Title

Influence of the RCP scenarios on the effectiveness of adaptive strategies in buildings around the world

Abstract:

High building energy consumption to guarantee users' thermal comfort has greatly impact the built environment worldwide. Energy saving strategies based on adaptive comfort models could be an opportunity to reduce the energy consumption of the built environment. However, climate change could modify the viability of these measures. The Representative Concentration Pathways (RCP) scenarios constitute the most updated scenario framework, with various tendencies depending on the radiative forcing in 2100, and Shared Socioeconomic Pathways (SSPs) scenarios were considered to study the demographic tendencies expected throughout the 21st century. This study analysed the effectiveness of using adaptive energy saving strategies with RCP and SSP scenarios around the world. A dataset composed of 997,000 locations was generated by assessing the application of the adaptive strategies in both the current scenario, RCP scenarios (2.6, 4.5, and 8.5 W/m 2) and the five SSP scenarios (SSP1-SSP5) in 2050 and 2100. The results showed that the increase of outdoor temperature reduces the regions where the application of the adaptive model is low, although its application is reduced in zones in which it is used most of the year (particularly in the RCP 8.5 scenario). Considering the SSP scenarios, it is expected that a greater percentage of population could apply the adaptive model throughout the year. Furthermore, adaptive cooling setpoint temperatures increase the saving data distribution in hourly degrees, so they are an effective measure to guarantee a greater resilience of the built environment in relation to the increase of energy demand of air conditioning systems.

Keywords:

Adaptive thermal comfort, climate change, built environment, Representative Concentration Pathways (RCP), Shared Socioeconomic Pathways (SSP)

1. Introduction

Climate change is among the main sustainability challenges in the 21st century [1]. Among other aspects, the greenhouse gases emitted through energy consumption have progressively increased the temperature of the planet. The built environment has a key role due to its high energy consumption [2,3]. Furthermore, the interrelations among economic crises, family units' loss of buying power, and high energy consumption have contributed to the emergence of social problems, such as fuel poverty [4,5]. The improvement of the energy performance would reduce the severity of climate change, thus leading to a greater well-being of society through various perspectives [6]. For this reason, several international agreements, such as the 2015 Paris Climate Conference, have been established among various countries. As a result, decarbonisation goals have been established in the building sector [7], such as the reduction of the energy consumption of the built environment between 90 and 100% [8–10].

It is therefore crucial to intervene in the built environment. One of the main aspects to deal with is the reason for high building energy consumption. The main type of building energy consumption is the use of HVAC systems, even more than other consumption sources such as domestic hot water [11] or electrical household appliances [12]. The use of these systems guarantees appropriate thermal comfort conditions inside buildings [13–15]. Their high consumption is mainly due to three types of factors: (i) a thermal envelope with a deficient performance, inter alia, due to the absence of thermal insulation and a lack of maintenance, (ii) HVAC systems with a low performance, and (iii) an inappropriate use of these systems. Regarding the first factor, the building stock was built in many countries before the first standards on energy efficiency [16–19]. Therefore, the heat transfer through the envelope is high (due to the combination of its huge surface with the high thermal transmittance [20–23]), thus implying a high energy demand. For this reason, most energy saving strategies are focused on improving the envelope. Many studies have dealt with this aspect, such as Aksoy and Inalli [24], Invidiata et al. [25] and Bhikhoo et al. [26]. The use of effective systems with a high performance is also among the most used energy conservation measures. However, the most appropriate use of HVAC systems is not considered, an aspect that could be interesting because of two aspects: (i) to avoid the rebound effects [27], which increase the energy consumption of the building due to the use change that users make with the energy improvement obtained in the building; and (ii) to be considered an energy saving strategy without the need of making economic investments. Regarding the latter, some studies have shown the advantages of using these systems more appropriately: Ghose et al. [28] determined that the appropriate use of the available resources could be more interesting than other energy saving measures, such as self-consumption. Moreover, Gianfrate et al. [29] set that an appropriate operational pattern of the HVAC systems could improve the situation of the family units in fuel poverty.

However, methodologies should be established to guarantee a more sustainable use of HVAC systems. One strategy could be the adaptive energy saving strategies [30–33], which are based on the use of adaptive thermal comfort models. These models are characterized by a perspective different from that of the static thermal comfort models developed by Fanger [34]. In this regard, Nicol and Humphreys [35] and Humphreys [36,37] showed that thermal comfort models in climate chambers were not adjusted to buildings with natural ventilation. As a result of these studies, field compilation works were conducted by Dear and Brager [38,39], thus developing the adaptive model from ASHRAE. Adaptive models are practically used in the energy saving through both adaptive natural ventilation and adaptive setpoint temperatures. On the one hand, natural ventilation is an effective strategy to reduce thermal loads in summer as it contributes the air intake from the exterior with a more appropriate temperature for thermal comfort, thus reducing both building energy consumption [40] with no economic cost [41,42] and the overheating risk [43]. However, its use depends on the climate conditions [44] and environment [45,46]. On the other hand, adaptive setpoint temperatures are based on the use of thermal comfort limits to configure the thermostat and take advantage of the energy saving expected by the nudging effect of the setpoint temperatures [47].

A key aspect of these measures is their bioclimatic character: they are effective according to the characteristics of the climate [48]. Thus, the possibilities of applying the adaptive strategies worldwide have been analysed [49]. Nevertheless, the implications related to climate change in the adaptive energy saving strategies should be studied in detail because of the variation of the outdoor conditions [50,51]. Although [49] analysed the impact of the future Greenhouse Gas (GHG) emissions A2 scenario in 2050, this scenario is an old approach for the evolution expected in the 21st century. The A2 scenario was included in the first group of the scenarios developed by the Intergovernmental Panel on Climate Change (IPCC), which is included in the Special Report on Emissions Scenarios (SRES) [52]. However, the IPCC has been continuously working on the development of more updated climate change scenarios, thus presenting the group of Representative Concentration Pathways (RCP) scenarios [53]. The RCP scenarios establish four evolution tendencies of climate according to the level of radiative forcing. These scenarios have been scarcely used to assess energy performance [54–57], although the impact of climate change on buildings is increasingly updated through them.

The RCP scenarios are therefore expected to modify the effectiveness of the adaptive strategies throughout the 21st century. For this reason, this research used the various RCP scenarios to analyse the potential of applying the adaptive strategies throughout the 21st century. A climate study was performed in 997,000 locations by analysing the changes caused by the RCP scenarios in 2050 and 2100. This threw light on both the effectiveness expected from the energy saving strategies and the energy policies that the governments of each region should develop. The energy analysis in the future implies to know more precisely the effectiveness of the energy strategies today adopted [58].

2. Methodology

2.1. Strategies based on adaptive thermal comfort models

Adaptive thermal comfort models allow variations to be established in the thermal comfort limits according to the variations of the outdoor temperature. Today there are many adaptive thermal comfort models. Most of them are included in various standards [59–64], although some studies have developed models for some regions [65–71]. One of the most used standards is ASHRAE 55-2017 [59] because it can be internationally used. The reason is the characteristics of the dataset used for its development: data from 4 continents. Its international application potential is therefore greater than that of ISSO 74[62], EN 16798-1:2019 [61] or GB/T 50785-2012 [72].

The adaptive thermal comfort model from ASHRAE 55-2017 is characterized by establishing two limits according to the percentage of acceptability. There are upper and lower limits for the 80% acceptability, and others for the 90% acceptability (Fig. 1). These variations are established through an increase or decrease regarding to the correlation straight line of the optimal temperature. As for these correlations (Eqs. 1-4), the limits are dependent variables of the prevailing mean outdoor temperature ($\overline{t_{pma(out)}}$) (Eq. 5). Moreover, $\overline{t_{pma(out)}}$ reflects the variations of the daily outdoor temperature. Apart from being useful to obtain upper and lower limit values, $\overline{t_{pma(out)}}$ also allows the application of the adaptive model to be determined. In this regard, lower (10 ºC) and upper (33.5 ºC) thresholds are established to apply the adaptive model. If the value of $\overline{t_{pma(out)}}$ is not between 10 and 33.5 ºC, the adaptive model cannot be applied.

$$Lower\ acceptability\ limit\ (80\%\ acceptability) = 0.31 \cdot \overline{t_{pma(out)}} + 14.3 \quad [ºC] \tag{1}$$

$$Upper\ acceptability\ limit\ (80\%\ acceptability) = 0.31 \cdot \overline{t_{pma(out)}} + 21.3 \quad [ºC] \tag{2}$$

$$Lower\ acceptability\ limit\ (90\%\ acceptability) = 0.31 \cdot \overline{t_{pma(out)}} + 15.3 \quad [ºC] \tag{3}$$

$$Upper\ acceptability\ limit\ (90\%\ acceptability) = 0.31 \cdot \overline{t_{pma(out)}} + 20.3 \quad [ºC] \tag{4}$$

$$\overline{t_{pma(out)}} = (1-\alpha) \cdot \sum_{d=1}^{n} \left(\alpha^{(i-1)} \cdot T_{ext,d}\right) \quad [ºC] \tag{5}$$

Where α is the weight assigned, with a value of 0.9 for climates with low synoptic-scale temperature Dynamic (e.g., latitudes close to the equator) and of 0.6 for mid-latitude climates [59].

The adaptive thermal comfort model can be used to establish energy saving strategies in buildings. These strategies are aimed to guarantee users' thermal comfort through an adaptive approach, so the use of HVAC systems is reduced. There are two adaptive strategies: (i) adaptive natural ventilation [73,74] (air-conditioning the thermal space when the outdoor temperature is within the thermal comfort ranges), and (ii) adaptive setpoint temperatures [75], using the value of the respective adaptive limit as setpoint temperature value (the lower limit for the heating setpoint temperature, and the upper limit for the cooling setpoint temperature). When the adaptive thermal comfort model cannot be applied (i.e., when $\overline{t_{pma(out)}}$ is lower than 10 ºC or greater than 33.5 ºC), the criterion established by Sánchez-García et al. [76] is used in this research, which is based on horizontally extending the thermal comfort limit values. The assumption in the expansion of the applicability limits supposes that the lower and upper thresholds maintain the difference between upper and lower acceptability limits (7ºC at 80% and 5ºC at 90%) during the whole range of the $\overline{t_{pma(out)}}$. Despite the fact is a contrasted methodology based on previous research, this is a limitation of the study.

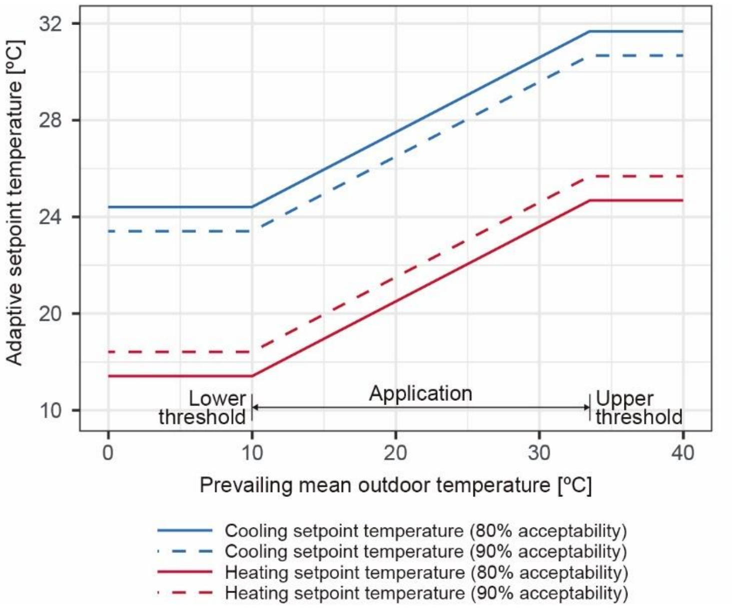

Fig. 1. Upper and lower limits of the adaptive thermal comfort model from ASHRAE 55-2017.

2.2. Analysis methodology of the feasibility of adaptive strategies by using climate data

Adaptive strategies are related to the bioclimatic strategies that can be used in architecture to reduce building energy consumption. These strategies consider local climate conditions with the aim of ensuring thermal comfort using environmental resources. The use of methodologies based on the data analysis of the outdoor climate allows the effectiveness of adaptive strategies to be determined. In previous studies, Bienvenido-Huertas et al. [77,78] developed an analysis methodology of the adaptive strategies by using climate data. This methodology is based on the analysis of the percentage of days when the adaptive model is applied, the percentage of annual hours when natural ventilation is used, and the saving in hourly heating and cooling degrees between adaptive setpoint temperatures and static setpoint temperatures.

To determine the percentage of days when the adaptive model is applied ($AATCM$), the number of days in which $\overline{t_{pma(out)}}$ is within the application thresholds is determined (between 10 and 33.5 ºC) (Eq. 6). The acceptability considered does not influence the analysis of the percentage of days when the adaptive model is applied because this aspect does not modify the application thresholds of the model.

$$AATCM = 100 \frac{\sum_{i=1}^{365} d_i}{365}$$

$$d_i = 1 \quad if\ 10 \leq \overline{t_{pma(out)}} \leq 33.5$$

$$d_i = 0 \quad if\ \overline{t_{pma(out)}} < 10 \tag{6}$$

$$d_i = 0 \quad if\ \overline{t_{pma(out)}} > 33.5$$

Where d_i is a value assigned to each day of the year by using the rules established.

The same rule used with $AATCM$ can be used to determine both the percentage of days when the adaptive model is not applied because $\overline{t_{pma(out)}}$ is greater than the upper threshold ($NAATCM - UT$) (Eq. 7) and the percentage of days when the adaptive model is not applied when $\overline{t_{pma(out)}}$ is lower than the lower threshold ($NAATCM - LT$) (Eq. 8).

$$NAATCM - UT = 100 \frac{\sum_{i=1}^{365} d_{NA-UT,i}}{365}$$

$$d_{NA-UT,i} = 1 \quad if\ \overline{t_{pma(out)}} > 33.5 \tag{7}$$

$$d_{NA-UT,i} = 0 \quad if\ \overline{t_{pma(out)}} \leq 33.5$$

$$NAATCM - LT = 100 \frac{\sum_{i=1}^{365} d_{NA-LT,i}}{365} \tag{8}$$

$$d_{NA-LT,i} = 1 \quad if\ \overline{t_{pma(out)}} < 10$$

$$d_{NA-LT,i} = 0 \quad if\ \overline{t_{pma(out)}} \geq 10$$

Where $d_{NA-UT,i}$ and $d_{NA-LT,i}$ are a value assigned to each day of the year by using the rules established.

Unlike the application percentages of the adaptive model, adaptive strategies are hourly analysed, thus obtaining a greater detail of results than daily analyses [79]. Moreover, the acceptability considered should be distinguished in adaptive strategies because it varies upper and lower thermal comfort limits. Regarding the adaptive natural ventilation strategies, the percentage of hours to apply natural ventilation was analysed. Two variables were considered: one for the 80% acceptability (V-80) (Eq. 9) and another for the 90% acceptability (V-90) (Eq. 10).

$$\text{V-80}=\frac{\sum_{i=1}^{8760} h_{80,i}}{8760}$$

$$h_{80i}=1 \quad if\ Eq.1 \leq T_{ext,i} \leq Eq.2$$

$$h_{80i}=0 \quad if\ T_{ext,i} < Eq.1 \tag{9}$$

$$h_{80i}=0 \quad if T_{ext,i} > Eq.2$$

$$\text{V-90}=\frac{\sum_{i=1}^{8760} h_{90,i}}{8760}$$

$$h_{90i}=1 \quad if\ Eq.3 \leq T_{ext,i} \leq Eq.4 h_{90i}=0 \quad if\ T_{ext,i} < Eq.3 \tag{10}$$

$$h_{90i}=0 \quad if T_{ext,i} > Eq.4$$

Where h_{80i} and h_{90i} are a value assigned to each hour of the year by using the rules established, and $T_{ext,i}$ is the outdoor temperature in the hour i.

On the other hand, the saving obtained with adaptive setpoint temperatures is characterized by comparing the hourly degrees obtained with both the adaptive setpoint temperatures and the static setpoint temperatures. That is, the adaptive setpoint temperatures are based on the adaptive comfort approach, which daily varies according to the prevailing mean outdoor temperature ($\overline{t_{pma(out)}}$) and the static setpoint temperatures are fixed throughout the year without considering the outdoor conditions. The analysis was independently carried out for heating and air conditioning systems: (i) hourly heating degrees with static setpoint temperatures (Eq. 11); (ii) hourly cooling degrees with static setpoint temperatures (Eq. 12); (iii) hourly heating degrees with the adaptive setpoint temperatures obtained with the 80% acceptability (Eq. 13); (iv) hourly cooling degrees with the adaptive setpoint temperatures obtained with the 80% acceptability (Eq. 14); (iii) hourly heating degrees with the adaptive setpoint temperatures obtained with the 90% acceptability (Eq. 13); (iii) hourly cooling degrees with the adaptive setpoint temperatures obtained with the 90% acceptability (Eq. 14). As for the static setpoint temperatures, this study analysed five temperatures for heating (19, 20, 21, 22, and 23 ºC) and five for cooling (23, 24, 25, 26, and 27 ºC). That supposes a wide range of fixed setpoint temperatures to achieve a proper comparison with adaptive approach. The degree saving was obtained through the subtraction of the hourly degrees obtained with both static and adaptive setpoint temperatures (Eq. 15).

$$\text{SHST-}T_{SH}=\sum_{i=1}^{8760}(T_{ext,i}-T_{SH}) \cdot X_{SH,i} \tag{11}$$

$$X_{SH,i}=1 \quad if\ T_{ext,i} < T_{SH}$$

$X_{SH,i} = 0 \quad if\; T_{ext,i} \geq T_{SH}$

$$\text{SCST-}T_{SC} = \sum_{i=1}^{8760}(T_{SC} - T_{ext,i}) \cdot X_{SC,i} \tag{12}$$

$X_{SC,i} = 1 \quad if\; T_{ext,i} > T_{SC}$

$X_{SC,i} = 0 \quad if\; T_{ext,i} \leq T_{SC}$

$$\text{AHST-80} = \sum_{i=1}^{8760}(T_{ext,i} - Eq.1) \cdot X_{AH,i} \tag{13}$$

$X_{AH,i} = 1 \quad if\; T_{ext,i} > Eq.1$

$X_{AH,i} = 0 \quad if\; T_{ext,i} \leq Eq.1$

$$\text{ACST-80} = \sum_{i=1}^{8760}(Eq.2 - T_{ext,i}) \cdot X_{AC,i} \tag{14}$$

$X_{AC,i} = 1 \quad if\; T_{ext,i} < Eq.2$

$X_{AC,i} = 0 \quad if\; T_{ext,i} \geq Eq.2$

$$\text{AHST-90} = \sum_{i=1}^{8760}(T_{ext,i} - Eq.3) \cdot X_{AH,i} \tag{15}$$

$X_{AH,i} = 1 \quad if\; T_{ext,i} > Eq.3$

$X_{AH,i} = 0 \quad if\; T_{ext,i} \leq Eq.3$

$$\text{ACST-90} = \sum_{i=1}^{8760}(Eq.4 - T_{ext,i}) \cdot X_{AC,i} \tag{16}$$

$X_{AC,i} = 1 \quad if\; T_{ext,i} < Eq.4$

$X_{AC,i} = 0 \quad if\; T_{ext,i} \geq Eq.4$

$$Hourly\ degree\ saving = Static\ degree\ hours - Adaptive\ degree\ hours \tag{17}$$

Where SHST-T_{HC} is the annual sum of the hourly heating degrees with the static setpoint temperature T_{SH} [ºC]; SCST-T_{HC} is the annual sum of the hourly cooling degrees with the static setpoint temperature T_{SC} [ºC]; AHST-80 and AHST-90 are the annual sum of the hourly heating degrees with the 80% and 90% acceptability, respectively [ºC]; ACST-80 and ACST-90 are the annual sum of the hourly cooling degrees with the 80% and 90% acceptability, respectively

2.3. Scenarios analysed

The goal of this study was the analysis of the influence of climate scenarios throughout the 21st century on the application of adaptive strategies worldwide. For this purpose, the most updated climate change scenarios (at the time when this study was conducted) were analysed. The Representative Concentration Pathways (RCP) scenarios were used, which are included in the 2014 report of the IPCC [80]. These scenarios describe various levels of greenhouse gases and radiative forcings that could take place in the future. There are four RCP scenarios (2.6, 4.5, 6.0, and 8.5). The numeric value indicates the change in energy flux in the atmosphere caused by natural or anthropogenic factors of climate change, which is called, radiative forcing in 2100 (e.g., 8.5 W/m^2 in the RCP 8.5 scenario). This study considered three scenarios (2.6, 4.5, and 8.5) because obtaining climate data in the RCP 6.0 scenario is something of a challenge. Based on these three scenarios, the global mean temperature is expected to be increased by the end of the 21st century between 0.3 and 1.7 ºC in the RCP 2.6 scenario, between 1.1 and 2.6 ºC in the RCP 4.5 scenario, and between 2.6 and 4.8 ºC in the RCP 8.5 scenario. This study therefore analysed a range of climate change scenarios: from the scenario closer to the Paris Agreement's goals [81] to the most unfavourable scenario (the RCP 8.5 scenario) [80]. The years analysed were 2050 and 2100. These two years were chosen due to their importance in the 21st century: 2050 corresponds to the decarbonisation date established by many international bodies, and 2100 corresponds to the date at the end of the century, coincident with the radiative forcing values that characterize each scenario.

This study also analysed the implications of the effectiveness of the adaptive strategies for world population. One of the limitations of the RCP scenarios is the lack of a socio-economic narrative of the demographic tendencies expected throughout the 21st century. Thus, the Shared Socioeconomic Pathways (SSPs) scenarios [82,83] were used. These scenarios describe narratives about the changes expected throughout the 21st century in relation to socioeconomic aspects, climate change, vulnerabilities, and the effectiveness of sustainable policies [84]. The demographic changes expected throughout the 21st century could therefore be analysed. Five narratives or SSP scenarios are distinguished [84,85]: (i) Sustainability (SSP1). This first scenario is based on a sustainable pathway throughout the 21st century, aiming to both the reduction of inequalities among countries and a consumption with a lower intensity of resources, among other aspects; (ii) Middle of the road (SSP2). This scenario does not differ from the patterns historically found with unequal growths among countries. As regards sustainability, international goals are pursued, but slowly; (iii) Regional rivalry (SSP3). Nationalism reappears in this scenario, with policies focused on the regional scope. The lack of an international awareness of sustainable goals contributes to the emergence of environmental problems in various regions; (iv) Inequality (SSP4). Inequalities among regions are increased, similarly to today. At the energy level, renewable energies and fossil fuels are developed; and (v)

Fossil-fueled development (SSP5). This scenario is based on a rapid increase of the world economy by increasingly consuming fossil fuels.

Thus, the five SSP scenarios were analysed to study the demographic implications from applying adaptive strategies. Likewise, there are similarities between the RCP and SSP scenarios. Rogelj et al. [86] determined the combinations of the RCP and SSP scenarios that are more likely to take place (Table 1). For instance, the RCP 8.5 scenario could only be combined with the SSP5 scenario. Thus, this study considered for the demographic analysis the combinations SSP-RCP found by Rogelj et al. [86]. The basis year (2010) was the same for all the SSP scenarios and was used for the current scenario. Likewise, the data of each SSP scenario were obtained for 2050 and 2100.

Table 1. The most appropriate combination of RCP and SSP scenarios according to Rogelj et al. [80].

RCP	SSP1	SSP2	SSP3	SSP4	SSP5
2.6	X	X		X	
4.5	X	X	X	X	X
8.5					X

2.4. Generation process of the dataset used in the research

The dataset was generated by following the steps included in Fig. 2. First, the hourly climate data of 17,000 locations around the world were obtained. For this purpose, METEONORM was used. METEONORM is a database of climate files composed of 8,325 weather stations located around the world and its use is guaranteed by several studies [87,88]. Based on the data provided by these weather stations, the hourly temperature values of a whole year are obtained with a stochastic model [89]. The period 2000-2019 was used for the current scenario. Likewise, METEONORM was used to obtain the climate data in the RCP 2.6, 4.5 and 8.5 scenarios in 2050 and 2100 in each location. Thus, 199,000 series of temperature data were obtained.

The analysis methodology described in Subsection 2.2 was applied to these data series, and the adaptive variables considered in the research were obtained (Table 2). After analysing the data, 16,000 locations were used for the spatial interpolation of the variables analysed through ArcGIS. For this purpose, the parallel inverse distance weighting (IDW) interpolation algorithm was used [90]. The remaining 1,000 locations were used to test the validity of the interpolations obtained. For this purpose, the statistical parameters of the determination coefficient (R^2) (Eq. 18), the mean absolute error (MAE) (Eq. 19), and the root-mean-square error (RMSE) (Eq. 20) were analysed.

$$R^2 = 100\left(1 - \frac{\sum_{i=1}^{n}(t_i - m_i)^2}{\sum_{i=1}^{n}(t_i - \bar{t}_i)^2}\right) \quad (18)$$

$$MAE = \frac{\sum_{i=1}^{n}|t_i - m_i|}{n} \quad (19)$$

$$RMSE = \left(\frac{\sum_{i=1}^{n}(t_i - m_i)^2}{n}\right)^{1/2} \quad (20)$$

Where t_i is the actual value, m_i is the model's prediction, and n is the number of instances in the dataset.

After generating the spatial distributions of each variable, the results were exported. A network of 997,000 locations was generated with a resolution of one-eighth degree (7.5 arc-minutes), and the value of each adaptive variable was obtained in each location (Fig. 3). The population data of the SSP scenarios were obtained through the spatial projections made by Jones et al. [84]. The demographic data of the starting year of the SSP (2010) were used for the current scenario, and the demographic data of each SSP in 2050 and 2100 were used for the future scenarios. The spatial projections were obtained from the Socioeconomic Data and Applications Center (SEDAC) of the U.S. National Aeronautics and Space Administration (NASA)[90].

Table 2. Acronyms used for the adaptive variables analysed.

Variable	Description
AATCM	Application of the adaptive thermal comfort model
NAATCM-UT	Non-application of the adaptive thermal comfort model: upper threshold
NAATCM-LT	Non-application of the adaptive thermal comfort model: lower threshold
V-80	Application of natural ventilation (80% acceptability)
V-90	Application of natural ventilation (90% acceptability)
SHST-19	Static heating setpoint temperature: 19 ºC
SHST-20	Static heating setpoint temperature: 20 ºC
SHST-21	Static heating setpoint temperature: 21 ºC
SHST-22	Static heating setpoint temperature: 22 ºC

SHST-23	Static heating setpoint temperature: 23 ºC
SCST-23	Static cooling setpoint temperature: 23 ºC
SCST-24	Static cooling setpoint temperature: 24 ºC
SCST-25	Static cooling setpoint temperature: 25 ºC
SCST-26	Static cooling setpoint temperature: 26 ºC
SCST-27	Static cooling setpoint temperature: 27 ºC
AHST-80	Adaptive heating setpoint temperature (80% acceptability)
AHST-90	Adaptive heating setpoint temperature (90% acceptability)
ACST-80	Adaptive cooling setpoint temperature (80% acceptability)
ACST-90	Adaptive cooling setpoint temperature (90% acceptability)

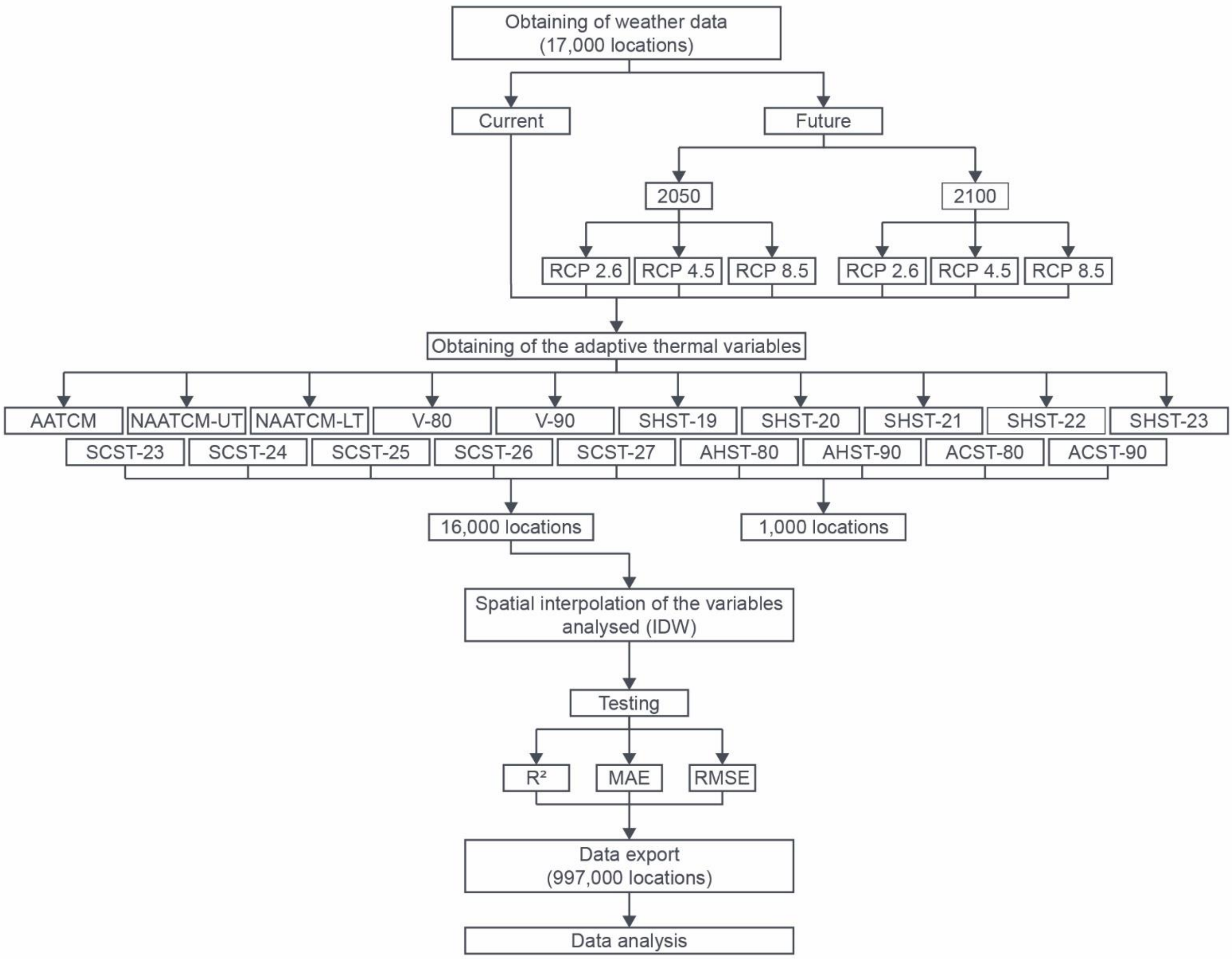

Fig. 2. Flowchart of the generation process of the dataset analysed in the research.

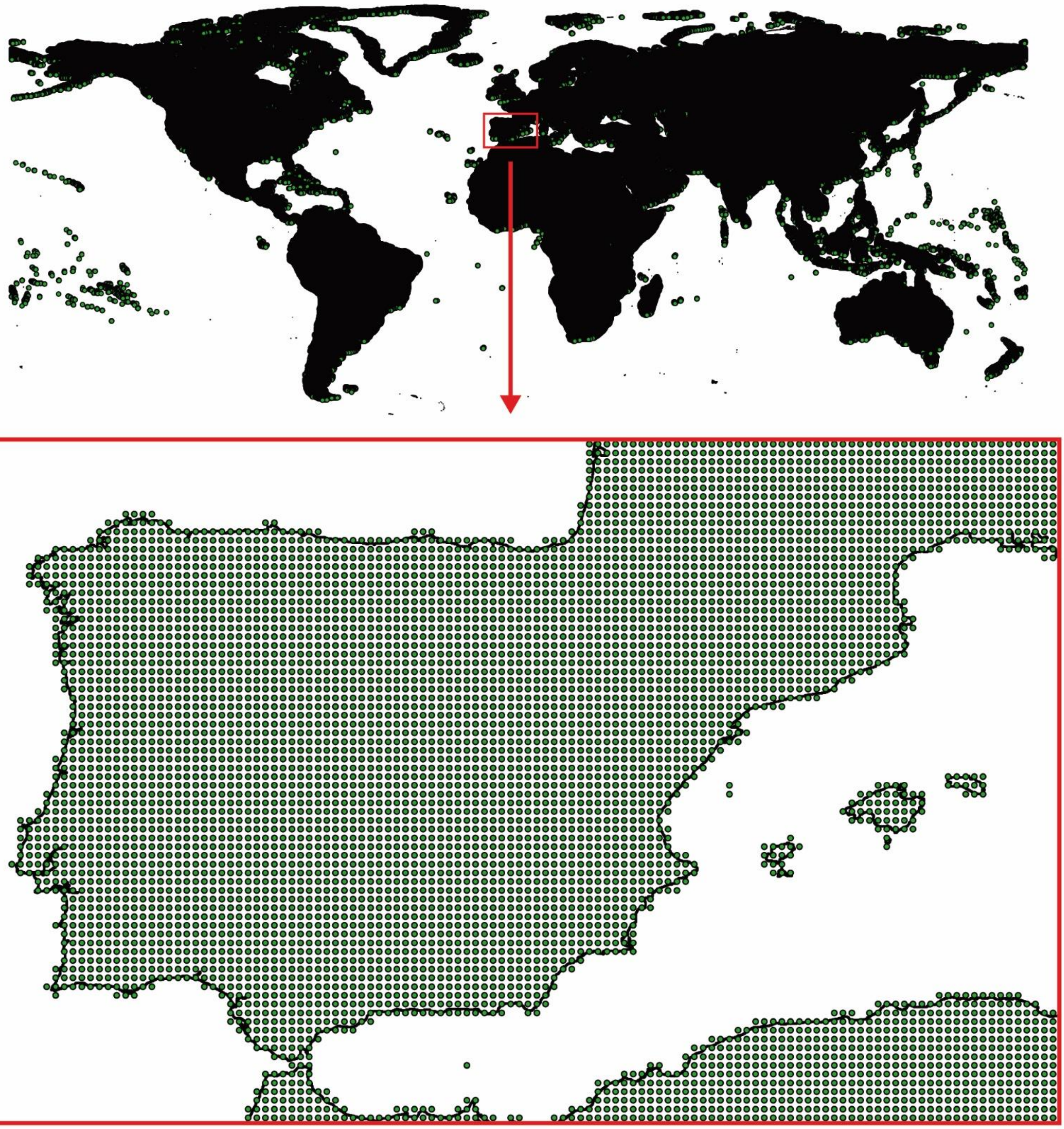

Fig. 3. Sample of the location analysed in the research.

3. Results and discussion

3.1. Application of the adaptive model from ASHRAE 55-2017

The performance of the spatial interpolations of each variable of the adaptive strategies was assessed. This analysis was independently performed for each combination of year and scenario used. Table 3 shows the results of the current scenario, and Table 4 shows the results of the future scenarios. The results obtained in the variables were satisfactory. There was a high similarity between the actual and the interpolated values of the testing dataset, with determination coefficients greater than 84% in all the variables, and with maximum values of up to 96.25%. Likewise, the error parameters were appropriate according to the value range of each variable. The percentage variables (AATCM, NAATCM-UT, NAATCM-LT, V-80, and V-90) obtained values for MAE and RMSE between 0.69 and 3.50% and between 2.58 and 8.12%, respectively. These error values were acceptable in the value scale of these variables (between 0 and 100%). Regarding the variables of both hourly heating degrees (SHST-19, SHST-20, SHST-21, SHST-23, AHST-80, and AHST-90) and hourly cooling degrees (SCST-19, SCST-20, SCST-21, SCST-23, ACST-80, and ACST-90), the values of the error parameters were appropriate for each variable. The values obtained in the statistical parameters were different in each variable, but appropriate according to the variable: (i) the variables of static heating setpoint temperatures obtained values of MAE that oscillated between 5,746.19 and 7,808.80 ºC (for an actual value scale in these variables of up to 437,071.00 ºC); (ii) similar values were obtained for the adaptive heating setpoint temperatures due to the similarity of the actual value range of these variables (of up to 396,775.0 ºC); (iii) as for cooling static setpoint temperatures, the values of MAE oscillated between 1,590.74 and 3,037.56 ºC (for an actual value range of up to 127,635.10 ºC); and (iv) adaptive cooling setpoint temperatures obtained values of MAE between 710.03 and 2,146.08 ºC due to the lower actual value range of these variables (of up to 67,999.28 ºC).

Table 3. Values obtained by assessing the testing statistical parameters of the variables of the current scenario.

Variable	R^2 [%]	MAE [(1)]	RMSE [(1)]
AATCM	95.08	3.20	6.68
NAATCM-UT	84.54	0.69	2.58
NAATCM-LT	95.96	2.73	6.30
V-80	93.63	2.90	5.66
V-90	92.90	2.28	4.55
SHST-19	96.07	6408.45	13940.36

SHST-20	96.13	6737.41	14381.06
SHST-21	96.17	7082.97	14829.19
SHST-22	96.21	7442.46	15281.70
SHST-23	96.22	7808.80	15735.87
SCST-23	90.05	3037.56	5852.29
SCST-24	89.80	2650.55	5138.66
SCST-25	89.64	2274.23	4449.19
SCST-26	89.56	1917.90	3802.50
SCST-27	89.52	1590.74	3215.15
AHST-80	96.04	6077.87	12952.14
AHST-90	96.10	6395.13	13326.57
ACST-80	89.92	710.03	1459.12
ACST-90	90.11	915.61	1803.37

(1) Unit according to each variable.

Table 4. Values obtained by assessing the testing statistical parameters of the variables of the future scenarios.

Year	Variable	RCP 2.6			RCP 4.5			RCP 8.5		
		R^2 [%]	MAE (2)	RMSE (2)	R^2 [%]	MAE (2)	RMSE (2)	R^2 [%]	MAE (2)	RMSE (2)
2050	AATCM	93.96	3.31	6.98	93.60	3.43	7.04	93.20	3.50	7.09
	NAATCM-UT	86.52	0.90	3.15	87.31	1.09	3.45	89.14	1.25	3.67
	NAATCM-LT	95.40	2.67	6.42	95.36	2.63	6.38	95.25	2.60	6.37
	V-80	94.06	2.78	5.27	94.12	2.78	5.12	94.06	2.78	5.04
	V-90	93.39	2.20	4.27	93.55	2.19	4.15	93.50	2.22	4.09
	SHST-19	96.08	5968.88	13089.48	96.04	5833.25	12846.72	95.86	5746.19	12809.67
	SHST-20	96.14	6279.07	13530.39	96.11	6131.30	13279.66	95.94	6044.84	13244.96
	SHST-21	96.19	6603.89	13977.73	96.17	6446.15	13719.16	96.01	6359.93	13684.85
	SHST-22	96.23	6943.13	14431.24	96.22	6775.50	14165.11	96.07	6688.91	14129.89
	SHST-23	96.25	7294.79	14888.97	96.26	7118.36	14616.05	96.12	7031.99	14579.25
	SCST-23	90.56	3384.31	6414.12	90.89	3559.64	6755.78	91.71	3729.49	6878.46
	SCST-24	90.29	3001.19	5706.69	90.56	3185.14	6064.53	91.43	3356.82	6208.62
	SCST-25	90.10	2616.85	5005.22	90.32	2803.90	5365.10	91.23	2973.80	5525.38

	SCST-26	90.00	2241.57	4332.21	90.15	2427.33	4683.47	91.09	2591.96	4857.01
	SCST-27	89.98	1888.91	3704.61	90.05	2064.98	4038.59	91.00	2224.27	4221.96
	AHST-80	96.10	5662.56	12105.79	96.05	5550.98	11895.99	95.87	5471.87	11868.23
	AHST-90	96.16	5977.65	12488.15	96.12	5858.19	12275.07	95.96	5779.10	12249.11
	ACST-80	90.35	867.40	1721.72	90.36	952.70	1895.41	91.03	1049.22	2052.57
	ACST-90	90.50	1093.55	2097.35	90.53	1190.07	2291.29	91.26	1294.02	2445.21
2100	AATCM	93.90	3.32	7.01	91.98	3.65	7.32	86.76	4.52	8.12
	NAATCM-UT	86.49	0.91	3.14	89.40	1.52	4.04	88.96	3.16	6.68
	NAATCM-LT	95.37	2.67	6.46	94.66	2.54	6.49	94.45	2.30	5.89
	V-80	94.09	2.80	5.26	93.21	2.85	5.05	87.33	3.21	5.60
	V-90	93.44	2.19	4.25	92.99	2.21	3.99	86.45	2.53	4.47
	SHST-19	96.04	5957.26	13099.36	95.79	5464.86	12257.49	95.19	4776.90	11131.29
	SHST-20	96.11	6265.11	13539.71	95.88	5751.17	12691.77	95.31	5034.11	11564.06
	SHST-21	96.16	6588.58	13986.43	95.96	6050.35	13130.05	95.43	5305.13	12000.11
	SHST-22	96.20	6927.58	14438.56	96.02	6364.58	13574.43	95.53	5591.28	12440.75
	SHST-23	96.23	7280.14	14894.74	96.07	6692.91	14025.99	95.63	5892.38	12886.90
	SCST-23	90.55	3383.09	6432.08	91.50	4007.82	7555.34	93.02	4883.90	8796.42
	SCST-24	90.27	3001.48	5726.31	91.14	3652.09	6899.24	92.73	4569.45	8234.52
	SCST-25	90.08	2617.30	5024.21	90.84	3279.07	6211.61	92.46	4232.75	7634.75
	SCST-26	89.98	2243.00	4349.48	90.62	2895.31	5513.68	92.23	3874.45	6999.79
	SCST-27	89.96	1890.05	3719.41	90.46	2516.28	4832.74	92.05	3498.52	6339.88
	AHST-80	96.07	5654.56	12103.72	95.82	5200.59	11331.99	95.22	4561.63	10292.71
	AHST-90	96.13	5967.68	12486.39	95.91	5500.38	11717.22	95.37	4839.13	10687.38
	ACST-80	90.39	859.33	1718.65	90.67	1195.32	2342.54	91.97	1834.48	3439.02
	ACST-90	90.53	1086.79	2096.79	90.85	1457.51	2783.73	92.17	2146.08	3933.15

(2) Unit according to each variable.

Thus, the interpolated values could be considered valid for the goal of this study. Appendix A includes the spatial representations of each adaptive variable analysed in the research. First, the distribution of the percentage of days of the year when the adaptive models were applied was analysed. The analysis was based on the number of data corresponding to intervals of 10% in the dataset obtained by 997,000 locations. Fig. 4 shows applicability of the adaptive thermal comfort model in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios. The application interval with more points corresponded to the interval between 90 and 100% of the days of the year, particularly in the current scenario, in which the interval corresponded to 298,426 points of the dataset (29.93%). Likewise, climate conditions in the current scenario presented a great potential to apply the adaptive models. An application range lower than 30% of the days of the year corresponded to 278,992 (27.98% of the dataset), and the application range greater than 50% of the days of the year corresponded to 50.90% of the dataset. The adaptive model from ASHRAE 55-2017 therefore presented a great application potential in the current scenario. However, the possibilities of applying the adaptive models varied in the future scenarios. This variation was similar in all the scenarios, although its severity level depended on the RCP scenario: locations with low percentages of application would be reduced, and the interval with a greater application (between 90 and 100%) would also be reduced. Likewise, the number of locations would increase in the application interval between 40 and 90%. However, the intensity of these changes also depended on the RCP scenario. Thus, the following variations took place in each scenario by going from the current scenario to 2050: (i) in the RCP 2.6 scenario, the intervals lower than 40% obtained decreases between 0.45 and 6.04%, and the interval between 90 and 100% obtained a decrease of 1.24%. The application intervals between 40 and 90% obtained increases between 0.24 and 1.63%; (ii) in the RCP 4.5 scenario, the intervals lower than 40% were similar to the RCP 2.6 scenario (with decreases between 0.49 and 6.10%), and the application interval greater than 90% obtained a decrease of 2.43%. Thus, the increase was greater in the intermediate intervals (between 0.36 and 2.36%); and (iii) the RCP 8.5 scenario was characterised by decreasing the application intervals lower than 30% as the other two scenarios, but with a greater increase in the interval between 90 and 100% (with a decrease of 3.43%). An increase of up to 3.20% was obtained in the intermediate intervals.

Thus, the scenarios in 2050 would modify the possibilities of applying the adaptive model with similar tendencies to those expected with the A2 scenario [77]. In general terms, the possibilities of applying the model were increased because the application percentage between 50 and 90% increased the amount of locations. However, the interval of greatest application (i.e., between 90 and 100%) decreased. Nevertheless, the major changes took place in 2100. Using the current scenario as reference, a greater difference among the tendencies of each scenario is expected in 2100. Moreover, the RCP 2.6 scenario obtained similar values to those obtained in 2050 (with increase and decrease deviations in the percentage values between 0.03 and 0.37%), and the greatest differences were detected in the RCP 4.5 and 8.5 scenarios. The application interval greater than 90% was reduced by 5.28% in the RCP 4.5 scenario, and by 14.24% in the RCP 8.5 scenario. Likewise, the interval between 40 and 90% increased the locations between 1.49 and 4.26 in the RCP 4.5 scenario, and between 1.41 and 10.04 in the RCP 8.5scenario. Although the adaptive model could present better possibilities of application throughout the 21st century, many locations with the greatest possibilities of application could be lost according to the scenario. This aspect directly influenced the percentage of days over and below the application threshold of the adaptive thermal comfort model from ASHRAE 55-2017. In the current scenario, the most predominant percentage of days of the year that exceeded the upper threshold (Fig. 5) was the lowest (i.e., the interval between 0 and 10%). This interval was the most predominant in the remaining combinations of scenarios and year analysed, although the percentage of locations was reduced. In this interval there were therefore percentage reductions of 2.60% with the RCP 2.6 scenario, 4.25% with the RCP 4.5 scenario, and 5.79% with the RCP 8.5 scenario in 2050. These increase tendencies were detected in the reduction of the percentage of days in which the adaptive model was not applied because the upper threshold was exceeded. The RCP 8.5 scenario with greater outdoor temperatures would generate a greater percentage of days exceeding the upper threshold in 2050. These variations in the interval between 0 and 10% of the days of the year exceeding the upper limit was increased in 2100: the RCP 2.6 scenario obtained a variation of 0.14% in comparison with 2050, and the variations of the RCP 4.5 and 8.5 scenarios were 4.24% and 15.85%, respectively. These variations increased the percentages of locations of the remaining intervals exceeding the upper limit. This was detected in two aspects: (i) the increase of the percentage of locations in the intervals greater than 10%, and (ii) the emergence of intervals with high percentages of days exceeding the upper limit that did not take place in the current scenario. In the former the percentages greater than 10% increased between 0.74 and 1.51% in 2050 and between 0.28 and 4.86% in 2100 in comparison with the current scenario. New intervals emerged in all the combinations of scenarios and year, from a maximum interval between 40 and 50% in the current scenario to intervals between 50 and 60% in 2050 with the RCP 2.6 and 4.5 scenarios and reaching an interval between 90 and 100% in some locations in 2100 with the RCP 8.5 scenario. These variations would also imply a lower percentage of days of the year when the adaptive model cannot be applied by being below the lower threshold (Fig. 6). Although in the current scenario the percentage of days when the adaptive model cannot be applied with a larger number of locations corresponded to the percentage between 0 and 10%, there were distribution locations in the remaining intervals. The climate variations expected throughout the 21st century reduced the high non-application intervals of the adaptive model, whereas in the interval between 0 and 10% of the days of the year there were increases between 1.07 and 2.06% in 2050 and between 1.14 and 5.42% in 2100.

These results therefore showed the greater vulnerability presented by the planet to apply adaptive strategies in the future. Although the increase of the outdoor temperature (which varies according to the RCP scenario) could mean a greater application in many areas, the zones presenting nowadays a greater application percentage throughout the year could be in more and more extreme situations by exceeding the upper threshold, thus limiting the possibility of applying the adaptive models. Apart from limiting the energy saving possibilities in the built environment of these locations, habitability conditions could also be affected. In this regard, the increase of the percentage of days of the year with values of $\overline{t_{pma(out)}}$ greater than 33.5 ºC could be a great challenge to achieve appropriate habitability conditions in the urban environment.

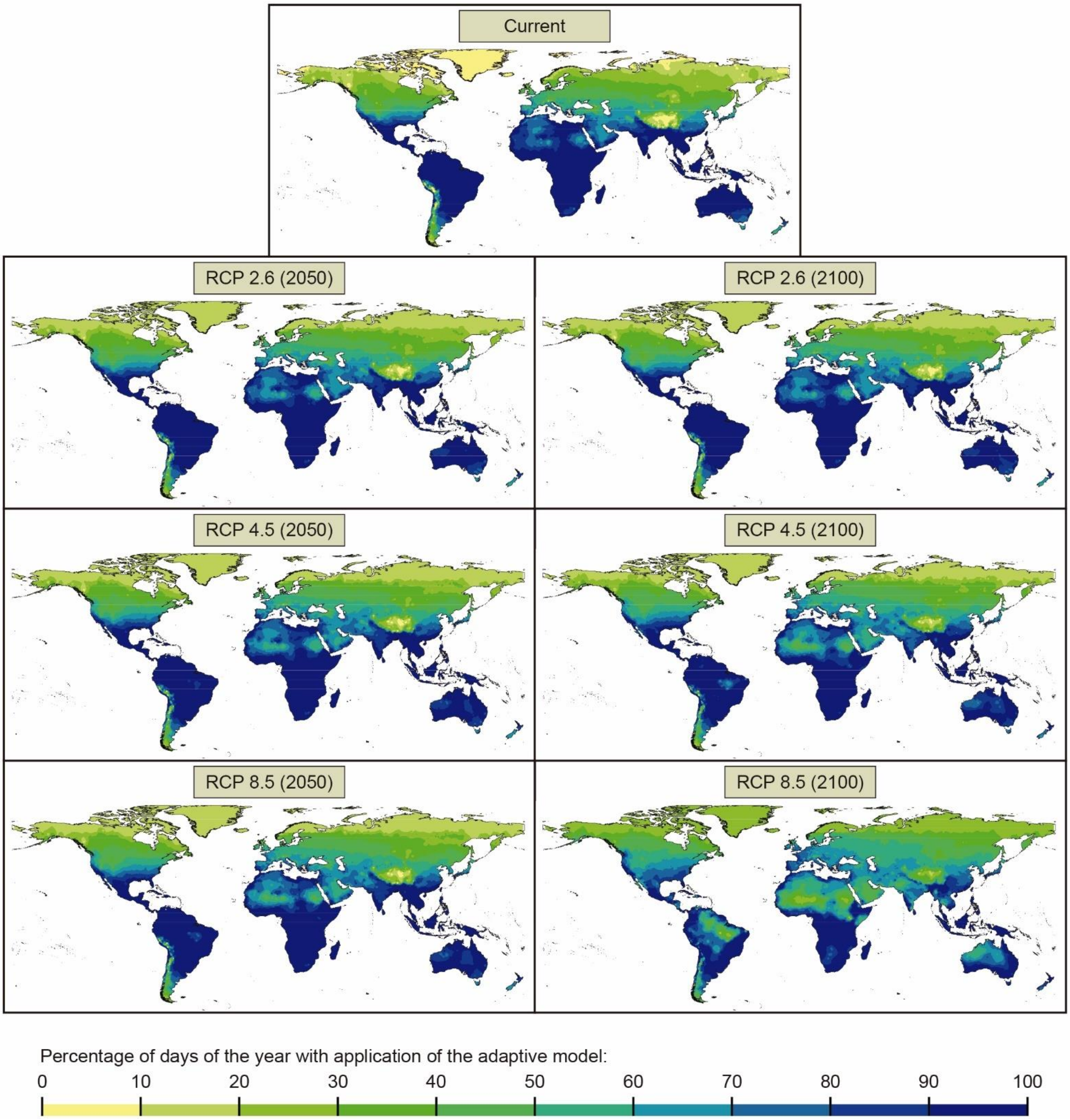

Fig. 4. Percentage of days of the year with application of the adaptive thermal comfort model in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

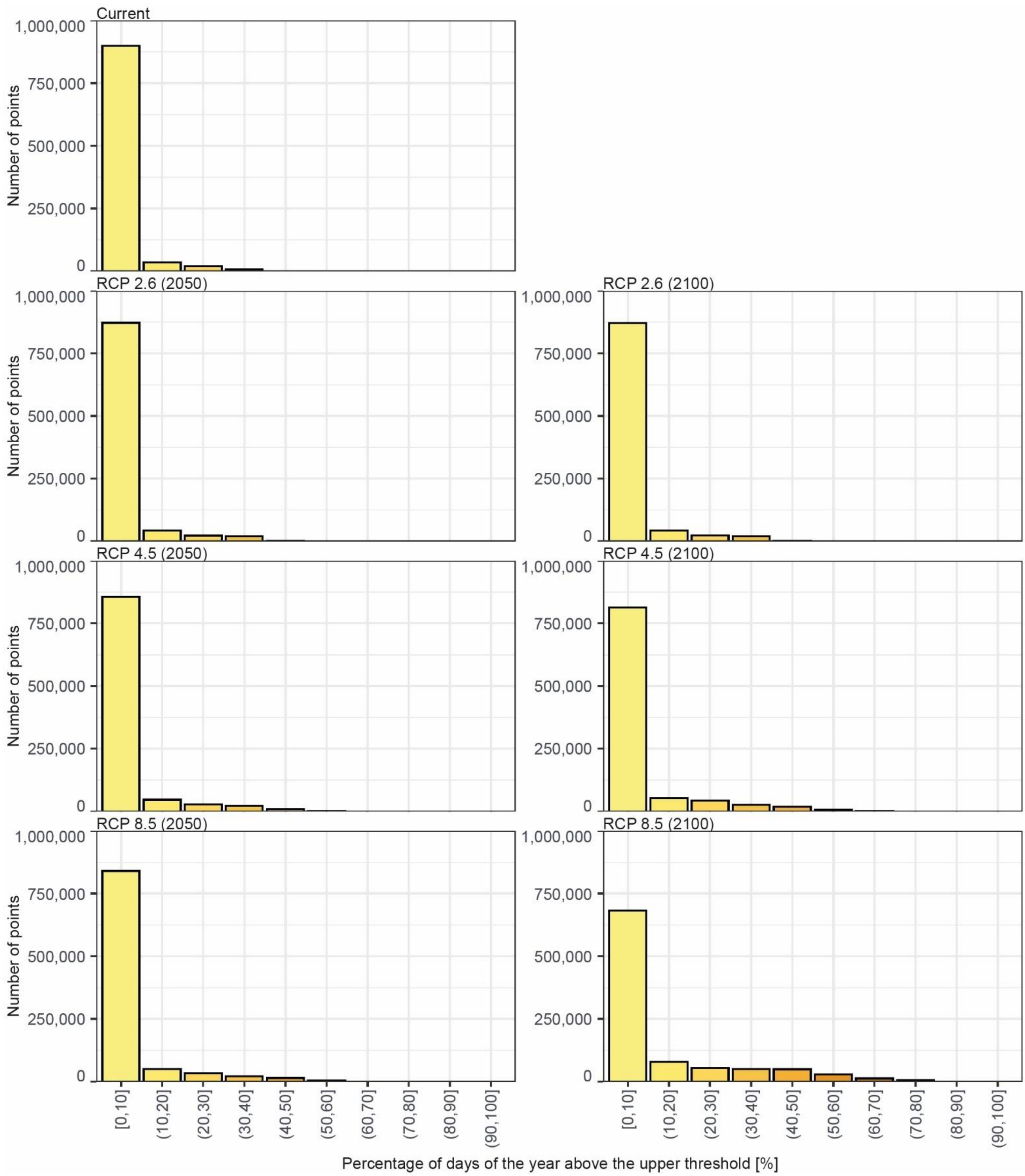

Fig. 5. Evolution of the annual percentage of days when the adaptive model cannot be applied by exceeding the upper threshold.

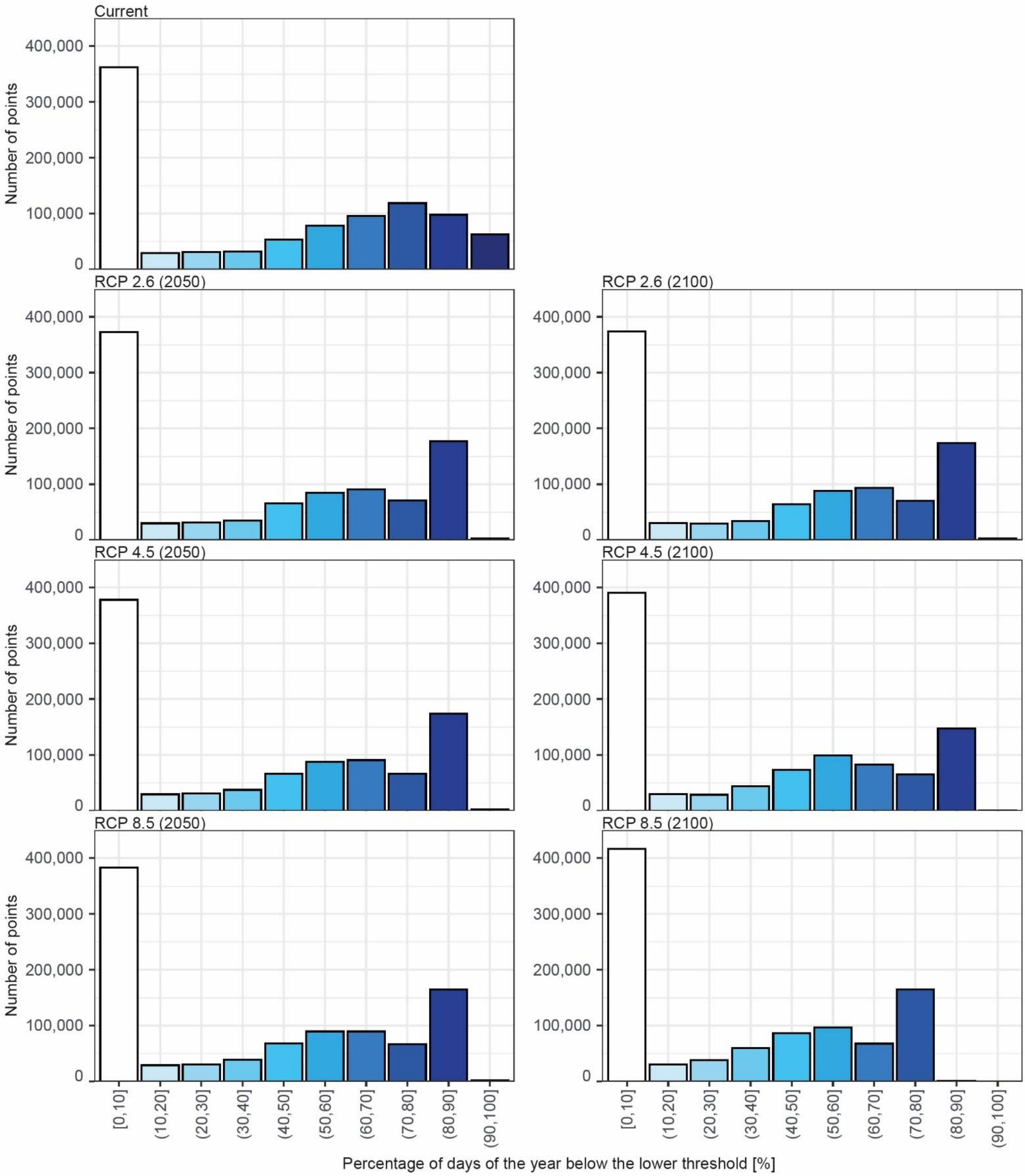

Fig. 6. Evolution of the annual percentage of days when the adaptive model cannot be applied by being below the lower threshold.

3.2. Potential of applying adaptive energy saving strategies

Apart from the tendencies detected in the potential of applying the adaptive model from ASHRAE 55-2017, the effectiveness of the adaptive energy saving strategies in the built environment should be known. As indicated in Section 2.1, the adaptive energy saving strategies could be divided into adaptive natural ventilation and adaptive setpoint temperatures. The former was assessed according to the percentage of hours of the year when the outdoor temperature was within the thermal comfort limits. Thus, the results should be independently analysed for the 80% (Fig. 7) and 90% (Fig. 8) acceptabilities. In the current scenario the most predominant interval of percentage of hours of the year to apply adaptive natural ventilation was between 0 and 10%: it corresponded to both 36.48% of locations in the 80% acceptability and 43.85% in the 90% acceptability. These values were related to latitudes close to the poles, prevailing the cold season throughout the year. However, the application percentages of adaptive natural ventilation were obtained in intervals greater than 10%. This corresponded to the warmest seasons, thus reducing the use of HVAC systems. Moreover, an application range of up to both 90 and 100% of the hours of the year was obtained in the 80% acceptability. This mainly took place in the latitudes close to the equator, but only in some locations. However, the interval between 20 and 80% of the hours of the year obtained a higher percentage of locations (43.42%). Thus, more than 43% of the locations that could apply the adaptive natural ventilation in at least warm seasons, including regions such as the Mediterranean area, thus becoming an interesting aspect to achieve a decarbonisation in this region due to the difficulties to implement nZEB standards [85]. However, the percentage of acceptability used to establish the thermal comfort limits should be considered due to the loss of effectiveness with the 90% acceptability. In this regard, the use of the 90% acceptability for natural ventilation in the current scenario reduced the maximum interval by the range between 70 and 80% (it was between 90 and 100% with the 80% acceptability), thus reducing the percentage of locations by 7.63% in the application interval between 20 and 80% of the hours of the year.

Regarding the impact of future scenarios on the possibility of applying natural ventilation, three aspects could be expected: (i) a reduction in the percentage of locations with the lowest application possibility of natural ventilation (between 0 and 10% of the hours of the year), (ii) a reduction in the greatest application percentages obtained in each category of acceptability from ASHRAE 55-2017, and (iii) an increase in the percentage of locations with an application greater than 20% of the hours of the year. However, and similarly to the application of the adaptive model, the intensity of the changes depended on the RCP scenario with respect to the current scenario. This can be seen in the lowest application percentage of the hours of the year: (i) the RCP 2.6 scenario obtained a reduction of 3.99% in 2050 and of 3.86% in 2100; (ii) the RCP 4.5 scenario obtained a reduction of 5.22% in 2050 and of 9.66% in 2100, and (iii) the RCP 8.5 scenario obtained a reduction of 7.06% in 2050 and of 15.13% in 2100. Thus, climate change would generate a greater possibility of applying natural ventilation throughout the year in the zones with the lowest application of natural ventilation in the current scenario. In general terms, climate change would limit the use of natural ventilation, particularly in the case of a high radiative forcing because the percentage of locations in applications greater than 30% of the hours of the year is reduced. Although these tendencies were detected in the A2 scenario [77], they did not show a high change tendency such as that obtained in the RCP 4.5 and 8.5 scenarios. Thus, the climate evolution throughout the 21st century could limit the use of adaptive natural ventilation in various magnitude commands. This is crucial in regions whose built environment is traditionally influenced by using natural ventilation [92–94].

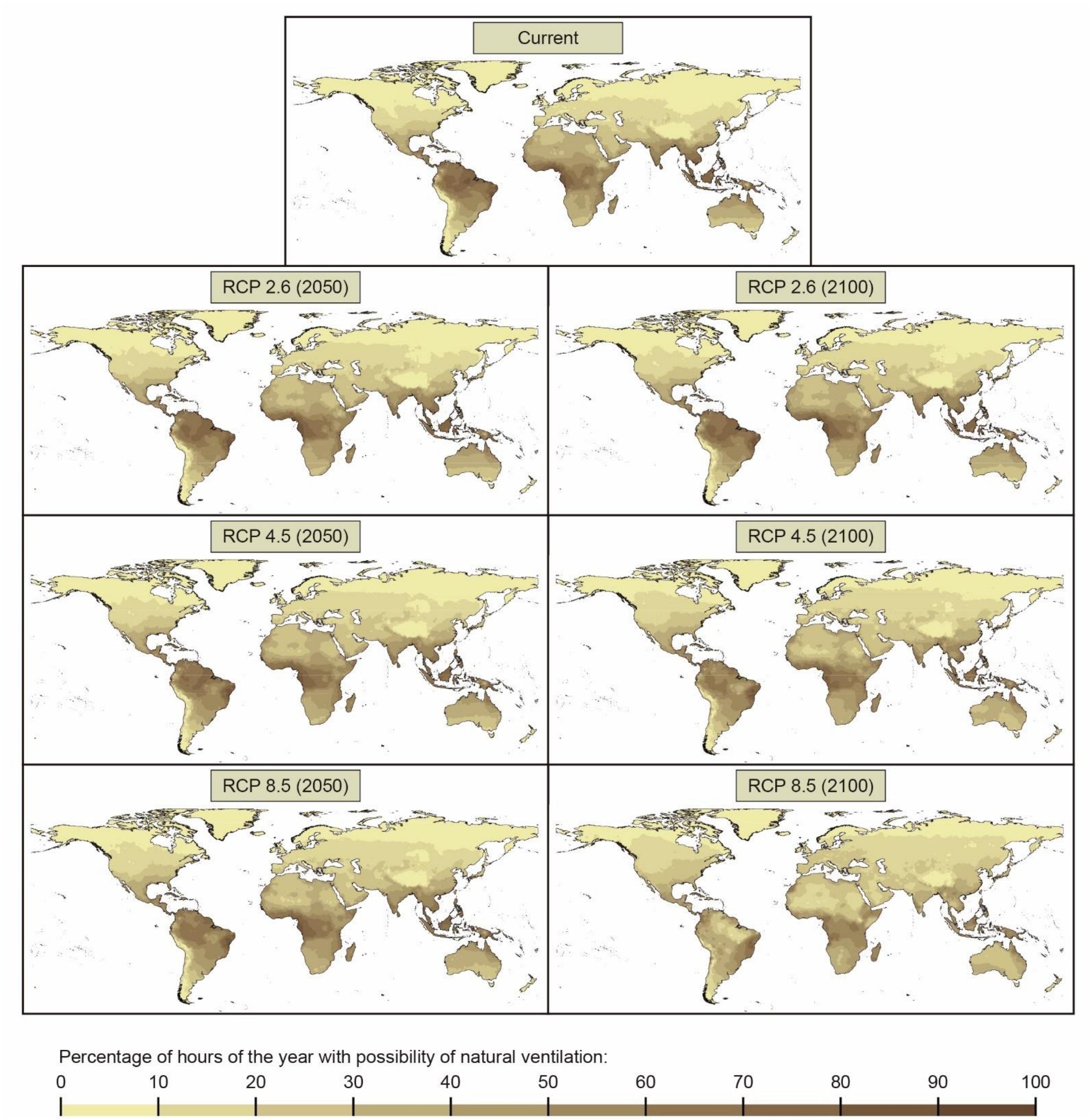

Fig. 7. Percentage of hours of the year to use the natural ventilation based on the 80% acceptability in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

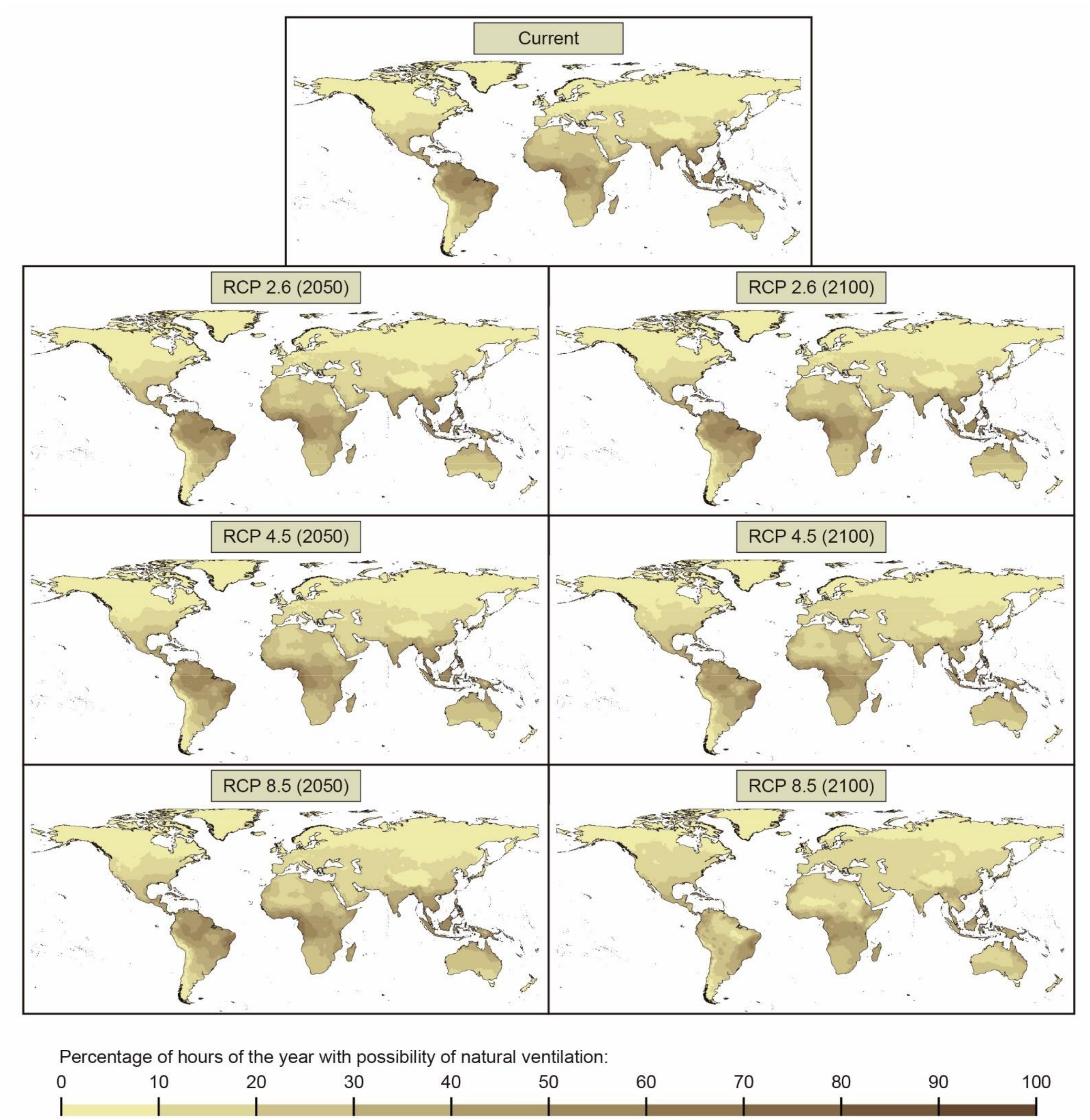

Fig. 8. Percentage of hours of the year to use the natural ventilation based on the 90% acceptability in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

Regarding the hourly saving in heating and cooling degrees by using adaptive setpoint temperatures, Fig. 9 shows the saving distributions obtained with respect to the static setpoint temperatures considered in the research. In addition, distinctions were made depending on whether the adaptive setpoint temperatures were adjusted to the 80% or 90% acceptability. As for the saving in heating degrees, the results showed the limitations of using adaptive setpoint temperatures to achieve savings in comparison with static patterns. However, there were many locations in which their use was counterproductive. This can be seen in the quartile distribution values of the 80% acceptability in the current scenario: (i) the saving in hourly degrees with respect to a static setpoint temperature of 19 and 20 ºC obtained negative values of 1442.98 and 121.46 ºC, respectively, in the value of the first quartile (Q1); and (ii) the minimum saving values obtained were always negative with respect to the static setpoint temperature of 21, 22 and 23 ºC. Nonetheless, positive values were obtained in the values of the second (Q2) and third (Q3) quartile: (i) saving values of 5,406, 11,890, 18,666, 25,709 and 33,009 ºC were obtained in Q2 with respect to the static setpoint temperatures of 19, 20, 21, 22 and 23 ºC, respectively; and (ii) saving values of 10,530, 18,720, 27,028, 35,441 and 43,937 ºC were obtained in Q3 with respect to the static setpoint temperatures of 19, 20, 21, 22 and 23 ºC, respectively. Likewise, the maximum values in the distributions oscillated between 14,017 and 49,057 ºC. Despite the limitations detected with the adaptive setpoint temperatures in certain regions, their use could save appropriate heating degrees with respect to static patterns, thus leading to both a lower building energy demand and a saving in the energy consumption. The saving depended on the static operational patterns existing before implementing the adaptive strategies. Thus, the use of an effective static pattern (through a low static setpoint temperature) limited the saving achieved by the adaptive setpoint temperatures. However, the possibility of obtaining values in the lower limit below 19 ºC (the lowest value considered for a static heating pattern) allowed savings to be achieved. Nonetheless, the use of the 90% acceptability would limit the effectiveness of the adaptive heating setpoint temperatures with respect to the static patterns with a low setpoint temperature, since the energy saving distributions were lower than with the 80% acceptability (with an average reduction of 5,995 ºC) and there were greater negative values in the quartiles (e.g., the saving distribution in heating degrees was characterised by presenting negative values in Q2 with respect to the static temperature of 19 ºC). The influence of climate change did not significantly vary the saving tendencies in heating degrees obtained with the adaptive setpoint temperatures, although the level of radiative forcing decreased the heating demand. Thus, the following average reduction values were obtained in the quartile values: (i) the RCP 2.6 scenario obtained a similar average reduction with respect to the current scenario throughout the 21st century, with values of 524 ºC in 2050 and of 513 ºC in 2100; (ii) the RCP 4.5 scenario obtained an average reduction of 731 ºC in 2050 and of 1341 ºC in 2100; and (iii) the RCP 8.5 scenario obtained an average reduction of 943 ºC in 2050 and of 2528 ºC in 2100. The RCP 4.5 and 8.5 scenarios progressively reduced the saving in hourly degrees obtained with the adaptive setpoint temperatures, particularly in 2100. Thus, the lowest heating energy demand caused by climate change is expected to imply a reduction of the effectiveness of the adaptive heating setpoint temperatures. This aspect mainly takes place due to the obtaining of higher values for the lower limit, reducing the thermal differential with respect to the reference values used for the static patterns.

Nevertheless, the adaptive setpoint temperatures could be greatly used for the cooling energy saving as positive energy saving results were obtained in most of the combinations analysed. With the 80% acceptability in the current scenario, the energy saving was positive in the quartile distribution values. Values oscillated between 2 and 452 ºC in Q1, between 695 and 4,345 ºC in Q2, between 5,387 and 20,806 ºC in Q3, and between 27,857 and 62,726 ºC in the maximum values. The use of the 90% acceptability implied an average reduction in the saving in cooling degrees of 1,864 ºC and the emergence of a negative value in Q1 in the assumption of a static setpoint temperature of 27 ºC. This was due to the high energy efficiency of this static setpoint temperature that could obtain values greater than the upper limit of the adaptive model in certain regions. Regarding climate change, the saving in cooling degrees increased. The average increase varied according to the scenario and year: (i) the RCP 2.6 scenario obtained an average increase in the saving with respect to the current scenario of 1,313 and 1,472 ºC in 2050 and 2100, respectively. Likewise, the maximum increases were 3,789 and 3,833 ºC in 2050 and 2100; (ii) the RCP 4.5 scenario obtained an average increase in the saving of 2,297 ºC in 2050 and of 2,783 ºC in 2100, with maximum values of up to 6,922 ºC; and (iii) the RCP 8.5 scenario obtained an increase in the saving achieved by the adaptive setpoint temperatures of 2,956 and 5,967 ºC in 2050 and 2100, respectively. Likewise, maximum increase values of 7,676 ºC in 2050 and of 16,631 ºC in 2100 were obtained.

These results therefore showed the great potential of using the adaptive setpoint temperatures to achieve energy savings in HVAC systems. The main potential is related to the degree saving in air conditioning systems, a key aspect in the climate context that the built environment should tackle throughout the 21st century because of a greater cooling energy demand. The use of adaptive cooling setpoint temperatures achieved important savings in all the assumptions of static patterns. Likewise, both heating setpoint temperatures and natural ventilation were also interesting measures to achieve energy savings by changing the operational pattern, although studies focused on each region or on each case study should be conducted to value the most appropriate way of implementing them due to the negative climate change impact expected through the RCP scenarios.

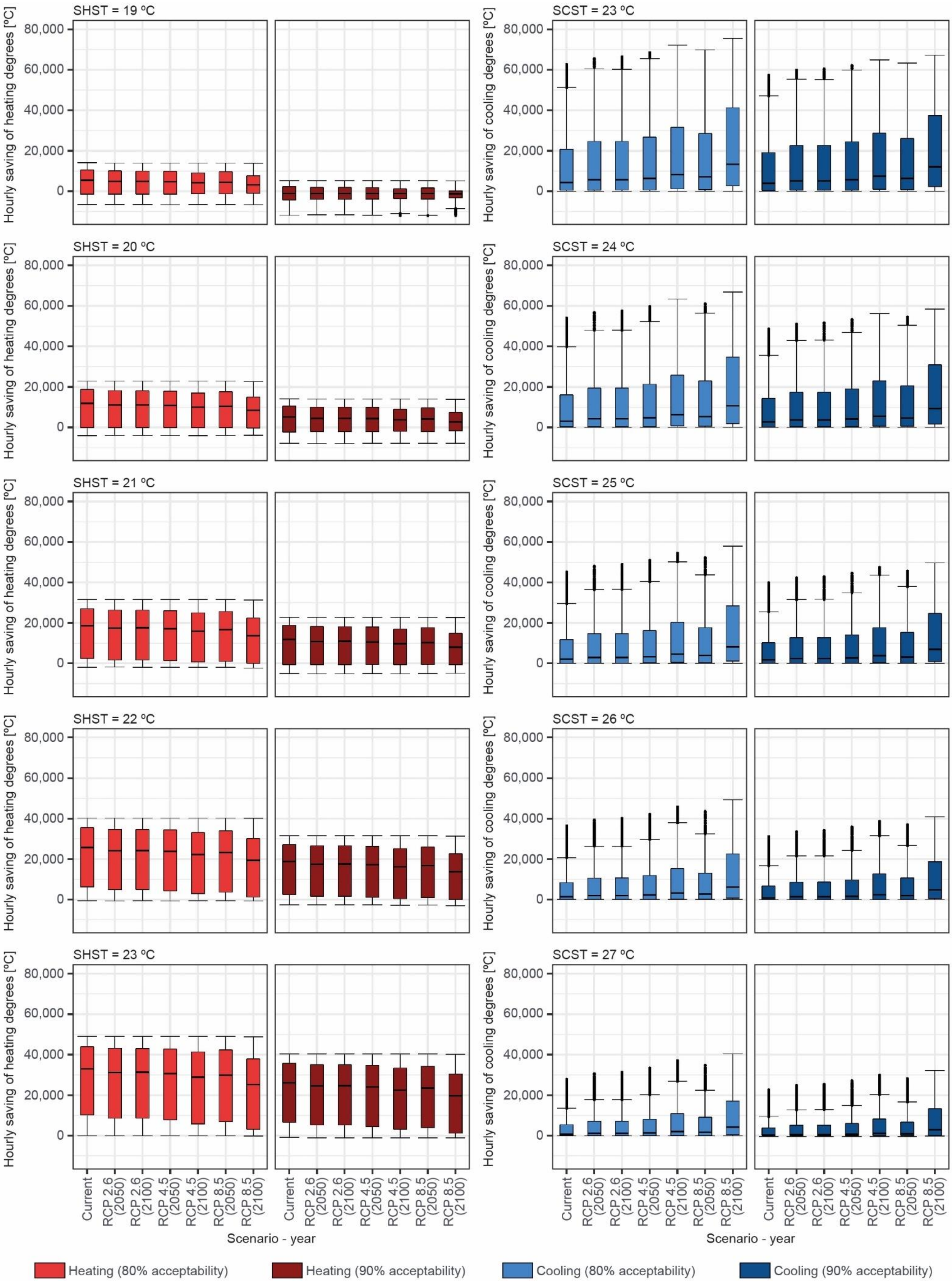

Fig. 9. Box plots with the degree saving between the adaptive and the static setpoint temperatures.

3.3. Relations between adaptive strategies and world population through the SSP scenarios

An essential aspect to analyse the application possibilities of the adaptive strategies worldwide is their influence on the world population. For this reason, the relations between the population tendencies throughout the 21st century and the adaptive variables were analysed (Fig. 10). Regarding the implications of the world population to apply the adaptive model from ASHRAE 55-2017, 53.3% of the world population in the current scenario lives in zones with an application percentage greater than 90% of the days of the year, and 1.96% of population lives in zones with an application percentage lower than 40%. The climate change effect changed the population percentage living in zones with an application percentage between 90 and 100%, with these variations being more important in the combinations of the RCP 4.5 and 8.5 scenarios with the most appropriate SSPs for each: (i) the percentage of population for this application interval oscillated between 54.72 (2050-SSP1) and 59% (2100-SSP4) with the RCP 2.6 scenario, (ii) the RCP 4.5 scenario obtained values between 49.55 and 53.12% in 2050 and between 42,57 and 49.33% in 2100, and (iii) the RCP 8.5 scenario obtained values of 48.04% in 2050 and of 29.29% in 2100. These values were fulfilled, together with the reduction of the population in the application percentage lower than 40% of the days of the year. It is therefore expected that climate change contributes to the fact that a greater percentage of population could apply the adaptive model throughout the year. However, the severity detected with the RCP 4.5 scenario and the population of SSP5 is a challenge to guarantee inhabitants' thermal comfort in most developing countries (as they are countries located in latitudes close to the equator). In addition, the percentage of the population living in regions with more days of the year when the upper threshold of the adaptive model is exceeded throughout the 21st century is increased. Regarding natural ventilation, the application percentage between 30 and 50% of the hours of the year obtained a progressive increase of the world population from the current scenario (30.02%) to the RCP8.5-SSP5 combination in 2100 (34.62%). Although the population living in the zone with the greatest application was progressively reduced (only SSP1, SSP2, and SSP4 obtained percentages between 2.08 and 2.67% of the population in 2100 with the RCP 2.6 scenario), the greatest concentration of population in the intermediate percentages showed the effectiveness of using natural ventilation to air-condition indoor spaces.

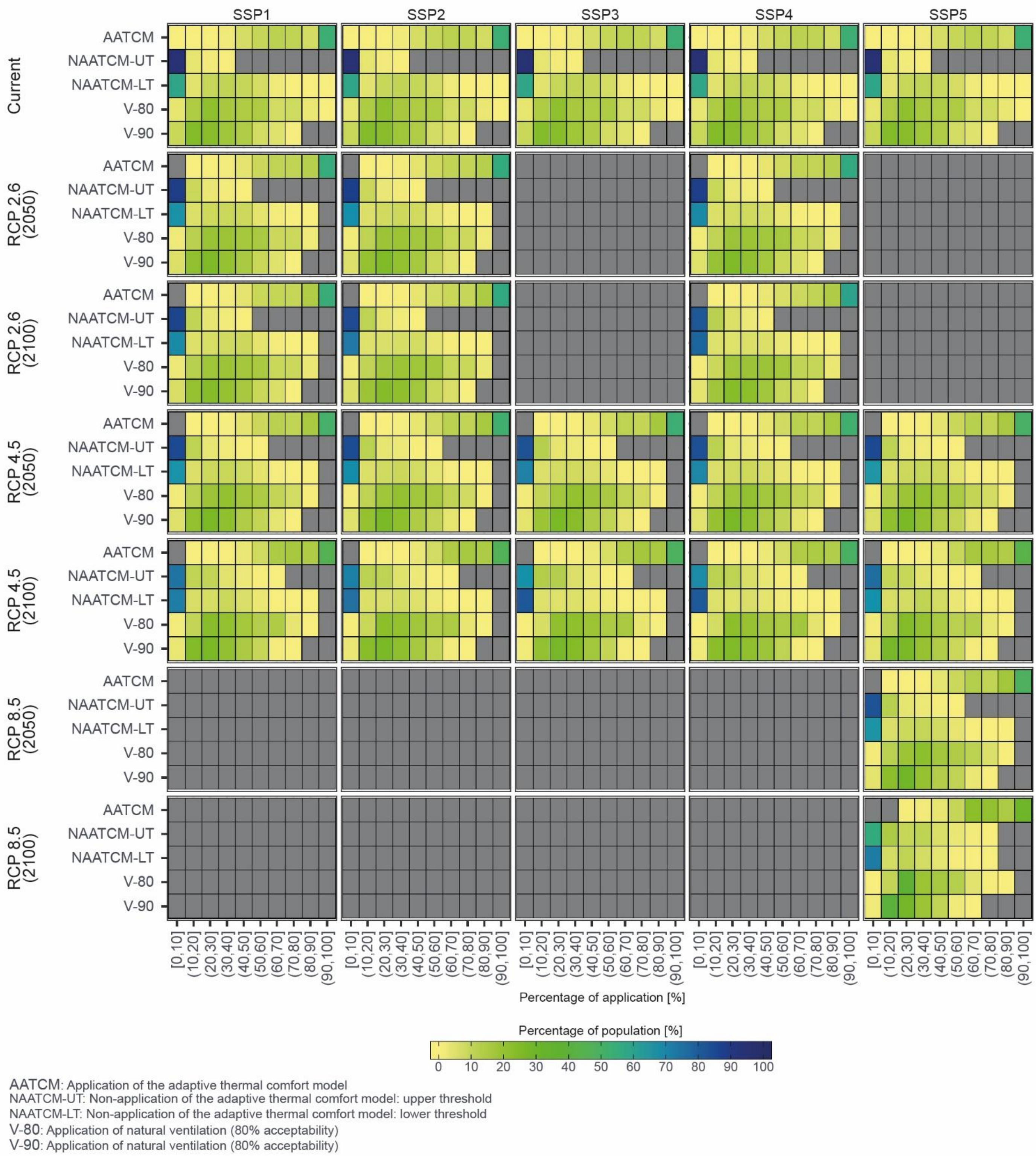

Fig. 10. Heatmap of the world population distribution with the SSP scenarios according to the relation of the application variables of the adaptive strategies.

4. Conclusions

This study analysed the influence of the RCP scenarios throughout the 21st century on the possibility of applying adaptive energy saving strategies in the built environment. Three aspects were analysed by using climate data worldwide: the possibilities of applying the adaptive model from ASHRAE 55-2017, the possibilities of applying adaptive natural ventilation, and the saving in hourly degrees with the adaptive setpoint temperatures. The RCP scenarios had various tendencies in the application of the adaptive measures. The RCP 2.6 scenario was characterised by a steady behaviour throughout the 21st century, with a general increase in the percentage of days in which the adaptive model can be applied. However, the RCP 4.5 and 8.5 scenarios generated a progressive loss in the application of the adaptive model, particularly the latter. The reason was a greater percentage of days in which the upper threshold to apply the adaptive model from ASHRAE (33.5 ºC) was exceeded, even obtaining locations with a percentage of days of the year between 60 and 100%. However, the most interesting aspect was the potential of applying the two energy saving measures related to the adaptive thermal comfort models: natural ventilation and adaptive setpoint temperatures. On the one hand, the RCP scenarios would reduce both the percentage of locations with the lowest possibility of applying natural ventilation (between 0 and 10% of the hours of the year) and the greatest application percentages obtained in each category of acceptability from ASHRAE 55-2017; moreover, the percentage of locations with an application greater than 20% of the hours of the year would be increased. This could imply that regions with a limited possibility of applying today natural ventilation move on to an intermediate level. Moreover, the stage based on using natural ventilation is expected to be longer in the Mediterranean area, thus limiting its use in the months with the greatest cooling energy demand. Likewise, the effectiveness of the vernacular architecture based on the potential of natural ventilation could be limited in regions with this type of designs.

On the other hand, variable savings could be achieved in heating and air conditioning systems by using adaptive setpoint temperatures. Although heating savings are expected in heating systems (particularly with respect to static operational patterns with high setpoint temperatures), the saving was greater in cooling systems. This aspect became very important by analysing the impact expected with the RCP scenarios, as the cooling energy demand is expected to prevail throughout the 21st century. The saving obtained with the adaptive heating setpoint temperatures slightly varied their distributions throughout the 21st century (with some reductions in 2100 with the RCP 4.5 and 8.5 scenarios), whereas the adaptive cooling setpoint temperatures obtained greater savings throughout the 21st century. Thus, adaptive models have a great potential to achieve reductions in the cooling energy consumption at the same time users' thermal comfort is kept. This becomes important due to the possible difficulties to achieve a total decarbonisation of the built environment in warm regions.

To conclude, the results of this study are of great interest to establish policies focused on improving the energy performance of the built environment. These results show the variable tendencies of the adaptive strategies throughout the 21st century and constitute a key aspect to develop energy policies. Furthermore, users' operational adaptation without the need of intervening in buildings could contribute to the mitigation of fuel poverty cases due to the difficulties of many families to finance energy conservation measures. Likewise, these measures could guarantee a more appropriate transition towards a decarbonisation of the built environment by 2050, an aspect difficult to achieve through the current energy renovation rate of the building stock. Nonetheless, there are limitations related to the type of data analysis. Through a multivariable analysis, future studies should focus on the influence of the combinations of insulation, orientation, form, and surface by using the adaptive strategies worldwide.

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Appendix

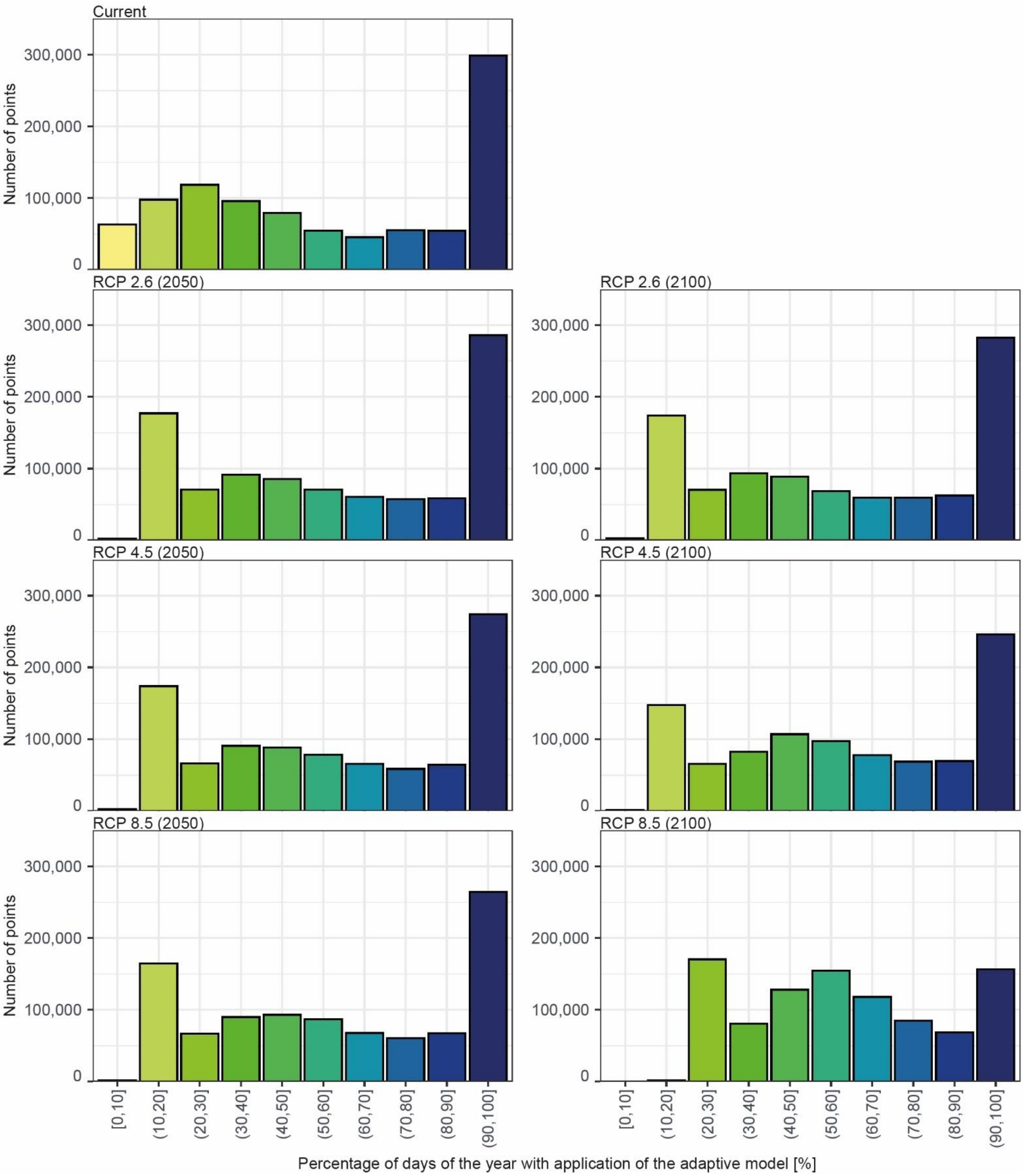

Fig. A1. Evolution of the annual percentage of days when the adaptive model can be applied in the various scenarios.

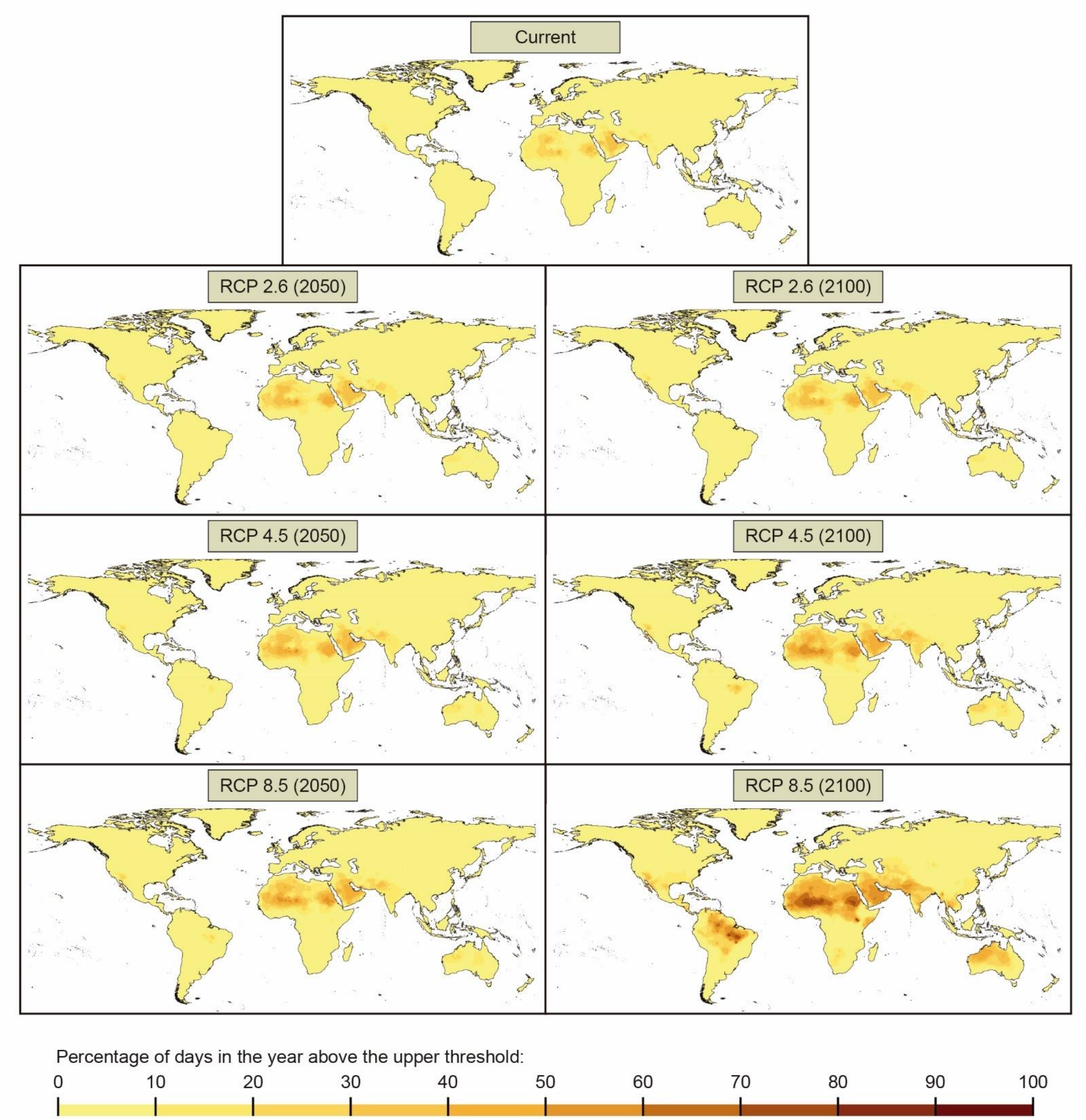

Fig. A2. Percentage of days of the year with non-application of the adaptive thermal comfort model (above the upper threshold) in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

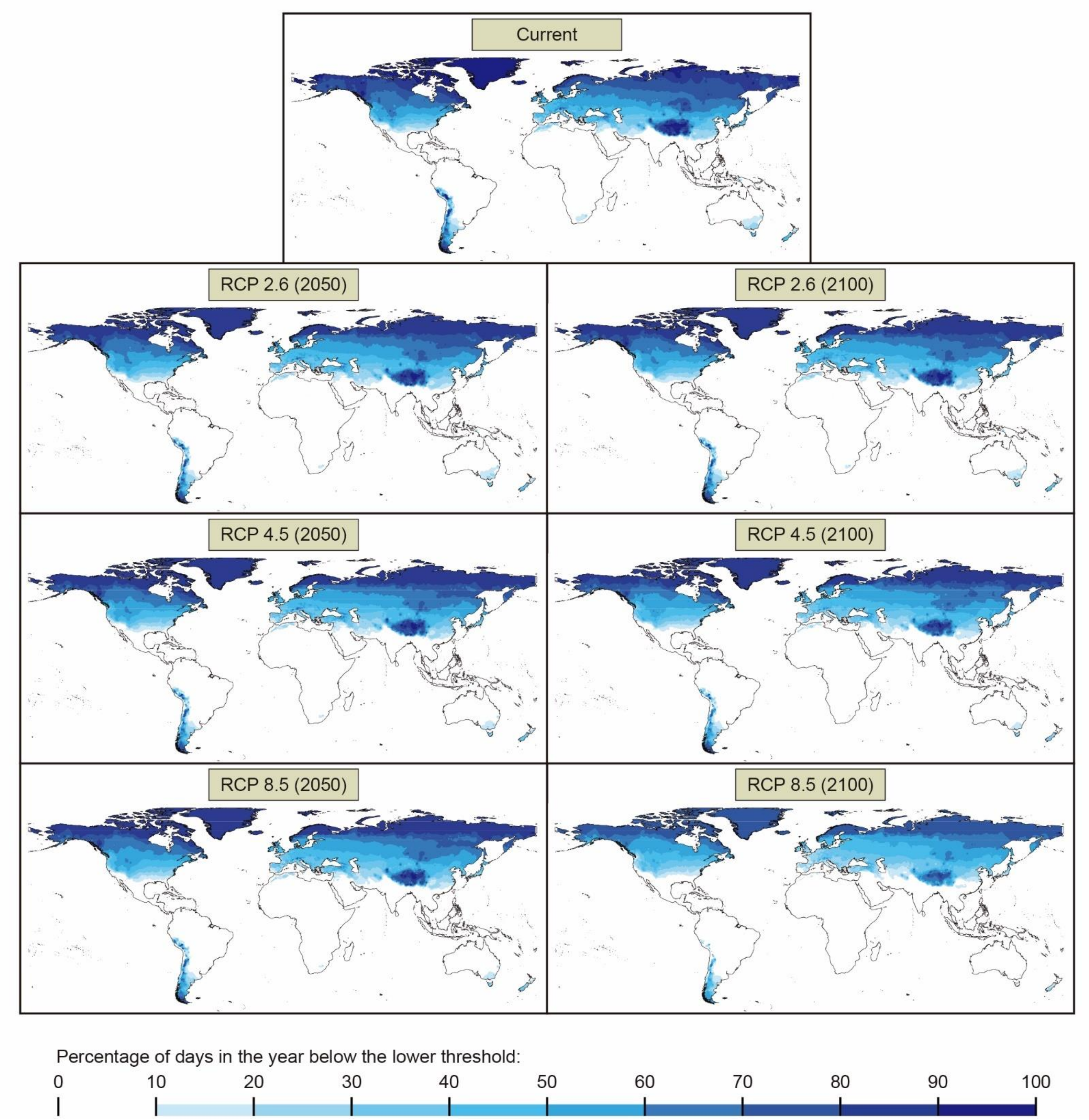

Fig. A3. Percentage of days of the year with non-application of the adaptive thermal comfort model (below the lower threshold) in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

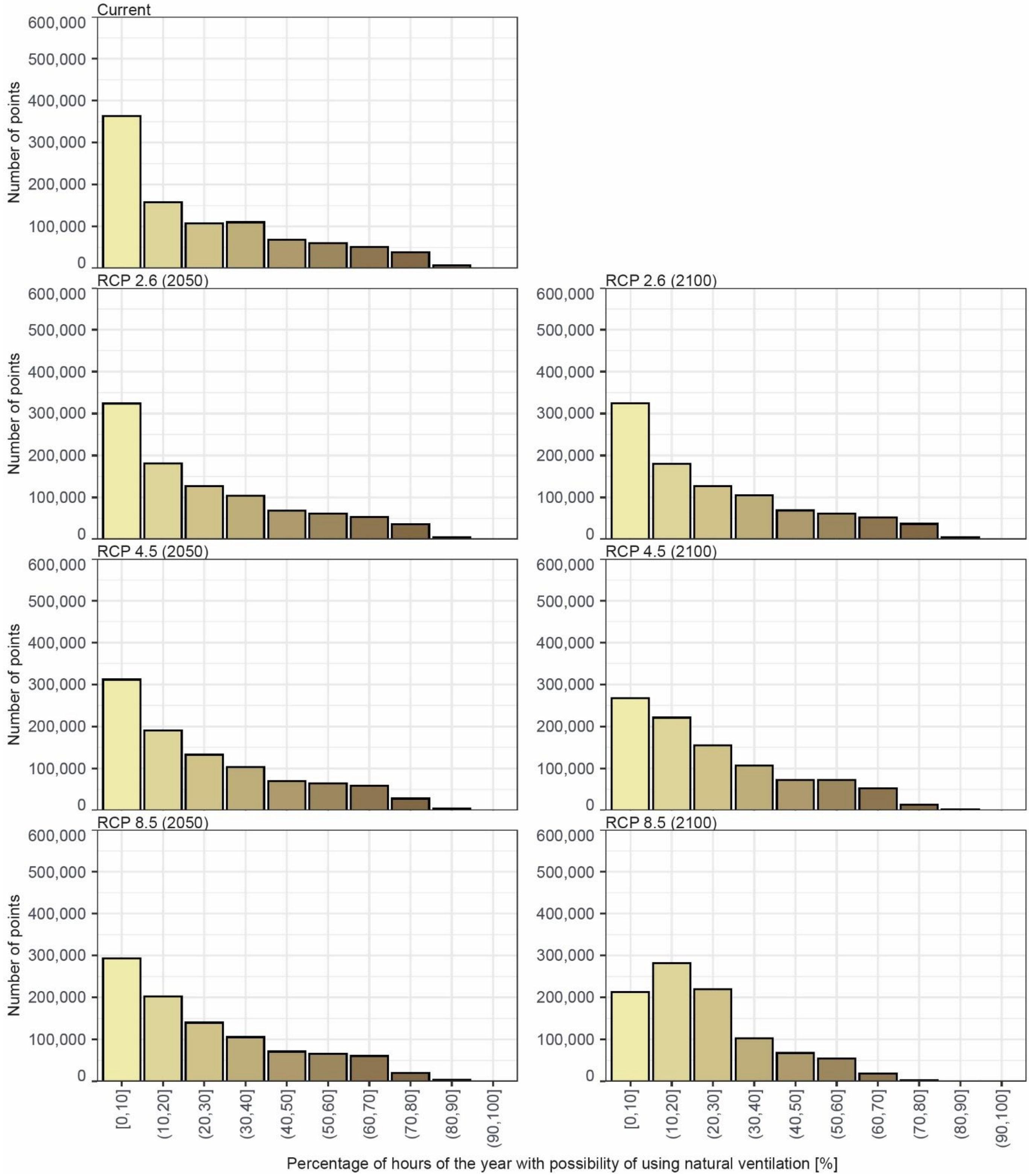

Fig. A4. Evolution of the annual percentage of hours when natural ventilation is used (80% acceptability).

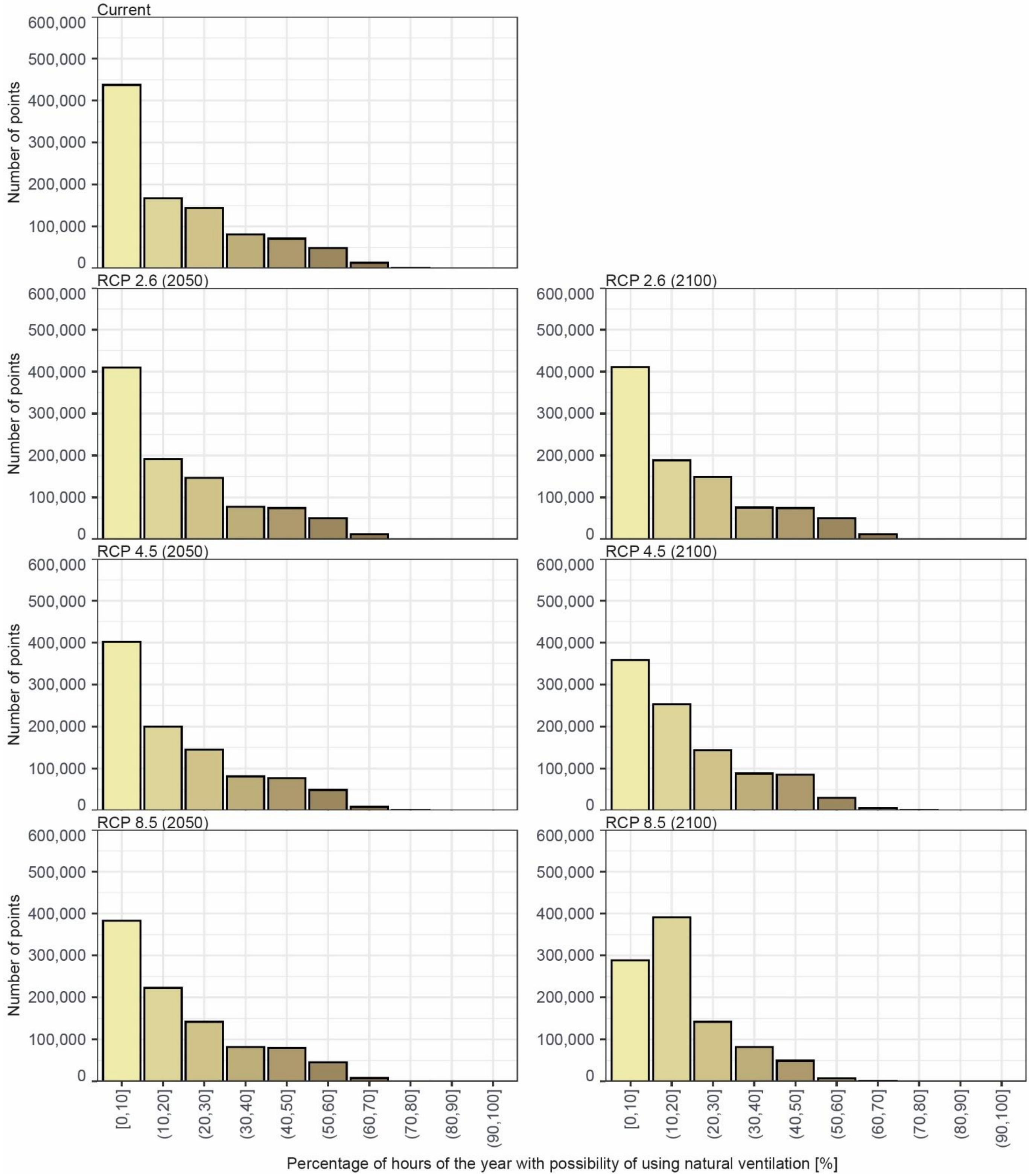

Fig. A5. Evolution of the annual percentage of hours when natural ventilation is used (90% acceptability).

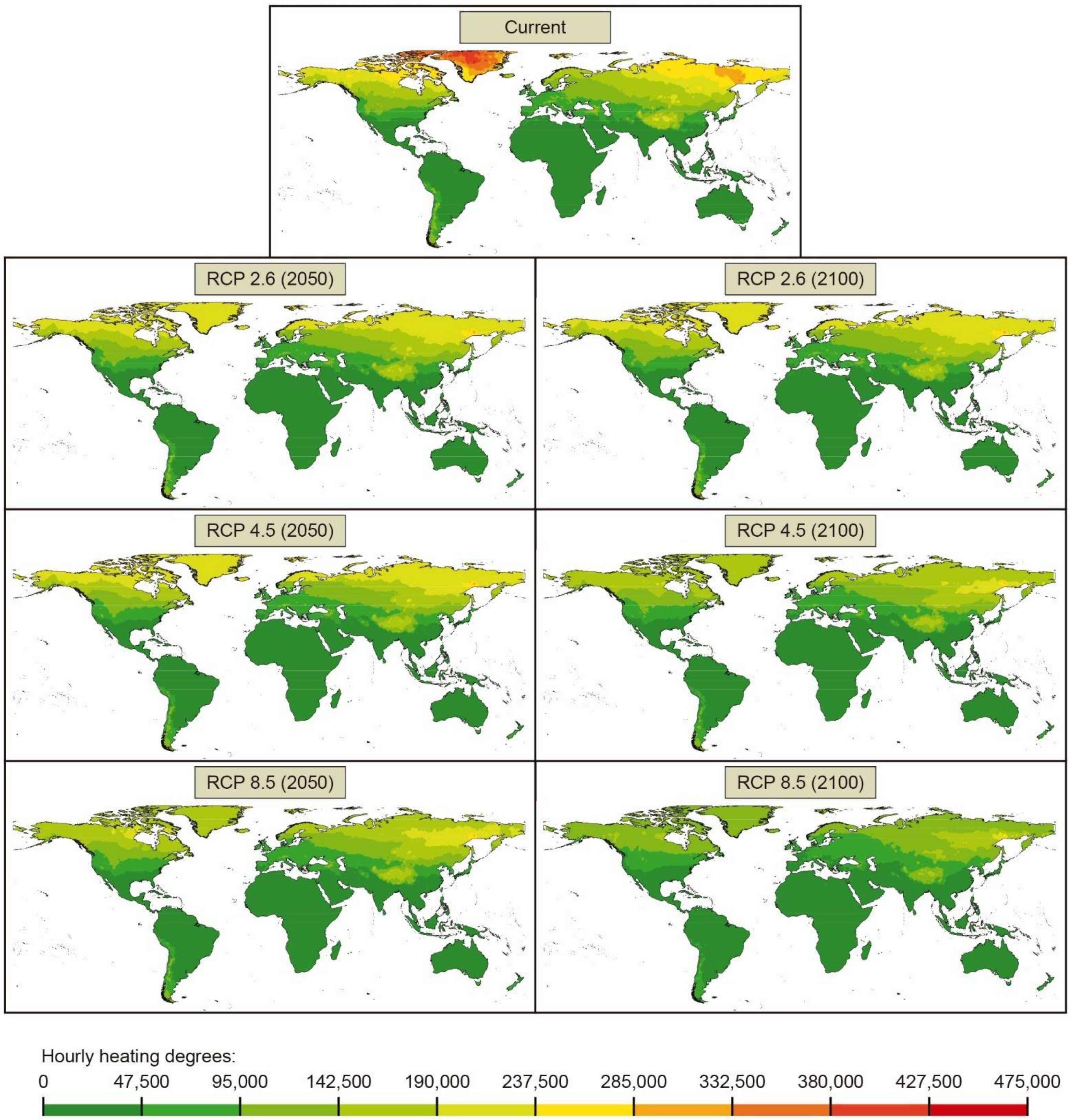

Fig. A6. Hourly heating degrees with a static setpoint temperature of 19 ºC in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

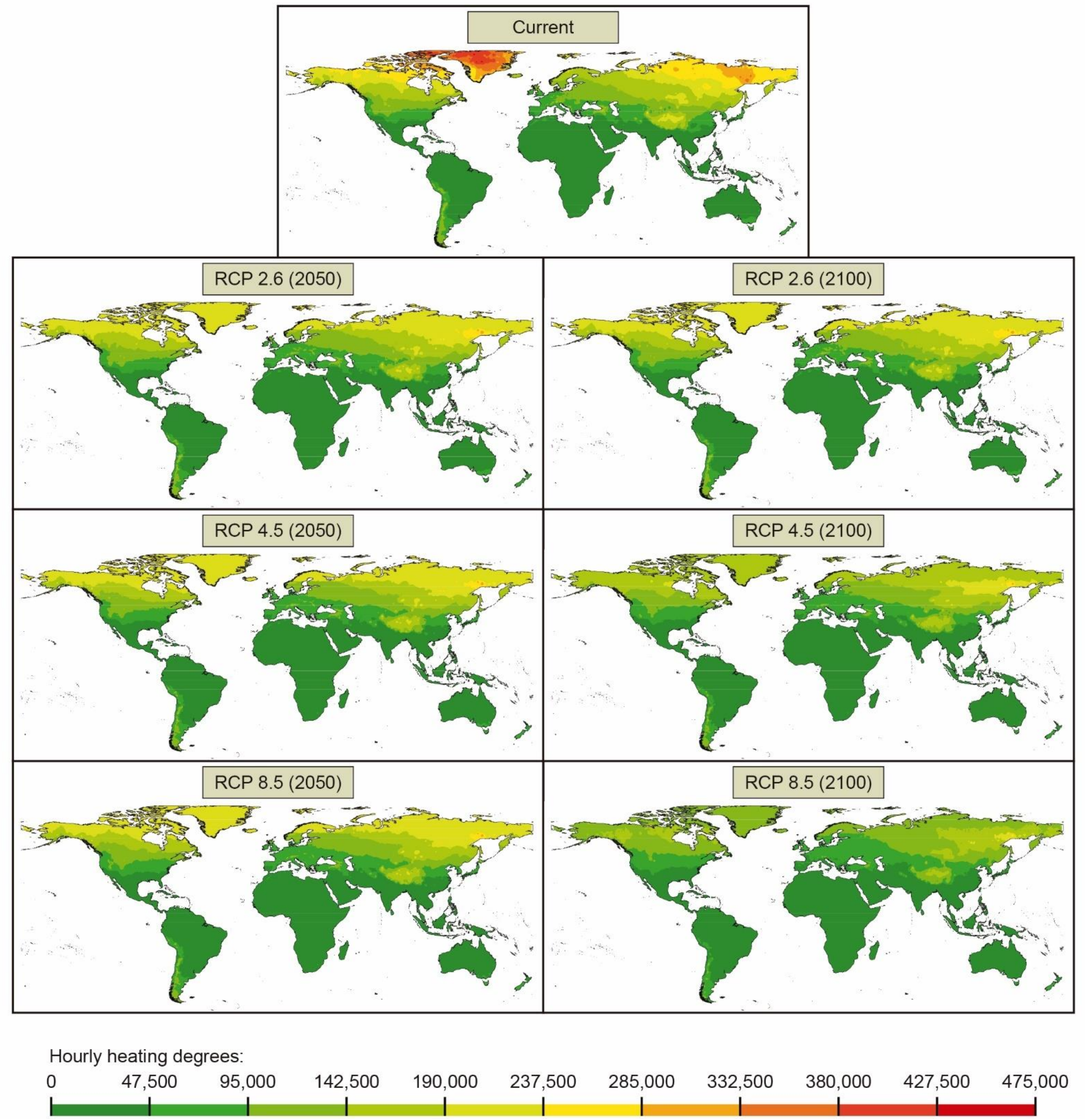

Fig. A7. Hourly heating degrees with a static setpoint temperature of 20 ºC in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

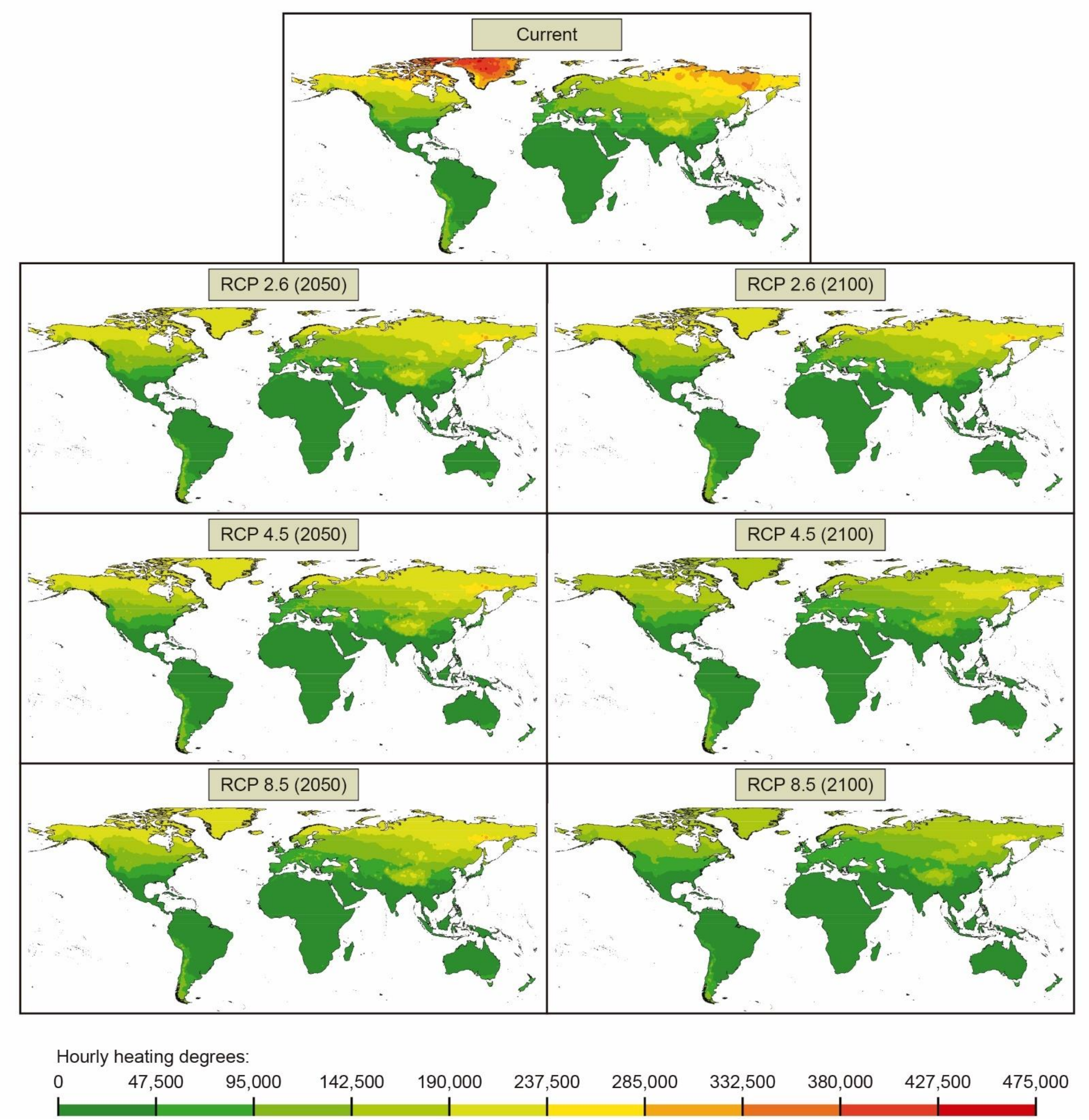

Fig. A8. Hourly heating degrees with a static setpoint temperature of 21 ºC in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

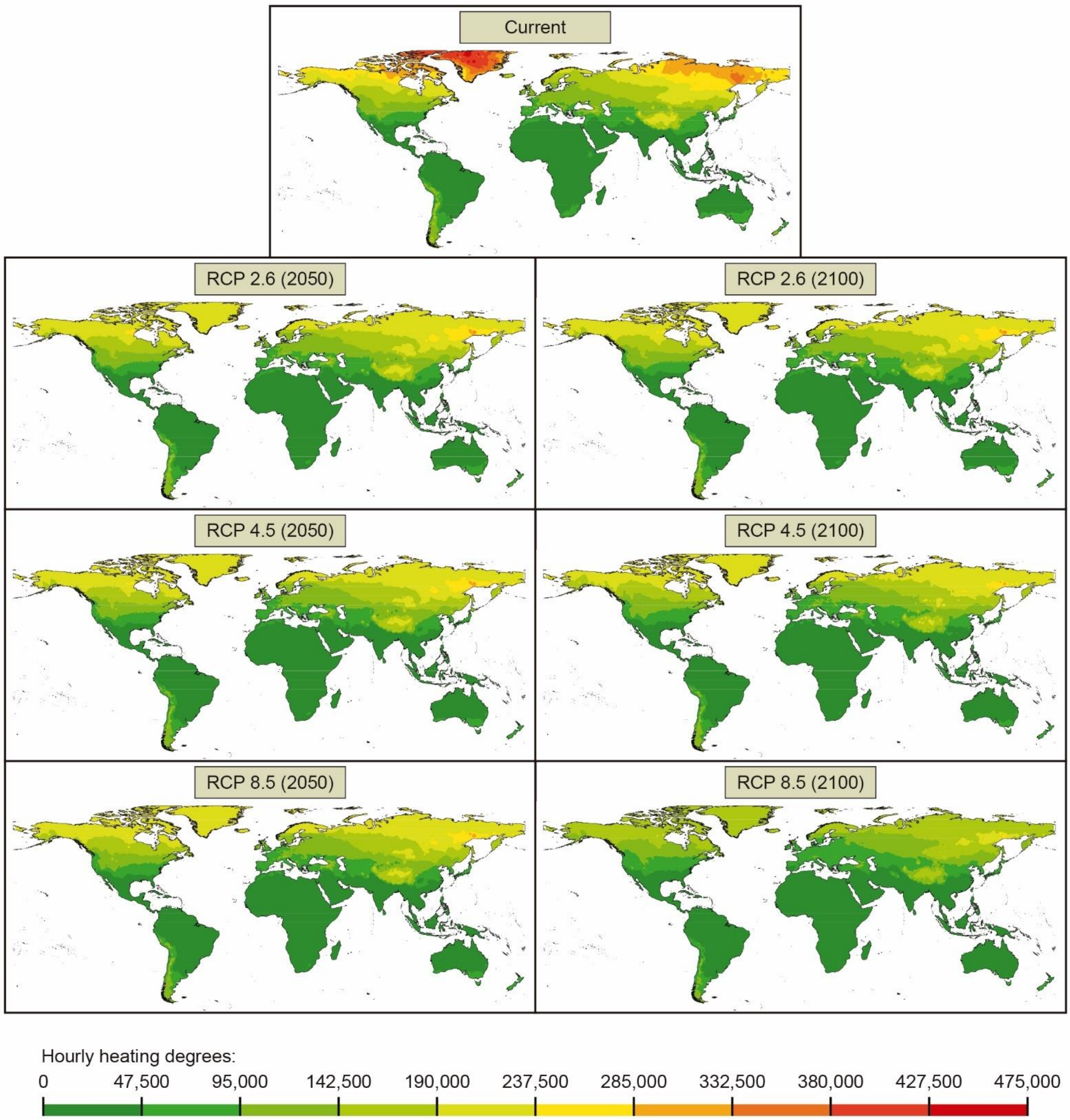

Fig. A9. Hourly heating degrees with a static setpoint temperature of 22 ºC in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

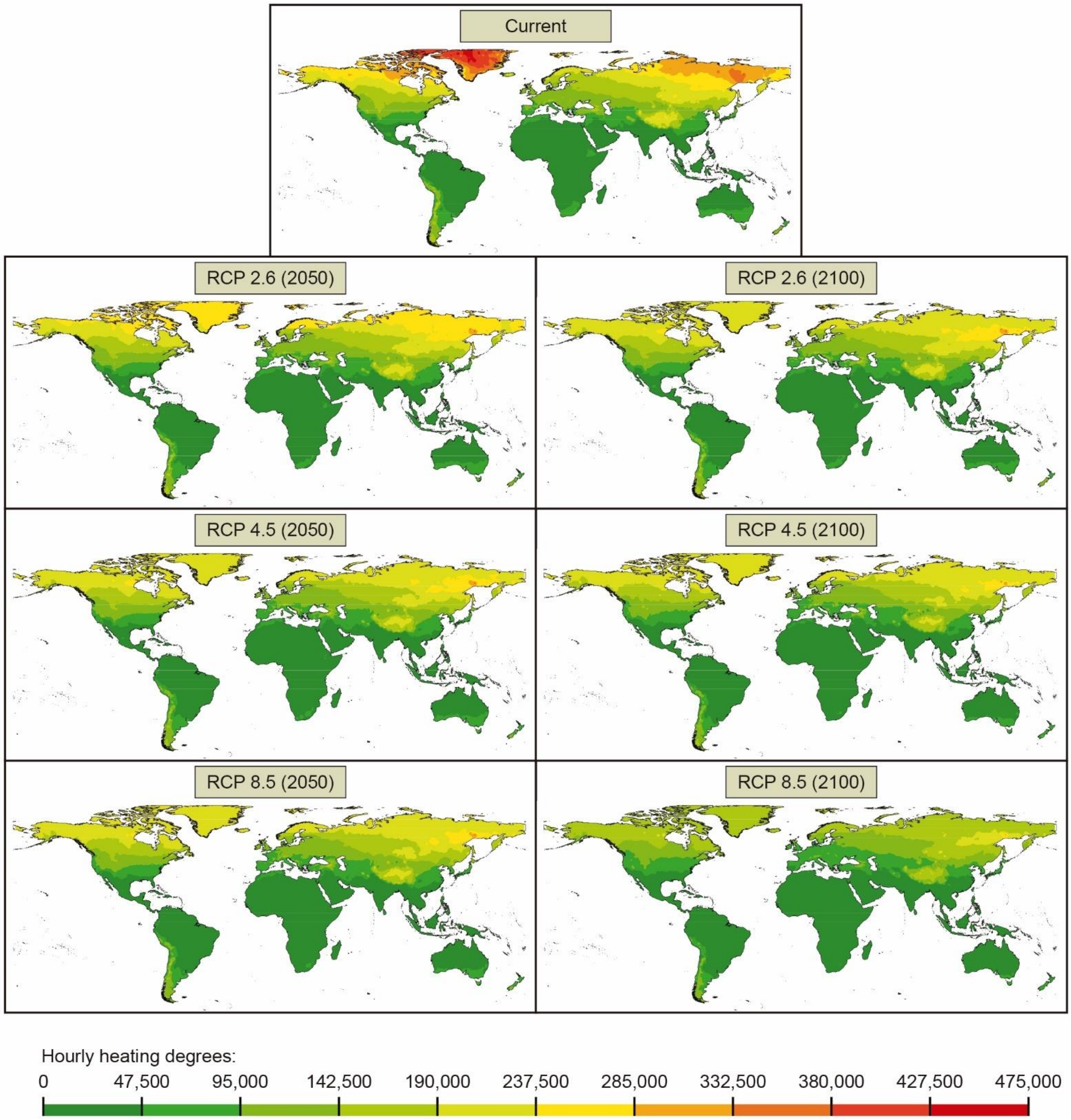

Fig. A10. Hourly heating degrees with a static setpoint temperature of 23 ºC in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

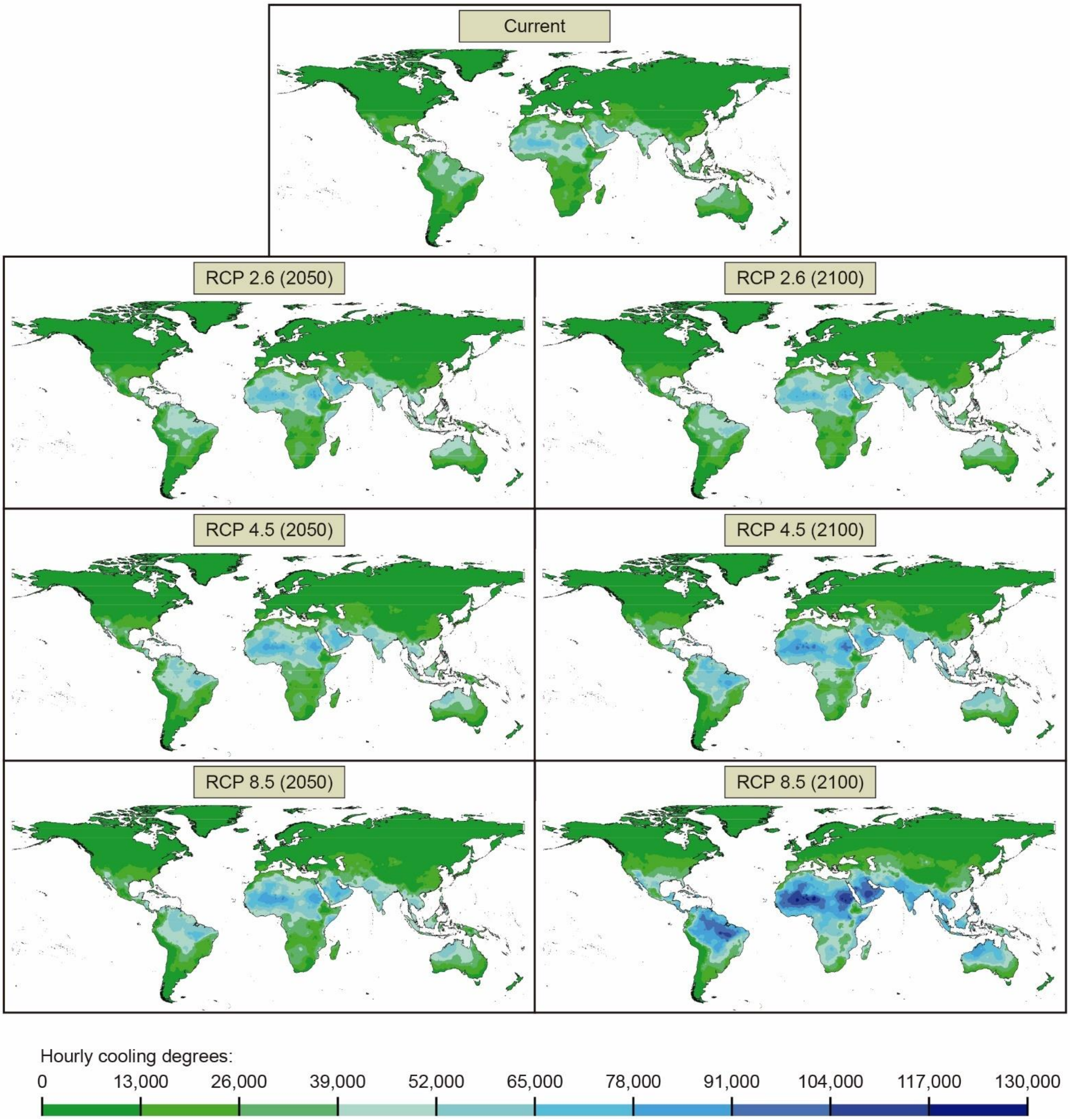

Fig. A11. Hourly cooling degrees with a static setpoint temperature of 23 ºC in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

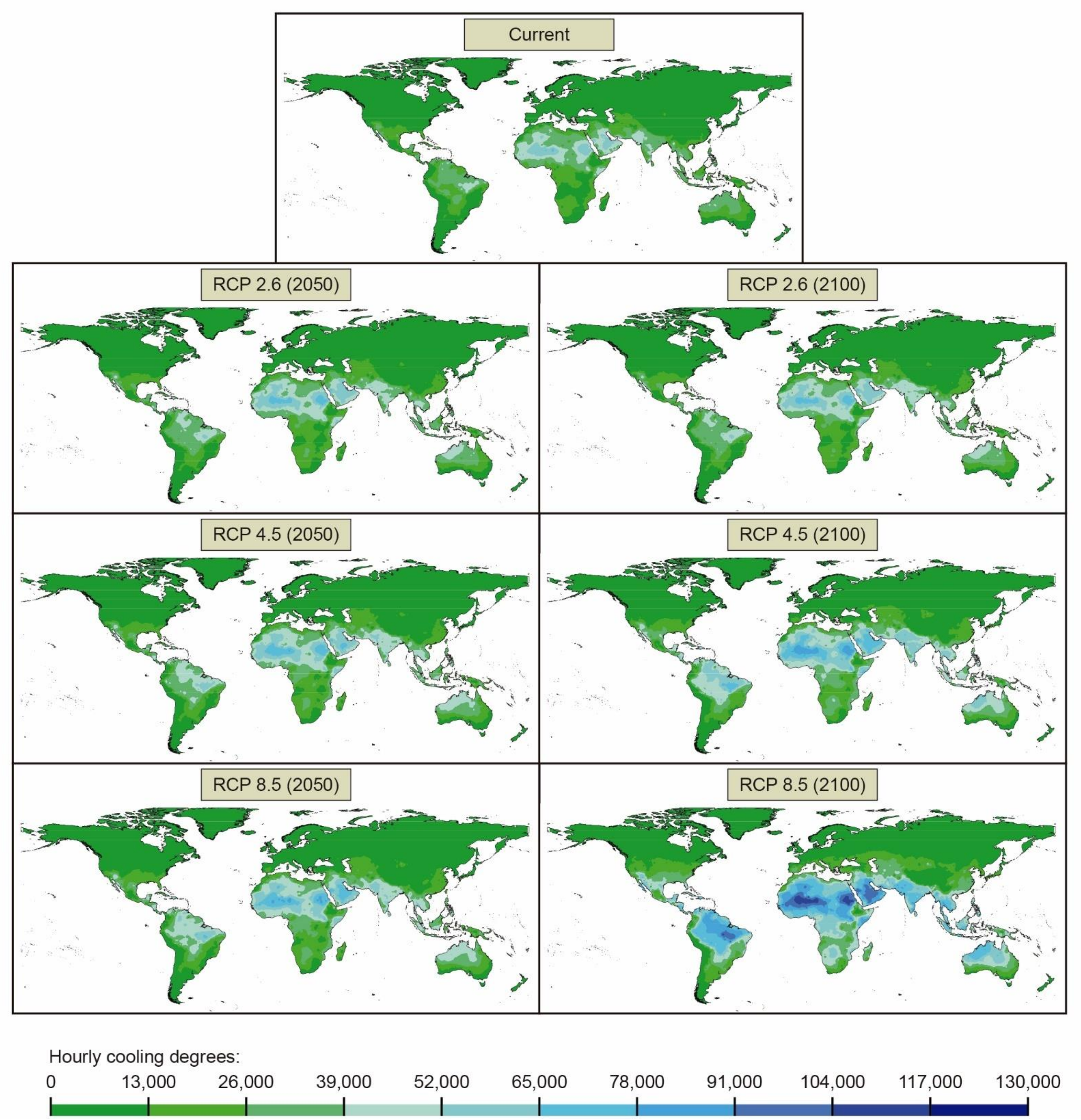

Fig. A12. Hourly cooling degrees with a static setpoint temperature of 24 ºC in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

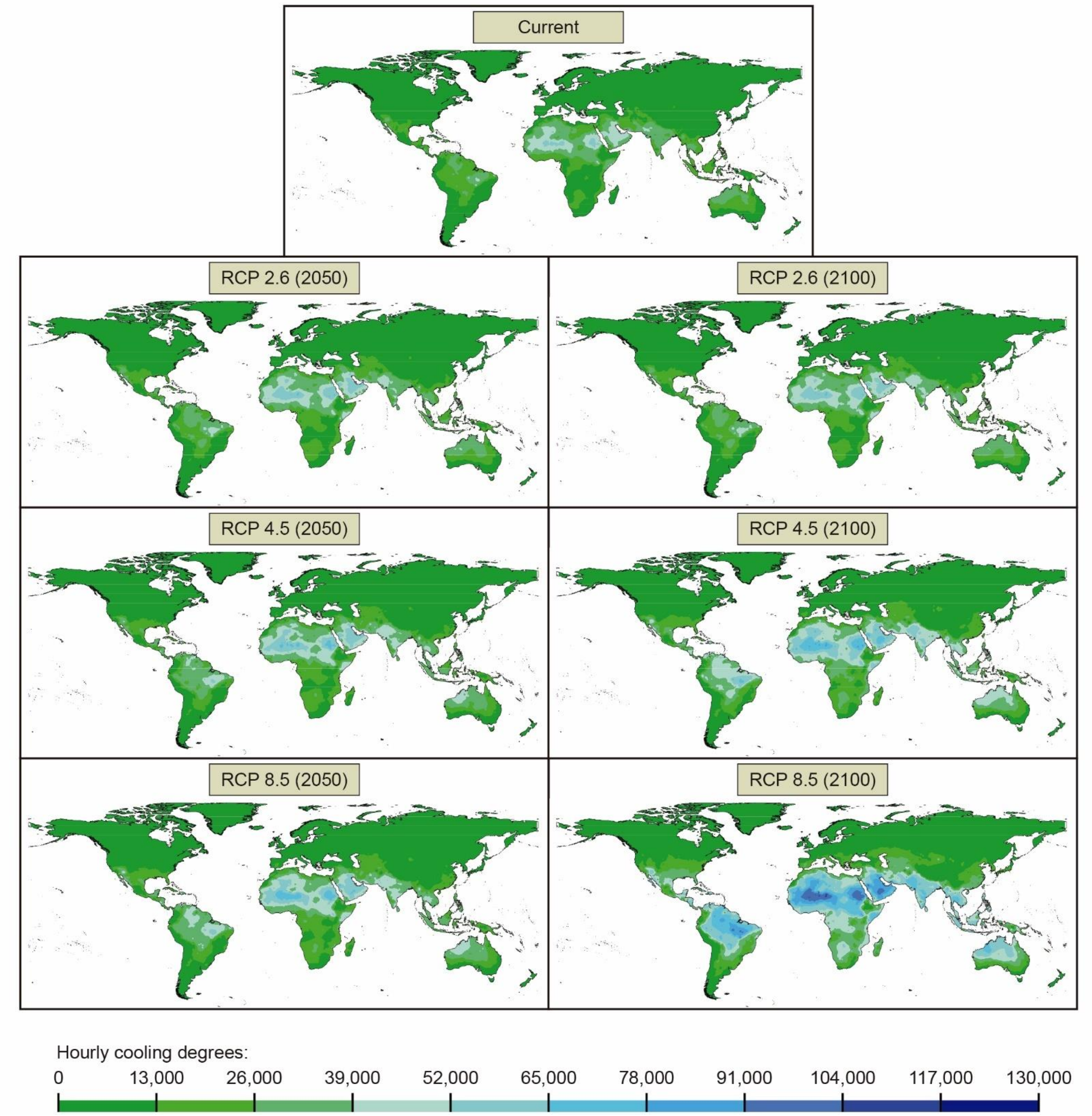

Fig. A13. Hourly cooling degrees with a static setpoint temperature of 25 ºC in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

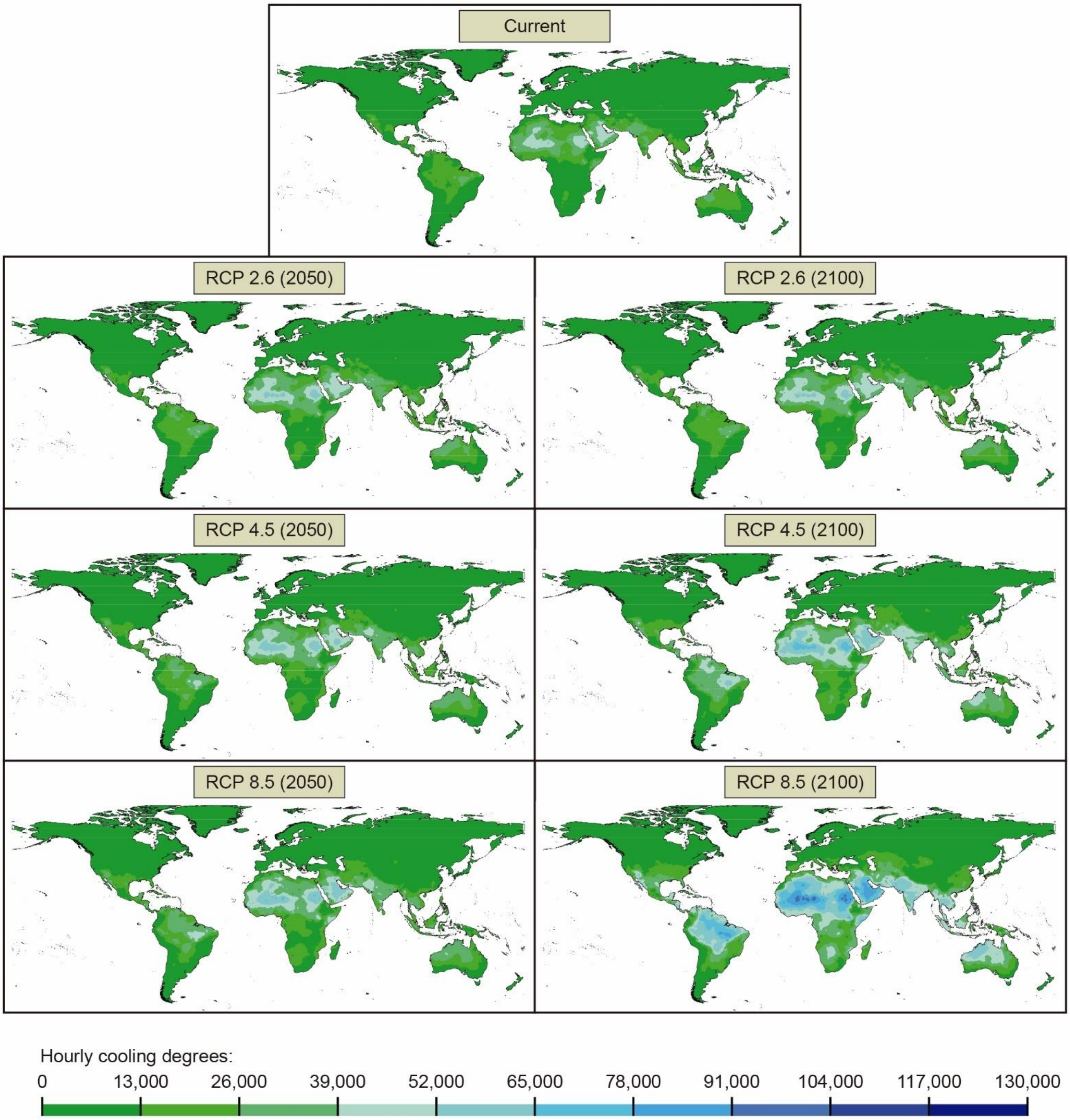

Fig. A14. Hourly cooling degrees with a static setpoint temperature of 26 ºC in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

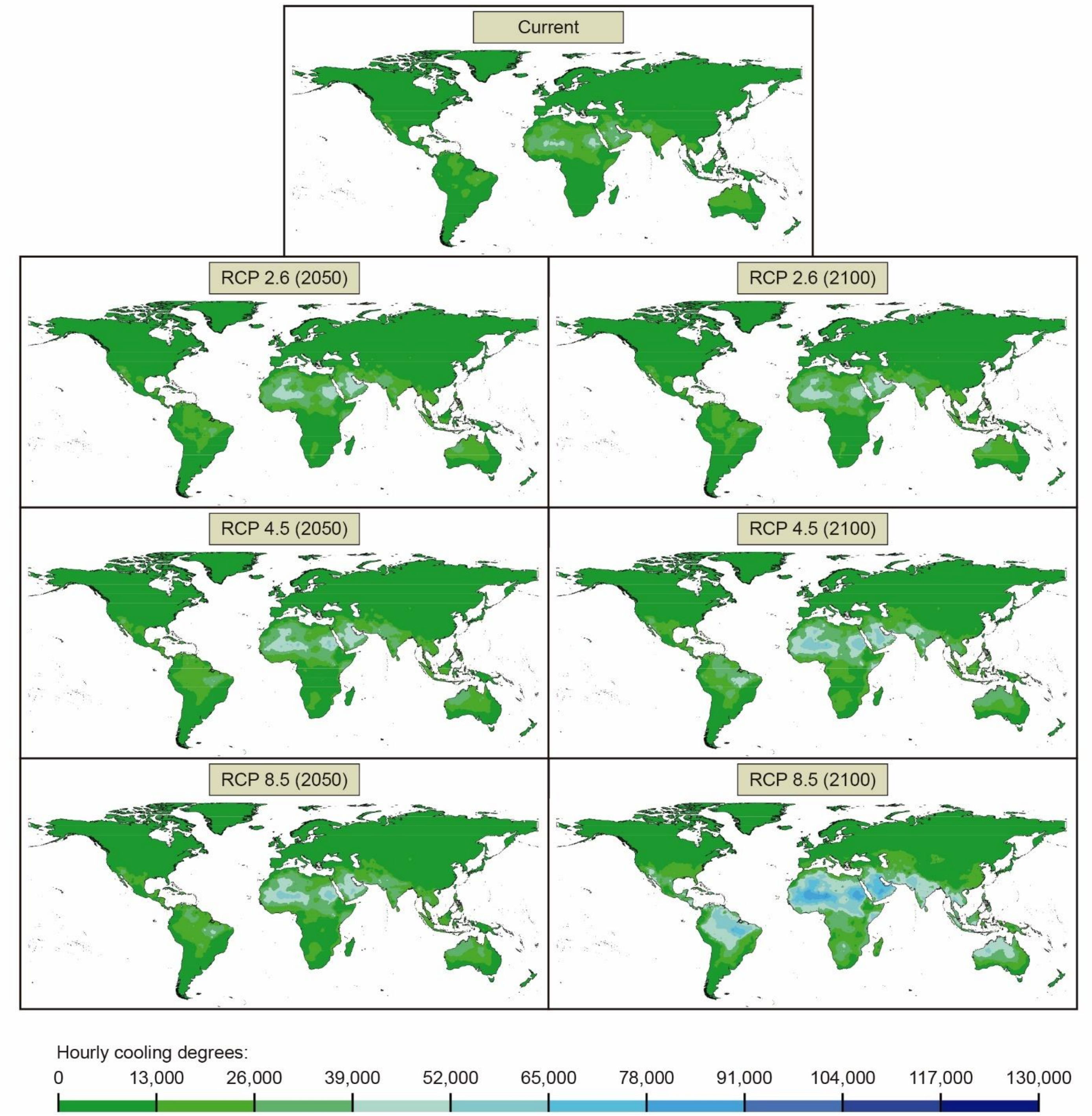

Fig. A15. Hourly cooling degrees with a static setpoint temperature of 27 ºC in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

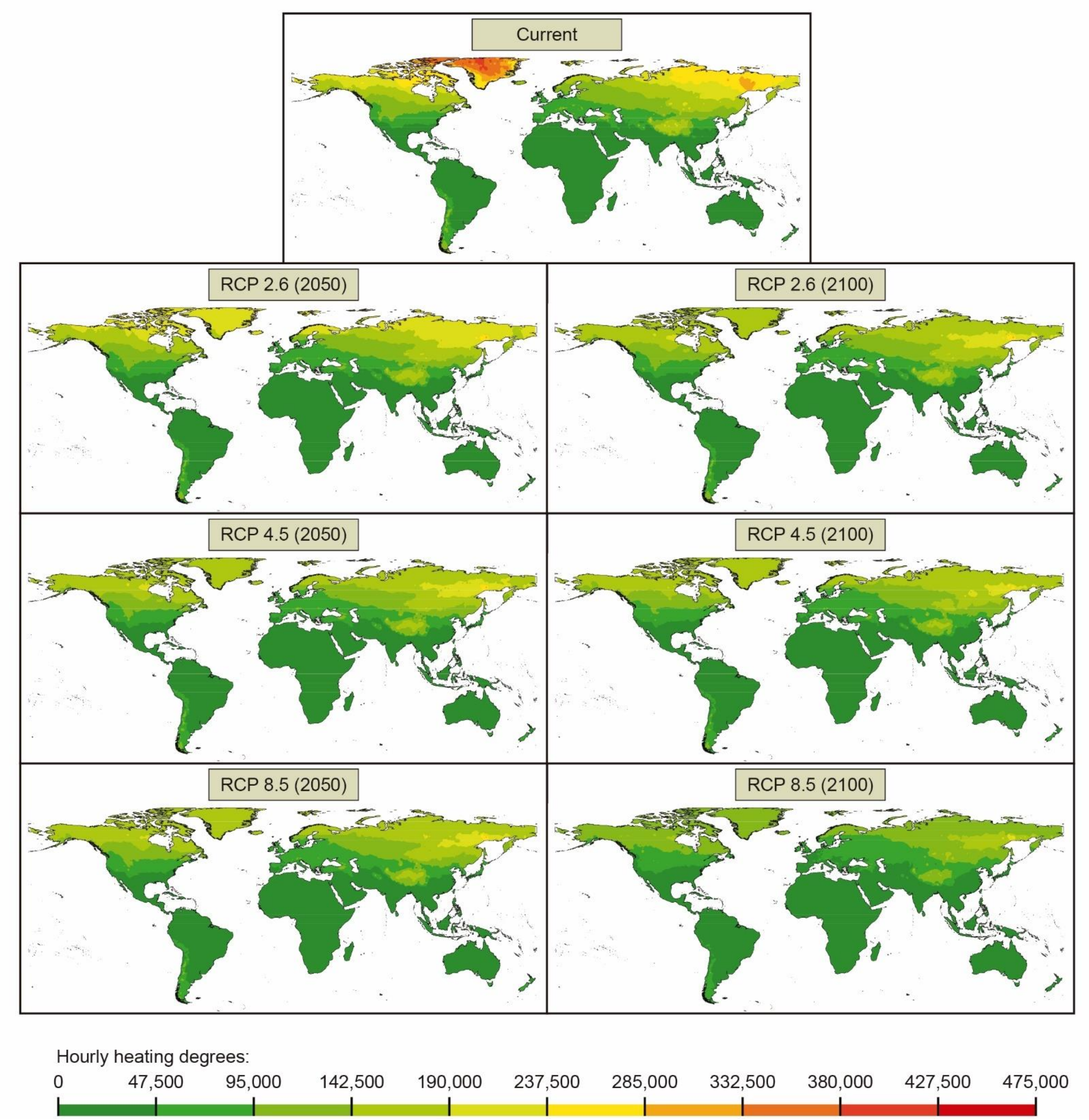

Fig. A16. Hourly heating degrees with an adaptive setpoint temperature based on the 80% acceptability in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

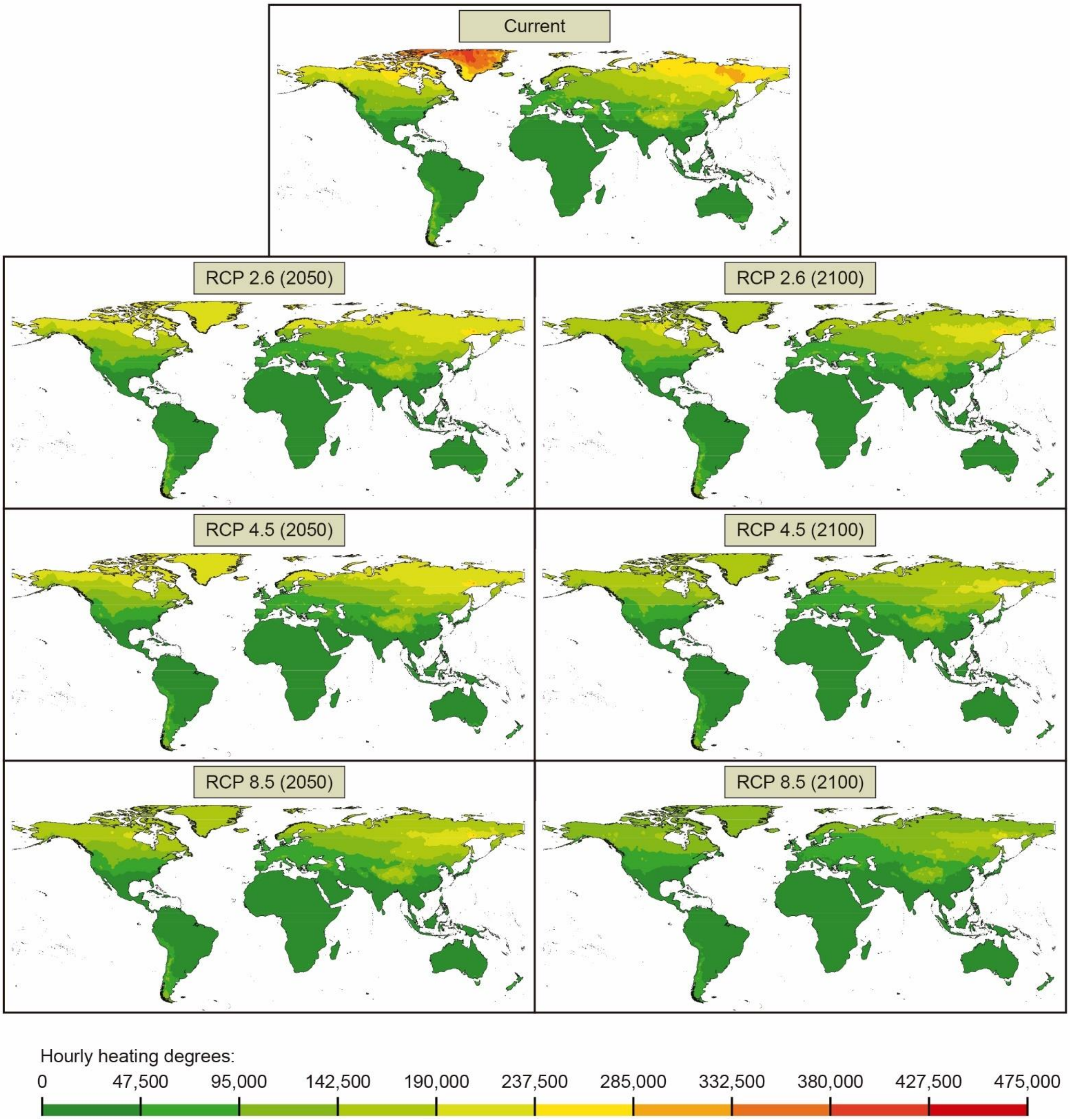

Fig. A17. Hourly heating degrees with an adaptive setpoint temperature based on the 90% acceptability in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

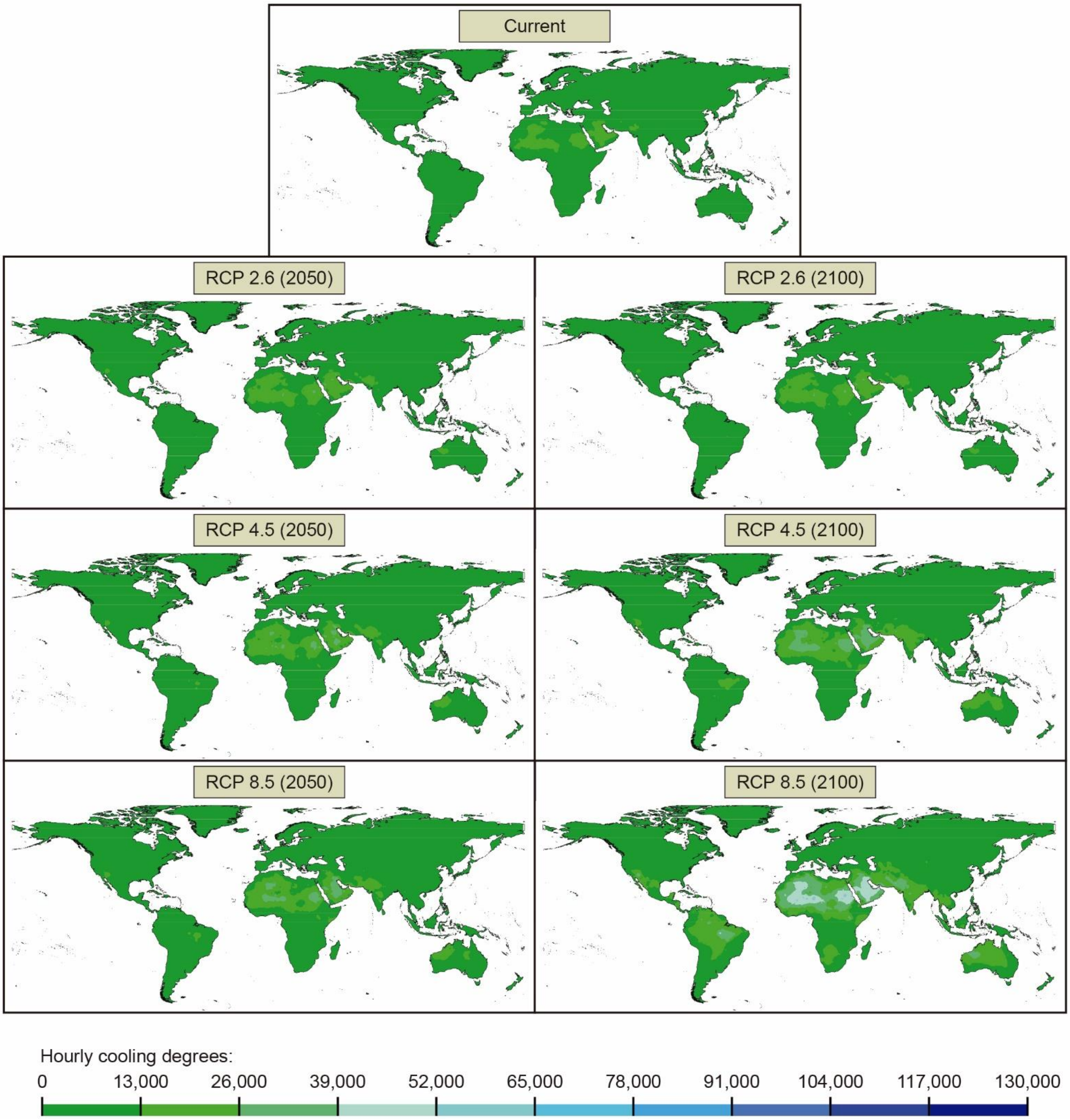

Fig. A18. Hourly cooling degrees with an adaptive setpoint temperature based on the 80% acceptability in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.

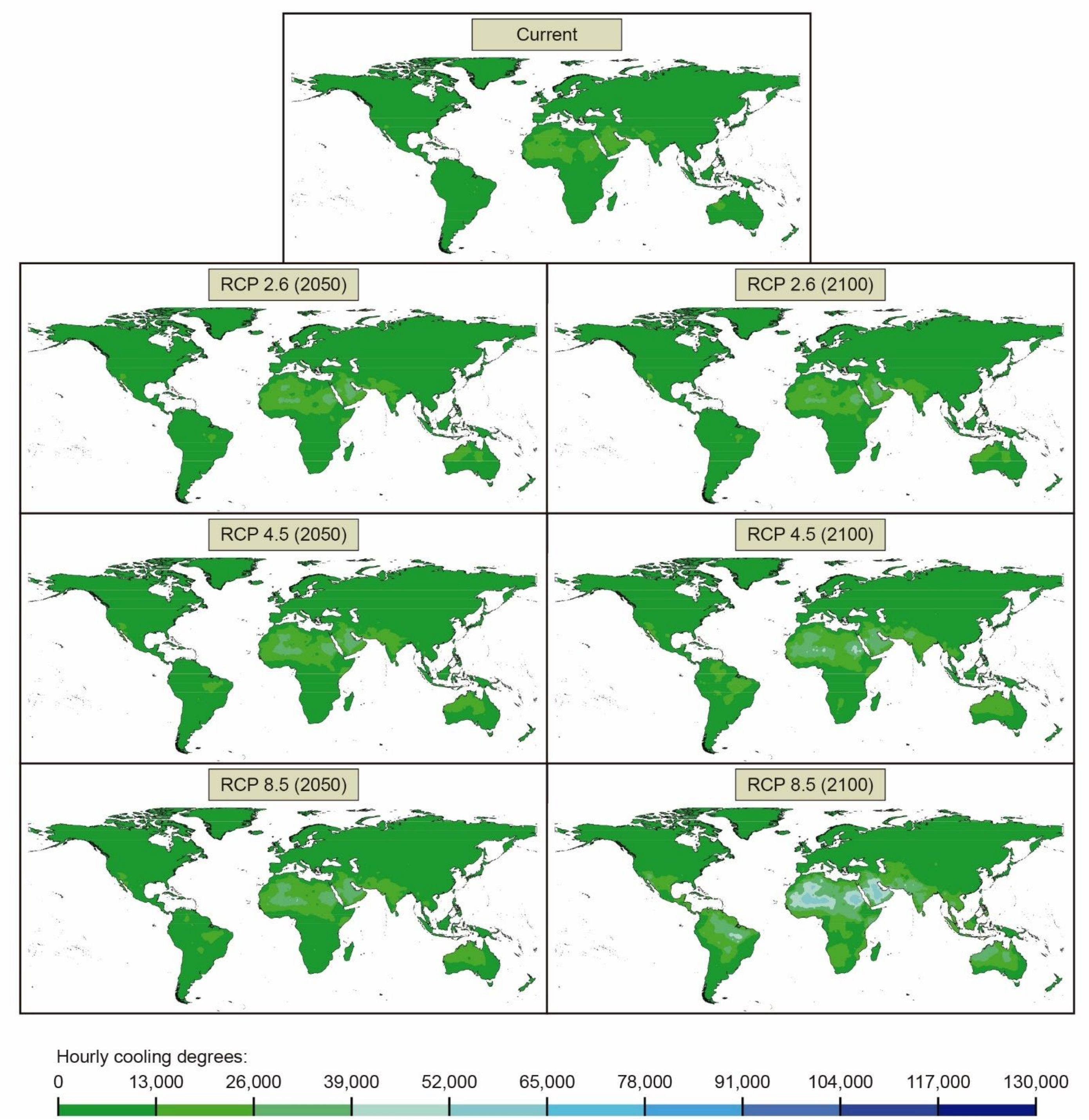

Fig. A19. Hourly cooling degrees with an adaptive setpoint temperature based on the 90% acceptability in the current scenario and in the RCP 2.6, 4.5 and 8.5 scenarios.