AIR QUALITY MANAGEMENT STRATEGIES IN URBAN AREAS: EFFECTS OF INTRODUCING HYBRID CARS IN MADRID AND BARCELONA METROPOLITAN AREAS (SPAIN)

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Abstract: On-road traffic represents the largest source of pollutants' emissions in urban areas. In southern Mediterranean countries exceedances of the NO_2 and PM10 European air quality targets are observed in urban environments. Moreover the budget of urban emissions contributes to the emissions of O_3 precursors (mainly NO_x) in a region where the concentration of photochemical pollutants still remains a problem especially during summertime. Air quality modeling, used as a management tool, permits to test abatement emissions strategies in advance. Nowadays, the substitution of vehicles by introducing new technologies (e.g. cleaner fuels, hybrid vehicles, fuel cells) or alternative fuels (e.g. biofuels, natural gas or hydrogen) is a common practice in conurbations around Europe. This work focuses on the assessment of the impacts on air quality due to the introduction of hybrid cars in the largest urban areas of Spain: Madrid (within a more continental environment), and the urban coastal city of Barcelona. The WRF-ARW/HERMES/CMAQ modeling system has been implemented and validated with a high resolution (1 km^2 and 1 hr) thanks to the calculation power of the MareNostrum supercomputer (94.21 TFlops peak). Due to the complex topography and climatic particularities of the study areas it becomes necessary to use high spatial and temporal resolution and to have a highly-disaggregated emission inventory of gaseous pollutants and particulate matter (HERMES model developed specifically for Spain). The model was applied during a representative summertime polluted episode. The introduction of a 10% or a 30% of hybrid cars in substitution of the oldest petrol and diesel cars of both cities proved to be effective to reduce NO_2, SO_2 and PM10 concentrations in the conurbations (i.e. a 37% reduction in NO_2 24-hr average concentration occurs in Madrid and a 18% in Barcelona when introducing a 30% of hybrid vehicles; moreover 24-hr average PM10 decreases up to 12% and 14% in Madrid and Barcelona, respectively). Nevertheless the O_3 concentrations slightly arise (being the 8-hr average concentration a 3% higher in Madrid and a 24% in Barcelona respect to the base case). The selected domains present a similar behavior with respect to their impacts, with a noticeable reduction of ground-level NO_x in downtown areas and an increase in the tropospheric ozone concentration in the VOC-limited areas. In downwind locations the precursors' emissions control causes a reduction of O_3 levels. The air quality modeling system proves to be a suitable and useful tool to manage urban air quality, especially when applied with this high resolution.

Key words: *Hybrid electric vehicles, urban air quality, management, tropospheric ozone, air quality modelling.*

1. INTRODUCTION

Improving air quality in urban areas is nowadays an important environmental challenge (Fenger, 1999; Baldasano et al., 2003). On-road traffic is the largest contributor to pollutants emissions in urban areas (Costa and Baldasano, 1996; Colvile et al., 2001; Querol et al., 2001; Artiñano et al., 2004) and it remains a key target for public health action in Europe (Künzli et al., 2000). The southern Mediterranean region frequently registers exceedances of the European air quality targets, particularly concerning PM10 and O_3 (Jiménez et al., 2006). Additionally high NO_2 levels are registered in conurbations (EEA, 2006). Therefore management strategies and improvements in current vehicle technologies are being tested (Nagl et al., 2006). This work defines two hybrids introduction scenarios in Barcelona and Madrid urban areas, the largest conurbations of Spain. The first scenario considers a low penetration and introduces a 10% of gasoline-electric hybrid cars instead of the oldest diesel and petrol private cars, the second scenario is more optimistic, considering the introduction of a 30% of gasoline-electric hybrids instead of the oldest diesel and petrol cars and taxis of the urban areas. The WRF-ARW/HERMES/CMAQ modeling system permits to assess the effects on air quality (O_3, SO_2, NO_2 and PM concentrations) with high resolution (1 km^2, 1hr), during a typical photochemical pollution episode of 2004.

2. METHODS

The WRF-ARW/HERMES/CMAQ mesoscalar model provides hourly air quality parameters for the final defined domains (Figure 1) for the 17-18 June, 2004 episode. This period was associated with the worst air quality situation in Barcelona and Madrid for 2004, corresponding to a usual traffic circulation pattern (avoiding holidays or weekends). It is representative of episodes of photochemical pollution, since these conditions dominate 45% of the annual and 78% of the summertime transport patterns over north-eastern 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).

These final domains (Figure 1) are centered in Barcelona and Madrid cities, but they cover larger areas in order to assess the evolution of the urban plume pollution: the North Eastern Iberian Peninsula –NEIP- (322 x 259 km^2) and the Central Iberian Peninsula - CIP - (181 x 214 km^2) respectively. They are solved with high temporal and spatial resolution (1 km^2 – 1 hr), which permits to detect subtle changes in urban air quality and improves the air quality assessment in very complex terrains, such as the studied (Jiménez et al., 2005). The initial and boundary conditions are provided by one-way nested simulations over a 1392 x 1104 km^2 domain centered in the Iberian Peninsula, that uses EMEP emissions for 2004 and disaggregated to 18 km. (Figure 1). A 48-hour spin-up was performed to minimize the effects of initial conditions for the final domains. The planned scenarios include: (H1) the introduction of a 10% of gasoline-electric hybrid cars instead of the oldest petrol and diesel private cars in Madrid and Barcelona and (H2) the introduction of a 30% of gasoline-electric hybrid cars instead of the oldest petrol and diesel private cars and taxis. The needed changes in the HERMES emissions model to introduce the hybrids scenarios are: (1) the modification of the vehicle fleet composition of the urban areas of interest; and (2) the introduction of speed dependent emission factors for the new categories of vehicles: hybrid cars. These were obtained from the EEA-EMEP CORINAIR methodology (Samaras and Zierock, 2007). The base case simulations were validated against air quality data from the monitoring network (46 air quality stations in the final study areas). The estimated mean normalized gross error agreed with the EU recommendations for air quality modeling (Directives 1999/30/EC, 2002/3/EC and 2008/50/EC).

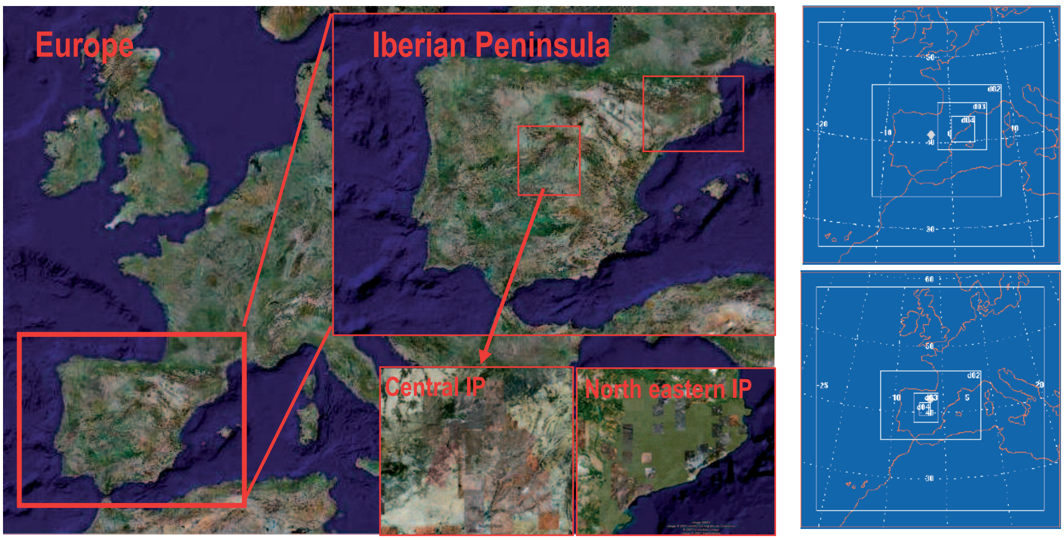

Figure 1. Nested domains defined to perform the simulations. D1 Europe: 55x55 cells of 54km, D2 Iberian Peninsula: 94x82 cells of 18 km, D3 Iberian Peninsula Area: 104x103 cells of 6 km, (a) D4 North-eastern Iberian Peninsula domain: 1 km resolution, (b) D4 Central Iberian Peninsula domain: 1 km resolution.

3. RESULTS AND DISCUSSION

The major air quality problems in the urban areas are related to NO_2 and PM10 concentrations, especially in Barcelona. In Madrid the photochemical regime also involves high O_3 levels in the conurbation. The differences in emissions origins, photochemical regime and atmospheric transport behaviour in both regions are reflected in the final air quality levels assessed (Tab. 1; Tab. 2). These factors also condition the different response to analogous on-road transport management strategies.

The hybrids scenarios reduce NO_2, SO_2 and PM (both PM10 and PM2.5) levels in the conurbations (Tab. 1; Tab. 2). H1 scenario reduces the 24 hr average NO_2 concentration in the Barcelona greater area in a 1.7% and the PM2.5 in a 0.4% (Tab. 1) The impact of this scenario in Madrid is larger than in Barcelona, being the NO_2 and PM2.5 levels a 6.3% and 5.8% lower than in the base case (Tab. 2). The finest fraction of particles is the most affected, because it is originated mainly by fuel combustion processes or chemical production. When the changes in the vehicle fleet are more pronounced, the effects both in emissions and air quality are deeper. The H2 scenario reduces NO_2 and PM2.5 in Barcelona downtown a 10.9% and a 3.6%, respectively, while in Madrid downtown they decrease a 35.2 % and a 7.3%. The emissions abatement in the urban areas reduces the formation of NO_2 and secondary particles in the urban plumes. These pollutants levels decrease for the Barcelona and Madrid downwind areas in both scenarios, being the effects more pronounced in the H2 scenario in the Madrid region. The low SO_2 concentration in the Barcelona greater area remains almost unaffected when introducing the hybrid cars scenarios, indicating its industrial origin. Madrid presents lower SO_2 concentrations in the base case and the hybrids introduction is more effective to reduce them (i.e. 5.5% reduction with the H2 scenario introduction).

The NO_x emissions locally act as an O_3 sink. Therefore the introduction of hybrid cars with the consequent NO_x emissions reductions may increase local O_3 concentrations. This is the overall effect in Barcelona, where both scenarios enhance an increase in O_3 levels (Tab. 1,Fig. 2). The 8-hr average concentration over the whole metropolitan area increases a 0.3% in the H1 scenario and a 0.5% in the H2 scenario, but the effect could be locally more important, being a 4.5% (15.2%) higher the O_3 levels in the Barcelona downtown area in the H1 (H2) scenario (Tab. 1). Nevertheless the highest concentration achieved is 60.3 $\mu g\ m^{-3}$, which is a half of the EU target for human health protection (Directive 2002/3/CE). In Madrid, higher O_3 levels occur in the metropolitan area (Tab. 2), with 8-hr average concentrations of 134.7 $\mu g\ m^{-3}$ in the base case. The introduction of hybrid cars produces a different effect on O_3 concentration depending on the analyzed period. When the O_3 production does not exist or remains low, the effect of reducing NO_x emissions is the local increase of O_3 levels respect to the base case (both when introducing a 10% or a 30% of hybrid cars). The NO_x role as an O_3 sink is mitigated (Figure 2). In the maximum O_3 production period (from 11.00 UTC to 15.00 UTC) the urban O_3 levels are reduced because of the lower amount of NO_x available to react (Figure 2). This behaviour affects maximum concentrations downtown, being a 1.5% lower in the H1 scenario than in the base case and a 6.4% lower in the H2 scenario. Due to the NO_x emissions reductions in the conurbations both scenarios decrease downwind O_3 concentrations.

Table 1. 8-hr average O_3, 24-hr average NO_2, SO_2, PM10 and PM2.5 concentrations in the Base Case (BC), the H1 scenario (introduction of a 10% of hybrid cars) and the H2 scenario (introduction of a 30% of hybrid cars) in the Barcelona greater area (BGA) and the Barcelona Downtown (B-D) area. Differences in average concentration between the BC and H1 and H2 scenarios.

17 June, 2004	**8-hr ave. O_3**		**24-hr ave. NO_2**		**24-hr ave. SO_2**		**24-hr ave. PM10**		**24-hr ave. PM2.5**	
Conc. ($\mu g\ m^3$)	**BGA**	**B-D**	**BGA**	**B-D**	**BGA**	**B-D**	**BGA**	**B-D**	**BGA**	**B-D**
BC	104.4	52.4	23.0	75.1	8.7	20.0	15.0	29.8	11.5	26.3
H1	104.6	54.7	22.6	73.0	8.7	19.9	15.0	29.3	11.4	25.8
H2	104.9	60.3	21.8	66.9	8.7	19.8	15.0	28.9	11.4	25.4
	8-hr ave. O_3		**24-hr ave. NO_2**		**24-hr ave. SO_2**		**24-hr ave. PM10**		**24-hr ave. PM2.5**	
Diff. ($\mu g\ m^3$)	**BGA**	**B-D**	**BGA**	**B-D**	**BGA**	**B-D**	**BGA**	**B-D**	**BGA**	**B-D**
BC-H1	-0.3	-2.4	0.4	2.0	0.005	0.1	0.04	0.5	0.04	0.5
BC-H2	-0.5	-8.0	1.2	8.2	0.01	0.2	0.1	0.9	0.1	0.9
	8-hr ave. O_3		**24-hr ave. NO_2**		**24-hr ave. SO_2**		**24-hr ave. PM10**		**24-hr ave. PM2.5**	
% diff.	**BGA**	**B-D**	**BGA**	**B-D**	**BGA**	**B-D**	**BGA**	**B-D**	**BGA**	**B-D**
BC-H1	-0.3%	-4.5%	1.7%	2.7%	0.1%	0.3%	0.3%	1.8%	0.4%	2.0%
BC-H2	-0.5%	-15.2%	5.1%	10.9%	0.2%	1.0%	0.4%	3.2%	0.6%	3.6%

Table 2. 8-hr average O_3, 24-hr average NO_2, SO_2, PM10 and PM2.5 concentrations in the Base Case (BC), the H1 scenario (introduction of a 10% of hybrid cars) and the H2 scenario (introduction of a 30% of hybrid cars) in the Madrid greater area (MGA) and the Madrid Downtown (B-D) area. Differences in average concentration between the BC and H1 and H2 scenarios.

17 June, 2004	**8-hr ave. O_3**		**24-hr ave. NO_2**		**24-hr ave. SO_2**		**24-hr ave. PM10**		**24-hr ave. PM2.5**	
Conc. ($\mu g\ m^3$)	**MGA**	**M-D**	**MGA**	**M-D**	**MGA**	**M-D**	**MGA**	**M-D**	**MGA**	**M-D**
BC	134.7	124.8	46.2	36.4	2.9	2.4	14.8	13.1	11.3	13.1
H1	134.2	124.5	43.2	33.7	2.9	2.3	14.2	12.6	10.7	12.6
H2	134.8	124.9	31.7	23.6	2.8	2.2	13.7	12.2	10.2	12.2
	8-hr ave. O_3		**24-hr ave. NO_2**		**24-hr ave. SO_2**		**24-hr ave. PM10**		**24-hr ave. PM2.5**	
Diff. ($\mu g\ m^3$)	**MGA**	**M-D**	**MGA**	**M-D**	**MGA**	**M-D**	**MGA**	**M-D**	**MGA**	**M-D**
BC-H1	0.5	0.3	2.9	2.7	0.1	0.1	0.7	0.5	0.7	0.5
BC-H2	-0.1	-0.1	14.5	12.8	0.2	0.1	1.2	1.0	1.2	1.0
	8-hr ave. O_3		**24-hr ave. NO_2**		**24-hr ave. SO_2**		**24-hr ave. PM10**		**24-hr ave. PM2.5**	
% diff.	**MGA**	**M-D**	**MGA**	**M-D**	**MGA**	**M-D**	**MGA**	**M-D**	**MGA**	**M-D**
BC-H1	0.4%	0.2%	6.3%	7.4%	2.2%	2.2%	4.4%	4.1%	5.8%	4.1%
BC-H2	-0.1%	-0.1%	31.4%	35.2%	5.5%	5.6%	7.8%	7.3%	10.2%	7.3%

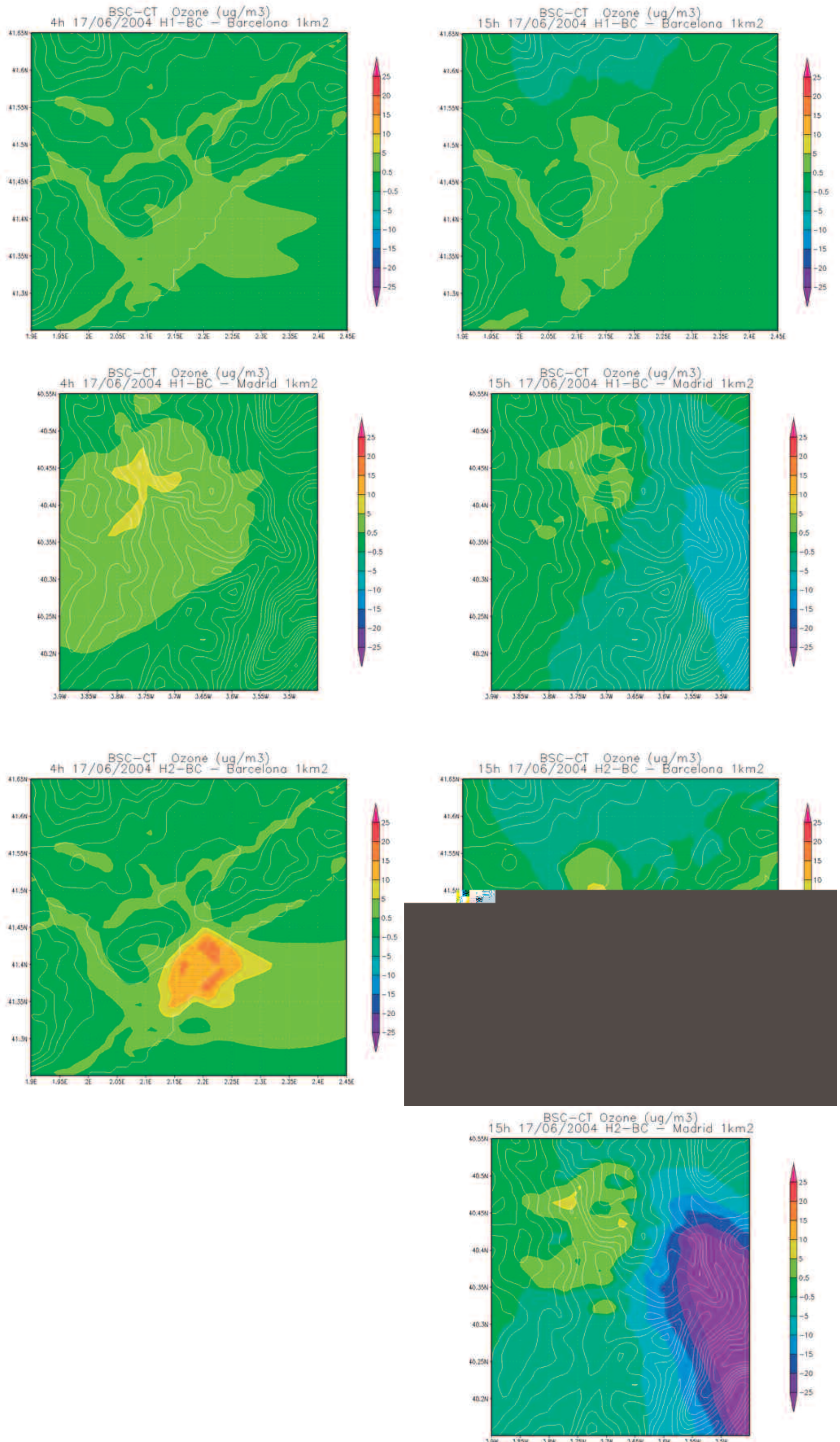

Figure 2. Differences in O_3 hourly average concentration between the H1 and the BC scenario (upper 4 panels) and between H2 and the BC scenario (bottom 4 panels) at 04.00 UTC and 15.00 UTC of 17 June for the Barcelona area (up) and the Madrid area (down).

4. CONCLUSIONS

The introduction of a 10% of gasoline-electric hybrid cars instead of the oldest petrol and diesel cars (H1) and the substitution of a 30% of the oldest petrol and diesel cars, including taxis, by gasoline-electric hybrid cars (H2) are tested for Barcelona and Madrid. The different responses to these changes are mainly due to: the particular vehicle fleet composition, the different contribution of economical or activity sectors to total emissions, the topography, meteorological conditions and the atmospheric transport, being Barcelona a typically coastal city and Madrid a continental one, and finally the different chemical regime existing in both of them (different NO_x-VOCs ratio that directly affects O_3 production response to emissions abatement strategies). All these particularities are taken into consideration in the WRF-ARW/HERMES/CMAQ model used.

The overall effect in both cities involves the reduction on NO_2 and PM2.5 levels; that is more pronounced in the H2 scenario, the daily NO_2 and PM2.5 concentrations are on average a 5.1% and a 0.6% lower in Barcelona and a 31.4% and a 10.2% lower in Madrid, respectively. The largest contribution of on-road transport to total emissions and the fact that the vehicle fleet is mainly constituted by cars (82%) is on the origin of the higher impact of this scenario in Madrid. The combustion in manufacturing industries is the largest contributor to SO_2 emissions in the North-eastern Iberian Peninsula domain, which makes the on-road traffic management not being an effective strategy to reduce SO_2 levels in the region. The introduction of a 30% of petrol hybrid cars, which reduces the SO_2 emissions in 0.05 t d^{-1}, involves the daily average concentrations of this pollutant decreasing just a 0.2% in the metropolitan area of Barcelona. The effects of the same scenario in Madrid are notably higher, with SO_2 daily concentration reductions of 5.5%. The O_3 concentrations in the conurbations locally increase, because of the limitation of the O_3 titration by fresh NO_x emissions. Nevertheless, the photochemical regime involves this increase being more important in Barcelona, while in Madrid the O_3 levels during the central hours of the day are reduced. In fact, the maximum concentrations downtown are lower in the H1 and H2 scenarios than in the base case. The introduction of hybrid cars in the urban areas (both H1 and H2) has positive effects in downwind areas, decreasing specially the NO_2, PM2.5 and O_3 levels.

The WRF-ARW/HERMES/CMAQ is a powerful tool to help decision makers. Thanks to the high resolution used and the intensive characterization of the studied areas (detailed vehicle fleet compositions, topography and emissions sources) permits to design realistic scenarios and detect subtle differences in air quality parameters.

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