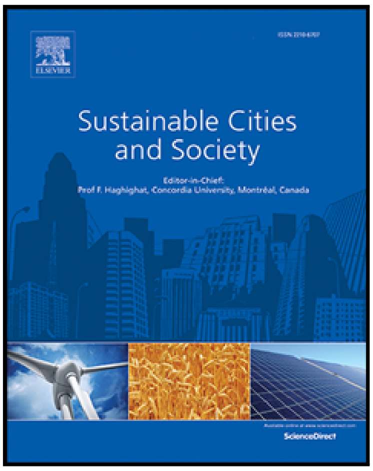

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Evolution of climate zones for building in Spain in the face of climate change

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Abstract

It is essential to design buildings that take on the dynamics of the climate throughout their entire life cycle, guaranteeing the development of a building stock that is certainly sustainable and resilient. This study's main objective is to demonstrate that the official Spanish climate zones for building do not represent the current climatic conditions and to show how these climate zones will evolve due to the impact of climate change. Given the significant impact that climate change will have on this country, as well as its climatic variety, the proposed methodology can be used as a reference in other regions. Updating of the climate zones of peninsular Spain for 49 cities has been carried out, through the adaptation of these zones to the RCP 4.5 and

RCP 8.5 scenarios. The results show that two-thirds of these cities are currently designing and constructing buildings with obsolescent climate data that do not take into account the current or future climate reality, which is significantly affecting previous calculations on the thermal performance of buildings. This work represents a significant scientific contribution in terms of reflecting on the current capacities and the possibilities of improving the building stock.

Keywords

building climate zone; climate change; building adapted to climate change; RCP 4.5; RCP 8.5

Highlights

- The climate zones of 49 cities in peninsular Spain have been updated.
- The climate zones were definition for RCP 4.5 and RCP 8.5 scenarios.
- The dynamics of changes under the RCP 4.5 and RCP 8.5 scenarios reflect variations in over 90% climate zones.

1. Introduction

The construction industry is currently considered one of the main sectors triggering the acceleration of climate change and the depletion of natural resources (Belussi et al., 2019; Cabeza & Chàfer, 2020; Díaz López et al., 2019; Ürge-Vorsatz et al., 2015). These changing environmental effects can have a substantial impact on the behaviour and performance of a building throughout its life cycle if they are not taken into account at the design stage (de Wilde & Coley, 2012). In this sense, if buildings are designed without considering climatic dynamics, within a short period, they will be unable to provide the adequate thermal comfort for which they have been designed, incurring an extra cost in terms of energy consumptionEC, and may cause the deterioration of building frames and structural components (Brown et al., 2016; Grøntoft, 2011; Nik et al., 2015; Troup et al., 2019).

In order to mitigate the impacts of climate change and considering the great potential for energy savings in the building sector, many countries are developing and constantly updating their standards and policies to include climate zones, a handy method for designing buildings with lower energy consumption, as well as high thermal comfort (Rakoto-Joseph et al., 2009). A climate zone is defined as an area for which common external conditions are characterised that allow the calculation of energy demand using different parameters. These classifications are based on the analysis of large amounts of meteorological, environmental and social data to contribute to the search for climate models that embrace all of the above (Walsh et al., 2017).

The number of climate zones depends on each country, the thresholds set, and the methodology used. For example, India uses a degree-day methodology using three different methods (ASHRAE equations; UKMO equations; and Schoenau–Kehrig-based method for different temperatures) (Borah et al., 2015); China uses an hourly weather database (Lam et al., 2005), while Portugal and Spain use climate severity indices

(Carpio, Jódar, Rodríguez, & Zamorano, 2015). In each of these cases, the classifications are based on the climatic series that existed at the time of their formulation. They therefore provide for the design of building stock capable of mitigating the climatic impacts arising from the conditions that existed when they were formulated (Carpio, Jódar, Rodríguez, & Zamorano, 2015), which are neither current not forward-looking. In this respect, numerous studies analysing changes in the heating and cooling energy consumptionEC of the residential buildings conclude that, in the future, the heating energy consumptionEC of buildings will decrease and the cooling energy consumptionEC will increase in conjunction with an increase in the number of days of indoor thermal discomfort (Amato et al., 2005; Asimakopoulos et al., 2012; Belzer et al., 1996; Berardi & Jafarpur, 2020; Guarda et al., 2020; Hekkenberg et al., 2009; Olonscheck et al., 2011; Seljom et al., 2011; Xu et al., 2012).

The literature review yields numerous studies that place particular emphasis on climate dynamism in the building design phase, without which the estimated energy demand could triple (Brown et al., 2016; Grøntoft, 2011; Nik et al., 2015; Troup et al., 2019). In this way, to assess changes in the heating and cooling energy consumptionEC of residential buildings, different techniques have been used to approximate future climatic conditions. Thus, in the work of Gaterell and McEvoy (Gaterell & McEvoy, 2005) it is assumed that the Milan weather file can be used to represent the UK climate in 2050 under a low emissions climate scenario and that of Rome for the UK climate by 2050 under a high emissions climate scenario.

Christenson et al. (Christenson et al., 2006) analysed how the impact of global warming increases the cooling energy demand of buildings. In the study by de Rosa et al. (de Rosa et al., 2014), a simplified building dynamic model, based on the electrical analogy, has been developed and implemented in the MATLAB/Simulink environment, in order to perform several analyses on the heating and cooling energy demand in a wide range of climatic conditions. Verichev et al. (Verichev et al., 2020) analyse the effects of climate change on variations in climatic zones and the heating energy consumption of residential buildings in southern Chile.

Studies have been conducted in which the effects of climate change on the heating/cooling energy consumptionEC have been analysed (Kendrick et al., 2012) on the basis of indoor temperature and thermal comfort (Barclay et al., 2012) and building adaptation methods in climate change conditions (Gupta & Gregg, 2012), based on scenarios developed by local meteorological institutes such as the United Kingdom Climate Impacts Program (UKCIP), the Royal Netherlands Meteorological Institute in the Netherlands (Hamdy et al., 2017), the Environment Agency of Abu Dhabi and the Ministry of Energy in the United Arab Emirates (Radhi, 2009), and the National Institute for Environmental Studies and Agency for Marine-Earth Science and Technology of Japan (Arima et al., 2016).

Besides, as can be seen, a large amount of research is focused on analysing the future effects of changes in the energy consumption of buildings. To a lesser extent, studies on the analysis of changes in climate zones for buildings are presented. For example, the future change of ASHRAE climate zones in some US cities (Z. J. Zhai & Helman, 2019) and China (Shi & Wang, 2020) has been considered. Moreover, it also analysed the future change in building climate zones in the southern part of Chile (Verichev, Zamorano, & Carpio, 2020) (Verichev et al., 2020)

For all the above reasons, it is essential to design and construct buildings today that can take on the dynamics of the climate throughout their entire life cycle; this will guarantee the development of a building stock that is certainly sustainable and resilient. Therefore, this study's main objective is to demonstrate that the current Spanish climate zones for building do not represent the current climatic reality and to show how these climate zones will change due to the impact of climate change. To this end, the following secondary objectives have been set: (i) updating of climate zones; (ii) analysis of the dynamics of changes in climate severity and climate zones for RCP 4.5 and RCP 8.5 scenarios. Spain has been selected as the study area due to its climatic variety, which will allow the applied methodology, results, and conclusions obtained to be used as a reference in other regions

2. Materials and methods

An update of the climatic zones of the CTE of Spain has been carried out in 49 cities in peninsular Spain in order to achieve the objectives of this study, as well as the definition of these climate zones to the RCP 4.5 and RCP 8.5 climate change scenarios in the future. The study area and the applied methodology are described below.

This paper studies the area of peninsular Spain, which includes a wide variety of climates. The temperature distribution is very irregular and is linked to the latitude in which it is situated, from the northern end at 43° 47' 38'' N to the southern end at 36° 00' 08'' N, and with a surface area of 494011 km^2. So, this implies critical thermal amplitudes in the interior of the peninsula and milder climates on the coast with less thermal amplitude, due to the effect of the thermal inertia of the seas and ocean. Furthermore, in this country, there is low investment in sustainable building, with the construction sector being one of its primary energy consumers, which translates into one of the highest consumption rates per Gross Domestic Product (GDP) in the European Union highlighting the urgent need to take measures to solve this problem.

2.1. Basis for the definition of CTE climate zones

In response to the need to adapt the technical requirements to this wide range of climatic conditions, the Technical Building Code came into force in 2006 through Royal Decree 314/2006 of March 17 (Ministry of Housing, 2006) and has been significantly modified under successive EU directives. The CTE is the regulatory framework that establishes the requirements that buildings must comply with concerning basic safety and habitability.

Within the CTE, the DB-HE (Basic Document on Energy Saving in the Technical Building Code) (Ministry of Housing, 2006) establishes a methodology for defining climate zones for buildings. Based on this methodology, the summer (SCS) and winter (WCS) climate severity indices are calculated. The climate severity index (CSI) is a unique number on a dimensionless scale that is specific to each location (Salmerón et al., 2013). The CSI is assessed as the ratio between the heating or cooling needs of a particular building, and that which the same building has in a reference location (Salmerón et al., 2013) and used in a methodology for defining climate zones for buildings in Spain.

Within the Basic Document on Energy Saving of the Spanish Building Code (CTE-DB-HE), the SCS is obtained through Eq. (1) (Ministry of Housing, 2006), where $CDD20_{jun\text{-}sep}$ is the sum of the cooling degree-days based on 20°C for the months from June to September, calculated through the hourly method, and aa=2.990E-03, bb=-1.1597E-

07, cc=-1.713E-01 are the regression coefficients. In the case of the WCS, Eq. (2) was applied, in which $\mathrm{HDD20}_{\mathrm{oct-may}}$ is the sum of the heating degree-days based on 20°C from October to May, calculated through the hourly method, and aa=3.546E-04, bb=-4.043E-01, cc=8.394E-08, dd=-7.325E-02, ee=-1.137E-01 are the regression coefficients, nn – sum of hours of sunshine duration in the period from October to May, NN – sum of maximum hours of sunshine duration possible for the months from October to May.

$$SCS = a \cdot CDD20_{jun-sep} + b \cdot {CDD20_{jun-sep}}^{2} + c \tag{1}$$

$$WCS = a \cdot HDD20_{oct-may} + b \cdot \frac{n}{N} + c \cdot {HDD20_{oct-may}}^{2} + d \cdot \left(\frac{n}{N}\right)^{2} + e \tag{2}$$

The summer climate zone is determined according to the SCS, with each DB-HE summer climate zone (1, 2, 3, 4) corresponding to the interval indicated in Table 1, where 4 is the climate zone with the hottest summer. Each winter climate zone of the DB-HE (α, A, B, C, D and E) corresponds to the WCS interval indicated in Table 1, where α is the climate zone with the warmest winter.

Finally, with the combination of a letter and a number (Table 1), the building climate zone code is obtained for any city or geographical location. According to the provisions of the CTE document DB-HE for the study area, 12 climate zones are presented (A3, A4, B3, B4, C1, C2, C3, C4, D1, D2, D3 and E1), based on five zones for winter (A, B, C, D and E) and four for summer (1, 2, 3 and 4).

It should be noted that the CTE, through the climatic zones, sets the maximums in terms of energy demand, the thermal transmittance permitted in interior enclosures and partitions, and the choice of the type of material to be used in carpentry, among others. Therefore, the correct assignment of the climatic zone influences the achievement of a sustainable building.

2.2. Methodology

The methodology used consists of the following phases (Fig. 1): (i) updating of climate zones; and (ii) analysis of the dynamics of changes in climate severity indices and climate zones for the RCP 4.5 and RCP 8.5 scenarios. Each of these is described below.

2.2.1. Updating of climate zones

In order to achieve the objectives of this work, the calculation methodology used by the CTE, and described in the previous section, has been used; besides, 77 meteorological stations of the Spanish State Meteorological Agency (AEMET) (State Meteorological Agency - AEMET - Spanish Government, 2020) with hourly temperature measurements have been identified (Table 2); and 65 of these 77 stations have sunshine hour measurements that meet the following selection criterion of a minimum 2-year measurement period between 2015 and 2018.

It should also be noted that this study aims to analyse building climate zones, so it was decided to use data from *in-situ* meteorological measurements, rather than, for example, metrological data from a typical meteorological year (TMY), which would be more suitable for studies related to the analysis of building energy consumption (Zhai & Helman, 2019). Furthermore, the TMY files do not contain data on hours of sunshine, which are necessary for the present study.

The 5th Assessment Report (AR5) of the IPCC (IPCC, 2013) notes that: *"Each of the last three decades has been successively warmer at the Earth's surface than any preceding* *decade since 1850".* According to AEMET (AEMET, 2020), in peninsular Spain, the average annual temperature for the period 1981-2010 is 13.7°C and average annual precipitation of 620 mm. The last decade of 2011-2020 was characterized by an average annual temperature of 14.26°C and average annual precipitation of 624 mm. Clearly, in the last decade, there has been a tendency to increase the average annual temperature in the territory of peninsular Spain. In the context of the observed intensification of global warming, it would be logical to use the data for the last decade to analyze the current state of climatic zones. The World Meteorological Organization (WMO), in the Guidelines on the Calculation of Climate Normals of the WMO (WMO, 2017), allow the use of reduced periods for climatic research. In the present study, since AEMET's hourly meteorological information is not publicly available, it was necessary to limit this study to 2015-2018. At the same time, the Guidelines on the Calculation of Climate Normals of the WMO (WMO, 2017) notes that: "*while such short periods cannot be considered to be climatological standard normals or reference normals, they are still useful to many users…*".

Spain's climate is highly varied due to its complex topography and geographical location. Interannual climate variability in Spain is high and is mostly conditioned by atmospheric circulation patterns in the northern hemisphere, particularly by the North Atlantic Oscillation (NAO) (Ministry of the Environment of Spain, 2005). The NAO index is used to quantify this oscillation (NOAA, 2021). At the same time, periods with predominantly positive or negative NAO index values are characterised by the predominance of different synoptic processes (Muñoz-Díaz & Rodrigo, 2004). In 2015, the NAO index's average annual value was 0.43, in 2016 -0.04, in 2017 0.22 and 2018 1.08 (NOAA, 2021).

The last decade is characterized by an average annual value of the NAO index of 0.19 (NOAA, 2021). Simultaneously, as well as the last decade, the period 2015-2018 is characterized by neutral-positive values of the NAO index. At the same time, with positive values of the NAO index, an increase in precipitation is observed in the central, western and southwestern parts of Spain (Castro et al., 2011), as well as observed a cooler climatic conditions in the Mediterranean region (Rousi et al., 2020).

According to the monthly meteorological bulletins presented on the official website of the AEMET (AEMET, 2020), a graph of average monthly temperatures in Spain for the periods 2011-2020 and 2015-2018 was presented (Fig. 2).

From this graph, it is noticeable that, on average, there are no differences between the monthly mean temperatures from October to May for the period 2015-2018 compared to 2011-2020. On the other hand, on average, the average monthly temperatures from June to September are slightly higher by 0.3°C in 2015-2018 compared to the period 2011-2020. At the same time, the average annual precipitation for the period 2015-2018 was 619 mm, which is not much different from the period 2011-2020 (AEMET, 2020). Based on all this and considering the general trends of global warming (IPCC, 2013), it can be concluded that this period may well be used to represent the last decade. In any case, the definition of climatic zones based on actual metrological data will be significantly useful for the specialists. Since the official document CTE (Spanish Ministry of Development. Descriptibe Document on Reference Climates (Documento Descriptivo Climas de Referencia)., 2017), it does not provide any information about the data, based on which the building climatic zones of Spain were determined.

For each weather station with temperature measurements, the SCS (Eq. 1) and WCS (Eq. 2) indices have been calculated. In the case of the WCS indexes, for stations without sunshine hours measurements, the data of the geographically closest stations are used; likewise, the values of the N parameter (Eq. 2) for each geographical station location was calculated with the “NOAA solar calculations year” program (NOAA ESRL GMD, 2019) by the NOAA Earth System Research Laboratory (ESRL) Global Monitoring Division.

That is, for each year in the period 2015-2018 and for each meteorological station, the values of both WCS and SCS indices were obtained. Then, for each station, the average values of both WCS and SCS indices were calculated for 2015-2018, based on the annual values of these indices.

For cities with one meteorological station (Table 2), both average WCS and SCS indices for 2015-2018 at this meteorological station were used to determine the climatic zones in these cities according to Table 1. For cities with two or three meteorological stations (Table 2), each indexes average values were calculated based on the average indexes for the period 2015-2018 at these meteorological stations. The resulting average values of the indices for cities were used to determine the climatic zones according to Table 1.

2.2.2. Analysis of the dynamics of changes in climate severity and climate zones for RCP 4.5 and RCP 8.5 scenarios.

In the AR5 of the IPCC, the primary quantitative parameter describing climate change is the total radiative forcing (RF) of the climate system. RF shows a change in the climate system's energy balance due to anthropogenic activity since 1750 and GHG emissions. In 2011, the RF value was 2.29 W/m^2. This report also presents a set of four possible scenarios of climate change, called Representative Concentration Pathways

(RCPs) (IPCC, 2013). These scenarios are characterised by the approximate calculation that gives the RF in the year 2100, with respect to the year 1750 taking into consideration different trajectories for emissions of long-lived greenhouse gases (LLGHGs) and short-lived air pollutants, the corresponding concentration levels and land use (Chuwah et al., 2013). In the following, a description is given of the two scenarios within which the present study is realised. These scenarios were selected due to their wide application in other studies related to climate change, building EC and climate zones for buildings (Verichev et al., 2020).

RCP 4.5. An intermediate stabilisation pathway in which RF is stabilised at approximately 4.5 W/m^2 after 2100. It will be necessary to limit emissions through increased use of electricity, lower-emission energies, CO_2 capture technologies and geological storage. The area of forests is also expected to increase for this scenario, compared to the current state. Furthermore, CO_2 emissions from energy and industrial sources are expected to increase until 2040 and then decrease to the prescribed atmospheric CO_2 concentration of 538 ppm in 2100. At the same time, by 2081–2100, the global mean surface temperature will increase by 1.8°C (likely range 1.1°C to 2.6°C) compared to the 1986–2005 climate period (IPCC, 2013).

RCP 8.5. During the 21st century, RF will grow steadily and reach 8.5 W/m^2 in 2100. Very high GHG emissions characterise the scenario. RCP 8.5 combines the assumptions of a steady increase in the global population, a moderate rate of technological change, and energy intensity improvements. In the long term, this leads to high energy demand and GHG emissions in the absence of a climate change policy. The prescribed CO_2 concentration is 936 ppm in 2100. At the same time, by 2081–2100, the global mean surface temperature will increase by 3.7°C (likely range 2.6°C to 4.8°C) compared to 1986–2005 (IPCC, 2013).

For peninsular Spain, the annual mean minimum temperature is expected to increase by 1.71°C (st.dev.=0.55°C) and by 3.54°C (0.76°C) for the RCP 4.5 and RCP 8.5 scenarios by the year 2085, respectively, compared to the climate period of 1971–2000. At the same time, the expected increase in the annual average maximum temperature will be 2.28°C (0.59°C) and 4.39°C (1.17°C), respectively, for RCP 4.5 and RCP 8.5 (National Platform for Adaptation to Climate Change, 2020).

Due to these expected changes, it was decided to analyse SCS and WCS indices and climate zones for building in the future (2055 and 2085). For this purpose, the following steps were carried out:

(i) First, for each weather station (Table 2), daily minimum and maximum temperature data were downloaded for the years 2055 and 2085 and for the RCP 4.5 and RCP 8.5 scenarios by the Platform on Adaptation to Climate Change (AdapteCCa) (National Platform for Adaptation to Climate Change, 2020). These temperature data are averages of 16 climatic models (Table 3). They are regional climate models added to different global climate models of the Coupled Model Intercomparison Project ver. 5 (CMIP5). Regional projections available from dynamical EURO-CORDEX (Coordinated Regional Climate Downscaling Experiment) downscaling methods (Jacob et al., 2020) and provide data with a spatial resolution of 0.11°. In addition, the data from these models are validated and adjusted with the real observations in a historical period (Casanueva et al., 2020; Gutiérrez et al., 2019).

(ii) Secondly, based on daily minimum and maximum temperatures, monthly average temperatures were calculated for the two future periods and the two climate change scenarios.

(iii) Thirdly, the difference values (or deltas) of the average monthly temperature between the baseline climate period (2018) and the two future periods (2055 and 2085) were calculated for RCP 4.5 and RCP 8.5.

(iv) Fourthly, the hourly data from the AEMET stations were modified, based on the monthly temperature deltas obtained. The modification of hourly temperature data was done according to methodologies already presented in other scientific works (Belcher et al., 2005; Chan, 2011; Jiang et al., 2018), based on which it is possible to apply a "shift" algorithm to modify baseline climate data, in order to modify hourly baseline climate temperature values by adding the projected monthly average difference for future years. For this purpose, Eqs. (3) and (4) (Ministry of Housing, 2006) were used to calculate CDD and HDD, respectively, where $\mathrm{CDD_{d,Y}}$ and $\mathrm{HDD_{d,Y}}$ are the daily values of CDD and HDD in the future; $\mathrm{T_{i,2018}}$ - the temperature of measurements in i-hour of the day in 2018 – a delta of monthly temperatures in j-month between years in the future (Y = 2055 and 2085) and the baseline climate.

$$\mathrm{CDD_{d,Y}} = \left[\sum_{i=1}^{24}\left(\left(\mathrm{T_{i,2018}} + \Delta\mathrm{T^{j}_{Y-2018}}\right) - \mathrm{T_b} +\right)^{+}\right]\frac{1}{24} \tag{3}$$

$$\mathrm{HDD_{d,Y}} = \left[\sum_{i=1}^{24}\left(\mathrm{T_b} - (\mathrm{T_{i,2018}} + \Delta\mathrm{T^{j}_{Y-2018}}\right)^{+}\right]\frac{1}{24} \tag{4}$$

Subsequently, the daily values of CDD and HDD are used to calculate monthly values. It should be noted that the modified data for future periods will repeat intraday fluctuations in accordance with the used baseline climate period, but the monthly parameters will be close in value to the monthly average parameters according to the data of climate models for future periods. In the context of the present study, the use of a different baseline period for data modification will have an insignificant effect on the variations of the values of CDD and HDD in future periods. The minor variations in the monthly values of CDD and HDD in the future, depending on the choice of the baseline climate period, will insignificantly affect the results of calculating indices SCS and WCS for future periods.

(v) Fifthly, based on the results of the CDD and HDD recalculation for future, the values of SCS (Eq. 1) and WCS (Eq. 2) were calculated for 2055 and 2085 for each meteorological station, taking into account only temperature changes, without estimating changes in the sunshine hours for the WCS index. This simplification was possible because the temperature in the climate models for the future already considers the changes in the radiative conditions of the atmosphere.

(vi) Finally, the WCS and SCS were calculated for cities, and the dynamics of the changes in climate zones were obtained; for this purpose, the procedure followed was the same as for the calculation of the climate zone definition in the previous section.

2.3. Data processing

The PI platform from OSIsoft (“OSIsoft | The PI System,” 2020) was used for the development of the work. It is used for persistent data storage and processing because it facilitates the management of vast amounts of data and events in real time. In order to audit the calculations performed in this research, according to the proposed hypothesis, a reliable and adaptable database was designed and built based on the meteorological data provided by AEMET. For the creation of this database, raw data points of two or three years of measurement were organised on the basis of the meteorological stations using parent–child relationships according to their location and the city where they are located. The database design was developed in three stages: (i) definition of a database schema in PI (definition of assets and attributes), (ii) design of the data import process, and, finally, (iii) definition of the analysis and data export procedure. In the last stage, the calculations explained later were carried out, as well as the analysis obtained with respect to the various scenarios proposed.

3. Results and discussion

3.1. Updating of climate zones by 2015–2018

Tables 4 and 5 and Fig. 3 show the updating of climate zones for the period 2015–2018 in 49 peninsular cities in Spain, which is analysed below.

3.1.1 Winter and summer climate severity indices by the period 2015–2018

This section analyses the results of the calculation of the WCS and SCS indices of the 77 weather stations (Table 4). As can be seen, the interval of the WCS index ranges from -0.06 (st.dev.=0.09) to 1.87 (0.06), with the maximum value in the city of Soria (station #65) located 1260 metres above sea level; and the minimum value was in the south of the peninsula, in Malaga. The negative values, close to 0, correspond to climatic areas dominated by warm winters in the winter climatic severity classification. ~~In these~~

~~areas, the requirements for achieving thermal comfort can be achieved without the need to implement heating systems, thanks to external gains, internal gains produced by equipment, personal activity, or the clothing factor. Such is the case of the Spanish island city of Santa Cruz de Tenerife, with a winter climate zone α.~~

In the case of the SCS, the resulting values range from 0.04 (0.02) at station #32 (La Coruña), located in the extreme northwest of the country and affected by the cold currents of the Atlantic Ocean, to a maximum of 2.52 (0.22) at station #20 in Córdoba. SCS values close to 0, corresponding to climate zone 1. In the case of La Coruña, the thermal comfort inside the homes in summer can be achieved without implementing cooling systems, due to the cool summer temperatures. Therefore, thermal comfort could be achieved with correct design of the building envelopes.

Finally, the comparison of the values of the climatic severities of the different stations of a city shows the effect of urban heat islands; this is the case of cities such as Barcelona, Valladolid, Soria, Valencia, and Tarragona, among others. In Barcelona (Table 4), the differences between the hottest conditions of station #11, in the city centre and near the sea coast (with WCS=0.23 (0.06) and SCS=1.48 (0.04)), and station #10 located outside the city centre in a forest area (with WCS=0.61 (0.07) and SCS=0.92 (0.06)) show the urban heat island effect. For this reason, it was decided to use the value of the average indices between stations in the same city to define the climate zones.

3.1.2. Evolution of climate zones in 2015–2018 concerning the CTE

The value of the average indices between the nearest stations of the same city was used to define the climate zones. Tables 5, 6 and 7 and Fig. 3 (d-f) present the average values of the WCS and SCS indices for all the capital cities of provinces in peninsular Spain, the climate zones identified for the period 2015–2018, as well as the maps of winter and summer climate zones, and climate zones for buildings in general.

As can be seen in Fig. 3f, Fig. 3c and Table 5, compared to the CTE document, for the period 2015–2018 there are no significant changes in the climate zones of the north (Basque Country and Cantabria), northwest (Galicia), southwest (Huelva) and eastern part of Andalusia. This is because these regions did not have such a notable climate change in their areas, compared to the period for which the CTE document was produced.

This is not the case in southern Spain and the Mediterranean coast (Fig. 3 a and d), where more marked changes are observed. For the period 2015–2018, 35% of the cities have changed their winter climate zone to warmer zones compared to the CTE climate zones (Table 6). Table 6 shows that a warmer zone will cover 17 cities compared to the CTE document, 7 of which will move from a D to a C rating. This can lead to inadequate management of resources, even generating pathologies such as humidity due to condensation, which can result in an unhealthy environment that ends up causing lung diseases, fungal growth and even uninhabitable housing.

The effect of global warming has led to the most noticeable changes in the summer period (increased repetition of anticyclones and heatwaves in summer), with a thermal effect on winter weather conditions. Thus, in the case of the summer period, 55% of the cities will change their areas to warmer ones (Table 6), compared to the CTE document zones. 25 cities show warmer climate zones in comparison with the CTE document; specifically, cities such as Girona and Ávila will change from zone 2 to zone

4 and from zone 1 to 3, respectively. Climate zone 4 is the most predominant, covering 45% of the cities, and the regions that have suffered the most significant variation are those located on the Mediterranean coast (Fig. 3 m,e and Fig. 4 b), due to the intense summer warming that the inland waters of the Mediterranean have experienced in recent years (Adloff et al., 2015).

Finally, when comparing the allocation of complete climate zones (winter and summer) of the CTE (Table 6) with the update for 2015–2018, 71% of the cities have changed their complete climate zone code. On the other hand, for the period 2015–2018, there is now a total of 14 climate zones for Spanish cities due to the appearance of three new zones which were previously only located in insular Spain: D4, E1 and α3. The appearance of the latter shows the climatic trend in the south of the peninsula towards climates that are more characteristic of subtropical areas.

The results analysed show that the allocation of climate zones given by the official document is not suitable for the current climate conditions, which puts at risk the achievement of truly sustainable buildings, for which precision in the allocation of a climate zone is fundamental when correctly sizing the sanitary hot water, heating and cooling systems, as well as the specific selection of the construction materials used.

3.2. Analysis of the dynamics of changes in climate severity and climate zones by the RCP 4.5 and RCP 8.5 scenarios

Once the climate zones had been updated for the years 2015–2018, these zones were defined for the years 2055 and 2085 according to the RCP 4.5 and RCP 8.5 scenarios of climate change. The results obtained are shown in Fig. 4 and Tables 6 and 7.

3.2.1. Dynamics of changes in 2055 and 2085 under the RCP 4.5 scenario

Fig. 4 (a,b) presents the results of the evolution of the WCS and SCS indices for the 49 cities under the RCP 4.5 scenario of climate change. It can be seen that by 2055 and 2085 the WCS index is almost halved, from an average value of 0.80 in 2015–2018 to 0.38 and 0.41 for 2055 and 2085, respectively. In the case of the SCS index, the projected average value is generally slightly higher than the average value for 2015–2018; this increase ranges from 1.35 for the period 2015–2018 to 1.76 and 1.68 for the periods 2055 and 2085, respectively.

It should be noted, in the case of the RCP 4.5 projection, that the period 2055 will be slightly warmer than the period 2085, due to the specifications of this projection. This is because GHG emissions in RCP 4.5 will peak around 2040, and then decrease. This shows that the results obtained for the WCS and SCS indices are consistent with the characteristics of this climate change scenario.

In the case of the dynamics of change for winter climate zones, as shown in Table 6, for the periods 2055 and 2085, 92% of the cities will change their climate zones for warmer ones in comparison with the CTE document. Specifically, for the period 2055, 24 cities will change their classification to a warmer one and 21 cities will be two zones warmer (for example, Barcelona will change from zone C to zone A). Similarly, by 2085, 28 cities will have changed their zone to a warmer one, and 17 cities will be two zones warmer. This is because under the RCP 4.5 scenario, the period 2055 is slightly warmer than the period 2085, so only 8% of cities will observe zone changes between these two periods (Table 6). Thus, in 2085 in cities such as Merida, Oviedo, Pontevedra, Santiago de Compostela, Zamora, and Zaragoza, there will be colder winter climate zones compared to 2055. Fig. 3 (j,g) shows how the geographical distribution of the winter climate zones for 2085 is similar to that for 2055. Finally, in Table 7, we see a significant increase in the presence of the qualification B concerning the CTE, present in 37% and 35% of the cities for 2055 and 2085, respectively; likewise, the qualification E disappears in both future periods.

In the case of dynamics of change for summer climate zones, for the periods 2055 and 2085, 73% of the cities will change their climate zones for warmer ones compared to the CTE document (Table 6). Of these, 10 and 11 cities changed to two zones warmer, in 2055 and 2085, respectively. As with the winter season, the differences between 2055 and 2085 are not significant, and only Bilbao will have a colder summer climate zone, and León a warmer one, for 2085 compared to 2055 (Fig. 3 h,k). Furthermore, by 2055 and 2085, 59% of the cities will be located in climate zone 4, while for CTE and 2015–2018 only 20% and 37% of the cities are considered to be in the warmest zone of the classification respectively (Table 7). This is due to the increase in the average value of the SCS index=2.12 (st.dev.=0.37) for the hottest summer zone 4 in the year 2085, compared to SCS=1.87 (st.dev.=0.32) in the period 2015–2018. This shows the need for the development of new summer zones within rating 4, with the consequent improvement in terms of building recommendations.

If the results are analysed from the point of view of the complete climate qualification, both for 2055 and 2085, 96% of the cities will see their climate zone changed (winter + summer) concerning the CTE document (Table 6). This is due to the drastic changes in the WCS and SCS indices, compared to the period 2015–2018. Only two cities (Cordoba and Huelva) will maintain the same climate zones as the CTE document. Moreover, in

Fig. 3 (i, l) it is observed how the geographical distribution of the climate zones for 2085 is similar to that for 2055; in fact, only 8 of the 49 cities in 2085 will have climate zones that differ with respect to 2055. The average of the WCS index between these two periods will not change more than 8%, and in the case of SCS only 0.4% (Fig. 4).

Consequently, the change in climate zones is related to the proximity of the absolute values of WCS and SCS to the limit value of the climate zones (Table 1). Therefore, a small change in the index can cause a change in the climate zone for a city. This can be a limiting factor for the zoning of the existing CTE, highlighting the need for a significant improvement in the development and methodology of the current regulations in force.

It should be noted that, when comparing both periods 2055 and 2085 with the update of areas for 2015–2018, the percentages decrease concerning the CTE document, 84% and 82% respectively. This once again demonstrates the need to update the CTE's climatic zones, which will contribute to reducing errors in sustainable building design, facilitating the adaptation of buildings to climate change through a reliable approach to the dynamic climate context.

As shown in Fig. 3 (i, l), by 2055 and 2085 half of the cities on the Mediterranean coast will come under the climate zone α4, a new letter–number combination does not present in the CTE, for regions with the hottest summers and the hottest winters. In the case of the cities on the northern coast, there will be a greater variety of climate zones, with the high summer temperatures softening and the winters becoming colder than on the Mediterranean coast. The same is true in the interior of the peninsula, where there is a heterogeneous distribution due to the complexity of the relief and the diversity of microclimate areas. Thus, by 2085, 22% of the cities will have a climate classification of B4, while only 2% of the cities will be located in zones B3 and D3 (Table 7).

Again, it is clear that, in a relatively short period, the current CTE building standards will not be adequate under the climate change scenario RCP 4.5. As a consequence, dynamic climate zones are required, which can cope with the climate dynamism that is already taking place and will peak around 2040; in other words, the applied standards for designed buildings will depend not only on the current climate zone but also on the projected future climate zone.

3.2.2. Dynamics of changes in 2055 and 2085 under the RCP 8.5 scenario

Fig. 4 (c,d) presents the results of the evolution of the WCS and SCS indices for the 49 cities under the RCP 8.5 scenario of climate change. In the case, a drastic decrease of the WCS index is observed from the average value of 0.80 in 2015–2018 to 0.41 and 0.26 for 2055 and 2085, respectively. In the case of the SCS index, the projected average value is slightly higher than the average value for 2015–2018. The drastic increase in the average value of the SCS is observed from 1.35 for 2015–2018 to 1.73 and 2.35 for 2055 and 2085, respectively.

It should be noted that the period 2085 will be much warmer than 2055 and 2015–2018, due to the specifics of this scenario, where emissions continue to increase throughout the 21st century. Therefore, the results obtained for the WCS and SCS indices are consistent with the idea of this climate change scenario. This more pessimistic projection of climate change will lead to more notable changes in terms of rising temperatures.

In the case of the dynamics of change for winter climate zones, as shown in Table 6, by 2055 90% of the cities will change; specifically, 27 cities will change their rating to one warmer and 17 to two warmers (for example, Barcelona will change from zone C to zone A). However, between the periods 2055 and 2085, 57% of cities will change their classification, compared to 8% in the RCP 4.5 (Table 6). This is due to the specifications of this scenario mentioned in the previous section.

By the period 2085, all cities will change their winter climate zone to warmer ones concerning the CTE. Specifically, three cities will change their rating to be three levels warmer (from D to A and from C to α), and 32 to two levels warmer. It should be noted that, as in the case of the RCP 4.5 scenario, the E rating will disappear for both future periods and the D rating for 2085 in the RCP 8.5.

In the case of the dynamics of change for summer climate zones, for the periods 2055 and 2085, 69% and 82% of the cities will change their climate zones for warmer ones compared to the CTE (Table 6). Thus, 12 and 17 cities change their zones to be two levels warmer, in 2055 and 2085, respectively. It should be noted that in 2085, 4 cities will change from having a rating of 1 (the coolest for summer) to a rating of 4. As with the winter season, the differences between 2055 and 2085 are significant, with 39% of cities changing their summer rating.

As shown in Table 7, by 2055 and 2085, 63% and 76% of the cities will be in climate zone 4. This is due to the drastic warming effect in Spain.

If the results are analysed from the point of view of the complete climate qualification, by 2055 concerning the CTE, 94% of the cities would have changed their climate zone (winter + summer) concerning the current regulations, and 100% of the cities for the year 2085 (Table 6). Fig. 3 (o, r) shows how the geographical distribution of the climatic zones will suffer a significant dynamism. However, contrary to the RCP 4.5 scenario, between 2055 and 2085 there will be significant changes, where the average of the WCS index between these two periods will change from 0.42 to 0.22, and in the case of SCS from 1.64 to 2.25 (Fig. 4). Consequently, the change in climate zones is related to the proximity of the absolute values of WCS and SCS to the limit value of the climate zones (Table 1).

As can be seen in Fig. 3 (r), by 2085, except for the cities of Gerona and Granada, all the cities on the Mediterranean coast would be included in the climate zone α4, whereas, in the coastal cities of the north of the Iberian Peninsula, as in the RCP 4.5 scenario, there will be a variety of climate zones. The same occurs in the interior of the peninsula. Thus, by the year 2085, 22% of the cities will have a climate classification of B4, while only 2% of the cities will be located in zones B3 and D3 (Table 7).

4. Discussion

The results show that most of the territory of peninsular Spain will be evolving into warmer climatic zones in a short period. In particular, Spain will soon see milder winters and warmer summers. Thus, in the future, Spain will have climates similar to those of the current countries of North Africa such as Morocco, Tunisia or Algeria. Specifically, most regions of Spain will be located in areas with negative WCS indices, which imply a decrease in the demand for heating in homes, but a very significant increase in the demand for cooling. Of course, the results of this study, based on a slightly simplified methodology, can be improved and refined by using hourly temperature data from an ensemble of regional climate models for future periods, as well as data on changes in hours of sunshine duration. It should be noted that the problems in Spain can be extrapolated to most countries in Mediterranean and Subtropical regions, where the current lack of rules or regulations on the adaptation of buildings to climate change results in obsolete building stock, which is unable to cope with the climatic dynamism that is already occurring.

Consequently, it is essential to adopt new climate zones that take climate dynamism into account. Thus, one solution to this problem could be to create new summer climate zones and technical requirements for building. Another solution would be to adopt the climate zones of those countries already experiencing the climate conditions that Spain can expect to have in future.

On the other hand, it should be noted that the literature analysis for this study did not find any examples of the development or implementation of dynamic building standards and requirements that take into account the changing climate zones. However, it should be noted that the key to the successful development of such building standards is a precise and reproducible methodology. For example, in Canada's case (National Energy Code of Canada for Buildings, 2011), a methodology similar to ASHRAE climate zoning is used (ASHRAE, 2013). This methodology makes it possible for the whole country to determine the evolution of climate zones in the future and to adjust building standards and requirements for different geographical locations, because, most likely, the warmer climate zones, which currently only exist in the United States, will in the future move to the territory of Canada. On the other hand, for the United States, the existence of climate zones 0A and 0B in the ASHRAE building code (ASHRAE, 2013) may provide a particular buffer of time for the development of dynamic building standards until these zones appear in the United States and then move northwards.

It is known that most countries will see their climatic conditions change in a short period, so policymakers must address this issue that will affect the building stock of each country. Therefore, building standards and regulations must establish limit values that can cope with climate dynamism in the different variables that affect energy demand—defining a balance between thermal and economic performance at the time of design and throughout the building's life cycle. An example of good practice in this regard could be Level(s). Level(s) is an information framework proposed by the European Union (EU) and developed by the Joint Research Centre (JRC) for sustainable buildings that aim to unite the entire value chain of the sector around a common European language for better building performance. Given that the basis of this framework is the adaptation of the European building stock to climate change, the findings of this research can be a key tool to create a climate database to support Level (s). It does this by examining the entire life cycle of buildings and their adaptation to change (Dodd et al., 2017a, 2017b). This instrument is intended to be key to the policies and standards of all EU countries, laying the foundation for the creation of genuinely resilient building regulations.

This work is an essential scientific contribution. It provides researchers and building professionals with information that will allow them to make predictions about climate change and adapt the basis of building design to future changes, thus mitigating their effects and optimising energy demand. Thus, this study's methodology and conclusions can be adapted and serve as a basis for the future drafting and implementation of regulations, plans, or strategies to improve the quality of building performance.

5. Conclusions

The results of the WCS and SCS indices for the period 2015–2018 have shown very significant changes in the climate zoning of 35 of the 49 cities of Spain compared to the CTE document. These results show that two-thirds of the cities analysed are currently designing and constructing buildings with obsolete climate data that do not take into account the current climate reality. Besides, the analysis of the dynamics of changes foreseen for the years 2055 and 2085, under the RCP 4.5 and RCP 8.5 scenarios, reflects variations of more than 90%.

In the case of the RCP 4.5 scenario, by 2085, only two cities will remain in the same climate zones as specified in the CTE. Cities will experience warmer winters and more suffocating summers, with their summer or winter climate rating varying by up to 3 points. Besides, new areas characteristic of island climates are emerging, as is the case with α4, as well as the disappearance of others such as E1. The significant increase in zone 4 is also evident. This shows the need to develop new zones for summer within rating 4, with the consequent improvement in terms of building recommendations. On the other hand, in the year 2085, and under the RCP 8.5 scenario, all cities will find themselves in warmer climatic zones. This intensifies the need to develop new summer climate zones and building recommendations that will help to preserve the correct thermal conditions in future periods.

For all these reasons and given that the use of an inadequate climate zone affects previous calculations of the thermal performance of a building, resulting in erroneous estimates of its energy demands, architectural and construction standards must be adapted to the real conditions of the urban environment, consider the main scenarios for the 2100 horizon and the urban heat island effect, to lead to building design that not only mitigates the effects of climate change but also adapts to them.

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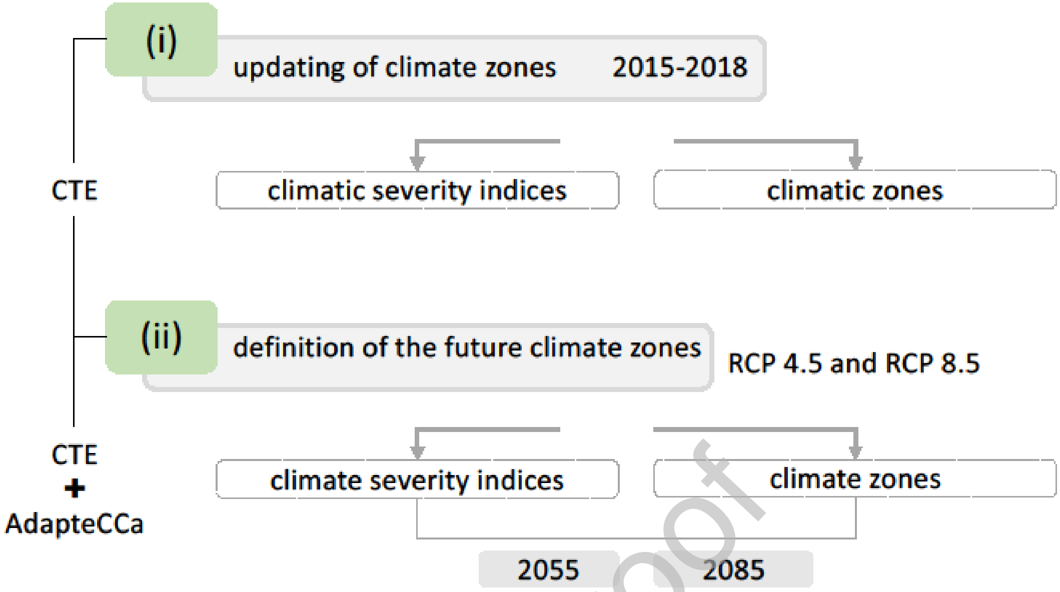

Fig. 1. Methodology

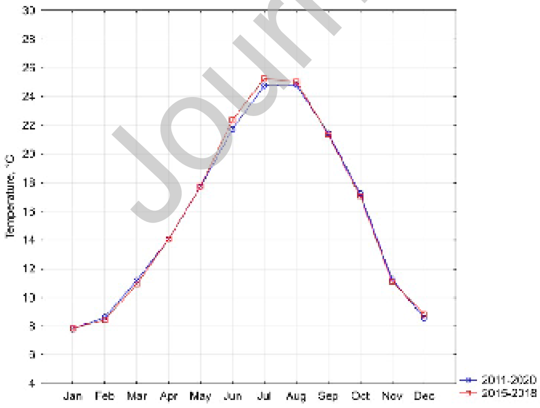

Fig. 2. Average monthly temperatures in Spain during the periods 2011-2020 and 2015-2018.”

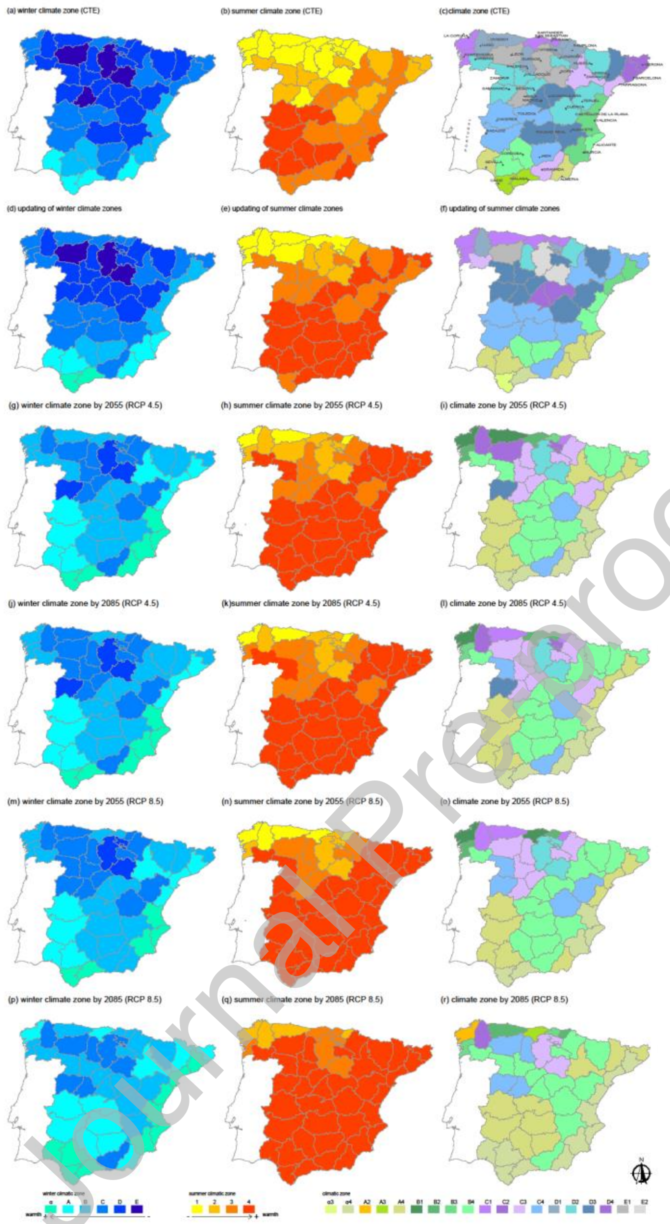

Fig. 3. Maps of winter (left column), summer (central column) and general climate zones (right column) according to CTE document (a-c), for period 2015-2018 (d-f), for future periods under RCP4.5 scenario (g-l) and under RCP8.5 scenario (m-r).

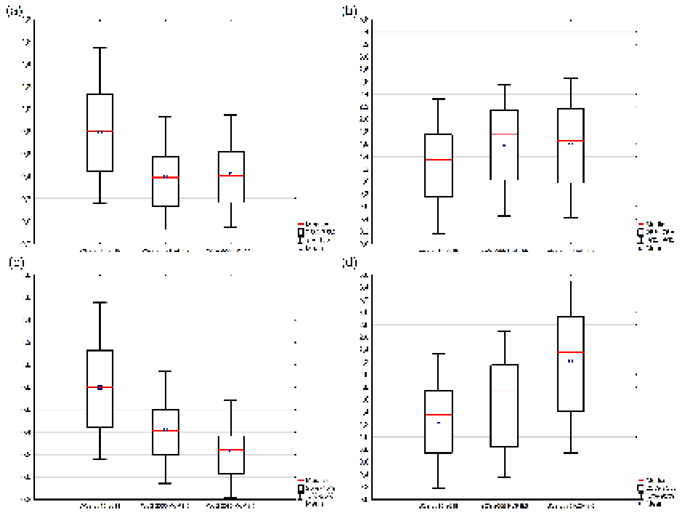

Fig. 4. Box-plots of values of the WCS (a,c) and SCS (b,d) indexes in 49 cities in mainland Spain for the period 2015-2018 and future periods.

Table 1. Intervals for zoning

Intervals for summer zoning					
	1	2	3	4	
	SCS ≤ 0.5	0.5 < SCS ≤ 0.83	0.83 < SCS ≤ 1.38	SCS > 1.38	
Intervals for winter zoning					
α	A	B	C	D	E
WCS ≤ 0	0 < WCS ≤ 0.23	0.23 < WCS ≤ 0.5	0.5 < WCS ≤ 0.93	0.94 < WCS ≤ 1.51	WCS > 1. 51

Table. 2 Weather stations

City	Weatherst	l[illegible]	altitude	City

	ations		(n)	
Albacete	1		676	Madrid
	2		702	
Alicante	3		22	Málaga
	4		43	

		[illegible]		
Alneria	5	[illegible]	21	
Ávila	6	[illegible]	1130	Mérida
	7	[illegible]	920	Murcia
Badaj	8	[illegible]	175	

oz		[illegible]		
	9	[illegible]	185	Ourense
Barcelona	10	[illegible]	408	Oviedo
	11	[illegible]	5	
Bilbao	12	[illegible]	42	Palenci

		[illegible]		a
Burgos	13	[illegible]	891	
Cáceres	14	[illegible]	10	Pamplona
Cádiz	15	[illegible]	2	Pontevedra
	16	[illegible]	28	Salananc

		[illegible]		a
Castellón	17	[illegible]	10	
	18	[illegible]	43	San Sebastian
Ciudad Real	19	[illegible]	628	Santander
Córd	20	[illegible]	90	

oba		[illegible]		
	21	[illegible]	275	Santiago de Compostela
Cuenca	22	[illegible]	948	
Girona	23	[illegible]	76	Segovia
Gr	24	[illegible]	56	Se

anada		[illegible]	7	villa
	25	[illegible]	687	Soria
	26	[illegible]	775	
Guadalajara	27	[illegible]	721	Tarragona
Hu	28	[illegible]	19	

elva		[illegible]		
Huesca	29	[illegible]	463	Teruel
	30	[illegible]	546	Toledo
Jaén	31	[illegible]	580	Valencia
La C	32	[illegible]	58	

oruña				
	33		98	Valladolid
León	34		912	
Lleida	35		185	Vitoria
	36		252	Zanora

Logroño	37		353	Zaragoza
Lugo	38		442	
	39		445	

Table 3. Climate models

Climate models	Institution

CNRM-CERFACS-CNRM-CM5-CLMcom-CCLM4-8-17	Centre National de Recherches Météorologiques, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, France
CNRM-CERFACS-CNRM-CM5-CNRM-ALADIN53	Centre National de Recherches Météorologiques, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, France
CNRM-CERFACS-CNRM-CM5-SMHI-RCA4	Centre National de Recherches Météorologiques, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, France
ICHEC-EC-EARTH-CLMcom-CCLM4-8-17	Irish Centre for High-End Computing
ICHEC-EC-EARTH-SMHI-RCA4	Irish Centre for High-End Computing
ICHEC-EC-EARTH-KNMI-RACMO22E	Irish Centre for High-End Computing
ICHEC-EC-EARTH-DMI-HIRHAM5	Irish Centre for High-End Computing
IPSL-IPSL-CM5A-MR-IPSL-INERIS-WRF331F	Institut Pierre Simon Laplace, France
IPSL-IPSL-CM5A-MR-SMHI-RCA4	Institut Pierre Simon Laplace, France
MOHC-HadGEM2-ES-CLMcom-CCLM4-8-17	Met. Office Hadley Centre, UK
MOHC-HadGEM2-ES-KNMI-RACMO22E	Met. Office Hadley Centre, UK
MOHC-HadGEM2-ES-SMHI-RCA4	Met. Office Hadley Centre, UK
MPI-M-MPI-ESM-LR-CLMcom-CCLM4-8-17	Max Planck Institute for Meteorology, Germany
MPI-M-MPI-ESM-LR-SMHI-RCA4	Max Planck Institute for Meteorology, Germany
MPI-M-MPI-ESM-LR-MPI-CSC-REMO2009	Max Planck Institute for Meteorology, Germany
NCC-NorESM1-M-DMI-HIRHAM5	Norwegian Climate Centre

Table 4. Calculated indices of winter (WCS) and summer (SCS) climate severity for the period 2015-2018.

City	weather station	City	
Albacete	1	Madrid	
	2		
Alicante	3	Málaga	
	4		
Almeri	5		

a		
Ávila	6	Mérida
	7	Murcia
Badajoz	8	
	9	Ourense
Barcelona	10	Oviedo
	11	
Bilbao	12	Palencia
Bur	13	

gos		
Cáceres	14	Pamplona
Cádiz	15	Pontevedra
	16	Salamanca
Castellón	17	
	18	San Sebas

		tian
Ciudad Real	19	Santander
Córdoba	20	
	21	Santiago de Compostela
Cuenca	22	
Giro	23	Seg

na		ovia	
Granada	24	Sevilla	
	25	Soria	
	26		
Guadalajara	27	Tarragona	
Huelva	28		
Huesca	29	Teruel	
	30	To	

		ledo
Jaén	31	Valencia
La Coruña	32	
	33	Valladolid
León	34	
Lleida	35	Vitoria
	36	Zamora
Logroño	37	Zaragoza

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Table 5. Indexes (WCS, SCS) and climate zones (CZ).

							RCP 4.5						RCP 8.5					
		2015-2018					2055			2085			2055			2085		
City	CZ (CTE)	WCS	St. dev.	SCS	St. dev.	CZ	WCS	SCS	CZ	WCS	SCS	CZ	WCS	SCS	CZ	WCS	SCS	CZ
Albacete	D3	0.930	0.08	1.585	0.13	C4	0.443	1.843	B4	0.472	1.837	B4	0.471	2.063	B4	0.234	2.756	B4
Alicante	B4	0.185	0.06	1.780	0.06	A4	-0.082	2.290	α4	-0.064	2.265	α4	-0.062	2.408	α4	-0.182	3.010	α4
Almería	A4	0.201	-	1.750	-	A4	-0.097	2.253	α4	-0.034	2.678	α4	0.302	0.630	A4	-0.035	0.996	α4
Ávila	E1	1.400	0.14	0.960	0.12	D3	0.778	1.222	C3	0.816	1.220	C3	0.833	1.268	C3	0.568	1.912	C4
Badajoz	C4	0.525	0.06	2.080	0.19	C4	0.112	2.354	A4	0.154	2.427	A4	0.122	2.342	A4	0.002	3.187	A4
Barcelona	C2	0.420	0.21	1.200	0.31	B3	0.060	1.748	A4	0.082	1.666	A4	0.089	1.733	A4	-0.031	2.356	α4
Bilbao	C1	0.740	0.10	0.430	0.05	C1	0.410	0.853	B3	0.431	0.793	B2	0.446	0.769	B2	0.254	1.214	B3
Burgos	E1	1.610	0.05	0.570	0.07	E2	1.072	0.757	D2	1.099	0.720	D2	1.121	0.760	D2	0.823	1.141	C3
Cáceres	C4	0.620	0.01	2.040	0.17	C4	0.128	2.361	A4	0.171	2.450	A4	0.148	2.382	A4	0.031	3.253	A4
Cádiz	A3	-	0.	1.	0.	α	-	1.	α	-	1.	α	-	1.	α	-	2.	α

		0.010	06	380	17	3	0.034	537	4	0.054	602	4	0.064	544	4	0.196	149	4
Castellón	B3	0.445	0.25	1.470	0.26	B4	0.091	1.975	A4	0.105	1.953	A4	0.124	1.953	A4	-0.027	2.580	α4
Ciudad Real	D3	0.800	0.08	2.160	0.19	C4	0.328	2.427	B4	0.365	2.436	B4	0.345	2.617	B4	0.145	3.426	A4
Córdoba	B4	0.390	0.12	2.470	0.23	B4	0.356	2.713	B4	0.347	2.776	B4	0.299	2.865	B4	0.099	3.638	A4
Cuenca	D2	1.130	0.10	1.380	0.12	D3	0.580	1.647	C4	0.622	1.622	C4	0.625	1.806	C4	0.363	2.520	B4
Gerona	C2	0.690	0.09	1.450	0.04	C4	0.232	2.031	B4	0.265	1.846	B4	0.268	2.056	B4	0.102	2.748	A4
Granada	C3	0.617	0.17	1.927	0.27	C4	0.560	2.043	C4	0.547	2.102	C4	0.482	2.257	B4	0.353	2.985	B4
Guadalajara	D3	0.950	0.09	1.690	0.12	D4	0.388	2.016	B4	0.420	2.011	B4	0.409	2.135	B4	0.231	2.937	B4
Huelva	A4	0.170	0.15	1.740	0.23	A4	0.135	1.864	A4	0.127	1.994	A4	0.092	1.957	A4	-0.065	2.667	α4
Huesca	D2	1.000	0.08	1.330	0.10	D3	0.408	1.771	B4	0.439	1.685	B4	0.434	1.830	B4	0.237	2.547	B4
Jaén	C4	0.420	0.21	2.330	0.32	B4	0.386	2.462	B4	0.375	2.470	B4	0.334	2.660	B4	0.156	3.417	A4
La Coruña	C1	0.655	0.14	0.080	0.06	C1	0.380	0.301	B1	0.401	0.364	B1	0.410	0.261	B1	0.226	0.554	A2

León	E1	1.550	-	0.330	-	E1	0.811	0.825	C2	0.833	0.845	C3	0.838	0.837	C3	0.587	1.403	C4
Lleida	D3	0.920	0.06	1.510	0.14	C4	0.264	2.038	B4	0.293	1.948	B4	0.293	2.114	B4	0.121	2.854	A4
Logroño	D2	1.010	0.01	0.920	0.04	D3	0.565	1.306	C3	0.591	1.212	C3	0.594	1.253	C3	0.370	1.779	B4
Lugo	D1	1.215	0.10	0.315	0.09	D1	0.698	0.511	C2	0.720	0.521	C2	0.746	0.443	C1	0.515	0.804	C2
Madrid	D3	1.035	0.13	1.475	0.33	D4	0.432	1.839	B4	0.464	1.857	B4	0.450	1.962	B4	0.261	2.765	B4
Málaga	A3	-0.001	0.08	1.777	0.19	α4	-0.022	2.168	α4	-0.035	2.232	α4	-0.036	2.326	α4	-0.165	2.990	α4
Mérida	C4	0.570	0.04	1.980	0.19	C4	0.190	2.249	A4	0.231	2.335	B4	0.199	2.309	A4	0.043	3.141	A4
Murcia	B3	0.190	0.04	2.100	0.10	A4	-0.072	2.611	α4	-0.051	2.633	α4	-0.059	2.833	α4	-0.191	3.505	α4
Ourense	D2	0.840	0.13	1.110	0.08	C3	0.373	1.502	B4	0.405	1.561	B4	0.418	1.427	B4	0.252	2.074	B4
Oviedo	D1	0.880	0.09	0.205	0.10	C1	0.494	0.439	B1	0.516	0.417	C1	0.533	0.360	C1	0.308	0.718	B2
Palencia	D1	1.475	0.11	0.820	0.15	D2	0.774	1.026	C3	0.799	1.015	C3	0.802	1.045	C3	0.557	1.543	C4
Pamplona	D1	1.024		0.750		D2	0.702	1.069	C3	0.679	0.976	C3	0.527	1.340	C3	0.310	1.884	B4

Pontevedra	C1	0.690	0.07	0.430	0.12	C1	0.364	0.794	B2	0.402	0.888	B3	0.403	0.725	B2	0.252	1.239	B3
Salamanca	D2	1.300	0.18	1.060	0.11	D3	0.936	1.347	D3	0.950	1.375	D3	0.916	1.389	C4	0.683	2.049	C4
San Sebastián	D1	0.820	0.17	0.090	0.01	C1	0.558	0.400	C1	0.577	0.269	C1	0.585	0.326	C1	0.341	0.735	B2
Santander	C1	0.610	0.09	0.170	0.16	C1	0.344	0.577	B2	0.366	0.547	B2	0.387	0.485	B1	0.217	0.879	A3
Santiago de Compostela	D1	0.900	0.13	0.345	0.09	C1	0.490	0.626	B2	0.521	0.676	C2	0.528	0.540	C2	0.355	0.938	B3
Segovia	D2	1.280	0.10	1.040	0.10	D3	0.679	1.329	C3	0.714	1.308	C3	0.725	1.347	C3	0.484	2.020	B4
Sevilla	B4	0.160	0.15	2.420	0.29	A4	0.129	2.532	A4	0.118	2.647	A4	0.080	2.658	A4	-0.092	3.386	α4
Soria	E1	1.705	0.22	0.535	0.20	E2	1.085	0.739	D2	1.128	0.699	D2	1.153	0.759	D2	0.810	1.192	C3
Tarragona	C3	0.395	0.08	1.355	0.38	B3	0.042	2.139	A4	0.068	2.097	A4	0.072	2.091	A4	-0.037	2.788	α4
Teruel	D2	1.280	0.09	1.090	0.11	D3	0.677	1.303	C3	0.714	1.249	C3	0.734	1.426	C4	0.451	2.043	B4
Toledo	C4	0.740	0.10	2.200	0.14	C4	0.296	2.557	B4	0.333	2.584	B4	0.315	2.701	B4	0.150	3.551	A4
Valencia	B3	0.280	0.07	1.540	0.17	B4	-0.03	2.133	α4	-0.01	2.164	α4	-0.00	2.149	α4	-0.12	2.802	α4

						8			6			4			8		
Valladolid	D2	1.390	0.16	0.940	0.21	D3	0.660	1.178	C3	0.688	1.181	C3	0.693	1.205	C3	0.463	1.795	B4
Vitoria	D1	1.320	0.12	0.460	0.09	D1	0.899	0.659	C2	0.919	0.585	C2	0.941	0.608	D2	0.665	0.957	C3
Zamora	D2	1.180	0.01	1.260	0.06	D3	0.496	1.598	B4	0.523	1.621	C4	0.517	1.630	C4	0.339	2.327	B4
Zaragoza	C3	0.700	0.03	1.565	0.06	B4	0.198	2.106	A4	0.231	2.020	B4	0.228	2.135	B4	0.055	2.869	A4

Table 6. Dynamics of changes in climate zones according to scenarios

scenario	change of scenario	winter climatic zone			summer climatic zone			winter + summer climatic zone
		change CZ	N. of cities modifying CZ	% of cities that change CZ	change CZ	N. of cities modifying CZ	% of cities that change CZ	% of cities that change CZ (winter + summer)
updating	CTE ⇒ 2015-2018	A ⇒ α	2	35%	1 ⇒ 2	4	55%	71%
		B ⇒ A	3		2 ⇒ 3	10		
		C ⇒ B	4		3 ⇒ 4	11		
		D ⇒ C	7		1 ⇒⇒ 3	1		
		E ⇒ D	1					
RCP 4.5	CTE ⇒ 2055	A ⇒ α	3	92%	1 ⇒ 2	8	73%	96%
		B ⇒ A	2		2 ⇒ 3	5		
		C ⇒ B	7		3 ⇒ 4	13		
		D ⇒ C	10		1 ⇒⇒ 3	4		
		E ⇒ D	2		2 ⇒⇒4	6		
		B ⇒ α	3					
		C ⇒ A	6					
		D ⇒ B	10					
		E ⇒ C	2					
	2015-2018 ⇒ 2055			82%			33%	84%
	2055 ⇒ 2085			8%			6%	16%
	CTE ⇒⇒2085	A ⇒ α	3	92%	1 ⇒ 2	7	73%	96%
		B ⇒ A	2		2 ⇒ 3	5		
		C ⇒ B	8		3 ⇒ 4	13		
		D ⇒ C	13		1 ⇒⇒ 3	5		
		E ⇒ D	2		2 ⇒ ⇒4	6		
		B ⇒ α	3					
		C ⇒ A	5					
		D ⇒ B	7					
		E ⇒ C	2					
	2015-2018 ⇒ ⇒2085			57%			33%	82%
RCP 8.5	CTE ⇒ 2055	A ⇒ α	2	90%	1 ⇒ 2	6	69%	94%
		B ⇒ A	2		2 ⇒ 3	3		

		C ⇒ B	7		3 ⇒ 4	13		
		D ⇒ C	14		1 ⇒⇒ 3	4		
		E ⇒ D	2		2 ⇒ ⇒4	8		
		B ⇒⇒ α	3					
		C ⇒⇒ A	6					
		D ⇒ ⇒B	6					
		E ⇒⇒ C	2					
	2015-2018 ⇒ 2055			76%			33%	84%
	2055 ⇒ 2085			57%			39%	67%
	CTE ⇒⇒ 2085	A ⇒ α	4	100%	1 ⇒ 2	3	82%	100%
		B ⇒ A	1		1 ⇒⇒⇒4	4		
		C ⇒ B	3		3 ⇒ 4	13		
		D ⇒ C	4		1 ⇒⇒ 3	6		
		B ⇒⇒ α	5		2 ⇒⇒4	11		
		C ⇒⇒ A	9					
		D ⇒⇒B	14					
		E ⇒⇒ C	4					
		C ⇒⇒⇒ α	1					
		D ⇒⇒⇒ A	2					
	2015-2018 ⇒⇒2085			96%			57%	98%

Table 7. Percentage of climate zones in different scenarios

climate zone			scenario					
					RCP 4.5		RCP 8.5	
			CTE	2015-2018	2055	2085	2055	2085
winter climate zone	+°C ↑	α	–	4%	10%	10%	10%	27%
		A	8%	10%	20%	16%	18%	27%
		B	12%	12%	37%	35%	31%	37%
		C	29%	37%	27%	33%	31%	16%
		D	43%	31%	6%	6%	6%	–
		E	8%	6%	–	–	–	–
summer climate zone	↓ +°C	1	31%	20%	6%	6%	10%	–
		2	22%	8%	16%	14%	12%	8%
		3	27%	27%	18%	20%	14%	14%
		4	20%	45%	59%	59%	63%	76%
climate zone (winter + summer)		α1	–	2%	–	–	–	–
		α2	–	2%	10%	10%	10%	20%
		A2	–	–	–	–	–	2%
		A3	4%	–	–	–	–	2%
		A4	4%	9%	17%	15%	15%	20%
		B1	–	–	4%	2%	4%	–
		B2	–	–	5%	4%	4%	4%
		B3	6%	4%	2%	2%	–	5%
		B4	6%	7%	22%	22%	24%	22%
		C1	8%	12%	2%	3%	5%	–
		C2	4%	–	5%	5%	2%	2%
		C3	6%	2%	11%	13%	11%	5%
		C4	10%	16%	3%	5%	6%	6%
		D1	14%	3%	–	–	–	–
		D2	18%	3%	3%	3%	5%	–
		D3	10%	14%	2%	2%	–	–
		D4	–	3%	–	–	–	–
		E1	–	1%	–	–	–	–
		E2	8%	3%	–	–	–	–