both factors. The results of the simulations are denoted by: S_0, S_A, S_B and S_{tot} respectively. Subsequently, the isolated contribution of factors A and B is given by,

$$\hat{S}_A = S_A - S_0 \tag{4.1}$$

$$\hat{S}_B = S_B - S_0 \tag{4.2}$$

Therefore, the simulation including both A and B is stated as:

$$S_{tot} = S_0 + \hat{S}_A + \hat{S}_B + \hat{S}_{AB} \tag{4.3}$$

Table 4.1: Notation used to quantify the interactions of different emissions according to the Factor Separation technique [a]

	Emissions
S_{tot}	Total (all the emissions)
S_0	None (only biogenic emissions)
$\hat{S}_{tot}$	Bogota's contribution = $S_{tot} - S_0$
$\hat{S}_N$	Nighttime (0100LT-0900LT)
$\hat{S}_D$	Daytime (1000LT-2400LT)
$\hat{S}_{DN}$	Mutual interaction between Nighttime and daytime
$\hat{S}_U$	Urban perimeter
$\hat{S}_R$	Rural
$\hat{S}_{UR}$	Mutual interaction between urban and rural
$\hat{S}_{OT}$	Others than traffic
$\hat{S}_T$	Traffic
$\hat{S}_{OTT}$	Mutual interaction between traffic and others
$\hat{S}_{OI}$	Others than industries
$\hat{S}_I$	Industries
$\hat{S}_{OII}$	Mutual interaction between industries and others
$\hat{S}_{OL}$	Others than light vehicles
$\hat{S}_L$	Light vehicles
$\hat{S}_{OLL}$	Mutual interaction between light vehicles and others
$\hat{S}_{OH}$	Others than heavy vehicles
$\hat{S}_H$	Heavy vehicles
$\hat{S}_{OHH}$	Mutual interaction between heavy vehicles and others

[a] Note that $S_{tot} = S_0 + \hat{S}_D + \hat{S}_N + \hat{S}_{DN} = S_0 + \hat{S}_U + \hat{S}_R + \hat{S}_{UR} = S_0 + \hat{S}_{OT} + \hat{S}_T + \hat{S}_{OTT} = S_0 + \hat{S}_{OI} + \hat{S}_I + \hat{S}_{OII} = S_0 + \hat{S}_{OL} + \hat{S}_L + \hat{S}_{OLL} = S_0 + \hat{S}_{OH} + \hat{S}_H + \hat{S}_{OHH}$. All the simulations are run with the same initial and boundary conditions. S_0 denotes the background concentrations. To obtain this value, a simulation with only biogenic emissions is run.

The term S_0 stands for the contribution due to other factors apart from A and B. The term $\hat{S}_{AB}$ stands for the contribution due to the interaction between A and B and is caused by the nonlinear processes taking place.

The factors to be studied are defined based on the results obtained from the previous section, following to the characterization of the chemical regimes and the identification of critical zones. First, nighttime and daytime emissions are investigated. The split between these two is set at 0900LT, that is, nighttime emissions include emissions from 0000LT (time when the simulation starts) until 0900LT, whereas daytime emissions are considered from 0900LT until 2400LT. This definition takes into account that significant O_3 production starts after 0900LT (values are lower than the background due to O_3 titration before 0900LT). Thermal winds, turbulence and mixing start gaining importance after this hour as well. Second, the influence of anthropogenic rural and urban emissions is studied. "Rural" emissions describe those released in the domain of study but outside the prescribed urban perimeter of Bogota. The role and contribution of these emissions to the formation of the plume are examined. Third, the impact of traffic and industrial sources is analyzed individually. Fourth, since traffic is the most important source of pollution in Bogota, the role of light and heavy traffic emissions is also evaluated. Heavy traffic corresponds to buses and trucks heavier than 3.5 tons.

The FS technique is applied to compare two factors at a time, so a total of 14 simulations is necessary to cover the issues proposed above (see table 4.1 for details): S_{tot}, S_0 which correspond to the base case and the background simulation (simulation run only with biogenic emissions); $\hat{S}_N$, $\hat{S}_D$ which correspond to the simulations with nighttime and daytime emissions; $\hat{S}_U$, $\hat{S}_R$, related to the urban and rural emission simulations. In the case of traffic and industrial sources, 4 simulations are required ($\hat{S}_{OT}$, $\hat{S}_T$, $\hat{S}_{OI}$ and $\hat{S}_I$), since they are not the unique sources of emission in the region, and we want to keep the directive of the analysis of two factors at a time. The same situation is presented for the analysis of light and heavy traffic ($\hat{S}_{OL}$, $\hat{S}_L$, $\hat{S}_{OH}$ and S_H). This notation will be used in the following to describe the individual contributions of each factor of interest. The same initial and boundary conditions are kept for all the simulations.

Daytime and nighttime emissions

Table 4.2 presents the contributions of daytime and nighttime emissions to the total concentrations of pollutants found at midday (the hour of the O_3 maximum), for each one of the critical regions defined in the previous section. The O_3 peaks in the NE and SE regions (177 and 139 ppb) present important contributions of nighttime emissions (fig. 4.6(a)), with 148 and 93 ppb respectively, indicating that emissions before 0900LT play a predominant role in the formation of the peak. This means that abatement strategies should be focused on the reduction of

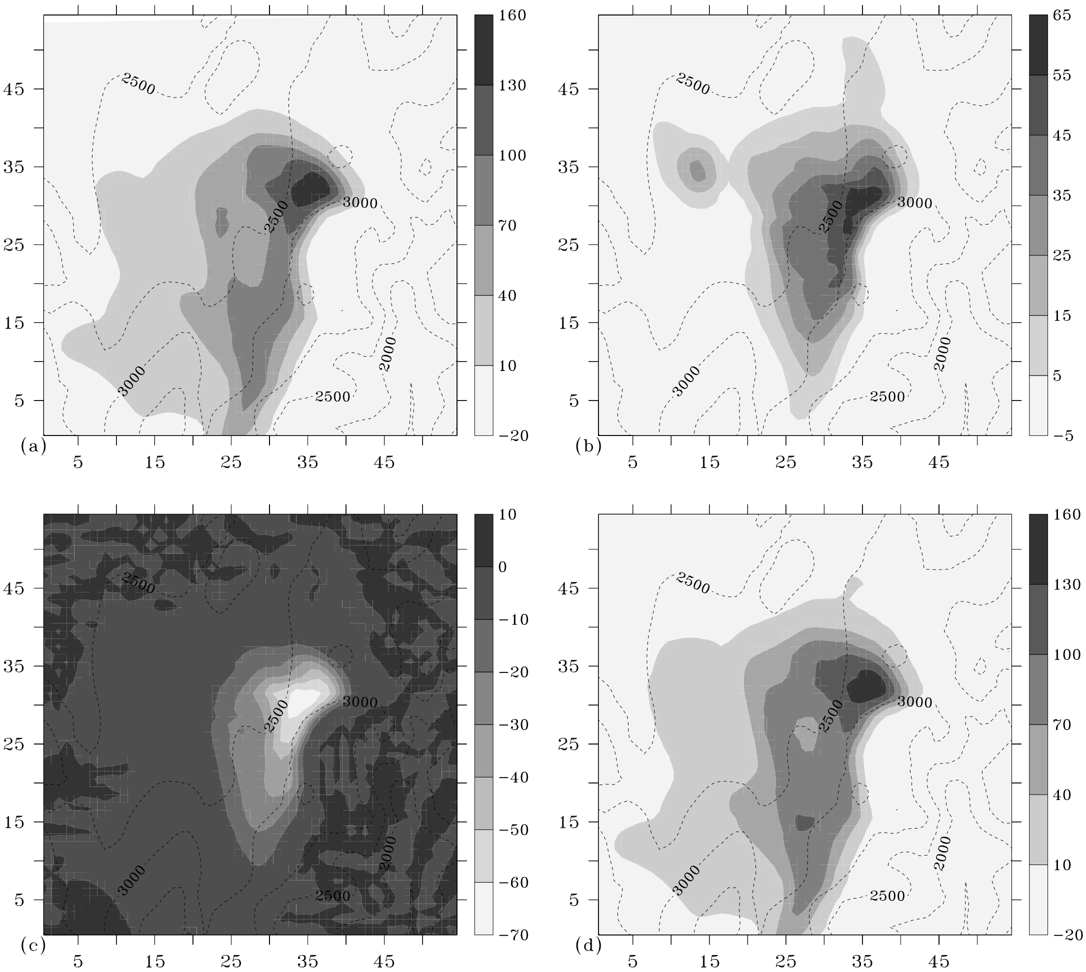


Figure 4.6: Contribution of nighttime and daytime emissions to O_3 formation (ppb) at the time of the maximum (1200LT). (a) $\hat{S}_N$, (b) $\hat{S}_D$, (c) $\hat{S}_{DN}$, (d) $\hat{S}_{tot}$.

nighttime emissions in order to influence the O_3 levels. The effect of the mutual interaction ($\hat{S}_{DN}$, fig. 4.6(c)) is negative over most of the domain, implying that emissions after 0900LT cause a reduction in the O_3 production due to an effect of saturation of the system. Observing at the values obtained for $\hat{S}_D$ (56ppb) and $\hat{S}_{DN}$ (-55ppb), it can be stated that the contribution of the day saturates itself. As we move from the NE to the center of the city, a more balanced repartition between $\hat{S}_N$ and $\hat{S}_D$ is observed, which is expected since emissions are being released downtown at this hour of the day. The NW region shows as well a predominance of daytime emissions at this hour of the day. This is explained by the fact that

Table 4.2: Contribution of nighttime and daytime emissions to pollutant concentrations (ppb) at 1200LT in 4 specific locations of the domain (fig. 4.5), according to the FS technique. NMVOC = Non methane volatile organic compounds.

		S_{tot}	S_0	$\hat{S}_N$	$\hat{S}_D$	$\hat{S}_{DN}$
NE	CO	4 399	1 984	1 779	642	-6
	NO_x	39	0	19	15	5
	NMVOC	196	84	71	37	4
	O_3	177	28	148	56	-55
SE	CO	2 789	2 004	562	209	14
	NO_x	9	0	3	5	1
	NMVOC	111	87	15	9	1
	O_3	139	35	95	28	-17
C	CO	3 262	2 003	281	1 001	-23
	NO_x	38	0	2	36	1
	NMVOC	149	87	9	53	0
	O_3	100	35	51	37	-23
NW	CO	2 040	1 998	31	11	0
	NO_x	11	0	0	11	0
	NMVOC	86	87	0	-1	0
	O_3	72	37	10	28	-3

this region, which does not undergo the effect of the morning rush hour emissions in Bogota, is located on an important industrial corridor with permanent emissions.

In the case of NO_x, similar total concentrations are found in the city center and in the NE (38 and 39 ppb), but they exhibit different contributions of $\hat{S}_N$ and $\hat{S}_D$. In the NE, $\hat{S}_N$ is predominant (19 ppb), indicating the presence of important amounts of NO_x emitted at nighttime and carried away with the wind. Downtown, freshly emitted NO_x is observed (36 ppb). A similar behavior is observed for both NMVOC and CO, indicating important $\hat{S}_N$ and $\hat{S}_D$ contributions in the NE and central regions respectively.

Urban and rural emissions

Urban and rural emission interactions (fig. 4.7, table 4.3) show that the plume of Bogota is mainly formed by the pollutants released by the city. 149 and 104 ppb

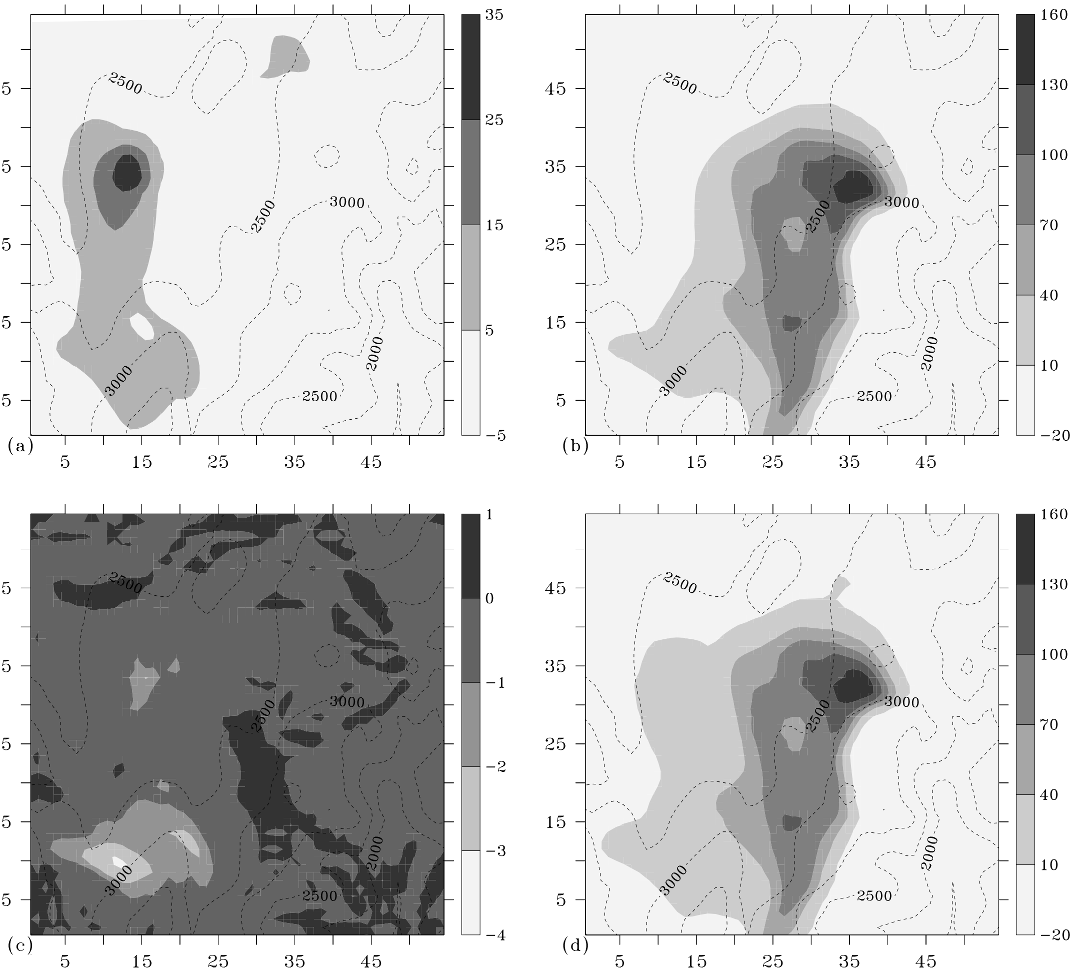


Figure 4.7: Contribution of urban and rural emissions to O_3 formation (ppb) at the time of the maximum (1200LT). (a) $\hat{S}_R$, (b) $\hat{S}_U$, (c) $\hat{S}_{UR}$, (d) $\hat{S}_{tot}$.

of the O_3 peaks in the NE and SE respectively are attributed to urban emissions ($\hat{S}_U$), with zero contribution from emissions outside Bogota ($\hat{S}_R$). In the same way, rural contributions are weak for all the domain, except for the NW region, whose contributions are mainly from rural origin (fig. 4.7(a)). If $\hat{S}_U$ and $\hat{S}_{tot}$ O_3 maps are compared (fig. 4.7(b) and (d)), similar levels of pollution are appreciated, but the plume formed by $\hat{S}_U$ is less expanded. The extension of the plume towards the NW in the base case simulation ($\hat{S}_{tot}$) is thus due to rural emissions. $\hat{S}_{UR}$ values remain close to zero, which implies that there is a very weak interaction between these two types of emissions.

Table 4.3: Contribution of rural and urban emissions to pollutant concentrations (ppb) at 1200LT in 4 specific locations of the domain (fig. 4.5), according to the FS technique.

		S_{tot}	S_0	$\hat{S}_R$	$\hat{S}_U$	$\hat{S}_{UR}$
NE	CO	4 399	1 984	1	2 414	0
	NO_x	39	0	0	39	0
	NMVOC	196	84	0	112	0
	O_3	177	28	0	149	0
SE	CO	2 789	2 004	1	786	-1
	NO_x	9	0	0	9	0
	NMVOC	111	87	0	25	0
	O_3	139	35	0	104	0
C	CO	3 262	2 003	0	1 259	0
	NO_x	38	0	0	38	0
	NMVOC	149	87	0	62	0
	O_3	100	35	0	65	0
NW	CO	2 040	1 998	25	16	1
	NO_x	11	0	11	0	0
	NMVOC	86	87	-1	0	0
	O_3	72	37	32	4	-1

The role of urban emissions is equally predominant for NO_x, NMVOC and CO in the NE, SE and center, but in the NW region rural emissions are more important.

Traffic and industrial sources

The simulation with only traffic emissions (fig. 4.8(a), table 4.4) shows that this type of emissions play the most important role in the NE and SE O_3 peaks of the plume, with 153 and 100 ppb respectively. Only the NW shows a predominance of other sources of emissions 9 and 29 ppb attributed to $\hat{S}_T$ and $\hat{S}_{OT}$ respectively (the same values are obtained correspondingly for $\hat{S}_{OI}$ and $\hat{S}_I$, see table 4.5). The negative values observed for $\hat{S}_{OTT}$ and $\hat{S}_{OII}$ indicate that the combination of industrial and traffic emissions leads to a reduction of O_3, that is, only traffic emissions would lead to higher values of O_3. The strong impact of traffic emissions is also observed for the other pollutants examined, except for NO_x in the NW which is

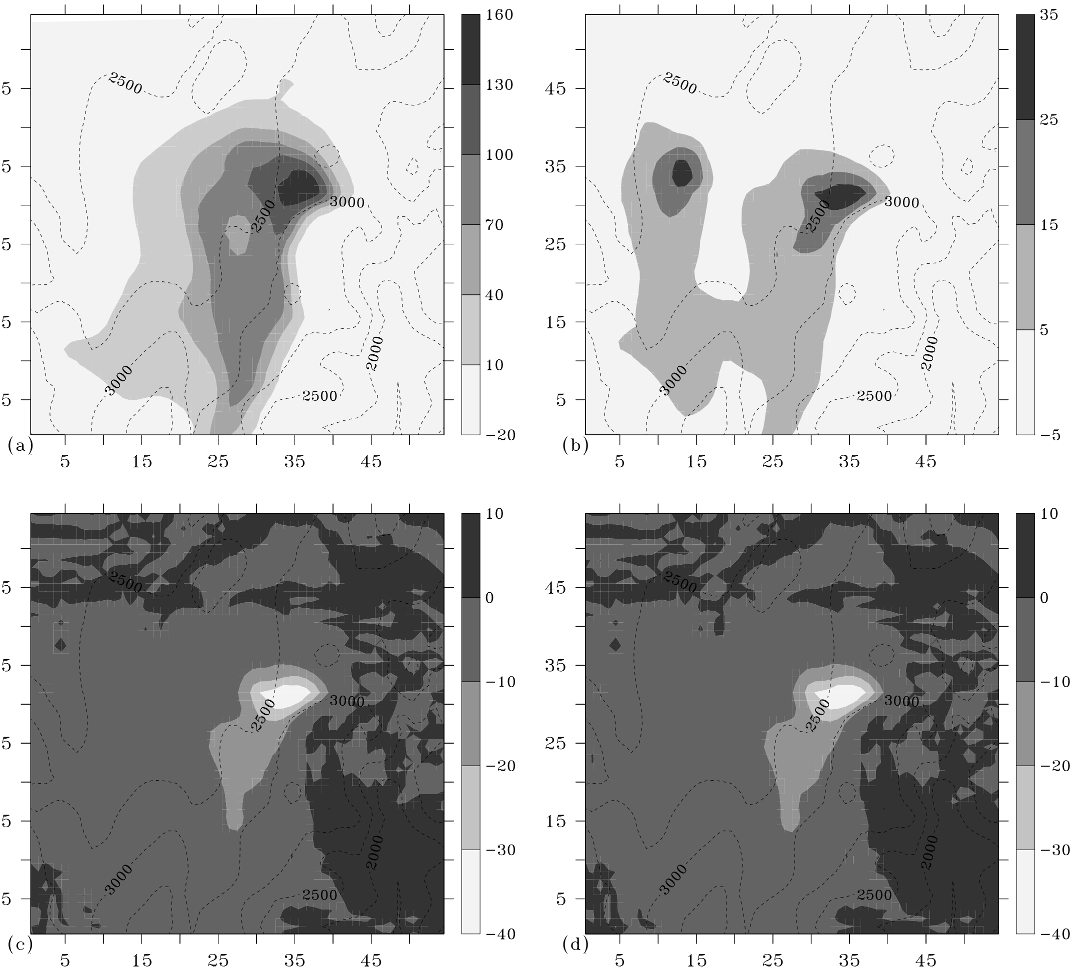


Figure 4.8: Contribution of traffic and industrial emissions to O_3 formation (ppb) at the time of the maximum (1200LT). (a) $\hat{S}_T$, (b) $\hat{S}_I$, (c) $\hat{S}_{OTT}$, (d) $\hat{S}_{OII}$. $\hat{S}_{OT}$ and $\hat{S}_{OI}$ are not shown

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mainly from industrial provenance.

Light and heavy traffic

Since traffic is a crucial source of pollution, it is worthwhile investigating the individual contributions of light and heavy vehicles. The most important aspect of this part is related to the positive values of the interactions $\hat{S}_{OLL}$ and $\hat{S}_{OHH}$ (fig.

Table 4.4: Contribution of traffic and other sources of emissions to pollutant concentrations (ppb) at 1200LT in 4 specific locations of the domain (fig. 4.5), according to the FS technique.

		S_{tot}	S_0	$\hat{S}_T$	$\hat{S}_{OT}$	$\hat{S}_{OTT}$
NE	CO	4 399	1 984	2 413	3	0
	NO_x	39	0	34	0	5
	NMVOC	196	84	109	-2	6
	O_3	177	28	153	24	-27
SE	CO	2 789	2 004	764	22	-1
	NO_x	9	0	7	1	1
	NMVOC	111	87	24	-1	2
	O_3	139	35	100	15	-11
C	CO	3 262	2 003	1 256	2	1
	NO_x	38	0	34	3	1
	NMVOC	149	87	61	0	1
	O_3	100	35	65	15	-15
NW	CO	2 040	1 998	44	-2	0
	NO_x	11	0	0	11	0
	NMVOC	86	87	1	-2	0
	O_3	72	37	9	29	-3

4.9, tables 4.6 and 4.7), obtained for the NE and SE regions. This demonstrates that it is the combination of both light and heavy traffic which leads to high levels of O_3. Additionally, a slightly stronger influence of heavy traffic emissions is perceived in the SE as compared to the NE. This is related to the temporal repartition attributed to light and heavy traffic. Higher values of the heavy traffic split are found before 0600LT with respect to those attributed after this hour, when the light traffic becomes more important. This means that heavy traffic emissions have more time to go southwards before the wind direction changes (see section 4.3), resulting in a larger contribution of this source in the SE. As for CO and NO_x, heavy traffic emissions appear to have the major contribution in all the regions (except for NO_x in the NW which is essentially from industrial origin). In the case of NMVOC, light traffic denotes the most significant source of emissions.

Table 4.5: Contribution of industries and other sources of emissions to pollutant concentrations (ppb) at 1200LT in 4 specific locations of the domain (fig. 4.5), according to the FS technique.

		S_{tot}	S_0	$\hat{S}_I$	$\hat{S}_{OI}$	$\hat{S}_{OII}$
NE	CO	4 399	1 984	2	2 413	0
	NO_x	39	0	0	34	5
	NMVOC	196	84	-5	-111	6
	O_3	177	28	24	153	-27
SE	CO	2 789	2 004	22	764	-1
	NO_x	9	0	1	7	1
	NMVOC	111	87	-2	25	2
	O_3	139	35	15	100	-11
C	CO	3 262	2 003	2	1 256	1
	NO_x	38	0	3	34	1
	NMVOC	149	87	-2	62	2
	O_3	100	35	15	65	-15
NW	CO	2 040	1 998	-2	44	0
	NO_x	11	0	11	0	0
	NMVOC	86	87	-2	1	0
	O_3	72	37	29	9	-1

4.5 Feasible emission scenarios

Since traffic plays the most important role in terms of levels of pollution in Bogota, this section is devoted to the study of three emission scenarios which aim to mitigate emissions from this source. They are all focused to heavy duty vehicles, and they are called feasible because they could be applied in the short or medium term to the city.

The first scenario has been recently implemented in Bogota (El Tiempo, 2006). It concerns the partial restriction of the circulation between 0600LT and 1000LT of the heavy traffic fleet (heavier than 5 tons) which does not comply with the city's regulation program (DAMA, 2006). It means that if a given vehicle does not have an approved regulation certificate, it is not allowed to run one day out of ten. This restriction is applied according to the last number of the plate. Thus, if no vehicle complies the regulation, 10% of the total heavy traffic is not running

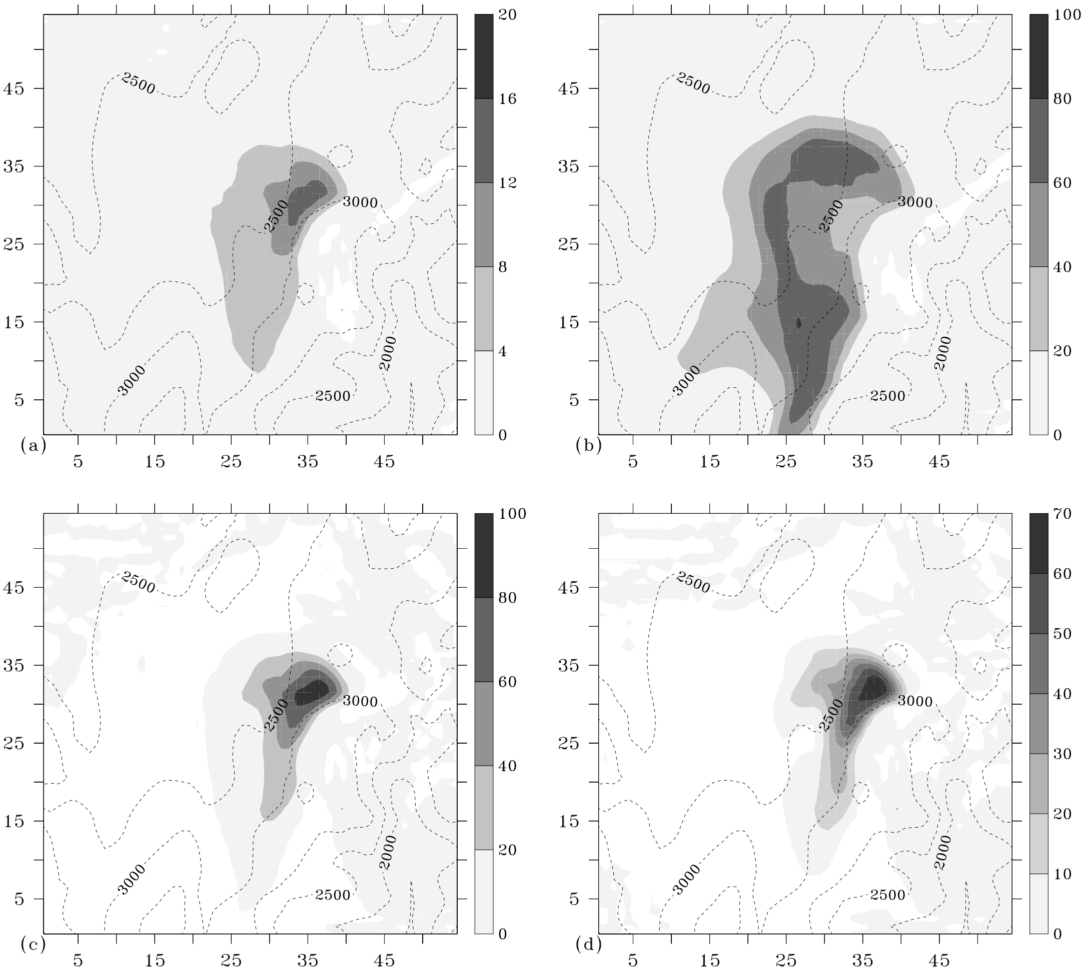

Figure 4.9: Contribution of light and heavy traffic emissions to O_3 formation (ppb) at the time of the maximum (1200LT). (a) $\hat{S}_L$, (b) $\hat{S}_H$, (c) $\hat{S}_{OLL}$, (d) $\hat{S}_{OHH}$. $\hat{S}_{OL}$ and $\hat{S}_{OH}$ are not shown.

in the city. To simulate this scenario, we assume that 10% of the total amount of heavy vehicles is not circulating. From now on this scenario will be denoted as Sc-1.

The second scenario involves the complete elimination of 20% of the buses circulating in the city. This scenario stands for the fact that at the moment there is an oversupply of buses in Bogota, calculated in around 20% (Giraldo, 2005). One of the reasons for this oversupply is attributed to a relatively recent implementation of a new bus system in the city (Skinner, 2004). We will refer to this scenario as Sc-2.

Table 4.6: Contribution of light vehicles and other sources of emissions to pollutant concentrations (ppb) at 1200LT in 4 specific locations of the domain (fig. 4.5), according to the FS technique.

		S_{tot}	S_0	$\hat{S}_L$	$\hat{S}_{OL}$	$\hat{S}_{OLL}$
NE	CO	4 399	1 984	372	2035	9
	NO_x	39	0	0	68	-30
	NMVOC	196	84	119	7	-13
	O_3	177	28	13	48	88
SE	CO	2 789	2 004	117	664	4
	NO_x	9	0	0	13	-5
	NMVOC	111	87	33	-5	-4
	O_3	139	35	6	83	15
C	CO	3 262	2 003	191	1 065	3
	NO_x	38	0	1	41	-4
	NMVOC	149	87	61	2	-1
	O_3	100	35	5	45	15
NW	CO	2 040	1 998	7	35	0
	NO_x	11	0	0	11	0
	NMVOC	86	87	2	-3	0
	O_3	72	37	0	35	0

The third scenario (Sc-3) represents an attempt to evaluate the impact of a combined measure consisting in the renewal of the fleet of buses and the improvement of the diesel's quality (for details about the fleet in Bogota and its emission factors (EF), see Zárate et al. (2006a)). It is expected that these two measures will take place within a few years in Bogota. To recalculate emissions for this scenario, standard CORINAIR EF proposed by EEA (1999) are assumed to be valid and thus applied. Nevertheless, such kind of scenarios should be more accurately simulated in the future using real-world EF.

Table 4.8 presents the maximum percentages of reduction attained for each of the scenarios simulated, as well as the time when they take place. Positive reduction percentages are observed for all the primary pollutants. Whereas Sc-1 and Sc-2 have relatively less impact (maximum reduction percentage = 12 %), Sc-3 shows important reductions in the simulated concentrations (maximum reduction percentage = 72 %). The reductions for CO and NO_x can be better observed in

Table 4.7: Contribution of heavy vehicles and other sources of emissions to pollutant concentrations (ppb) in 4 specific locations of the domain (fig. 4.5), according to the FS technique.

		S_{tot}	S_0	$\hat{S}_H$	$\hat{S}_{OH}$	$\hat{S}_{OHH}$
NE	CO	4 399	1 984	2 032	377	6
	NO_x	39	0	63	0	-25
	NMVOC	196	84	4	117	-9
	O_3	177	28	51	30	69
SE	CO	2 789	2 004	642	140	3
	NO_x	9	0	11	1	-3
	NMVOC	111	87	-6	32	1
	O_3	139	35	82	18	4
C	CO	3 262	2 003	1 062	194	3
	NO_x	38	0	36	4	-2
	NMVOC	149	87	1	61	0
	O_3	100	35	47	20	-2
NW	CO	2 040	1 998	37	5	0
	NO_x	11	0	0	11	0
	NMVOC	86	87	-1	0	0
	O_3	72	37	8	29	-2

Table 4.8: Maximum percentages of reduction in concentrations obtained for the simulation of emission scenarios (the hour of the day when this reduction takes place is presented in parenthesis). In the case of Sc-3, the production of O_3 starts earlier, hence the peak in town appears two hours earlier (fig. 4.12(a)). This generates the high percentages of O_3 increase at 1000LT (98 %).

	Sc-1	Sc-2	Sc-3
CO	3 (0900LT)	7 (1000LT)	72 (0900LT)
NMVOC	1 (0900LT)	1 (1000LT)	6 (1000LT)
NO_x	5 (1100LT)	12 (0900LT)	55 (0900LT)
O_3	-4 (1200LT)	-10 (1000LT)	-98 (1000LT)

fig. 4.10. For all the three scenarios, the most important reductions of primary pollutants are observed in the morning, in the central and eastern part of the city. Another important reduction is observed at 2200LT, towards the western part of the city. An example of the NO_x reductions attained for Sc-2 is presented in fig.

4.11.

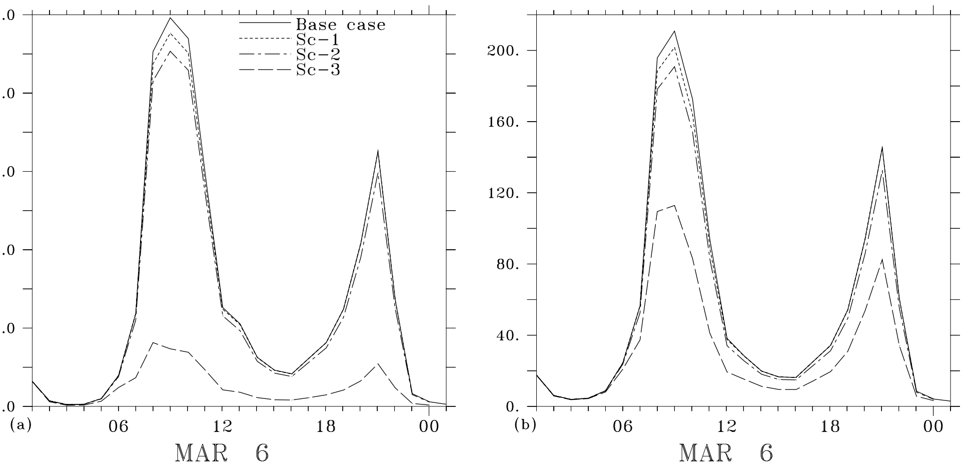

Figure 4.10: Comparison of TAPOM simulated concentrations obtained in one of the measuring stations downtown (Nacional), for the base case (solid line) and different emission scenarios: Sc-1 (dotted line), Sc-2 (dashed dotted line) and Sc-3 (dashed line). (a) CO, ppm. (b) NO_x, ppb.

Due to the non-linearity of O_3, results are not as straightforward as primary pollutants. For all the scenarios, maximum simulated O_3 concentrations are bigger than the corresponding ones obtained in the base case. In the case of Sc-3, the production of O_3 starts earlier, hence the peak in town appears two hours earlier (fig. 4.12(a)). This generates the high percentages of O_3 increase at 1000LT (98 %). As for the O_3 maximum, Sc-3 produces 20 ppb more than the base case (fig. 4.12(b)). This peak appears at 1100LT (one hour earlier than the peak in the base case), which implies that it is closer to the city core (the wind starts blowing towards the east after 1000LT).

4.6 Conclusions and outlook

In this study, a deeper understanding of the air pollution problem in Bogota has been attained throughout the use of modelling tools. The evolution of the chemical regimes of the plume has been characterized for the particular pollution episode which occurred during 6 and 7 March 2002 in Bogota. In the early morning, the

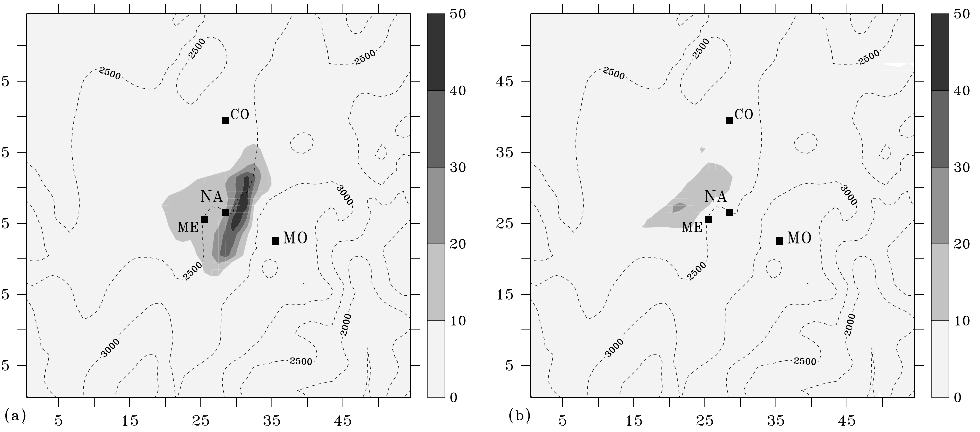

Figure 4.11: Geographical localization of maximum NO_x reductions attained for the simulation of emission scenarios. This figure presents the example of Sc-2 (reductions of primary pollutants are attained at the same places for the three scenarios evaluated). The map plots NO_x (Base case) − NO_x(Sc-2). (a) 0900LT. (b) 2200LT. For all the three scenarios, the most important reductions of primary pollutants are observed in the morning, in the central and eastern part of the city. Another important reduction is observed at 2200LT, towards the western part of the city. Measuring stations: Nacional (NA) and Merck (ME) are located in the central part of the city, Corpas (CO) in its northern border and Monserrate (MO) on the top of one of the eastern mountains bordering the plateau.

VOC-sensitive zone encompasses nearly all the city, and then this zone shrinks and moves eastwards. At 1300LT, when the air masses have aged, the plume becomes entirely NO_x-sensitive. This implies that an increase in the O_3 levels might be expected in the morning hours when applying abatement strategies focused mainly on the mitigation of NO_x.

The main agents leading to high levels of pollution in the city have been identified using the factor separation technique proposed by Stein and Alpert (1993). Hypothetical scenarios were used to analyze the impact of nighttime and daytime, urban and rural, traffic and industrial, and light and heavy traffic emissions. From this analysis, we conclude that pollution in Bogota comes mainly from emissions released before 0900LT in the city itself, and the main source of pollution is on-road traffic. Moreover, heavy duty traffic contributes with the most important proportions of all the pollutants except VOCs, whose principal source are the light vehicles. This means that O_3 levels in Bogota are produced by a combination of NO_x from heavy vehicles and VOCs from light vehicles.

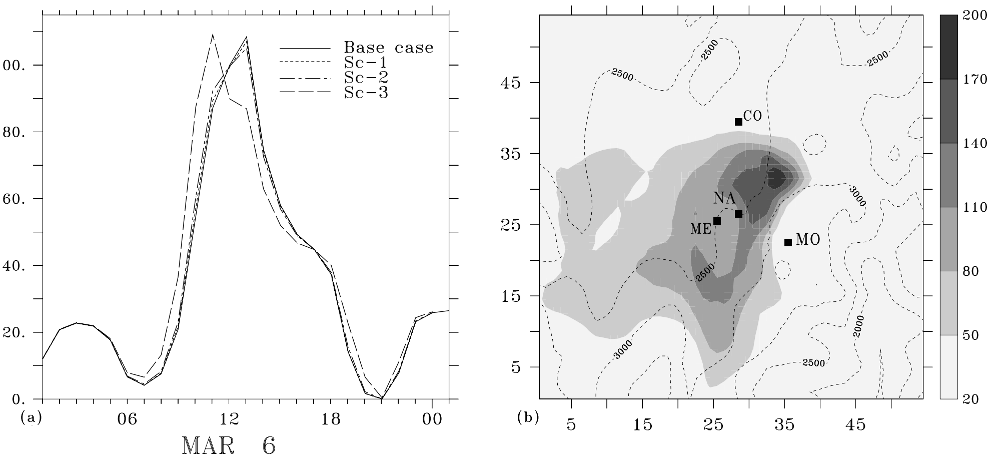

Figure 4.12: Comparison of simulated O_3 concentrations for the base case (solid line) and different emission scenarios: Sc-1 (dotted line), Sc-2 (dashed dotted line) and Sc-3 (dashed line). (a) Time series at Nacional station. (b) Map of simulated O_3 for Sc-3, 1100LT. The black squares illustrate some measuring stations (see fig. 4.3).

Three viable abatement strategies having as target the heavy duty vehicles, have also been evaluated. Simulated concentrations of primary pollutants decrease proportionally with the decrease of emissions, whereas O_3 reacts differently due to the non-linear processes governing its production and destruction. For all the abatement strategies evaluated, higher O_3 levels were achieved in town. The biggest challenge when evaluating abatement strategies for Bogota, is related to the lack of validated real-world traffic EFs. Sc-1 and Sc-2 propose a restriction in the circulation of heavy vehicles of the current fleet. The reduction percentages obtained for these two scenarios may be underestimated due to the fact that we count on average validated EFs for only two classes of vehicles (light and heavy, Zárate et al. (2006a)). Restricted vehicles (old buses for example) surely contribute more to emissions than those vehicles allowed to circulate. In Sc-3, a renewed fleet running with a high quality fuel is assumed and thus CORINAIR traffic EFs were applied. A drastic reduction of levels of primary pollutants was hence obtained, whereas O_3 levels increased considerably. The abatement of O_3 is therefore bounded to a decrease in the levels of VOC in the city, whose main contributors are the light traffic. Further research is needed in order to accurately estimate real emissions in the city for such scenario. Furthermore, this work shows that different abatement strategies can be formulated depending on the region of the city to be treated or the pollutant to be tackled. Additionally, in order to mitigate pollution it is necessary to take actions on different types of emission sources.

Finally, an integrated assessment of pollution abatement strategies in Bogota should comprise the analysis of emission scenarios under other meteorological and dispersion conditions. Though care must be taken before generalizing conclusions about the efficiency of abatement strategies tested for a particular episode, these results contribute to reinforce the knowledge about air quality in the city of Bogota.

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Chapter 5

Modelling particulate matter with an heterogeneous-phase model in Bogota.

Abstract

Aiming to understand the transport and formation of aerosols during a typical 2-day air pollution episode in Bogota, a mesoscale air quality model is applied and evaluated. The formation of secondary aerosols is studied, as well as the interactions between the gas and aerosol phases. 3 abatement strategies which concern the mitigation of heavy traffic emissions are evaluated in terms of PM_{10}. This work is a preliminary approach to the simulation of PM_{10} in Bogota and is useful to widen the understanding of the problem and to outline future research fronts.

5.1 Introduction

Studies of long-term exposure to airborne particulate matter (PM) suggest an increased mortality, increased risk of chronic respiratory illness and of developing various types of cancer, at levels of exposure that are currently experienced by urban populations in both developed and developing countries (Moussiopoulos, 2003; WHO, 2005). PM_{10} (particles smaller than 10 µm) represents the particle mass that enters the respiratory track and it includes both the coarse (particle size between 2.5 and 10 µm) and the fine particles (less than 2.5 µm, $PM_{2.5}$). The former is primarily produced by mechanical processes such as construction activities, road dust re-suspension and wind, whereas the latter originates primarily from combustion sources. In most urban areas, both coarse and fine mode particles are present, but the proportion of particles in these two side ranges is likely to vary substantially between cities around the world, depending on local geography, meteorology and specific PM sources.

The chemical and physical properties of PM are important for assessing environmental impact as well as adverse health effects (Moussiopoulos, 2003). These properties also need to be taken into account in selecting methods for PM emission regulation and control. Moreover, the determination of the best control strategy is not straightforward since PM results from primary particle-phase emissions and from their gas-phase precursor substances; the later leading to the formation of secondary PM.

PM_{10} is one of the most serious air pollution problems in Bogota. Between 1998 and 2002, Bogota's air quality network showed an increase of 12% in levels of this pollutant (Molina and Molina, 2004). Around half of the measuring stations do not comply the annual local standard (65 µg m^{-3}), and the 24-h standard (170 µg m^{-3}) is also frequently exceeded (about 10% of the daily average data exceed this standard, UNIANDES/EPFL (2001); DAMA (2006)).

Chapter 2 indicates values of PM_{10} emissions for mobile and industrial sources in Bogota, with mobile sources including only car exhaust emissions. Nonetheless, other sources must be taken into account when simulating urban aerosols. First, natural sources such as soil and rock debris (fugitive windblown dust), biomass burning, etc. Second, other anthropogenic sources namely fugitive sources (roadway dust from paved and unpaved roads, construction, farming operations, etc) and non-exhaust traffic emissions (tyre and brake wear). The calculation of such emissions is difficult and in many cases it is not yet clear which compounds, what magnitude and under which conditions they move in the atmosphere (Friedrich and Reis, 2004). The exact estimation of the contribution of these sources is out of the limits of this work.

Yet, applying an air quality model helps to the understanding of the processes taking place and allows to prioritize lines of work. The aim of this contribution is to simulate PM_{10} for a given pollution episode which took place in the region of Bogota in 6 and 7 March 2002, and to evaluate the impact of some abatement strategies when applied for the same episode. For this purpose, a mesoscale air quality model capable of simulating both the gas and the aerosol phase as well as their interactions is used. Sections 5.2 and 5.3 present the description of the model and the way PM emissions are prepared respectively. The results of the simulations are described in section 5.4. Section 5.5 evaluates some feasible abatement strategies to reduce PM_{10}.

5.2 Model description

TAPOM (Transport and Air POllution Model, Martilli et al. (2003); Junier et al. (2005)), developed at LPAS, is a transport and photochemistry three dimensional Eulerian model. It uses a terrain following grid with finite volume discretization. It includes the RACM lumped species mechanism (Stockwell et al., 1997), the Gong and Cho (1993) chemical solver for the gaseous phase, the transport algorithm developed by Collela and Woodward (1984), and Clappier (1998), as well as the solar radiation module TUV developed by Madronich (1998) to calculate the photolysis rate constants.

The module simulating aerosols in TAPOM includes 10 chemical species (table 5.1) and deals with 4 size ranges: (i) 0 - 0.125 µm, (ii) 0.125 - 0.625 µm, (iii) 0.625 - 2.5 µm, and (iv) 2.5 - 10 µm. The model simulates heterogeneous dynamic processes such as “gas-to-particle conversion”. This process consists in the diffusion of vapor molecules of a given gas-phase substance over the surface of the particle, reaction and further incorporation to it. It is thus possible to calculate the change in the particle size if the rates of diffusion and reaction are known. The gas-phase chemical species that interact with aerosols in TAPOM are: HNO_3 (Nitric Acid), HCl (Chlorhydric Acid), VOCs (Volatile Organic Compounds) and NH_3 (Ammonia). In the presence of clouds or water vapor, SO_2 (Sulfur Dioxide) also interacts with aerosols. After each iteration of the numerical simulation, aerosols are reclassified in their corresponding size range according to the values described above.

Table 5.1: Chemical species of Aerosols simulated by TAPOM

Name in TAPOM	Chemical species
aSOD	Na^+
aHYD	H^+
aAMN	${NH_4}^+$
aNIT	${NO_3}^-$
aHCl	Cl^-
aSUL	${SO_4}^=$
aWAT	H_2O
aCAR	Elemental or black carbon
aORG	Organic carbon
aCRU	Crustal material

TAPOM deals with inorganic and organic aerosols in different ways. To treat the multiphase multicomponent thermodynamics and kinetics of inorganic aerosols, the ISORROPIA module (Nenens et al., 1998) has been incorporated to TAPOM. On the other hand, organic aerosols are produced from the gas-phase VOCs, but once created, they are treated as passive substances.

The grid of 55 km x 55 km with a resolution of 1-km in both x and y directions, described in chapter 3, is run with TAPOM. The obtention of the meteorological data used for the simulations is also presented in 3. Initial and boundary conditions are primarily set at the same values for each chemical species, and a pre-run of one day with the same emissions and wind fields is conducted, in order to provide more realistic initial conditions for the simulation. Data provided by the monitoring network (DAMA, 2006) is used to establish the initial and boundary conditions of total PM_{10}.

5.3 Preparation of the Emissions

Mobile and industrial sources in Bogota emit 4.5 and 8.1 ton day^{-1} of PM_{10} respectively (see chapter 2, with mobile sources including only car exhaust emissions. To the knowledge of the author, there is no information concerning the chemical speciation or the size distribution of such emissions. Missing data can thus be resumed in three main points: (i) contributions from other sources, (ii) size distribution of all the emissions, and (iii) chemical speciation for each source, each size range. To fulfill this information, a number of assumptions have to be made. Though geographical distribution of particle sources, sizes and speciation is highly non-uniform, the ground of such assumptions is based on a detailed analysis of data collected for other urban agglomerations around the world (Hien et al. (2001); Querol et al. (2001); Molina and Molina (2002); Samara et al. (2003); Salvador et al. (2004); Held et al. (2004); Mathis et al. (2005) and many others). They are summarized here:

- 25% of the total PM_{10} emissions correspond to both car exhaust and industrial emissions. 50% correspond to fugitive sources such as resuspension and construction, and 25% to other sources (windblown dust, fires, agriculture, aircrafts, etc.). This emission distribution is used for the size range 2.5 - 10.0 µm simulated by TAPOM.

- 45% of the total mass of PM_{10} emissions is attributed to particles with a size smaller that 2.5 µm. 50% of these particles are attributed to car exhaust and industrial emissions, 25% to fugitive sources and 25% to other sources. The same emission distribution is used for the smaller 3 size ranges simulated by TAPOM (0 - 0.125 µm, 0.125 - 0-625 µm and 0.625 - 2.5).

- Spatial and temporal distributions of car exhaust and industrial PM_{10} emissions are known (2). 80% of the daily fugitive sources are assumed to take place between 0600 and 2200LT, and 20% in the rest of the hours (evenly distributed each hour). On the other hand, 80% of the “other” sources (wind-blown dust, fires, agriculture, aircrafts, etc.) is equally distributed between 0600 and 1800LT, and 20% in the rest of the hours. Both fugitive and other sources are distributed homogeneously in the city.

- The chemical speciation used for the emissions is presented in tables 5.2 and 5.3. Their values are based on data presented by Harrison et al. (2004); Held et al. (2004).

Table 5.2: Chemical speciation of aerosols by source as used for the simulations over Bogota, for particle sizes between 2.5 and 10 µm, % of mass

Species	Traffic	Industries	Fugitive	Others
aSOD	8	0	0	0
aHYD	0	0	0	0
aAMN	1	10	2	3
aNIT	8	18	2	13
aHCl	8	5	2	2
aSUL	8	12	2	13
aWAT	4	5	2	5
aCAR	7	12	0	14
aORG	14	16	0	14
aCRU	42	22	90	36

5.4 PM_{10} numerical simulations and results

5.4.1 Comparison with measurements

Both simulated and measured concentrations of PM_{10} (fig. 5.1 and 5.2) show an important morning peak, with high values, and a smaller peak at night. The morning peak is related to high emissions from traffic circulation in the morning rush hour and a low mixing height, whereas the nightly peak is associated with the nightly rush hour. The intensities of the peaks are in good agreement with observations for stations like CADE, Merck, MMA, Nacional and Santo Tomás.

Table 5.3: Chemical speciation of aerosols by source as used for the simulations over Bogota, for particle sizes <2.5 µm, % of mass

Species	Traffic	Industries	Fugitive	Others
aSOD	0	0	0	1
aHYD	0	0	0	0
aAMN	4	20	10	7
aNIT	8	13	5	12
aHCl	1	1	15	1
aSUL	13	18	5	19
aWAT	6	7	10	10
aCAR	35	20	0	14
aORG	28	18	0	25
aCRU	7	3	55	11

The simulation underestimates values for stations like Cazucá, Corpas, Escuela and Fontibón, which might be due to an underestimation in localized emissions.

Observed PM$_{10}$ morning peaks are in general bigger for 6 March than for 7 March. Three aspects might explain that difference: emissions, dispersion (wind speed and turbulence) and/or chemistry. Since observed peak morning values for CO, NO$_x$ and wind speed do not indicate a particularly important difference between the two days, differences cannot be attributed to the dispersion effects. The difference can perhaps be attributed to a change in the chemical composition of emitted aerosols between the two days which in turn generates less secondary particles. Nevertheless, this cannot be proved at the moment.

5.4.2 Plume of PM$_{10}$ and secondary particles

The plume of PM$_{10}$ indicates its highest values at 0900LT (fig. 5.3(a)), in the center of the city. Since PM$_{10}$ is mainly a primary pollutant, concentrations decrease afterwards due to dispersion. When the slope winds develop thanks to the effect of the sun, the plume moves towards the northeast as the day passes by. At 1300LT (fig. 5.3(b)), a maximum is observed in the same region where the maximum of Ozone is presented (fig. 3.10). This value illustrates the production

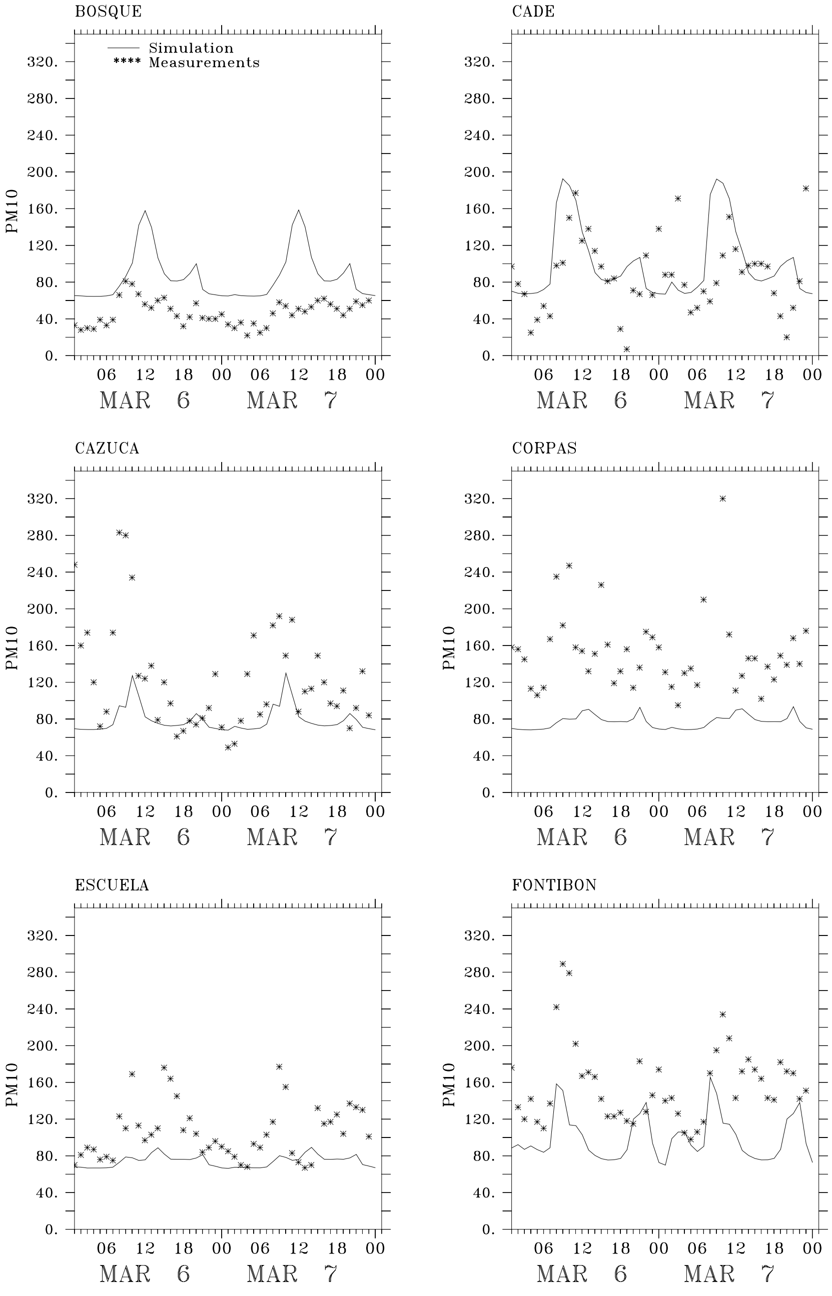

Figure 5.1: Simulated (solid line) and observed (stars) PM_{10} (µg m^{-3}, normal conditions) time series for different stations: Bosque, Cade, Cazucá, Corpas, Escuela and Fontibón. See chapter 3 for localization of the monitoring stations.

of secondary particles from emissions in the morning, that are transported with the wind. At 1600LT the production has decreased (fig. 5.3(c)) and particles are

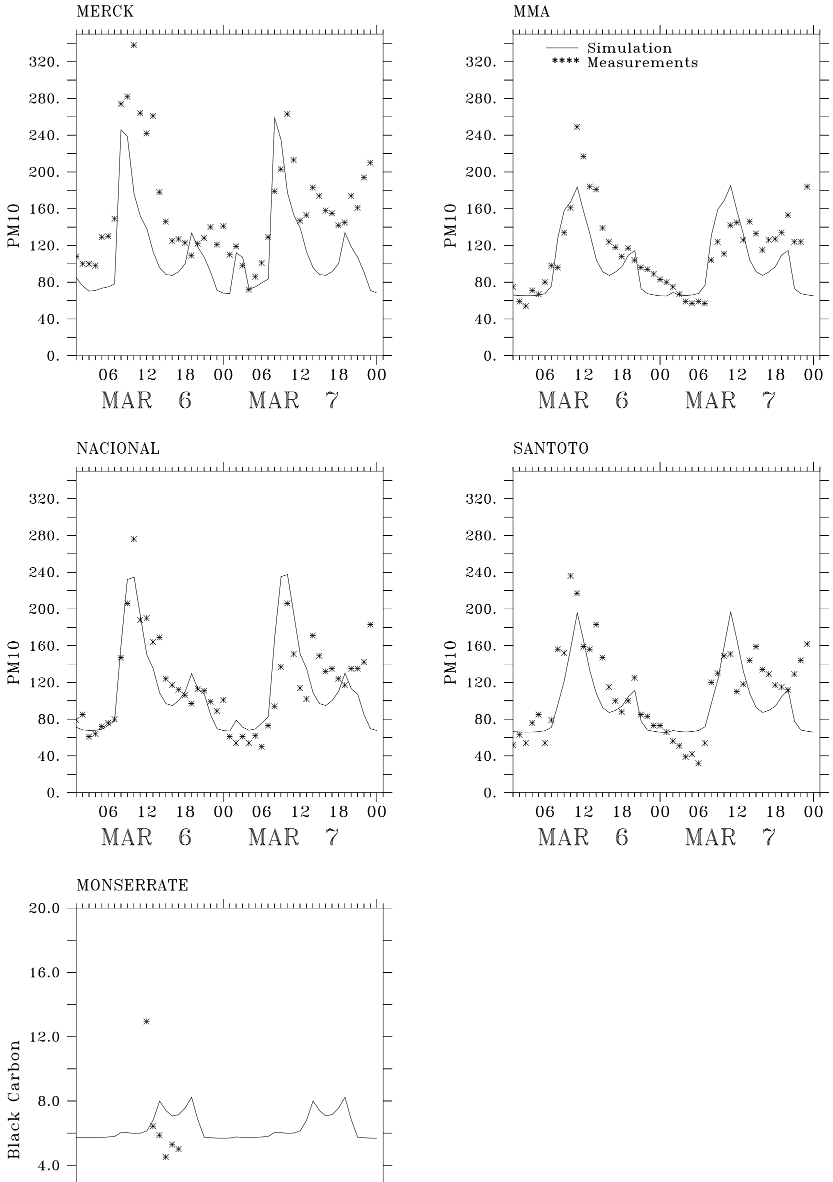

Figure 5.2: Simulated (solid line) and observed (stars) PM_{10} (µg m^{-3}, normal conditions) time series for different stations: Merck, MMA, Nacional and Santo Tomás. Monserrate station presents simulated (solid line) and measured (stars) values of elemental carbon at the conditions of Bogota. See chapter 3 for localization of the monitoring stations.

dispersed. A new peak appears in the center of the city at 1900LT, corresponding to the emissions from the nightly rush hour (fig. 5.3(d)).

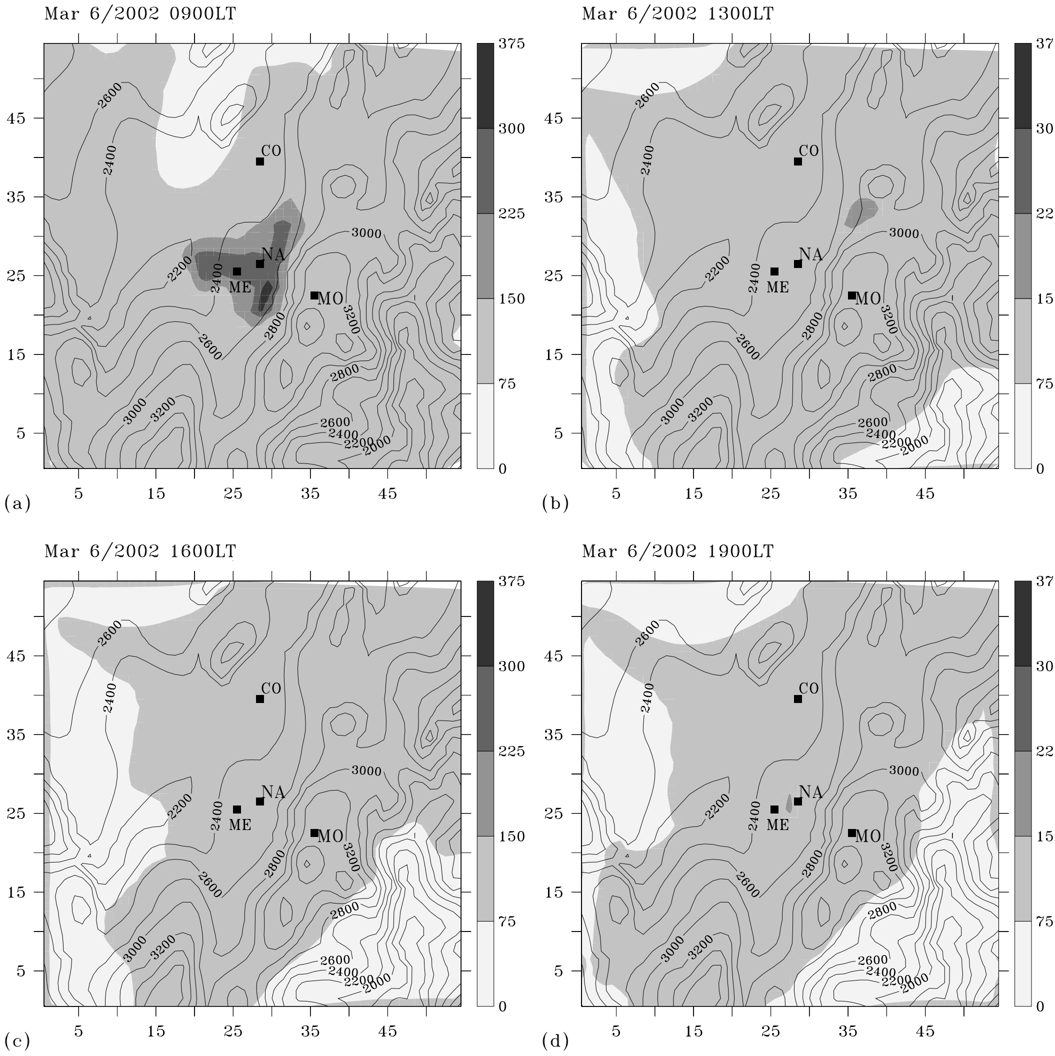

Figure 5.3: Map of PM_{10} concentrations simulated by TAPOM in the domain used for the air quality simulations (55km x 55 km). Some measuring stations are presented for reference: CO:Corpas, ME:Merck, NA:Nacional, MO:Monserrate. Values are presented in µg m^{-3} at normal conditions. (a) 0900LT, (b) 1300LT, (c) 1600LT, (d) 1900LT.

In order to better understand the production of secondary aerosols, a simulation in which emitted aerosols are treated as passive tracers is run (from now on this simulation is called "passive aerosol" case). In this simulation, the chemistry is switched off. The difference in concentrations between the base case (when both gas and aerosol chemistry are active) and the passive aerosol case is presented in fig. 5.4, for some of the chemical species that react with gas-phase species (Sulfate, Organic Carbon, Nitrate and Ammonium). This difference indicates thus the amount of secondary particles produced. aSUL, aORG and aNIT reflect mostly positive values (fig. 5.4(a), (b) and (c)), corroborating the formation of secondary aerosols produced from the chemical species in the gas-phase. Results confirm the fact that the reaction to produce aNIT is about 10 times faster than the one to produce aSUL (Seinfeld and Pandis, 1998). When the gas-phase chemistry is activated, values of aAMN are smaller than in the passive aerosol case (fig. 5.4(d)), due to the conversion of this aerosol to gaseous NH_3. As for aCRU and aCAR, the difference between the two cases is zero (not shown) since they are not a secondary product.

The plume of total secondary PM_{10} is represented in fig. 5.5 (the PM_{10} difference between the base case and the passive aerosol case). Negative values of this difference are observed in the center of the city, at 0900LT (5.5(a)). It indicates that aerosols sink in the gas-phase, reacting with the freshly emitted gaseous species. Aerosols, as the gaseous pollutants, are also pushed towards the southwest in the early morning. At 1100LT (fig. 5.5(b)), two plumes are formed over the city, one towards the northeast and the other one towards the southeast. The maximum value of secondary aerosols is reached at this time (about 80 $\mu g\ m^{-3}$). At 1600LT (fig. 5.5(c)), the plume has expanded towards the north and south, trapped in the converge front created by winds blowing from the east and the west (see chapter 3).

To observe the effects of aerosols over the gas-phase, a simulation in which only gaseous compounds are emitted is run (the aerosols are not activated). Gas-phase concentrations of this simulation are compared to gas-phase concentrations of the base case simulation (both gas-phase and aerosol chemistry are activated). A production of HCl and NH_3 in the gas-phase is observed when aerosols are activated in the simulation (base case, fig. 5.6(a) and (b)). aHCL and aAMN act as sources for these two gaseous compounds. The production of aNIT represents a sink of gaseous HNO_3, which is reflected in the decreased concentrations found for the base case when compared to those for the case when aerosols are not activated (fig. 5.6(c)).

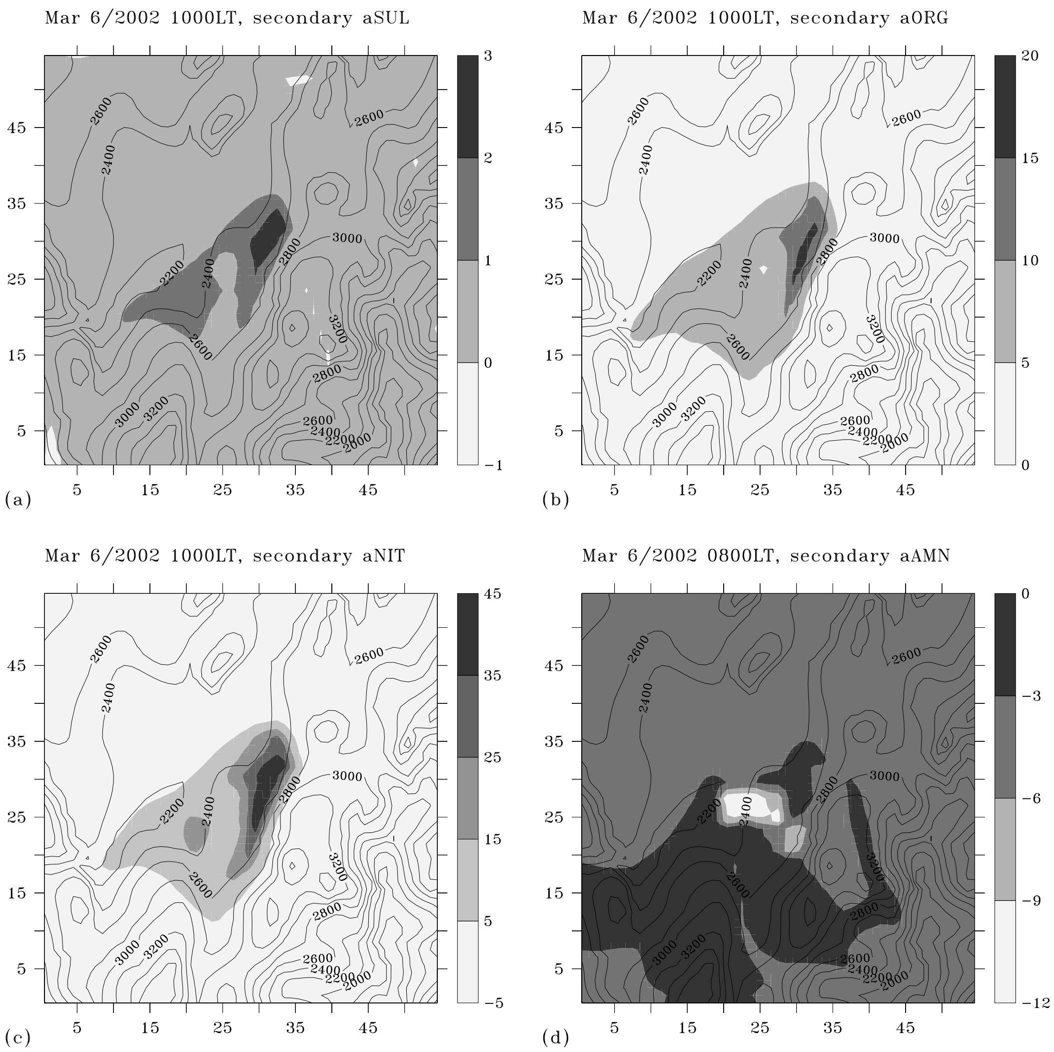

Figure 5.4: Simulation of the production of secondary aerosols (≤ 10 µm) by chemical species. The difference between simulated concentrations of the base case (both gas-phase and aerosol chemistry are active) and the “passive aerosols” case (the chemistry of the gas-phase is inactivated) is presented. Values are presented in µg m^{-3} at normal conditions, for the hours of maximum differences. (a) aSUL (Sulfate), (b) aORG (Organic Carbon), (c) aNIT (Nitrate), (d) aAMN (Ammonium).

5.5 Evaluation of Emission scenarios

The same abatement scenarios assessed in chapter 4 have been evaluated for particles. The first scenario concerns the partial restriction of the circulation between 0600LT and 1000LT of the heavy traffic fleet (> 5 ton) which does not comply with

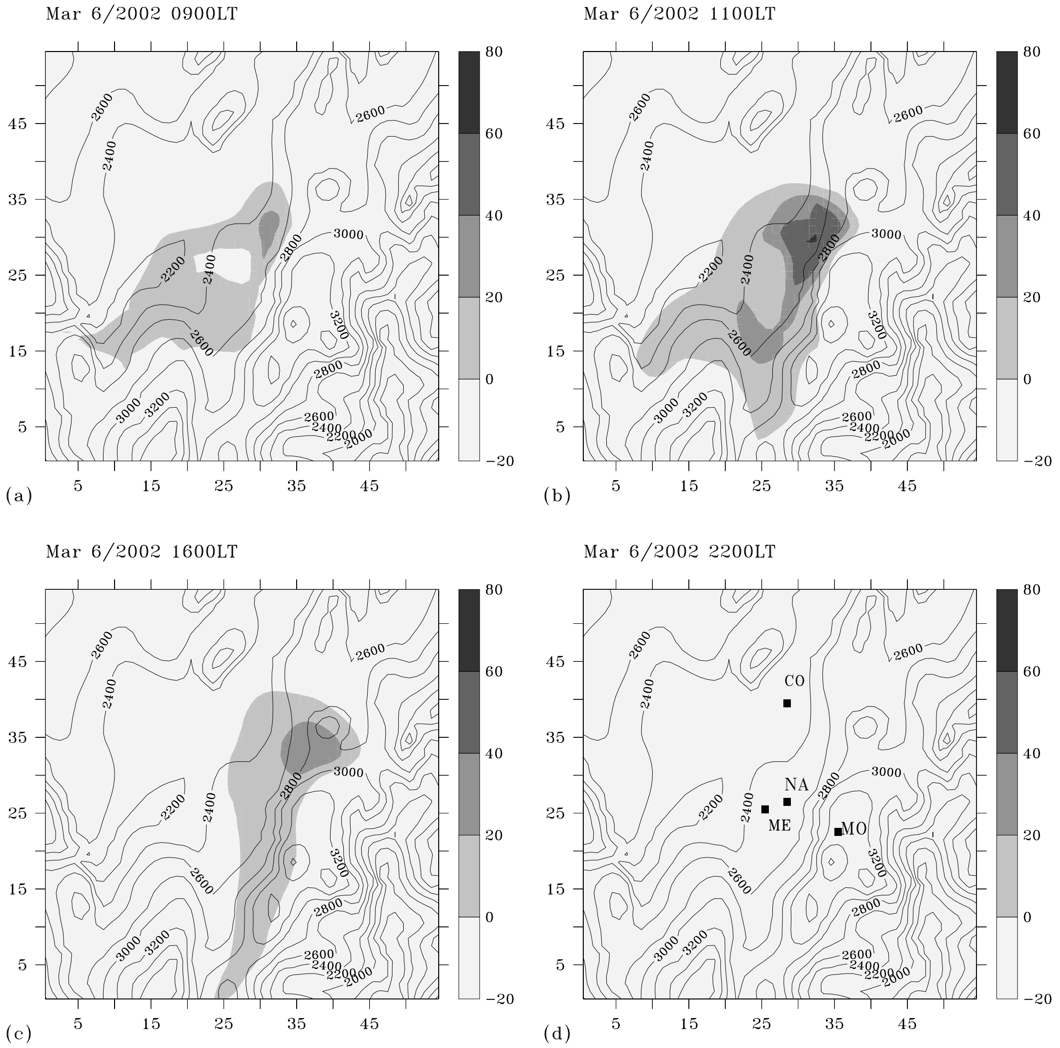

Figure 5.5: Simulation of the production of total secondary PM_{10}. The difference between simulated concentrations of the base case (both gas-phase and aerosol chemistry are active) and the "passive aerosols" case (the chemistry of the gas-phase is inactivated) is presented. Values are presented in $\mu g\ m^{-3}$ at normal conditions. (a) 0900LT, (b) 1100LT, (c) 1600LT, (d) 2200LT.

the city's regulation program (DAMA, 2006). It means that if a given vehicle does not have an approved regulation certificate, it is not allowed to run one day out of ten. This restriction is applied according to the last number of the plate. Thus, if no vehicle complies the regulation, 10% of the total heavy traffic is not running in the city. To simulate this scenario, we assume that 10% of the total amount of

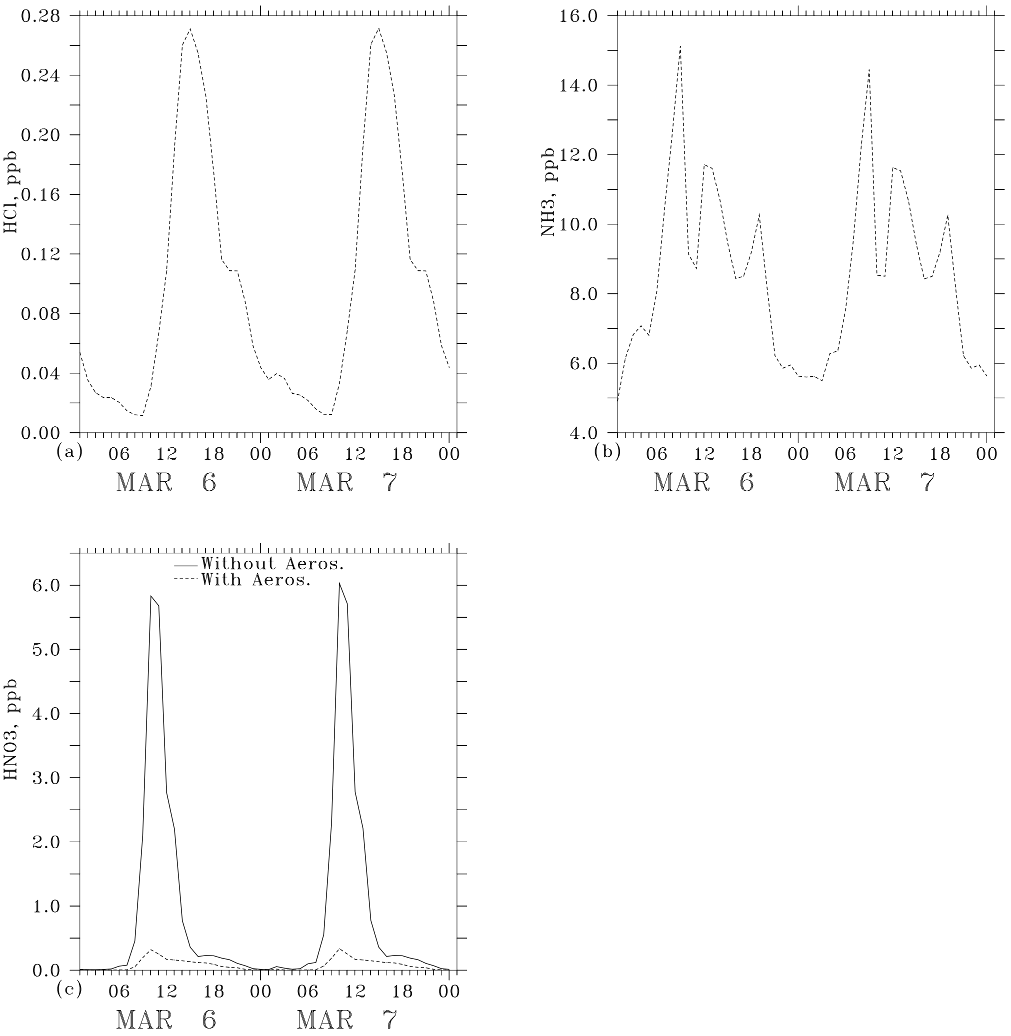

Figure 5.6: Simulated gas-phase concentrations of HCl, NH_3 and HNO_3 (ppb), using the heterogeneous-phase model TAPOM. (a) and (b) show values obtained for the base case simulation (heterogeneous chemistry activated). The production of HCL and NH_3 is zero when the aerosols are not included in the simulation. (c) Concentrations of HNO_3 for the simulation incorporating the heterogeneous chemistry (dashed line) and the simulation incorporating gas-phase chemistry only (solid line).

heavy vehicles is not circulating. From now on this scenario will be denoted as Sc-1.

The second scenario involves the complete elimination of 20% of the buses circulating in the city. This scenario stands for the fact that at the moment there is an oversupply of buses in Bogota, calculated in around 20%. One of the reasons for this oversupply is attributed to a relatively recent implementation of a new bus system in the city. We will refer to this scenario as Sc-2.

The third scenario (Sc-3) represents an attempt to evaluate the impact of a combined measure consisting in the renewal of the fleet of buses and the improvement of the diesel's quality (for details about the fleet in Bogota and its emission factors (EF), see chapter 2). It is expected that these two measures will take place within a few years in Bogota. To recalculate emissions for this scenario, CORINAIR EF (EEA, 1999) are assumed to be valid and thus applied. Nevertheless, such kind of scenarios should be more accurately simulated in the future using real-world EF.

Results of the simulation of these scenarios are presented for four of the main monitoring stations in the central part of Bogota (fig. 5.7). Sc-1 and Sc-2 do not have an important repercussion over the simulated concentrations of PM_{10}. A decrease in PM_{10} concentrations is perceived only for Sc-3. This implies that only a renewal in Bogota's fleet and a change in the fuel quality will truly contribute to the decrease of levels of particles in Bogota. Nevertheless, decreases shown by the model for Sc-1 and Sc-2 might be underestimated for two reasons: (i) we count on average emission factors for all the heavy traffic in Bogota, and vehicles put out of service or not complying the regulation might be those which contribute the most to emissions. Further research is needed in order to obtain more accurate and detailed real-world emission factors in the city. (ii) total traffic PM_{10} emissions might be underestimated in this work, giving too much weigh to other emissions as it is explained in section 5.3. This would not reflect adequately the effect of traffic PM_{10} reductions.

5.6 Conclusions and outlook

PM_{10} have been simulated for a pollution episode in Bogota using an heterogeneous-phase air quality model. A reliable assessment of urban PM pollution is crucial in terms of the promotion of public health, and modelling is a necessary step in understanding the effects of changes in emissions on ambient concentrations. Nevertheless, the modelling approach requires good measurements and most of all, a good and complete emission inventory. Results presented in this work should be

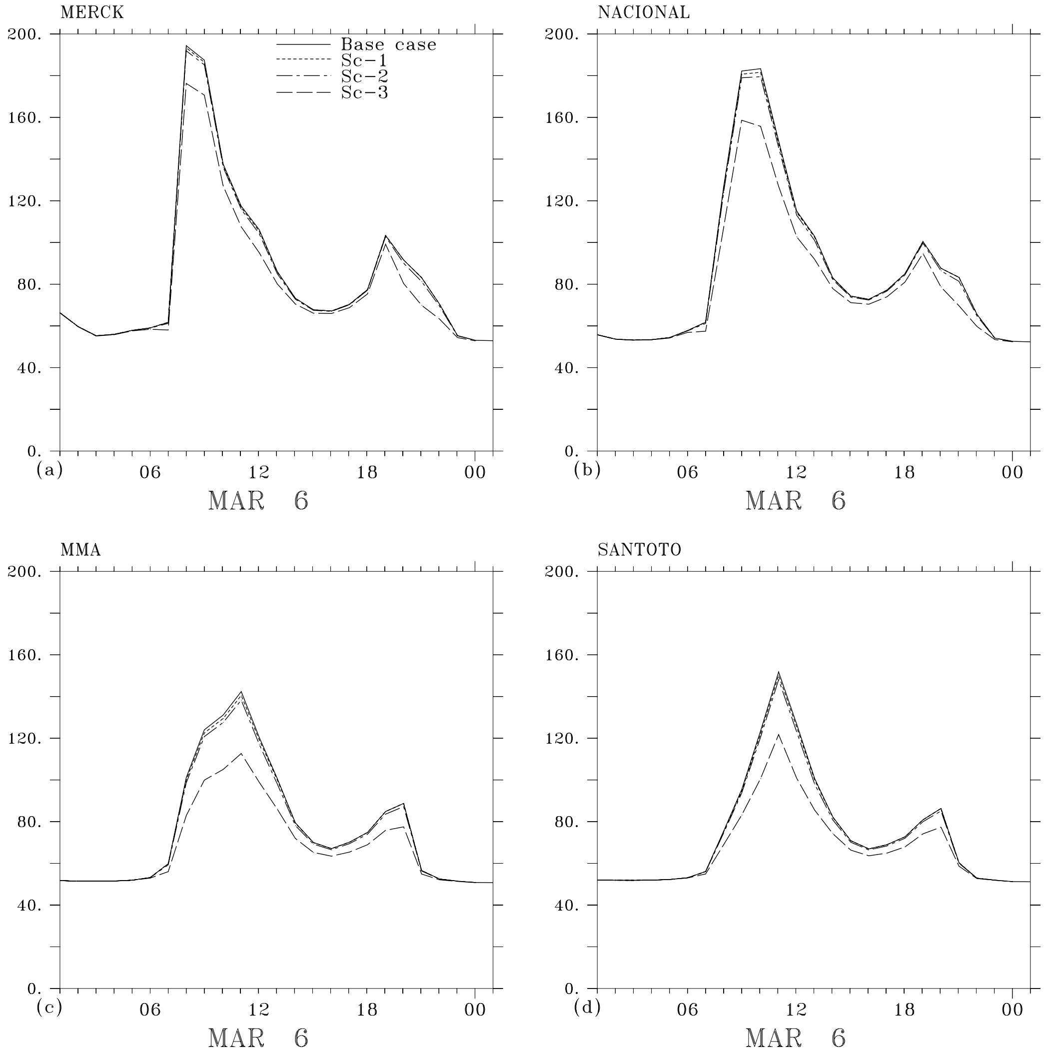

Figure 5.7: Comparison of simulated PM_{10} concentrations (µg m^{-3}) for the base case (solid line) and different emission scenarios: Sc-1 (dotted line), Sc-2 (dashed dotted line) and Sc-3 (dashed line), for different measuring stations, using the heterogeneous-phase model TAPOM.

regarded thus as a preliminary contribution in the simulation of aerosols in Bogota. Further research is needed in several fields such as the evaluation of the contribution of other sources apart from car-exhaust (traffic) and industries, the size distribution of PM_{10} by source, the chemical composition, and real-world detailed traffic emission factors.

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Chapter 6

Conclusions and Outlook.

This work was devoted to the investigation of the sources, dispersion patterns and chemical transformations of air pollutants in Bogota. For this purpose, an emission inventory (EI) was generated and meteorological and air quality tools were applied to the city. The analysis presented was based on the study of a particular air pollution episode which took place in the region on 6 and 7 March 2002. The results of the present thesis mark the starting point to a full understanding of the dynamics of the atmosphere on Bogota's plateau, and open a new possibility to manage air quality through a scientifically-based approach. The following items summarize the main conclusions and the answers to the questions for which this thesis was conceived. Future perspectives are many and they stand for the questions that have emerged throughout the development of the present work. They represent the ground to a very interesting and useful future field of research.

- The first part of this thesis treats the topic of emissions (chapter 2). Three main issues can be concluded for this part: (i) On-road traffic plays the most important role in terms of contributions of air pollutants to the atmosphere in the city, (ii) In the case of Bogota, a significant difference is found between real-world in-situ traffic emission factors (EFs) and those proposed by standard bottom-up methodologies. This difference is so important that calls for further research in order to better quantify the individual contribution per type of vehicle and for different travelling speeds. It is definitely worth to deepen in this aspect of the research, not only for the sake of the city of Bogota, but also for many cities which undergo similar pollution problems and do not count on sufficient data to fulfill the requirements of the standard

EI methodologies. The first step to act on air pollution mitigation consists in accurately quantifying the amounts of pollutants released to the atmosphere. (iii) Since evaluating uncertainties is an impractical task when there are not enough data, different options should be investigated in order to estimate the accuracy of EIs. In this work, air quality models are proposed as an alternative to evaluate the proximity of an EI to reality. This method demands extreme care in the analysis of the results because many factors are involved (for example meteorology), but it is an inexpensive and rapid way to obtain a first notion of the degree of approximation of the EI to reality. Hence, the method is not a one-time task. A continuous recalculation of the emissions by source and consecutive evaluation with the model is required. Furthermore, the simulation of several episodes or even long-time runs are strongly advised to obtain a comprehensive analysis.

- Aiming to generate a better EI, future versions of it should include other sources which have not been taken into account in the present work. Namely, in the case of on-road traffic, motorcycles and non-exhaust traffic emissions (tyre and brake wear). Some improvements are also needed for other sources: obtaining an adequate hourly repartition of industrial emissions and recalculation of biogenic emissions. For the later, three types of information are required: (i) type of vegetal species in the region, (ii) geographical distribution of them, and (iii), appropriate biogenic EFs. Future efforts should be made with the purpose of collecting these data.

- The second field of study in this thesis comprises the application of meteorological and air quality models over the region of Bogota (chapter 3). Results were validated with measurements taken during a specific pollution episode which took place in the region during March 2002. The use of the models allowed to obtain a broader vision of the air pollution problem in Bogota. Bogota's wind pattern is not only influenced by the configuration of the plateau and the surrounding mountains, but also by topographical accidents such as the Magdalena valley, the central Andean mountain range crossing the country, and the Eastern Plains. The models indicated that these features play a significant role on the atmospheric circulations perceived over the plateau. Under given circumstances such as the episode chosen for simulation, the morning pollution is flushed downwind towards the southwest of the city, to be transported again over it due to the development of a strong slope wind which penetrates the plateau from the Magdalena valley. Ozone, apart from being a critical pollutant, is a very good tracer of the plume of pollutants for this particular case, since it is photochemically produced along the day. Sharp peaks of this compound are observed in the center of the city at midday, indicating the transport of the plume from side to side of the city. Moreover, pollutants remain trapped not far from the city as a result of the convergence front created between the slope winds coming from the Magdalena valley and the Eastern Plains. Hence, pollutants return over the city during nighttime pushed by the descending nightly slope wind. Though the simulation of other episodes or long term simulations are recommended, the episode investigated along this study represents a common critical situation found during the first dry season of the year in Bogota.

- Concentrations of volatile organic compounds (VOCs) and their chemical speciation, in and outside the city, would increase the understanding of the photochemical processes taking place. What is more, knowledge about VOC levels in the city is crucial as a public health issue. This aspect is proposed as a future branch of research in order to acquire a comprehensive understanding of the problem.

- The third section of this dissertation encompasses the use of modelling tools to deepen in the analysis of the composition of Bogota's air pollution plume (chapter 4). Traffic emissions released between 0500LT (local time) and 0900LT contribute significantly to the high levels of pollution in the city which are observed mainly in the morning hours. Moreover, the Ozone peaks, whose maximum values appear at midday, can be mainly attributed to the summed contribution of VOCs from light traffic and NO_x from heavy traffic. In the morning the city is in the VOC-sensitive chemical regime (for the particular conditions of this study) implying that abatement strategies focused to mitigate NO_x will cause an increase in the levels of Ozone. Short-term feasible abatement strategies in Bogota concern the reductions of heavy traffic emissions. Three of them have been evaluated with the model and plausible reductions of primary pollutants concentrations and increases of Ozone levels are confirmed. Abatement strategies focused on heavy traffic produce an increase in the Ozone levels since they are the most important contributors of NO_x. The simulated reductions obtained for primary pollutants are probably underestimated due to the lack of more detailed real-world EFs, since old buses (contributing the most to emissions) are sensed to be restricted or put out of service. Supplementary simulations should be performed in the future aiming to evaluate abatement strategies targeting the light traffic. Additionally, abatement strategies should be examined under different meteorological conditions in order to formulate definitive conclusions.

- The forth contribution of this thesis covers the simulation of PM_{10} (chapter 5). The highest concentrations are obtained downtown in the morning hours. A maximal production of secondary aerosols is observed around 1100LT towards the northeastern part of the city. In order to perform the simulations, a number of assumptions had to be made due to lack of data. There is a major need to improve the EI of particles for the city: sources are missing, as well as size distribution and chemical speciation. Three scenarios addressed to the control of heavy traffic emissions were applied. Results indicate that only a change in both the fleet and the quality of the fuel used generate important repercussions over the levels of PM_{10} achieved in the city. Nevertheless, this result is only partial until improving the emission inventory input to the model. A more precise quantification of PM_{10} emissions is proposed as an essential branch of research in Bogota.

- The air quality model indicates that abatement strategies directed to mitigate air pollution might have contradictory effects depending on the pollutant to be tackled. The emission scenario which attains the most important reductions in PM_{10}, generates the largest increase in the levels of O_3 in the city. At this point, the utility of air quality modelling arises. It is a very useful tool to decompose the problem and prioritize actions of pollution mitigation. I really hope that the product of this work, *the modelling tool*, serves as instrument to the environmental authorities to facilitate the design of abatement strategies of air pollution. I really hope that this, in turn, will bring a better quality of life to the citizens of Bogota.

Chapter 7

Epilogue.

In this part of the thesis I would like to place the discussion from a different point of view. I use the parallel made between *allopathic medicine* and *preventive medicine.* The Compact Oxford English Dictionary defines *allopathic medicine* as "the treatment of disease by conventional means, i.e. with drugs having effects opposite to the symptoms". *Preventive medicine*, or preventive care, is defined as a set of measures taken in advance of symptoms to prevent illness or injury. This thesis has been conducted from the point of view of *allopathic medicine*, applied to the environment. In other words, I used a scientific approach to understand the origins of the symptoms and afterwards I formulated recommendations to treat and if possible vanish them.

The *preventive care* approach forces us to seriously consider the reasons to develop such symptoms. In medicine, symptoms show a body imbalance. In the case of air pollution, the imbalance can be attributed to two factors: excessive human concentration in a relatively small area and a disproportional energy consumption carried out by this human mass. In the present, the equation is simple: energy consumption implies fuel burning and thus emissions of pollutants.

Controlling excessive human concentration is a very difficult problem, especially for a city like Bogota. Many political, social and economical issues take part, hence it is far too complicated to think of changing such situation. On the other hand, energy consumption, fuel burning and emissions are linked to many aspects. They are linked to the technological state of the art. To give just an example, the vehicle technology has evolved during the last few years to decrease the emissions of particles through the use of filters.

Nevertheless, energy consumption is linked to our habits to a large extent. We grew up in societies whose paradigm is the search for comfort, which is only normal if we think in terms of a species who wants not only to preserve itself but also to keep the best possible quality of life. We develop habits in order to maintain such comfort. One can plead that with the forthcoming scientific improvements, it is possible to keep a high level of comfort without really increasing energy consumption and emissions of pollutants. In the example of vehicles, an icon of comfort, one can argue that future scientific developments will allow a positioning in the market of vehicles which use other types of fuels or energy supplies, less harmful to the environment. I do not know until what extent it is true and how long it will take, only time will tell.

In view of that, it is our responsibility to reflect on our habits as they are, to consider their consequences for us and for future generations. What is more, to make a step behind and ask ourselves why we have such habits. Do we really have them because they imply comfort? Perhaps we have them because everybody does, and we have not taken the time to think about it. Perhaps we have a car because we have learnt that it is a matter of good social status to have one. Often, it is the award of several years of study and work. If we live in a society in which it is not necessarily well seen to use a car, would we use it? - We can plead that we are obliged to have a vehicle because public means of transportation are of bad quality, using them takes time, and time *is* money. It might be true, but, are we really willing to create a critical mass and to exert pressure in order to improve the public transport situation?

The issues of energy consumption and pollutant emissions are not only limited to vehicles. We can widen our reflection in many aspects. We can re-consider our habits and bear in mind that small changes might bring significant impacts on the environment. One additional example of an usual situation in Colombia: plastic grocery bags are commonly used to transport home our purchase. They are used normally once and thrown away afterwards. Most plastic bags are made from polyethylene, and not only they take about a 1 000 years to decompose, but they are made from crude oil and natural gas, nonrenewable resources.[1] Perhaps we can keep the bags and use them a second time in the supermarket, or simply minimize the amount we consume. This is a simple example between many to illustrate that we can implement elementary actions that would have an impact without seriously affecting our comfort.

To sum up, we can ask governments to do something about air pollution. It is our right and it is their duty to make short and long term decisions which stand for our common welfare. But we can also contribute if we take the time to think about our habits and how we can influence the situation. We can implement an EcoLife with small changes in our habits without detriment to our comfort. This might be a powerful way to apply *preventive medicine* to our environment.

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[1] When one ton of plastic bags is reused or recycled, the energy equivalent of 11 barrels of oil are saved. In New York City alone, one less grocery bag per person per year would reduce waste by two million kilograms and save US$ 250 000 in disposal costs. U.S. Environmental Protection Agency (EPA, 2007). http://www.epa.gov/region1/communities/shopbags.html.

Chapter 8

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Since these years have offered me very challenging experiences, I have many people to thank. I express my deep esteem for all those mentioned below.

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To all the natural forces looking after....

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2000	7th International conference on wetland systems for water pollution control. University of Florida. Lake Buena Vista, Florida, U.S.A.

Publications

Giraldo, E., Zarate, E., 2001. Development of a conceptual model for vertical flow wetland metabolism. Water Science & Technology 44, 273-280.

Zarate, E., Giraldo, E., 2001. Removal of Hydrogen sulphide BOD from brackish water using vertical flow wetlands in a coastal caribbean environment. Water Science & Technology 44, 361-367.

They lived by principles of nature, as part of nature. They paid great respect to Mother Earth and related to the wild animals around them. They worshipped the natural forces and the seasons. Most of all, they understood the forces of nature and tried to gain knowledge about the secrets the universe holds.

It was a people that believed in a balance between the elements, a harmony between the gods and the goddesses, male and female, light and dark, positive and negative. They did not separate the day from the night or the spirit from the body. Nature is an endless cycle and we need all the elements that are around us, and also within us.

Andrea Haugen, Hagalaz Runedance, 1996.