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Energy saving potential in current and future world built environments based on the adaptive comfort approach

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ABSTRACT

The building sector is among the main energy users in the world, and its consumption patterns are strongly affected by changes in climate conditions. The consumption prediction in future scenarios is one of the greatest challenges. The application of recent techniques, such as adaptive thermal comfort strategies, constitutes an opportunity to reduce energy consumption. This study aims at clarifying their worldwide application potential in two scenarios, current and 2050, linking it to predictions on world population distribution and on the development level of countries. By interpolating 15,897 meteorological database, worldwide maps were made to quantify the applicability of the model and to show that such applicability would largely benefit both developing countries and most world population.

1. Introduction

The reduction of the climate change impact and the development of a sustainable society represent the main challenges for society in the 21st century (World Wildlife Fund, 2014), mainly due to, among other reasons, high energy consumption indexes and greenhouse gas emissions of the building sector (Stern et al., 2016). In 2010, buildings were responsible for 32% of primary energy consumption at a global level and for 19% of the overall greenhouse gas emissions (Intergovernmental Panel on Climate Change, 2014). This impact could also be greater in certain regions, depending on their development levels. In the European Union, buildings were responsible for 40% of the total energy consumption (European Environment Agency, 2017) and for 36% of greenhouse gas emissions (Rodríguez-Soria et al., 2015). In the 2015 Paris Climate Conference, a total of 195 countries committed to significantly decrease greenhouse gas emissions to reduce the progressive temperature rise, thereby resulting in ambitious objectives for 2050, both at community (European Commission, 2011) and national levels (Ministry of Energy (Chile), 2017; Ministry of the Environment (Japan), 2017; Parliament of the United Kingdom, 2008). Most programmes establish a demanding objective: to reduce the greenhouse gas emissions of buildings between 90 and 100% (Ministry of Energy (Chile), 2017; Ministry of the Environment (Japan), 2017; Parliament of the United Kingdom, 2008).

Consequently, many countries have developed several energy standards, all of them based on the climate zones of each country. Such standards, however, do not provide enough energy saving strategies as most standards are focused on the improvement of envelopes (Attia et al., 2017; Colclough et al., 2018) and do not analyse HVAC systems (the main reason of building energy consumption (International Energy Agency, 2017a, 2017b)). In addition, standards are based on a simplification since fixed values for setpoint temperatures are considered, thus generally causing a high thermal gradient between the internal demand and the external temperature (Sánchez-García et al., 2019b). Nevertheless, buildings

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could be more efficiently used by implementing energy saving strategies based on adaptive thermal comfort models (Luo et al., 2015). The reason is that the energy performance of buildings highly depends on users' thermal perception (Aghniaey and Lawrence, 2018), and adaptive models are the most appropriate for mixed buildings from the point of view of energy saving and of users' thermal comfort (Luo et al., 2015). The adaptive thermal comfort approach is commonly applicable to buildings with natural ventilation, establishing a close relationship between outdoor and indoor environmental conditions. Users therefore feel a wider range of temperatures than that felt by occupants of buildings continuously using HVAC systems. As a result, their comfort threshold is wider and more dynamic depending on the external temperature (Dear and G.S. Brager, 2002; McCartney and Nicol, 2002). As for energy saving, the use of adaptive measures has been analysed in various studies. On the one hand, the use of natural ventilation has been widely studied as an effective strategy to reduce the building energy consumption (Chen et al., 2018; Neves et al., 2019; Salcido et al., 2016) as it reduces the number of hours in which air conditioning systems are used. Moreover, on using natural ventilation, occupants are more tolerant of temperature variations than those using air conditioning systems (Fiorentini et al., 2019; Kim et al., 2019). However, the potential for using natural ventilation is not the same throughout the world and depends on the climatic characteristics of each region (Gokarakonda et al., 2019). On the other hand, the possibility of using adaptive setpoint temperatures adapted to the variability of the external temperature has also been applied in various studies: (i) Ge et al. (2018) studied the variation of setpoint temperatures in an university building in Hangzhou (China). Setpoint temperatures of 19.9 °C for heating and 26.8 °C for cooling were used, thus decreasing the cooling energy consumption; (ii) Barbadilla-Martín et al. (2017) used as adaptive setpoint temperatures the neutral temperatures of a comfort model designed for Seville for mixed-mode buildings. The energy consumptions obtained by using static (22.3 °C and 23.5 °C) and adaptive (21.5 °C and 24 °C) setpoint temperatures were compared. Energy savings of 11.4% in heating and of 27.5% in cooling were obtained; (iii) another studies conducted in office buildings were performed by using as setpoint temperatures the adaptive comfort limits of the EN 15251:2007 standard (Sánchez-García et al., 2019b, 2017). The results showed a reduction of the energy consumption between 36.7 and 59.5% with respect to the use of static setpoint temperatures; (iv) Sánchez-Guevara Sánchez et al. (2017) studied 3 residential buildings located in 3 Spanish cities. The authors used monthly adaptive setpoint temperatures obtained with the ASHRAE 55−2017 standard. An energy saving between 20 and 80% was obtained; (v) in another study, different from the previous one, the energy saving was quantified in a residential building located in the same cities but using daily adaptive setpoint temperatures obtained with the ASHRAE 55−2017 standard (Sánchez-García et al., 2019a). The results obtained a saving in the energy consumption between 10 and 46% with respect to the recommendations of the Spanish building technical code on setpoint temperatures in this type of buildings; and (vi) in a recent study, Sánchez-García et al. (2019c) analysed the energy saving achieved with the 3 categories of the EN 15251:2007 standard. The results showed that the energy saving was of 31.34% for the category I, and of 69.91% for the category III.

As a result, both the use of adaptive energy saving measures based on using natural ventilation in buildings when the external temperature is within the limits of adaptive thermal comfort and the use of adaptive setpoint temperatures when it is necessary to use HVAC systems constitute effective measures without the need of a high economic investment, thereby facilitating the achievement of the energy saving objectives established by various countries under predicted climate change scenarios. Some researchers are currently studying the possibility of linking the potential of the adaptive thermal comfort to energy poverty with the aim of solving that social problem (Bienvenido-Huertas et al., 2019a; Alexis Pérez-Fargallo et al., 2018b).

Most studies have analysed the application of adaptive strategies in certain regions without studying the climate impact at a global scale. The percentage of population and the impact of the economic development of countries should also be assessed to establish the real potential of such strategies. This study analyses the potential of applying adaptive energy saving strategies to the whole world, the population included by each application range, and the relationship with the development levels of countries. The hourly temperature values of the 15,897 locations were analysed. Moreover, the energy saving achieved by using the main adaptive saving strategies (natural ventilation and adaptive setpoint temperatures) was assessed in the whole world. Such strategies were also analysed in an unfavourable climate change scenario in the year 2050.

This paper is divided into four sections. Firstly, the theory and calculation method from ASHRAE 55−2017 are described. Secondly, the methodology of this research is described by analysing the following aspects: climate data, development level of countries, world population, and data analysis. Thirdly, the results are discussed. This section is in turn divided into three parts: (i) the potential of application of adaptive strategies in current scenario; (ii) the potential of application of adaptive strategies in climate scenario in the year 2050; and (iii) the potential energy saving with adaptive strategies. Finally, the main conclusions of results are drawn.

2. Adaptive thermal comfort model

Adaptive thermal comfort models are developed by various studies (López-Pérez et al., 2019; Pérez-Fargallo et al., 2018a) and standards (American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), 2017; European Committee for Standardization, 2007; Instituut Voor Studie En Stimulering Van Onderzoek, 2004; Ministry of Housing and Urban-Rural Development (China), 2012). Regarding the latter, the most developed standard including an adaptive model was ASHRAE 55−2017 (American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), 2017), which could be considered as an international implementation of an adaptive thermal comfort model because the data used in its development correspond to 160 buildings from countries of 4 continents (Carlucci et al., 2018). This model therefore presents a greater potential of international implementation than other models, e.g., the European Standard EN15251 (European Committee for Standardization, 2007). The ASHRAE 55−2017 establishes two different categories of acceptability: 80 and 90%. The use of a category influences the demands of the comfort model, with 90% being the most restrictive category. The ASHRAE 55−2017 recommends using the category of 80% as a level of 90% acceptability is quite difficult to be achieved and limits the use of such models (American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), 2017). The results of this study are therefore based on the category of 80% of the standard. Lower and upper thermal comfort limits are determined through the prevailing mean outdoor air temperature ($\overline{t_{pma(out)}}$) (see Equation (1)), which is a weighted average of daily external temperatures ($T_{ext,d}$) in a period between 7 and an indeterminate number of days before the day considered for calculation. The upper limit is determined based on the value used for α. The inverse of 1- α determines the number of days needed for the weighted sum of $t_{pma(out)}$ To calculate the model limits, both Equations (2) and (3) should be used provided that $\overline{t_{pma(out)}}$ ranges between 10 and 33.5 °C. Out of these limits, the adaptive comfort model finds no application, so HVAC systems should be used to keep acceptable conditions inside buildings.

$$\overline{t_{pma(out)}} = (1-\alpha)\cdot\sum_{d=1}^{n}\left(\alpha^{(i-1)}\cdot T_{ext,d}\right) \quad [^{\circ}C] \tag{1}$$

$$\text{Upper acceptability limit} = 0.31\cdot\overline{t_{pma(out)}} + 21.3 \quad [^{\circ}C] \tag{2}$$

$$\text{Lower acceptability limit} = 0.31\cdot\overline{t_{pma(out)}} + 14.3 \quad [^{\circ}C] \tag{3}$$

Adaptive energy saving strategies consist in using, on the one hand, natural ventilation during the hours when the external temperature is within the limits of acceptability of 80% (Equation (2) and (3)) and, on the other hand, HVAC systems when natural ventilation is not feasible (Bienvenido-Huertas et al., 2019b; Sánchez-García et al., 2019b). Additionally, HVAC operates by using adaptive setpoint temperatures according to the limit values obtained through Equations (2) and (3) so that Equation (2) is used for the cooling setpoint temperature, and Equation (3) for the heating setpoint temperature (Sánchez-García et al., 2019b). Consequently, and according to this model, buildings are cooled when the hourly external temperature is above the adaptive cooling setpoint temperature. As for heating, active systems are used when the external temperature is below the adaptive heating setpoint temperature. If $\overline{t_{pma(out)}}$ is lower than 10 °C or higher than 33.5 °C, HVAC systems should always be used with a fixed value for setpoint temperatures corresponding to the extension of the adaptive model limits (see Fig. 1) (Sánchez-García et al., 2019a).

In such way, the adaptive comfort model aims at achieving thermal comfort inside buildings based on two strategies:(i) natural ventilation when outside temperatures from previous days fall within a certain range; and (ii) HVAC systems come into play when external temperatures do not allow for the use of natural ventilation. Logically, this study informs about the potential of application of such strategies, but their actual applicability depends on a variety of factors, such as the typology of buildings, modes of ventilation, outdoor climate and gender (Rupp et al., 2019).

3. Methodology

The methodology of this study is based on analysing the potential of application of adaptive strategies (which were described in Section 2). To do this, the obtaining of climate data (current and future), the daily and hourly analysis of adaptive strategies, the saving of degrees with the use of adaptive setpoint temperatures, and the relationship of these adaptive strategies with the population and with the development level of countries were carried out in different phases of this research. Fig. 2 summarises the flowchart of the study.

3.1. Climate data for present and future scenarios

Weather data were obtained through METEONORM, a climate file database containing 8325 weather stations located all over the world and whose reliability has been assessed by various studies (Bellia et al., 2015; Hatwaambo et al., 2009; Kameni et al., 2019; Osman and Sevinc, 2019). Hourly temperature values were obtained with a stochastic model (METEONORM, 2019a) from those stations. Available data embraces the periods 1961–2000 and 2000–2009. As climate conditions can slightly vary from year to year (Calcabrini et al., 2019), climate data were obtained by analysing climate conditions during several years. The present study considered the period 2000–2009 for the calculations in 15,897 locations all around the world (Fig. 3). This data was processed and used to calculate the $t_{pma(out)}$(Equation (1)) which, together with the procedure described in Section 2, allowed for calculating the potential of application of adaptive strategies in what has been called the present scenario.

The same process was done for the future scenario (2050), but first the predicted change of temperatures in 2050 should be clarified. The A2 scenario from the Intergovernmental Panel on Climate Change (IPCC) (Nakićenović and Swart, 2000) was selected as the most unfavourable scenario (METEONORM, 2019b) to estimate the meteorological data from the considered 15,897 stations. Briefly speaking, this scenario foresees an increase between 2 and 5.4 °C by the end of the 21st century with respect to the values recorded in the last decade of the 20th century (Intergovernmental Panel on Climate Change, 2007). The year 2050 was also selected because it is the year considered by several developed countries (European Commission, 2011; Ministry of Energy (Chile), 2017; Ministry of the Environment (Japan), 2017; Parliament of the United Kingdom, 2008) as the target year for reducing carbon dioxide emissions.

3.2. Development level of countries

The economic development of countries has been analysed in the present scenario by using the World Economic Situation and Prospects (WESP) 2019, developed by the United Nations (United Nations, 2019). WESP divides all countries into three categories: developed countries (DC), countries in transition (CT), and developing countries (DingC). Regarding Countries in transition, some of

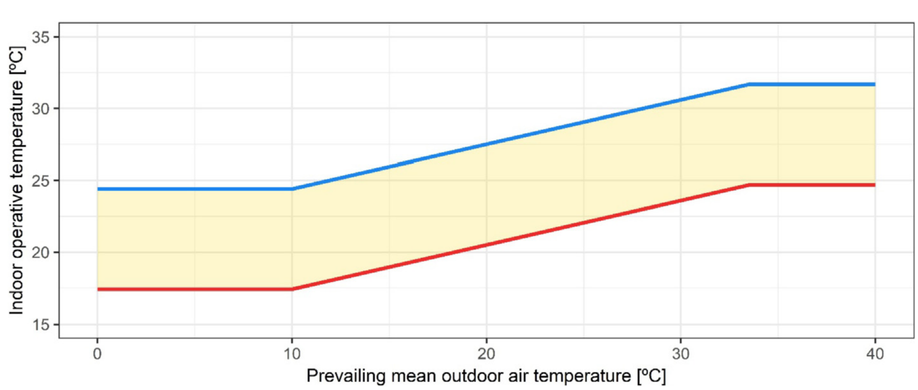

Fig. 1. Setpoint temperatures for the category of 80% of the adaptive model from ASHRAE 55. Red line is the lower limit, and blue line is the upper limit. The shady area is the range in which the internal temperature is within the acceptability of the adaptive model.

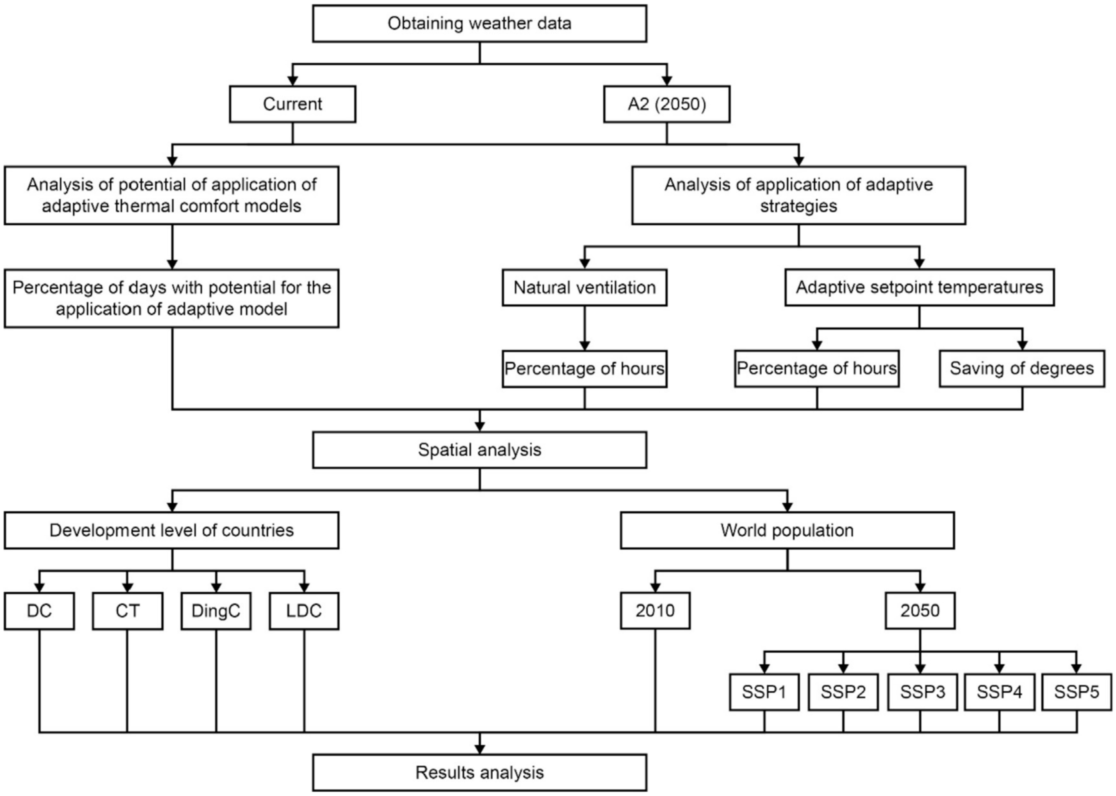

Fig. 2. Flowchart of this study.

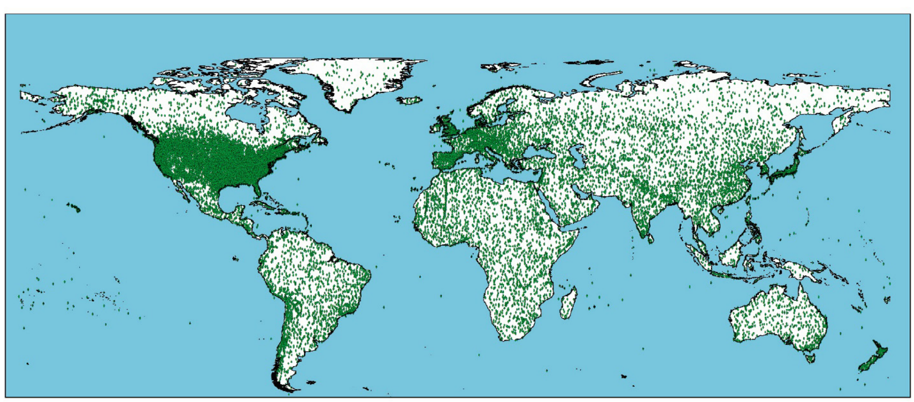

Fig. 3. Distribution of the 15,897 locations considered in the analysis.

them could be considered whether a developed country or a developing country, although WESP treats them as a different typology. Also, as for developing countries, a subcategory is known as least developed countries (LCT). This new classification is decided both by the United Nations Economic and Social Council and the United Nations General Assembly. The criteria for inclusion require that certain thresholds are met regarding per capita gross national income, an economic vulnerability index, and a human assets index. The countries considered in each classification are included as follows:

- Developed countries (DC): Canada, United States, Australia, Japan, New Zealand, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia, Iceland, Norway, and Switzerland.
- Countries in transition (CT): Albania, Bosnia and Herzegovina, Montenegro, Serbia, The former Yugoslav Republic of Macedonia, Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan.
- Developing countries (DingC): Algeria, Egypt, Libya, Morocco, Tunisia, Cameroon, Congo, Equatorial Guinea, Gabon, Kenya, Botswana, Eswatini, Mauritius, Namibia, South Africa, Zimbabwe, Cabo Verde, Côte d'Ivoire, Ghana, Nigeria, Brunei Darussalam, China, Democratic People's Republic of Korea, Fiji, Hong Kong (Special Administrative Region of China), Indonesia, Malaysia, Mongolia, Papua New Guinea, Philippines, Republic of

Korea, Samoa, Singapore, Taiwan Province of China, Thailand, Viet Nam, India, Islamic Republic of Iran, Maldives, Pakistan, Sri Lanka, Bahrain, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, State of Palestine, Syrian Arab Republic, Turkey, United Arab Emirates, Bahamas, Barbados, Belize, Guyana, Jamaica, Suriname, Trinidad and Tobago, Costa Rica, Cuba, Dominican Republic, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Argentina, Plurinational State of Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, and Bolivarian Republic of Venezuela.
- Least developed countries (LCT): Angola, Benin, Burkina Faso, Burundi, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Niger, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, Somalia, South Sudan, Sudan, Togo, Uganda, United Republic of Tanzania, Zambia, Cambodia, Kiribati, Lao People's Democratic Republic, Myanmar, Solomon Islands, Timor-Leste, Tuvalu, Vanuatu, Afghanistan, Bangladesh, Bhutan, Nepal, Yemen, and Haiti.

The classification of countries regarding their economic development has stayed the same for both the present and the future scenario. Indeed, some countries, especially those among the countries in transition, could reach the category of developed economies in 2050 (United Nations, 2019), but, to limit the variables of the study, this classification has been kept the same for both scenarios.

3.3. World population and future projections

The third variable considered is the distribution of the world population. The Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2017; Riahi et al., 2017) were used to analyse the impact of adaptive strategies on world population. SSPs are part of a new scenario of growth of societies in future, thus facilitating the analysis of the impacts on climate change, the analysis of international policies and strategies, and the possible vulnerabilities (O'Neill et al., 2017; Riahi et al., 2017). A total of five different scenarios of SSPs are distinguished, and each is associated with various tendencies in several factors, including demography (Ebi et al., 2014). The five SSPs and their population tendencies are as follows (Jiang and O'Neill, 2017; Samir and Wolfgang, 2017): (i) Sustainability (SSP1), in which is assumed that societies develop sustainably, human welfare is improved, and a low death rate is developed. In the case of developed countries, families can make their work compatible with their family life, so the birth rate is medium. Regarding the other countries, a demographic transition is assumed so the birth rate is low. Migration levels among countries are considered medium; (ii) Middle of the road (SSP2), in which all birth, death, and migration rates are considered medium for all countries; (iii) Regional rivalry (SSP3), in which a greater development of national security strategies hinders international development. Birth rate is high in developing countries, and low in developed countries. Death rate is considered high and migration is restricted due to security policies; (iv) Inequality (SSP4), which is a scenario of great inequalities, both at international and local levels. In the same fashion as in the present scenario, countries with higher birth rates stay the same. As for developed countries, birth rate is low, whereas death rate is medium. Migration is considered to be sustained; and (v) Fossil-fueled development (SSP5), which contributes to a rapid technological and economic growth. Birth rate is high in rich countries, and low in the rest. Death rate is low in all countries, and migration is commonplace between countries.

A recent study (Jones and Neill, 2016) conducted a spatial projection of world population in the various SSPs and for each decade between 2020 and 2100. From a spatial projection of the population for 2010, projections of urban and rural population were carried out for 232 countries in each SSP (Jones and Neill, 2016). Population data of the year 2010 were used for the current scenario and the 5 SSPs of the year 2050 for the future scenario. Spatial projections were obtained from the Socioeconomic Data and Applications Center (SEDAC) of the U.S. National Aeronautics and Space Administration (NASA) (Jones and O'Neill, 2017).

3.4. Climate data analysis

The potential of application for adaptive comfort models was analysed in 15,897 locations obtained with METEONORM both in the current scenario and the 2050 scenario (A2). As mentioned above, the category of 80% of the adaptive model from ASHRAE 55-2017was used in this study. The α-values recommended by ASHRAE 55–2017 were used: 0.9 for climates with low synoptic-scale temperature dynamic (e.g., latitudes close to the equator) and 0.6 for mid-latitude climates. The prevailing mean outdoor air temperature ($\overline{t_{pma(out)}}$) was determined by using the external temperature values of the last days of each location (Equation (1)). The number of days was determined based on the inverse of 1-α: 74 days for 0.9 and 15 for 0.6. The percentage of days of the year that offer potential for the application of adaptive strategies was determined according to whether $\overline{t_{pma(out)}}$ was within the considered range (Equation (4)).

$$PDAAM = \frac{\sum_{i=1}^{365} d_i}{365} \quad (4)$$
$$d_i = 1 \quad \text{if } 33.5 \geq \overline{t_{pma(out)}} \geq 10$$

Where *PDAAM* is the percentage of days with potential for the application of adaptive strategies [%]; and d_i is a value assigned to each day of the year. If $\overline{t_{pma(out)}}$ is between 10 and 33.5 °C, a value of 1 is assigned (there is potential for application); if such condition is not fulfilled, then a value of 0 is assigned (there is not such potential for application).

The potential of application of the natural ventilation was assessed as follows: first, the number of hours during the year during which natural ventilation is feasible was determined by the sum of annual hours when the external temperature was within the 80% acceptability limit (ASHRAE 55–2017); then, this number was divided into 8,760, that is, the whole year (Equation (5)).

$$PHNV = \frac{\sum_{i=1}^{8760} h_i}{8760} \quad (5)$$
$$h_i = 1 \quad \text{if Upper acceptability daily limit } \geq T_{ext,i} \geq \text{Lower acceptability daily limit}$$

Where *PHNV* is the percentage of hours when the adaptive natural ventilation has potential for application [%]; and h_i is a value assigned to each hour of the year: 1 and 0, in the same fashion as the former parameters.

The potential saving for heating and cooling degrees were assessed by comparing the calculated heating and cooling degrees for the static and the adaptive setpoints. Static setpoint temperatures corresponds to the classical approach to building heating and cooling, where indoor temperatures are static (i.e. the thermostat is set to 20 °C in winter and 22 °C in summer). In contrast, adaptive setpoint temperatures were determined according to the 80% limit of acceptability per ASHRAE 55; this means that indoor thermostats of buildings would dynamically modify setpoint temperatures in summer and winter depending on the external variations during the preceding days (Equation (6) and (7)). The potential saving was compared against 3 static setpoints for heating (20, 21 and 22 °C) and 3 for cooling (25, 25 and 27 °C).Such setpoints were selected due per standards and national regulations (European Committee for Standardization, 2007; The Government of Spain, 2013). Finally, the potential of saving for heating was calculated by the difference between heating degrees for heating (Equations (8)–(10)) and for cooling (Equations (11)–(13)).

$$T_{AH,i} = Lower\ acceptability\ daily\ limit \tag{6}$$

$$T_{AC,i} = Upper\ acceptability\ daily\ limit \tag{7}$$

$$StaticHD_R = \sum_{i=1}^{8760} \left(T_{ext,i} - T_{SH,R,i}\right) \cdot X_{HS} \qquad X_{HS} = 1\ if\ T_{ext,i} < T_{SH,R,i} \tag{8}$$

$$AdaptiveHD = \sum_{i=1}^{8760} \left(T_{ext,i} - T_{AH,i}\right) \cdot X_{HA} \qquad X_{HA} = 1\ if\ T_{ext,i} < T_{AH,i} \tag{9}$$

$$SHDH_R = StaticHD_R - AdaptiveHD \tag{10}$$

$$StaticCD_R = \sum_{i=1}^{8760} \left(T_{SC,R,i} - T_{ext,i}\right) \cdot X_{CS} \qquad X_{CS} = 1\ if\ T_{ext,i} > T_{SC,R,i} \tag{11}$$

$$AdaptiveCD = \sum_{i=1}^{8760} \left(T_{AC,i} - T_{ext,i}\right) \cdot X_{CA} \qquad X_{CA} = 1\ if\ T_{ext,i} > T_{AC,i} \tag{12}$$

$$SCDH_R = StaticCD_R - AdaptiveCD \tag{13a}$$

Where $StaticHD_R$ is the annual sum of the difference degrees between hourly static setpoints for heating and the external temperature [ºC]; R is the reference value selected for static setpoint temperatures. Regarding heating temperatures, R has values of 20, 21, and 22 °C, and in the case of cooling temperatures, R has values of 25, 26, and 27 °C; $T_{SH,R,i}$ is the hourly value of static setpoint temperature for heating in an i-hour [ºC]; $T_{ext,i}$ is the hourly value of external temperature in an i-hour [ºC]; *AdaptiveHD* is the annual sum of difference degrees between hourly adaptive setpoints for heating and the external temperature [ºC]; $T_{AH,i}$ is the hourly value of adaptive setpoint temperature for heating in an i-hour [ºC]; $SHDH_R$ is the annual saving of heating degrees of adaptive setpoints with respect to static setpoints of value R [ºC]; $StaticCD_R$ is the annual sum of the difference degrees between hourly static setpoints for cooling and the external hourly temperature [ºC]; $T_{SC,R,i}$ is the hourly value of static setpoint temperature for cooling in an i-hour [ºC]; *AdaptiveCD* is the annual sum of difference degrees between hourly adaptive setpoints for cooling and the external temperature [ºC]; $T_{AC,i}$ is the hourly value of adaptive setpoint temperature for cooling in an i-hour [ºC]; and $SCDH_R$ is the annual saving of cooling degrees of adaptive setpoints with respect to the static setpoints of value R [ºC]. X_{HS}, X_{HA}, X_{CS}, X_{CA} are logic values with a value of 1 when the condition given in the equations is fulfilled, and 0 if not. This consideration allowed to distinguish heating periods from cooling periods.

Spatial analyses were conducted with ArcGIS. For the spatial interpolation of the 15,897 points analysed, the parallel inverse distance weighting (IDW) interpolation algorithm was used (Watson and Philip, 1985). The spatial interpolation conducted with IDW consists in considering that the unknown value of a point is more influenced by the values of the nearest points than the further points, and the weight of points among them is proportional to the inverse of the distance among the points raised to a power p:

$$Z = \frac{\sum_{i=1}^{n} \frac{Z_i}{D_i^p}}{\sum_{i=1}^{n} \frac{1}{D_i^p}} \tag{13b}$$

Where Z is the interpolated value, Z_i are the values of known points, and D_i are the distances between the known points and the interpolated point.

After generating the various distributions of application of adaptive strategies, coincidences between the zones generated, population data, and development levels described above were analysed.

4. Results and discussion

4.1. Potential for application of adaptive strategies

Despite the potential of energy saving by using adaptive strategies in the operation of HVAC systems in buildings, it is necessary to analyse the application potential of the Earth's climate conditions. As the essential requirement for using such strategies is that $\overline{t_{pma(out)}}$ ranges between 10 and 33.5 °C, the possibilities of application in the various regions of the Earth were analysed. Fig. 4 summarises the results. Earth's climate conditions were favourable to apply such models. Approximately 34.18% of the Earth's ground surface (without including water bodies and the Antarctica) presented a percentage of application greater than 50% throughout the year. It is also important to note that, in the case of a percentage of applying adaptive models between 90 and 100% of the days of the year, the surface percentage was 20%. So, almost ¼ of the Earth's ground surface has acceptable conditions to use adaptive models practically the whole year.

Another aspect to be considered is the percentage of population in the various areas of application. Whereas the percentage of surfaces with a lower application of adaptive models (i.e., with a percentage of application lower than 50%) was 65.82%, the percentage of world population in such areas was only 8.53%. Most world population lives therefore in regions under favourable climate conditions to implement adaptive strategies during more than 50% of the year. In this sense, it is important to note the high percentage of population in the most favourable application range (between 90 and 100%), corresponding to 56.26% of world population.

The relationship between the development level of countries

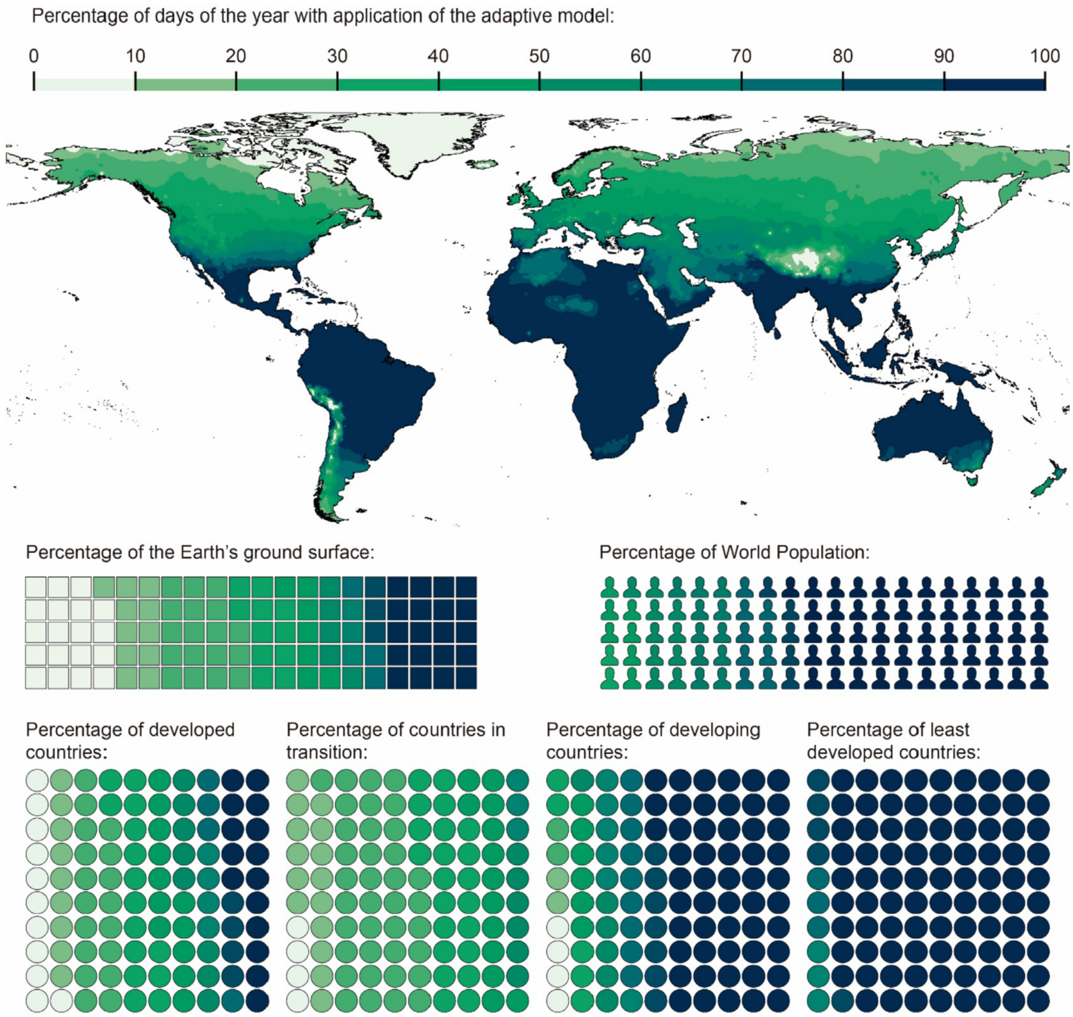

Fig. 4. Percentage of days of the year with application of adaptive models in the current scenario. The percentage of the Earth's ground surface, world population, and application in countries depending on the development level are indicated. In waffle charts, each icon is equivalent to 1%.

and the application of models was also important to analyse because it could influence the sustainable development strategies of the building stock. Most developing countries were found to have favourable conditions to implement adaptive models as 81.07% of their surface allow such models to be implemented during more than 50% of the days of the year (with 53.26% being the surface area for the application range between 90 and 100%), including South Africa, Brazil and Mexico. Regarding countries with a lower economic development, the percentage of application between 90 and 100% reached 88.98% of their surface area. Finally, in the case of developed countries, some areas were under favourable conditions to implement adaptive models, such as those located in the Mediterranean region (e.g., Spain, Greece, or Italy), Japan or Australia.

4.2. *Influence of climate scenario in the year 2050*

The current climate scenario is favourable to implement adaptive models. However, how future climate variations will affect their application is unknown. Given most of the objectives proposed by various countries are based on reducing carbon dioxide emissions by 2050, the possibilities of application of adaptive models in that year were analysed. The percentage of influence on world population in the different scenarios of demographic growth were assessed consistent with the SSPs. The impact of the new climate change scenario (characterized by an increase of the external temperature) slightly modified the percentages of application of adaptive models (see Fig. 5). Generally, it was found a slightly greater application of models, with an increase percentage between 0.07 and 1.32% in the applications between 50 and 90%. The areas under more unfavourable conditions presented a decrease percentage in their surface area of 5.08%. A slight reduction was also found in the range of greater application (between 90 and 100%) due to a greater percentage of days in which $\overline{t_{pma(out)}}$ was higher than 33.5 °C. This aspect was proved in the case of developing and least developed countries because the total percentage of application throughout the year had a reduction between 1.34 and 14.31%, but the surface percentage increased in other favourable percentage of application (e.g., between 80 and 90%). At a demographic level, five possible climate change scenarios were found to have a similar tendency to the application of models: (i) as for the most unfavourable possibilities of application (lower than 50%), the population of such areas was reduced between 3.96 and 4.93%; (ii) in the areas with total application throughout the year (greater than 90%), the population percentage decreased depending on the scenario. There were therefore reductions between 0.03 and 2.25% for the scenarios SSP1, SSP2, and SSP5, whereas for SSP3 and SSP4 there was an increase of 2.05 and 1.06%, respectively; and (iii) in the

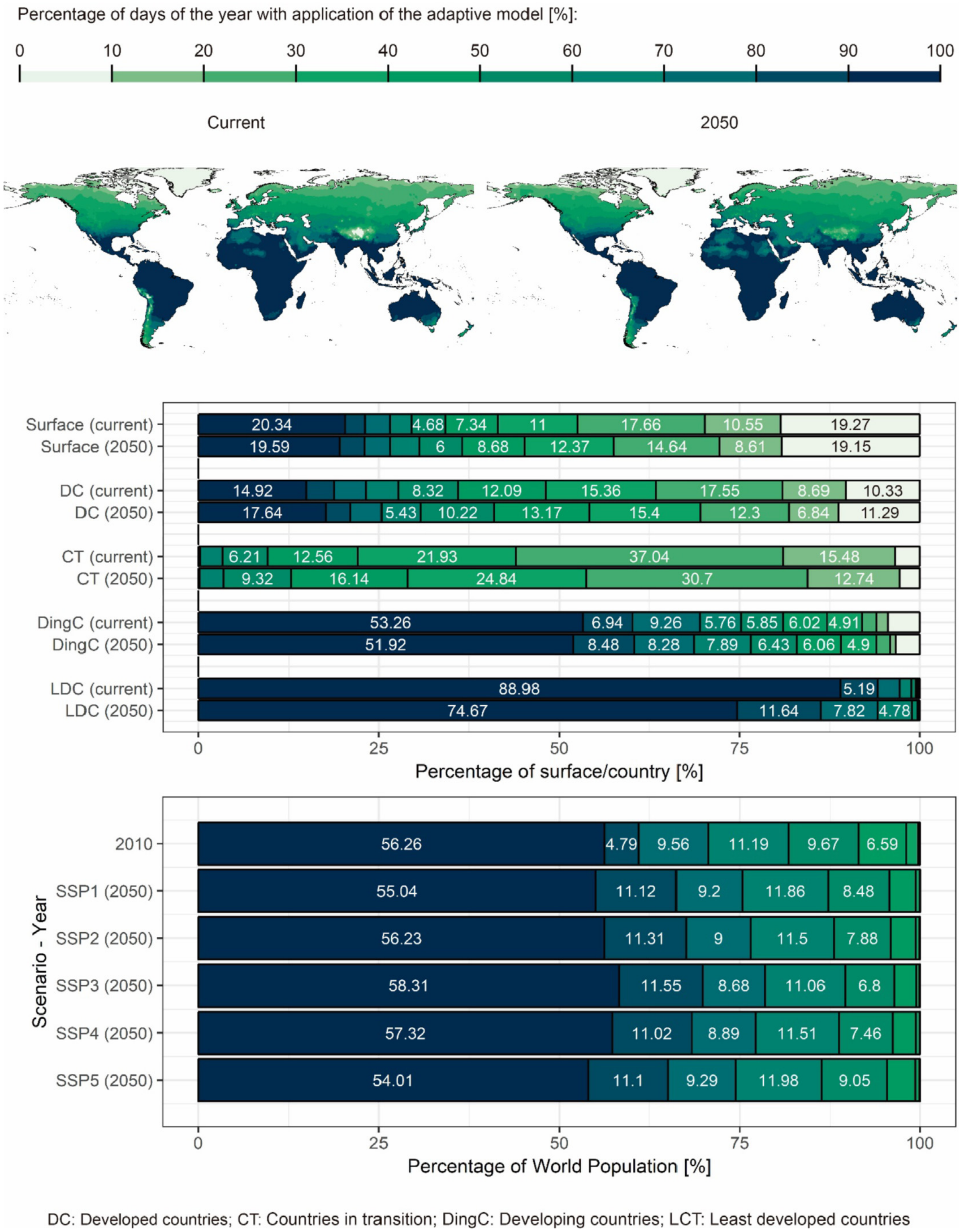

Fig. 5. Comparison of the percentage of days of the year with application of adaptive models between the current and 2050 scenarios. The variations in the percentage of the Earth's ground surface, world population, and application in countries depending on the development level are indicated.

case of favourable applications of adaptive models (i.e., between 50 and 90% of the days of the year), population in such regions increased between 2.88 and 6.21%. As a result, the application of adaptive models continues to be favourable in the case of an unfavourable climate change scenario in 2050. Moreover, the increase of external temperatures can contribute to a greater implementation of this kind of strategies because of the percentage reduction presented by the most severe climate regions. Both at the development level of countries and population level in the various scenarios, the areas with application of adaptive models higher than 50% were those most influencing such indicators.

4.3. Adaptive energy saving strategies

The analysis of the application of adaptive models is not enough to assess the impact of applying adaptive energy saving strategies. For this reason, the application of both typologies of adaptive strategies was analysed: (i) natural ventilation (i.e., when the external temperature is within the applicability limits of the category of 80% from ASHRAE 55), and (ii) adaptive setpoint temperatures. The results related to natural ventilation are first discussed. Fig. 6 represents the percentage of application of natural ventilation strategies similarly as developed in previous sections. The

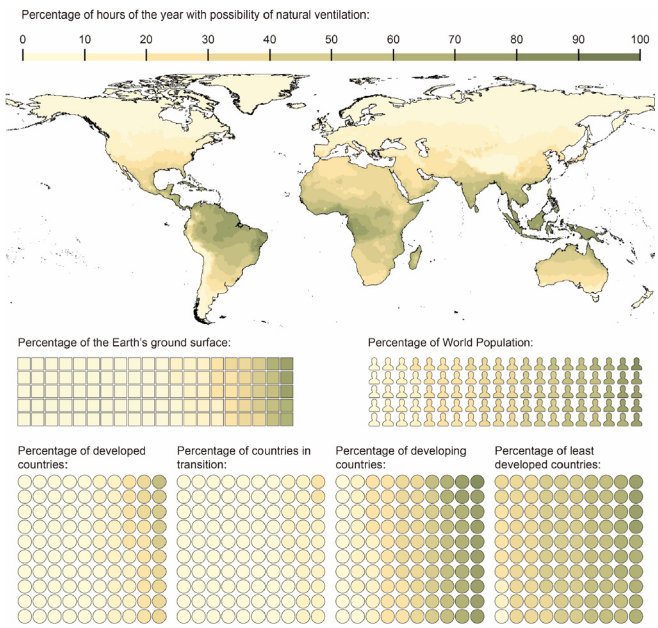

Fig. 6. Percentage of hours of the year with possibility of using natural ventilation strategies in the current scenario. The percentage of the Earth's ground surface, world population, and application in countries depending on the development level are indicated. In waffle charts, each icon is equivalent to 1%.

application of such strategies presented a progressive increase in the latitudes near to the equator. Very populated countries (e.g., Brazil, India or Indonesia) had favourable conditions to apply natural ventilation strategies (with a percentage between 50 and 90% of the hours of the year) because the monthly thermal oscillation in these areas were very low and with acceptable external temperature values to apply such strategies. Regarding the areas with greater latitudes, the application of natural ventilation strategies depends on the warmest seasons. In this sense, in areas such as the Mediterranean region, the use of natural ventilation techniques was clearly different between the warmest and coldest seasons. For example, Seville had a total of 2544 h when natural ventilation strategies could be applied as well as distributed by seasons: 8.22% in winter, 31.68% in spring, 38.13% in summer, and 22.37% in autumn. Such percentage values showed a greater difference in higher latitudes, together with a reduction of the total number of hours (e.g., the area of Berlin had a total of 1183 h, of which 65.51% corresponded to summer, 27.98% to winter, and 6.51% to autumn).

By analysing the 2050 scenario, it was found that the use of a high percentage of hours of the year (greater than 60%) had reductions in the Earth's ground surface in which natural ventilation can be applied (see Fig. 7). A variation was also found in the application of natural ventilation strategies: such application was reduced in areas with a percentage between 70 and 90%, whereas it would be increased in those countries where the natural ventilation was only applied in isolated periods (e.g., countries of the Mediterranean zone). Although the effect of climate change would slightly limit the use of such strategies in the latitudes near to the equator, they would be more used throughout the year in other areas with middle latitudes. Such effect generated that the percentage of world population had a decrease of more than 2.68% and 2.04% in the applications between 70 and 80% and 50 and 60%, respectively, while the applications between 60 and 70% and 40 and 50% showed increases higher than 4.26% and 4.7%, respectively. An increase in the application of natural ventilation was also found in the developed countries and in the countries in transition, while in the developing countries there was a slight decrease in their possibilities of application.

Therefore, natural ventilation could be used when external temperatures fall within a very specific range. If those conditions are outside that range (hot or cold weather), this ventilation is useless, and the building would have to resort to traditional HVAC systems. In this point, adaptive setpoint temperatures could have an important energy saving.

As discussed in section 2, adaptive set point temperatures depend on the variation of the external temperatures during the previous days, in contrast with static setpoint temperatures, and they come into play when HVAC systems are necessary. Therefore, it seems logical to analyse until which extent those adaptive setpoints can lead to potential savings in both heating and cooling in comparison with the former, both for the present scenario and for 2050 (Figs. 8 and 9). The information is presented through world maps and violin plots: (i) the world maps depict the potential of saving when comparing the static and adaptive set point temperatures in the different regions of the world, according to a colour scale; and (ii) the violin plots depict a statistical distribution of the potential savings globally, together with a box-plot. This type of plot is an evolution of the box-plots and includes information of the kernel density and rotating them to both sides of box [87]. The density of the hourly saving degrees is therefore represented. In such way, both the geographical and the statistical distribution of the potential savings can be assessed, which are expressed in heating and cooling degrees, respectively.

Regarding heating, the larger number of saving of degrees was found in areas where ventilation is not feasible and temperatures for the cold and warm season greatly differ (Fig. 8). Logically, the higher the static set point (i.e. 22 °C), the larger the potential saving, because the difference between the static and adaptive value would be larger.

Therefore, maximum saving in heating degrees were found to be between 20,789 °C (static setpoint 20 °C) and 38,007 °C (static setpoint 22 °C). Regions such as the American Midwest, the Andes Highlands stretching from Colombia to Chile, the Argentinian Patagonia, Central Europe, Central and Eastern Asia and the Southern fringes of Africa and Australia would see the greatest reduction in heating degrees, that is, mainly developed and transition economies. In turn, these strategies would reduce the energy consumption for the most common typologies of buildings (International Energy Agency, 2017b). A similar pattern can be found regarding the predicted scenario for 2050, but assuming that potential savings would be smaller due to the increase of external temperatures in accordance with the IPCC A2 scenario; violin plots show this tendency, showing a small shift in their base.

Regarding the potential saving for cooling degrees, some differences can be outlined (Fig. 9). In the present scenario, the largest potential for saving was between 24,051 °C and 38,398 °C, which could be found mainly in equatorial regions: Brazilian Amazonia, the Arabian Peninsula, India, and South-East Asia. Therefore, there was a sharp contrast between unpopulated and heavily populated regions, although all of them belonged to developing nations. Secondly, as the IPCC A2 scenario predicted a raise of temperatures for 2050, the effects on the potential saving by using adaptive set point temperatures were much more evident; when compared with the current scenario, the potential savings ranged from 5000 °C to 7000 °C and could be found in the same geographical areas. It also should be highlighted that those saving will be particularly relevant in very populated countries that will face strong change in their building stock as a consequence of intense processes of urbanization ("Population estimates and projections | DataBank," 2019), such as India, Indonesia, Bangladesh, and the Philippines. Violin plots showed a more pronounced change; their

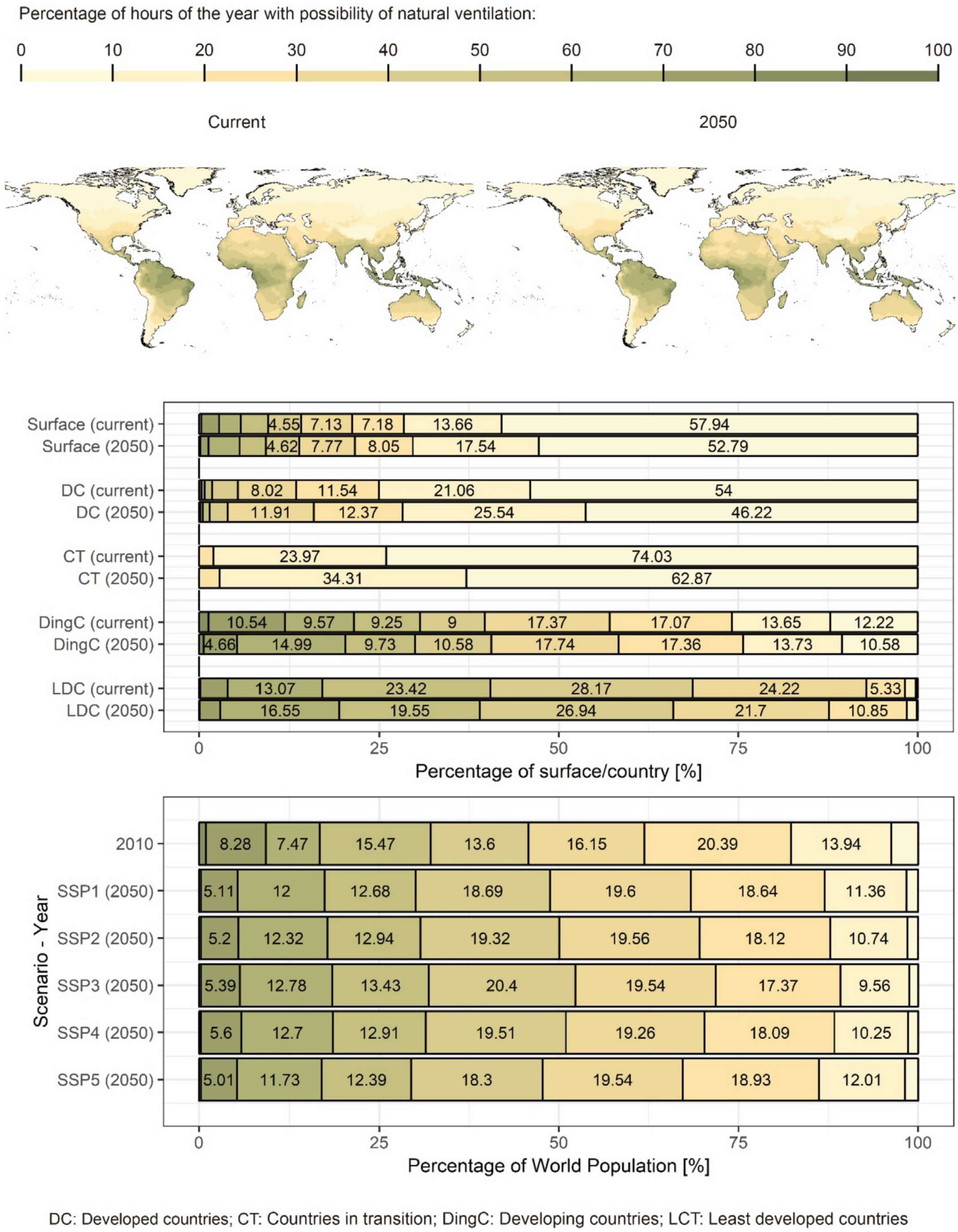

Fig. 7. Comparison of the percentage of hours of the year with possibility of using natural ventilation strategies in current and 2050 scenarios. The variations in the percentage of the Earth's ground surface, world population, and application in countries depending on the development level are indicated.

shape was more constant and the average for the box and whiskers was higher; that means that globally there will be further room for potential savings in cooling degrees in 2050 and those savings will be evenly distributed between the lower, middle and upper tier.

5. Conclusions

This study aimed at clarifying the potential of application of the adaptive comfort model and its related strategies for present time and for 2050, also in relation with the development level of countries and the distribution of world's population. The main conclusions are presented, together with some considerations about the methodology hereby used and the limitations of this study.

The analysis of three indicators (surface area, population, and development of each country) showed the strong relationship between most of the Earth's ground surface and the most populated areas with greater application percentages of adaptive models. Around 34.18% of the Earth has showed potential for the application of the adaptive models during more than 50% of days of the year. It is remarkable that some highly populated regions belonging to both developing countries (i.e. Brazil, India, Southwestern China,

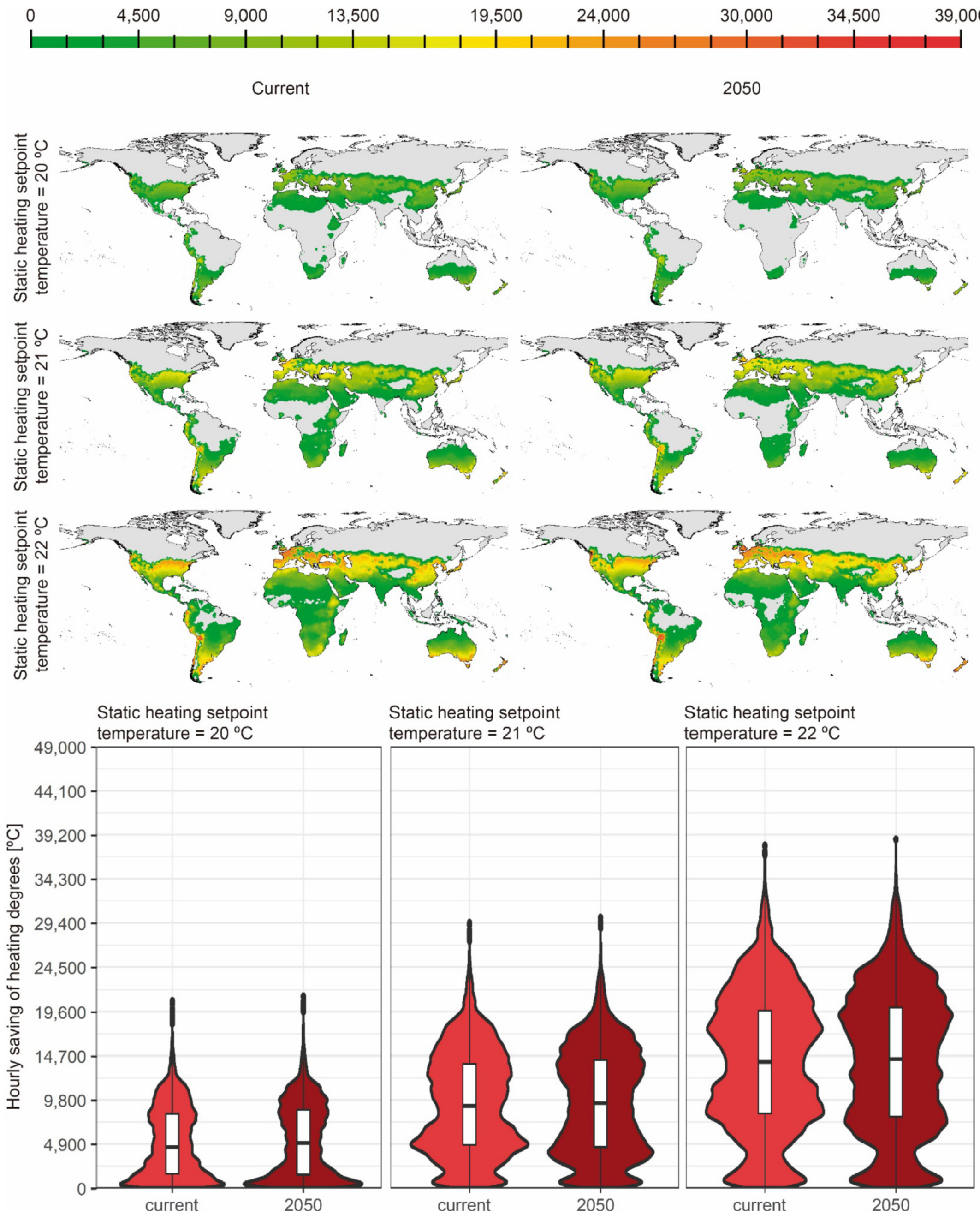

Fig. 8. Comparison of saving of heating degrees by using adaptive setpoint temperatures with respect to configurations of static setpoint temperatures between the current and 2050 scenarios. Grey areas are the regions not considered in the analysis (whether by the use of natural ventilation for both the static and adaptive setpoint, or by an application lower than 50% in adaptive models). Violin and box plots of the distribution of the hourly saving of heating degrees are represented in the lower part of the figure.

Indonesia, Sri Lanka or Pakistan) and least developed countries (Democratic Republic of the Congo, Angola, and Myanmar) showed potential for the application of such model during more than 90% of the year; the same tendency was found for the year 2050. Despite the studies on this topic are scarce, it can be mentioned that reports from the International Energy Agency show a similar tendency (International Energy Agency, 2018) regarding the demand for cooling equipment in 2050. Sharp increments of cooling degrees are expected in countries such as India (13%), Brazil (25,4%), and Indonesia (19,5%) in 2050 due to the change in climate conditions, but considering a static setpoint temperature for cooling of 18 °C.

This study shows that there might be a complex interplay between the change in climate conditions, the variation of adaptive setpoint temperatures and the heating and cooling degrees. This research clarifies that the latter are strongly influenced by the two formers. In such way, adaptive set point temperatures offer a great potential for containing the energy expenditure on heating and cooling, in comparison with the static setpoint temperatures considered in this study and in others (International Energy Agency, 2018). These conclusions pave the way for future research that could consider other static temperatures apart from those, which are the ones recommended by current standards.

This study also clarifies that adaptive strategies, such as natural ventilation and adaptive setpoint temperatures, should be more

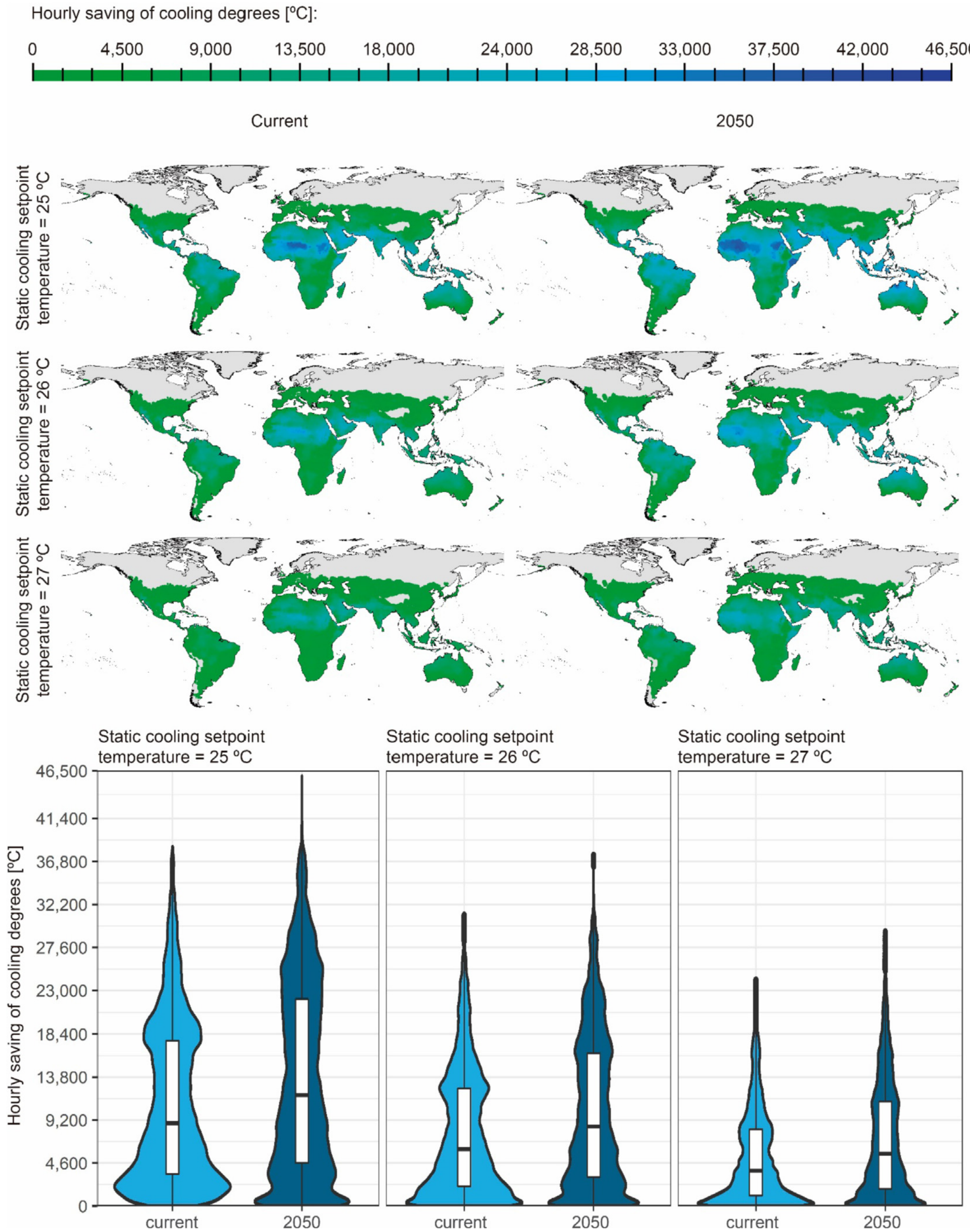

Fig. 9. Comparison of saving of cooling degrees by using adaptive setpoint temperatures with respect to configurations of static setpoint temperatures between the current and 2050 scenarios. Grey areas are the regions not considered in the analysis (whether by the use of natural ventilation for both the static and adaptive setpoint, or by an application lower than 50% in adaptive models). Violin and box plots of the distribution of the hourly saving of cooling degrees are represented in the lower part of the figure.

focused on the potential savings of cooling degrees, rather than of heating degrees. This conclusion is also supported not only by the fact that a global increase of temperatures would bring higher temperatures, but also by the geographical distribution of this change. Once again, the energy demand of HVAC systems in populated regions of developing countries located within the tropics will increase in the future (International Energy Agency, 2018) and the adaptive model can help in reducing this growing demand. What is more, according to projections by private organizations (PWC, 2017), some of those countries will be among the largest economies in 2050: China (1st), India (2nd), Indonesia (4th) or Brazil (5th), being able to influence global policies on sustainable development.

This study has also some limitations that should pave the way for further research on this topic. First, as discussed before, the interplay between static and dynamic setpoint temperatures and the external conditions could represent an issue. Different values from the three considered in this study both for heating and cooling could be discussed. In the case of cooling, the static setpoint of 18 °C considered in other studies (International Energy Agency, 2018) could offer insightful conclusions. Second, the issue about the availability of meteorological data in densely populated areas could be raised (Fig. 3); despite this should be a problem in less populated areas, some contexts, such as countries from South East Asia, can be challenging. The authors are aware of this and feel necessary to search for additional data in future research. Third, in connection with the availability of data, it should be stressed that this study has been conducted on a large scale; local variations of climate and phenomena such as urban heat island are not considered here; therefore, such conclusions should be understood in relation to large geographical areas and could be the seed for local studies that consider the specific characteristics of climates, regions, cities, and countries.

Finally, those limitations suggest different approaches for future studies. First, although ASHRAE 55 and EN 15251 are the two main internationally recognised standards in this field, some countries have started to devise and implement their owns, such as Chile (Building Research Establishment, 2016), and research to define these standards in others context, such as the Mediterranean climate, is on its way (Sánchez-García et al., 2018). This suggest that future studies should consider alternative standards adapted to local peculiarities. Besides, the 90% adaptability limit, which was not considered in this study, might offer additional insights in future research. Second, a rather direct method of interpolation between stations with available meteorological data has been used in this research, but an alternative approach might include a more complex interpolation, which could, in turn, help in solving the issue of the areas with scarce data.

In sum, this research is considered a starting point that has clarified, at a global scale, how adaptive comfort could help in providing with a sustainable pathway for the development of countries from present time to 2050. Providing their inhabitants with thermal comfort in both existing and new buildings while containing the energy demand for HVAC seems to be a challenging goal for the near future and the adaptive comfort models could be of great help in achieving it.

Declaration of competing interestCOI

The authors declare no competing interests.

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