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Comprehensive air quality planning for the Barcelona Metropolitan Area through traffic management

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ABSTRACT

This work analyses the projected improvements in urban air quality for 2015 in the coastal city of Barcelona (north–eastern Iberian Peninsula). To do so, the WRF–ARW/HERMES/CMAQ modelling system is applied at very high resolution (1 km x 1 km and 1 hour). The analysis is done by projecting the emissions of a base–case scenario defined for 2004 to three different future scenarios for 2015, each one representing a different set of traffic mobility management measures. Such measures integrate re–distribution of the current urban road network into "super–square blocks" as well as redirecting the traffic. The study is made more consistent by considering specific projections per sector of emission, mainly focusing on the vehicular fleet (introduction of technological improvements and the use of alternative fuels). The results of comparing the base–case versus the future scenarios indicate that the mobility management measures, technological improvements, use of alternative fuels and projection of emissions from different sectors will help to reduce the mean concentrations of atmospheric pollutants in downtown Barcelona, and also in the outskirts and in the metropolitan area.

Keywords:
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1. Introduction

The impact of air pollution is a key subject in the climate and environment field (Akimoto, 2003; Baldasano et al., 2003). According to the European Environment Agency (EEA, 2005), air pollution is the environmental factor with the greatest impact on health in Europe. Epidemiological studies associate increases of air pollution with higher rates of mortality and morbidity (Pope et al., 2002; Hurley et al., 2005, WHO, 2006).

Nowadays, poor air quality in cities is often caused by vehicular emissions (Crabbe et al., 1999; Colvile et al., 2001; Ghose et al., 2004; Guo et al., 2007). Forced traffic reductions, such as the military conflict in the city of Haifa (Israel) during the summer of 2006 (Yuval et al., 2008) or during the 2008 Olympic Games in Beijing (China) show reductions in measured air pollution levels (Wang and Xie, 2009). Hence, the public administrations are currently testing management strategies to reduce on–road traffic emissions. The two main strategies are: (1) reducing the number of vehicles, (2) mitigating emissions per vehicle either by changing the traffic speed patterns (Baldasano et al., 2010) or by using alternative fuels in new–technology vehicles, e.g. hybrids, fuel cells, natural gas, bio fuels, etc. (Wang et al., 2008; Moriarty and Honnery, 2008a; Moriarty and Honnery, 2008b; Stephens–Romero, et al., 2009; Goncalves et al., 2009a).

The local administration of the Spanish region of Catalonia, following the European regulations (EC, 2008), has defined several zones of air quality related to its topography, climatology, population density and emissions from industrial or transport sources. One of these zones is the Barcelona Metropolitan Area, which includes the city of Barcelona, one of the largest coastal European conurbations and representative of a Mediterranean city. This area presents several problems in air quality mainly related to PM_{10} and NO_2. During 2008, seven air quality stations exceeded the annual limit of PM_{10} (40 µg/m^3), the maximum level being 62 µg/m^3. The particulate matter characterization shows that the on–road transport is the principal cause of exceeding the thresholds set by the regulations (Generalitat de Catalunya, 2009). With respect to NO_2 levels, six out of the fourteen stations which do not meet the threshold were traffic–urban stations (annual limit value plus the tolerance in 2008: 44 µg/m^3). The maximum level was measured in the Barcelona–Eixample station (65 µg/m^3), an urban traffic station located in downtown Barcelona.

In order to reduce the aforementioned levels, several management strategies of traffic mobility are planned to be implemented in the city of Barcelona by 2015. This work studies the impact of such strategies on air quality, analysing three different future scenarios: (1) business as usual scenario, which represents what would happen if no measure were adopted; (2) super–blocks scenario, where the road network is redistributed; and (3) super–blocks reversal scenario, which adds to the previous scenario some reversal of directions. The super–blocks are a mobility management measures that consists of transforming inner streets with light traffic intensity into pedestrianised areas, in order to achieve better traffic flow on the streets which delimit the super–block (Rueda, 2008). Such future scenarios have been compared to a base–case scenario for 2004. The pollutants considered are gas–phase (O_3, NO_2, SO_2, CO) and particulate matter (PM_{10}).

2. Methodology

In this section we describe the methodology applied in the air quality study of Barcelona for 2015. First, we present the air quality modelling system used on this study, which integrates: (1) a meteorological model (WRF–ARW), (2) an emission model (HERMES), and (3) the air quality model (CMAQ). Second, we detail the implementation of the future scenarios in the HERMES emission model. Finally, we characterize the days of study by their meteorological conditions.

2.1. Modelling system

The WRF–ARW/HERMES/CMAQ modelling system is a three–dimensional, Eulerian simulation system representing state–of–the–art air quality modelling. The detection of subtle air quality variations in urban areas and the description of the dynamics of pollutants on an hourly basis in very complex terrains, like the study case presented, demands the use of very high resolution models (Jimeenez et al., 2005; Jimenez et al., 2006a). Four nested domains were defined for the simulations (Figure 1a). The final domain (Figure 1b) covers the entire north–eastern Iberian Peninsula (271 km x 232 km) and is centred in the city of Barcelona. The spatial resolution of this domain is 1 km x 1 km and the temporal resolution is 1 hour. This resolution permits to assess the effects of future scenarios in the Barcelona Metropolitan Area (BMA) (Figure 1c) and the area inside the Barcelona Ring Roads (BRR) (11 km x 10 km), as well as to detect the urban plume behaviour in downwind areas. The availability of the MareNostrum supercomputer hosted by the Barcelona Supercomputing Center–Centro Nacional de Supercomputacion (BSC–CNS), together with advances in the parallelization of air quality model codes, makes it possible to run high–resolution simulations and to consider a large number of scenarios.

The Weather Research and Forecasting model (WRF) (Michalakes et al., 2005; Skamarock et al., 2005) provides the meteorological parameters as input to the Model–3 Community Multiscale Air Quality model (CMAQ) (Byun and Schere, 2006). The specific parameterizations of CMAQ and WRF–ARW are summarized in Table 1.

The High Elective Resolution Emission Modelling System (HERMES) provides the emissions to the air quality model. HERMES has been developed specifically for Spain with a high spatial (1 km x 1 km) and temporal (1 h) resolution (Baldasano et al., 2008). This model focuses on the estimation of gas and particulate matter pollutants, including the ozone precursors. HERMES in its current version refers to the year 2004 as the database reference period and considers emissions from: (1) power generation plants, (2) industrial activities, (3) domestic–commercial and solvents use, (4) on–road transports, (5) ports, (6) airports and (7) biogenic emissions.

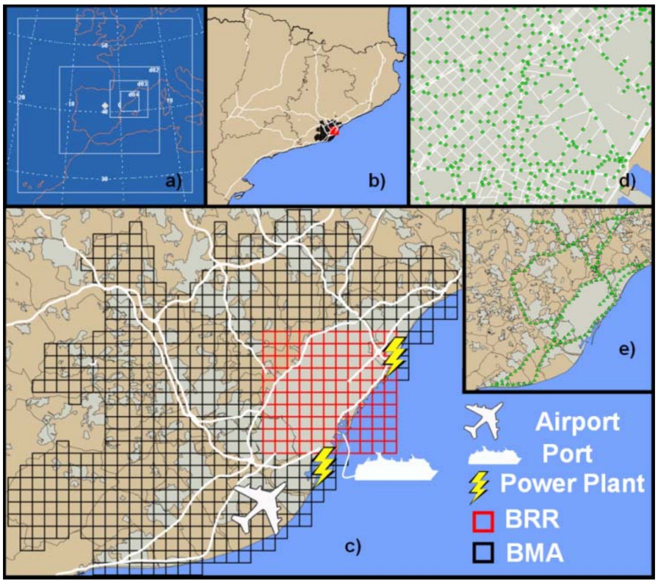

Figure 1. ***(a)*** *Four nested domains used in the simulations (the final domain centred in Barcelona covers 271 km x 232 km);* ***(b)*** *Detail of the final domain; Barcelona Metropolitan Area (BMA, black) which integrates the area inside the Barcelona Ring Roads (BRR, red);* ***(c)*** *BMA and BRR and the principal sources of emissions;* ***(d)*** *Detail of the traffic observation points for the city of Barcelona (area between the streets: Ramblas-Paralel-Gran Via); and* ***(e)*** *Points with hourly traffic information available for the access roads to the city of Barcelona.*

For this study, an important module within HERMES is that which estimates the on–road traffic emissions. This module uses mainly a bottom–up approach and takes into account 72 diesel and petrol vehicle categories (including Euro II and Euro III emission standards) according to COPERT III – EEA–EMEP/CORINAIR methodology (Ntziachristos and Samaras, 2000; EEA, 2006). These categories are divided by fuel type, vehicle weight, age of vehicle and cubic engine capacity, each of them having their specific emission factors, defined as function of traffic speed. The HERMES traffic emissions module includes hot exhaust, cold exhaust and evaporative emissions. It also estimates particulate matter produced by brakes abrasion, tire wear and pavement erosion.

The vehicular fleet of the HERMES traffic emissions module is defined specifically for Barcelona using data provided by the national traffic management organisation of Spain for 2004

Table 1. *Specific parameterizations used in the modelling system for CMAQ and for WRF-ARW*

Model	**Meteorology**	**Chemistry**
Model Version	**WRF-ARW v2.2.1**	**CMAQ v4.5**
Domains (Nx,Ny,Nz,Hor. Res.)	D1: 100, 103, 33, 27x27 km	-
(Met. Dom. contains 33 sigma vertical layers	D2: 114, 102, 33, 9x9 km	-
cover the troposphere (up to 50 hPa) with 12	D3: 171, 192, 33, 3x3 km	-
under the PBL.	Final D.: 273, 234, 33, 1x1 km	Final D: 271, 232, 32, 1x1km
Initial and boundary conditions	NCEP/FNL 1ºx1º	BC: Iberian Peninsula simulation (Baldasano et al., 2011) IC: 48-h Spin-up
Parameterizations	Boundary l.:YSU Microphisics: WSM3 Cumulus Scheme: Kain-Fritsch Land Surf. Mod. : Noah Long Wave: RRTM Short Wave: Dudhia	Chemical Model: cb4 Aerosol Model: AERO3 Adv: Yamartino mass-conserving Dif: Eddy diffusivity theory Aerosol d. v.: aero-depv2 Dry d. r.: Models-3

(DGT, 2008), and distributed in the 72 aforementioned categories. The model includes a definition of the road network, dividing it in stretches (inside the 1 km x 1 km cells) with specific temporal disaggregating profiles (distinguishing between month and day–type: weekday–holiday), specific average speed, daily average traffic (number of vehicles per day), stretch length and route type (highway, road or urban street). Concerning urban streets, the information available covers the total road network of Barcelona and identifies five distinct areas. These areas are differentiated by the prevalence of specific vehicles (mopeds, private cars, taxis, buses and heavy duty vehicles); this data is detailed in Goncalves et al. (2009a). The road transport emissions are based on the daily average traffic (DAT) measured at over 2 700 observation points throughout Barcelona city and the traffic speed of each stretch, generating an attributed digital vector map for all the highways, freeways, main roads (DAT > 200) and urban streets (Figure 1d). The original vector database information has been provided by Tele Atlas MultinetTM.

In order to improve on–road traffic emissions an hourly–variable speed of traffic has been established according to the methodology of Goncalves et al. (2008) for the main access roads to the city of Barcelona (Figure 1e), instead of using a specific constant speed for each stretch. This variable speed is applied for the base case and future scenarios. Also, the new regulation of limiting traffic speed to 80 km/h has been implemented for the access roads to Barcelona (Baldasano et al., 2010).

2.2. Implementation of future scenarios in the HERMES emission model

To compare the air quality between 2004 and 2015, we defined in HERMES one emission base–case scenario (BC) for 2004 and three future emission scenarios for 2015 (Table 2). Each of these future scenarios represents a projection of the emissions from 2004 to 2015 applying a different set of traffic mobility management measures on BRR:

(1) Business as usual scenario (BAU), which represents what would happen if no measure was adopted, taking into account the tendency of the last years, i.e. 37% more journeys with respect to BC. The number of journeys can be defined as the total trips per day in the BRR taking into account: i) intern connections, ii) connections between BRR and other areas and iii) connections between two points outside BRR that cross such area.

(2) Super–blocks scenario (SB), which considers the redistribution of the road network in super–blocks reducing the number of journeys by 32% with respect to BC (and 50% with respect to BAU).

(3) Super–blocks reversal scenario (SBR), which considers the super–blocks jointly with the introduction of some strategic reversal of directions, 24% reduction in the number of journeys with respect to BC (and 44% with respect to BAU).

In order to make a more accurate and consistent model projections based on 2004 emissions, we also need to consider specific projections per sector for the final domain. Each projected city developments was defined for the emission sectors in HERMES according to the population forecast described in IDESCAT (2008), Energy Plan for Catalonia (Generalitat de Catalunya, 2006) and others (Table 3). For the particular case of on–road traffic emissions, and to better estimate the vehicular fleet for 2015, we took into account not only technological changes (such as improvements of the existing engines, introduction of hybrid vehicles, etc.) but also the use of alternative fuels (increase in the use of natural gas and biofuels, etc.).

2.3. Selection and description of the studied episodes

In order to study air quality effects of the future scenarios of study are defined in Section 2.2, two typical days were selected (February, 11th – wintertime conditions; June, 18th 2004 – summertime conditions). The two target days are selected to cover typical winter and summer stagnant meteorological conditions, which are often associated with local–to–regional episodes of air pollution (Millan et al., 2002; Perez et al., 2004) and usually related to exceedances of air quality thresholds in the BMA (Jimeenez–Guerrero et al., 2008; Goncalves et al., 2009b). The days are selected based on two criteria: (1) days characterized by poor air quality according to the air quality data monitored in the studied area and (2) working days where the traffic follows a typical working day pattern. The February, 11th and June, 18th 2004 episodes are characterized by stagnant conditions with recirculation of air masses at the local scale. It is common to observe several–days of air mass recirculation in south–western Europe. According to Jorba et al. (2004), these conditions dominate 45% of the annual atmospheric transport patterns over the north–eastern Iberian Peninsula. The typical winter pattern is associated with a large accumulation of primary pollutants (e.g., NO_x and PM_{10}); whereas a typical summer pattern is characterized by an enhanced photochemical production of pollutants (e.g., O_3).

The winter's day meteorology (February, 11th 2004) is defined by stagnant conditions over the Iberian Peninsula. High surface pressures are observed over Portugal and Spain, associated with an anticyclone located over south–western United Kingdom. Under such conditions, air masses accumulate over the region for several days, causing an increase of the pollutant concentrations. The wind speed at surface levels is moderate to weak, leading to calm conditions that can last for several days. On the other hand, the summer day (June, 18th 2004) is characterized by a weak synoptic forcing. A low pressure gradient over the domain is observed with light north–westerly synoptic flows aloft. The intense summer heating promotes the development of mesoscale phenomena such as up– and downslope winds, as well as sea and land breezes in mountainous and coastal areas, respectively. Under these meteorological conditions, the accumulation and chemical formation of pollutants is usually observed leading to an increase on pollutant concentrations at surface levels (Baldasano et al., 1994).

Table 2. *Scenarios defined for the year 2015 together with the base case applied inside the ring roads in the city of Barcelona (BRR)*

Scenario	Acronym	Description	Journeys per day	Δ vehicles respect to Base Case	Avg. speed (km/h)	Year
Base Case	BC	Situation in 2004	2 720 936	-	19.5	2004
Business as usual, road network on 2015	BAU	Represents what would happen if no measure were adopted, taking into account the tendency of the last years	3 719 741	+37%	10.8	2015
Road network with super-blocks in year 2015	SB	Application of super-blocks in year 2015	1 859 871	-32%	18.4	2015
Road network with super-blocks and reversal of direction 2015	SBR	Application of super-blocks and reversal of direction in year 2015	2 066 579	-24%	20.2	2015

Table 3. *Criteria taken into account for the projection of the different sectors for the year 2015, including modifications in the vehicular fleet for the year 2015*

Sector	Projection criteria	
Power generation	The perspective in the evolution of power generation has been implemented according to the Energy Plan for Catalonia (2015) bearing in mind the planned opening of new combined-cycle power plants and the closure of some of the existing plants (Generalitat de Catalunya, 2006).	
Industry	The industrial sector does not plan substantial changes and therefore it is kept constant in the different scenarios.	
Domestic-Commercial Solvents	These two sectors are directly related with demography, so their projection is proportional to the evolution of the population for 2015 (IDESCAT, 2008)	
On-road traffic	• Introduction of the new regulation of speed limitation to 80 km h^{-1} (December 2007) in the accesses to the city of Barcelona (Goncalves et al., 2008; Baldasano et al., 2010). • Consideration of the points of traffic density with hourly speed data for the base-case scenario and future scenarios. • Re-distribution of the zones defined for the distribution of the vehicular fleet, taking into account that the industrial outskirts develops into urban mobility. • Upgrade of the vehicular fleet (DGT, 2008) to the horizon of 2015 considering technological improvements (engines, hybrid vehicles, etc.) and new fuels (natural gas, biofuels):	
	General vehicles	Gradual introduction of new European emission standards Euro 4, Euro 5 and Euro 6 standard in the temporal scenarios for 2015.
	Mopeds and motorbikes	Renewal of 10% per year in the number of mopeds and motorbikes, taking into account the data from the composition of the vehicle fleet (DGT, 2008).
	Natural gas	Increase in the use of this fuel (5% for 2015), based on EU documents (COM-2001-547).
	Biodiesel	For biofuels, its use has been estimated as 7% for 2015, as biodiesel (B20).
	Hybrids	Hybrids are considered as 10% of the new private cars in the period 2010-2015.
	Private cars/ commercial vehicles	Renewal of 9% per year in the number of heavy duty vehicles and private cars, taking into account the data from the composition of the vehicle fleet (DGT, 2008).
	Taxis	Constant number, a proportional distribution is established for the different fuels (gasoil, natural gas, hybrids and biodiesel).
	Buses, public transportation	Renewal of 8% per year (DGT, 2008).
Biogenic	No changes have been implemented in biogenic emissions with respect to the base-case scenario.	
Airports Ports	The growth in their activity is a function of the projection made by the Relevant Authorities (AENA, 2008; Barcelona Port Authority).	

3. Results and Discussion

In this section we present the results of the emission model and the air quality model. For each of these two models the current situation (BC) is analysed, followed by an evaluation of the changes introduced by the three future scenarios.

3.1. Emission model results

Base–case scenario emissions. This study shows that on–road traffic emissions are the major pollutant source in the final domain (Figure 1b), representing 52% of the total NO_x emitted, followed by industry and power generation sectors (28% and 10%, respectively). Concerning PM_{10} emissions, industry is the highest source (58%) followed by on–road traffic (25%). Power generation is the third PM_{10} contributor, representing 12% of the total emissions.

As the domains become smaller, thus closer to Barcelona city (BMA and BRR, Figure 1c), the percentage of on–road traffic emissions becomes higher. In the BMA, the total emissions are estimated as 85.15 t NO_x/day for the BC scenario in the summer episode (June, 18^{th}) (Table 4), from which 46.38 t NO_x/day corresponds to on–road traffic emissions, representing 54.5%. Concerning BRR, on–road traffic emissions are more significant, 72.8% of the total emissions (17.02 of 23.38 t NO_x/day).

Future emission scenarios. To estimate future emissions for the final domain of study, the HERMES model was run for each projected city development as described in Table 3. Concerning on–road traffic emissions, the projection of the vehicular fleet (introduction of technological improvements and the use of alternative fuels) leads to a reduction of traffic emissions. Inside the BRR, besides the specific projections of the emission model, the mobility management measures produce significant reduction of emissions in the area as shown below.

Inside the BRR, NO_x on–road traffic emissions in the BC scenario are estimated as 17.02 t/day for the summer day (June, 18^{th}). These emissions are reduced to 11.09 t/day (34.8%) in the BAU scenario, due to the projection of the vehicular fleet and despite the increase in the number of journeys. In the 2015 scenarios, the modification of the mobility into super–blocks (SB and SBR) and the introduction of a reversal of direction in some areas (SBR), along with the reduction of journeys, lead to a key reduction of emissions. For SB the emissions of NO_x show a decrease of 73% (4.60 t/day), whereas for SBR it is 3.64 t/day (78.0% lower). Hence, comparing SB and SBR scenarios, the introduction of a reversal of direction increases the mobility and compensates the effect of the reduction in the number of journeys.

The projection of traffic emissions leads to a total emission reduction despite the fact that other emission sectors have grown according to its specific projection. The total emissions in the BC scenario (23.38 t/day) are slightly lower in the scenario BAU (22.37 t/day, decrease of 4.3%). For the SB and SBR scenarios, the emissions are reduced to 15.88 t/day (32.1%) and 15.03 t/day (35.7%), respectively.

Table 4. *NO_x estimated emissions by sector for the summer day and total amount for the other pollutants*

			Barcelona Ring Roads				Barcelona Metropolitan Area			
			BC	**BAU**	**S.B.**	**SBR**	**BC**	**BAU**	**S.B.**	**SBR**
NO_x Emissions	(t/day)	On-road traffic	17.02	11.09	4.60	3.74	46.38	21.75	15.29	14.46
		Power generation	2.35	7.00	7.00	7.00	2.86	11.66	11.66	11.66
		Industry	1.83	1.83	1.83	1.83	23.72	23.72	23.72	23.72
		Dom.-commercial	1.45	1.46	1.46	1.46	2.81	2.99	2.99	2.99
		Solvents	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		Biogenic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		Airports	0.05	0.08	0.08	0.08	4.49	7.59	7.59	7.59
		Ports	0.70	0.92	0.92	0.92	4.89	6.56	6.56	6.56
	% of total emissions	On-road traffic	72.8%	49.6%	29.0%	24.9%	54.5%	29.3%	22.6%	21.6%
		Power generation	10.0%	31.3%	44.1%	46.6%	3.4%	15.7%	17.2%	17.4%
		Industry	7.8%	8.2%	11.5%	12.1%	27.9%	31.9%	35.0%	35.4%
		Dom.-commercial	6.2%	6.5%	9.2%	9.7%	3.3%	4.0%	4.4%	4.5%
		Airports	0.2%	0.4%	0.5%	0.5%	5.3%	10.2%	11.2%	11.3%
		Ports	3.0%	4.1%	5.8%	6.1%	5.7%	8.8%	9.67%	9.8%
		Total NO_x	23.38	22.37	15.88	15.03	85.15	74.26	67.80	67.00
		Δ Total emissions NO_x	-	-4.3%	-32.1%	-35.7%	-	-12.8%	-20.4%	-21.3%
Total emissions per pollutant	(t/day)	PM_{10}	2.17	1.89	1.40	1.35	12.26	11.46	10.98	10.93
		CO	98.34	43.74	27.20	24.92	222.37	106.01	90.16	88.56
		NMVOC	52.34	42.26	35.55	34.79	129.11	105.92	99.30	98.61
		SO_2	2.18	1.78	1.76	1.76	19.51	17.84	17.82	17.82
	Variation (%)	PM_{10}	-	-12.9%	-35.5%	-37.8%	-	-6.5%	-10.4%	-10.8%
		CO	-	-55.5%	-72.3%	-74.7%	-	-52.3%	-59.5%	-60.2%
		NMVOC	-	-19.3%	-32.1%	-33.5%	-	-18.0%	-23.1%	-23.6%
		SO_2	-	-18.3%	-19.3%	-19.3%	-	-8.6%	-8.7%	-8.7%

Improvements in the on–road traffic sector, focused on the area inside the BRR, also affect the total emissions of the BMA domain, which are estimated as 85.15 t/day in the scenario BC. In the future scenarios, the projection of specific emissions for each sector leads to a reduction in the total NO_x emissions. Such emissions are reduced to 74.26 t/day (12.8%) in T, to 67.80 t/day (20.4%) in SB and to 67.00 t/day (21.3%) in SBR.

NO_x has been selected for the analysis since it is one of the typical pollutants associated with on–road traffic and, together with particulate matter, represents the main pollutant associated with low air quality in Barcelona (Jimenez–Guerrero et al., 2008). As shown for NO_x emissions (Table 4), the measures defined for the different scenarios of mobility, together with the future projections by sectors, lead to significant reductions in the emissions for all the pollutants inside the BRR.

Regarding PM_{10}, significant reductions are observed with respect to the BC, from 2.17 t/day to 1.89 t/day in BAU (12.9%), to 1.40 t/day (35.5%) in SB and to 1.35 t/day (37.8%) in SBR. The observed reductions are lower in the BMA domain than in the BRR. The 12.26 t/day estimated for the BC scenario is reduced to 10.93 t/day in SBR (10.8%).

Regarding CO, its emissions show a greater reduction because its principal source of emission is on–road traffic, and technological improvements lead to a high reduction of on–road emissions of CO. In SBR, CO emissions are reduced from 98.34 t/day to 24.92 t/day (74.7%) inside the BRR domain, and from 222.37 t/day to 88.56 t/day (60.2%) in the BMA domain. The reductions in non–methane volatile organic compounds (NMVOC) emissions are from 52.34 to 34.79 t/day in the BRR (33.5%) and from 129.11 to 98.61 t/day in the BMA (23.6%).

The introduction of new technological improvements in traffic reduces SO_2 emission significantly: from 2.18 to 1.76 t/day in the BRR (19.3%) and 19.51 to 17.82 t/day in the BMA (8.7%). The higher SO_2 reductions are related to port sources due to the Directive 2005/33/EC (EC, 2005) which limits sulphur contents in marine fuels.

The emission model estimates a similar amount of pollutants for the two days of study. For the sake of simplicity, the emission data are analysed only for the summer day. The considered days only differ significantly in the NMVOCs emissions, mainly coming from biogenic sources; they can also come from evaporative sources and domestic–commercial solvents use. Owing to higher surface temperature and radiation during summertime, NMVOCs emissions in the BMA are estimated as 129.11 t/day in the summer day, whereas in the winter day these are lower; 107.62 t/day.

3.2. Air quality model results

Validation of the base case simulation. The WRF–ARW/HERMES/ CMAQ modelling system has been used to predict the ground–level of O_3, NO_2, SO_2 and PM_{10} for the February, 11th and the June, 18th 2004.

The statistical values obtained as a result of the evaluation (Table 5) meet the criteria established in the US EPA Guidelines and the uncertainty objectives set by the European Directives (e.g. the average MNGE for selected air quality stations is 26.65% for O_3 predictions, 49.78% for NO_2, 47.95% for SO_2 estimations and 38.59% for PM_{10}). This study gathers the experience of previous works in the target area. A deeper discussion of this modelling system evaluation can be found in Jimenez–Guerrero et al. (2008).

Table 5. *Summary of the model evaluation for the base-case scenario in the stations inside the Barcelona Metropolitan Area*

	MNBE (%)	MNGE (%)	UPA (%)
O_3	5.86	26.65	-5.18
NO_2	-27.12	49.78	-31.87
SO_2	-32.77	47.95	-29.23
PM_{10}	15.19	38.59	-14.82

Base–case scenario air quality. The air quality simulation was executed for the final domain with a resolution of 1 km x 1 km and 1 hour (Figure 1b). The highest concentrations of NO_2 in BC are observed along the road axis, since on–road traffic constitutes the main source of primary pollutants in the region (Goncalves et al., 2009b). For PM_{10}, the highest concentrations are not only related to on–road traffic, but also to point industrial sources. The simulations of BC for the winter and summer episodes (Figure 2) show high concentrations for both the primary pollutants (NO_2 and PM_{10}).

Daily average NO_2 concentration for the summer day (June, 18th) exceeds 60 µg/m^3 throughout the city of Barcelona, reaching to levels up to 70 µg/m^3 in a large part of the city (Figure 2). These levels are higher than the annual limit value (40 µg/m^3) established by the European regulations (EC, 2008). Such regulations establish a very high hourly level (200 µg/m^3) but not a daily limit. Following this premise, the annual limit has been selected considering that if some daily average exceeds the annual limit, the annual average will probably exceed it too. In the winter case, fairly similar NO_2 concentrations are observed (50–70 µg/m^3), which also exceed the annual limit value. The NO_2 dispersion presents a flow perpendicular to the coast and dominated by the north–western winds. The very complex coastal terrain induces mesoscale phenomena which controls the surface wind flows. Sea–breezes and mountain–valley winds contribute to the accumulation and recirculation of air masses. The littoral mountain chain (1 000 – 1 500 m in height) acts as a barrier, recirculating NO_2 towards the city. River valleys also channel the NO_2 flow.

Concerning the PM_{10} concentrations, high point levels of daily average concentration (more than 35 µg/m^3) are modelled in Barcelona and also around industrial sources in both winter and summer days. Such levels are very close to the limit values (daily: 50 µg/m^3; annual: 40 µg/m^3). An important contribution of exhaust and non–exhaust emissions from road transport is measured in Barcelona (Querol et al., 2004; Amato et al., 2010), together with the contribution of marine aerosol, which can add up to 3 µg/m^3 as an annual average. Furthermore, in summer the higher temperatures and solar radiation lead to the formation of secondary aerosols, thus contributing to the higher levels of particulate matter when compared with the winter levels (Jimeenez–Guerrero et al., 2008).

Nowadays, as shown for the days of study, SO_2 does not entail air quality problems in Barcelona city. This is a consequence of the SO_2 emission reductions in Europe (Vestreng et al., 2007). Daily SO_2 concentration is far from the daily limit value (125 µg/m^3) and slightly exceeds the annual limit value for vegetation (20 µg/m^3) that cannot be applied to Barcelona. The SO_2 is emitted mainly from large isolated point sources in the BMA (around the port, some power stations and small industries), as a result of fuel combustion with high percentage of sulphur. In this area, SO_2 is instantaneously mixed in high layers in the atmosphere, then transported and dispersed following the plume dynamics.

Finally we consider O_3, for which the days of study show different levels. The winter day presents a regular pattern: less than 55 µg/m^3 of maximum 8 h average. Only in downwind areas this maximum reaches to 60 µg/m^3. On the contrary, for the summer day, O_3 concentrations are increased by four key factors. Firstly, prevailing intense photochemistry in the region (Vautard et al., 2005), next the local formation and transport (Lelieveld et al., 2002; Gerasopoulos et al., 2005; Cristofanelli and Bonasoni, 2009), third, the persistent subsidence over the region (Perez et al., 2004) and finally the low O_3 depletion over the sea. O_3 is lower in the downtown areas, with levels below 55 µg/m^3 of maximum 8 h average, than in downwind areas, where it exceeds 100 µg/m^3. Lower O_3 levels are observed in Barcelona (below 70 µg/m^3) and in its main access roads (between 80–85 µg/m^3) where the levels of primary pollutants are higher. This behaviour is due to the higher concentration of fresh NO that acts as an O_3 sink, and to the depletion of radicals via HNO_3 formation by NO_2 consumption (Atkinson, 2000).

The modelling results indicate, however, an overestimation of nocturnal values, which are depicted with recurrent low daily variations due to uncertainties in the modelled nocturnal NO_x cycle, which is a common feature in chemical transport models (Jimenez et al., 2006b). The areas affected by more local traffic emissions (i.e. high NO_x emissions) are better characterized with a more pronounced daily O_3 variability (Pay et al., 2010).

Air quality in the future scenarios for the year 2015. In order to assess the influence of the mobility strategies, the analysis focuses inside the ring roads of the city of Barcelona (Barcelona Ring Roads, BRR) and its wider metropolitan area (Barcelona Metropolitan Area, BMA). These two domains are analogous to those defined for emissions (Figure 1c). The results of the air quality modelling system indicate that the mobility management measures together with the projection of emissions for the different sectors involve a reduction in the average concentration in the downtown Barcelona, outskirts and metropolitan area (Table 6 and Figure 3).

For NO_2, the daily average concentration for the BRR domain in the summertime day (June, 18th) is estimated as 57.8 µg/m^3 in the BC scenario. Despite the increase in the number of journeys (37%), NO_2 levels decrease (on average) in the scenario BAU to 55.1 µg/m (4.6%), due to the projected changes in the vehicular fleet. With the implementation of mobility measures, more air quality improvements are observed in the BRR. In SB 24 h average of NO_2 decreases to 48.1 µg/m^3 (16.7%), and to 47.2 µg/m^3 in SBR (18.3%). Concerning the wintertime day, higher reductions of NO_2 are observed compared to the summer case, due to a higher O_3 formation. The 24 h average in BC of 49.4 µg/m^3, is reduced in BAU to 42.9 µg/m^3 (13.1%), to 37.4 µg/m^3 in SB (24.2%), and to 36.7 µg/m^3 in SBR (25.6%).

Such NO_2 variations are shown in Figure 4. The improvements are located around the roads; the 24 h average reduces up to 15 µg/m^3, and up to 20 µg/m^3 downtown. Despite such reductions, air quality levels slightly exceed the annual limit (40 µg/m^3) in a large part of Barcelona city. The increases are located around the airport and around the port of Barcelona (increase of 15 µg/m^3) due to the projected increase in port activity and the installation of a new power plant. It should be noted that the emissions from ports and airports have a significant effect on air quality in their surrounding areas (e.g. Unal et al., 2005; Graham and Raper, 2006; Schurmann et al., 2007, Lucialli et al., 2007; among others). Such increases around these airports agree with the results of Carslaw et al. (2006), which indicate that the airport contribution may involve an increase in 27% of the annual mean NO_2 in the vicinity of the airport and up to 15% in surrounding observational stations.

The local reduction of NO_2 due to the mobility management scenarios in the BRR and to the projection of the vehicular fleet, also induce regional reductions in the BMA (Table 6 and Figure 3). For the summer day (June, 18th) the average is 29.1 µg/m^3 in the BC and decreases to 24.4 µg/m^3 (16.1%) in SB, and to 24.2 µg/m^3 (16.7%) in SBR. Related to wintertime levels in the BMA domain, the NO_2 levels of 34.8 µg/m^3 in BC, are reduced in the future scenarios to 28.6 µg/m^3 (T), 27.5 µg/m^3 (SB) and 27.4 µg/m^3 (SBR).

These reductions of nitrogen oxides in downtown Barcelona can lead to a raise in O_3 concentration downwind (Goncalves et al., 2009b). This behaviour is characteristic of VOC–sensitive areas, usually produced in conditions with low VOCs to NO_x ratios (Sillman and He, 2002). This phenomenon has been widely described in Jimeenez and Baldasano (2004) for the city of Barcelona. In both days of study, O_3 concentration increases where NO_2 emissions decreases (Figure 4). In addition, in the port area (where the introduction of a new power plant and the projection of port activities raise NO_x emissions) O_3 concentration diminishes. The 8 h O_3 average concentration for the BRR clearly shows this

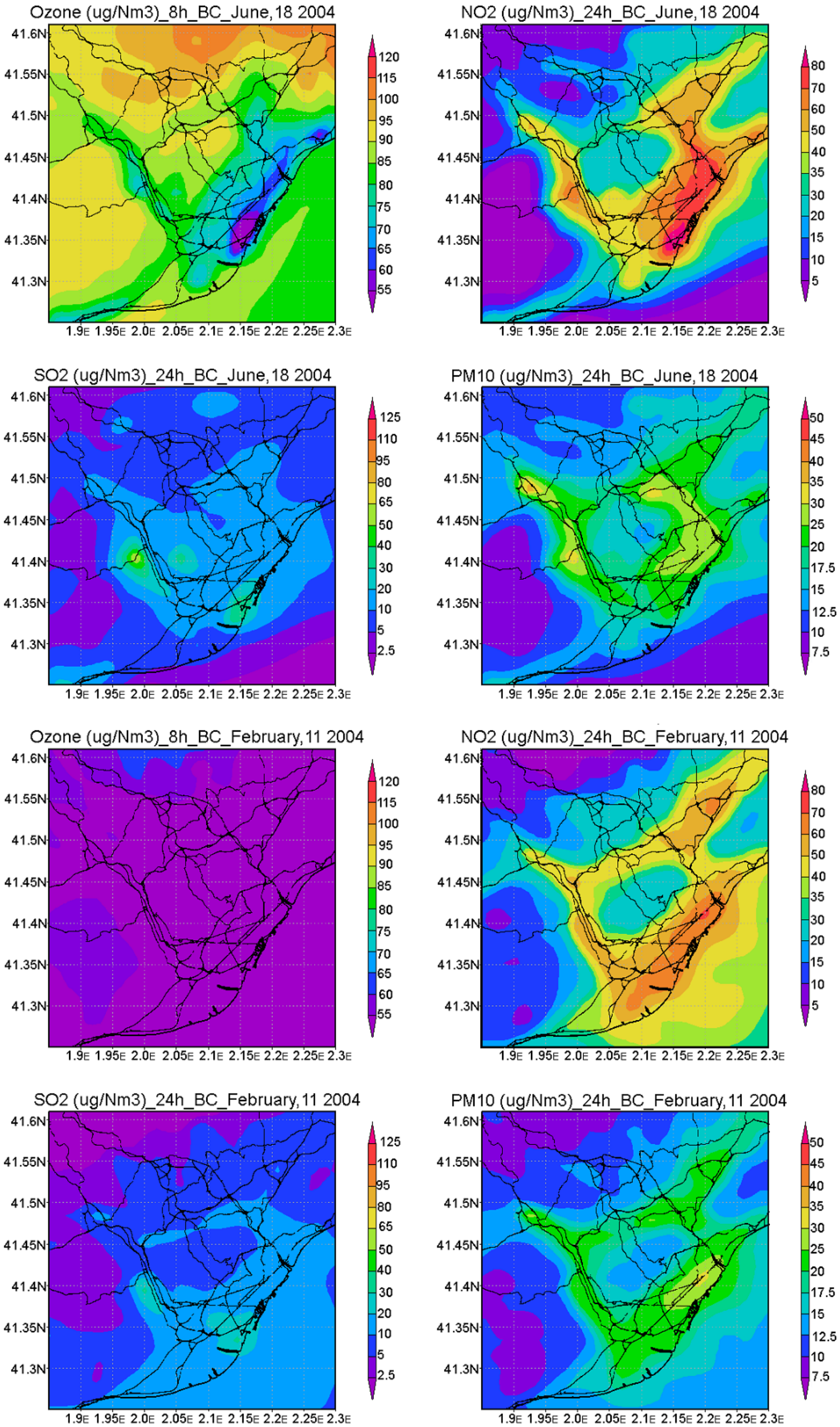

Figure 2. *(Upper panel) 8-h O_3 average and 24-h NO_2, SO_2 and PM_{10} average concentration for the BC scenario in the BMA for summertime day in the base-case scenario (June, 18th 2004). (Lower panel) Id. for the wintertime day in the base-case scenario (February, 11th 2004).*

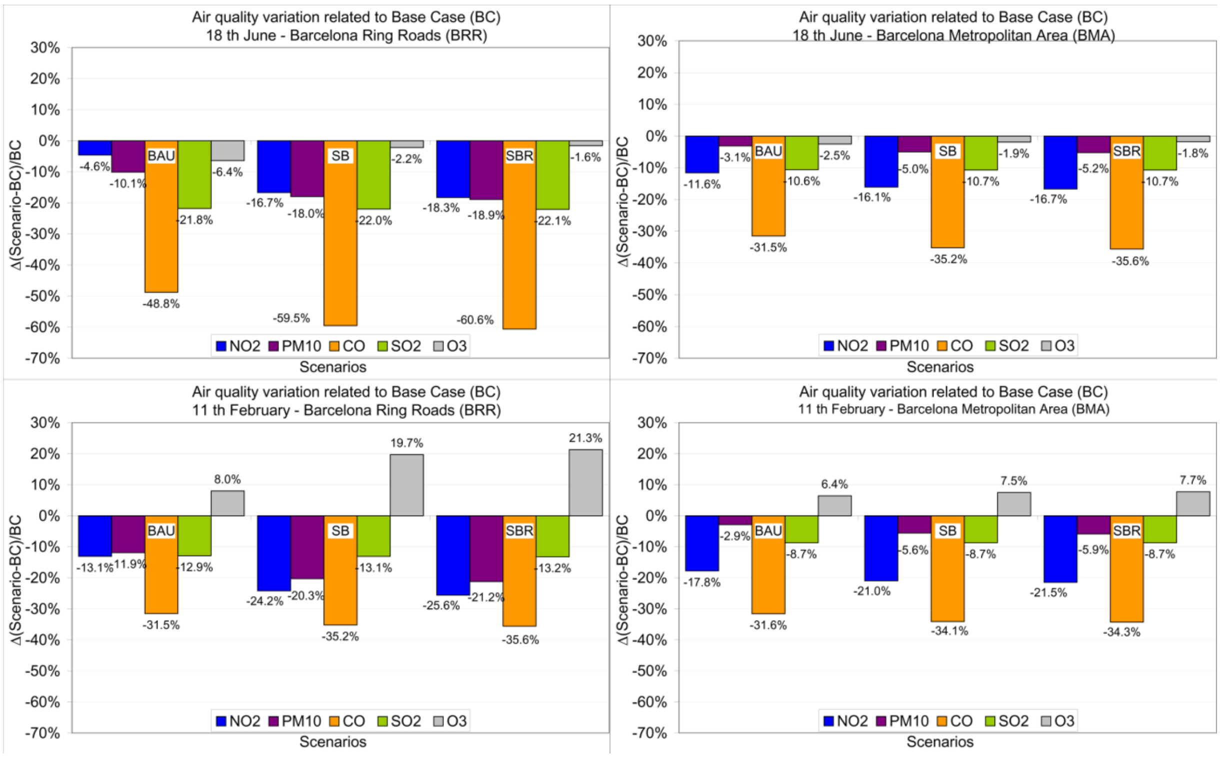

Figure 3. *Air quality deviations with respect to the Base Case (BC) per scenario (BAU, SB and SBR) (upper panel-left) June, 18th and BRR, (upper panel-right) June, 18th and BMA, (lower panel-left) February, 11th and BRR, (lower panel-right) February, 11th and BMA.*

Table 6. *Average concentrations inside the Barcelona Ring Roads (BRR) and the entire Barcelona Metropolitan Area (BMA) for NO_2, PM_{10}, CO, SO_2 and O_3 during the summer and winter days, classified by mobility scenario*

	BRR	**BC**	**BAU**	**SB**	**SBR**	**ΔBAU**	**ΔSB**	**ΔSBR**	**BAU (%)**	**SB (%)**	**SBR (%)**
Summer (June, 18th)	NO_2 (μg/m^3)	57.8	55.1	48.1	47.2	-2.7	-9.7	-10.6	-4.6%	-16.7%	-18.3%
	PM_{10} (μg/m^3)	21.3	19.1	17.4	17.2	-2.1	-3.8	-4.0	-10.1%	-18.0%	-18.9%
	CO (mg/m^3)	0.4	0.2	0.2	0.2	-0.2	-0.2	-0.2	-48.8%	-59.5%	-60.6%
	SO_2 (μg/m^3)	15.3	12.0	12.0	12.0	-3.3	-3.4	-3.4	-21.8%	-22.0%	-22.1%
	O_3 (μg/m^3)	71.3	66.8	69.7	70.1	-4.6	-1.6	-1.2	-6.4%	-2.2%	-1.6%
	BMA	BC	BAU	SB	SBR	ΔBAU	ΔSB	ΔSBR	BAU (%)	SB (%)	SBR (%)
	NO_2 (μg/m^3)	29.1	25.7	24.4	24.2	-3.4	-4.7	-4.9	-11.6%	-16.1%	-16.7%
	PM_{10} (μg/m^3)	15.5	15.1	14.8	14.7	-0.5	-0.8	-0.8	-3.1%	-5.0%	-5.2%
	CO (mg/m^3)	0.2	0.1	0.1	0.1	0.0	-0.1	-0.1	-31.5%	-35.2%	-35.6%
	SO_2 (μg/m^3)	10.5	9.4	9.4	9.4	-1.1	-1.1	-1.1	-10.6%	-10.7%	-10.7%
	O_3 (μg/m^3)	83.2	81.2	81.7	81.8	-2.1	-1.6	-1.5	-2.5%	-1.9%	-1.8%
Winter (February, 11th)	BRR	BC	BAU	SB	SBR	ΔBAU	ΔSB	ΔSBR	BAU (%)	SB (%)	SBR (%)
	NO_2 (μg/m^3)	49.4	42.9	37.4	36.7	-6.5	-12.0	-12.6	-13.1%	-24.2%	-25.6%
	PM_{10} (μg/m^3)	21.0	18.5	16.8	16.6	-2.5	-4.3	-4.4	-11.9%	-20.3%	-21.2%
	CO (mg/m^3)	0.2	0.1	0.1	0.1	-0.1	-0.1	-0.1	-46.0%	-53.5%	-54.1%
	SO_2 (μg/m^3)	14.4	12.6	12.5	12.5	-1.9	-1.9	-1.9	-12.9%	-13.1%	-13.2%
	O_3 (μg/m^3)	27.2	29.4	32.6	33.0	2.2	5.4	5.8	8.0%	19.7%	21.3%
	BMA	BC	BAU	SB	SBR	ΔBAU	ΔSB	ΔSBR	BAU (%)	SB (%)	SBR (%)
	NO_2 (μg/m^3)	34.8	28.6	27.5	27.4	-6.2	-7.3	-7.5	-17.8%	-21.0%	-21.5%
	PM_{10} (μg/m^3)	15.8	15.3	14.9	14.9	-0.5	-0.9	-0.9	-2.9%	-5.6%	-5.9%
	CO (mg/m^3)	0.1	0.1	0.1	0.1	0.0	0.0	0.0	-31.6%	-34.1%	-34.3%
	SO_2 (μg/m^3)	10.5	9.6	9.6	9.6	-0.9	-0.9	-0.9	-8.7%	-8.7%	-8.7%
	O_3 (μg/m^3)	41.5	44.1	44.6	44.6	2.7	3.1	3.2	6.4%	7.5%	7.7%

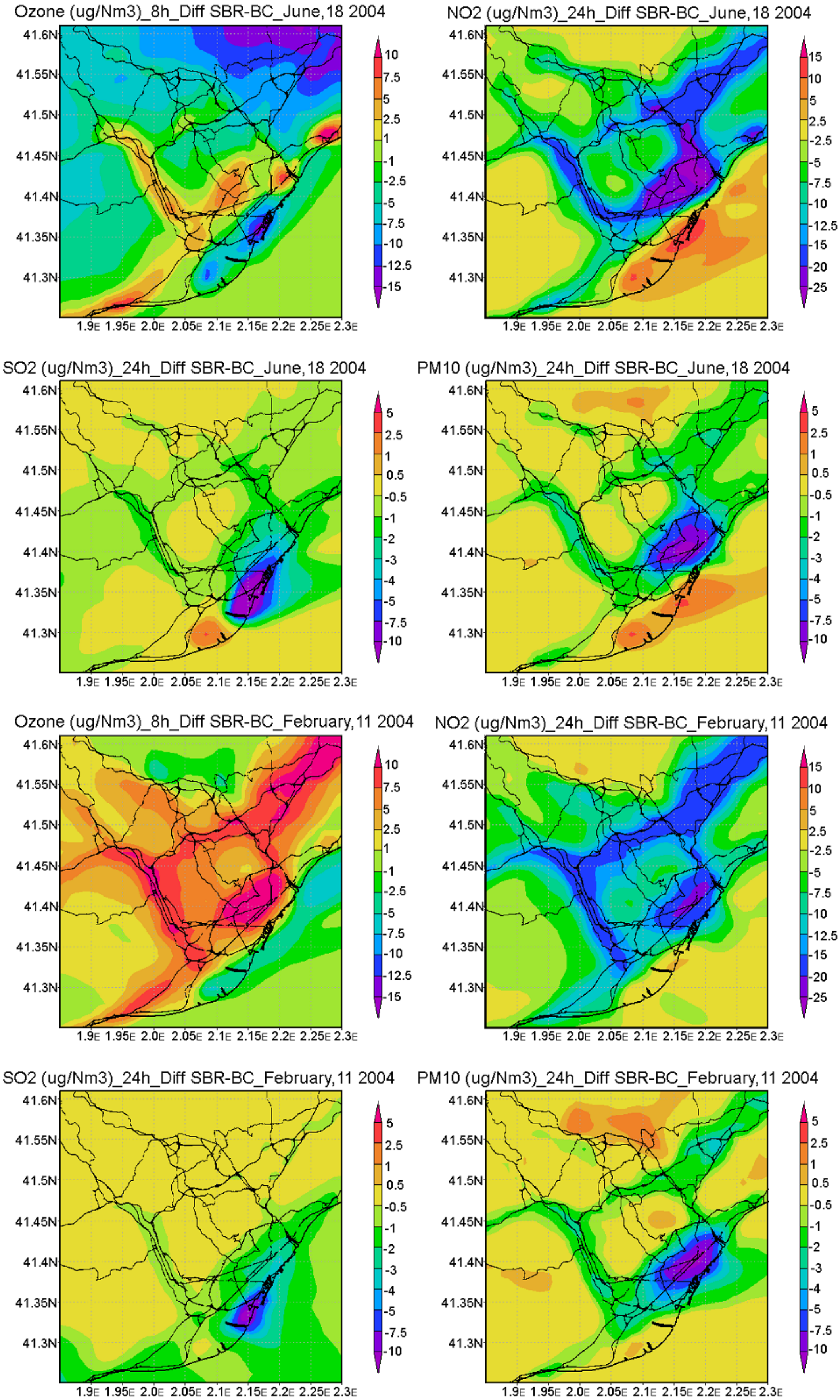

Figure 4. *(Upper panel) Improvement in urban air quality (green-blue colours) for the summer day: (left-right and top-bottom): differences in the concentration between the scenarios SBR and BC for 8-hr ozone and 24-hr nitrogen dioxide, sulphur dioxide and particulate matter PM_{10} (all differences in µg/m^3). (Lower panel) Id for the winter day.*

behaviour (Table 6). For the summer day in BC the 8 h O_3 concentration (71.3 μg/m^3) is reduced for all the future scenarios: to 66.8 μg/m^3 (T), 69.7 μg/m^3 (SB) and 70.1 μg/m^3 (SBR). Regarding the winter day, the 27.2 μg/m^3 of BC slightly increase in the 2015 scenarios to 29.4 μg/m^3 (T), 32.6 μg/m^3 (SB) and 33.0 μg/m^3 (SBR).

Similarly to the emission analysis, the air quality model results have been focused on NO_2, because it represents the main pollutant associated to poor air quality in Barcelona (together with particulate matter) and it is often associated to on–road traffic.

The emission reduction also affects air quality values for other primary pollutants: PM_{10}, CO and SO_2. When introducing the traffic mobility measures, the PM_{10} concentration inside the BRR decreased for the summer case 10.1%, 18.0% and 18.9% in the scenarios T, SB and SBR, respectively. For winter, the reductions are: 11.9% (T), 20.3% (SB) and 21.2% (SBR). Taking into account the BMA domain, lower reductions in PM_{10} are observed, between 2.9 and 5.9%. In the case of CO, high pollutant reductions are observed due to technological improvements in on–road transport. Such reductions range from 46.0–60.6% inside the BRR and 31.5–35.6% in the BMA. Concerning SO_2, the reductions are between 12.9–22.1% (BRR) and 8.7–10.7% (BMA). The highest SO_2 reductions are observed around the port (Figure 4) due to the application of the Directive 2005/33/EC limiting the sulphur content of marine fuels (EC, 2005).

4. Summary and Conclusions

This work aims to study the impact of traffic management scenarios on future air quality when projected to the year 2015 in the city of Barcelona and its area of influence by means of a complex air quality modelling system applied with very high temporal and spatial resolution (1 km x 1 km and 1 hour). Several traffic mobility management measures have been planned to be in place for the year 2015. Each measure is represented by a future scenario: the first depicting what would happen if no measures were adopted (scenario BAU). The two other future scenarios plan solutions to improve the urban mobility based on: (1) re–distribution of the present road network in blocks (scenario SB); and (2) re–distribution in super–blocks with the introduction of several reversal of direction (scenario SBR). The introduction of the mobility measures for 2015 is complemented through a comprehensive projection of the emissions per sector. The traffic mobility measures together with the technological improvements in the vehicular fleet and the introduction of alternative fuels allow reductions in the air pollution levels. Such future scenarios have been compared with the base–case scenario for 2004. The highest abatement is observed in downtown Barcelona (more than 15 μg/m^3 for daily NO_2 and 5 μg/m^3 for daily PM_{10}), where the mobility strategies are applied, but a reduction is also observed in its surrounding area.

In summary, the planned traffic management scenarios and the technological improvements lead to significant reduction of emissions leading to improvements in air quality. Nevertheless, the air quality levels remain high and close to the limit values for NO_2 and PM_{10} (EC, 2008). Hence, further measures and actions have to been taken into account in order to solve urban air quality–related problems.

Finally, we conclude that model simulation proves to be a suitable tool for the management and assessment of urban air quality.

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