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Air quality models sensitivity to on-road traffic speed representation: Effects on air quality of 80 km h^{-1} speed limit in the Barcelona Metropolitan area

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ABSTRACT

Atmospheric modeling permits to quantitatively assess the effects of emissions abatement strategies in urban areas, which are mainly oriented to reduce on-road traffic sector contributions. Nowadays the emissions inventories are one of the causes of uncertainties in air quality modeling. This work explores the improvements in urban air quality assessment by using the WRF-ARW/HERMES/CMAQ modeling system when switching from constant on-road traffic speed to hourly variable speeds taken from measurement campaigns in the emissions model. Furthermore, the effects of limiting the speed circulation in the Barcelona Metropolitan area to 80 km h^{-1} are assessed. A photochemical pollution episode representative of summertime conditions (corresponding to the year 2004) in the northeastern Iberian Peninsula and fitting in a usual traffic circulation pattern (working day) is selected to carry out the study. The introduction of variable speed in the HERMES emissions model affect the model evaluation in the urban area, improving specifically the O_3 precursors estimates, and consequently O_3 predictions in the area (reductions in mean normalized gross error (MNGE) around 1%). The speed limitation effects assessed with the modified modeling system represent improvements in air quality levels; specifically it reduces local NO_2, SO_2 and PM10 levels, up to 5.7%, 5.3% and 3.0% over the area affected by the speed limit, respectively. The O_3 concentrations slightly increase in the urban area (up to 2.4%), due to the chemical regime (NO_x emissions reduction in a VOCs limited area), but the effects in the urban plume are negligible. The need for air quality models as management tools makes essential to improve the emissions models accuracy, by introducing changes to better represent real conditions.

1. Introduction

The southern Mediterranean region and specifically the Iberian Peninsula frequently undergo summertime photochemical pollution episodes, which involve exceedances of the air quality targets set by the European Union, specifically concerning PM10 and O_3 levels (Jiménez et al., 2006), additionally high NO_2 levels are registered in conurbations (EEA, 2006a). Improving air quality in urban areas is nowadays an important environmental challenge (Fenger, 1999; Baldasano et al., 2003). The public administrations are testing management strategies mainly addressed to reduce on-road traffic emissions, because this sector is the largest contributor to anthropogenic pollutants emissions in the urban environments (Costa and Baldasano, 1996;

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Colvile et al., 2001; Querol et al., 2001; Artiñano et al., 2004; Ghose et al., 2004; Nagl et al., 2007). These strategies intend to either reduce the number of vehicles circulating on conurbations, in particular by urban tolls or parking taxes, or to mitigate the unitary emissions by vehicle, either using alternative fuels and new technology vehicles (hybrids, fuel cells, natural gas, biofuels, etc.) or changing the vehicle circulation speed.

The reduction of the number of vehicles circulating and therefore fossil fuel consumption decreases emissions and greenhouse gases outcome related to on-road traffic sector. The introduction of alternative fuels and new technologies normally involves the reduction of specific pollutants emissions. However, it may have secondary impacts such as unexpected changes in emissions composition (Richter and Williams, 1998; Fenger, 1999). Moreover the continuous growth of the vehicles use in the next 25 years would cancel the effects of technological improvements; therefore an exclusively technological answer to environmental problems related to transport could not be expected (Cannibal and Lemon, 2000). The combination of different strategies may be applied in the future.

A complementary way of reducing traffic emissions consists in changing the speed circulation patterns. The speed dependency of emissions varies as a function of the pollutant, depending on the vehicle age, weight and cubic capacity of the engine. Therefore a unique optimal speed circulation for atmospheric pollutants for the whole range of vehicles in an urban fleet does not exist (Keller et al., 2008). Nevertheless, it is a widely adopted traffic management strategy, because its benefits concern not only pollutants emissions, but also reduces congestion, noise and traffic accidents.

The design of strategies to reduce tropospheric O_3 is affected by the non-linearity of the reactive transport of pollutants and the uncertainty that the kinetics of O_3 represent in atmospheric chemistry (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). The third generation Eulerian grid models represent nowadays the state-of-the-art in air quality modeling. The emissions inventories are found one of the main causes of uncertainties in this kind of models predictions (Russell and Dennis, 2000). In particular, on-road traffic modules need more emissions measurements from vehicle types and pollution control technologies to parameterize emissions (Carslaw and Beevers, 2005). Currently, the most used on-road traffic emission models, such as MOBILE or COPERT, apply average speeds to estimate the emission factors for vehicles. An accurate prediction of circulation speed is a key issue to get better traffic emissions models (Smit et al., 2008).

This work pursues two objectives: (1) to assess the performance of the WRF-ARW/HERMES/CMAQ air quality model when changing the constant speed by road stretch initially considered in HERMES by hourly speed cycles obtained from experimental campaigns for several roads in the Barcelona Metropolitan area; and (2) to analyze the effects of introducing a speed limit of 80 km h^{-1} in the road network of Barcelona Metropolitan area on air quality, which is planned by the regional administration to ameliorate the air quality conditions.

2. Methods

2.1. Modeling system

The Weather Research and Forecasting (WRF) model (Michalakes et al., 2005) provides the meteorology parameters as inputs to the Models-3 Community Multi-scale Air Quality (CMAQ) model (Byun and Schere, 2006). The High Elective Resolution Emission Modeling System (HERMES) has been developed specifically for Spain with a high resolution (1 km^2–1 h) (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 taking the year 2004 as calculation basis) considers the emissions from: (1) power generation plants, (2) industrial installations, (3) domestic and commercial fossil fuel use, (4) domestic and commercial solvents use, (5) road transport, (6) ports, (7) airports and (8) biogenic emissions.

The traffic emissions module of HERMES considers fundamentally a bottom-up approach and takes into account 72 diesel and petrol vehicles categories (including Euro II and Euro III emission standards) according to COPERT III – EEA-EMEP/CORINAIR methodology (Nziachristos and Samaras, 2000; EEA, 2006b); divided by fuel type, vehicle weight, age of the vehicle and cubic capacity; each of them with its specific emissions factors, defined as a function of the circulation speed. The emissions account in HERMES traffic module considers hot exhaust, cold exhaust and evaporative emissions. It also estimates particulate matter produced by brakes abrasion, tire wear and pavement erosion. The vehicular fleet is defined for Spain and specifically for Barcelona in this case of study using data provided by the national traffic management organism of Spain for 2004, and distributed in the 72 previous mentioned categories. The model includes the definition of the road network, dividing it in stretches (inside the 1 km^2 cells) with specific temporary disaggregating profiles (distinguishing day-type: weekday-holiday, and month), specific average speed, daily average traffic (number of vehicles per day), stretch length, route type (highway, road or urban) and circulation zones. This information is obtained both from local and national agencies and covers a 67% of the intercity roads length for the whole national territory, which in traffic volume involves approximately 80–85% of the total. Concerning urban roads, the available information covers the total road network for Barcelona and Madrid Greater areas, which involves 50% of the national urban traffic volume.

The WRF-ARW/HERMES/CMAQ was applied to the final study area with high spatial (1 km^2) and temporal (1 h) resolution (Fig. 1). The use of fine resolution was demanded by the necessity of assessing the subtle air quality variations in urban areas, as shown in the CityDelta project (Cuvelier et al., 2007; Thunis et al., 2007); and in order to describe the transport and transformation of pollutants, as well as the dynamics on an hourly basis in very complex terrains (Jiménez et al., 2005, 2006). Four one-way nested

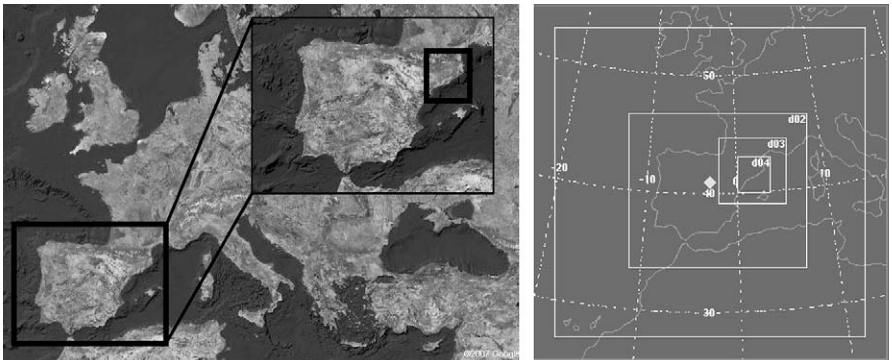

Fig. 1. Four one-way nested domains defined to perform the air quality simulations (D1 – European domain 55 × 55 cells of 54 km; D2 – Iberian Peninsula domain 94 × 82 cells of 18 km; D3 – Iberian Peninsula Zone: 104 × 103 cells of 6 km; D4 – northeastern Iberian Peninsula domain 322 × 259 cells of 1 km).

domains were defined for the simulations, centering the final domain (D4) in Barcelona (Fig. 1), which covers the northeastern Iberian Peninsula (322 × 259 km^2), to assess not only the effects in the urban area, but also to detect the urban plume behavior in downwind areas. The availability of the MareNostrum supercomputer hold in the BSC-CNS, together with the advances in the parallelization of air quality model codes, has allowed the high resolution simulations.

The initial and boundary conditions for the CMAQ simulations 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 2004 and disaggregated to 18 km (Fig. 1). A 48-h spin-up was performed to minimize the effects of initial conditions for the innermost domain. The chemical mechanism selected for the simulations following the criteria of Jiménez et al. (2003) was Carbon Bond IV including aerosols and heterogeneous chemistry. NO_x and volatile organic compounds (VOCs) speciation of HERMES emissions are detailed in Parra et al. (2006).

A critical episode of photochemical pollution was selected according to elevated air quality data monitored in the study area. The traffic circulation pattern should be adapted to usual working day conditions. The chosen episode was the 17–18 June 2004 (Thursday and Friday). It corresponds to a typical summertime low-pressure gradient with very high levels of photochemical pollutants (especially O_3 and PM10) over the entire Iberian Peninsula. These conditions dominate 45% of the annual and 78% of the summertime transport patterns over northeastern Spain (Jorba et al., 2004) and are associated with local-to-regional episodes of air pollution related to high levels of O_3 during summer (Toll and Baldasano, 2000; Barros et al., 2003; Jiménez et al., 2006)

2.2. HERMES modifications and the 80 km h^{-1} scenario definition

This section describes the three different emissions cases analyzed in this work: (1) the base case of HERMES, which considers constant speed by road stretch (CS); (2) the HERMES-modified case, which introduces variable speed cycles for the Barcelona area (VS); and (3) the scenario considering the introduction of a 80 km h^{-1} speed limit in the Barcelona area (V80).

2.2.1. From constant to variable speed in HERMES on-road traffic module

During the last decades the information included and processed in the emissions models became more and more complex, intending to be closer to reality. In this sense from the constant average speed by road type (highway, road and street) considered by on-road traffic emission models in the nineties (Costa and Baldasano, 1996), there was an evolution to a specific speed definition by road stretch (Parra et al., 2006). The next step in speed representation might be oriented towards the inclusion of variable speeds, based on measurement campaigns, as proposed in this work.

Initially a constant average speed by road stretch (obtained from the TeleAtlas cartography for 2004) was considered in the HERMES traffic module. The real circulation conditions, such as traffic congestion, involve variations of this ideally represented speed. Hourly averaged speeds obtained from measurement campaigns (RACC, 2008) are implemented in the main roads of the Barcelona Metropolitan area. The campaign covers an area of 30 km of radius from the conurbation of Barcelona and provides information about traffic circulation speed in the working days from 15 May to 28 July 2006 and from 20 September to 17 October 2006, in selected roadways (the B-10, Ronda Litoral, B-20 (C-32), Ronda de Dalt – Túnel de Vallvidriera (C-16), C-58, C-31 (N and S), C-32, B-23 and A 2), which involve 360 road stretches of those defined in HERMES (in pale blue and red dots in Fig. 2). These include both roads and highways. The constant speed circulation was changed in these locations by a daily speed cycle based on the real data with hourly discrete values (i.e. Fig. 3 depicts the daily speed cycle for the C-31 highway stretches as defined in HERMES-modified). The traffic volume (number of vehicles by km in a daily basis) affected is 32% estimated for the Barcelona area (Fig. 2, in yellow).

2.2.2. 80 km h^{-1} speed limit scenario (V80)

The model is used to assess the pollutants emissions variation and the air quality changes when introducing a traffic management scheme based on regulated speed. The plan of the regional government imposes a maximum speed

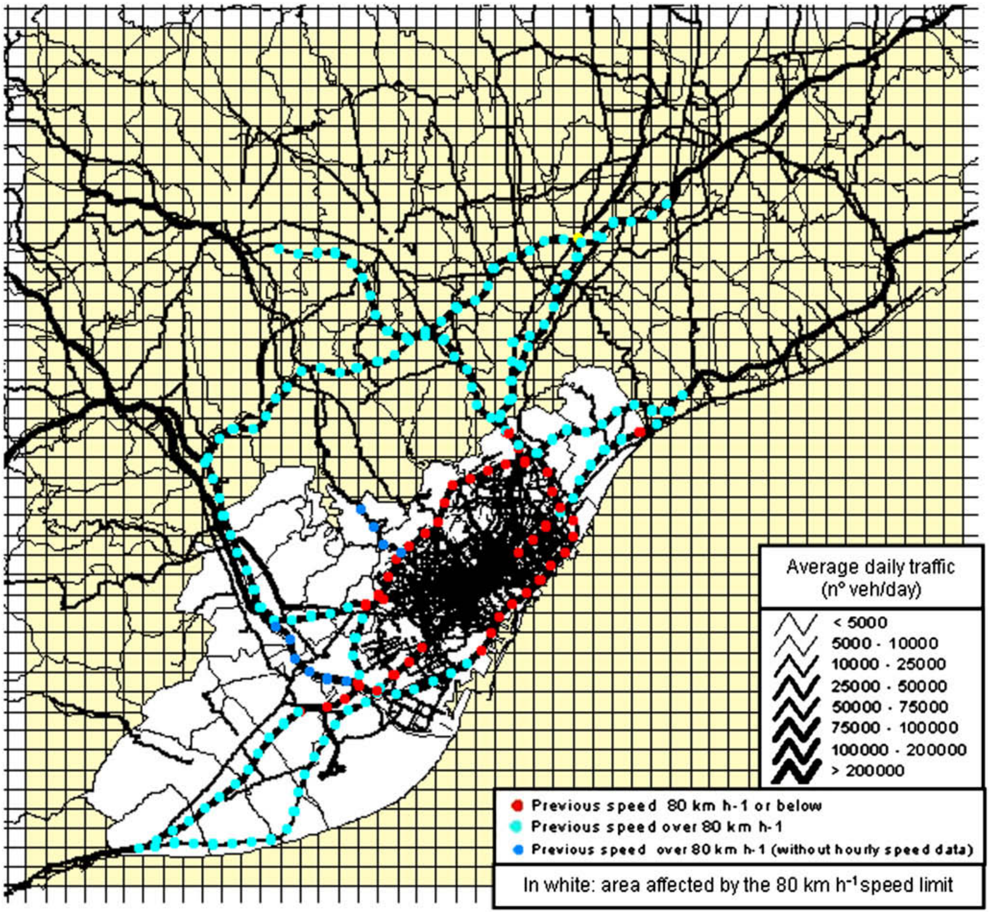

Fig. 2. Road network description implemented in HERMES, zoom over the Barcelona area, the thickness of the road stretches indicates the average daily traffic (AVT) circulating by them. The pale blue and red dots denote those locations where hourly speed data were available. The speed limit measure was introduced only in the Barcelona Metropolitan area (in white). The red dots denote those locations affected by the speed limit that were already circulating at or below 80 km h^{-1}, and therefore remain unaffected by the limitation. The blue dots inside the Barcelona Metropolitan area were changed to 80 km h^{-1} in the V80 scenario. The area of the northeastern Iberian Peninsula selected for the emissions variation analysis is depicted in yellow. It covers 2112 km^2, with 1457 km^2 over land surface.

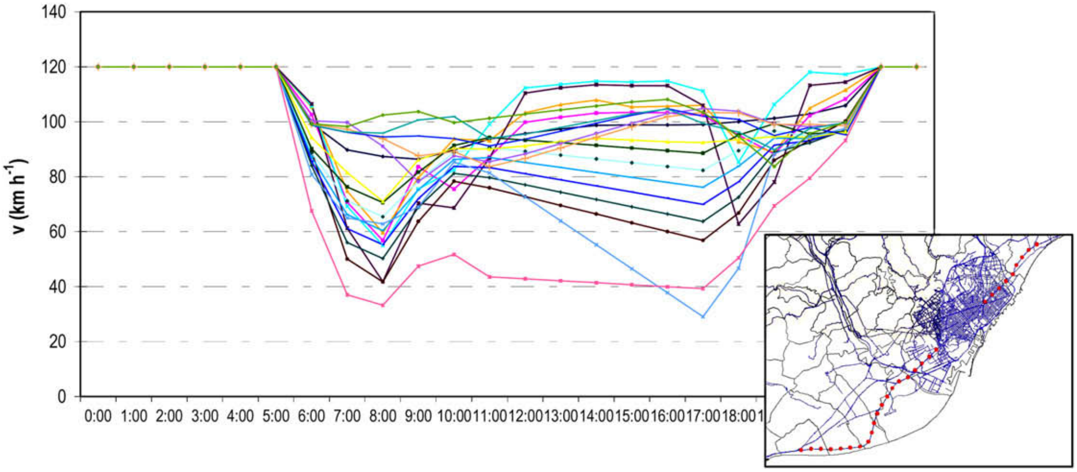

Fig. 3. Speed dependency considered in HERMES-modified for the depicted highway in the Barcelona area (red dots). The variable speed data are available from 6:00 to 23:00 h, the 24:00 to 5:00 h period is covered with the previous constant speed provided by the TeleAtlas cartography. In this case the constant speed previously considered in HERMES was 120 km h^{-1}.

of 80 km h^{-1} for motorways, dual carriageways and main roads of the Barcelona Metropolitan area. This scenario is introduced in the traffic emissions module by changing the speed circulation in the affected road stretches. The new speed limit is introduced only in those roads which had a previous average speed higher than 80 km h^{-1} (in blue dots over the Barcelona Metropolitan area in Fig. 2-a), taking into account real driving conditions and congestion patterns. It is assumed that congestion would not affect these 80-limited roads, because they were not affected before and road capacities may increase by decreasing the circulation speed. Therefore constant speed of 80 km h^{-1} is considered for the whole road links affected.

3. Results and discussion

3.1. Traffic emissions analysis: base case with constant speed (CS), base case with variable speed (VS) and 80 km h^{-1} speed limit scenario (V80)

The northeastern Iberian Peninsula domain covers 83 398 km^2 and is located in the Mediterranean littoral. The major sources of pollutants emissions are the urban areas of Barcelona, accounting for 3.1 million inhabitants, and Tarragona, which is located in a densely industrialized area, and the road network connecting the Iberian Peninsula with France, all of them located along the coastal axis. The HERMES–CS model estimates 158.1 t d^{-1} of NO_x emitted for 18 June. Fifty per cent is produced by on-road traffic, which constitutes the main source of primary pollutants in the region, contributing also with a 48% of the 759.6 t d^{-1} of NMVOCs emitted in the domain. In this particular case 33% comes from biogenic sources. The power generation and the industrial sectors are the main emitters of SO_2 and primary particles, accounting for a 93% and a 73% of the mass emissions (162.6 t d^{-1}, 47.4 t d^{-1}), respectively.

The Barcelona urban traffic (Fig. 2-a) is responsible for 47–58% of on-road traffic emissions depending on the pollutant. The variable speed introduction in the model (HERMES–VS) produces a reduction of 4.2 t d^{-1} of NO_x, 0.1 t d^{-1} of SO_2 and 0.3 t d^{-1} of primary particulate matter (PM10) emissions, while the NMVOC emissions increase in 0.5 t d^{-1}. The largest changes occur in CO emissions estimates, considering constant speeds by stretch the total amount of CO was 610 t d^{-1}; the HERMES–VS provides an estimation of 595 t d^{-1} emitted for the whole northeastern Iberian Peninsula domain (D4 in Fig. 1).

Focusing the analysis on the Barcelona area (Fig. 2-a) the changes in the traffic emissions (Fig. 4) by the introduction of the variable speed involve reductions of 5.7% of NO_x, 5.1% of CO, 4.8% of SO_2 and 5.1% of PM10 emissions. The NMVOCs estimated for the area increase by 0.3%. These changes would have effects in pollutants concentrations predicted in the area and hence in the performance of the model estimates.

The strategy of introducing an 80 km h^{-1} speed limit for the Barcelona Metropolitan area road network (V80 scenario) reduces emitted NO_x and CO from traffic in a 1.0%, and PM10 and SO_2 by 0.9% within the Barcelona area, while the NMVOC emissions increase in 0.01% respect to the variable speed base case (Fig. 4). These variations are four times lower than those due to the change from constant to variable speed, because several limited roads were already circulating at speeds lower than 80 km h^{-1}, especially during the daytime periods in which congestion is larger: morning and afternoon traffic peaks (Fig. 3). Keller et al. (2008) obtain equivalent emissions trends when introducing the 80 km h^{-1} speed limit in Swiss highways, previously considered as circulating at 120 km h^{-1}; NO_x emissions decrease during summertime by 4.3% and NMVOC emissions remain almost constant. The vehicle fleet composition and the extent of the management measure differ from our study and they do not consider congestion effects, which explain the differences observed in the emissions variations ratio.

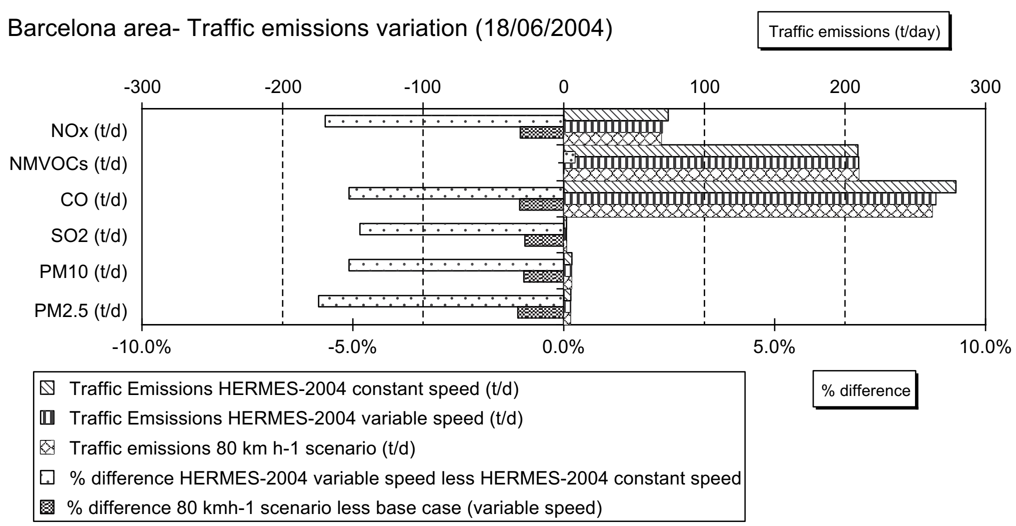

Fig. 4. Traffic emissions estimations provided by HERMES in the base case (constant speed), in the modified base case (variable speed) and in the scenario that considers the 80 km h^{-1} speed limit in the Barcelona area. The emissions account is provided for the Barcelona area (Fig. 2) for the 18 June 2004.

3.2. Air quality model evaluation: changes in model performance when including HERMES–VS

Air quality surface station hourly data (provided by the Environmental Department of the Catalonia Government, Spain) over the domain of study are used to evaluate the performance of WRF-ARW/HERMES/CMAQ 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, 2002/3/EC and 2008/50/EC assumes an uncertainty of 50% for O_3, and between 50% and 60% for NO_2 and SO_2 hourly concentrations estimations, for the air quality objective for modeling assessment methods. This uncertainty is defined as the maximum error of the measured and calculated concentration levels. The statistical values obtained as a result of the evaluation considering the estimated emissions of HERMES with constant speed representation by road stretch meet the uncertainty objectives set by the European Directives.

Additionally the modified modeling system, when introducing variable speed cycles in the Barcelona Metropolitan area, is used to assess the air quality levels in the region. These predictions were validated against the same air quality stations data. Table 1 lists the mean normalized bias error (MNBE), corresponding to the average differences between the modeled and the observed concentrations (Eq. (1)), mean normalized gross error (MNGE), corresponding to the absolute values for the differences between modeled and observed concentrations (Eq. (2)) and unpaired peak accuracy (UPA), corresponding to the differences in modeled and observed peak concentrations (Eq. (3)) of the constant and the variable speed scenarios.

$$\mathrm{MNBE}(\%) = \frac{(\mathrm{MOD} - \mathrm{OBS})}{\mathrm{OBS}}100 \quad (1)$$

$$\mathrm{MNGE}(\%) = \frac{\mathrm{abs}(\mathrm{MOD} - \mathrm{OBS})}{\mathrm{OBS}}100 \quad (2)$$

$$\mathrm{UPA}(\%) = \frac{\max(\mathrm{MOD}) - \max(\mathrm{OBS})}{\max(\mathrm{OBS})}100 \quad (3)$$

Where MOD are the concentrations estimated by the model and OBS are the monitored concentrations.

The results for several stations selected over the Barcelona area (Table 1, Fig. 5-a) indicate that the model underestimates O_3 concentrations, both using HERMES–CS and HERMES–VS emissions as inputs. The introduction of variable speeds based on experimental data involves light improvements in O_3 predictions, reducing in some cases the statistical parameters, i.e. in L'Hospitalet or Montcada air quality stations from 1 to 2% reductions on MNBE, MNGE and UPA are observed.

The underpredictions of NO_2 concentrations occurring in the Barcelona area (i.e. BCN-Eixample, L'Hospitalet or St Vicenç) are not improved with the methodological change in HERMES. The NO_x emissions from traffic considering the real time speed cycles are lower than those previously estimated by using the HERMES data with constant speed.

Table 1
Model evaluation statistical parameters for the HERMES (CS – constant speed) and the HERMES-modified (VS – variable speed) simulations for several AQS (Fig. 5-a) in the Barcelona area

BCN-Eixample AQS	MNBE (%)		MNGE (%)		UPA (%)	
	CS	VS	CS	VS	CS	VS
O_3	−11	**−11**	11	**11**	−19	*−18*
NO_2	−42	**−42**	44	**44**	−29	**−29**
PM10	−35	**−35**	40	**40**	−2	*−1*
SO_2	−37	**−37**	60	**60**	−47	**−47**
L'Hospitalet	MNBE (%)		MNGE (%)		UPA (%)	
AQS	CS	VS	CS	VS	CS	VS
O_3	−14	*−13*	18	*17*	−29	*−28*
NO_2	−21	−23	35	36	−15	−15
PM10	−37	−38	47	48	−53	−54
Sta Coloma	MNBE (%)		MNGE (%)		UPA (%)	
AQS	CS	VS	CS	VS	CS	VS
O_3	−48	**−48**	48	**48**	−52	**−52**
NO_2	49	**49**	62	**62**	3	**3**
SO_2	−26	**−26**	39	**39**	14	**14**
BCN-Gracia	MNBE (%)		MNGE (%)		UPA (%)	
St Gervasi AQS	CS	VS	CS	VS	CS	VS
NO_2	−54	−55	54	55	−46	**−46**
PM10	−7	**−7**	35	**35**	8	9
SO_2	−48	**−48**	52	**52**	−8	**−8**
St Vicenç	MNBE (%)		MNGE (%)		UPA (%)	
AQS	CS	VS	CS	VS	CS	VS
O_3	−8	**−8**	18	*17*	−13	**−13**
NO_2	−12	**−12**	72	**72**	1	**1**
PM10	−23	**−23**	63	**63**	−66	**−66**
Granollers	MNBE (%)		MNGE (%)		UPA (%)	
AQS	CS	VS	CS	VS	CS	VS
O_3	−9	*−8*	21	*20*	0	2
NO_2	6	*3*	57	**57**	−42	**−42**
SO_2	−75	**−75**	75	**75**	−84	**−84**
Montcada	MNBE (%)		MNGE (%)		UPA (%)	
AQS	CS	VS	CS	VS	CS	VS
O_3	−25	*−23*	27	*26*	−32	*−31*
NO_2	1	−3	32	33	−11	**−11**

Italic values reflect an improvement in and underline values reflect a worsening.

The underpredictions may be caused by traffic related emissions, either due to uncertainties in emissions factors or to an underestimation of the real traffic volumes. Nevertheless, the origin of the discrepancies between modeled and measured NO_2 levels could not only be attributed to the emissions estimates, but also to the chemistry representation in the model or the meteorological predictions, which particularly showed problems in representing wind fields during calm situations such as those investigated in this study (Jiménez et al., 2008).

The model tends to underestimate both SO_2 and PM10 average and peak concentrations in the Barcelona area. When introducing the HERMES–VS data the PM10 predictions remain almost constant, improving at some points (i.e. 1% reduction in the UPA for the BCN-Eixample PM10 estimates) but worsen in others (i.e. 1% increase of the MNGE in the L'Hospitalet station for PM10 predictions). One of the reasons for the PM10 underpredictions in the area can be found in the emissions model itself, which does not take into account natural sources of primary

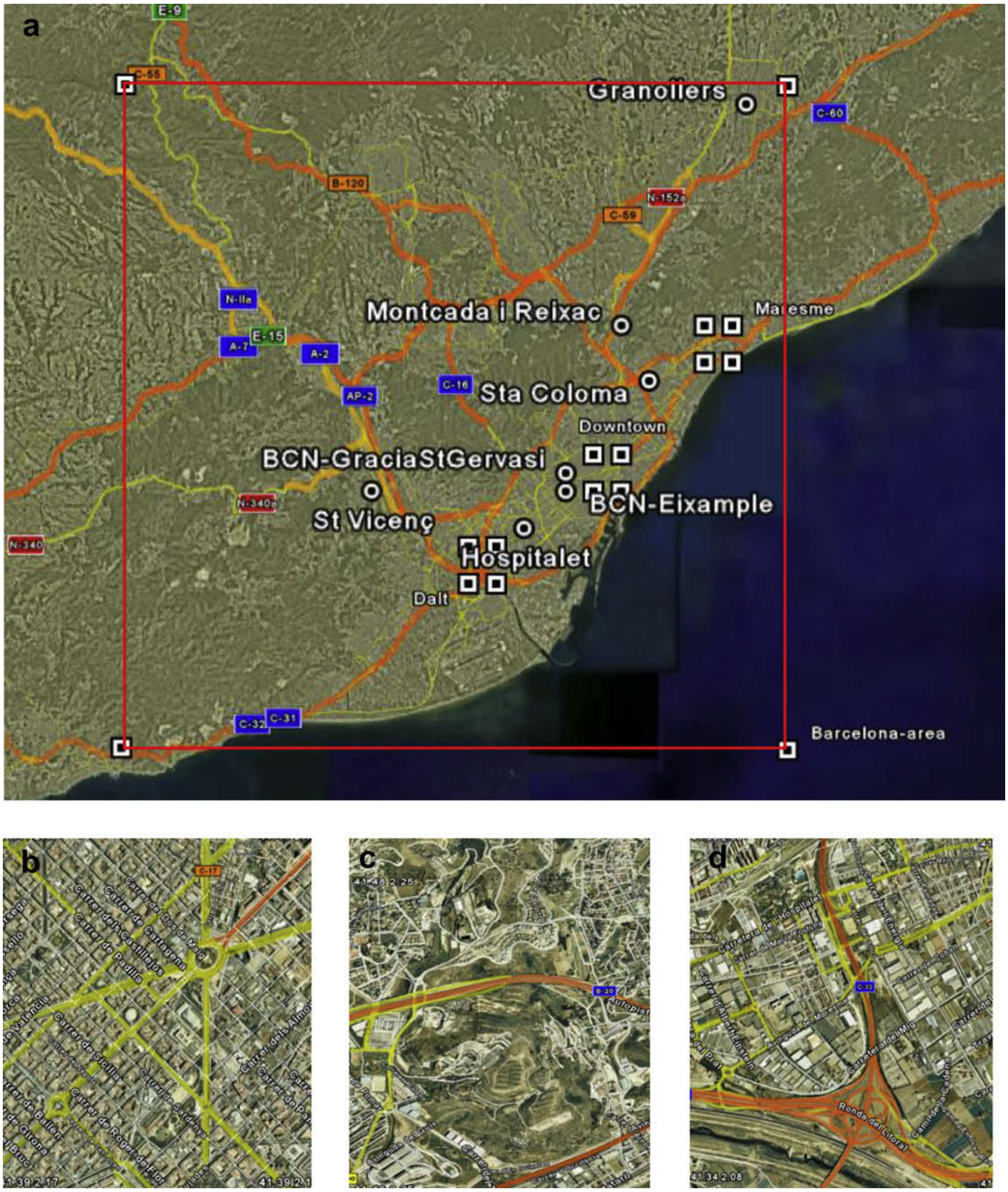

Fig. 5. (a) Selected air quality stations in the Barcelona area to perform the model assessment with HERMES and HERMES-modified. Inside the red square: Barcelona area (40×40 km^2, 41°15″0″N – 41°36″36″N; 1°49″48″E – 2°18′36″E), (b) Barcelona downtown (2×2 km^2, 41°23′24″N – 41°24′36″N; 2°10′12″E – 2°11′24″E), (c) Barcelona Maresme (2×2 km^2, 41°27′36″N – 41°28′48″N; 2°15′0″E – 2°16′12.00″E), (d) Barcelona Dalt (2×2 km^2, 41°20′24″N – 41°21′36″N; 2°4′48″E – 2°6′0.00″E) domains selected for the evaluation of the management strategy effects on air quality.

particulates such as erosive or saltation processes or marine aerosols which may be important for the area of study (Vautard et al., 2005). Moreover the inaccuracies in representing accumulation and transport patterns during this low gradient pressure situation could be other source of these underpredictions. The SO_2 emissions contribution of the on-road traffic sector in the northeastern Iberian Peninsula domain accounts for 2% of the daily mass emissions. The improvement of the traffic representation in the Barcelona area (which accounts for a 49% of SO_2 traffic related emissions in that region) does not involve appreciable changes in model performance, indicated by constant statistical parameters for all stations.

3.3. Air quality variation when introducing the limit in speed circulation to 80 km h^{-1}

The photochemical simulation results for the **north-eastern Iberian Peninsula** during the 17–18 June 2004 show that the maximum O_3 concentrations occur in downwind areas from Barcelona city after the maximum photochemical activity hours (Fig. 6-a,b show the

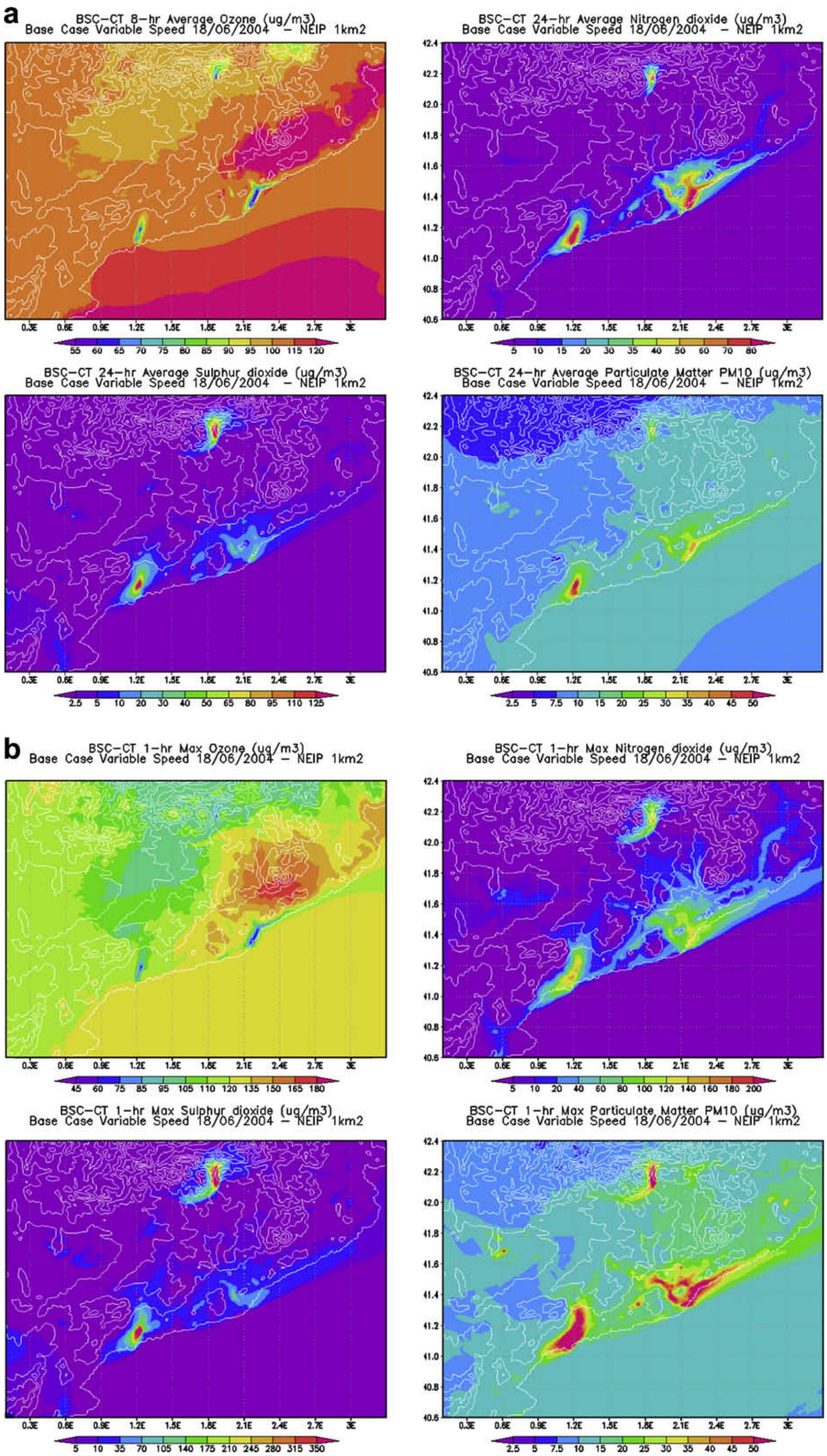

Fig. 6. (a) 8-h Average O_3, 24-h average NO_2, SO_2 and PM10 concentrations ($\mu g\ m^{-3}$) and (b) maximum hourly concentrations of O_3, NO_2, SO_2 and PM10 ($\mu g\ m^{-3}$) in the northeastern Iberian Peninsula domain in the base case estimated with HERMES-modified (variable speed), 18 June 2004.

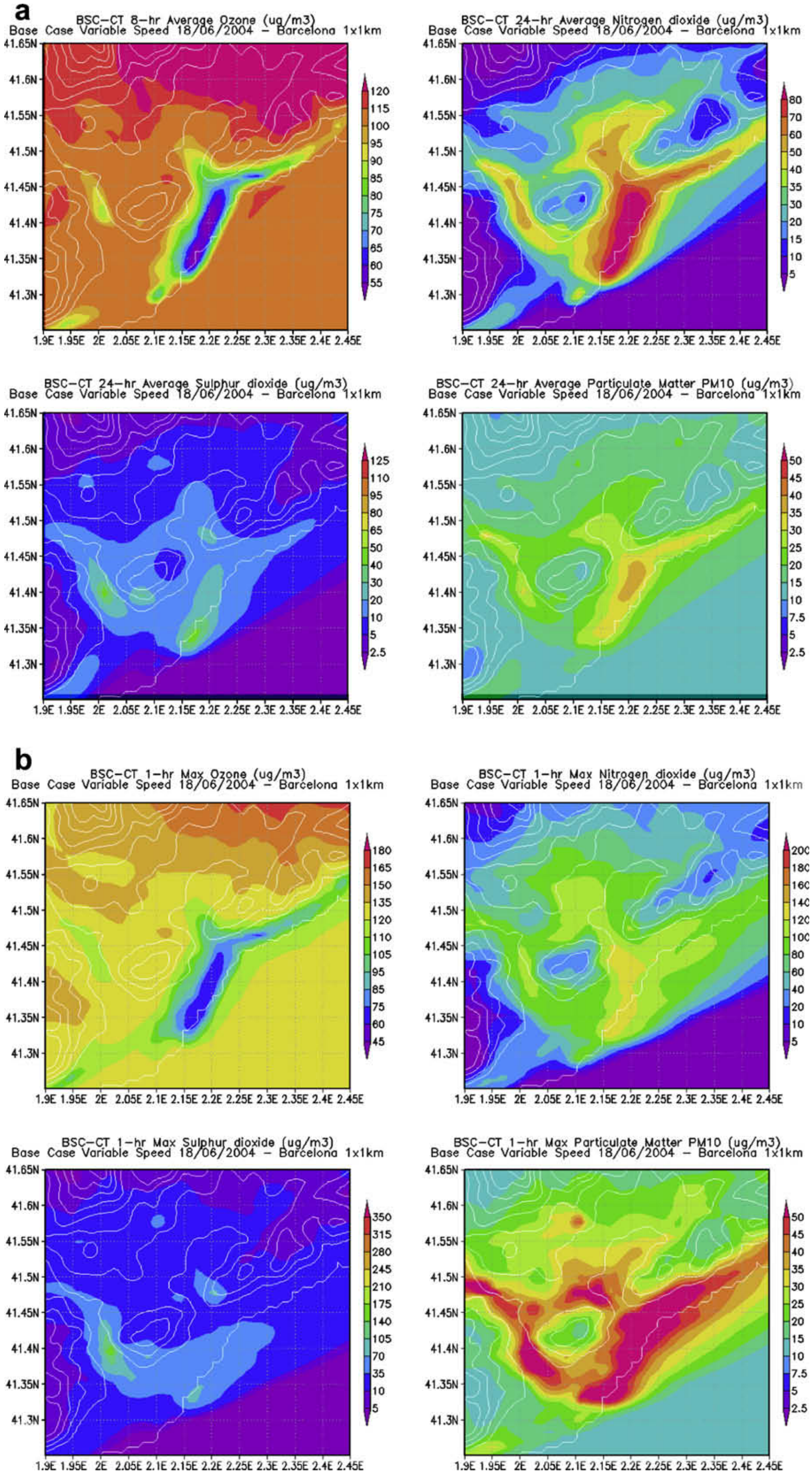

Fig. 7. (a) 8-h Average O_3, 24-h average NO_2, SO_2 and PM10 concentrations ($\mu g\, m^{-3}$) and (b) maximum hourly concentrations of O_3, NO_2, SO_2 and PM10 ($\mu g\, m^{-3}$) in the Barcelona area in the base case estimated with HERMES-modified (variable speed), 18 June 2004.

simulation results for the 18 June). During the day the increase of the solar radiation and the temperature (reaching 30–35 °C) promote the high levels of O_3, exceeding in some cases the population information threshold (180 μg m^{-3}) and the 8-h average objective to human health protection (120 μg m^{-3}). The stagnant conditions involve very similar atmospheric circulation patterns during the 17–18 June, controlled by the sea breezes regime. The main difference concerns the photochemical pollution accumulation that takes place over the Mediterranean Sea, a characteristic process in this region during summertime (Baldasano et al., 1994; Jiménez et al., 2006; Gonçalves et al., in press). The major air quality problems in the **Barcelona urban area** are related with NO_2 and PM10 levels. The hourly maximum NO_2 concentrations exceed 200 μg m^{-3} and the PM10 overpasses the 50 μg m^{-3} (Fig. 7).

When introducing the 80 km h^{-1} limitation, the 24-h average $\mathbf{NO_2}$ concentration over the whole **Barcelona area** (Fig. 5-a) on the selected days decreases by 0.7% and 0.8% (Table 2). The largest reductions are observed in those areas that are directly affected by the speed limitation. In the Maresme and Dalt areas, which are located in the northern and southern ways out of Barcelona conurbation, respectively (Fig. 5-c,d) the reduction of the 24-h average NO_2 concentration amounts up to 5.7%. Both areas include roads limited to 80 km h^{-1}. The effects in downtown (Fig. 5-b), where most city dwellers may be affected, are lower; the average NO_2 reduction being 0.1% and 0.3%. The benefits are also reflected in the urban plume, specifically the hourly maximum NO_2 concentration reduces up to −2.5 μg m^{-3} in the downwind region (Fig. 8).

The NO_x emissions reductions in a VOCs limited area cause an 8-h average $\mathbf{O_3}$ concentration increase of 0.1% over the **Barcelona area** (Table 2). In detail the largest changes in O_3 concentration (up to 3.5 μg m^{-3} on average; Fig. 9) are observed in the areas over the speed-limited roads. Specifically the Maresme area reflects deeply the management measure effect; increases in O_3 average concentration amount up to 2.5%, due to the dominant northwesterlies controlling the pollutants plume displacement. The effect decreases with distance to the conurbation. The 8-h average O_3 concentrations downwind are between 0.75 and 1.25 μg m^{-3} higher than those in the base case (Fig. 8), which is two orders of magnitude lower than the average value in these areas, ranging from 100 to 120 μg m^{-3}.

The reduction on primary pollutants emissions affects the $\mathbf{SO_2}$ and **PM10** local levels over **Barcelona area** (Fig. 8). The maximum hourly concentrations of SO_2 and PM10 are up to 0.12 μg m^{-3} and 0.75 μg m^{-3} lower than the base case values, respectively. PM10 is also slightly reduced in the urban plume (−0.05 μg m^{-3}, Fig. 9). In the urban area the PM2.5 fraction dominates the particulate matter concentration, ranging the reductions from −0.3% to −4.2% in mass (Table 2). The coarse fraction of particulate matter (PM10–PM2.5) is hardly affected by the introduced measure, indicating that the main reductions of PM are due to the reduction on exhaust combustion particulates and decrease of precursors' emissions.

The SO_2 levels in the **urban area** are relatively low compared to the legal thresholds. The maximum 24-h average concentration occurs in the downtown area during 18 June, and reaches 20.4 μg m^{-3} (Table 2), which is far from the legislation threshold (125 μg m^{-3}). The speed

Table 2
Pollutant concentrations (μg m^{-3}) in selected domains of the Barcelona area for the 17–18 June in the base case scenario (VS) and the scenario introducing speed circulation limits of 80 km h^{-1} (V80) in selected domains of the Barcelona area: BCN – Barcelona area; BCN DT – Barcelona Downtown; BCN M – Barcelona Maresme; BCN D – Barcelona Dalt (Fig. 5)

VS: HERMES–VS: Variable circulation speed based on measurement campaign.
V80: Scenario including speed limitations to 80 km h^{-1} in the Barcelona Metropolitan area road network.
17 J: 17 June 2004; 18 J: 18 June 2004.

Conc. (μg m^{-3})	24-h Average NO_2		24-h Average SO_2		8-h Average O_3		24-h Average PM10		24-h Average PM25	
	VS	V80	VS	V80	VS	V80	VS	V80	VS	V80
BCN 17 J	22.8	22.7	8.7	8.7	105.6	105.8	15.0	15.0	15.0	14.9
BCN 18 J	22.9	22.7	8.4	8.4	108.1	108.3	15.9	15.8	15.8	15.8
BCN DT 17 J	74.6	74.5	20.0	20.0	55.6	55.6	29.8	29.8	29.8	29.8
BCN DT 18 J	77.0	76.7	20.4	20.4	67.2	67.3	30.4	30.4	30.3	30.2
BCN M 17 J	40.5	39.5	9.6	9.5	74.2	76.0	19.6	19.4	19.5	19.3
BCN M 18 J	49.6	48.4	11.2	11.2	79.6	81.6	25.2	24.9	25.1	24.8
BCN D 17 J	34.9	34.1	11.8	11.8	93.5	93.7	16.8	16.7	16.7	16.5
BCN D 18 J	35.1	33.1	11.5	10.9	102.3	102.6	17.9	17.4	17.8	17.3

Difference between the V80 scenario and the base case (HERMES–VS)

Conc. (μg m^{-3})	24-h Average NO_2		24-h Average SO_2		8-h Average O_3		24-h Average PM10		24-h Average PM25	
	V80–VS	%	V80–VS	%	V80–VS	%	V80–VS	%	V80–VS	%
BCN 17 J	−0.2	−0.7	−0.01	−0.1	0.1	0.1	−0.03	−0.2	−0.03	−0.2
BCN 18 J	−0.2	−0.8	−0.01	−0.1	0.2	0.1	−0.03	−0.2	−0.03	−0.2
BCN DT 17 J	−0.1	−0.1	−0.01	−0.03	0.05	0.1	−0.04	−0.1	−0.04	−0.1
BCN DT 18 J	−0.2	−0.3	−0.01	−0.1	0.1	0.2	−0.1	−0.2	−0.1	−0.2
BCN M 17 J	−1.0	−2.5	−0.04	−0.4	1.8	2.4	−0.2	−1.1	−0.2	−1.1
BCN M 18 J	−1.2	−2.3	−0.05	−0.4	2.0	2.5	−0.3	−1.0	−0.3	−1.0
BCN D 17 J	−0.7	−2.1	−0.02	−0.2	0.2	0.2	−0.1	−0.7	−0.1	−0.7
BCN D 18 J	−2.0	−5.7	−0.61	−5.3	0.3	0.2	−0.5	−3.0	−0.5	−3.0

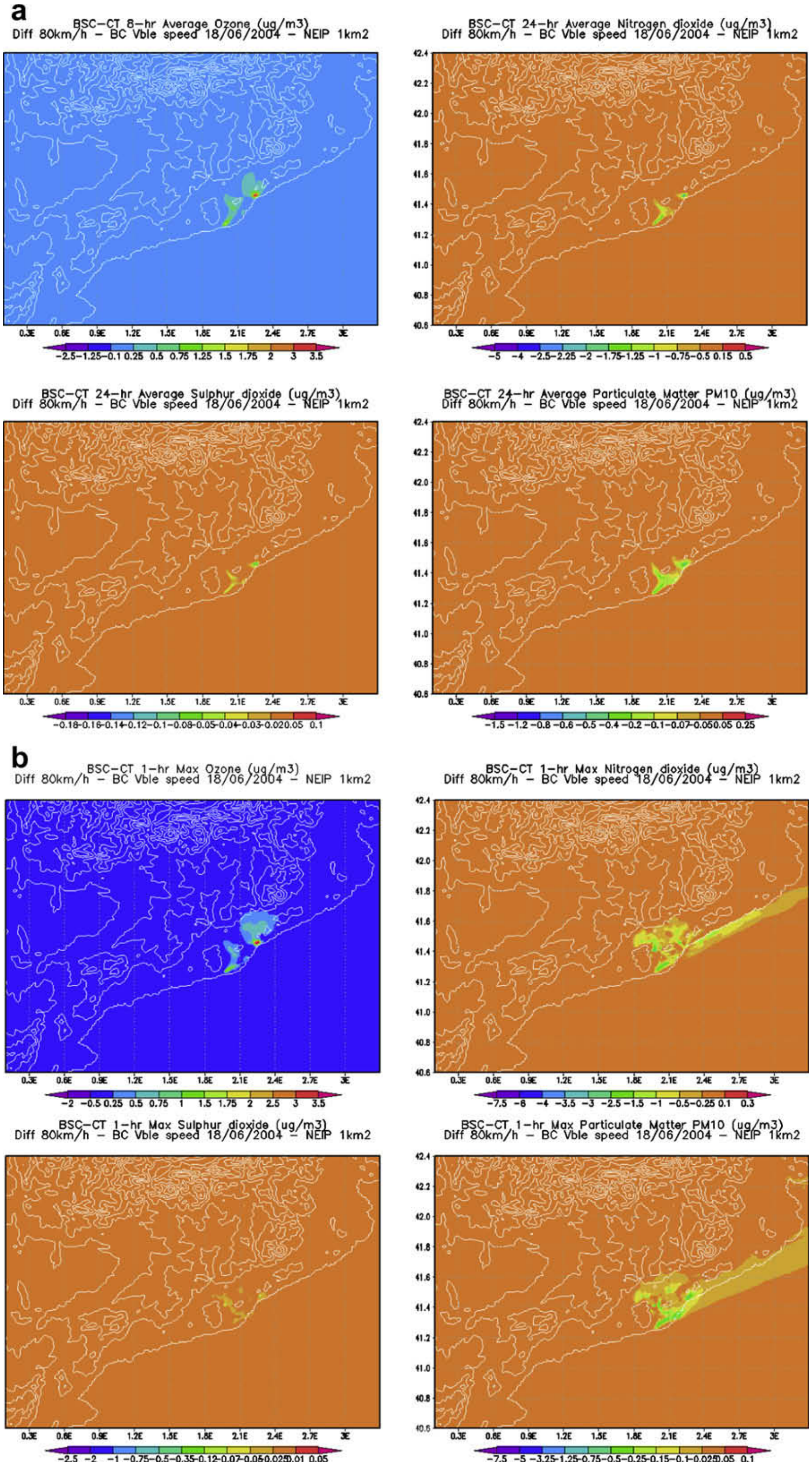

Fig. 8. Differences in (a) 8-h average O_3, 24-h average NO_2, SO_2 and PM10 concentrations ($\mu g\,m^{-3}$) and (b) maximum hourly concentrations of O_3, NO_2, SO_2 and PM10 ($\mu g\,m^{-3}$) in the northeastern Iberian Peninsula when introducing the speed limit of 80 km h^{-1}, 18 June 2004.

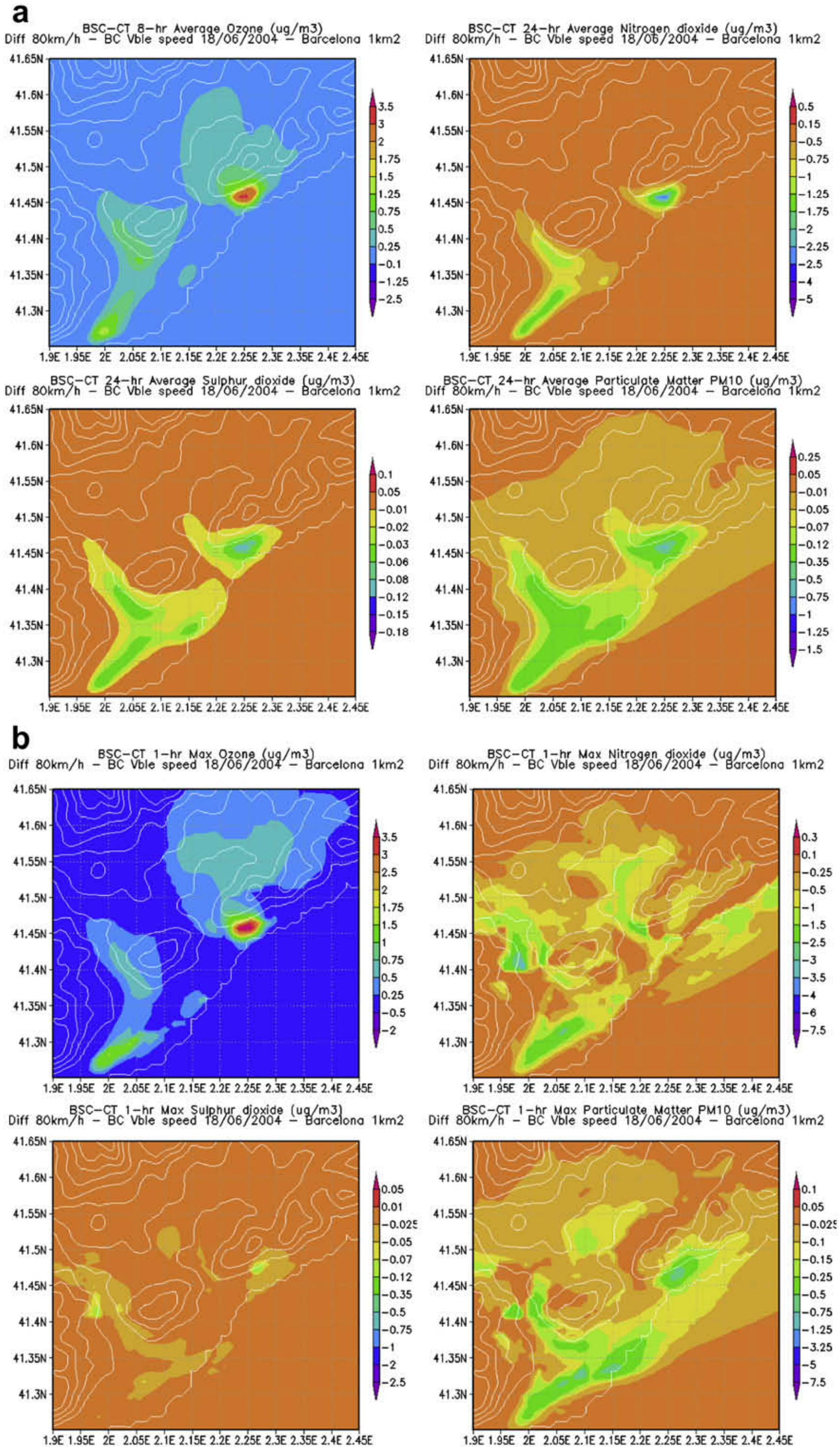

Fig. 9. Differences in (a) 8-h average O_3, 24-h average NO_2, SO_2 and PM10 concentrations ($\mu g\,m^{-3}$) and (b) maximum hourly concentrations of O_3, NO_2, SO_2 and PM10 ($\mu g\,m^{-3}$) in the Barcelona area when introducing the speed limit of $80\ km\,h^{-1}$, 18 June 2004.

limit restriction decreases the average concentration downtown by 0.1%. The largest reductions occur in the Dalt area (-5.3%). The effects on studied air quality parameters concentrate over the locations of the $80\ km\,h^{-1}$ limited speed roads, the largest changes being those estimated for the Dalt and the Maresme areas. The average downtown levels vary up to $\pm0.3\%$, reflecting a lighter effect in those areas not directly affected by the measure (Table 2).

4. Conclusions

In developed countries different strategies are being tested and put into practice in order to abate the negative environmental effects of on-road traffic, without decreasing population mobility. State-of-the-art air quality models and computer resources allow to assess the effects of hypothetical mitigation measures in advance.

The average speed dependency of current on-road traffic emissions models predictions, such as HERMES, based on COPERT III methodology, demands for more precise and realistic representation of vehicles circulation speed. The traffic emissions account based on constant average speeds does not take into account the characteristics of the road networks or the speed variability due to specific driving behavior. Variable speed based on measurement campaigns is supposed to reduce uncertainties in emissions and air quality estimations. The HERMES emissions model was modified by introducing variable speed data, which caused reductions of the NO_x, CO, SO_2 and PM10 traffic emissions estimates for the Barcelona area by 5.6%, 5.1%, 4.8% and 5.1%, respectively.

The variable speed introduction in the WRF-ARW/HERMES/CMAQ model locally improved the O_3 predictions (around 1% reduction on the statistical parameters estimated), even though the results differed for the NO_2, SO_2 and PM10 concentrations, depending on the air quality station considered. Further work must be oriented to extend these measurement campaigns in time, in order to represent the circulation patterns that could occur for at least an annual cycle. The speed representation by vehicle type might be also introduced.

The modeling system was applied to assess the effects on air quality of the $80\ \mathrm{km\,h^{-1}}$ speed restriction planned for the Barcelona Metropolitan area. The analysis of real circulation patterns shows that the traffic on some of the affected roads was still circulating at speeds around $80\ \mathrm{km\,h^{-1}}$ or lower, mitigating the effects of the management strategy. The changes in emissions estimates of the limit speed introduction are lower than those expected. The NO_x, SO_2, PM10, NMVOCs and CO traffic emissions over the Barcelona area are 3.2% lower on average when considering variable speed than those estimated with the constant speed by road stretch representation, while the introduction of the speed limitation to $80\ \mathrm{km\,h^{-1}}$ causes a further reduction of only 0.6%. This may be due to both the effect of traffic congestion and the relatively small affected area, exclusively the Barcelona Metropolitan area. Consequently the effects on air quality predicted by the model focus on the Barcelona area, mainly over the affected roads, where the reductions on NO_2, SO_2 and PM10 levels reach up to 5.7%, 5.3% and 3.0% on 24-h average concentration, respectively. The NO_x emissions decrease in a VOCs limited area, such as Barcelona, produces local increases of O_3 concentrations, especially in the urban plume over the roads affected by the speed limit (up to 2.4%); nevertheless the O_3 concentrations in downwind areas remain practically constant. The most positive effects of the management measure are observed for PM2.5, the most dangerous fraction for human health.

This work highlights the need for more detailed emissions inventories, specifically concerning on-road traffic, in order to improve the reliability of air quality modeling as a management tool and help decision makers. It also shows the importance of introducing more realistic parameters into the emissions models and the changes that they involve in the air quality model predictions.

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