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Numerical Simulation of the Effects of Increasing Urban Albedo on Air Temperatures and Quality over Madrid City (Spain) by Coupled WRF/CMAQ Atmospheric Chemistry Model

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Additional information is available at the end of the chapter

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Abstract

Meteorological and photochemical impacts of increasing urban albedo or reflectance over Madrid city have been simulated using a mesoscale climatic model (WRF) coupled to an air quality modeling system (AEMM/CMAQ). We have evaluated the influence over the concentration of the main pollutants of two different interventions with increasing levels of albedo enhancement over all urban categories: a low albedo or cool roofs scenario (Alb1), where only roof albedo was modified (+0.35), and a high albedo scenario (Alb2), increasing both roof albedo (+0.35) and pavement albedo (+0.15). Simulations were run for two periods of 72 h, representative of summer and winter conditions. In both scenarios, surface air temperatures were cooled, with averaged midday reductions at the urban area of -0.2 (-0.5) $^{\circ}\text{C}$ for winter (summer) for Alb1 and -0.3 (-0.7) $^{\circ}\text{C}$ for winter (summer) for Alb2. Peak summer midday cooling at city center was -1.4°C and -1.6°C for Alb1 and Alb2, respectively. Pollutant concentrations were modified, with reductions in O_3 levels, higher in summer, and increases in NO_2 levels, bigger in winter period. Slight increases were also observed in winter for SO_2 and particulate matter ($\text{PM}_{2.5}$ and PM_{10}) in both scenarios.

Keywords: WRF, BEM, CMAQ, urban albedo, air quality, Madrid city, cool roofs

1. Introduction

Adaptation to climate change by increasing the reflectance of human settlements has been proposed as a simple and cost-effective geo-engineering strategy to offset the rise of temperatures

associated with global warming at local and regional scales [1]. The use of higher albedo roofs and/or pavements (cool roofs and pavements) has shown effective surface air cooling in simulation experiments over many cities in the world [2]. Due to lower surface temperatures, an improvement in air quality can be obtained by slowing temperature-dependent photochemical reaction rates of formation of secondary pollutants, such as ozone, and reducing biogenic hydrocarbon emissions. Additional indirect benefits are linked to lower energy demand for summer cooling of buildings and its associated emissions in power plants [3]. On the contrary, due to the depression of the planetary boundary layer level (PBL) height caused by cooler temperatures, and to possible changes in local wind patterns, reduced mixing and dilution of pollutants can raise their levels by accumulation in some areas. Ground-level ozone (O_3), particulate matter (PM), nitrogen oxides (NO_x), and sulfur oxides (SO_2) are most health-concerned pollutants, and their urban concentration levels can be affected by surface modification. O_3 is a secondary pollutant resulting from the reaction between NO_x oxides and volatile organic compounds (VOCs) in the presence of sunlight. Higher O_3 concentration levels are directly related to warming in urban heat islands, reaching peak levels in summertime [4].

Most numerical simulations of the impact of albedo increase on pollutants have been developed over US cities, in general with different urban fabrics than in Europe, where compact mid-rise urban categories occupy most of the city centers. In pioneering mesoscale numerical simulations [5], extreme surface albedo enhancement resulted in ozone reductions in California. Simulating a more feasible albedo increase over southern US cities with high insolation levels, [6] obtained ozone reductions linked to cooler summer ambient air temperatures. However, only Sacramento showed significant peak ozone-level reductions due to a wider urban surface (25,000 ha). Applying comparable albedo increase levels, it has been simulated significant air quality benefits over California [7], suggesting that there is a maximum albedo increase implementation threshold above which no further benefits are obtained that should be determined for every urban case. There are scarce mesoscale simulation experiments to investigate the impact of albedo enhancement on pollutants other than ozone. In another simulation the effect on air quality during a heat wave episode of albedo increase at high latitudes (Montreal, Canada) was reported [8], with no significant effect on ozone levels, and slight reductions in $PM_{2.5}$ levels (2 ppb), associated with a decrease in PBL height, that counteracted the cooling impact on ozone formation. Applying an extreme albedo increase over Stuttgart (Germany), a peak urban temperature cooling down to -1.7°C and decreases in mean ozone concentration were reported [9]. However, secondary undesirable effects were an increase of primary pollutants (NO_x and CO) and an increase in peak ozone concentration due to a higher intensity of reflected UV shortwave radiation. To date, the impact of urban albedo enhancement on temperatures and air quality has never been assessed over Spanish urban areas by numerical modeling. Spanish cities may give key information for this research, due to the high levels of annual and summer insolation and to the hot summer Mediterranean climate in most of the country, with high annual number of clear skies that maximize the thermal and energy-saving potential benefits of changes in solar reflectivity [10]. On the other hand, an undetermined minimum critical intervention surface is also needed to obtain significant modifications in local atmospheric variables by land cover changes [6]. Madrid city is the biggest urban area in Spain, with broadly five million inhabitants in its metropolitan

area, and the fourth most populated city in Europe. Emissions of air pollutants in Madrid are mostly originated from anthropogenic sources, with the traffic sector as the main contribution activity to the emissions of the whole region. In the last years, the Regional Government of Madrid has developed an ambitious action plan to improve the air quality for the period 2013–2020, called *Plan Azul+*. A WRF mesoscale simulation [11] showed that the *Plan Azul+* measurements were effective in the reduction of NO_2 levels over urban areas with high traffic influence. However, this simulation showed slight increases in ozone concentration (1–2%) in areas where typically ozone levels were low, and mitigation measures did not cause remarkable reductions in the rest of pollutants selected in the plan. Thus, prior to the establishment of recommendations for policymakers to include albedo enhancement in urban planning, the balance between potential climatic and air quality benefits and disturbances of widespread cooling the urban air must be assessed. Here, we have used a meteorological model (WRF), an emission model (AEMM), and a photochemical model (CMAQ) to assess the impact on meteorology and air quality of widespread urban albedo increase at two feasible levels of implementation: cool roofs (Alb1) and Alb2 (cool roofs + cool pavements). Changes in surface air temperatures and main pollutants are given for two 72-h period representative of summer and winter seasons.

2. Materials and methods

Numerical simulations of urban surface modification over Madrid city have been designed to test the impact of two increasing surface albedo scenarios, conducted by coupling WRF/AEMM/CMAQ. Urban layer was simulated by an urban energy model (BEM) coupled with an urban canopy model for simulations [12]. We have considered up to 10 urban categories. Air quality analysis has been focused over the main pollutants of health concern, namely O_3 , NO_2 , SO_2 , CO , $\text{PM}_{2.5}$ and PM_{10} .

2.1. Study area

Surface modification was simulated over the urban land cover of Madrid city, which is located in the center of the Iberian Peninsula. Its geographical position and topography determine a temperate continental Mediterranean climate with cold humid winters, with temperatures usually below 0°C , and warm dry summer, with temperatures above 30°C , frequently reaching peak values over 40°C , and high nocturnal temperatures [13, 14].

2.2. Simulation domains

In **Figure 1** we show nested modeling domains over the city of Madrid. Modeling is built over a mother domain (d01) with 27 km spatial resolution, centered at 40.383°N 3.717°W , and a domain size of $2727 \times 2727 \text{ km}^2$. This domain is intended to capture synoptic features and general circulation patterns. The first nested domain (d02), with a spatial resolution of 9 km, covers a domain size of $1575 \times 1413 \text{ km}^2$. The third domain (d03) with 3 km of spatial resolution has a domain size of $660 \times 561 \text{ km}^2$. The fourth domain covers the province of Madrid

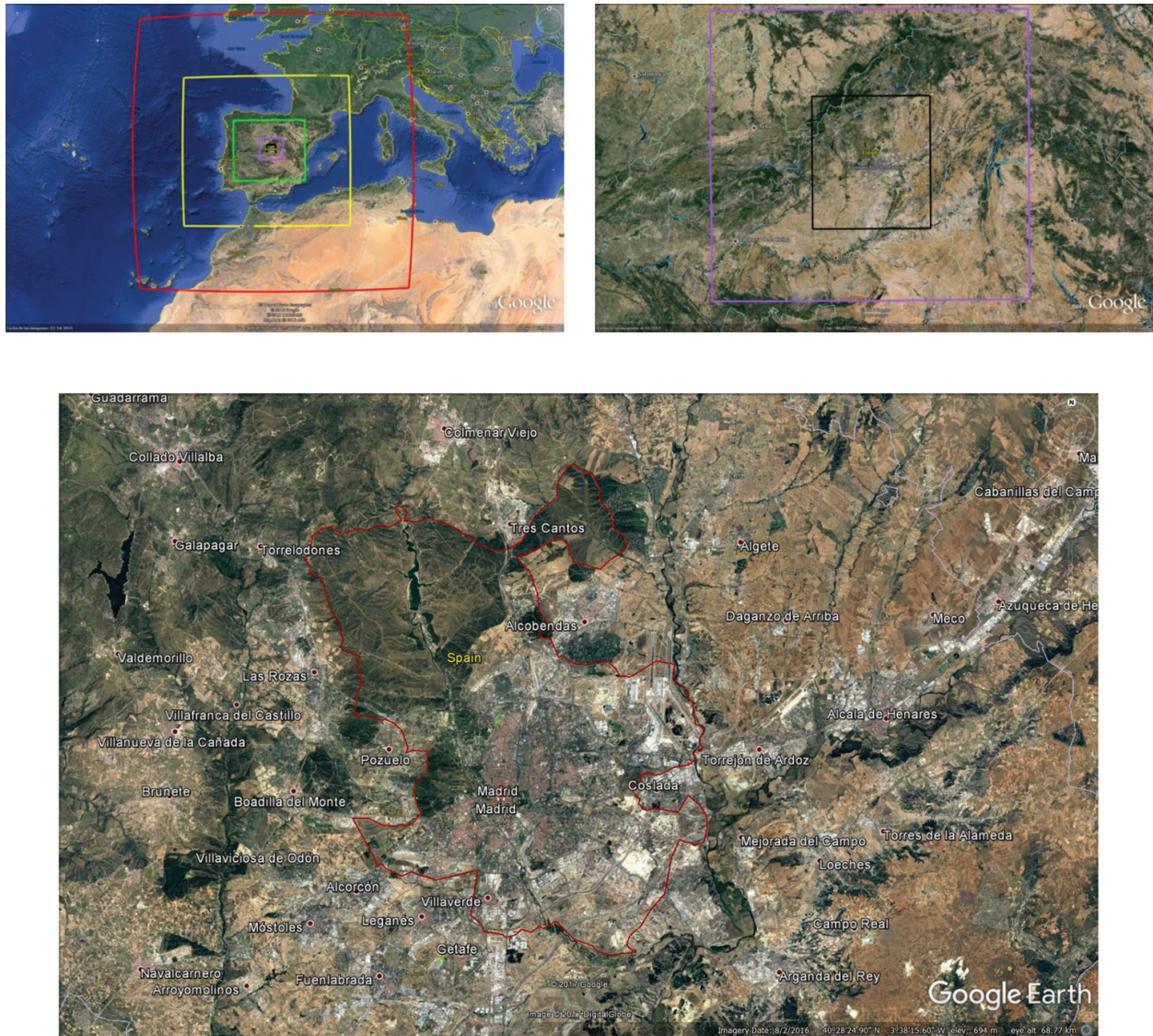


Figure 1. Up: Modelling domains for simulations: d01, d02, d03, d04 and d05 (left), and d04 and d05 (right). Down: Madrid local municipality (red line) and surrounding metropolitan area [Images generated using Google Earth].

and nearest provinces, with an extension of $217 \times 199 \text{ km}^2$ and grid resolution of 1 km^2 . The innermost fifth domain encloses Madrid metropolitan area, covering $80.3 \times 90.3 \text{ km}^2$, and grid resolution 333 m .

2.3. Modeling approach

The air quality modeling system used to evaluate albedo scenarios was composed by a coupled WRF/AEMM/CMAQ model. To configure it, we have followed the guidelines indicated in the Guide on the use of models for the European Air Quality Directive [15]. Emission and photochemical modeling configuration used here have been previously validated elsewhere [11], using a numerical deterministic evaluation during the development of the *Plan Azul+*, considering the Maximum Relative Directive Error [15] referred in the European Directive EC/2008/50. Meteorological simulations have been performed using the

Weather Research and Forecasting-Advanced Research WRF (WRF-ARW) version 3.2 [16], developed by the National Center of Atmospheric Research (NCAR). Urban categories have been adapted from The World Urban Database and Access Portal Tools [17, 18]. URBPARM.TBL was an adapted file for Madrid city according to our knowledge of urban morphology. Meteorology-Chemistry Interface Processor (MCIP) version 4.3 was used to prepare WRF output to the photochemical model. The annual anthropogenic emissions inventory of the Regional Government of Madrid has been used (version 2010). This inventory has a horizontal resolution of $1 \times 1 \text{ km}^2$ and includes emissions classified by Selected Nomenclature for Air Pollution (SNAP) sectors. We have used an Air Emission Model (AEMM) [11, 19] to adapt emissions to domains d04 and d05, using monthly and weekly profiles from the Unified EMEP model and vertical profiles from [20]. Emissions have been adapted under the requirements of the chemical modules considered in the photochemical model CMAQ. We have considered only anthropogenic emissions to avoid the influence of albedo modifications over the natural emissions, since the parameterizations that define them depend on meteorological conditions. This assumption is valid considering that the urban metropolitan area of Madrid is strongly dominated by anthropogenic local sources, being the natural emissions not very important, and only provide a remarkable contribution in areas far away of the city of Madrid [11]. To simulate the physical and chemical processes into the atmosphere, the US Environmental Protection Agency models-3/CMAQ model has been used [21]. Here, we have used CMAQ v5.0.1, considering CB-5 chemical mechanism and associated EBI solver [22] and AERO5 aerosol module [23]. Initial and boundary conditions for d04 domain are used from inner profiles and for d05 conditions are provided by the results of simulation of d04 domain. Coupled WRF/AEMM/CMAQ has been validated over Madrid city [11]. Another assessment of coupled WRF/CMAQ over Madrid city was reported [24], for an annual period and 1 km resolution, including a comparison of meteorological and air quality observations between WRF bulk urban canopy parameterization (UCP) (used here) and an alternative building energy model (BEP). As temperature predictions were not improved by WRF-BEP and the differences on wind direction and PBL height were not remarkable, we decided to use bulk UCP for computing time savings. Simulations have been executed over a computing cluster owned by Meteosim SL (Spain) and formed by 28 nodes and 308 cores.

2.4. Simulation results

Meteorological, emissions, and photochemical simulations have been conducted for two 72 h periods representative of both summer and winter of the year 2008: the period between June 30, 2008 and July 2, 2008 (hereinafter referred to as summer), and the period between January 1, 2008 and January 3, 2008 (hereinafter referred to as winter). The previous 24 h were taken as spin-up time to minimize the effects of initial conditions. A total amount of six simulations have been done for each period and three increasing albedo scenarios, defined from feasible levels of intervention obtained from literature [2, 25] as: (a) default scenario: using default value of albedo for all urban categories; (b) cool roofs scenario (Alb1): increasing from 0.20 to 0.55 the roof surface albedo for all urban categories; (c) cool roofs + pavement scenario (Alb2), with the same roof albedo increase as Alb1 plus an increase in pavement surface albedo from 0.15 to 0.30 for all urban categories. Spatial distributions and changes in pollutants levels at the innermost domain are reported, given as recommended time-weighted exposure parameters [26].

3. Results and discussion

3.1. Albedo changes

Averaged changes in surface albedo at the innermost domain resulting from the modification of roofs and pavements albedo over urban land cover are shown in **Figure 2a** and **b**. Maximum albedo change occurred as expected at the most compact area of town center, with +0.2 for both scenarios. No significant difference observed in this peak albedo increase between both intervention levels (data not shown for Alb2), was due to low ratio pavements/roofs at the dense urban structure of the urban category where they occur, tagged as compact mid-rise in the WUDAPT. On the contrary, surface albedo change differences were observed between scenarios at the open mid-rise category (enclosing most of the rest of the urban area inside the M40 highway belt), with +0.06 for Alb1 and +0.1 for Alb2, respectively. These two categories of residential use encompass the major proportion of urban potential intervention areas, along with the southeast belt of industrial-commercial use, where albedo increased +0.14 and +0.18, in Alb1 and Alb2, respectively.

3.2. Temperature changes

The spatial distribution of temperature changes was dependent on both the distribution and the level of albedo change. In **Figure 2c–f**, 72-h averaged changes at 12 h UTC are given. City center (compact mid-rise urban category) showed the most intense cooling in all cases, reaching the highest midday cooling intensity in summer of -1.4 and -1.6°C , for Alb1 and Alb2, respectively (**Figure 2d** and **f**). Little temperature change was observed in non-urbanized areas with small surface modification. In winter, much lower but significant cooling occurred, with maximum levels of -0.4 and -0.5°C , for Alb1 and Alb2, respectively, at the city center as well (**Figure 2c** and **e**). Thus, albedo enhancement was much more efficient in cooling air surface temperatures during summer periods, due to higher solar incidence angle. The spread of cooler air from city center toward the NE was due to predominant SW winds during the summer period, with averaging speed of 9.7 m s^{-1} (data not shown).

3.3. Changes in pollutant levels

After albedo enhancement, changes in pollutants were characterized by a decrease in O_3 in both periods, but higher in summer, and an increase in NO_2 in both periods. Averaged values for every 72-h period and scenarios are given in **Figure 3**. Spatial distributions of changes for ozone are given in **Figure 4**, in both scenarios and at the innermost domain. For the rest of pollutants, Alb1 scenario changes are given in **Figures 5** and **6**. Slight increases in PM_{10} and in SO_2 occurred in winter with negligible changes in summer. Little changes were observed in CO levels.

When cool pavements were added to cool roofs (Alb2), differences in distribution of pollutants other than ozone were not remarkable (Alb2 changes in **Figure 3**). Areas of major changes in pollutants after albedo increase extended through city center and NE rural areas in summer. This NE spread during the summer period was again associated due to dominant

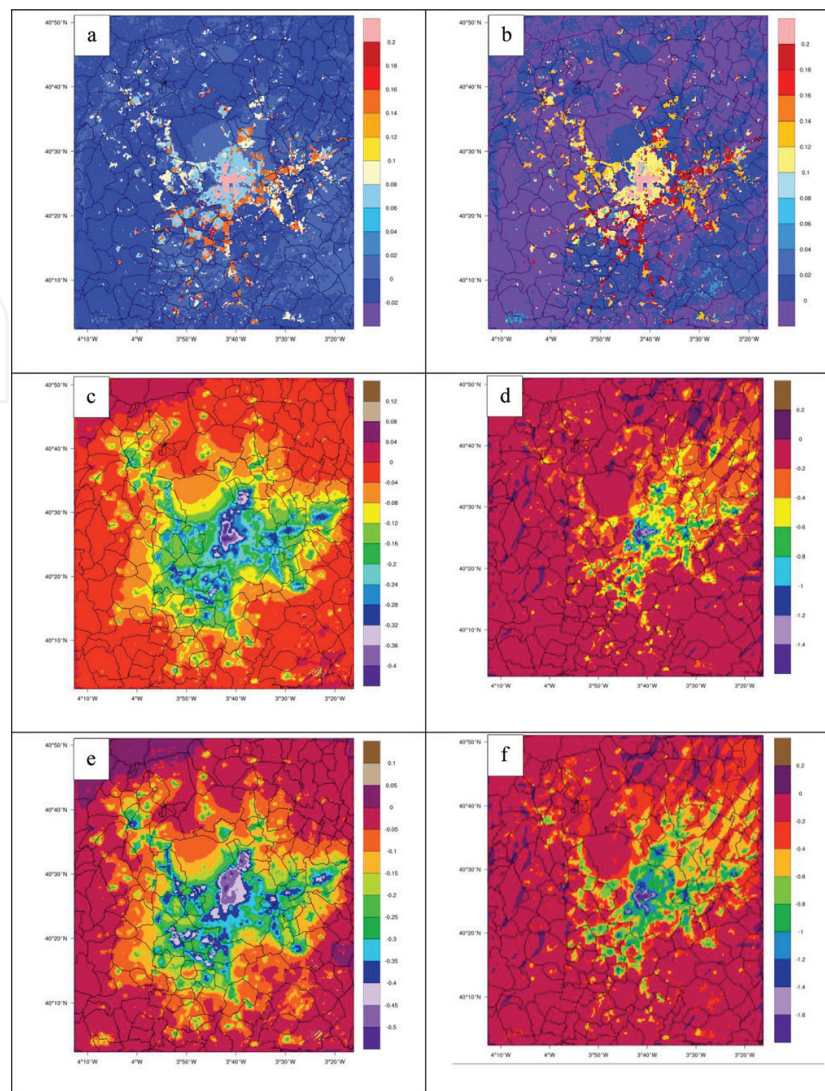


Figure 2. Spatial distribution of average albedo (a, b), and midday (12 UTC) temperature differences ($^{\circ}\text{C}$) between default and both Alb1 (c, d) and Alb2 (e, f) scenarios, and for the winter (a, c, e) and summer periods (b, d, f) at 12 UTC. Black lines limit municipalities, the biggest and innermost boundary is Madrid city (605.77 km^2).

SW winds in those days (data not shown). Highest reduction in O_3 levels occurred during the summer period (**Figure 4b** and **d**), when more intense cooling occurred as well. Eight-hour maximum reductions of around $-4 \mu\text{g m}^{-3}$ were reached at the city center. These results show that widespread cool roofs deployment over Madrid would benefit ozone levels at the city center, with additional reductions upwind depending on meteorological conditions. If additional cool pavements were implemented (Alb2), ozone reduction would extend further across most of the city, though reductions below the $-4 \mu\text{g m}^{-3}$ threshold were not observed in this scenario. In winter period both scenarios show scarce benefits for ozone reduction, as expected from limited surface air temperature cooling and lower rates of ozone formation in default scenario (data not shown). Our ranges of O_3 reduction are in accordance with similar mesoscale experiments of albedo modification [7, 9] with no local increases detected in our case, as other simulation studies have reported [3]. After albedo modification, NO_2 levels increased, mainly at the city center and at Barajas airport in winter (**Figure 5a** and **b**) only

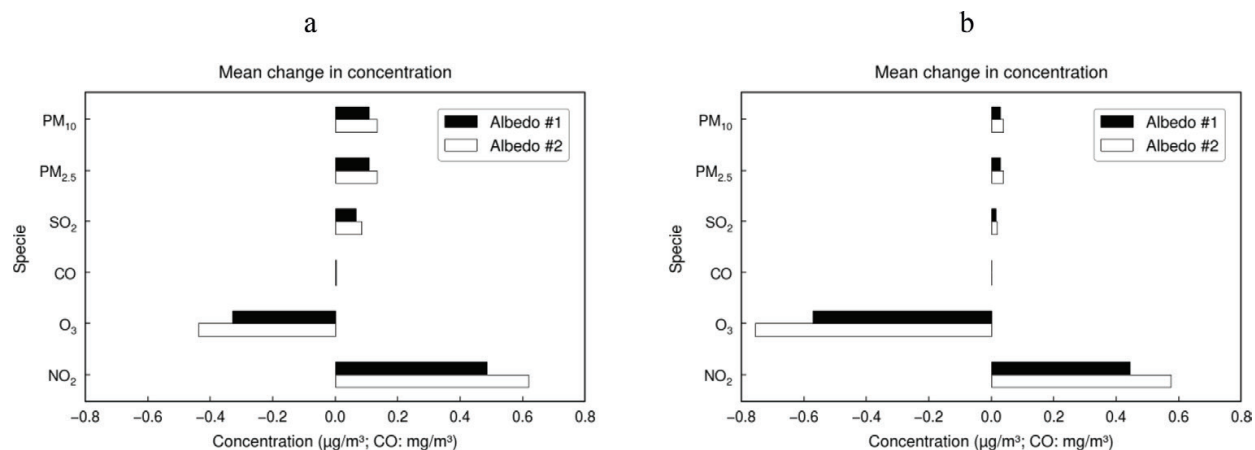


Figure 3. Mean change in pollutants concentration after albedo increase averaged for the winter (a) and the summer period (b).

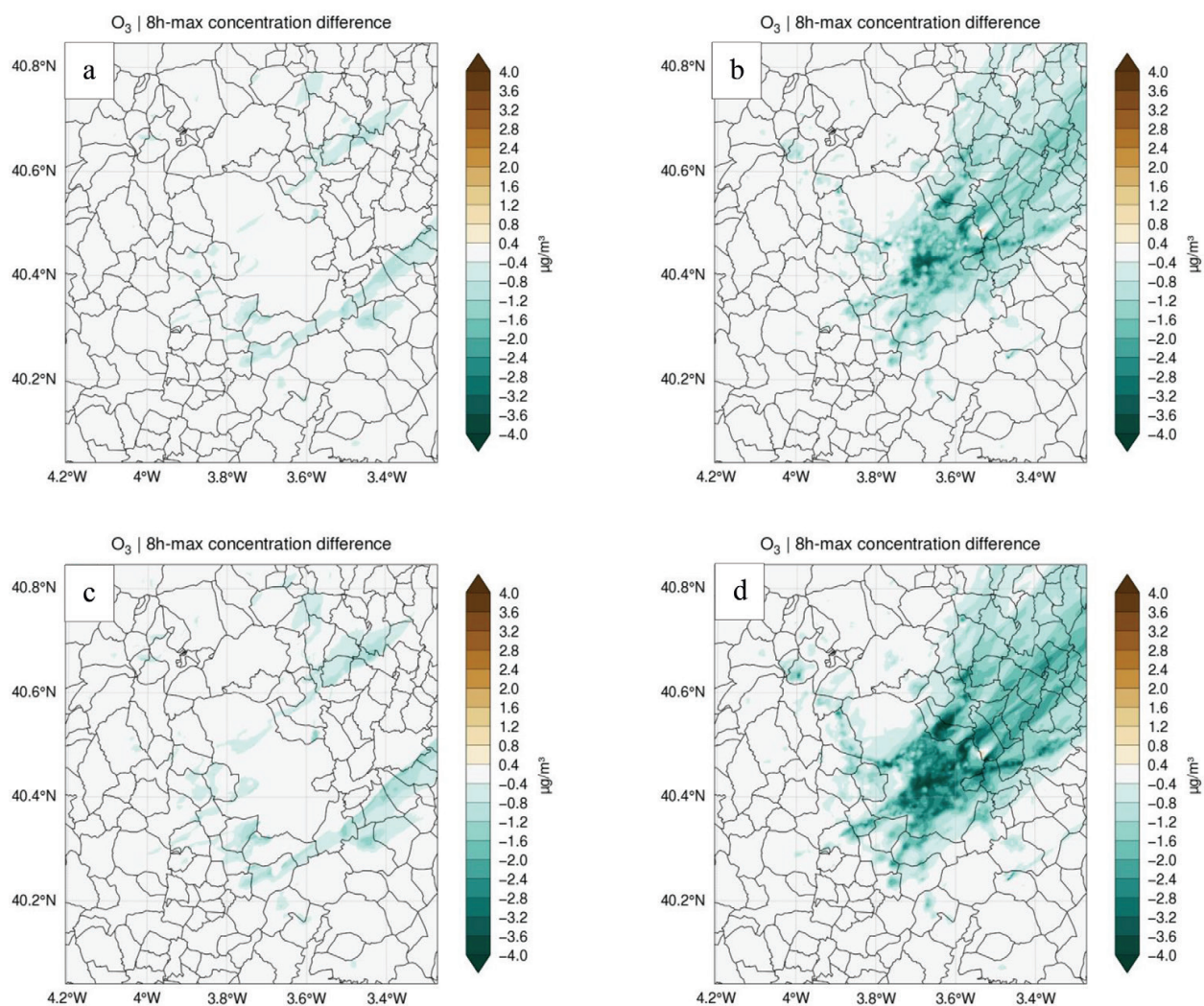


Figure 4. Spatial distribution of changes in O₃ maximum 8 h levels between default and Alb1 (a, b) and Alb2 scenarios (c, d) and for winter (a, c) and summer (b, d) ($\mu\text{g m}^{-3}$).

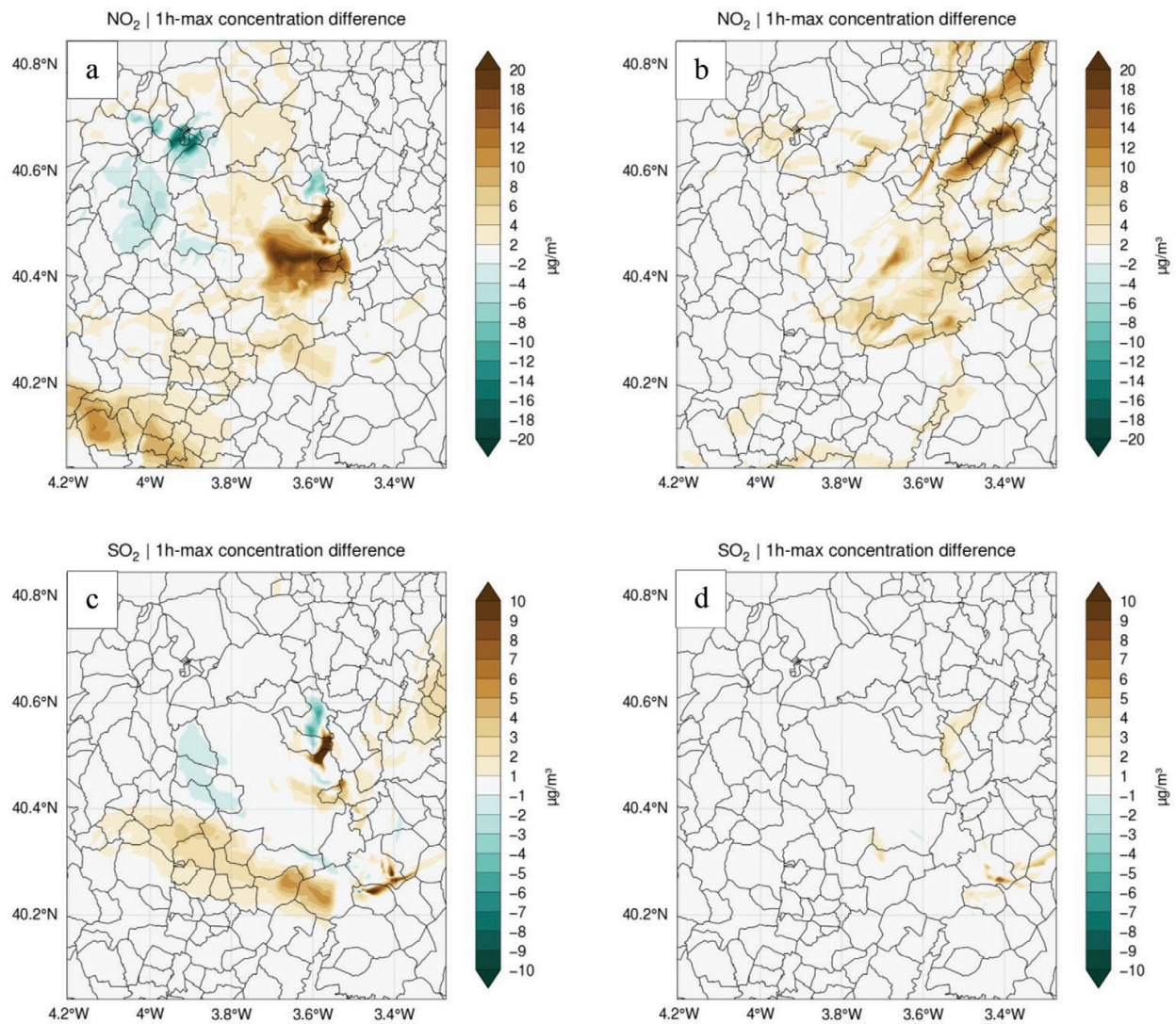


Figure 5. Spatial distribution of changes in NO₂ (a, b) and SO₂ (c, d) maximum 1 h levels between default and Alb1 scenario for winter (a, c) and summer (b, d) ($\mu\text{g m}^{-3}$).

Alb1 data are shown. Winter reductions were observed at some highly populated areas NW of Madrid city. At both periods, peak increases in 1 h—maximum concentrations reached up to $+20 \mu\text{g m}^{-3}$. At the city center, summer increases were below winter changes, though peaks of $+20 \mu\text{g m}^{-3}$ were reached at the pollutants spreading area NW of the city due to wind conditions. However, and contrary to O₃ changes, spatially averaged changes in NO₂ were very similar at both periods (**Figure 5**).

Increases in SO₂ occurred in winter at the highly populated municipalities SW of the city and around the airport and NE corridor, with peak 1 h maximum differences of $10 \mu\text{g m}^{-3}$ (**Figure 5c and d**). Decreased levels were observed in some municipalities west of the city. No significant changes occurred for summer in SO₂ levels in Madrid city, with slight increases NE of the airport and SE of the municipality. Spatial changes between scenarios were not remarkable for the rest of pollutants (data not shown).

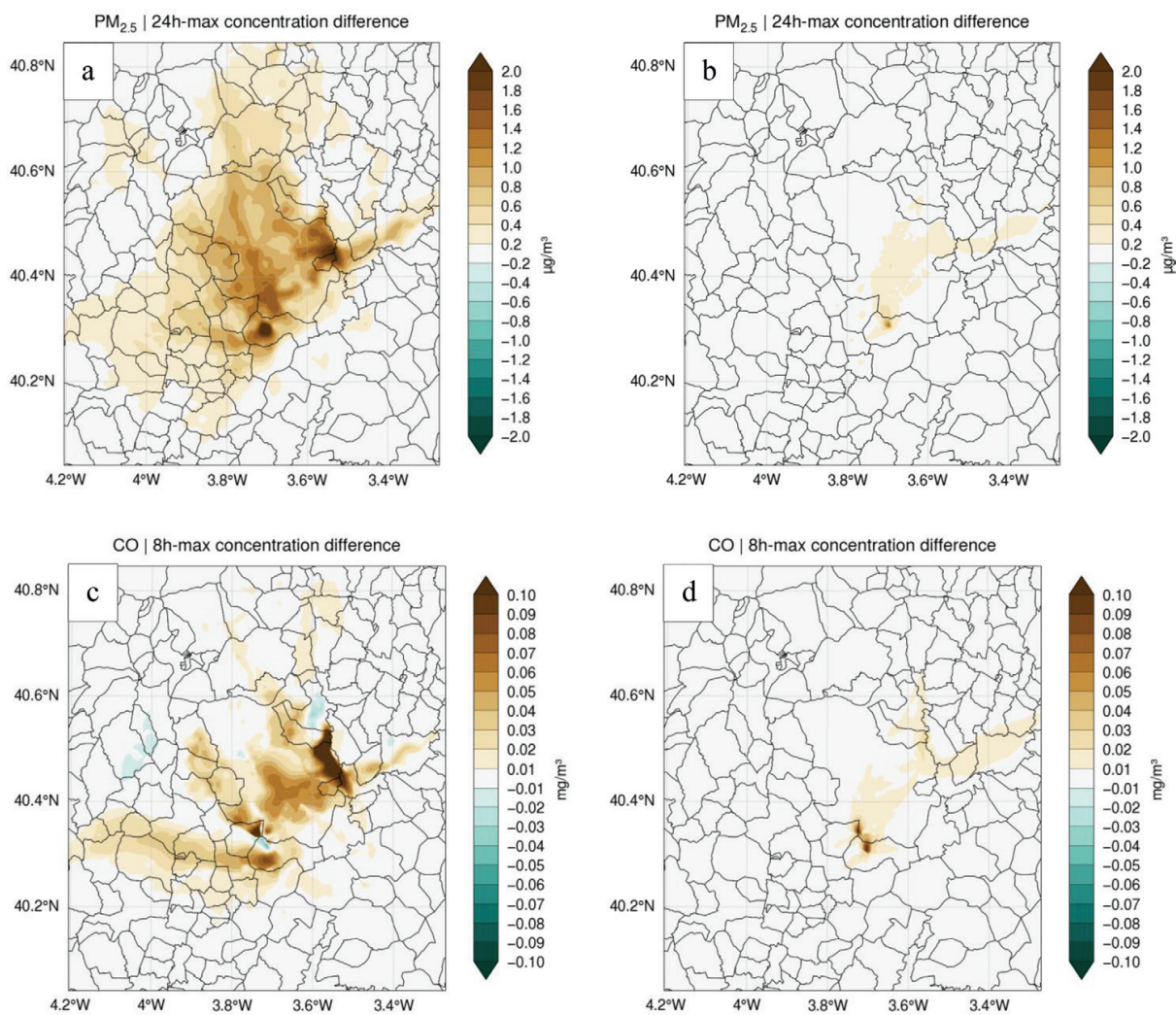


Figure 6. Spatial distribution of changes in $\text{PM}_{2.5}$ daily value (a, b) and CO 8-h maximum levels (c, d) between default and Alb1 scenarios for winter (a, c) and summer (b, d) scenarios ($\mu\text{g m}^{-3}$).

Slight differences were observed in the distribution of changes between $\text{PM}_{2.5}$ (**Figure 6a** and **b**). Increases in $\text{PM}_{2.5}$ were much higher in winter. Peak daily values increased above $2 \mu\text{g m}^{-3}$ in both scenarios, located around Barajas airport and south of the city. In summer on the contrary, little changes in $\text{PM}_{2.5}$ were observed for both scenarios, with small increases in the city center below $0.4 \mu\text{g m}^{-3}$. For CO, small increases were detected in city center (**Figure 6c** and **d**), with maximum $+0.1 \text{ mg m}^{-3}$ also around the airport and SW of the city.

According to our simulations, it was clear that albedo enhancement caused citywide air cooling with associated pollutant changes directly linked to temperature reduction. Our model shows that cool roofs and pavements reduce outdoor temperatures slowing reaction rates of ozone formation [3]. However, observed increases in the levels of other pollutants were caused by depression of PBL height associated with cooler air, limiting pollutant dispersion, and vertical mixing. Spatial distribution matches with cooling and shows peak change levels below 100 m (**Figure 7**), in areas where pollutants show higher increments. In summer, PBL height can fall to 90 m, but lower emissions and meteorological conditions generated lower increments. O_3 summer reductions by slower formation rates must probably be partly offset by PBL fall. In terms of averaged changes from maximum levels

at default scenario inside the limits of Madrid city after implementing the highest level of surface modification (Alb2 scenario) were approximately summer reductions in O_3 around to -4.4% and winter increments around $+16\%$ for NO_2 , $+10\%$ for SO_2 and $PM_{2.5}$, and $+5\%$ of CO . If only cool roofs were implemented (Alb1), these maximum thresholds would be the same for all pollutants but with a lower spatial reduction at the urban center for O_3 (data not shown)

Thus, our results confirm that citywide cool roofs deployment is a feasible effective measure to reduce summer air temperatures and control the ozone pollution over Madrid metropolitan area. Further benefits can be obtained extending albedo enhancement with cool pavements. In consequence, this surface modification strategy should be considered along with other actions in air quality plans over Madrid. According to numeric simulations of the application of measures proposed in *Plan Azul+*, carried out with a similar modeling approach [11], 2% O_3 increases would be expected over Madrid region and up to $+6 \mu g m^{-3}$ (1 h-maximum) at the center of town. For the rest of pollutants, the simulated effect of the *Plan* predicted reductions in NO_2 up to $11 \mu g m^{-3}$ but only slight global reductions below 5% of CO , PM_{10} , $PM_{2.5}$, and SO_2 . However, our simulation shows undesired impacts of albedo enhancement that need further research before a real implementation was to be considered, as in winter cool roofs might partly offset the reductions predicted in the plan for pollutants other than ozone. Anyhow, and given the nonlinear dynamics of the atmospheric processes, it would be advisable to make new simulations for longer representative seasonal periods, combining measures of *Plan Azul+* with increasing levels of intervention of surface albedo change, to determine the balance between benefits and disadvantages on air quality of a global action plan. A key outcome of our simulation is that the increment in pollutants other than ozone occurs mainly in winter period, where ozone formation rates are low and the concentration of other pollutants is higher. On the contrary, in our summer simulation, albedo caused limited increases in these pollutants, along with a maximized ozone reduction. According to our results, an ideal implementation of cool roofs and/or pavements would be a seasonally changing system of increased reflectance only on warm periods, with little or no albedo change for colder months. Furthermore, such a system would avoid winter penalty due to increased

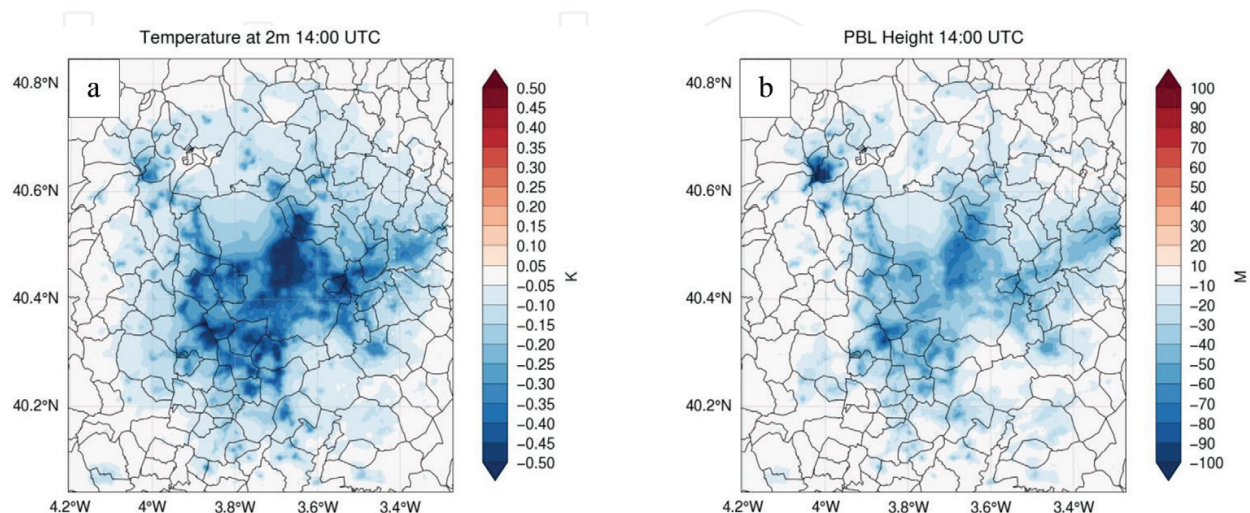


Figure 7. Temperature at 2m (a) and PBL height (b) differences between Alb2 scenario and default scenario for the winter period at 14 UTC.

heating demand [27]. A real experience of seasonal surface albedo change is applied over 20,000 reflective greenhouses in Almeria province, 500 km south of Madrid, where whitewash slaked/lime painting is applied over the roofs to limit excess heating inside the greenhouses in summer and is washed out in September to allow enough winter radiation inside them. The implementation of high albedo in the area has caused mean outdoor surface air temperature cooling, locally offsetting the impact of global warming [28, 29]. The levels of albedo enhancement simulated here (round +0.1 at the pixel level) are similar to those implemented on the field over Almeria area, but with more than double intervention surface at Madrid urban area, well above the minimum critical intervention area for efficient cooling at similar comparable latitudes and insolation. As our temperature data show, expected changes in net solar income at the surface should be comparable in both observed and simulated experiences, with differences in air temperature impact due mostly to location and surface canopy parameters of the urban fabric. However, our results are site and time dependent and have been generated from the specific coupled modeling configuration applied over Madrid city, for the periods simulated, and for the emissions inventory used. Further extensive research with optimized mesoscale modeling should also include the impact of albedo enhancement on cloud cover and precipitation pattern, as rain causes wet deposition of pollutants improving air quality. As our results show, depression of PBL height and dynamics of cooler air over the city might cause reduced vertical mixing and affect to the dilution of pollutants [30]. Other undesirable effects on the microclimate of the city and surrounded areas cannot be discarded and should be studied, such as modifications in the wind pattern and the hydrological cycle in the region [31]. Finally, these results do not account for additional benefits such as reduced cooling energy use and associated reductions in emissions from point sources, neither on the potential negative impacts on heating energy use in winter [3].

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Conflict of interest

The author declares no competing financial interest.

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