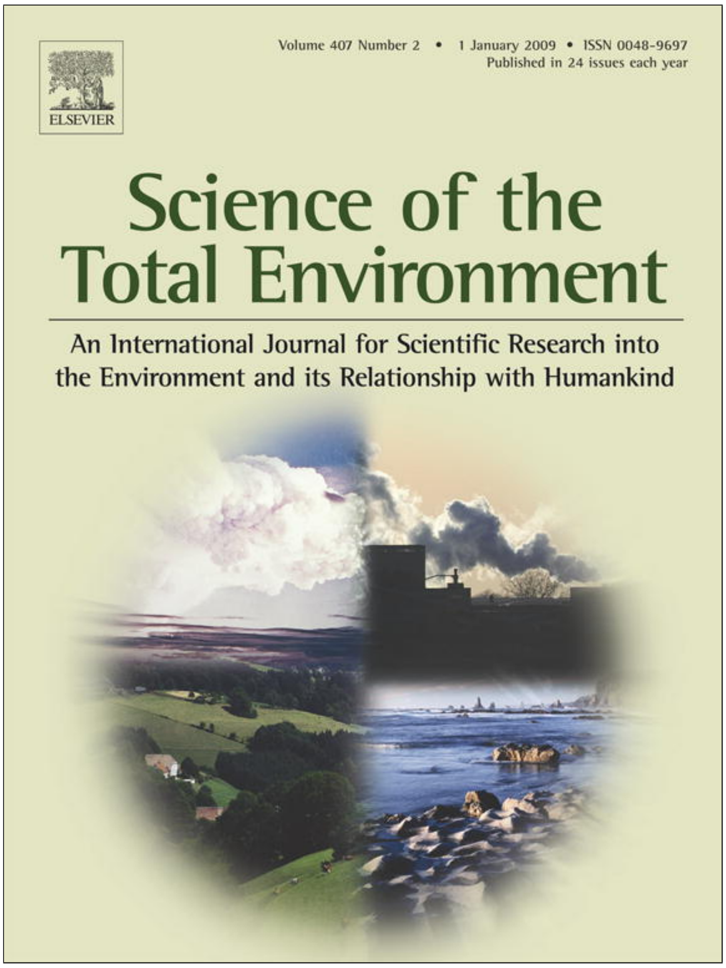

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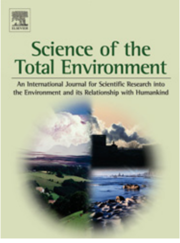

High resolution modeling of the effects of alternative fuels use on urban air quality: Introduction of natural gas vehicles in Barcelona and Madrid Greater Areas (Spain)

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ABSTRACT

The mitigation of the effects of on-road traffic emissions on urban air pollution is currently an environmental challenge. Air quality modeling has become a powerful tool to design environment-related strategies. A wide range of options is being proposed; such as the introduction of natural gas vehicles (NGV), biofuels or hydrogen vehicles. The impacts on air quality of introducing specific NGV fleets in Barcelona and Madrid (Spain) are assessed by means of the WRF-ARW/HERMES/CMAQ modeling system with high spatial–temporal resolution (1 km^2, 1 h). Seven emissions scenarios are defined taking into account the year 2004 vehicle fleet composition of the study areas and groups of vehicles susceptible of change under a realistic perspective. O_3 average concentration rises up to 1.3% in Barcelona and up to 2.5% in Madrid when introducing the emissions scenarios, due to the NO_x reduction in VOC-controlled areas. Nevertheless, NO_2, PM10 and SO_2 average concentrations decrease, up to 6.1%, 1.5% and 6.6% in Barcelona and up to 20.6%, 8.7% and 14.9% in Madrid, respectively. Concerning SO_2 and PM10 reductions the most effective single scenario is the introduction of 50% of NGV instead of the oldest commercial vehicles; it also reduces NO_2 concentrations in Barcelona, however in Madrid lower levels are attained when substituting 10% of the private cars. This work introduces the WRF-ARW/HERMES/CMAQ modeling system as a useful management tool and proves that the air quality improvement plans must be designed considering the local characteristics.

1. Introduction

Improving the air quality in large conurbations is currently a major concern (Fenger, 1999; Baldasano et al., 2003). Nowadays, on-road traffic is the main anthropogenic contributor to air pollutant emissions in urban areas (Costa and Baldasano, 1996; Oduyemi and Davidson, 1998; Crabbe et al., 1999; Colvile et al., 2001; Ghose et al., 2004; Guo et al., 2007). It accounts for the largest mass fraction of fine particulate matter (Querol et al., 2001; Manoli et al., 2002; Artiñano et al., 2004; Vallius et al., 2005), which is associated with increased mortality (Pope and Dockery, 2006); and it is also an important source of carbon monoxide (CO) and nitrogen oxides (NO_x) (Colvile et al., 2001; Tsilingiridis et al., 2002). Furthermore, the reduction of PM and ozone (O_3) levels in Europe is of particular emphasis in the Clean Air for Europe (CAFE) program of the European Commission (Cuvelier

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et al., 2007; Thunis et al., 2007; Vautard et al., 2007). The non-linearity of the reactive transport of pollutants and the uncertainties related to the kinetics of O_3 affect the design of control strategies to reduce tropospheric O_3 (Sillman et al., 1998; Jiménez and Baldasano, 2004); therefore the evaluation of air quality management strategies requires the use of air quality models to perform quantitative impact studies (Ponche and Vinuesa, 2005).

In urban areas different plans for the reduction of emissions concerning on-road traffic are currently being tested, varying from the introduction of new technologies or alternative fuels in vehicles, to traffic or urban planning schemes. Among others, the European Commission (EC, 2001) promotes the introduction of biofuels, natural gas (NG) and hydrogen as fuels. Air quality modeling associated with emissions scenarios has become an important tool for assessing the effects of these strategies on advance, providing the variation of pollutants concentration (Schell et al., 2002; Ponche and Vinuesa, 2005; Vautard et al., 2005; Mediavilla-Sahagún and ApSimon, 2006; Reis et al., 2000). Different studies have been performed related to the impacts of alternative fuel use, such as ethanol or compressed natural gas on air quality, human health or related costs (e.g. Asia–Beijing (Cheng et al., 2007), USA–Albuquerque (Gaffney et al., 1997), USA–nationwide (Jacobson, 2007) and urban areas of the United States (Cohen et al., 2003)).

This work aims to investigate the impact on urban air quality of seven feasible scenarios of emissions reduction, which consider the introduction of natural gas vehicles (NGV) in the two largest cities of Spain: Barcelona and Madrid. The changes on air quality are assessed by means of the WRF-ARW/HERMES/CMAQ modeling system in terms of O_3, nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and PM10 concentrations.

2. Methods

The WRF-ARW/HERMES/CMAQ modeling system is a three-dimensional, Eulerian simulation system representing the state-of-the-art in air quality modeling. It was applied with high spatial (1 km^2) and temporal (1 h) resolution. The detection of subtle air quality variations in urban areas, as shown in the CityDelta project experience (Cuvelier et al., 2007; Thunis et al., 2007), and the description of the dynamics of pollutants on an hourly basis in very complex terrains as those studied (Jiménez et al., 2005, 2006) demands for the use of fine scale.

The base case is defined taking into account the year 2004 data and the emissions scenarios designed (Gonçalves et al., submitted for publication) intended to be as feasible as possible, defining the vehicle fleet groups susceptible of change and considering the substitution of the oldest diesel and petrol vehicles by NGV. In detail the scenarios are: (E1) Scenario 1. Substitution of 100% of urban buses fleet by NGV; (E2) Scenario 2. Substitution of 50% of taxis fleet by NGV; (E3) Scenario 3. Substitution of 50% of intercity buses fleet by NGV; (E4) Scenario 4. Substitution of 50% of light commercial vehicles fleet by NGV; (E5) Scenario 5. Substitution of 10% of private cars fleet by NGV; (E6) Scenario 6. Substitution of 100% of heavy duty freight transport vehicles fleet by NGV; (E7) Scenario 7. Combined scenario. The main conclusions of the estimations of traffic emissions (summary in Table 1) are that the introduction of 50% of natural gas commercial light vehicles is the most effective scenario in reducing NO_x (−15%), SO_2 (−15%) and PM10 (−24%) in Barcelona area, while in Madrid substituting 10% of private cars involves larger reductions of NO_x (−11%) and CO (−17%) emissions. Changes in traffic emissions when transforming all urban buses, 50% of taxis or the whole heavy duty vehicles fleets to natural gas are lower than 5% in both conurbations. The largest variation in traffic emissions is obtained in the combined scenario (i.e. up to 35% reduction on NO_x and up to 41% in PM10).

2.1. *Modeling system*

Four nested domains were defined for the simulations (Fig. 1a and b), centering the final domains (D4) in Barcelona and Madrid. They cover the northeastern Iberian Peninsula (322×259 km^2) and the Central Iberian Peninsula (181×214 km^2) respectively, to assess not only the effects in urban areas, but also to detect the urban plume behavior in downwind areas.

The Weather Research and Forecasting (WRF) Model (Michalakes et al., 2004) provides the meteorology dynamical parameters as inputs to CMAQ. The HERMES emission

Table 1 – Summary of emissions reduction from on-road traffic (kg d^{-1}) for each scenario in Barcelona and Madrid areas (further details on Gonçalves et al., submitted to The Science of the Total Environment; January, 2008)

	Barcelona					Madrid				
	(Domain of 130 km^2 defined in the North Eastern IP region and centered in the urban area)					(Domain of 373 km^2 defined in the Central IP region and centered in the urban area)				
Pollutant (kg d^{-1})	NO_x	NMVOCs	CO	SO_2	PM10	NO_x	NMVOCs	CO	SO_2	PM10
Base case scenario (EB)	23949	72740	116162	736	7356	66700	95767	297574	1832	18238
%	NO_x	NMVOCs	CO	SO_2	PM10	NO_x	NMVOCs	CO	SO_2	PM10
E1-EB	−3.6%	−0.2%	−0.2%	−4.2%	−3.1%	−2.7%	−0.4%	−0.2%	−3.9%	−2.9%
E2-EB	−2.8%	−0.1%	−0.2%	−6.2%	−4.2%	−1.8%	−0.1%	−0.1%	−4.3%	−3.9%
E3-EB	−2.0%	−0.1%	−0.1%	−2.2%	−1.8%	−3.8%	−0.4%	−0.2%	−4.0%	−4.3%
E4-EB	−15.1%	−1.0%	−8.3%	−15.1%	−24.5%	−6.7%	−1.1%	−5.5%	−6.9%	−13.9%
E5-EB	−7.8%	−3.3%	−12.1%	−3.9%	−4.6%	−10.9%	−6.9%	−16.8%	−5.9%	−8.1%
E6-EB	−3.4%	−0.2%	−0.2%	−4.1%	−2.8%	−1.3%	−0.1%	−0.1%	−1.9%	−1.3%
E7-EB	−34.7%	−5.0%	−21.0%	−35.6%	−41.0%	−27.3%	−8.9%	−22.9%	−27.0%	−34.3%

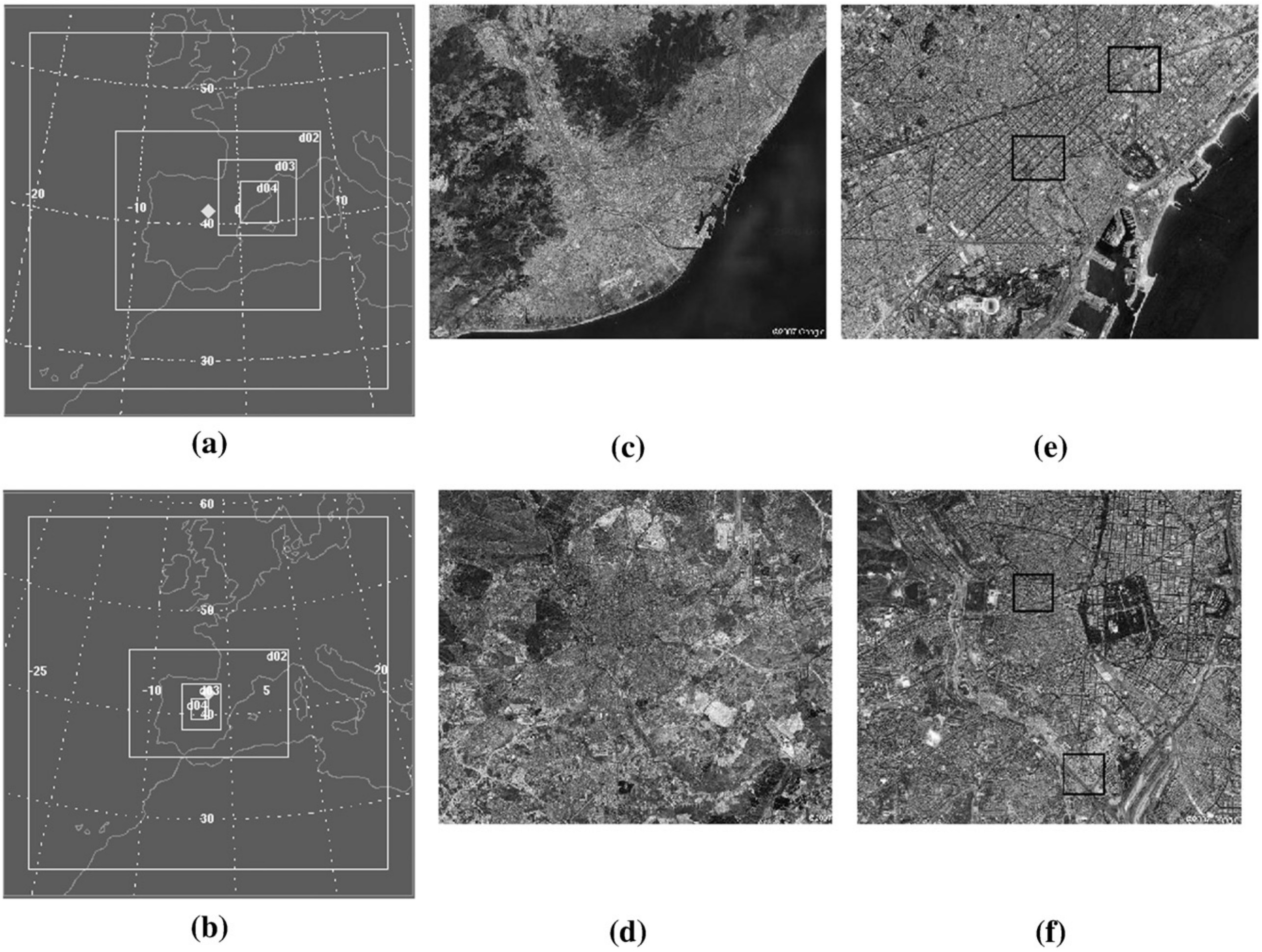

Fig. 1 – Nested domains used for NE Iberian Peninsula–Barcelona (a) and Center of Iberian Peninsula–Madrid (b). Domains defined to the results analysis: (c) Barcelona area (41°15′N–41.°30′N; 1°50′E, 2°27′E); (d) Madrid area (40°09′ N–40°33′ N; 3°54′ W–3°27′ W); (e) Barcelona–Downtown (41°23′21″N; 2°10′05″E) and Barcelona–Gloriès (interval: 41°24′12″N; °11′13″E); (f) Madrid–Downtown (interval: 40°25′04″N; 3°41′59″W) and Madrid–Legazpi (interval: 40°23′28″N; 3°41′42″W).

model has been developed in the Barcelona Supercomputing Center — Centro Nacional de Supercomputación (BSC-CNS) to estimate the emissions of gas and particulate matter pollutants for Spain using a high spatial and temporal resolution (1 km^2 and 1 h). The chemistry transport model used to compute the concentrations of photochemical pollutants was CMAQ (Byun and Ching, 1999). The initial and boundary conditions were derived from a one-way nested simulation covering a domain of 1392×1104 km^2 centered in the Iberian Peninsula, that used EMEP emissions for the year 2004 and disaggregated to 18 km. A 48-hour spin-up was performed to minimize the effects of initial conditions for both domains. The chemical mechanism selected for the simulations (following the criteria of Jiménez et al., 2003) was CBM-IV including aerosols and heterogeneous chemistry. NO_x and volatile organic compounds (VOC) speciation of HERMES emissions, as required by CBM-IV, are detailed in Parra et al. (2006). The horizontal resolution considered was 1 km, and 32-sigma vertical layers cover the troposphere.

This resolution requires of high-performance computing. The availability of the MareNostrum supercomputer hold in the BSC-CNS, together with the advances in the parallelization of air quality model codes, have allowed the high-resolution simulations and the large number of scenarios.

2.2. *Description of the studied episode: 17–18 June, 2004*

The impacts on air quality for the different NG substitution scenarios have been assessed for a critical episode of photochemical pollution, selected according to air quality data monitored in the study areas, but also considering that the traffic circulation pattern should be usual (working days).

Table 2 – Summary of the model evaluation for the 17–18 June, 2004 episode

	MNBE (%)	MNGE (%)	UPA (%)
O_3	−4%	15%	−9%
NO_2	−6%	28%	−4%
SO_2	−12%	28%	−12%
PM10	−3%	26%	−9%

Table 3 – Summary of the European Directives related to air quality and human health protection

Pollutant	Human health protection threshold	Limit date	European directive
O_3	120 $\mu g/m^3$ 8-h average concentration[a]	2010	2002/3/CE
	180 $\mu g/m^3$ 1-h average concentration[b]		
	240 $\mu g/m^3$ 1-h average concentration[c]		
PM10	50 $\mu g/m^3$ 24-h average concentration[d]	2005	1999/30/CE
	40 $\mu g/m^3$ Annual average concentration		
	50 $\mu g/m^3$ 24-h average concentration[e]	2010	
	20 $\mu g/m^3$ Annual average concentration		
SO_2	350 $\mu g/m^3$ 1-h average concentration[f]	2005	1999/30/CE
	125 $\mu g/m^3$ 24-h average concentration[g]		
NO_2	200 $\mu g/m^3$ 1-h average concentration[h]	2010	1999/30/CE
	40 $\mu g/m_3$ annual average concentration		

[a] It won't be surpassed more than 76 times during a 3 years period.
[b] Population information threshold.
[c] Alert threshold.
[d] It won't be surpassed more than 35 times a year.
[e] It won't be surpassed more than 7 times a year.
[f] It won't be surpassed more than 24 times a year.
[g] It won't be surpassed more than 3 times a year.
[h] It won't be surpassed more than 18 times a year.

The 17–18 June, 2004 episode is characterized by a western recirculation in the synoptic scale, a typical summertime situation in southwestern Europe. These conditions dominate 45% of the annual and 78% of the summertime transport patterns over the coastal Mediterranean areas (Jorba et al., 2004) and 36% of the annual and 45% of the summertime situations in the central–continental areas of the Iberian Peninsula. They are frequently associated with local-to-regional episodes of air pollution related to high levels of O_3 during summer (e.g. Toll and Baldasano, 2000; Barros et al., 2003; Ortega et al., 2004; Taghavi et al., 2004; Cousin et al., 2005; Coll et al., 2005; Jiménez et al., 2006; among others), being the study case one of the most polluted episodes of the year 2004 in the considered areas.

These days were characterized by a weak synoptic forcing, so that mesoscale phenomena, induced by the topography of the regions, may be expected to be dominant. A high sea-level pressure and negligible surface pressure gradients over the domain characterize this episode, with low northwesterlies aloft. The large solar radiation and the low cloudiness promotes the development of mesoscale phenomena like mountain winds, sea and land breezes in coastal areas, and the development of the Iberian thermal low in the centre of the Iberian Peninsula. The atmospheric behavior of the selected domains differ, being the North-eastern Iberian Peninsula a coastal area characterized by very complex terrain, which affects the pollutants dynamics. The processes occurring involve layering and accumulation of pollutants and photochemical pollutants formation at high levels. In the Central Iberian Peninsula the much simpler topography and the absence of the sea-breezes control involves the formation of a convective cell due to thermal phenomena which controls the dynamics of pollutants,

Table 4 – 8-h O_3 and 24-h NO_2 average concentration in Barcelona and Madrid areas

	Barcelona area			Madrid area		
	O_3 8-h average concentration			O_3 8-h average concentration		
	Conc ($\mu g\ m^{-3}$)	ΔConc ($\mu g\ m^{-3}$)	Variation (%)	Conc ($\mu g\ m^{-3}$)	ΔConc ($\mu g\ m^{-3}$)	Variation (%)
Base case	76.9	–	–	86.0	–	–
Scenario 1	77.0	0.09	0.12%	86.2	0.21	0.24%
Scenario 2	77.0	0.07	0.09%	86.1	0.13	0.15%
Scenario 3	77.0	0.05	0.07%	86.3	0.28	0.33%
Scenario 4	77.3	0.40	0.52%	86.5	0.52	0.60%
Scenario 5	77.1	0.19	0.25%	86.8	0.83	0.97%
Scenario 6	77.0	0.09	0.11%	86.1	0.10	0.12%
Scenario 7	77.9	0.97	1.26%	88.1	2.12	2.47%
	NO_2 24-h average concentration			NO_2 24-h average concentration		
	Conc ($\mu g\ m^{-3}$)	ΔConc ($\mu g\ m^{-3}$)	Variation (%)	Conc ($\mu g\ m^{-3}$)	ΔConc ($\mu g\ m^{-3}$)	Variation (%)
Base case	35.0	–	–	22.2	–	–
Scenario 1	34.8	−0.20	−0.56%	21.8	−0.44	−1.98%
Scenario 2	34.9	−0.15	−0.42%	22.0	−0.28	−1.24%
Scenario 3	34.9	−0.11	−0.32%	21.6	−0.61	−2.73%
Scenario 4	34.1	−0.89	−2.54%	21.1	−1.12	−5.04%
Scenario 5	34.6	−0.46	−1.30%	20.4	−1.82	−8.20%
Scenario 6	34.8	−0.19	−0.55%	22.0	−0.21	−0.95%
Scenario 7	32.9	−2.15	−6.13%	17.7	−4.58	−20.59%

Variation among scenarios.

occurring the photochemical formation of pollutants in all the atmospheric column under the PBL (Baldasano et al., 1994; Millán et al., 1997; Soriano et al., 2001; Gangoiti et al., 2001; Pérez et al., 2004; Jiménez et al., 2006). The modeling system used proved to be capable of reproducing this kind of processes (Gonçalves et al., 2008).

The photochemical simulation results for the northeastern and Central Iberian Peninsula show that the maximum O_3 concentrations occur in downwind areas from Barcelona and Madrid cities after the maximum photochemical activity hours. During the day the increase of the solar radiation and the temperature (reaching 30–35 °C in both domains) promote the high levels of O_3, exceeding in some cases the population information threshold (180 $\mu g\ m^{-3}$).

3. Results and discussion

3.1. *Validation of the base case simulation*

Hourly data from air quality surface stations (provided by the Environmental Departments of the Catalonia and Madrid Governments, Spain) averaged over the domains of study are used to evaluate the performance of WRF-ARW/HERMES/CMAQ for predicting ground-level O_3, NO_2, SO_2 and PM10 during the episode of 17–18 June, 2004.

The European Directives 1999/30/EC and 2002/3/EC assume an uncertainty of 50%, defined as the maximum error of the measured and calculated concentration levels, as the air

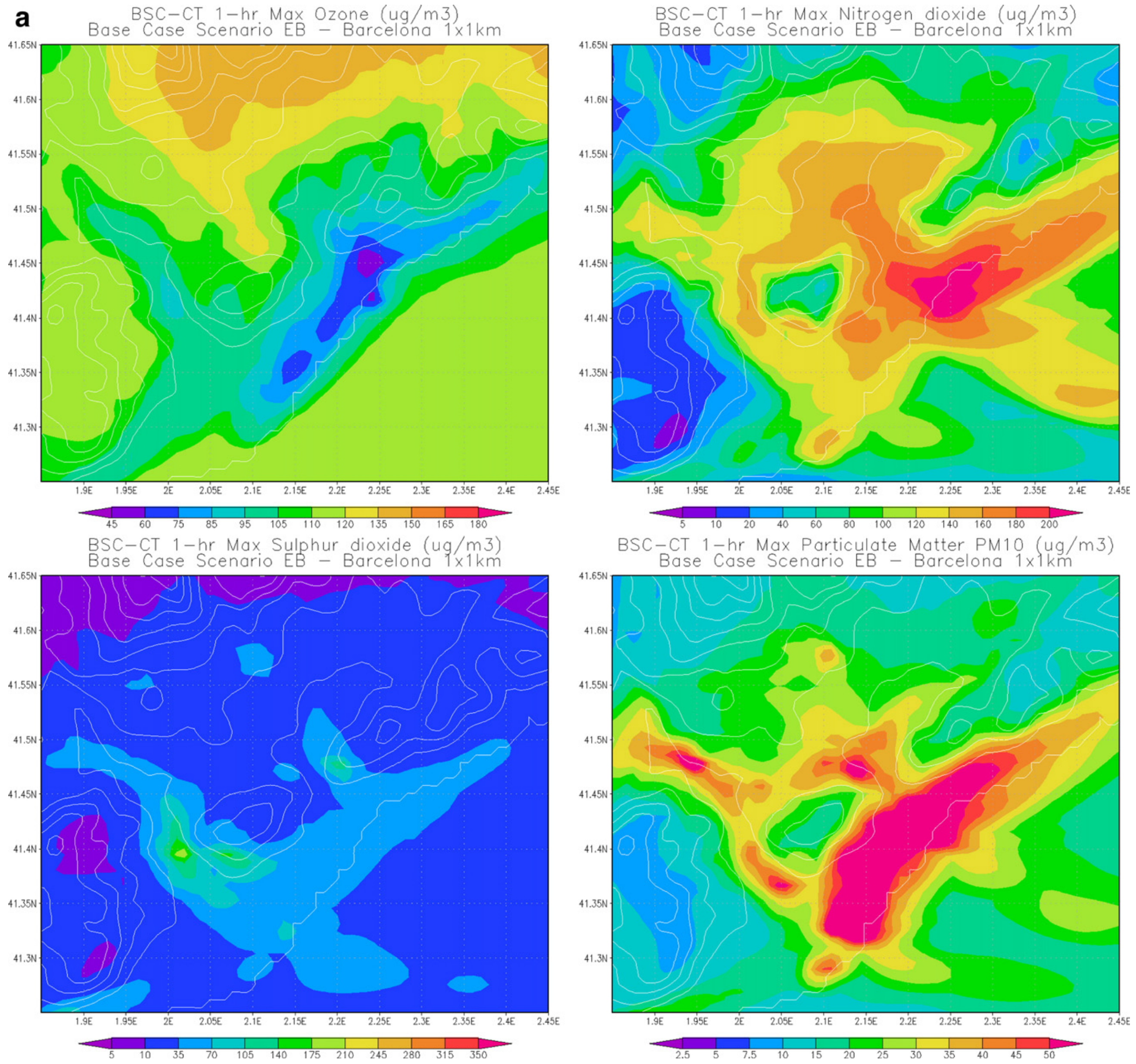

Fig. 2 – Maximum hourly concentration of O_3, NO_2, SO_2 and PM10 for the base case scenario in the Barcelona area (a) and in the Madrid area (b); and 8-h O_3 average concentration and 24-h NO_2, SO_2 and PM10 average concentration for the base case scenario in the Barcelona area (c) and the Madrid area (d) during the episode (17–18 June, 2004).

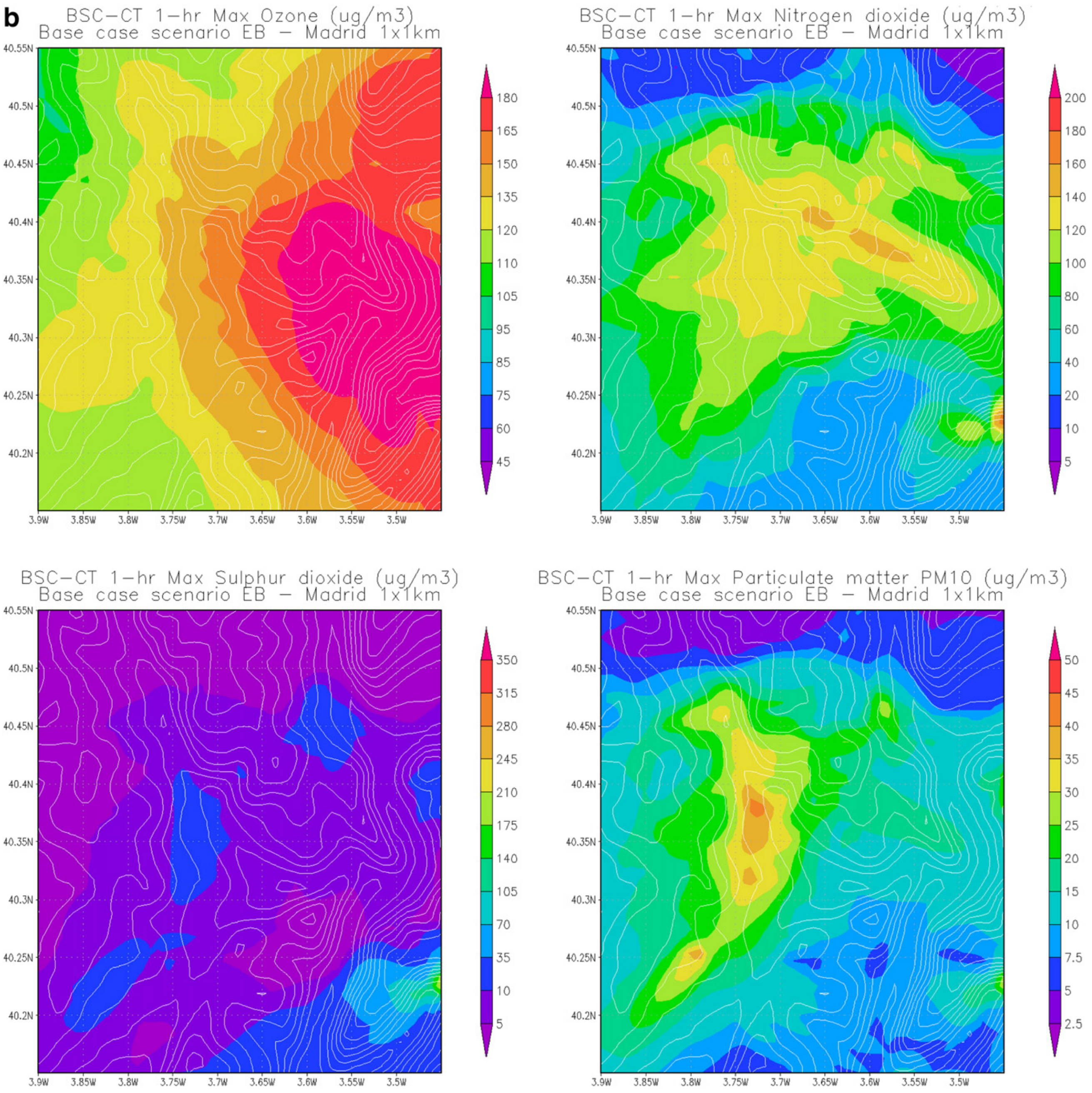

Fig. 2 (***continued***).

quality objective for modeling assessment methods. In addition, the US Environmental Protection Agency (US-EPA) has recently developed new guidelines (US EPA, 2005) that indicate that it is inappropriate to establish a rigid criterion for a model acceptance or rejection. However, in the EPA guide for the 1-hour ozone attainment demonstrations (US EPA, 1991), several statistical goals were identified for operational model performance. Although there is no criterion for a “satisfactory” model performance, US EPA (1991, 2005) suggested values of ± 10–15% for the mean normalized bias error (MNBE), ±15–20% for the unpaired peak prediction accuracy (UPA) and 30–35% for the mean normalized gross error for concentrations above a prescribed threshold (MNGE) to be met by modeling simulations of O_3, to be considered for regulatory applications.

The statistical values obtained as a result of the evaluation (Table 2) 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 15% for O_3 predictions, 28% for NO_2 and SO_2 estimations and 26% for PM10). They confirm the need for working with fine grids in areas where the influence of on-road traffic is important; it becomes essential for addressing air quality processes in urban and industrial areas, whereas for rural areas larger grids may be allowed, for example, to capture the non-linearity of the O_3 chemical formation as a function of precursor concentrations (Jang et al., 1995; Jiménez et al., 2005). A deeper discussion on this model evaluation can be found in Jiménez-Guerrero et al. (2008).

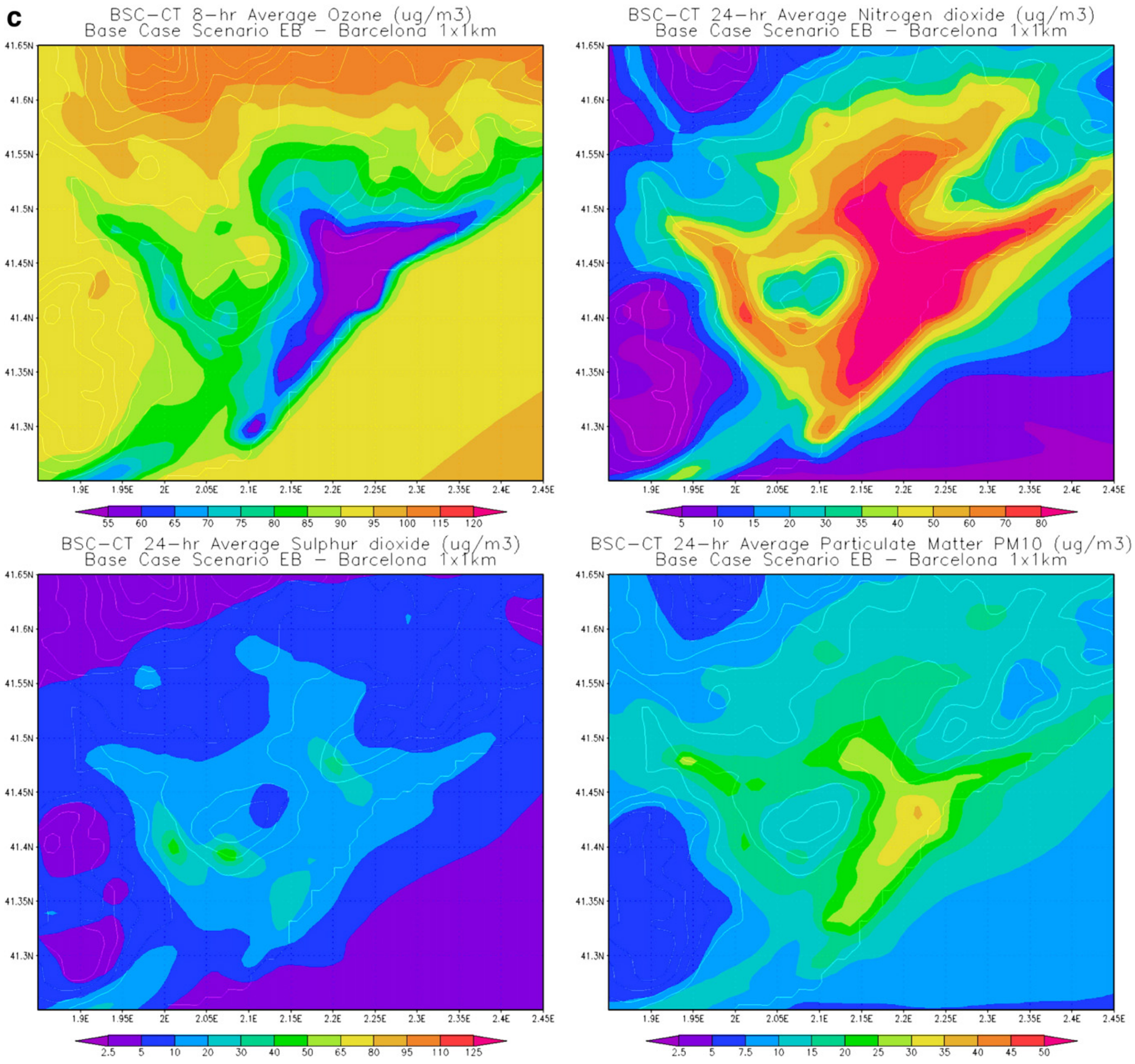

Fig. 2 (*continued*).

3.2. *Providing numerical results*

The simulations provide the hourly and average concentrations for all species considered in each cell of both northeastern and Central Iberian Peninsula domains (D4) (Fig. 1a and b). In order to assess the influence in Barcelona and Madrid, the analysis focuses on these areas, defining three domains in each of them (Fig. 1c to f): (1) two domains covering the greater areas in order to identify the average behaviors (Barcelona area, Madrid area); (2) two smaller domains (4 km^2) over downtown areas to define the direct effect on the city dwellers (Barcelona–Downtown, Madrid–Downtown); (3) finally, two domains (4 km^2) corresponding to the areas with the largest traffic density to estimate the largest changes achieved in cities (Barcelona–Gloriès, Madrid–Legazpi).

To compare the numerical results with European air quality targets (see Table 3) the maximum hourly concentrations for O_3, NO_2, SO_2 and PM10, the O_3 8-h average concentration and the daily average NO_2, SO_2 and PM10 concentrations are estimated. Also the variations in maximum and hourly concentration for each domain and scenario are calculated.

3.3. *Impacts of NGV on urban air quality: comparison among scenarios*

The base case scenario simulation for 17–18 June, 2004 indicates that the NO_2, SO_2 and PM10 concentrations are lower in Madrid than in Barcelona. Nevertheless, modeled O_3 values are higher in Madrid. For instance, the O_3 8-h average concentration is 76.9 µg m^{-3} in Barcelona and 86.0 µg m^{-3} in Madrid area (Table 4).

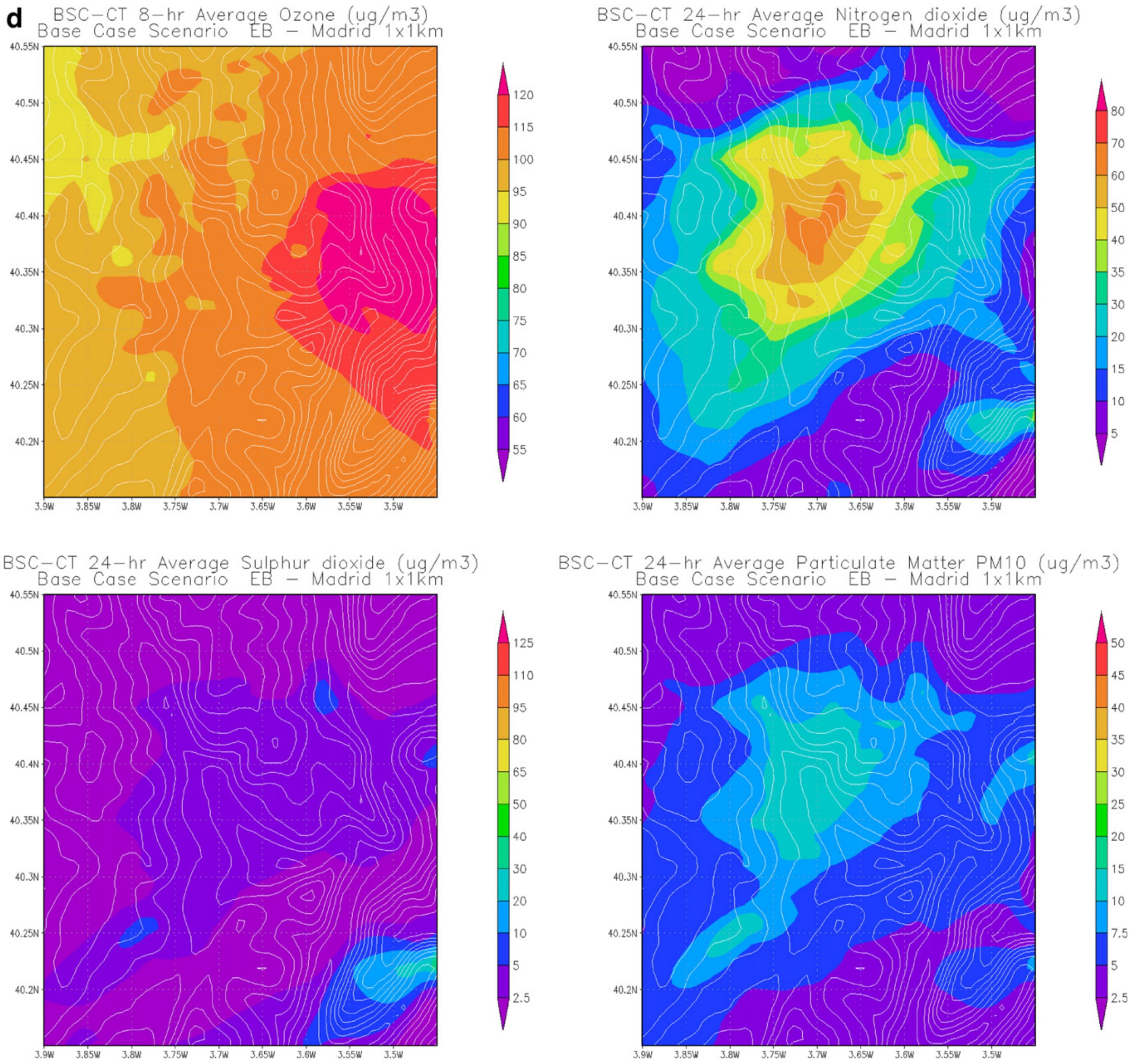

Fig. 2 (*continued*).

Both in Barcelona and Madrid areas the O_3 concentration is lower in downtown than in downwind areas (Fig. 2), due to the higher concentrations of NO that acts as an O_3 sink and to the depletion of radicals via HNO_3 formation by NO_2 consumption (Atkinson, 2000). Moreover the mobility data considered in both cities to estimate on-road traffic emissions distinguished four concentric zones in Madrid and five in Barcelona from the city centre. In these zones the circulation of specific vehicle types is enhanced face to others, according to their activity. The taxis, urban and intercity buses, commercial light vehicles and heavy duty freight transport vehicles were treated separately; resulting i.e. in a larger number of taxis or urban buses circulating in the very centre of the city and a larger number of freight transport vehicles in the outskirts (see Gonçalves et al. (submitted for publication) for details). The gradient of O_3 concentrations over the greater areas suggests that NO_x emissions are larger in the downtown due to a larger volume of traffic and to its specific typology: mainly petrol and diesel cars and light duty commercial vehicles.

The on-road traffic highly influences urban air pollution, resulting i.e. the highest NO_2 concentrations in the base case scenario along the road axis (Fig. 2). In Barcelona, NO_2 concentrations downtown are especially remarkable, exceeding in some cases the EU-limit for 1-hour average concentration (200 $\mu g\ m^{-3}$). Also PM10 and SO_2 concentrations are higher downtown than in the surrounding areas, but the SO_2 levels remain low in all cases (1-h maximum concentration lower than 350 $\mu g\ m^{-3}$ — limit for 1-h average concentration set by the EU-, and 24-h average concentration lower than 125 $\mu g\ m^{-3}$ — limit for 24-h average concentration, see Table 3). Problems related to air quality in

Madrid downtown are mainly associated to NO_2 and PM10, but the concentrations do not exceed the European targets in any case.

The NGV scenarios result in an increase of urban O_3 levels. This variation is larger in the combined scenario, E7 (Fig. 3), when the changes in the vehicle fleet are more pronounced (up to 26.1% of vehicles substituted in Barcelona and up to 23.1% in Madrid), which has a direct effect on emissions variation, see Table 1 (i.e. reductions in NO_x traffic derived emissions of −34.7% and −27.3%, respectively). The 8-h average concentration reaches 77.9 $\mu g\ m^{-3}$ in the Barcelona area domain (+1.3%) and 88.1 $\mu g\ m^{-3}$ in the Madrid area (+2.5%). This effect can be locally more important, i.e. for the Barcelona Downtown area increases of 7.8% are registered (79.3 $\mu g\ m^{-3}$ (+7.8%)). The highest concentration is estimated for Madrid–Legazpi: 147.0 $\mu g\ m^{-3}$ (+2.4%).

The introduction of NGV promotes the reduction of the NO_x concentration in cities, making O_3 concentration rise in most cases. This behavior is characteristic of VOC-sensitive areas, usually produced in conditions with relatively low VOCs and high NO_x (Sillman and He, 2002; Jiménez and Baldasano, 2004). Similar studies (Reis et al., 2000; Guariso et al., 2004) have reported analogous results locally in VOC-controlled areas when reducing NO_x emissions. In the case of Madrid the results suggest that it could be under a transition sensitivity regime; the response of the O_3 concentration presents a different trend depending on the ratio of NO_x/VOCs emissions reductions in each scenario. For example when transforming

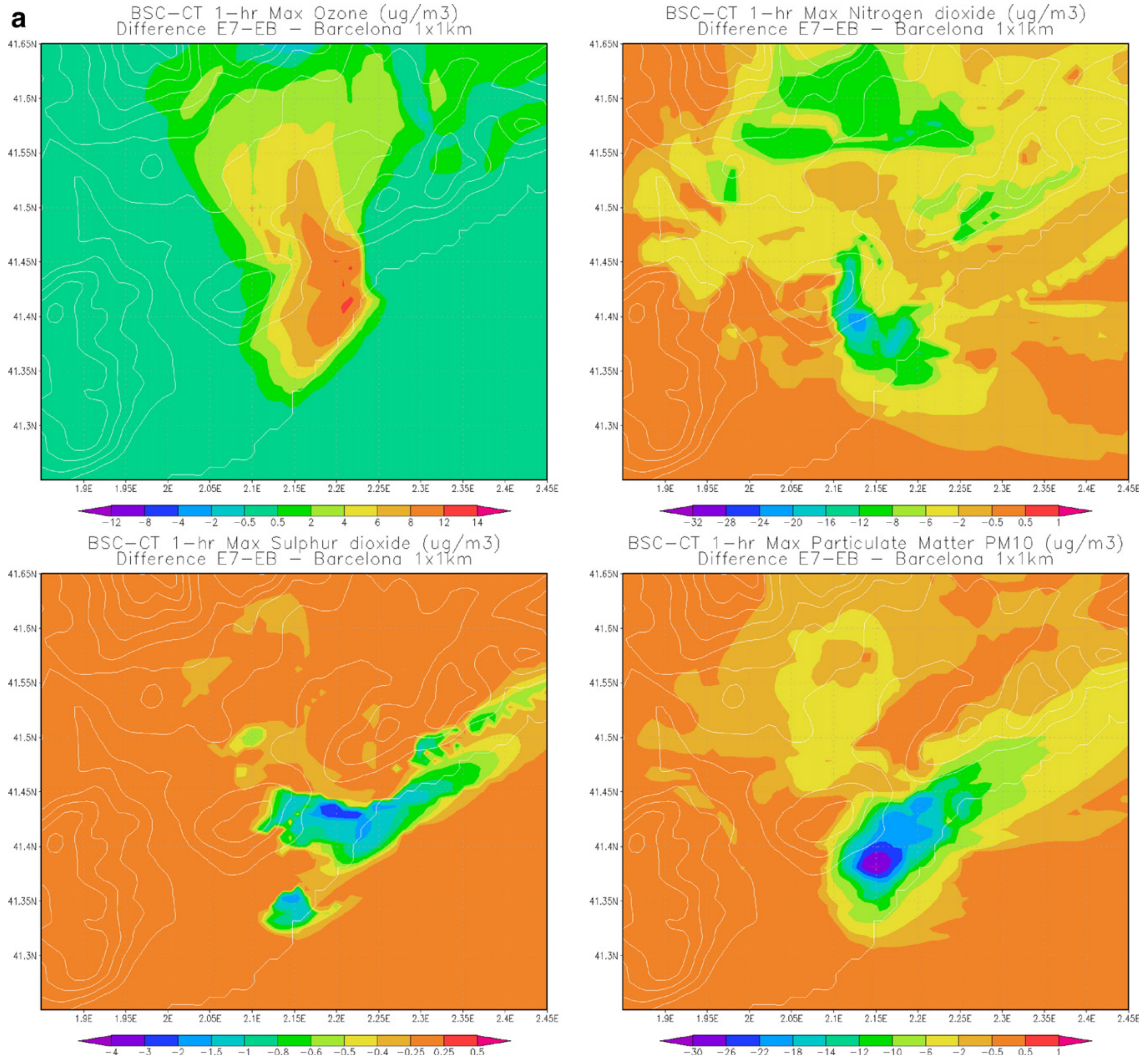

Fig. 3 – Difference in maximum hourly concentration of O_3, NO_2, SO_2 and PM10 in Barcelona area (a) and Madrid area (b); and difference in 8-h O_3 average concentration, and 24-h NO_2, SO_2 and PM10 average concentration in Barcelona area (c) and Madrid area (d) between the combined scenario and the base case scenario ($\mu g\ m^{-3}$) during the episode (17–18 June, 2004).

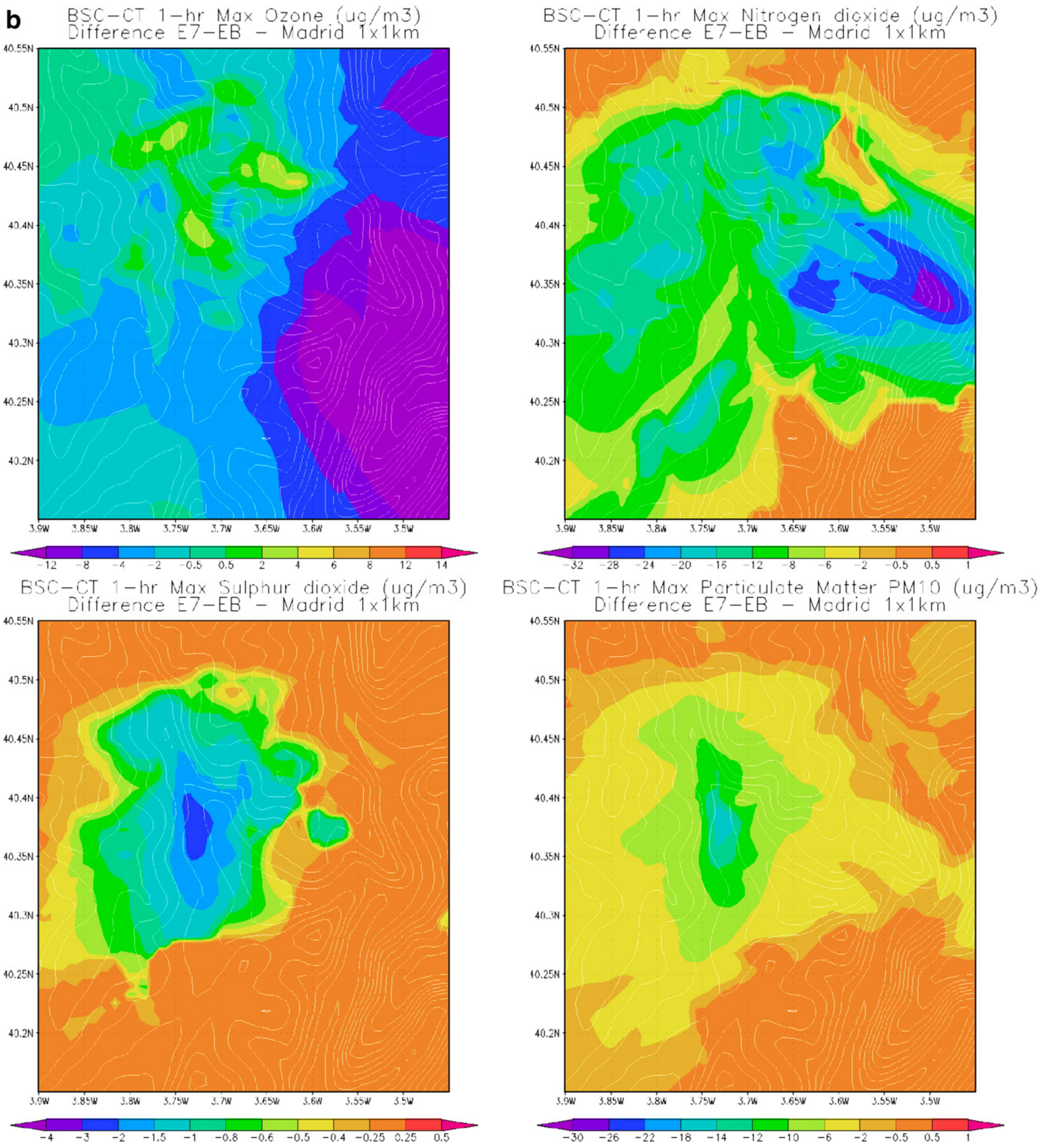

Fig. 3 (*continued*).

the 10% of the private cars to NG (E5) the O_3 maximum hourly concentration in Madrid–Downtown and Madrid–Legazpi domains slightly decreases (−1.0% and −2.1%).

The O_3 urban peaks increase with decreasing NO_x emissions for Barcelona area (Fig. 4), except when introducing 10% of NGV as private cars (E5). In this case a slight reduction in the maximum concentration is observed (around 0.5%), which does not affect the trend in 8-h average concentration (Table 4). On the other hand, for the Madrid area, a slight reduction on NO_x emissions (up to 0.04 k mol d^{-1}, Fig. 4) involves higher O_3 peaks, but for largest changes on NO_x emissions, the O_3 peaks locally decrease, being up to 3.7% lower in case of changing a 10% of private cars by NGV (E5) or up to 5.4% in case of introducing the combined scenario (E7). Moreover a decrease of O_3 8-h average concentrations when introducing in E5 and E7 occur in downwind areas of the Central Iberian Peninsula domain.

The effects on air quality of introducing NGV are positive in both urban areas in terms of NO_2, SO_2 and PM10 concentrations,

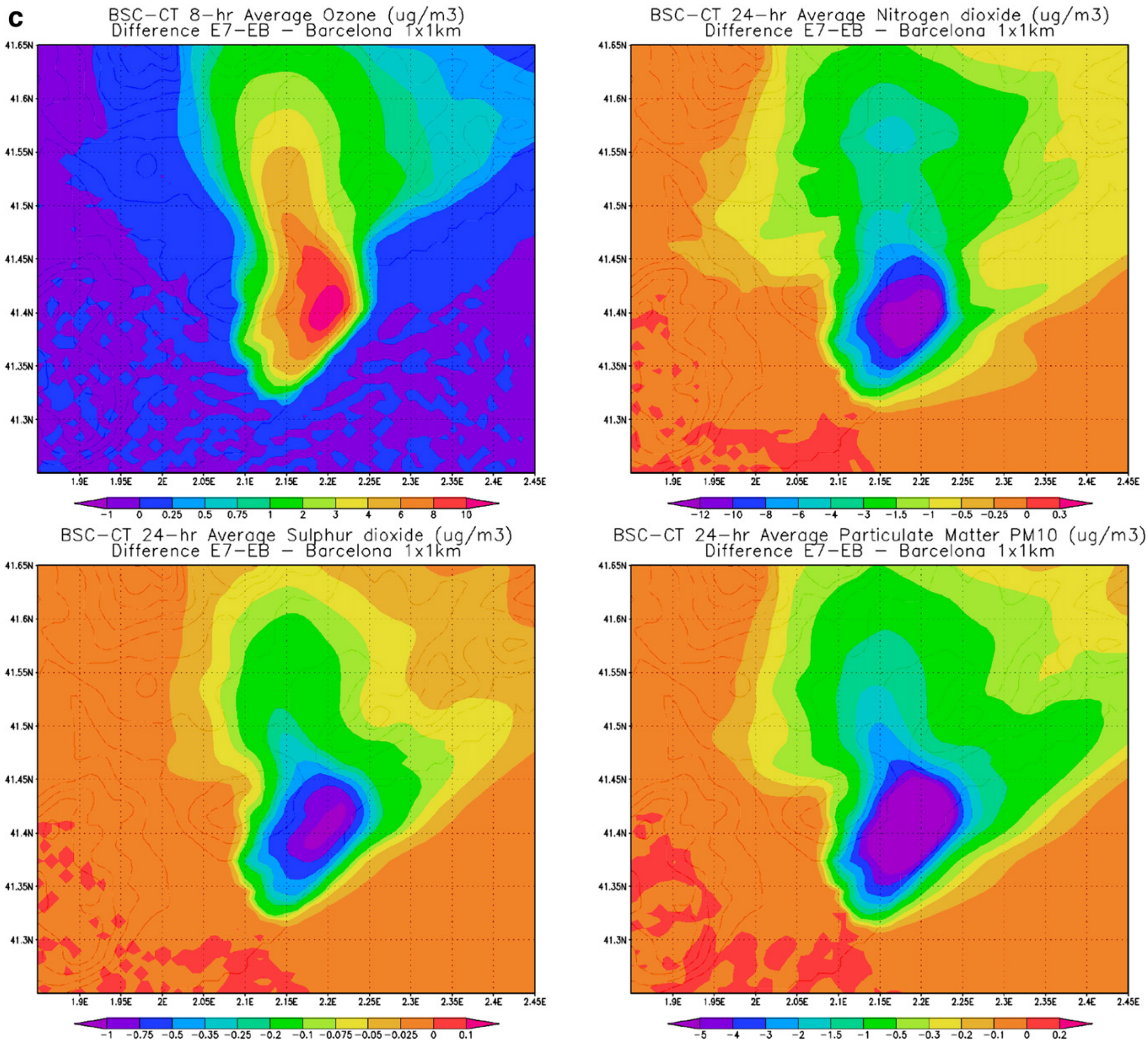

Fig. 3 (*continued*).

reducing both average and maximum hourly values in all scenarios tested. The E7 involves the largest reductions in all cases (Fig. 3). The NO_2 24-h average concentration in Barcelona reduces up to 6.1% (32.9 μg m^{-3},Table 4) from the base case scenario (35.0 μg m^{-3}). In Madrid the same scenario involves a reduction of 20.6% (17.7 μg m^{-3}; 22.2 μg m^{-3} in the base case; Table 4). The largest change is observed in Madrid–Legazpi domain where NO_2 24-h average concentration decreases 23.2%, from 63.6 μg m^{-3} to 48.8 μg m^{-3}.

The PM10 average reduction over Barcelona is 6.6% (9.7 μg m^{-3}; 10.4 μg m^{-3} in the base case; Table 5) and over Madrid is 14.9% (4.2 μg m^{-3}; 4.9 μg m^{-3} in the base case; Table 5. However the introduction of E7 affects particularly the maximum hourly concentration in Madrid–Downtown, where a reduction of 42.8% is estimated (from 33.7 μg m^{-3} to 19.3 μg m^{-3}).

The effects in SO_2 concentrations are more noticeable in Madrid than in Barcelona (up to 8.7% reduction in E7 for the 24-h average concentration, Table 5) reflecting the different composition of the emission sources between cities. While Madrid is characterized by a commercial and tertiary industrial activity in Barcelona a heavier industrial component is present, that has a direct effect on the weight of traffic contribution to SO_2 emissions (estimated in 53% of total SO_2 in mass for Madrid and 21% for Barcelona in Gonçalves et al., submitted for publication) and indirectly involves that a traffic emissions abatement strategy could be more effective in reducing SO_2 concentrations in Madrid than in Barcelona.

Introducing 50% of NG commercial light vehicles is the most effective scenario in reducing NO_2 in Barcelona (−2.5% on 24-h average concentration; Table 4), nevertheless in Madrid better results are achieved when changing the 10% of the private cars fleet (−8.2% on 24-h average concentration; Table 4). The vehicle fleet of Madrid city is mainly composed of diesel and petrol private cars and taxis (82% of the total

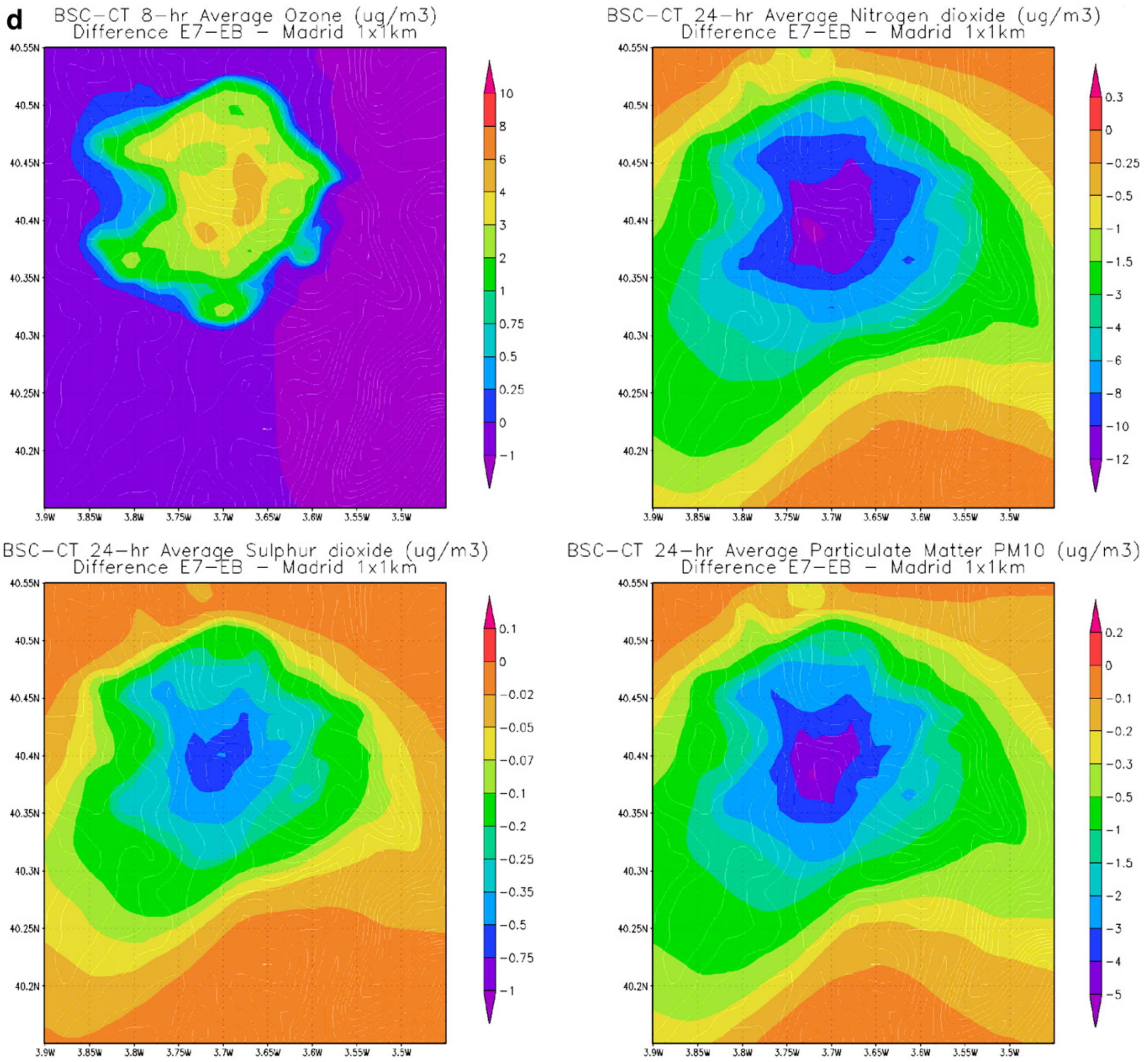

Fig. 3 (*continued*).

number of vehicles face to a 66% in Barcelona), which determines the important effect on the air quality of this scenario, according also with the estimated emissions reductions (15% reduction in NO_x traffic emissions in Barcelona and 10% reduction in Madrid, Table 1).

In order to reduce SO_2 and PM10 concentrations, the most effective measure involves the substitution of the oldest diesel and petrol light commercial vehicles, which are important contributors to the emission of these species. The major changes on air quality are registered both downtown and in the outskirts with an important industrial activity, which steps up this kind of vehicles circulation.

The substitution of the whole urban bus fleet in both cities, the 50% of the intercity buses or the 100% of the heavy duty freight transport vehicles by NGV is negligible in terms of air quality (<3% variation in the ground level concentration of pollutants in almost all cases) due to the relatively low number of vehicles involved (<1.5% of the total vehicle fleet in cities) and the low fuel substitution associated, from 1.4 to 3.2% of conventional fuels changed by NG. The diesel heavy duty vehicles substituted are usually large contributors to PM10 and SO_2 emissions, therefore the largest effects are noticed in these pollutants concentrations (e.g. the introduction of 50% of NG intercity buses involves −6.1% change in PM10 maximum hourly concentration in Madrid–Downtown).

The variations in pollutants concentrations when transforming the 50% of the taxis to NG cars are not remarkable; however they are more important in Madrid than in Barcelona area. All taxis substituted are considered as diesel cars, so that the effects are mainly noticed in terms of SO_2 and PM10 concentrations, e.g. in Madrid–Downtown the SO_2 maximum hourly concentration reduces 4.6% (from 10.1 $\mu g\, m^{-3}$ in the base

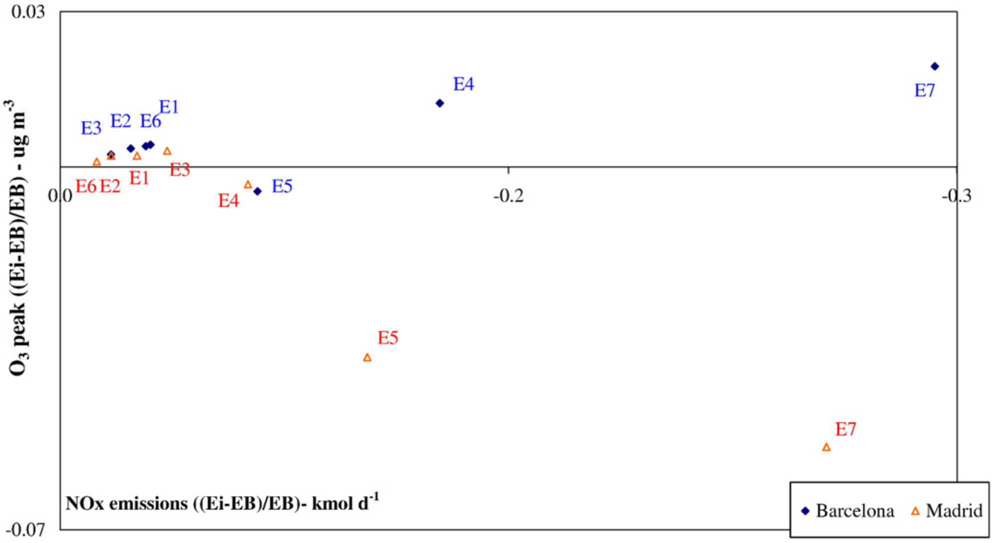

Fig. 4 – Changes in O_3 peak concentration when changing the NO_x emissions by natural gas vehicles introduction in Barcelona and Madrid areas. 17–18 June, 2004. EB: Base case scenario, *Ei*: i scenario, with i = 1, …7.

case to 9.6 μg m^{-3}) and PM10 maximum hourly concentration 6.1% (from 33.7 μg m^{-3} to 31.7 μg m^{-3}).

4. Conclusions

A photochemical pollution episode of the year 2004 is selected in order to assess the effects of the strategies to abate on-road transport emissions under the worst case perspective. The 17–18 June situation is representative of 45% and 36% of the annual transport patterns in the synoptic scale for the northeastern and Central Iberian Peninsula, and frequently corresponds to highly polluted situations. The results of the base case simulation indicate that the air quality improvement strategies in Barcelona and Madrid areas must be addressed mainly to reduce NO_2 and PM10 ground levels, which are larger in downtown areas due to the pervasive traffic emissions. O_3 levels could generate air quality problems, involving exceedances of the European targets in downwind areas, but not in the conurbations. Despite the

Table 5 – 24-h SO_2 and PM10 average concentration in Barcelona and Madrid areas

	Barcelona area			Madrid area		
	SO_2 24-h average concentration			SO_2 24-h average concentration		
	Conc (μg m^{-3})	ΔConc (μg m^{-3})	Variation (%)	Conc (μg m^{-3})	ΔConc (μg m^{-3})	Variation (%)
Base case	7.7	–	–	1.5	–	–
Scenario 1	7.7	−0.01	−0.18%	1.5	−0.02	−1.28%
Scenario 2	7.7	−0.02	−0.25%	1.5	−0.02	−1.30%
Scenario 3	7.7	−0.01	−0.09%	1.5	−0.02	−1.29%
Scenario 4	7.7	−0.05	−0.65%	1.4	−0.03	−2.28%
Scenario 5	7.7	−0.01	−0.17%	1.4	−0.03	−1.88%
Scenario 6	7.7	−0.01	−0.18%	1.5	−0.01	−0.63%
Scenario 7	7.6	−0.12	−1.52%	1.3	−0.13	−8.67%
	PM10 24-h average concentration			PM10 24-h average concentration		
	Conc (μg m^{-3})	ΔConc (μg m^{-3})	Variation (%)	Conc (μg m^{-3})	ΔConc (μg m^{-3})	Variation (%)
Base case	10.4	–	–	4.9	–	–
Scenario 1	10.4	−0.05	−0.48%	4.9	−0.06	−1.21%
Scenario 2	10.4	−0.07	−0.66%	4.8	−0.08	−1.64%
Scenario 3	10.4	−0.03	−0.29%	4.8	−0.09	−1.79%
Scenario 4	10.0	−0.42	−3.99%	4.6	−0.31	−6.24%
Scenario 5	10.4	−0.08	−0.74%	4.7	−0.17	−3.49%
Scenario 6	10.4	−0.05	−0.44%	4.9	−0.03	−0.54%
Scenario 7	9.7	−0.69	−6.60%	4.2	−0.73	−14.92%

Variation among scenarios.

SO_2 concentrations are higher in downtown areas than in the outskirts, they do not involve problems related to human health.

This study tests several feasible emission scenarios based on the specific vehicle fleet composition of each conurbation and differentiating vehicles fleets not only by their category (weight, age, fuel), but also by the activity they develop (taxis, public transport vehicles, etc). Hence, the system allows us to determine which specific groups of vehicles involve the largest improvements for the abatement of a specific pollutant.

As shown, the largest reductions are achieved in the combined scenario and the individual scenarios proving to be more effective in reducing NO_2, SO_2 and PM10 concentrations are the transformation of 50% of commercial light vehicles (involving approximately the 10% of current fuel substitution by NG of the EU proposal to 2020) and the 10% of private cars (around the 5% of current fuel substitution by NG proposed to 2010 by the EU). The latter is especially remarkable when considering NO_2 reductions in Madrid area. Urban O_3 concentrations slightly increase when reducing NO_x emissions, although for Madrid area the chemical sensitivity regime makes O_3 peaks decrease in the scenarios with largest NO_x emissions reductions.

The efficacy of the tested measures depends not only on the number and category of the vehicles substituted, but also on the specific characteristics of the conurbation. Madrid is a more favorable scenario to introduce traffic management strategies than Barcelona, where other emission sources must be controlled in addition, especially when referring to the decrease of PM10 and SO_2 levels. On the other hand, except for O_3, the levels of pollutants are higher in Barcelona, so that it becomes essential to introduce air quality management strategies in this area.

The simulation system WRF-ARW/HERMES/CMAQ proves to be a suitable tool for the management and assessment of urban air quality especially when applied with high spatial and temporal resolution.

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