Regional and urban downscaling of global climate scenarios for health impact assessments

Roberto SAN JOSÉ[1], Juan Luis PÉREZ[1], Libia PÉREZ[1], Rosa María GONZÁLEZ[2] , Julia PECCI[3], Antonio GARZÓN[3], Marino PALACIOS[3]

[1]Environmental Software and Modelling Group, Computer Science School, Technical University of Madrid, Campus de Montegancedo, Boadilla del Monte, 28660 Madrid, Spain.
roberto@fi.upm.es
[2]Dept Geophysics and Meteorology, Faculty of Physics, Ciudad Universitaria, 28040 Madrid, Spain.
[3]Indra S.A., C/ Mar Egeo, 4, Pol. Industrial 1, 28830 San Fernando de Henares, Madrid Spain

Received: 03/04/2015
Accepted: 01/09/2015

Abstract
In this contribution we have used global climate RCP IPCC scenarios to produce climate and air pollution maps at regional (25 km resolution) and urban scale with 200 m spatial resolution over Europe and five European cities in order to investigate the impact on meteorological variables and pollutant concentrations . We have used the very well known mesoscale meeorological model WRF-Chem (NOAA, US). We have used 2011 as control past year and two RCP scenarios from CCSM global climate model with 4.5 W/m^2 and 8.5 W/m^2 for 2030, 2050 and 2100 years. After running WRF-Chem model, using the boundary conditions provided by RCP scenarios with the emissions of 2011, we have performed a detailed downscaling process using CALMET diagnostic model to obtain a full 200 m spatial resolution map of five European cities (London, Antwerp, Madrid, Milan, and Helsinki). We will show the results and the health impacts for future RCP IPCC climate scenarios in comparison with the 2011 control year information for climate and health indicators.
Finnally, we have also investigated the impact of the aerosol effects in the short wave radiation mean value. Two simulations with the WRF-Chem model have been performed over Europe in 2010. A baseline simulation without any feedback effects and a second simulation including the direct effects affecting the solar radiation reaching the surface as well as the indirect aerosol effect with potential impacts on increasing or decreasing the precipitation rates. Aerosol effects produce an increase of incoming radiation over Atlantic Ocean (up to 70%) because the prescribed aerosol concentrations in the WRF-Chem without feedbacks is substantially higher than the aerosol concentrations produced when we activate the feedback effects. The decrease in solar radiation in the Sahara area (10%) is found to be produced because the prescribed aerosol concentration in the "no feedback" simulation is lower than when we activate the feedback effects.
Key words: Climate, Downscaling, Health, Indicators, Aerosols, WRF-Chem

ISSN: 0214-4557
http://dx.doi.org/10.5209/rev_FITE.2015.v27.51201

Escenarios climáticos globales de alta resolucion para entornos regionales y urbanos con estudios de impacto en la salud

Resumen

En esta contribución se han considerado dos escenarios climáticos globales RCP IPCC para producir información de clima y calidad del aire a escala regional (25 km de resolución) y escala urbana (200 metros) sobre Europa y cinco ciudades europeas utilizando el modelo WRF-Chem (NOAA,US), con el objetivo de investigar el impacto en las variables meteorológicas y las concentraciones de contaminantes. El año 2011 se ha establecido como el año de control, los dos escenarios RCP del modelo climático global CCSM elegidos son 4.5 W/m2 y 8.5 W/m2 y los resultados mostrados son para los años 2030, 2050 y 2100. Tras ejecutar el modelo WRF-Chem con condiciones de contorno suministradas por los escenarios RCP con emisiones del año de control, se ha realizado un refinamiento de escala con el modelo de diagnóstico CALMET para obtener mapas de 200 metros de las cinco ciudades europeas. En este trabajo se muestran los resultados y los impactos de los futuros escenarios comparados con el año de control considerando indicadores climáticos y de salud.

Adicionalmente, hemos investigado el impacto de los efectos de los aerosoles en el valor medio de la radiación de onda corta. Se han llevado a cabo dos simulaciones con el modelo WRF-Chem sobre Europa para el año 2010. En la simulación de control no se han tenido en cuenta los efectos de retroalimentación (feedback). En la segunda simulación se han incluido los efectos directos en la radiación solar, con potenciales reducciones de la misma en la superficie, y los efectos indirectos, principalmente relacionados con los potenciales impactos en la precipitación. Los efectos de los aerosoles producen un incremento en la radiación solar en el área del Atlántico Norte (hasta un 70 %) porque las concentraciones de aerosoles prescritas en el modelo WRF-Chem sin "feedbacks" son sustancialmente superiores a aquellas concentraciones producidas cuando activamos los "feedbacks". El descenso observado en la radiación solar en el área del Sahara (10 %) se produce porque las concentraciones de aerosoles prescritas en el modelo sin "feedbacks" son inferiores a aquellas encontradas cuando activamos los efectos de "feedback".

Palabras clave: Clima, Refinamiento, Salud, Indicadores, Aerosoles, WRF-Chem

Contents:

Normalized reference

San José R., Pérez J.L., Pérez L., González R.M., Pecci J., Gazón A., Palacios M. (2015). Regional and urban downscaling of global climate scenarios for health impact assessments. *Física de la Tierra*, Vol. 27, 227-251.

1. Introduction

Under future climate conditions it is expected that the pollutant concentrations will change. These relations are documented in several studies (Mickley et al., 2004; Stevenson et al., 2006; Liao et al; 2007; Weaver et al., 2009). These changes may pose health risks to the population, so it is a challenge the ability of cities to adapt to and mitigate the climate change. A current research challenge is to implement tools that allow us to calculate the impact of climate change on air quality and health of citizens at the urban level The aim of this paper is to describe the application of a system for assessment the impact of the global climate on urban climate, air quality and health. The future of air quality, however, is not just a matter of emissions. We also need to consider global climate change with the aim to integrally assess impacts on air quality (ozone and particles) and local climate (heat waves, apparent temperature), as well as the effects on population health. In addition, due to the interdisciplinary nature of the subject, this task requires the collaboration of professionals from various areas such as climate science, air quality and public health.

In the cities, climate change affects the levels of air pollution because production, dispersion and deposition of pollutants, such as ozone and particulate matter depends in part on the local values of temperature, wind, solar radiation and precipitation. Then, knowing the present and future impacts of climate change on air quality as well as on mortality and morbidity of citizens should be a priority for researchers. Keep in mind that to be studying urban areas need information from very high resolution to capture the high spatial variability of air pollution within a city.

Global climate model (GCMs) cannot provide information at scales finer than 100 km and the processes at the unresolved scales are important (Cooney, 2012). Providing information at finer scales can be achieved using dynamical downscaling. The starting point of the dynamical downscaling is a set of global coarse-resolution meteorological fields (from a GCM model), which are used to provide the initial and boundary conditions to a regional climate model (RCM). A key issue, which is solved in this paper, is how to calculate the impact of the global climate at fine resolution over urban areas. The major problem of simulating high resolution urban scales is the big computational demand of the dynamical downscaling tools and this is very relevant to climate studies where you the simulated periods and scenarios are multiple.

Our goal is to quantitatively estimate the local impact on health due to global climate on the cities to enable the authorities to implement the most appropriate policies and strategies to minimize the effects of climate on citizens. Rapid advances in computing and atmospheric physics, especially in using downscaling techniques offer new opportunities to investigate health problems related to urban climate.

Computational simulations with climate forced over five European cities: Madrid, Antwerp, Helsinki, Milan and London (Kensington-Chelsea area) have been developed with 200 meters of spatial resolution during the last level of the nesting approach. Between the global and urban level, we have an intermediated level (regional) with 25 km of spatial resolution covering all Europe. We have used 2011 year as reference run (present) and 2030, 2050 and 2100 as future years. We have downscaled two of the Representative Concentrations Pathways (RCPs) (Moss et al., 2010), RCP4.5 and RCP8.5 defined by the Intergovernmental Panel on Climate Change (IPCC) in the Fifth Assessment Report (AR5).

This work is part of FP-7 EU DECUMANUS project. The aim of this project is the development and consolidation of a set of sustainable decision support services that allow city managers to deploy geo-spatial products in the development and implementation of their energy efficiency and climate change strategies, in meeting the diverse challenges of sustainable urban planning and development. The

DECUMANUS services will offer information to the end users (city managers). The information will be produced by the scientific team operating the proposed tools as the dynamical technique described in this research work for urban and health information.

Aerosols are known to affect weather and climate via several ways but the feedback effects are one of the most uncertain research areas in air quality and climate modelling (Jacob and Winner, 2009). These uncertainties diminish our capability to generate reliable climate projections and to provide accurate weather and air quality predictions so, research tasks should be addressed to reduce these uncertainties. Aerosols and their precursors have both natural sources resulting from desert dust lifting, sea spray, volcanic eruptions, biogenic organic emissions and anthropogenic sources such as fossil fuel and biomass burning. The aerosols may produce a reduction of downward solar radiation (direct effect), a change in near surface temperature and thermal stability due to absorption of solar radiation which leads subsequently to a change in cloudiness (semi-direct effect) a decrease in cloud drop size but an increase in cloud droplet number concentrations through their role as cloud condensation nuclei (indirect effect). These effects have been observed in the past (Kaufman and Fraser, 1997). New studies have been developed to study the multiple interactions between meteorology and chemistry in the atmosphere, for example aerosol-cloud-radiation feedback effects (Zhang, 2008; Zhang et al., 2010; Forkel et al., 2012) and interactions between temperature, gas-phase chemistry and aerosols (Baklanov et al., 2014) We can also find opposite effects of the aerosols on the meteorological variables, for example the precipitation. Aerosols can decrease solar radiation on surface, so less heat is available for water evaporation and a reduction of precipitation is observed. On the other hand, depending of the absorbing characteristics of the aerosols (mineral dust, black carbon, etc) they could energize convective clouds and thus increasing precipitation (Levin and Brenguier, 2009). Feedback effects can be particularly important during strong particles episodes (Konovalov et al., 2011; Wong et al., 2012; Chen et al., 2014).

Realistic simulation of the feedback effects requires the use of integrated meteorology-chemistry on-line models that include detailed treatment of aerosol life cycle and aerosol impacts on radiation (direct effects) and clouds (indirect effects) (Yang et al., 2011; Bangert et al.,2012; Baklanov et al., 2014). Historically, the study of these effects has been done separately in modelling approaches. Chemistry and weather forecasts have been developed as separate disciplines, leading to the creation of separate modeling systems that are only loosely coupled (offline) (Grell and Baklanov, 2011). Fully coupled on-line models, where meteorological and chemical processes are solved together on the same grid and with the same physical parameterizations are able to simulate the complex aerosol-cloud-radiation feedback effects (Zhang et al. 2008). Recent case studies have shown that the inclusion of feedback effects can improve the model performance for specific cases and conditions (Yang et al., 2011; Bangert et al., 2012; Forkel et al., 2012). More research and studies are needed to investigate how the inclusion of feedback effects within on-line air quality models affects the simulation results over Europe for a longer simulation episode.

2. Methodology

We propose to use a chain of computational models to go from the global scale to the urban scale. Figure 1 shows the conceptual outline of the system for assessment of the impacts of the global climate at urban level. Data from the GCM Community Earth System Model (CESM) is the first link in the chain. The dynamical climate-air pollution dynamical downscaling to regional level is based on the WRF-Chem model (Grell et al., 2005). WRF-Chem model (version 3.4.1, September 2011) has been used to develop the first level of the downscaling. It includes the RADM2 gas phase mechanics, the MADE inorganic aerosol scheme, and the SORGAM aerosol module for secondary organic aerosols (SOA). For the final step in the downscaling proccess we have selected a very well-known meteorological diagnostic model, CALMET (Scire et al., 2000) from California Air Resources Board (CARB) -V5.8.4 July, 31, 2013. CALMET is applied to process the downscaling from 25 km. spatial resolution to 0.2 km spatial resolution domain centered over the five European cities. CALMET model can avoid the high computational cost of the three dynamical downscaling levels that we will need to go from 25 km to 0.2 km. CALMET- as a diagnostic model, does not produce "dynamics" as WRF-Chem model. At urban level, the air pollution modelling part of the system includes the air quality model CMAQ.

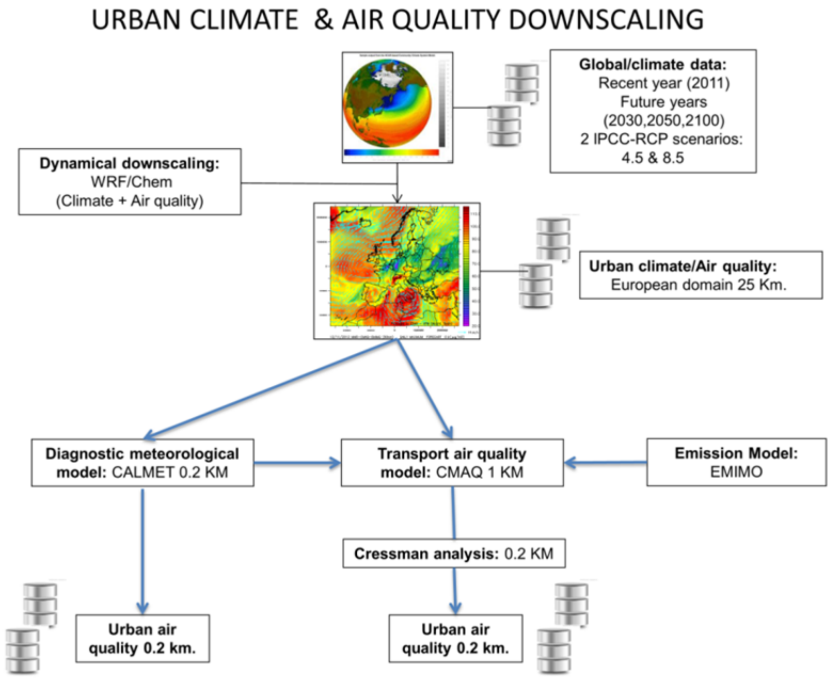

Figure 1. Conceptual overview of the model chain (from global to urban) used in the present study.

The Air Quality (AQ) downscaling over the cities is performed by running the CMAQ model over the specific cities with a spatial resolution of 1 km, using the WRF-Chem Europe scale model results for forcing and boundary conditions – a procedure also known as off-line nesting. The city air quality downscaling is performed by operating the air quality model with interpolated meteorology (from 200 meters to 1 km of spatial resolution from the diagnostic meteorological model CALMET. The urban air quality simulations take boundary concentrations—including top boundary—every hour from the European WRF-Chem simulation. We have used an adapted version of CMAQ for this task using “linear chemistry” which reduces on about 50% the total computational time. We will call CMAQL to the CMAQ version with linear chemistry. The calculated near-surface concentrations with 1 km of spatial resolution from the urban scale air quality simulations are finally refined to gridded data with 200 meters of spatial resolution through Cressman analysis (Cressman, 1959). This solution allows interpolating concentrations from 1 km grid cells to a regular grid with 200 meters of spatial resolution. The Cressman objective analysis method was applied for such interpolation, considering concentration records taken with hourly frequency. Furthermore, it needs less computational resources than other spatial interpolation methods. It is suitable in operative contexts or rough interpolations.

The air quality downscaling requires gridded emissions in the form of annual averages for six pollutants: NOx, NH3, PM, SO2, VOC and CO which are calculated with the emission model EMIMO (San Jose et al., 2008) The last step is to quantify the future short-term health effect of the global climate focus on the direct effects of global climate in the city level in relation to temperature and air pollution concentrations.

The estimated percentage of mortality/morbidity attributable to exposure variables: temperature, heat waves, ozone concentrations or particles concentrations are calculated by day to day and them average to month and year periods. Several health effects or outcomes are calculated for mortality and morbidity: All causes mortality, cardiovascular mortality, respiratory mortality, respiratory hospital admissions and cardiovascular hospital admissions. These outcomes are for all ages, except in case of the heat waves where mortality + 65 years old are calculated. The short-term health effects of the heat are analysed based on two exposure variables: Apparent Temperature (AT) and Heat waves (HW). Only summer months (June-August) are considered to study the health effects of the heat waves days. Exposure to heat waves takes into account the extreme day values using the maximum apparent temperature (ATMAX) and high night temperatures by the minimum temperature of the day (TMIN). Heat waves days were defined as days with ATMAX exceeding a threshold value or days in which TMIN exceeds other threshold value. For air quality indicators we have used PM10 and O3 pollutants. For PM10 the exposure indicator is the daily mean and for ozone we used the daily maximum 8-hour average. The health outcomes have been chosen based on data availability in agreement with the data uses in the epidemiological studies providing RRs. The relationship between the exposure variable and its effect on health is defined with a log-linear regression (Poisson) and is called exposure-response function (ER). If we derive this function we obtain the Equation 1 which calculates the change in mortality or morbidity by a change in the exposure variable,

$$\Delta y = y_0(e^{\beta\Delta C} - 1) \qquad (1)$$

where y0 is the baseline incidence rate of the studied health effect, β is a parameter which define the mortality effect estimation from epidemiological studies, ΔC is the change of the exposure variable (future minus present).

Our system calculate percentage (%) of change of the health effect, so it is independent from the population and the incidence rate. The epidemiological studies do not report the β parameter of the C-R function, they publish the relative risk (RR) associated with a given change in the exposure variable, but β and RR are related following the Equation 2,

$$\beta = \frac{Ln(RR)}{\Delta c} \quad (2)$$

For this analysis, we selected the two RCPs most used by the climate modeling community, RCP4.5 and RCP8.5, which represent relatively low and high greenhouse gas projections/radiative forcing, respectively. RCP4.5 is a scenario where greenhouse gas concentrations are stabilized after 2100, due to emissions reduction prior to 2100. RCP8.5 is a scenario with increasing emissions over the century.

In order to investigate the impact of aerosol feedback effects, two WRF-Chem simulations are compared for 2010. The two simulations differ by the aerosol-meteorology interactions that were considered. The first simulation (baseline, NONFBIT1) is not taking into account any interactions between simulated aerosol concentrations and meteorology, i.e. solar radiation is not affected by the simulated aerosol concentrations and also simulated cloud droplet numbers and radiative properties do not depend on the simulated aerosol numbers. The second simulation (FBES3) differs from the baseline simulation by the inclusion of these effects (direct and indirect aerosol effect). This simulation also includes some aqueous phase chemical reactions within the cloud droplets.

3. Results

3.1 Urban scale

For validation we have compared the hourly model outputs for present conditions (2011) following reanalysis scenario (NNRP) to hourly observations. The NCEP/NCAR Reanalysis data set (1948-2014) was a continually updating gridded data set that represented the state of the Earth's atmosphere, incorporating observations and numerical weather prediction (NWP) model output from 1948 to September 2014. It was a joint product from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). The NCEP/NCAR Reanalysis Products (NNRP) have a global resolution of T62 (209 km) with 28 vertical sigma levels.

All the observations are from the urban background monitoring stations networks of Madrid, Antwerp, Milan and Helsinki (London has only air pollution observations) included in the simulation domain. All measurements and model results are average to obtain a representative value of the domain. A statistical evaluation of the pairing of the gas species outputs (SO2, NO2, CO, O3 and PM10) and meteorological parameters (temperature, wind and precipitation) in time (hourly) between WRF/Chem-CALMET-CMAQL outputs and monitoring stations datasets are shown in Table1 and Table 2. There are three metrics, Normalized Mean Bias (NMB), Root Mean Standard Error (RMSE), and the correlation coefficient (R2).

Table 1. Statistical evaluations of WRF/Chem-CALMET-CMAQL outputs in comparison to observations from air quality urban networks.

Air quality Monitoring Station (Avg stations)		NMB (%)	RMSE (µg/m3)	R2
Madrid	SO2	1.07	4.68	0.54
	NO2	1.21	31.23	0.43
	CO	-1.12	186.48	0.57
	O3	1.89	18.80	0.78
	PM10	-1.03	16.17	0.24
Antwerp	SO2	2.52	3.46	0.22
	NO2	1.66	23.69	0.52
	CO	-1.67	137.10	0.57
	O3	-1.55	19.44	0.69
	PM10	-1.80	16.08	0.48
Milan	SO2	-1.29	2.98	0.31
	NO2	1.34	36.05	0.51
	CO	-1.21	513.85	0.69
	O3	-1.14	20.38	0.85
	PM10	-1.00	25.77	0.65
Helsinki	SO2	-1.29	2.70	0.38
	NO2	1.36	16.51	0.39
	CO	1.83	106.49	0.49
	O3	1.58	18.48	0.57
	PM10	1.08	15.24	0.27
London	SO2	1.09	2.32	0.17
	NO2	1.27	44.02	0.33
	CO	-1.76	124.57	0.40
	O3	1.71	20.46	0.66
	PM10	1.46	13.52	0.48

Table 2. Statistical evaluations of WRF/Chem-CALMET-CMAQL outputs in comparison to observations from meteorological stations.

Meteorological Monitoring Station (Avg stations)		NMB (%)	RMSE	R2
Madrid	Wind Speed	129.78	1.83	0.65
	Temperature	-1.02	1.36	0.98
	Precipitation	-10.82	0.13	0.52
Antwerp	Wind Speed	20.49	1.39	0.80
	Temperature	-7.72	1.99	0.94

	Precipitation	-24.14	0.18	0.37
Milan	Wind Speed	53.21	1.35	0.50
	Temperature	-9.87	2.60	0.96
	Precipitation	-27.88	0.17	0.68
Helsinki	Wind Speed	25.53	1.97	0.74
	Temperature	-8.74	2.31	0.94
	Precipitation	4.11	0.17	0.58

The comparison shows that the simulated average concentrations for the present and real situation are within the variability of the measured levels. The simulated O3 concentrations are lower than observed concentrations for Antwerp and Milan indicating that the climate and air quality simulations representing present conditions, underestimate the O3 concentrations. The tendency, for comparison of simulated and measured concentrations, is to a slight overestimation. The underestimation of ozone can be attributed to overestimated surface wind speeds and/or underestimations of emissions. Wind speed is over-predicted for all cities. The high wind speed bias is mainly attributed to a poor representation of surface drag exerted by the unresolved topography in the 25 km European domain of the WRF-Chem. The average simulated levels are within the inter-annual variability of the measured concentrations with the majority of the R2 values over 0.5. The statistical evaluation shows strong evidence that high resolution downscaling procedure could achieve reasonably good performance, particularly for bias (NMB) and R2 statistics.

In this part, we show examples of the spatial distribution of the forecasted health impact for the 2100 year under the two IPCC climate scenarios (4.5 and 8.5) over the five European cities: Madrid (Figure 2), Helsinki (Figure 3), Milan (Figure 4), Antwerp (Figure 5) and London (Figure 6) for different health outcomes.

Figure 2a shows increases of cardiovascular mortality up to 0.37% by PM10 under RCP4.5 scenario and spatially the highest values of the health impact appear to be concentrated into the city centre (high population density area) but opposite effect is expected under RCP8.5 scenario, Figure 2b, with slightly reductions in the city centre.

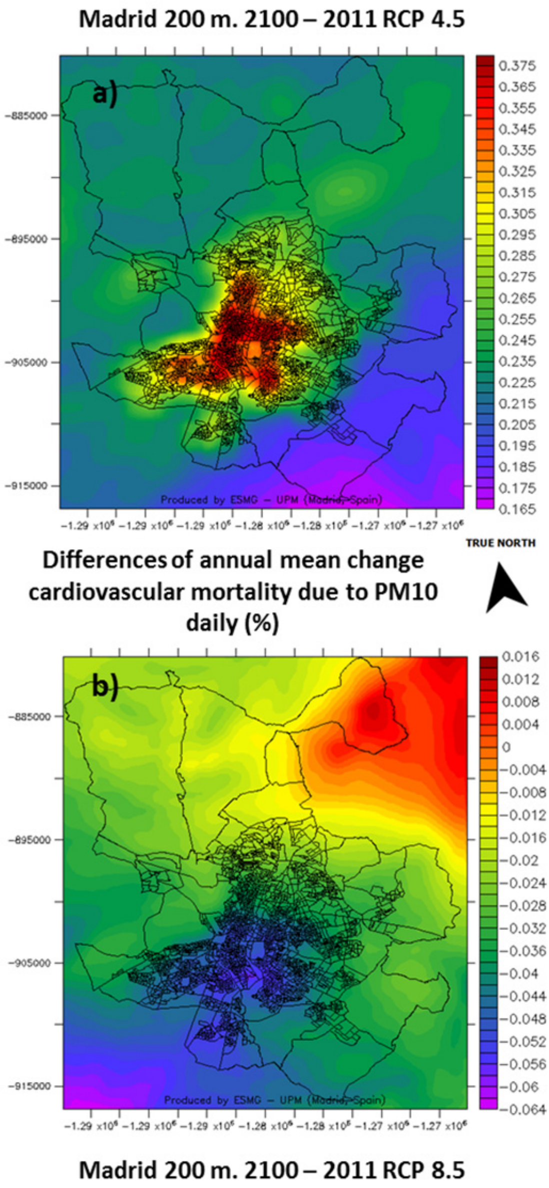

Figure 2. Year 2100, differences (%) of annual mean changes short-term cardiovascular mortality due to PM10 daily average concentrations over Madrid (200 m resolution) under RCP4.5, a) top, and RCP8.5, b) bottom, climate scenarios respect to 2011.

Figure 3a shows an estimated increase in annual average of the hospital admissions due to O3 concentration between 0.05% and 0.08 % for 2100 respect to 2011 under the RCP4.5, but an decrease is expected under the RCP8.5, Figure 3b. The major impacts are located in the North of the Helsinki area.

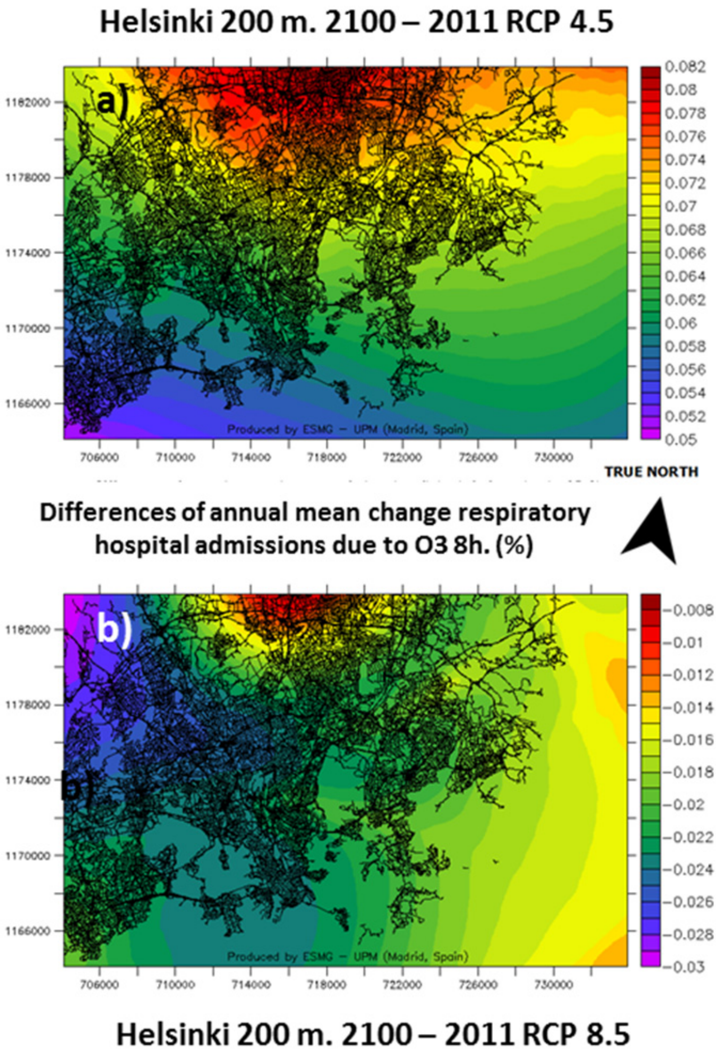

Figure 3. Year 2100, differences (%) of annual mean changes short-term respiratory hospital admissions due to O3 8 hours average maximum concentrations over Helsinki (200 m) under RCP4.5, a) top, and RCP8.5, b) bottom, climate scenarios respect to 2011.

Figure 4b shows than the year 2100 can be increases up to 64% in the mortality with respiratory causes due to heat waves for people with more than 65 years old under RCP8.5 and opposite effect are showed in the RCP4.5, Figure 4a. So the efforts to reduce emissions following the RCP4.5 scenario will produce improve the people health because the temperature of the Milan will be reduced.

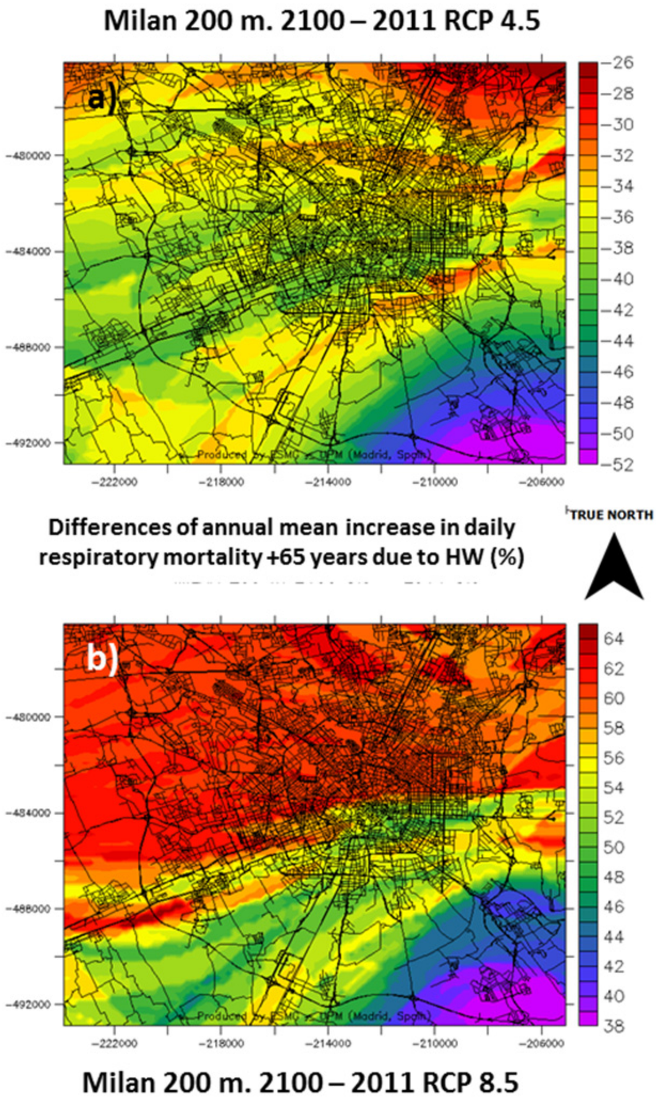

Figure 4. Year 2100, differences (%) of annual mean changes short-term respiratory mortality due to heat waves days over Milan (200 m) under RCP4.5, a) top, and RCP8.5, b) bottom, climate scenarios respect to 2011.

Figure 5a and Figure 5b show that in case of Antwerp the mortality with respiratory problems due to O3 concentrations will be reduced for year 2100 under the two studied climate scenarios, so global climate in this case it is not a big problem for the health of the cities. The major reductions are expected in the South of the city under the RCP4.5 scenario.

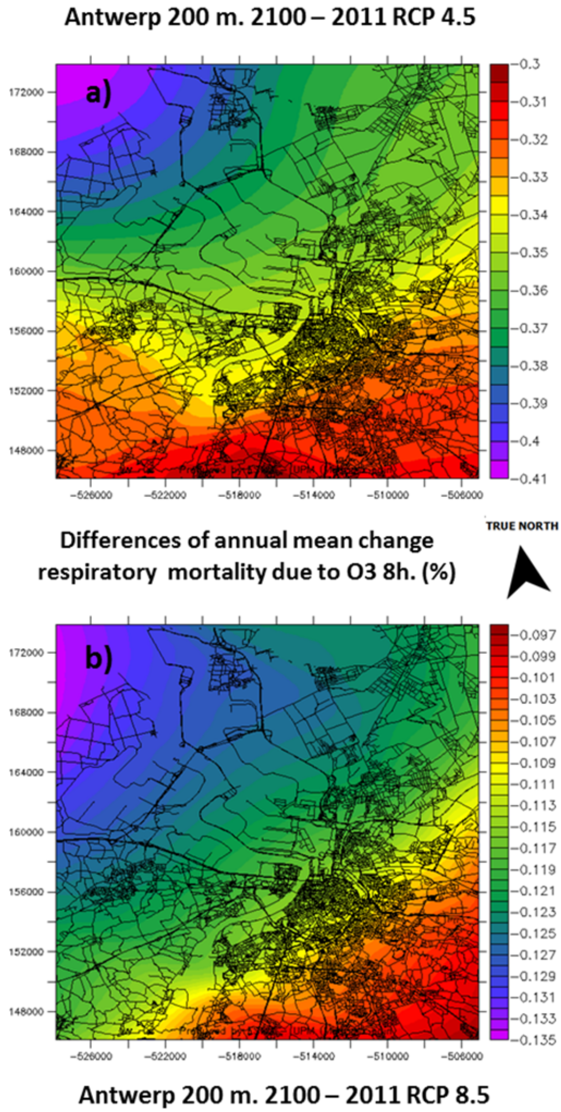

Figure 5. Year 2100, differences (%) of annual mean changes short-term respiratory mortality due to O3 8 hours average maximum concentrations over Antwerp (200 m) under RCP4.5, a) top, and RCP8.5, b) bottom, climate scenarios respect to 2011.

Figure 6a and Figure 6b show that in case of the Kensington and Chelsea area (London) the mortality with respiratory problems due to increments of the apparent temperature (AT) will be increased for year 2100 under the two studied climate scenarios, so global climate in this case it is a big problem for the health of the citizens, specially under the RCP8.5 scenario with increases up to 5.3 %.

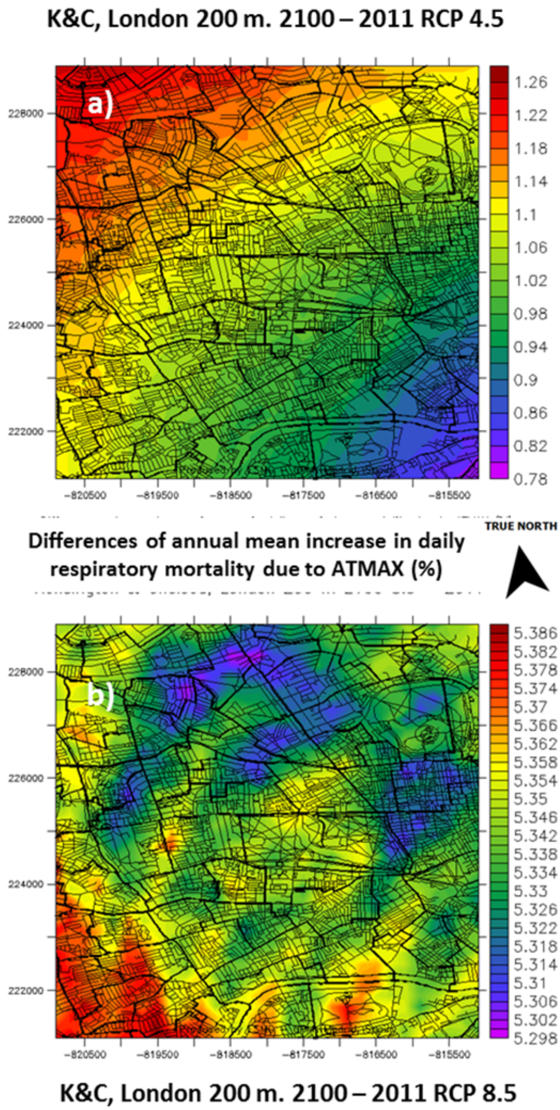

Figure 6. Year 2100, differences (%) of annual mean changes short-term respiratory mortality due to maximum daily apparent temperature (AT) over Kensington and Chelsea (London). (200 m) under RCP4.5, a) top, and RCP8.5, b) bottom, climate scenarios respect to 2011.

3.2 Regional scale

The domain is defined in a Lambert Conformal Conic projection that includes 270 x 225 grid points with 25 km of horizontal resolution. The vertical grid extends over 33 stretched layers from the surface to a fixed pressure of 50 hPa (about 20 km), with the lowest level thickness of 24 m close to the ground model. The runs have been integrated over individual 2-day periods. Each run also included a meteorological spin up time of one day prepared using the meteorological WRF model with identical physical options. Chemical fields at the end of a 2-day simulation have been passed on as initial fields for the following simulation. In this scheme global meteorological data are used as input to WRF every two days.

Figure 7 shows the projections for changes in annual mean surface temperature (Fig. 7a) and precipitation (Fig. 7b). RCP4.5 future climate projection produces decreases of air temperature (except in 2050 Madrid) and a tendency to increases the precipitation while RCP8.5 tends to reduce the precipitation and to increase the temperature.

The spatial distributions of the changes in mean O3 between the periods 2030, 2050 and 2100 compared to 2011 year for the simulations are shown in Figure 8. With the RCP8.5 climate change scenario, O3 mean values increase in southern Europe and for 2100 the increases are located around Greece. The increase is generally in the range 4–5 µg/m3 on average. Decrease of mean O3 concentrations is shown in the northern part of the model domain, expect with RCP4.5 for year 2100 where the increases are located over Mediterranean area. About ozone is important to remind that we kept the O3 precursor emissions and boundary concentrations constant over time at their year 2011 values to isolate the effect of meteorological changes. Earlier studies have shown that the two main drivers for the increasing surface O3 in southern Europe are: a) the decrease in dry deposition of O3 concentrations due to reduced soil water and thereby reduced vegetation uptake, and b) the increase in biogenic isoprene emissions with the decrease in dry deposition being the dominant effect in the southernmost parts of Europe and both, being equally important in central Europe. The reasons for the reduced concentrations in northern Europe have not been addressed in detail here but both cloudiness and precipitation increase in northern Europe in the climate projections which should lead to increased scavenging of ozone precursors and less solar radiation for driving the photochemistry. Also it is important that since temperatures are low during the winter and spring, warming during these seasons may not lead to increased concentrations of secondary pollutants such as O3 as expected with the RCP8.5

.

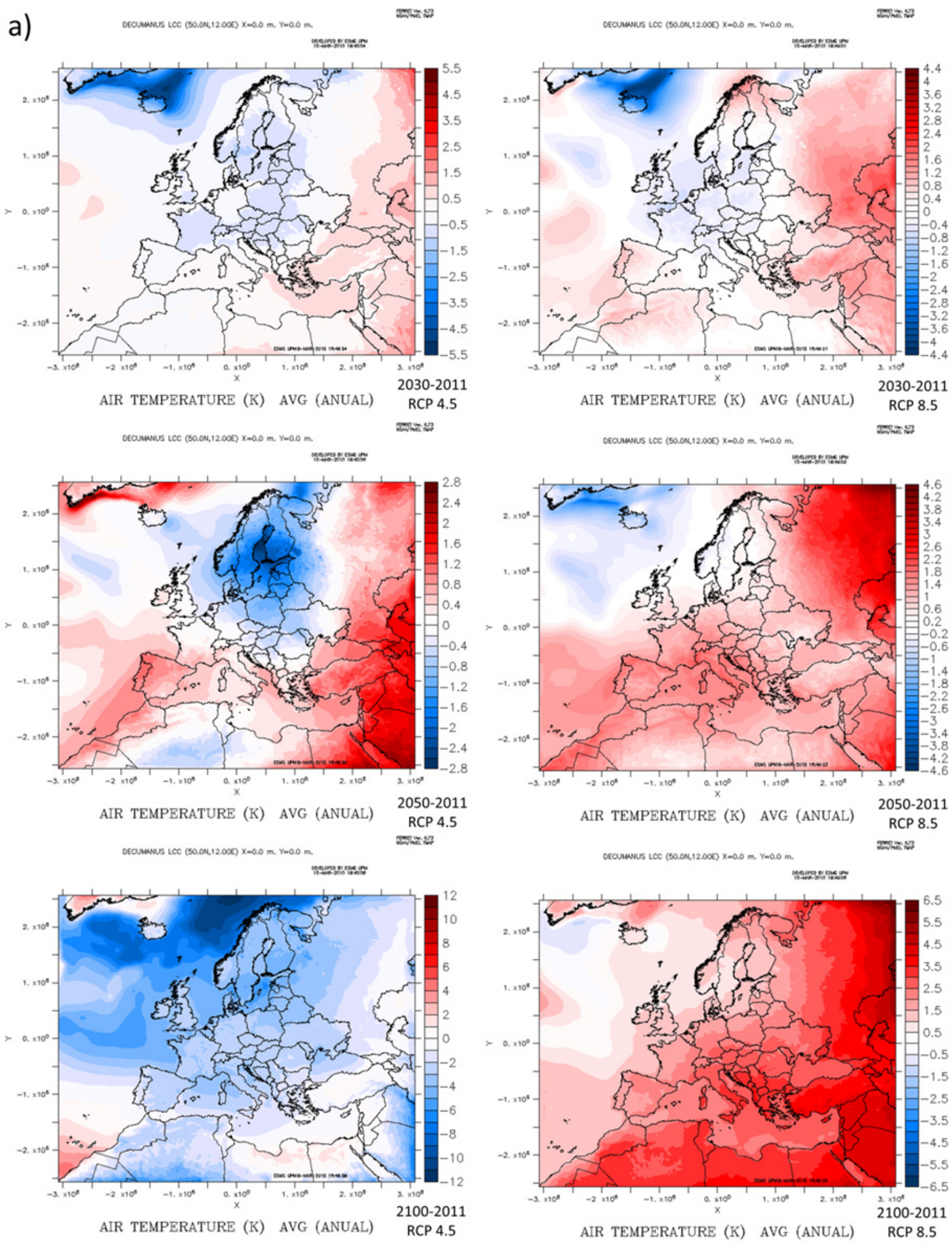

Figure 7a. Spatial distribution of the differences in annual mean air temperature in K for 2030 (upper), 2050 (middle), 2100 (bottom) respect to 2011 following RCP4.5 (left) and RCP8.5 (right) scenarios with WRF-Chem model over Europe with 25 km resolution

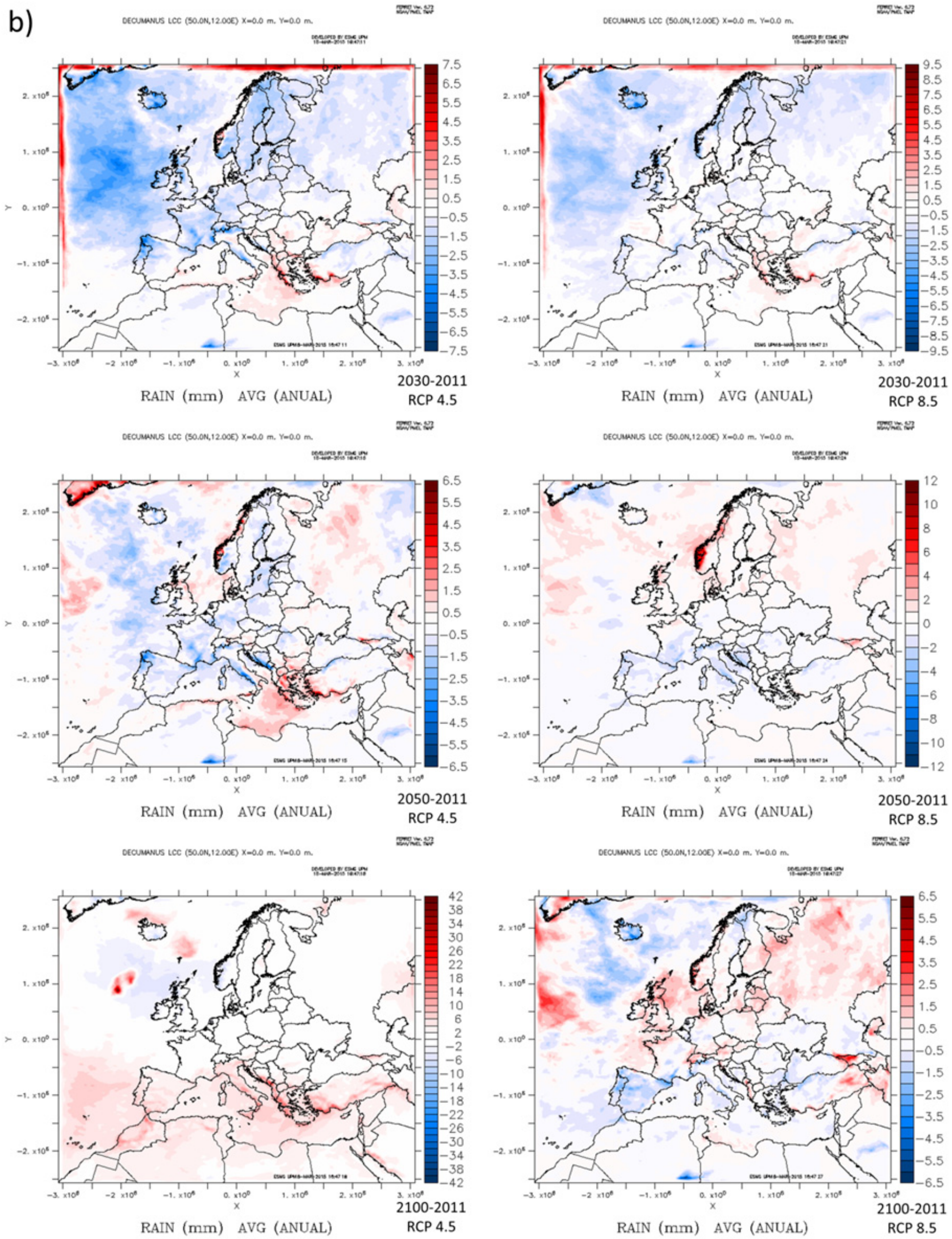

Figure 7b. Spatial distribution of the differences precipitation in mm, for 2030 (upper), 2050 (middle), 2100 (bottom) respect to 2011 following RCP4.5 (left) and RCP8.5 (right) scenarios with WRF-Chem model over Europe with 25 km resolution.

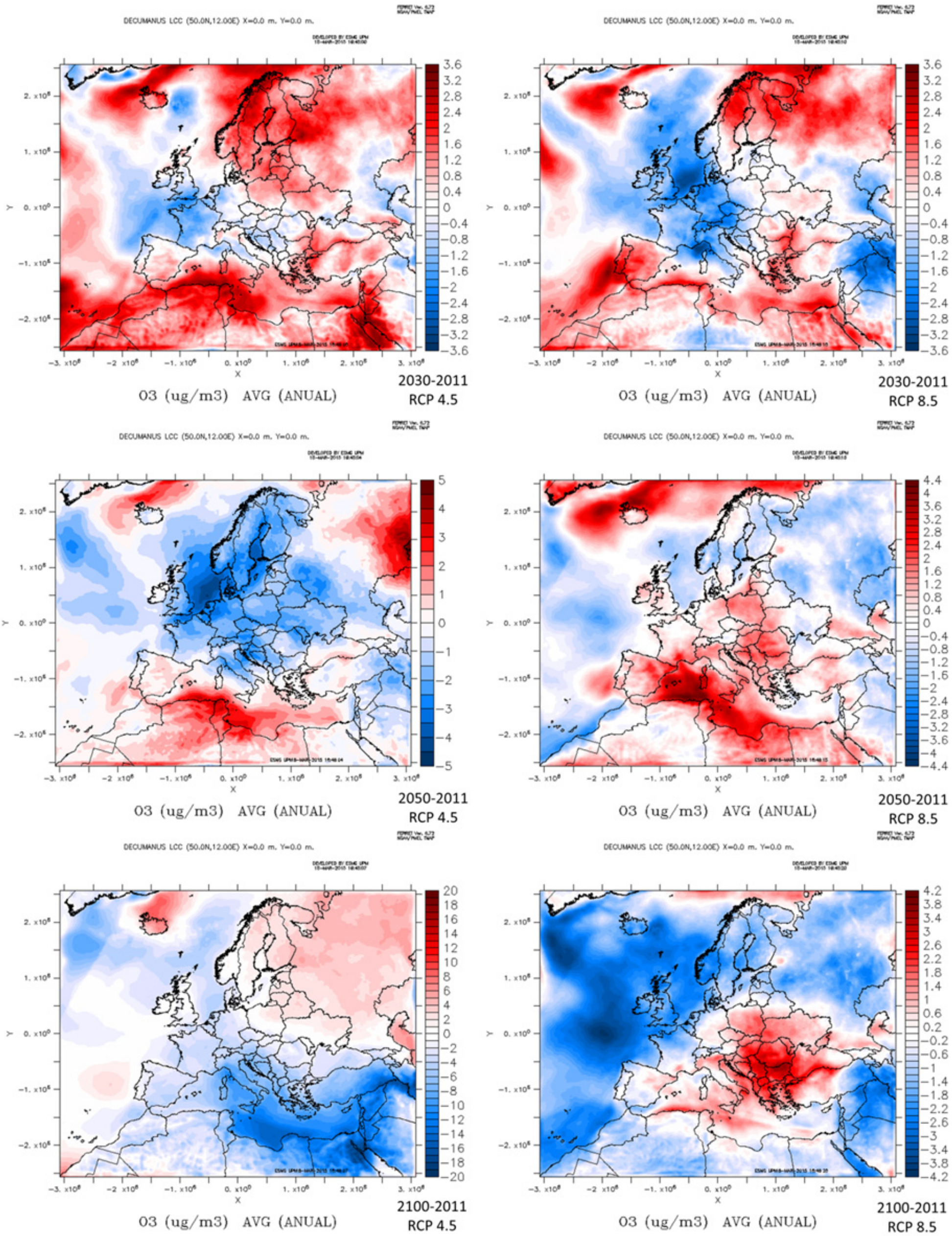

Figure 8. Spatial distribution of the differences in annual mean ozone for 2030 (upper), 2050 (middle), 2100 (bottom) respect to 2011 following RCP4.5 (left) and RCP8.5 (right) scenarios with WRF-Chem over Europe with 25 km resolution.

Now we investigate the sensitivity of the aerosol effects (direct plus indirect feedback effects) in the radiation over Europe in 2010. Two yearly simulations have been performed. Figure 9 shows the yearly mean shortwave radiation for base case (NONFBIT1) and absolute differences (FBES3-NONFBIT1) between the feedback effects simulation FBES3 and the base case.

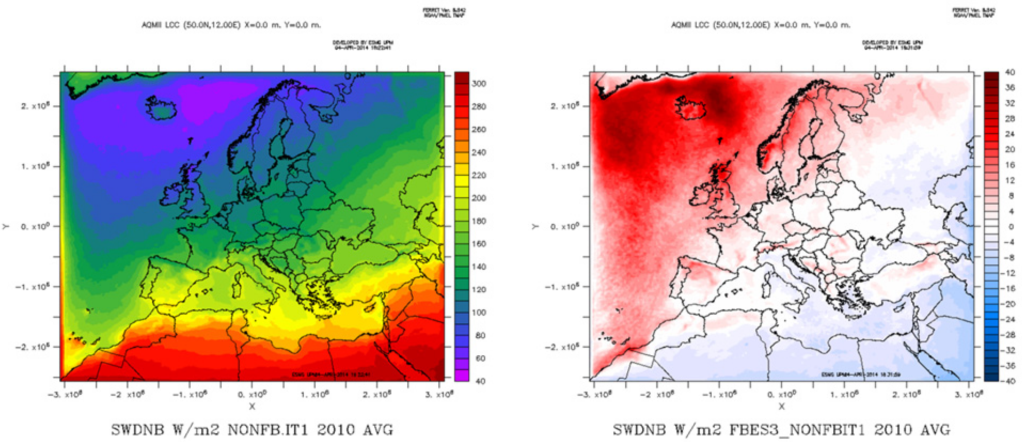

Figure 9. 2010 mean incoming short wave radiation at the surface for the base case (NONFBIT1, left) without feedback and simulated changes (FBES3-NONFBIT1, right) due to effects of aerosols.

The simulation FBES3 which in includes the direct aerosol effect and the impact of simulated aerosol concentrations on cloud droplet formation (and thus the indirect aerosol effect) shows higher values of solar radiation over Atlantic Ocean and North Sea. The yearly mean short wave radiation is up to 70% (40 W/m^2) higher for FBES3 than for the non-feedback effects simulation. This strong impact is found for the areas of the domain with lowest solar radiation where cloud cover is an important factor. Absorption of solar radiation by black carbon (BC) and other aerosols can reduce cloud formation ("semi-direct effect"). However, due to very low aerosol concentrations over the North Atlantic this effect cannot be responsible for the simulated lower cloud water content and higher solar radiation in the feedback case. Low aerosol concentrations with approximately 300 particles cm^{-3} (yearly average) are found for this region. When aerosol cloud interactions depend on simulated aerosol concentrations, as in simulation FBES3, these small particle number concentrations result in cloud droplet numbers around 30 cm^{-3} for the North Atlantic area. This droplet number concentration is much lower than the droplet number concentrations that are assumed for the baseline case NONFBIT1. There, a value of 250 cloud droplets cm^{-3} is used throughout the modelling domain, which is the assumed default value when no feedback effects of simulated aerosol concentrations on cloud condensation is considered.

The very low cloud droplet numbers for FBES3 result in an earlier onset of precipitation than for the baseline case. We have observed a significant reduction (close to 70%) of the cloud liquid water path over the North Atlantic area when feedback effects are activated, values of 196 g/m^2 are observed on NONFBIT1 (base) and only 60 g/m^2 on FBES3 (feedback effects case). Also we found similar values of cloud fraction, 93% in case of NONFBIT1 and 90% for FBES3. This strong decrease of the cloud liquid water content and the associated increase in global radiation can be observed for WRF-Chem not only for the MOSAIC aerosol module but also when the MADE/SORGAM aerosol module (Forkel et al., 2014; Kong et al., 2014) as it results mainly from the definition of the baseline conditions.

Reduction of incoming solar radiation via backscattering occurs over the southern part of the domain where shortwave radiation is reduced up to 30 W/m^2 (10%). This reduction is due to the direct aerosol effect by Saharan dust. This effect may probably be under-estimated due to the lack of the coarse dust fraction in the FBES3 simulation. The base simulation NONFBIT1 considers also the coarse dust fraction because a new dust fluxes constant and a desert dust improvement for spurious fluxes was introduced in the baseline simulation. However, since the simulated aerosol concentrations are not considered for the calculation of radiative transfer and cloud condensation of the baseline simulation, this addition of coarse dust in NOFBIT1 has no impact on the further discussion. When aerosol cloud interactions are explicitly considered, high aerosol particle numbers can result in high cloud numbers and an increased cloud optical depth. Over the Saharan increase of cloud optical depth due to high aerosol particle numbers plays only a minor role in this area due to the absence of clouds.

4. Conclusions

This research has shown an example of the assessment of the impact of global climate change on urban climate, air quality and health. The information provided by the presented tool can be used for integrated assessment of air pollution and climate change adaptation and therefore develop more appropriate mitigation strategies. We have studied the impact of climate change over five European cities, Madrid, Antwerp, Milan, Helsinki and London (Kensington and Chelsea area) with 200 m spatial resolution, using two different future projections of global climate: RCP4.5 and RCP8.5 scenarios. The modelling system was used to simulate climate and air quality for present (2011) times and future (2030, 2050 and 2100) times, using 2011 emissions inventory, because of we were interested on knowing the impact of future climate projections in urban domains with very high spatial resolution. So that, only one input data, -boundary conditions from climate model projections-, is changed in each simulation. We compare the future years 2030, 2050 and 2100 with control year

2011 from a health impact point of view. Comparison of simulations for present situation (2011, with reanalysis data as boundary and initial conditions) shows acceptable agreement with measurements in the urban background for climate realizations.

The biggest impacts of health effects by the pollutants are Respiratory mortality due to O3 (Antwerp, Milan and London), Hospital admissions due to O3 (Helsinki) and Cardiovascular mortality by PM10 (Madrid). In the RCP4.5 scenario reductions occur in all variables related to temperature values, except in 2050 Madrid which increases are founded. The RCP8.5 scenario is characterized by temperature increases from 2050, reaching the maximum impact in 2100, especially in Madrid and Milan with large increases. Due to RCP4.5 scenario is characterized by decreases in temperature, this situation produces improvements in mortality by climate, especially during 2100 over Milan. RCP8.5 scenario is the opposite and results show increases in the human health problems by temperature. The worst impacts are expected over Milan and Madrid, 2100. The impact on Milan is double than of Madrid and Madrid impacts are three times more than over Helsinki, Antwerp and London.

To investigate the sensitivity of the aerosol effects (direct plus indirect feedback effects) on meteorological variables and pollutant concentrations WRF-Chem model is applied over Europe in 2010. Two yearly simulations have been performed. The two case studies consist of one simulation without feedback effects (base) and the second one with direct aerosol effect, aerosol cloud interactions and indirect effects turned on. Simulated feedback effects between aerosol concentrations and meteorological variables and on pollutant distributions strongly depend on the aerosol concentrations and the clouds. As expected, the feedback effects are sometimes only minor effects, but a first analysis confirms that the sensitivity of the meteorology and air pollution to the aerosol concentrations can also be very important under certain circumstances. Although too low aerosol particle concentrations were simulated the results demonstrate the relevance of aerosol effects.

Acknowledgements

The authors acknowledge the computer resources and technical assistance provided by the Centro de Supercomputación y Visualización de Madrid (CeSViMa). The authors thankfully acknowledge the computer resources, technical expertise and assistance provided by the Red Española de Supercomputación. We acknowledge the DECUMANUS EU project from EU Space Call FP7-SPACE-2013-1 at SPA.20131.1-06.

References

BAKLANOV, A., SCHLÜNZEN, K.H., SUPPAN, P., BALDASANO, J., BRUNNER, D., AKSOYOGLU, S., CARMICHAEL, G., AND 32 AUTHORS MORE (2014). Online coupled regional meteorology-chemistry models in Europe: current status and prospects. *Atmos. Chem. Phys*. **14**, 317-398.

BANGERT, M., NENES, A., VOGEL, B., VOGEL, H., BARAHONA, D., KARYDIS, V.A., KUMAR, P., KOTTMEIER, C., BLAHAK, U. (2012). Saharan dust event impacts on cloud formation and radiation over Western Europe. *Atmos. Chem. Phys.* **12**, 4045-4063.

CHEN, S., ZHAO, C., QIAN, Y., LEUNG, L.R., HUANG, J., HUANG, Z., BI, J., ZHANG, W., SHI, J., YANG, L., LI, D., LI, J. (2014). Regional modeling of dust mass balance and radiative forcing over East Asia using WRF-Chem. *Aeolian Res*., **15**, 15-30.

COONEY, C.M. (2012). Downscaling climate models: sharpening the focus on local-level changes. *Environ Health Perspect*, **120**, A24–A28. Published online 2012 Jan 1. doi: 10.1289/ehp.120-a22

CRESSMAN G.P. (1959). An operational objective analysis system. *Mon. Weather Rev*. **87**, 367-374.

FORKEL, R., WERHAHN, J., BUUS HANSEN, A., MCKEEN, S., PECKHAM, S., GRELL, G., SUPPAN, P. (2012). Effect of aerosol-radiation feedback on regional air quality e a case study with WFR/Chem. *Atmos. Environ.,* **53**, 202-211.

FORKEL, R., BALZARINI, A., BARÓ, R., CURCI, G., JIMÉNEZ-GUERRERO, P., HIRTL, M., HONZAK, L., IM, U., LORENZ, C., PÉREZ, J.L., PIROVANO, G., SAN JOSÉ, R., TUCCELLA, P., WERHAHN, J., ZABKAR, R. (2014). Analysis of the WRF-Chem contributions to AQMEII phase2 with respect to aerosol radiative feedbacks on meteorology and pollutant distribution. *Atmos. Environ*., **115**, 630-645.

GRELL, G. AND BAKLANOV, A. (2011). Integrated modeling for forecasting weather and air quality: A call for fully coupled approaches. *Atmos. Environ*., **45**, 6845-6851.

GRELL, A.G., PECKHAM, S.E., SCHMITZ, R., MCKEEN, S.A., FROST, G., SKAMAROCK, W.C., EDER, B. (2005). Fully coupled 'online' chemistry in the WRF model. *Atmos. Environ*., **39**, 6957-6976.

JACOB, D.J. AND WINNER, D.A. (2009). Effect of climate change on air quality. *Atmospheric Environment,* **43**, 51-63.

KAUFMAN, Y.J. AND FRASER, R.S. (1997). The effect of smoke particles on clouds and climate forcing. *Science*, **277**, 1636-1638.

KONG, X., FORKEL R., SOKHI, R.S., AND 21 AUTHORS MORE (2014). Analysis of meteorology-chemistry interactions during air pollution episodes using online coupled models within AQMEII phase-2. *Atmospheric Environment*, **115**, 527-540.

KONOVALOV, I.B., BEEKMANN, M., KUZNETSOVA, I.N., YUROVA, A., ZVYAGINTSEV, A.M. (2011). Atmospheric impacts of the 2010 Russian wildfires: integrating modelling and measurements of an extreme air pollution episode in the Moscow region. *Atmos. Chem. Phys*. **11**, 10031-10056.

LEVIN, A., AND BRENGUIER J.L. (2009). Effects of Pollution and Biomass Aerosols on Clouds and Precipitation: Observational Studies. Aerosol Pollution Impact on Precipitation A Scientific Review, 205-242. Springer. Zev Levin and William R. Cotton Editors. ISBN: 978-1-4020-8689-2. e-ISBN: 978-1-4020-8690-8

LIAO, K.J., TAGARIS, E., MANOMAIPHIBOON, K., NAPELENOK, S. L., WOO, J.H., HE, S., AMAR, P., RUSSELL, A.G. (2007). Sensitivities of ozone and fine particulate matter formation to emissions under the impact of potential future climate change. *Environ. Sci. Technol*., **41**, 8355–8361.

MICKLEY, L. J., JACOB, D. J., FIELD, B. D., RIND, D. (2004). Effects of future climate change on regional air pollution episodes in the United States. *Geophys. Res. Let*., **31**, L24103.

MOSS, R.H., EDMONDS, J.A., HIBBARD, K.A., MANNING, M.R., ROSE, S.K. VAN VUUREN, D.P., CARTER, T.R., EMORI, S., KAINUMA, M., KRAM, T., AND 9 AUTHORS MORE (2010). The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747–756.

SAN JOSE R, PEREZ, J.L., MORANT, J.L., GONZALEZ, R.M. (2008). European operational air quality forecasting system by using MM5-CMAQ-EMIMO tool. *Simulation Modelling Practice and Theory*, Volume 16, Issue 10, The Analysis of Complex Systems, November 2008, Pages 1534-1540, ISSN 1569-190X, doi: 10.1016/j.simpat.2007.11.021

SCIRE, J.S., ROBE F.R., FERNAU M.E., YAMARTINO, R.J. (2000). A User's Guide for the CALMET Meteorological Model (Version 5). Earth Tech, Inc., Concord, MA 01742.

STEVENSON, D.S., DENTENER, F. J., SCHULTZ, M.G., ELLINGSEN, A., AND 36 AUTHORS MORE. (2006). Multimodel ensemble simulations of present-day and near-future tropospheric ozone. *J. Geophys. Res.,* **111**, D08301, doi:10.1029/2005JD006338.

WEAVER, C. P., LIANG, X. Z., ZHU, J., ADAMS, P. J., AMAR, P., AVISE, J., CAUGHEY, M., CHEN, J., COHEN, R. C., COOTER, E., DAWSON, J. P., GILLIAM, R., GILLILAND, A., GOLDSTEIN, A. H., GRAMBSCH, A., AND 40 AUTHORS MORE (2009). A preliminary synthesis of modeled climate change impacts on US regional ozone concentrations. *Bull. Am. Meteorol. Soc*., **90**, 1843–1863.

WONG, D.C., PLEIM, J., MATHUR, R., BINKOWSKI, F., OTTE, T., GILLIAM, R., POULIOT, G., XIU, A., YOUNG, J.O., KANG, D. (2012). WRF-CMAQ two-way coupled system with aerosol feedback: software development and preliminary results. *Geosci. Model Dev*. **5**, 299-312.

YANG, Q., GUSTAFSON J.R., W.I., FAST, J.D., WANG, H., EASTER, R.C., MORRISON, H. (2011). Assessing 699 regional scale predictions of aerosols, marine stratocumulus, and their interactions during 700 VOCALS-REx using WRF-Chem. *Atmospheric Chemistry and Physics*, **11**, 11951–11975.

ZHANG, Y. (2008). Online-coupled meteorology and chemistry models: history, current status, and outlook. *Atmos. Chem. Phys*., **8**, 2895-2932.

ZHANG, Y., WEN, X.-Y., JANG, C.J. (2010). Simulating chemistry-aerosol-cloud-radiation-climate feedbacks over the continental US using the online-coupled Weather Research Forecasting Model with chemistry (WRFChem). *Atmos. Environ*., **44**, 3568-3582.