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MODELLING OF URBAN CLIMATE IMPACTS USING REGIONAL AND URBAN CFD MODELS. APPLICATION TO MADRID (SPAIN) AND LONDON (UK)

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ABSTRACT

The following paper presents the technique that can be used to produce climatic scenarios at urban scale with a spatial resolution of 10 m based on the results of the global climate models for the different RCP climate scenarios. To make the dynamic scaling process, we use the well-known mesoscale model WRF-Chem (NOAA, USA) to produce meteorological and air quality information at different scales. We start at a first level that covers all of Europe with a spatial resolution of 25 km, until it reaches the city level with a resolution of meters, which is simulated with the model MICROSYS-CFD. To show its use, 2011 was used as reference year and 2030, 2050 and 2100 as future years, with two possible scenarios RCP 4.5 and RPC 8.5. The expected impacts on wind conditions and NO2 concentrations are shown in two European cities: Madrid and London.

1 INTRODUCTION

Global climate change can have significant effects in urban areas (IPCC 2013). It is expected that cities will increase the number of heat waves, as well as their intensity, are also expected to have poor air quality by increasing concentrations of air pollutants, so it is very important to study the effects of climate change in the cities. In addition, the urbanization of green areas increases the exposure of the population to the effects of climate change. Half of the world's population lives in urban areas and over 80% of the population is expected to live in a city by 2020 (Rosenzweig et al., 2010). This situation has led scientists to devote part of their efforts to providing detailed information on the impacts of climate on cities and thus to help understand the relationship between global climate change and urban areas. This information will allow the authorities to propose and evaluate different mitigation and adaptation strategies to implement the best strategies (Robert and Kummert 2012).

One of the first problems of the urban microclimate is the wind comfort of the pedestrian. The climate change has consequences for the pedestrian wind environment. High-rise buildings plus new wind condition can introduce high wind speed at pedestrian level, which can lead to uncomfortable or even dangerous conditions. The objective is to maintain comfortable and safe pedestrian level wind conditions that are appropriate for the season and the intended use of pedestrian areas. Information on future wind flow patterns around buildings under different global climatic conditions may be important for planners to ensure pedestrian comfort and adequate ventilation to improve air quality. Urban areas will see their levels of air pollution worsen as climate change will affect emissions, dispersion and deposition of pollutants such as ozone and particulate matter, which in turn depend on local weather data such as temperature, wind, radiation and rainfall (Cooney 2012).

Future climate scenarios have been calculated with global climate models (GCMs) but with an approximate spatial resolution, around one degree, which makes it impossible to reflect or simulate local phenomena occurring on an urban scale. A possible solution is to apply dynamic downscaling techniques (Dickinson et al., 1989), where GCMs outputs are used as inputs (initial conditions and limits) to regional climate models (RCMs) with spatial resolution up to 1 km (Kikumoto et al., 2015). Finally, when it comes to urban areas with buildings, the spatial resolution of 1 km is still insufficient and we have to go to Computational Fluid Dynamics (CFD) models, which already allow us to do simulations with spatial resolution of meters.

The best boundary and initial conditions must be given for real simulations (Blocken et al., 2008). Buildings make the flow and dispersion of pollutants a complex simulation phenomenon (Piringer et al., 2007). The atmospheric flow and, therefore, the urban microclimate are influenced by the urban constructions (streets, buildings, etc.), so the urban modeling systems should consider this influence and include in their simulations the buildings as well as their effects on flows (ventilation, street canyons, etc.). The modeling system also requires information on emissions, vehicle emissions are one of the main sources of pollution in urban areas. Thanks to the high performance computing resources we can use CFD models to simulate large urban areas with very high spatial and vertical resolution covering several years of simulation. In pedestrian winds and dispersion of pollutants, CFD models can provide adequate responses (Westbury et al., 2002).

The horizontal resolution of the global climate models is typically around 100 – 150 km. It is clear that this is not enough to resolve detailed topography, landuses, and chemistry and building effects. GCMs are downscaled to higher resolution so that their outputs can be used as inputs to impacts models to explore how changes in climate might impact on specific fields. There are two common methods for downscaling future climate projections at finer spatial scales: dynamic downscaling and statistical downscaling. Dynamic downscaling is a method based on running regional / urban climate models (RCMs) over a specific area and the model receives boundary conditions from the global climate model. Typically, the RCM simulation does not feed back into the GCM, but adds regional detail in response to finer-scale forcing (e.g., topography, land use/land cover) as it interacts with the larger-scale atmospheric circulation. Statistical downscaling produces a few variables based on relationships derived from observations, which are applied in the future. The main advantage is that the procedure is not computationally very demanding. However, the method is of limited value, because you need observations, and local feedbacks are not taken into account. Furthermore, the relations derived from the present might be not true in the future.

Jacob and Winner (2009) give a review of studies have provided estimates of climate effect on air quality through correlations of air quality with meteorological variables, perturbation analyses in chemical transport models (CTMs), and CTM simulations driven by general circulation model (GCM) simulations of 21st-century climate change. Dynamical downscaling has been studied since the early 1990s (Dickinson et al., 1989; Leung et al. 1996) using regional models with coarse resolutions (around 50 km). More recently, finer spatial resolution has been applied: Bell et al. (2004) 40 km and Salathé et al. (2008) 15 km. Gao et al. (2012) implemented a dynamical downscaling system with the WRF model up to 4 km of spatial resolution over Eastern US. The WRF was also driven by outputs from de CESM model.

This research work presents a numerical modelling tool to investigate the interaction between climate change scenarios at urban level with the micro climate and air pollution of the cities. The system has been applied for years 2030,2050 and 2100, but only 2100 results will be showed because this year will expect the biggest impacts of future climate scenarios respect to the present (2011) over Madrid and London. This work is part of the EU FP-7 DECUMANUS project. The objective of this project is the development and consolidation of a set of services to support sustainable choices that enable city managers to deploy geospatial products in the development and implementation of strategies for energy efficiency and climate change, in meeting the many challenges of sustainable urban planning and development. The DECUMANUS services provide information to end users (city managers).

2 MATERIAL AND METHODS

2.1 CLIMATE SCENARIOS

As an example of the use of the proposed modeling system, the years 2011, 2030, 2050 and 2100 have been modeled considering two possible Intergovernmental Panel on Climate Change (IPCC) climatic scenarios such as Representative Concentration Pathways (RCPs) 4.5 (RCP 4.5) and 8.5 (RCP 8.5). The IPCC report identifies up to four climate scenarios, from very strong mitigation scenarios (non-realistic) (RCP2.6) to a business-as-usual scenario (RCP8.5). The choice of the worst-case scenario (8.5) and the best-realistic-case scenario (4.5) was motivated by the goal of displaying extreme changes that can be forecasted at city scale to allow implementing mitigation and adaptation strategies.

All simulations have been run for full year time period. The climate scenario RCP 8.5 will be achieved if it is not reducing emissions and represents the failure of actions to curb global warming by 2100. RCP 8.5 (Rao et al., 2006) is developed by the modeling team MESSAGE and the Integrated IIASA Assessment Framework at the International Institute for Applied Systems Analysis (IIASA), Austria. RCP 8.5 increases greenhouse gas emissions over time and represents a set of scenarios leading to high levels of greenhouse gas concentration. The underlying factors of the scenario and evolution are based on the A2r scenario detailed in (Riahi et al., 2008). This can be considered as a scenario without mitigation measures and therefore with high emissions of gases, similar to Special Report on Emissions Scenarios (SRES) A1FI.

The RCP scenario 4.5 is similar to the lower gas emission scenarios (B1) published by the IPCC in its AR4 report. RCP 4.5 (Clarke et al., 2007, Moss et al., 2010) is developed by the MiniCAM modeling team at the Joint Institute for Global Change Research (JGCRI) of the Pacific Northwest National Laboratory. It is a scenario characterized by the stabilization of emissions in which the total radiative forcing is stabilized around the year 2050 thanks to the use of technologies and strategies to reduce emissions of greenhouse gases (Clarke et al., 2007). More details on the simulation and terrestrial carbon emissions are given by (Wise et al., 2009). RCP 4.5 can be considered as a climate change mitigation scenario.

2.2 DOWNSCALING

As a starting point in our modeling exercise, we used global data with a six-hour time resolution that was generated using the Earth Community System Model (CESM) version 1.0, using the climate scenarios RCP 4.5 and RCP 8.5. The data is available to the scientific community on the Grid web of Earth System. As a regional model, we used the predictive model of meteorological and chemical research (WRF / Chem) to a spatial resolution of 1km. As intermediate levels a new domain has been simulated covering all of Europe with a spatial resolution of 25 km, and another of 5 km with a domain sufficient to cover the city to study. The nesting of the domains 25, 5, 1 is done through the boundary conditions (Byum et al., 1998).

To move to a resolution of meters and take into account the effects of the buildings we have used the MICROSYS CFD system on two urban areas of Madrid and London. Simulated areas have a very high density of buildings, as will be seen in the results. MICROSYS is based on the CFD MIMO model, (Ehrhard et al., 2000). The CFD model is a Reynolds-Average Navier-Stokes (RANS) with k–ε turbulent model runs in a steady-state mode (San Jose et al. 2009). Figure 1 shows the architecture of the simulation framework from the global climate model to the buildings city level. Madrid computational domain is 1200 by 1200 grid cells for 10 meters of spatial resolution and London is 600 by 530 grid cells. The height of the 3D domain is 100 meters.

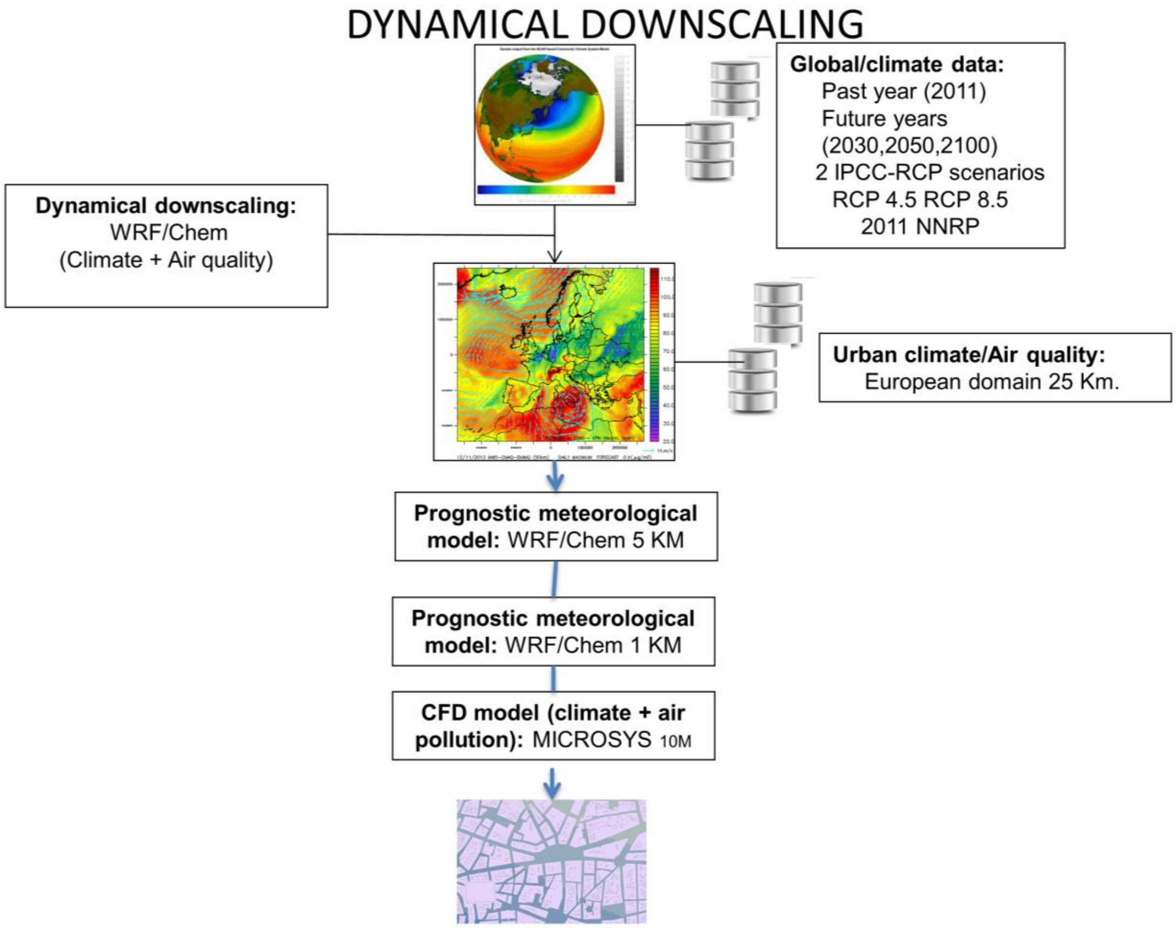

Figure 1: Conceptual overview of the model chain used in the present study.

For air quality predictions, in addition to meteorology, we need emission data in each cell of six pollutants: NOx, NH3, PM, SO2, VOC and CO. In order to generate the necessary data, we have used the EMIMO model (San Jose et al., 2009). This is an emissions model that is capable of estimating - in a combined bottom-up and top-down approach - primary contaminants at a spatial resolution of meters and a time resolution of 1 hour.

3 RESULTS AND CONCLUSIONS

For the year 2030 and 2050 although different meteorological and air quality behavior is expected for the RCP 4.5 and RCP 8.5 scenarios, the differences are not particularly significant. In the year 2100 a very different behavior of the atmosphere is expected if we compare both scenarios, so in this work we will focus on analyzing the results of the year 2100.

3.1 RESULTS

Figure 1 shows the projections of changes in the average annual surface temperature for the year 2100 compared to 2011. For the European domain with 25 km of spatial resolution, we can see a clear trend towards global warming according to the climatic scenario RCP 8.5 (+ 5ºK). On the other hand, in the

RCP 4.5 scenario, a strong cooling effect (-6 ° K) can be expected for the year 2100, especially in northern Europe.

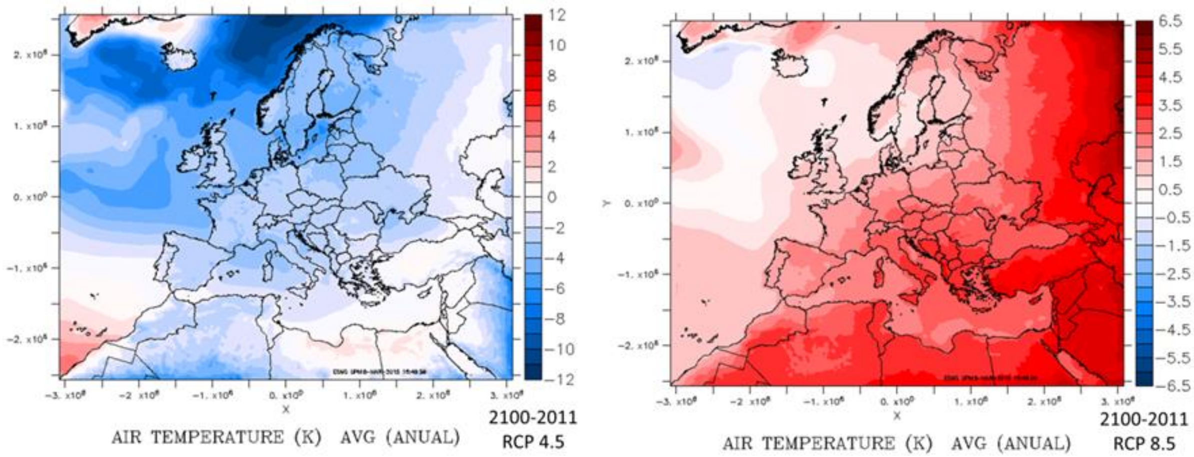

Figure 2: Spatial distribution of the differences in annual mean air temperature (Kº) for respect to 2011 following RCP 4.5 (left) and RCP 8.5 (right) scenarios with WRF-Chem over Europe with 25 km. resolution.

Spatial differences (1 km of spatial resolution) of minimum temperature changes between (the large future) 2100 and 2011 (present) for RCP 4.5 and RCP 8.5 in the two European cities calculated with the WRF/Chem modelling system are showed. Madrid is in the Figure 3 and London Figure 4.

In Figure 3, in the case of the climatic scenario RCP 4.5, in the northern zone of the domain we observe a decrease of the minimum temperature for the year 2100 up to 2.5 degrees Celsius if we compare it with the one of the 2011 and reductions of 1.8 degrees, in the central area of the city. The climactic scenario RCP 8.5 results in an increase of the minimum temperature for the year 2100 to 1.4 degrees Celsius compared to the temperature of 2011 in the center of Madrid. This would increase the effects of the urban heat island.

In case of the London domain (Figure 4), we observe decreases in the NO2 concentrations over the areas closest the river in the scenario 4.5, while in the 8.5 scenario slight increases are observed over the same area. The decline is justified by increased precipitation and ventilation of the area.

Steady state simulations of airflows and pollutant concentrations over Madrid and London have been carried out using the CFD model described above with 10 meters of spatial resolution. Sample results in Figure 5 to Figure 8 are presented. Figure 5 is from all Madrid computational domain and Figure 6 is a zoom over 1 km by 1 km area to see better the wind complexity. The same scheme for Figure 7 and Figure 8 but over London area and them show NO2 concentrations.

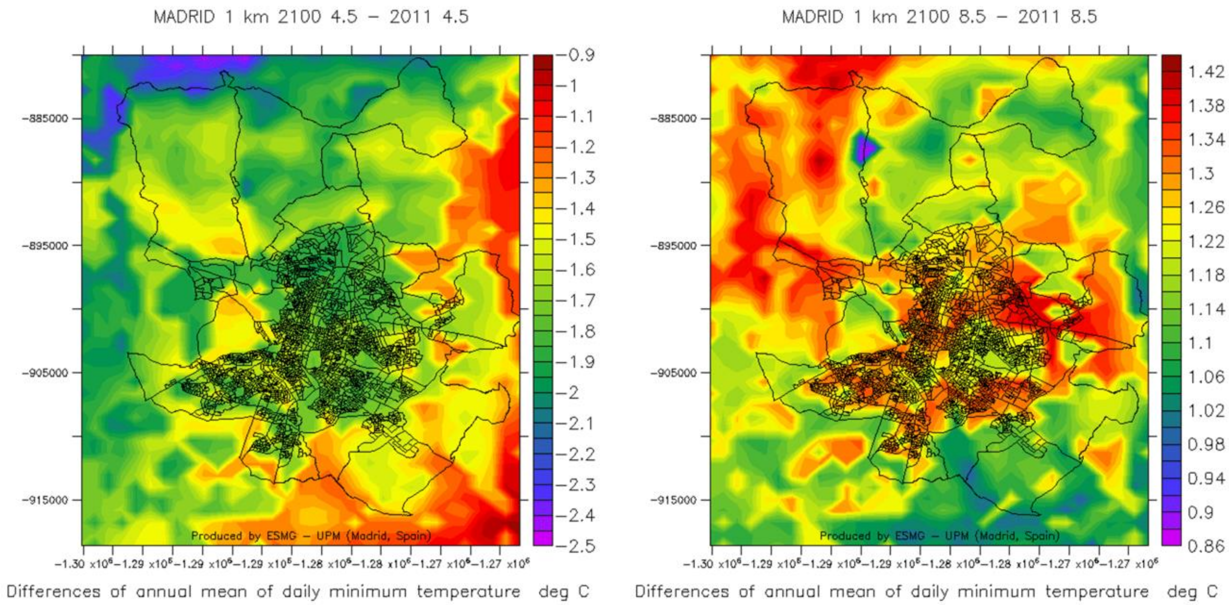

Figure 3: Spatial distribution of the differences (ºC) between 2100 and 2011 (1 kilometer of resolution) of one-year average minimum air temperature RCP 4.5 (left) and RCP 8.5 (right). Final results from the dynamical downscaled simulations using WRF-Chem over Madrid.

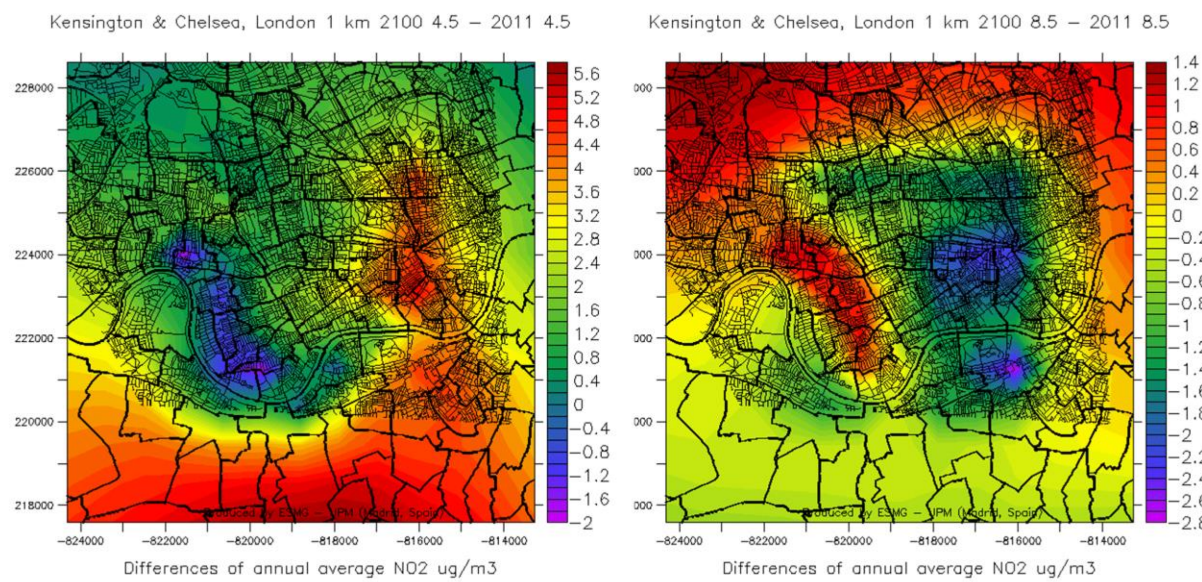

Figure 4: Spatial distribution of the differences (ug/m3) between 2100 and 2011 (1 kilometer of resolution) of one-year average NO2 concentrations. RCP 4.5 (left) and RCP 8.5 (right). Final results from the dynamical downscaled simulations using WRF-Chem over Kensington and Chelsea (London, UK).

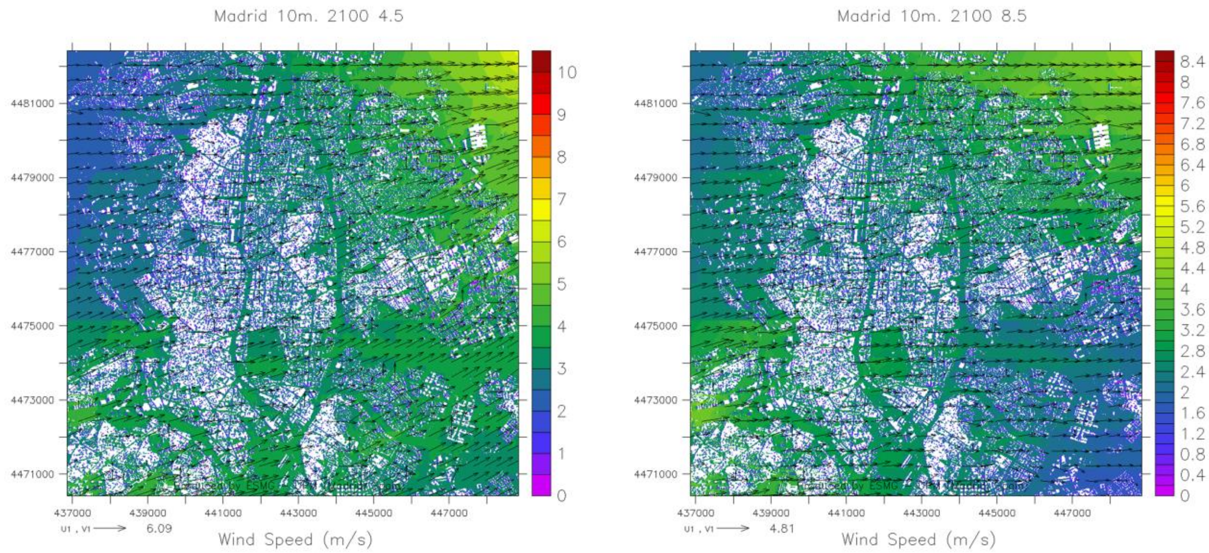

Figure 5: Madrid wind vectors and wind speed (m/s) over Madrid (average winter day) for 2100 under scenario 4.5 (left) and scenario 8.5 (right).

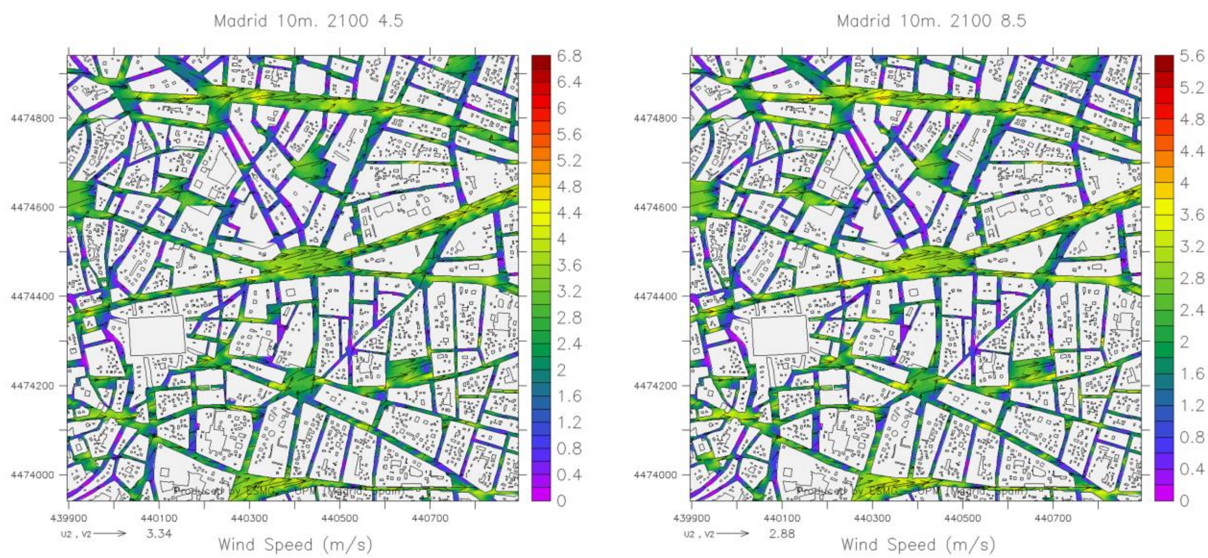

Figure 6: Zoomed-in area (1km by 1 km) of Madrid wind vectors and wind speed (m/s) over Madrid (average winter day) for 2100 under scenario 4.5 (left) and scenario 8.5 (right).

The wind is south-easterly for both scenarios but its speed is bigger in the scenario 4.5 than the 8.5. The simulated wind is strong in some regions around tall building, however in most regions the simulation wind speed close to building is lower than the wind speed in open areas, indicating that buildings act to retard wind speed.

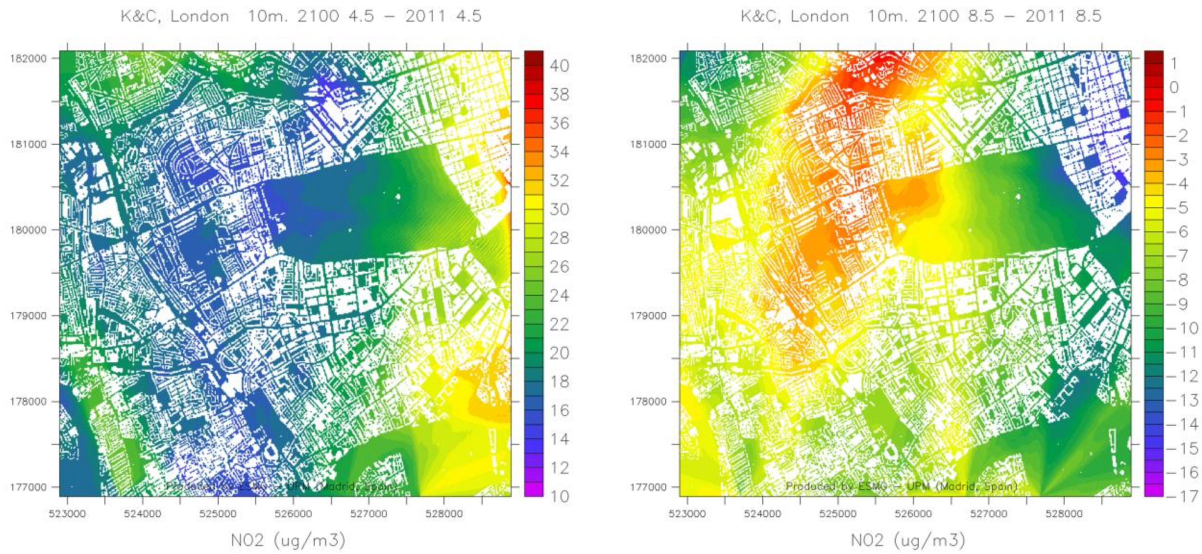

Figure 7: Differences of NO2 concentrations over London (average spring day) between 2100 and 2011 under scenario 4.5 (left) and scenario 8.5 (right).

We observed strong increases in NO2 in the eastern part of the domain up to 40 ug / m3 under the scenario 4.5, while the 8.5 scenario decreases are expected, with no changes respect to 2011 in the central part of the domain.

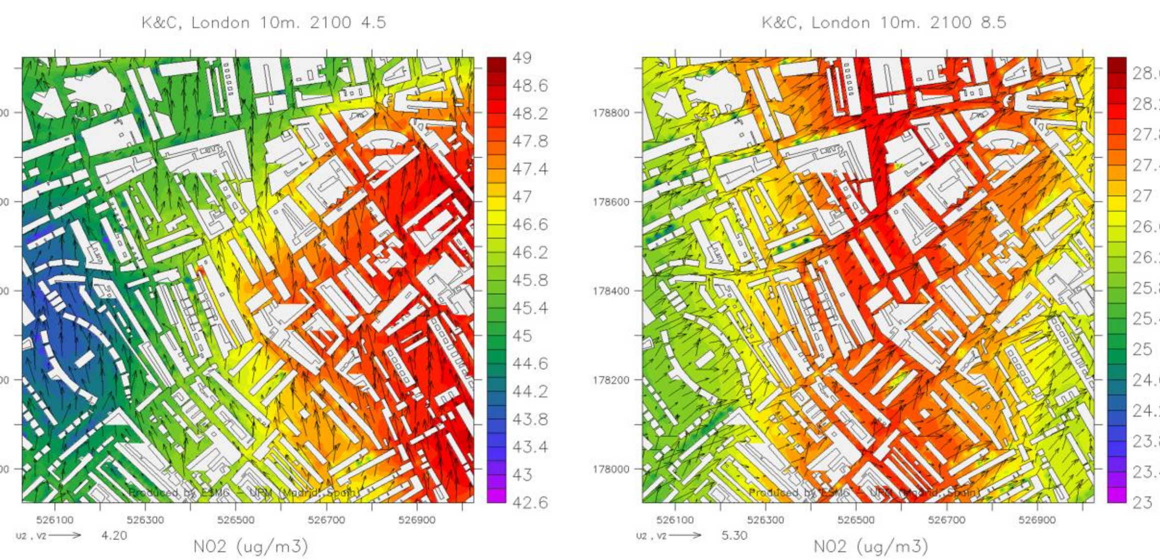

Figure 8: Zoomed-in area (1km by 1 km) of NO2 concentrations over London (average spring day) for year 2100 under scenario 4.5 (left) and scenario 8.5 (right).

Weak pollutant dispersion is observed in the east part of the domain under scenario 4.5 but in the scenario 8.5 the maximum values are observed in the central part due to different wind patterns between 4.5 and 8.5.

3.2 CONCLUSIONS

A micro climate and air pollution coupled simulation assessment tool was proposed and applied to study the future wind conditions and NO2 concentrations over Madrid and London under two IPCC RCP possible scenarios, 4.5 and 8.5. The information can be used for local decision makers and stakeholders in order to developing strategies to reduce these impacts. Simulation results summarize the climate and air pollution of the cities and how change with the different climate scenarios. These information combined with terrain analysis, land use and urban planning and management policy etc, it can draw the urban climate map and improve strategies to improve urban environment, mitigate climate effect and air pollution problems. The results can help to understand the characteristics of urban climate and air quality, this knowledge can be used to propose planning strategies. The tool identify the priority areas of the city which are classified as hotspots because the potential impacts are higher that other parts of the city. The modelling system also allows probing local implementation of climate strategies to select the most efficient. So our models can be used for forecasting climate impacts and to check the effectiveness of specific management strategies.

Since the objective is to study the effects of climate, local emissions and urban morphology for the year 2011 have also been used for the years 2030, 2050 and 2100. This allows to isolate the effect of climate change and to know its impact on the city. The modeling system tool uses a CFD model in its last level of nesting that takes the initial and counter conditions of the WRF/Chem model. The tool has been applied to examine the future urban flow and the dispersion of pollutants in two densely urbanized urban areas such as Madrid and London.

Representative examples of future climate impacts have been shown, according to the IPCC RCP 4.5 and RCP 8.5 scenarios. In the European scale with 25 km of spatial resolution we have been able to observe how by 2100 large changes in air temperature are expected, with warming in the cities for the climatic scenario RCP 8.5 and cooling for RCP 4.5. In high-resolution simulations for cities we have seen how buildings influence impacts and how hot spots are distributed throughout cities. The more complicated flows occur around buildings. In the future, the tool will continue to work with validation studies to determine the uncertainty associated with modeling.

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