Impact of Climate Change on Thermal and Wind Comfort over Madrid, Milan and London

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***Abstract*—**It is known that he global climate change has impact on pedestrian wind and thermal comfort. The objective of this paper is to quantify the effects of climate change on the thermal and wind comfort over three European cities. The pedestrian comfort allows describing the combined effect of changes in multiple climate variables and measuring the impact on population. For this objective we have used a dynamical downscaling process to get meteorological data with 50 meters of spatial resolution starting on 1º. Two IPCC climate scenarios have been run RCP 4.5 (stabilization emission scenario) and RCP 8.5 (little effort to reduce emissions) for present (2011) and future (2030, 2050 and 2100) over: Madrid, Milan and London. Hourly meteorological data is used to simulate the changes in wind comfort and physiologically equivalent temperature (PET) at the future respect to present. We use the PET as thermal comfort index. The Dutch wind nuisance standard NEN 8100 is used to assess the pedestrian wind comfort, which applies a discomfort threshold for the hourly mean modeled wind speed. This work demonstrates the magnitude of spatial variability on comfort index caused by the urban elements. The very high resolution of the results allows identifying areas of the city with uncomfortable conditions for the city, so these areas have elevated exposure to the climate change from a pedestrian comfort point of view. Quantitative information about citizen comfort allows preparing plans and implementing adaptation strategies to reduce effects of climate change on the citizen.

***Keywords*—** Comfort, Thermal, Climate, Wind.

I. Introduction

In urban areas, microclimatic conditions and morphological characteristics of the city regulate the comfort of local pedestrians. In urban areas, wind conditions have an impact on natural ventilation of buildings, thermal comfort of people as well as in the dispersion of atmospheric pollutants but outdoor human comfort in an urban environment can be affected by a wide range of parameters, including wind speed and direction, air temperature, relative humidity, solar radiation, atmospheric gas concentrations, human activity, clothing level, age, etc. Urban wind is strongly influenced by obstacles such as buildings (theirs structures and direction). Also wind conditions affects thermal comfort [1]. Comfort in urban areas has received much attention in recent years in a wide recognition that microclimatic conditions contribute to the quality of life in cities. In general, basic understanding of how the weather affects humans and the environment is a key aspect and helps improve resilience to climate change. The global climate can amplify the risk to expose the citizens to discomfort in the cities, and most of the people live in cities because they are particularly vulnerable to the climate change. For example, the buildings retain heat at night and modify the ventilation because they are as obstacles to the wind. The atmospheric flow and microclimate on urban areas are influenced by the urban characteristics, and improve atmospheric turbulence [2]. To mitigate this effects the urban geometry, vegetation, building material and other aspect can play an important role [3]. Global Climate Models (GCMs) have a coarse resolution, so we need to use higher resolution numerical modelling to get precise data about the urban micro climate [4]. Last developments in computer science and atmospheric science, particularly in the use of dynamical downscaling techniques provide opportunities to investigate climate effects on the pedestrian comfort [5]. We have chosen a dynamical downscaling process, using models of climate and air quality high resolution both regional and urban level, including a model of computational fluid dynamics (CFD) to take into account the effects of buildings , ventilation effects and shade given in a city. CFD simulations are computationally very demanding but it is based on physical laws and it produces a full suite of climate outputs variables. Climate change is often discussed in terms of changes in isolate indicators; however, in order to evaluate its impact on citizen, it is necessary to analyze the combined effect of different meteorological variables. The comfort expresses the level of human satisfactions in a given environment. Comfort is closely linked to human health and is thus a key component in our daily operations [6]. In this study, thermal and wind comfort in urban areas with two different climate scenarios were investigated through meteorological data modelled with very high spatial resolution, 50 meters. For the comfort analysis we have used several meteorological variables: wind speed, wind direction, air temperature, air humidity and radiation. Unfortunately data of these parameters with very high spatial resolution are not available in the climate community, so the major climate and comfort studies use coarse resolutions. Studies on the impact of urban climate on human comfort are very few. The past studies examining the consequences of climate change for the pedestrian comfort typically quantify the impacts at a relatively course spatial resolution. However, average responses have little value [7],

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therefore, it must be conducted at a fine scale, taking into account the 3D shape of the buildings and urban local conditions.

II. Methodology

We use result with 50 meters of spatial resolution and one hour of temporal resolution from a dynamical downscaling process. We made use of a single year of simulated meteorology and air quality in this study to capture peak events that may have been moderated or lost from a statistical average over successive years. The assessments consider the projected impacts of climate change considering three future years 2100, 2050 and 2030 against the baseline situation 2011.Future climatic conditions have been identified in two climate scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) [8] in the Fifth Assessment Report (AR5). The two selected global climate scenarios, RCP 4.5 [9] and RCP 8.5 [10] are the most used by the scientific community because they represent relatively low and high greenhouse gas projections/radiative forcing respectively. Also, the choice of the worst-case scenario (RCP 8.5) and the best-realistic-case scenario (RCP 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. We start with datasets of the future climatic conditions generated by the model CESM forces with the RCP scenarios. The next step is to apply a dynamical downscaling process with a regional climate model (WRF/Chem) and the last step is to run the CFD MICROSYS model to take into account the buildings of the cities. The description of the dynamical downscaling method was published already, for detailed information; refer to publication [11]. The simulation results provide the data required for a robust assessment of the human comfort based on requirements established by the specific wind comfort and thermal comfort indexes. The study areas corresponding with three European urban areas: Madrid 12 km by 12 km, Milan 10 km by 10 km and Kensington and Chelsea, London with 6 km by 5.3 km; assuming no changes in urban land uses. These three cities have a variety of building sizes and land cover types.

A. Thermal comfort

To understand thermal comfort and its effects on the human being, air temperature is not an adequate indicator. 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. In this study, thermal comfort is determined using the PET comfort index [12]. PET quantifies the combined effect of future changes in air temperature, air humidity, wind speed and radiation on the people's thermal perception and thermo-physiological stress. To determine PET, the meteorological variables—air temperature, vapor pressure, wind speed and mean radiant temperature—are needed. Characteristics of human beings are set as constants, i.e. the internal heat production is 80 W and the heat transfer resistance of clothing is 0.9 clo [13]. PET is a steady-state model involving all heat exchange processes between the human body and its environment. PET evaluates the thermal conditions in a physiologically significant manner. It "is defined as the air temperature at which the human energy budget for the assumed indoor conditions is balanced by the same skin temperature and sweat rate as under the actual complex outdoor conditions to be assessed"

B. Wind comfort

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) applies a discomfort threshold for the hourly mean wind speed (UTHR) of 5 m/s for all types of activities [14]. Depending on the exceedance probability P of the threshold wind speed, the code defines five quality classes of wind comfort 0–4 These quality classes define a good, moderate or poor wind climate for the activities traversing, strolling and sitting [15].

III. Results

The model simulations of the two climate scenarios for the future (2030, 2050 and 2100) were then compared with the present (2011). The differences in each 50 meters grid cell give us the impact of the global climate. A comparison of current and future conditions, projected by the scenarios, shows remarkable changes which are showed in the next figures corresponding to maps of the spatial distribution of the main results.

C. Thermal Comfort

Figure 1 shows the spatial distributions of the differences of the average annual PET over area of 2 km. by 2 km of Kensington and Chelsea between 2100 and 2011. PET is expected to increase by 1.5 ºC with RCP 8.5 and decrease by 3.7 ºC with RCP 4.5. The less impact zone corresponding to the water body (river), so water bodies can help to mitigate the impacts of the climate change. Evapotranspiration, improve thermal comfort by reducing air temperature and increasing humidity [16]. The most sensible areas are which the density of the buildings is high.

Figure 2 shows the spatial distributions of the differences of the average annual PET over area of 2 km. by 2 km of Madrid between 2100 and 2011. PET is expected to increase by 2.0 ºC with RCP 8.5 and decrease by 3.0 ºC with RCP 4.5. Open streets are the most affected by the climate change. The increments expected to Madrid are larger than in case of London.

Figure 3 shows the spatial distributions of the differences of the average annual PET over area of 2 km. by 2 km of Madrid between 2050 and 2011. PET is expected to increase by 2.3 ºC with RCP 8.5 and increase by 0.6 ºC with RCP 4.5. In case of Milan PET is expected to increase in the both climate scenario, but the increments are higher in the RCP 8.5 than in the RCP 4.5. In case of Milan, the increments are generalized on all streets and open areas.

After to analyze the imagens the RCP 8.5 projections show a shift towards warmer conditions is all cities. PET values will increase in most areas with the RCP 8.5 climate scenarios and cooling will occur in the RCP 4.5. Higher increments of PET values are found for Madrid and Milan (cities of south of Europe) respect to London (north of Europe). The highest PET values can be observed in the end of the century (2100).

D.Wind Comfort

Now we show the differences of the annual exceedance probabilities (P > 5 m/s) for wind nuisance for future respect to the present and the accompanying quality classes according the Dutch Standard NEN 8100 over a zoom area of 2 km. by 2 km.. Figure 4 corresponding with London, 2050 with climate scenario RCP 8.5. Figure 5 is a Madrid area for year 2110 with RCP 4.5 and finally figure 6 is a zoom of Milan for year 2030 and RCP 8.5.

The map with wind classes at pedestrian level in London for the future situation (Figure 4) shows open large areas with quality class 4 which means poor quality of wind comfort for all activities (traversing, strolling and sitting), also same streets are high quality from a wind comfort point of view. The changes of the probability that wind speed are more than 5 m/s range from -3% to 4 % with very high spatial variability. In case of Madrid (Figure 5), the majority of the streets present good quality of wind comfort, except a big avenue (Castellana) with poor quality zones. Some hot spots are identified by increments of the exceedance probabilities of wind speed up to 7%. In case of Milan (Figure 6) we can expect small increments of the local wind velocities, so the good quality of the wind comfort will remain in the streets, although the open areas can be moved to the moderate quality class for traversing activity.

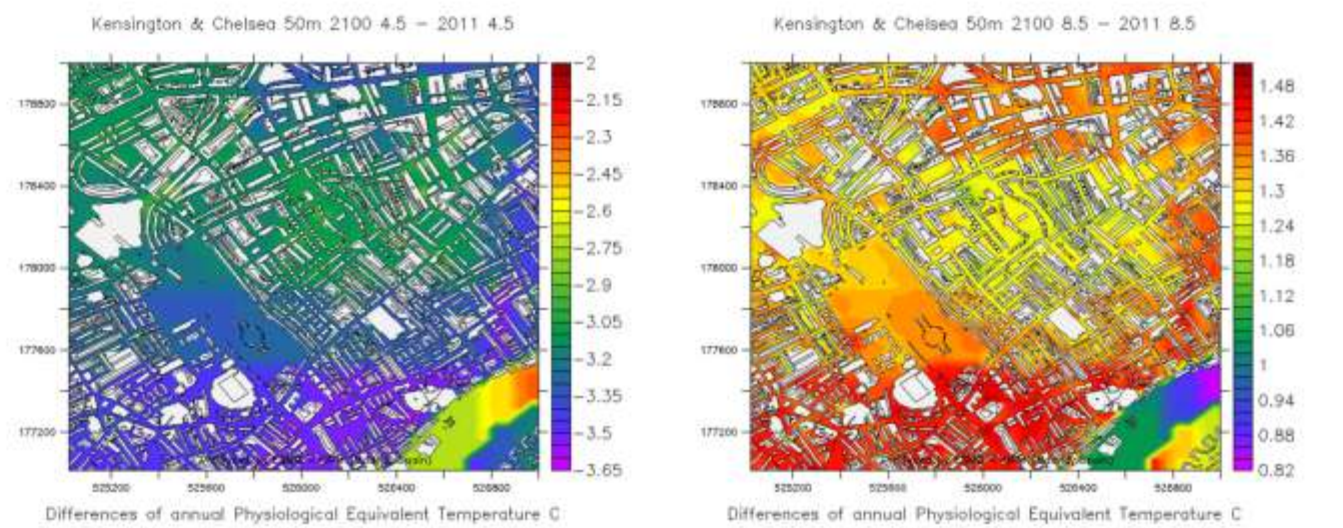

Fig. 1. Differences of annual Physiological Equivalent Temperature (ºC), London, 2100-2011, 50 m spatial resolution, RCP 4.5 (left) and RCP 8.5 (right).

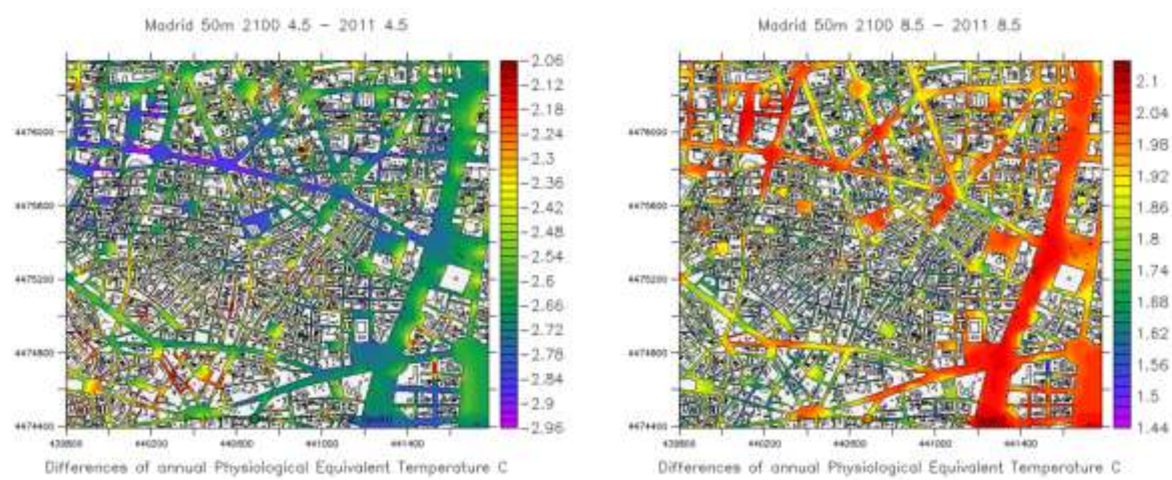

Fig. 2. Differences of annual Physiological Equivalent Temperature (ºC), Madrid, 2100-2011, 50 m spatial resolution, RCP 4.5 (left) and RCP 8.5 (right).

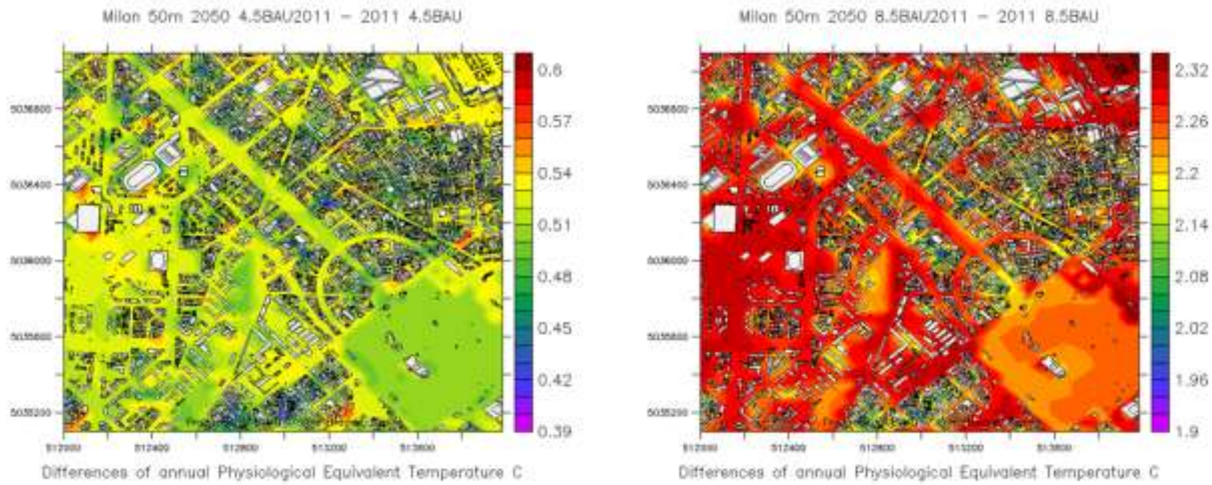

Fig. 3. Differences of annual Physiological Equivalent Temperature (ºC), Milan, 2050-2011, 50 m spatial resolution, RCP 4.5 (left) and RCP 8.5 (right).

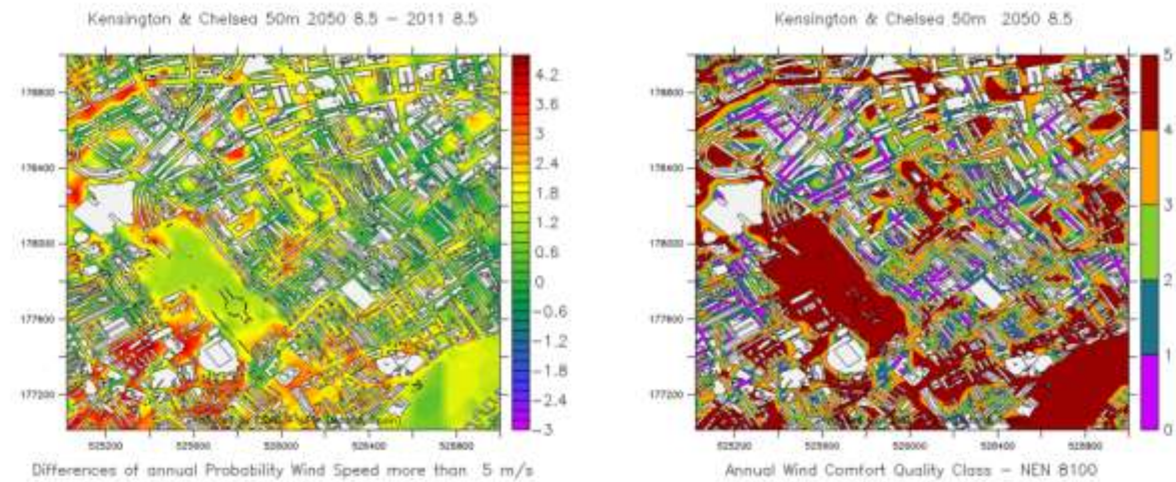

Fig 4. Differences of annual probability than wind speed is higher than 5 m/s over London, 2050-2011, 50 m spatial resolution, RCP 8.5 (left) and the corresponding quality class NEN 8100 for the future situation

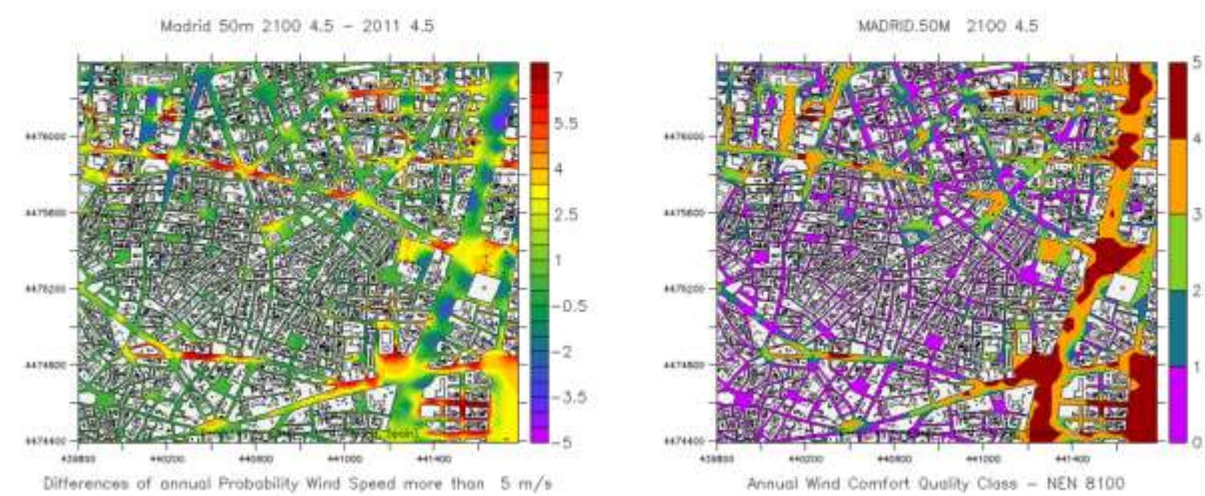

Fig 5. Differences of annual probability than wind speed is higher than 5 m/s over Madrid, 2100-2011, 50 m spatial resolution, RCP 4.5 (left) and the corresponding quality class NEN 8100 for the future situation.

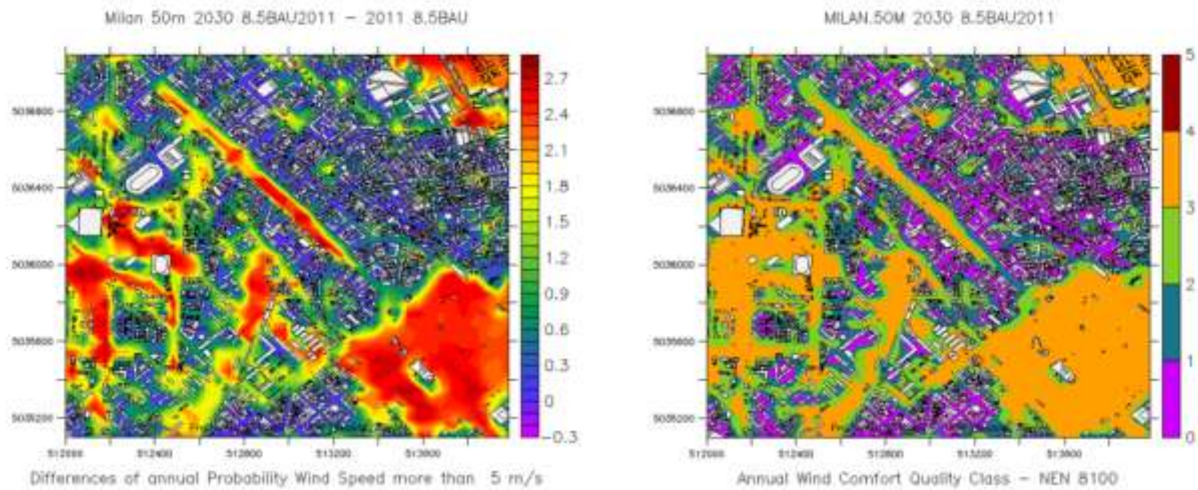

Fig 6. Differences of annual probability than wind speed is higher than 5 m/s over Milan, 2030-2011, 50 m spatial resolution, RCP 8.5 (left) and the corresponding quality class NEN 8100 for the future situation.

The reduction in the effects of the wind speeds of the cities can be explained by change in surface roughness as well as enhanced temperatures that reduce pressure over the city forming a center of low level convergence. Densely constructed buildings may serve as obstacles to wind. On the other hand, open areas can enhance wind tunnelling effect, which is associated with strong wind that cause discomfort in the outdoor.

E. Evaluation

Madrid meteorological stations were used to evaluate the accuracy of the modelling system outputs (Table 1). For evaluation we have compared the hourly model outputs for present conditions (2011) following reanalysis scenario (NNRP) to hourly observations. The monitoring stations have been identified with theirs typical identifier names. “AVG Stations” 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 meteorological observations of the Madrid.. 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.

TABLE 1. MADRID RESULTS OF THE EVALUATION OF THE RESULTS OF THE MODELLING SYSTEM

	PARAMETER	NMB(%)	RMSE	R2
AVG STATIONS	WS (m/s)	33,4	2,42	0,51
Fuencarral	WS (m/s)	36	2,24	0,37
Moratalaz	WS (m/s)	14,2	1,7	0,42
Villaverde	WS (m/s)	23,6	2	0,52
China	WS (m/s)	57,2	2,97	0,55
Acustica	WS (m/s)	45,8	2,61	0,41
Hortaleza	WS (m/s)	36,6	2,44	0,55
AVG STATIONS	T (ºC)	1,02	1,37	0,98
Fuencarral	T (ºC)	3,65	1,58	0,98
San Blas	T (ºC)	2,83	1,53	0,98
Villaverde	T (ºC)	1,48	1,43	0,98
China	T (ºC)	-3,29	1,75	0,98
Calidad aire	T (ºC)	4,77	2,24	0,96
Hortaleza	T (ºC)	0,26	1,47	0,98

The results of the comparison between the modelled data and the observed data show that the simulated values are within the ranges of measured data. 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 the wind speed (WS) in some monitoring locations. The statistical evaluation shows significant evidence that high resolution downscaling procedure could achieve reasonably good performance, particularly for BIAS and R2 statistics. In case of the temperature are really good results, the prediction is within 5% error which is one of the most important input values for the energy model with very impacts on the building energy prediction.

IV. Conclusion

The objective of this research was to study the impacts of the global climate change on pedestrian comfort for Madrid, Milan and London using very high spatial resolution (50 meters) meteorological information which has been dynamical downscaled from a global scale to a street level scale where a CFD model has been applied. In this study climate projections were based on two IPCC scenarios: RCP 8.5 and RCP 4.5.

The results of this research show that comfort consequences on humans of climate change should be taking into account. The RCP 8.5 will produce climate conditions that are more stressful to people and affect theirs health and will being. In addition, the changed comfort conditions will lead to higher energy consumption as a result of the increased need for cooling or for heating depending of the climate scenario. RCP 8.5 is characterized by temperature increments. The results from this study could be usable by local authorities and stakeholders for assisting in developing better polices on urban planning to mitigate the effects of the climate change on the pedestrian comfort. This study may enhance current understanding of environment problems related to comfort in the cities.

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