Direct Impacts of Global Climate Change on Urban Areas

Roberto San José, Juan L. Pérez, Libia Pérez, Julia Pecci, Antonio Garzón, and Marino Palacios

Abstract—**There are many signals of the impacts of global climate on pedestrian wind and thermal comfort, citizen health by exposure to the climate and air pollution concentrations and building energy demand energy. We have studied direct effects of the two future (2030, 2050 and 2100) climate projections, IPCC RCP 4.5 (stabilization emission scenario) and RCP 8.5 (little effort to reduce emissions), respect to present (2011), over three European cities: Madrid, Milan and London with very high spatial resolution: 50 meters. Climatic variables and air pollution concentrations are dynamically downscaled from 1 °to 50m using a computational dynamical downscaling modelling system. The outputs of the Community Earth System Model (CESM) and its coupling with Weather Research and Forecasting and Chemical (WRF/Chem) model (25 km, 5km and 1km spatial resolutions) provides present and future climate scenarios. The output from the WRF/Chem model at 1 km resolution is used to drive a micro-scale computational fluid dynamics model, MICROSYS (50 m). The methodology to estimate percentages of climate/pollution-related deaths and hospital admissions due to global climate are based on epidemiologic analysis of weather/air pollution and health data to characterize and quantify mortality/morbidity associations. Building energy simulations are implemented with the EnergyPlus model using buildings prototypes which are based on ASHRAE 90.1 Prototype Building Modeling Specifications. Also urban comfort (wind, thermal) indicators from a pedestrian point of view are calculated. We propose to use the Dutch wind nuisance standard (NEN 8100) which applies a discomfort threshold for the hourly mean modeled wind speed. The physiological equivalent temperature (PET) is calculated every grid cell as index of the urban thermal comfort. This work is part of the European project DECUMANUS We have identified the highlight areas with elevated exposure to global climate from different point of views: comfort, health and energy; this information can be used to prepare plans and implement adaptations to reduce effects of climate change on the citizen and building energy demand.**

Index Terms—**Climate change, energy demand, health, dowscaling.**

I. Introduction

The urban areas are the zones where the local response to the global change is more pronounced [1] and most of the people live in cities, so it is necessary to provide predictions of the global climate impacts at the urban scale [2]. Future climate change impacts are derived using Global Climate Models (GCMs) to project future changes in climate. 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, chemistry and building effects [3]. There is very high confidence that climate change will impact on human health directly. Climate change will exacerbate existing health problems. Health impacts on morbidity and mortality are related with weather conditions and air pollution concentrations. Also it is clear than global climate will affect the pedestrian comfort [4] focus on thermal and wind comfort. Finally the outdoor temperature will be modified by global climate, so the energy use for cooling and heating the building will be affected [5]. In previous studies [6], climate change was found to have significant implications for energy consumption in buildings. The past studies examining the consequences of climate change for the energy demand typically quantify the impacts at a relatively course spatial resolution. However, average responses have little value [7], therefore, it must be conducted at a fine scale, taking into account the 3D shape of the buildings and urban local conditions.

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 commonly methods to downscale future climate projections to finer spatial scales: dynamical downscaling and statistical downscaling. Dynamical downscaling is a method that runs regional/urban climate models (RCM) over 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, [8]. In case or the urban areas with building blocks, this resolution is not enough and we need to make Computational Fluid Dynamics (CFD) simulations with meters of spatial resolution. It is computationally very demanding but is based on physical laws and it produces a full suite of climate and air pollution outputs variables Statistical downscaling produce a few variables based on relationships derived from observations, which are applied in the future, the main advantage is that it is not computationally very demanding but it is very limited because you need observations and local feedbacks are not taking into account and the relation on the present could be not true in the future. We propose a climate and air pollution dynamical downscaling methodology that combines state-of-the-art of different meteorological-air quality models, which objective is the transformation of global model outputs into high spatial resolution products. Atmospheric flow and microclimate over urban areas are influenced by urban features, and they enhance atmospheric turbulence, and modify turbulent transport, dispersion, and deposition of atmospheric

Manuscript received September 1, 2016; revised November 2, 2016.

Roberto San José, Juan L. Pérez, and Libia Pérez are with Environmental Software and Modelling Group, Computer Science School, Technical University of Madrid (UPM), Madrid, Spain (e-mail: roberto@fi.upm.es, jlperez@fi.upm.es, lperez@fi.upm.es).

Julia Pecci, Antonio Garzón, and Marino Palacios are with Indra S.A., C/ Mar Egeo, 4, Pol. Industrial 1, 28830 San Fernando de Henares, Madrid, Spain.

doi: 10.18178/ijesd.2017.8.3.949

pollutants [9]. We propose to use a Computational Fluid Dynamic (CFD) model to produce detailed simulations of the wind flow and turbulence in the urban canopy.

This research is part of the European project DECUMANUS (Development and Consolidation of Geospatial Sustainability Services for Adaptation and Climate Change Urban Impacts) funded by the EU SPACE CALL in 2013. DECUMANUS is dedicated to provide urban intelligence, providing services accessible to urban managers dealing with societal challenges including climate change, based on the philosophy that it is possible to adapt to, and mitigate, the challenges if you can understand and measure them.

II. Methodology

This work examines the climate change impacts under two Representative Concentration Pathways (RCP), [10] currently being used to drive global climate model simulations for the IPCC ́s Fifth Assessment Report (AR5), RCPs 4.5 and 8.5, across of three sectors: pedestrian comfort, citizen health and building energy demand for heating/cooling over three urban areas: Madrid, Milan and Kensington and Chelsea (London). The IPCC report [11] 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. The 8.5 pathway arises from little effort to reduce emissions and represents a failure to curb warming by 2100. It is characterized by increasing greenhouse gas emissions over time and represents scenarios in the literature leading to high greenhouse gas concentration levels [12]. RCP 4.5 is similar to the lowest-emission scenarios (B1) assessed in the IPCC AR4. It is a stabilization scenario where total radiative forcing is stabilized around 2050 by employment of a range of technologies and strategies for reducing greenhouse gas emissions. This can be considered as a weak climate change mitigation scenario [13].

A. *Dynamical Downscaling*

Fig. 1 summarizes the chain of models utilized for the dynamical downscaling process. Outputs from the global climate model Community Earth System Model (CESM) every six hours are downloaded over Europe at 25 km horizontal resolution and one hour temporal resolution with the WRF/Chem regional/urban climate and air pollution model [14], they are used as boundary and initial conditions (BCs and ICs). WRF/Chem is an on-line chemical and meteorological model, so the chemistry and meteorology are embedded into one code. Then with a one way nesting approach over 5 km and 1km resolution grid over the cities.

At 1km level WRF/Chem uses a sophisticated urban canopy model (UCM) scheme to represent near-surface processes over urban areas. The UCM is based on the Town Energy Budget approach [15]. The UCM adopts the turbulent flux resistance network approach in the canyon [16], which takes into account air re-circulating and venting for turbulent heat flux calculation within the canyon. Shadowing is represented in terms of sky view factors that depict the area of each urban surface and the sky that is visible by other urban surfaces (e.g., walls and road). The UCM is coupled to WRF/Chem every simulation physics time step. WRF (meteorological model) and the UCM exchange radiation, sensible heat, latent heat and momentum fluxes are coupled to the WRF planetary boundary layer turbulence closure parameterization. The 1km simulations are used as initial and boundary conditions for the urban micro-scale runs with CFD model MICROSYS running at 50 meters spatial resolution. MICROSYS is based into the MIMO CFD model, which takes into account buildings obstacles. The model includes steady three-dimensional system of Reynolds equations, k-ε model of turbulence and the ‘advection-diffusion’ equation to simulate pollution transport on-line coupled with a simple chemistry mechanism for O3-NOx relationships. Surface energy fluxes have been implemented into MICROSYS code based on the procedures applied in UCM and NOAA Land-surface model. A micro shadow model SHAMO (UPM) has been run to calculate shadow areas (including reflections in urban areas) and short wave radiation in high resolution (meters) domains. Future simulations were run with present-time emissions in order to isolate the effects of climate change. Emissions are generated with a mixed top-down and bottom-up approaches using the city specific data supplied by the cities (population, traffic, landuses) which are implemented in the emission model EMIMO [17].

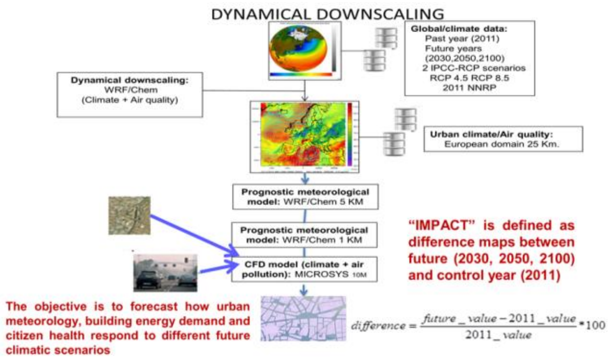

Fig. 1. Flow chart of the dynamical downscaling simulation tool.

B. *Health Impact*

The methodology to estimate percentages of climate/pollution-related deaths and hospital admissions due to global climate are based on epidemiologic analysis of weather/air pollution and health data to characterize and quantify mortality/morbidity associations. The exposure-response relationships estimated from the epidemiological studies were applied to projections of climate. The short-term relationship between the daily number of deaths/hospital admissions and day-to-day fluctuations in exposure variables (temperature, heat waves, ozone and particles) for many cities are published in different scientific papers. 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 analyzed 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 [18], which calculates the change in mortality or morbidity by a change in the exposure variable.

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

where y_0 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 [19].

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

C. Energy Demand

To obtain the hour-by-hour energy consumption during the years, data for multiple climatic variables in the form of 8760 hourly records per variable (dry bulb temperature, wet bulb temperature, global solar radiation, wind speed, wind direction, humidity, and pressure) for each year were produced. Weather data is used not only to drive the hour-by-hour response of the building to the climate, but also to size the systems in model, thus affecting capacities, performance curves, and possibly the types of systems to use. All the effects have an impact on the predicted energy use in the model. Sixteen prototype buildings have been simulated with urban climate atlas from the centre of domain. Building energy usage was estimated by simulating sixteen prototypical buildings with the EnergyPlus model from U.S. Department of Energy [20]. EnergyPlus is the dynamic building energy simulation engine for modeling building; heating, cooling, lighting and ventilating EnergyPlus is a well-known and highly validated model that is the industry standard model. EnergyPlus model has been validated in numerous tests from ASHRAE. EnergyPlus is a highly detailed building thermal load simulation program that relies on detailed user inputs. EnergyPlus calculates heating and cooling loads, and energy consumption, using sophisticated calculations of heat gain and heat loss including transient heat conduction though building envelop elements. It also accounts for heat and mass transfer that impact sensible and latent thermal loads due to ventilation and infiltration. Additionally, the model has detailed calculations of heat transfer to or from the ground and comprehensive models of solar gain through the fenestration and opaque envelop components. Building features needed for implementation in EnergyPlus, were taking from the ASHRAE 90.1 Prototype Building Modeling Specifications. Outdoor ventilation air requirements and schedules are defined following the ASHRAE 90.1 Prototype Building Modeling Specifications; PNNL (2014) Table I describes the types of buildings used with the most important building model information.

TABLE I: THE ARRANGEMENT OF CHANNELS

Id	Type	Total Area (m2)	Floors	Window Fraction	People
1	High-Rise Apartment	7837	10	30%	163
2	Mid-Rise Apartment	3131	4	20%	67
3	Hospital	22428	5	16%	767
4	Large Hotel	11346	7	30%	1494
5	Small Hotel	4013	4	11%	239
6	Large Office	46321	12	38%	2429
7	Medium Office	4980	3	33%	268
8	Small Office	511	1	20%	28
9	Outpatient Healthcare	3804	3	20%	419
10	Fast Food	232	1	20%	94
11	Sit Down Restaurant	511	1	17%	288
12	Standalone Retail	2294	1	7%	370
13	Strip mall	2090	1	10%	337
14	Primary School	6871	1	35%	1433
15	Secondary School	19593	2	33%	6095
16	Non-refrigerated warehouse	4598	1	1%	13

III. RESULTS

The modelling system described in the last section was used to assess the impacts of projected global climate conditions in three European urban areas: Madrid 12 km by 12 km, Milan 10 km by 10 km and Kensington and Chelsea, 6 km by 5.3 km; assuming no changes in urban landuses. These three cities have a variety of building sizes and land cover types. The first level with 50 km covers the covers the whole of Europe, 1 km domains cover all the cities (Madrid, London and Milan). The simulations are run for 2030, 2040 and 2100 (future) and 2011 (present).

A. Evaluation

TABLE II: PERFORMANCE METRICS FOR MILAN

ID	POLLUTANT	NMB (%)	RMSE (ug/m3)	R^2
5	SO2	-5,27	3,6	0,21
0	NO2	-0,01	38,07	0,51
1	NO2	4,77	46,3	0,38
2	NO2	22,15	46,6	0,45
3	NO2	-34,29	46,33	0,41
4	NO2	-8	44,62	0,38
5	NO2	-23,95	45,74	0,45
6	NO2	-7,94	45,3	0,41
7	NO2	3,62	46,72	0,35
8	NO2	15,35	49,18	0,47
0	CO	-0,05	574,4	0,67
1	CO	-12,03	689,43	0,53
2	CO	-1,82	768,99	0,6
6	CO	-0,23	643,2	0,52
7	CO	11,49	722,49	0,57
8	CO	-0,91	764,07	0,54
0	O3	-1,87	21,09	0,84
4	O3	-5,39	22,49	0,81
5	O3	-2,96	24,2	0,82
6	O3	2,07	20,71	0,84
0	PM10	-0,24	30,95	0,58
5	PM10	-4,88	31,37	0,56
6	PM10	3,88	32,49	0,55
7	PM10	-0,37	32,91	0,58
5	PM25	0,51	28,05	0,54
0	C6H6	3,46	1,52	0,57
1	C6H6	-1,78	2,13	0,43
7	C6H6	5,43	1,58	0,54

We have evaluated one year simulation for the present (2011) which is driven for the global reanalysis data (NNRP), which are the most realistic global data of the past. Air pollution concentrations were compared against all available measurements of the air quality networks of Milan and Kensington and Chelsea included in the high resolution domains (50 m). The monitoring stations have been identified with a number. Number 0 means the average of the values where stations are located. The following statistical metrics have been used in this study to verify the performance of the modelling system when compared with the air quality observations of the London and Milan. Bias or mean error (BIAS) is defined as the mean of the differences between the simulated outputs and observations. Root Mean Square Error (RMSE) is a frequently used measure of the difference between values predicted by a model and the values actually observed. It measures the average magnitude of the error and it is defined as the measure of the combined systematic error (bias) and random error (standard deviation).Therefore, the RMSE will only be small when both the variance and the bias of an estimator are small. Pearson correlation coefficient (R2) is defined as the measure of the linear dependence between the simulated results and the observational data, giving a value between +1 and −1 inclusive. It thus indicates the strength and direction of a linear relationship between these two variables. A value of 1 implies that a linear equation describes the relationship between models and the observations perfectly, with all data points lying on a line for which the model values increase as the data values increase. The correlation is −1 in case of a decreasing linear relationship and the values in between indicates the degree of linear relationship between the model and the observations. Results are presented in the Table II for Milan and Table III for London. The results of the comparison between the modelled data and the observed data show that the simulated concentrations are within the ranges of measured data. The simulated concentrations regarding the observed concentrations are better in Milan than London. In Milan we have more detailed information about traffic flows and the micro scale emissions are more precise than in case of London. The average simulated levels are within the inter-annual variability of the measured since most of the R2 values exceed the value of 0.5, except SO2 but SO2 concentrations are very low in the cities. The statistical evaluation shows significant evidence that high resolution downscaling procedure could achieve reasonably good performance, particularly for BIAS and R2 statistics.

TABLE III: PERFORMANCE METRICS FOR LONDON

ID	POLLUTANT	NMB (%)	RMSE (ug/m3)	R^2
0	SO2	0,51	2,56	0,19
1	SO2	-62,07	3,08	0,26
2	SO2	-11,74	2,9	0,12
0	NO2	33,58	48,26	0,35
1	NO2	-31,67	35,57	0,38
2	NO2	22,02	48,87	0,24
3	NO2	50,52	57,67	0,31
4	NO2	44,21	62,17	0,25
5	NO2	50,42	68,78	0,34
0	CO	17,73	136,87	0,37
1	CO	-8,47	119,33	0,36
2	CO	19,47	176,36	0,27
1	O3	-58,2	33,26	0,61
0	PM10	34,87	18,39	0,46
1	PM10	16,09	17,39	0,41
2	PM10	36,36	18,05	0,42
5	PM10	46,38	22,71	0,44

B. Pedestrian Comfort

High-rise buildings can introduce high wind speed at pedestrian level, which can lead to uncomfortable or even dangerous conditions. Assessment of wind comfort involves a combination of the meteorological data (model results) with a comfort criterion. We propose to use the Dutch wind nuisance standard (NEN 8100) which applies a discomfort threshold for the hourly mean wind speed (UTHR) of 5 m/s for all types of activities. Depending on the exceedance probability P of the threshold wind speed, the code defines five quality classes of wind comfort. Fig. 2 shows an example of the wind comfort classes for Madrid, year 2050 under two possible global climate scenarios. We can observe that in the big avenue on the right part (Castellana Avenue), for 2050 the global climate scenario 4.5 will produce more uncomfortable areas by strong winds. The comfort quality class is much better between the buildings.

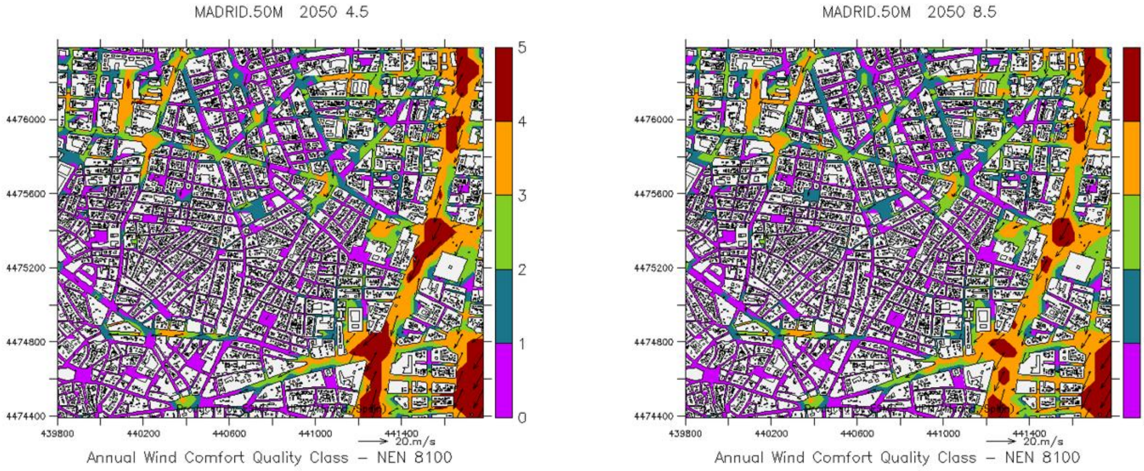

Fig. 2. Annual wind comfort quality class, NEN 8100. Madrid, 2050, 50 m spatial resolution, RCP 4.5 (left) and RCP 8.5 (right).

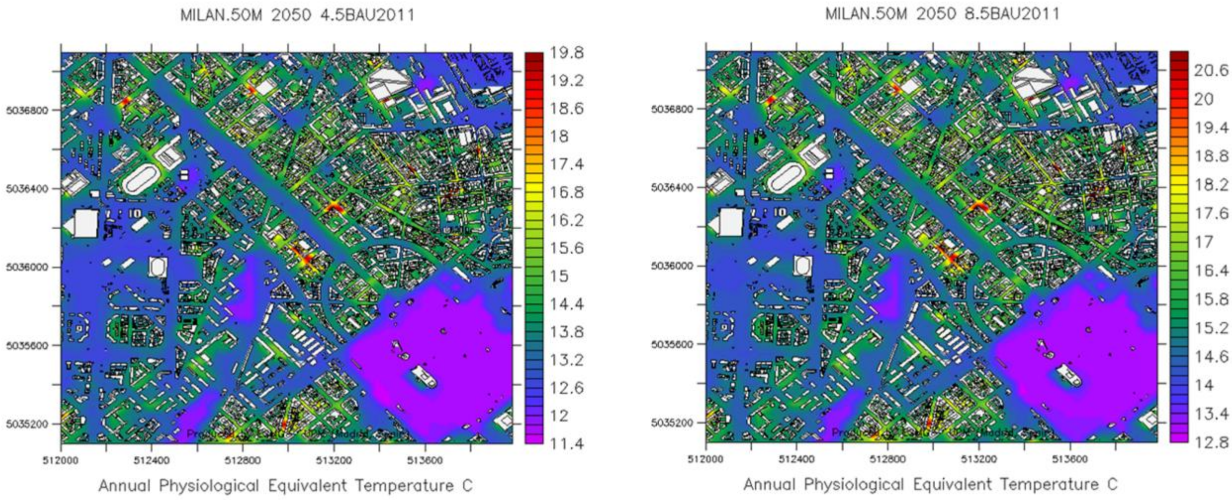

Fig. 3. Annual Physiological Equivalent Temperature (℃), Milan, 2050, 50 m spatial resolution, RCP 4.5 (left) and RCP 8.5 (right).

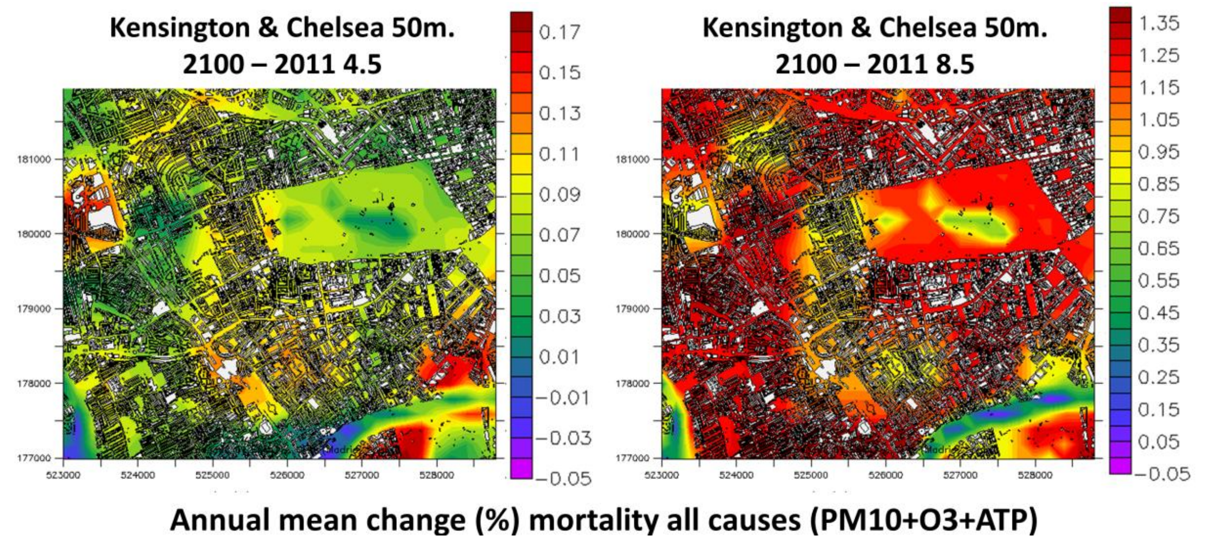

Fig. 4. Yearly average of spatial distribution of the differences (%) mortality for natural causes due to air pollution and temperature for 2100 respect to 2011 following RCP 4.5 (left) and RCP 8.5 (right) scenarios with WRF-Chem-MICROSYS over Kesington-Chelsea (London) with 50 m. spatial resolution.

Outdoor thermal comfort is governed by winds conditions, both direct and diffuse solar irradiation, the exchange of long-wave radiation between a person and the environment. A crucial element in the assessment of thermal comfort is the development of a comfort index which appropriately reflects the comfort sensation of a person in a given situation. We propose the following thermal comfort index: The physiological equivalent temperature (PET) which is defined as the air temperature of a reference environment in which the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed [21]. The PET is based on the "Munich Energy Balance Model for Individual" (MEMI) and has taken into account of both the environmental climatic parameters (including air temperature, wind speed, relative humidity etc) and the human factors (clothing index, activities etc). Fig 3. shows an example of the PET for Milan, year 2050 under two possible global climate scenarios. We can observe that the global climate scenario RCP 8.5 can go the PET up to 20.6 ºfor year 2050 in some hot spots.

C. Health Impact

Combined health effects of pollutants and plus climate (temperature effects) are showed for 2100 London, Fig 4. and 2050 Milan Fig 5 with 50 m. spatial resolution under two possible global climate scenarios.

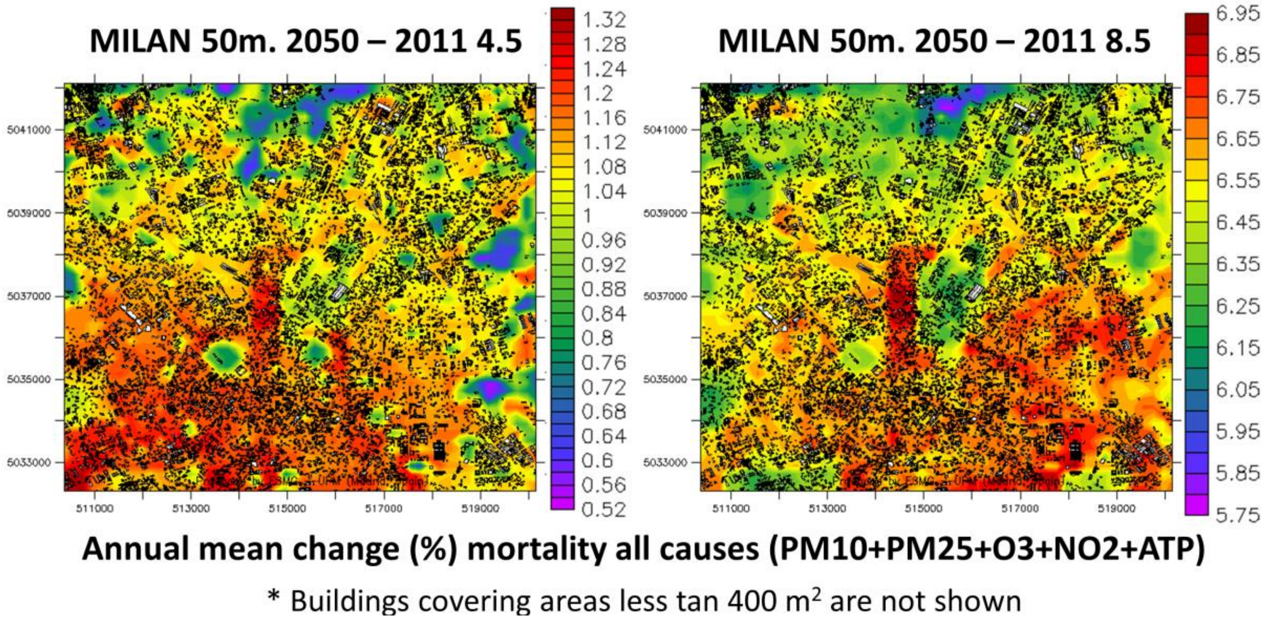

Fig. 5. Yearly average of spatial distribution of the differences (%) mortality for natural causes due to air pollution and temperature for 2050 respect to 2011 following RCP 4.5 (left) and RCP 8.5 (right) scenarios with WRF-Chem-MICROSYS over Milan with 50 m. spatial resolution.

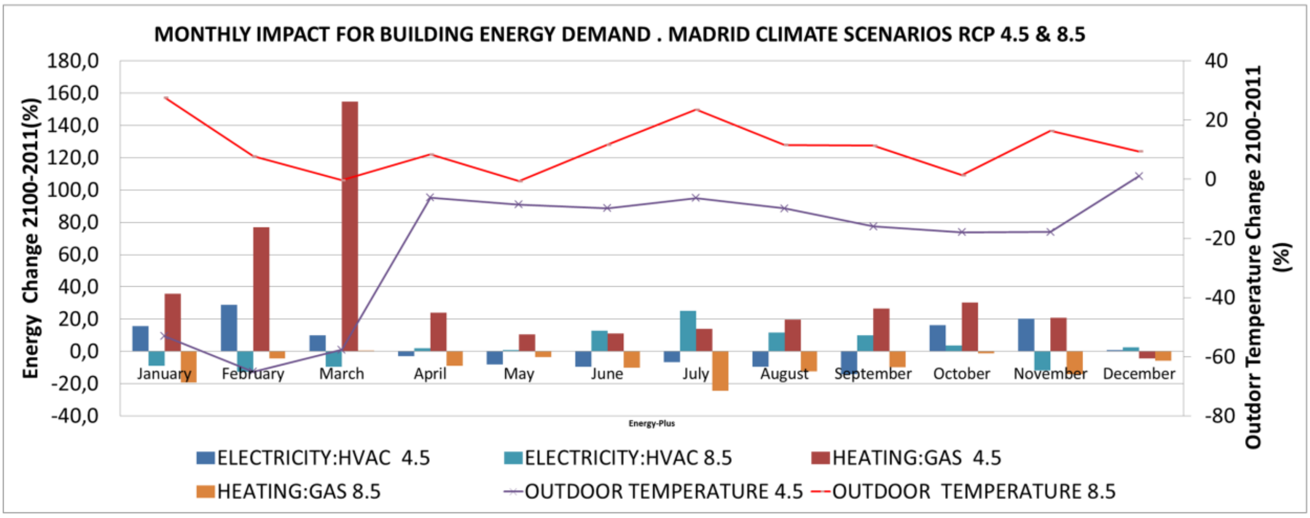

Fig. 6. Change 2100-2011 (%) in monthly energy demand (gas and electricity) and outdoor temperature under two climate scenarios for Madrid.

In the case of London in 2100, the mortality (%) impacts, increases in mortality and higher in 8.5 scenario than in 4.5 scenario. the expected increases in temperature will cause increased mortality especially in the years 2050 and 2100 with the climate scenario 8.5 .Areas with high density of buildings are the most affected. Water bodies reduce the health impacts. In case of Milan, the impacts on mortality changes (%) due to air pollution (all pollutants) together with the impact of temperature (climate) are higher in 8.5 scenario than in 4.5 scenario. in 2050 it is expected to aggravate the effects on health, especially in the climate scenario 8.5 by strong increases in temperature. Scenario 4.5 slight increases due to increased air pollution and temperatures are expected South part of the city is the most sensible.

D. Energy Demand

We will focus on the results of the EnergyPlus simulations. We have run 128 simulations (2 years, 2 climate scenarios, 2 cities and 16 building types). Fig. 6 shows the changes (%) in energy demand for the heating (gas) and electricity (HVAC system) averaged for the sixteen types of buildings for Madrid and Fig 7 for London by the 2100 as compared to the 2011 under climate scenarios 4.5 and 8.5 plus changes in the monthly average outdoor temperature.

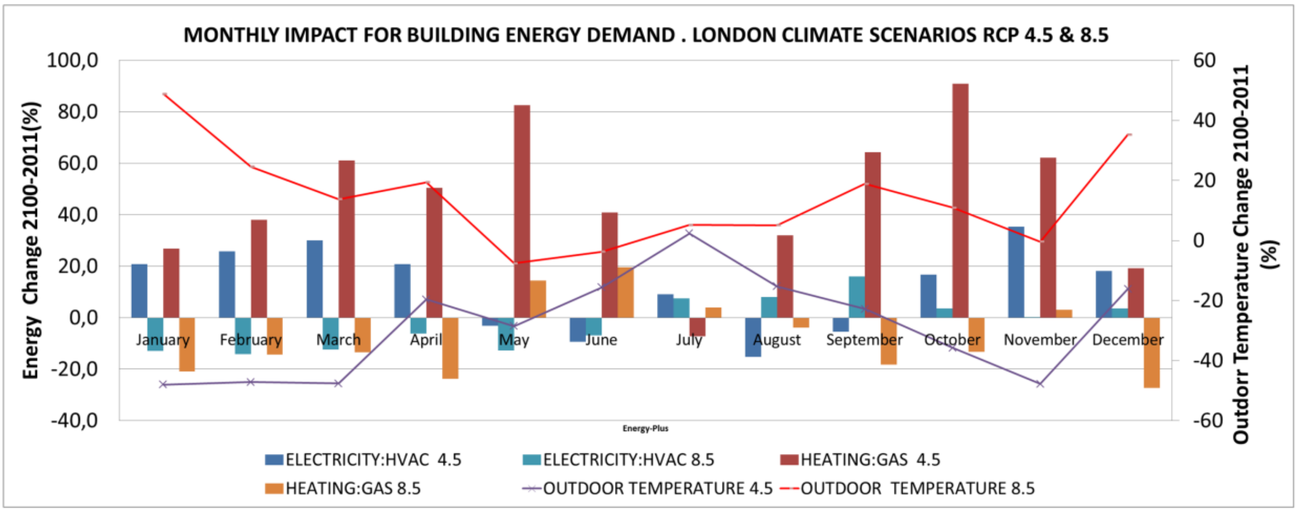

Fig. 7. Change 2100-2011 (%) in monthly energy demand (gas and electricity) and outdoor temperature under two climate scenarios for London.

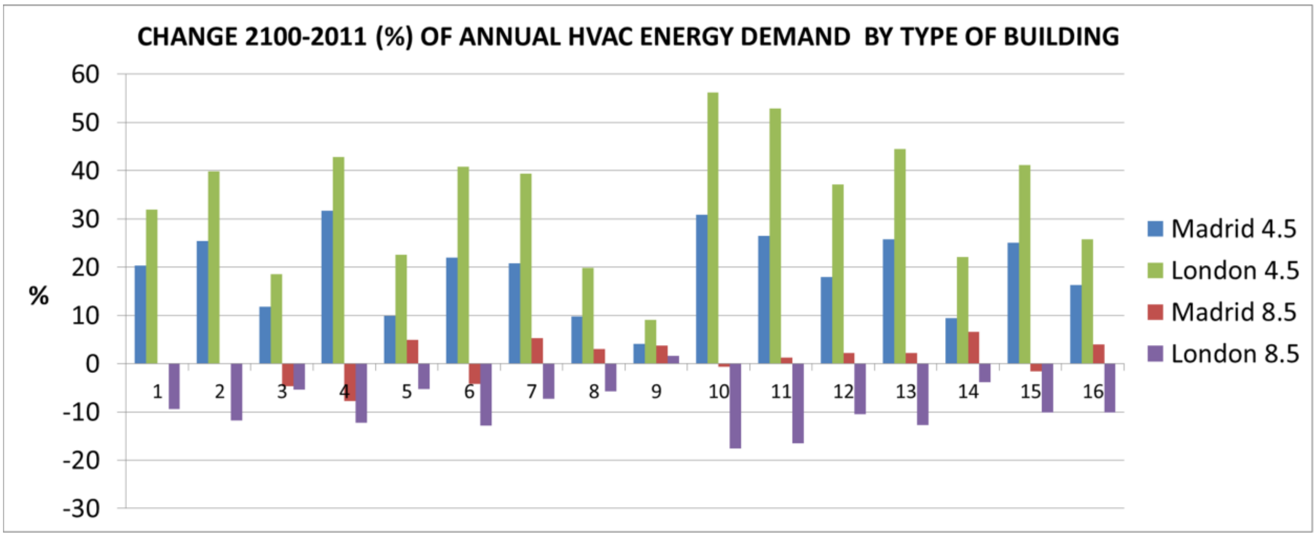

Fig. 8. Change in annual HVAC energy demand for sixteen different types of buildins, Madrid and London, RCP 4.5 and RCP 8.5

The energy demand for each type of building (16) has been averaged. The total energy demand (gas + electricity) used for building cooling and heating will increase between 18.74 % for Madrid and 31.36 % for London under the RCP 4.5 climate scenario. The main reason is a high increase of the gas consumption for heating (36.63 % Madrid and 44.45% London) because 2100 will be cooler than 2011. The energy demand for each type of building (16) has been averaged. The total energy demand (gas + electricity) used for building cooling and heating will decrease between -2.72% for Madrid and -8.5 % for London under the RCP 8.5 climate scenario. Because of the global warming the heating energy usage will decrease. The cooling energy consumption will increase only during summer months. In general, the changes in London will be higher than those in Madrid, because buildings in London need more energy for heating. However, the increase and decrease of each type of buildings are different. Fig. 8.

For example, the heating energy consumption of small office building in Madrid will reduce by almost 48.85 % and 14.23% for large office. Figure 6 compares the impact of climate change on HVAC annual total energy demand for the sixteen types of buildings (ids in Table I) in the two cities by the 2100 respect to 2011 under the two possible climate scenarios. Hospital buildings (ids, 3, 8) and office large buildings (id 6) experience the smallest relative change in energy demand. Restaurants (ids 10 and 11) suffer the most from global climate, primarily because all zones are exposed to the outdoors together with the retail strip malls by the same reason. Heating energy percentage reductions of small buildings are generally larger than that of the big buildings. Small buildings are more sensitive to the weather changes because of their low volume to surface area ratio.

IV. Conclusion

We have presented a dynamical downscaling approach to study the impacts of the global climate change on pedestrian comfort, human health and building energy demand over urban areas with high spatial resolution; the information can be used for assessment of integrated climate change adaptation and mitigation strategies. A nesting procedure was used to assess the effects of climate change on three urban areas: Madrid, Milan and London with very high spatial resolution under two IPCC RCP possible scenarios, 4.5 and 8.5. The model chain included a global climate model (CESM), as well as mesoscale-urban (nested WRF/Chem with UCM spanning from 50 to 1 km resolution) and microscale (MICROSYS) models. 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 we were interested on knowing the impact of future climate projections in urban domains with very high spatial resolution. The microscale air pollution results were evaluated, respectively, using observations from existing air quality stations. The evaluation of WRF-Chem and MICROSYS coupling showed the utility of modelling system. In particular, in the Milan case study where we received much more detailed information to calculate local emissions. In general, the simulations show acceptable agreement with measurements in the urban background for climate realizations. The nested modelling approach proposed and used is portable to other cities, requiring only the adjustment of model parameters and inputs to suit the locality. In the high resolution simulations we have observed that the building influence is very important to detect hot spots or sensible areas to be affected by the climate change. The information can be used for local decision makers and stakeholders in order to developing strategies to reduce these impacts.

Heating and cooling energy consumption of sixteen different types of buildings during 2011 and 2100 in Madrid and London cities, were simulated by using EnergyPlus model under two possible climate projections: RCP 4.5 and RCP 8.5. The findings do support the conclusion that climate change will have a large effect in the building energy consumption. The increase and decrease of energy consumption for each type of building are different. Heating energy percentage reductions of small buildings are generally larger than those for large buildings. Hospital and large office buildings experience the smallest relative change in energy demand. Restaurants suffer the most from global climate change, primarily because all zones are exposed to the outdoors together with the retail strip malls by the same reason.

ACKNOWLEDGMENT

The UPM authors acknowledge the computer resources and technical assistance provided by the Centro de Supercomputación y Visualización de Madrid (CeSViMa). The UPM 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. Ordnance Survey data for London: © Crown copyright and database rights 2015 OS 100021668.

REFERENCES

[1] K. W. Oleson, A. Monaghan, O. Wilhelmi, M. Barlage, N. Brunsell, J. Feddema, L. Hu, and D. F. Steinhoff, "Interactions between urbanization, heat stress, and climate change," *Climatic Change*, vol. 129, pp. 525-541, 2010.

[2] K. Riahi *et al*., "RCP 8.5 — A scenario of comparatively high greenhouse gas emissions," *Climatic Change*, vol. 109, pp. 33–57, 2011.

[3] K. Markakis *et al*., "Climate-forced air-quality modeling at the urban scale: sensitivity to model resolution, emissions and meteorology," *Atmos. Chem. Phys*., vol. 15, pp. 7703–7723, 2015.

[4] D. Millstein and S. Menon, "Regional climate consequences of large-scale cool roof and photovoltaic array deployment," *Environ. Res. Lett*., vol. 6, 2011

[5] G. H. Radhi, "Evaluating the potential impact of global warming on the UAE residential buildings — A contribution to reduce the CO2 emissions," *Building and Environment*, vol. 44, pp. 2451-2462, 2009.

[6] C. Cartalis, A. Synodinou, M. Proedrou, A. Tsangrassoulis, and M. Santamouris, "Modifications in energy demand in urban areas as a result of climate changes: An assessment for the southeast Mediterranean region," *Energy Conversion Manage*, vol. 42, pp. 1656–1674, 2001.

[7] T. J. Wilbanks and R. W. Kates, "Global change in local places: How scale matters," *Climatic Change*, vol. 43, pp. 601–628, 1999.

[8] F. Giorgi, C. Jones, and G. R. Asrar, "Addressing climate information needs at the regional level: The CORDEX framework," *WMO Bull*., vol. 58, no. 3, pp. 175–183, 2009.

[9] M. Piringer *et al*., "A sensitivity study of separation distances calculated with the Austrian Odour Dispersion Model (AODM)," *Atmospheric Environment*, vol. 41, pp. 725-1735, 2007.

[10] D. P. Vuuren *et al*., "The representative concentration pathways: An overview," *Climatic Change*, vol. 109, pp. 5−31, 2011.

[11] IPCC, *Climate Change*, The Physical Science Basis; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013.

[12] T. Wilbanks *et al*., "Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies," *Intergovernmental Panel on Climate Change*, Geneva, 2008, p. 132.

[13] T. J. Wilbanks *et al*., "The next generation of scenarios for climate change research and assessment," *Nature*, vol. 463, pp. 747-756, 2010.

[14] G. A. Grell *et al*., "Fully coupled 'online' chemistry in the WRF model," *Atmos. Environ*., vol. 39, pp. 6957-6976, 2005.

[15] V. Masson, "A physically-based scheme for the urban energy budget in atmospheric models," *Boundary Layer Meteorol*, vol. 94, pp. 357-397, 2000.

[16] I. Harman *et al*., "Scalar fluxes from urban street canyons. Part II: Model," *Boundary Layer Meteorol*, vol. 113, pp. 387-409, 2004.

[17] R. S. Jose *et al*., "European operational air quality forecasting system by using MM5-CMAQ-EMIMO tool," *Simulation Modelling Practice and Theory*, vol. 16, issue 10, 2007.

[18] M. L. Bell *et al*., "The exposure–response curve for ozone and risk of mortality and the adequacy of current ozone regulations," *Environ Health Perspect*, vol. 114, pp. 532–536, 2006.

[19] U.S. EPA (U.S. Environmental Protection Agency), "BenMap: environmental benefits mapping and analysis program user's manual, appendix," Research Triangle Park, NC:U.S. EPA, Office of Air Quality Planning and Standards, 2010.

[20] Department of Energy, EnergyPlus Engineering Reference, The Reference to EnergyPlus Calculations, Department of Energy, Washington, DC. 2010

[21] P. Höppe, "The physiological equivalent temperature — A universal index for the biometeorological assessment of the thermal environment," *Int J Biometeorol*, vol. 43, pp. 71–75, 1999.

R. San Jose is professor of the Technical University of Madrid, the director of Environmental Software and Modelling Group in the Computer Science School of UPM. He has more than 300 scientific publications in relevant Journal Citation Index Journal. He completed his PhD in 1982 related to the unstable surface turbulent boundary layer parameterisation. He has been involved in air pollution modelling mainly using three-dimensional mesoscale models, such as MM5 and CMAQ. He has been a full professor since 2001.