INFLUENCE OF FUTURE CLIMATE CHANGES SCENARIOS ON THE FEASIBILITY OF THE ADAPTIVE COMFORT MODEL IN JAPAN

Abstract:

Adaptive comfort models have emerged as a sustainable way of providing comfort in connection with local climate. Additionally, climate change has posed an additional challenge. In previous studies, the authors clarified how climate change would affect the feasibility of the adaptive comfort model at a worldwide scale, but local considerations for some countries remained unsolved. This study presents the first comprehensive research on the applicability of the adaptive comfort model in Japan not only for current, but also for future scenarios considering the climate change. Remarkable differences across Japanese regions were found, especially between the Northern underpopulated regions of Hokkaidō and Tōhoku and the cities that belong to the Taiheiyō Belt. In general, the adaptive comfort model will find application both in current and future scenarios, but natural ventilation will not play an important role. Special attention should be drawn to the potentials saving of cooling degrees that can be achieved if adaptive setpoint temperatures become commonplace in the future in the Kantō region. These results pave the way for the consideration of the adaptive comfort model as a resilient strategy to adapt to the future changes in climate scenarios for the building industry.

Keywords:

Adaptive thermal comfort; climate change; heating and cooling degrees; HVAC system; Japan; natural ventilation.

1. Introduction

The urban built environment is progressively increasing the building energy consumption and contributing to the acceleration of climate change (Stern et al., 2016). Buildings are responsible for 32% of the primary energy consumption at a global level and for 19% of greenhouse gas emissions (Intergovernmental Panel on Climate Change, 2014). In the 2015 Paris Climate Conference, a total of 195 countries committed to significantly reduce greenhouse gas emissions to minimise the rapid increase of external temperatures, thus leading to ambitious goals for the year 2050, in which reductions of building energy consumption are usually established between 90 and 100% (Energía 2050. Política Energética de Chile, 2017; Outline of Long-term Low-carbon Vision, 2017; Climate Change Act 2008, 2008).

In the Asian continent, Japan is one of the countries with the greatest greenhouse gas emissions (Huang et al., 2016). At the beginning of 2010, these emissions increased in Japan by 9% with respect to the levels from 1990 (Takemoto, 2011). These values are highly related to the building energy consumption, since in some regions, such as Tokyo, buildings were responsible for approximately 50% of carbon dioxide emissions (Tokyo Metropolitan Government, 2011). So, most efforts of energy policy aim to reduce the energy consumption of the building sector (de Oliveira, 2011). In addition, some studies have shown that the reduction of Japanese building energy consumption could minimise the cases of energy poverty, although maintaining adequate thermal conditions (Okushima, 2019; Tabata & Tsai, 2020).

For this purpose, and in accordance with Kyoto Protocol's goals, the country has implemented a low carbon economy for the year 2050 by reducing carbon dioxide emissions between 60 and 80% with respect to the level from 1990 (Huang et al., 2016). In the Japanese context, it is also important to stress the Fukushima crisis in 2011, which changed the energy policy of the country towards a lower dependence on fossil fuels (Duffield, 2016). Measures to invest in alternative energy sources and to reduce the energy consumption of the countries were established.

To achieve these demanding goals based on the reduction of greenhouse gas emissions, people are required to change to a more sustainable lifestyle. As for buildings (residential buildings, offices and shopping centres), users should adopt new thermal behaviour guidelines to reduce the high HVAC system energy consumption. Several research studies have stressed the influence of Japanese user's behaviour guidelines on energy consumption (Goto et al., 2007; Lopes et al., 2005; Mustapa et al., 2016), particularly on the consumption of HVAC systems as these systems are usually the main reason of consuming energy in buildings (International Energy Agency, 2017a, 2017b). An important measure implemented by the Japanese government is that office buildings regulate the cooling setpoint temperature by 28°C through 'setsuden' (literally meaning "energy saving") campaigns, as well as to contribute to appropriate clothes for hot periods through campaigns such as 'Super cool biz' (Indraganti et al., 2013a).

However, internal thermal acclimatisation criteria are usually based on static setpoints. Most studies on thermal comfort have been conducted with laboratory methods in climate chambers based on the thermal models of Fanger (1970). These models consider a static behaviour of thermal comfort limits, with a narrow range between the lower and the upper limit. Nevertheless, authors are increasingly considered studies with field methods in actual buildings based on adaptive thermal comfort approaches (Brager & De Dear, 1998; Carlucci et al., 2018). In these models, users can modify certain parameters related to their behaviour to reach comfort, thus reducing the energy consumption by limiting the use of HVAC systems, in comparison with the traditional approach of Fanger (Aghniaey & Lawrence, 2018).

The use of energy saving measures based on adaptive thermal comfort models (also known as adaptive energy saving measures) has been analysed by various research studies (Bienvenido-Huertas, Sánchez-García, Rubio-Bellido, et al., 2020; Sánchez-García, Rubio-Bellido, et al., 2019). The use of these thermal comfort models could influence two aspects of the thermal performance of the internal space: natural ventilation and setpoint temperatures. Also, users can use other techniques such as changing clothes and other adaptive behaviours (Indraganti, 2010, 2011).

Natural ventilation can be applied when the external temperature is within certain thermal tolerance limits that could be considered by users as acceptable. This technique therefore depends on the external climate conditions, as well as on other aspects, such as the own design of the building and its orientations (Nomura & Hiyama, 2017). The natural ventilation of buildings has been studied in mixed-mode buildings in Japan to ensure acceptable internal conditions (Nomura & Hiyama, 2017; Numanaka et al., 2015). However, these studies do not specify the limits which are considered adequate for the external temperature.

On the other hand, the energy saving by using adapted adaptive setpoint temperatures, in comparison with those based on the models of Fanger, has also been analysed by various research works (Bienvenido-Huertas, Sánchez-García, & Rubio-Bellido, 2020; Bienvenido-Huertas, Sánchez-García, Rubio-Bellido, et al., 2020; Sánchez-García, Rubio-Bellido, et al., 2019). These works have been carried out in different building typologies, both residential and office, and are characterised by saving the energy consumption by 50%.

It is therefore evident that the use of adaptive comfort models would determine when the external temperatures could lead to this thermal adaptation of users inside buildings. For this reason, the authors assessed in a previous study (Bienvenido-Huertas, Rubio-Bellido, Pérez-Fargallo, et al., 2020) the possibilities to apply adaptive strategies in all countries by using the adaptive thermal comfort model from ASHRAE 55-2017 (ASHRAE, 2017). The study showed that adaptive models are more possible to be applied when buildings are located in warm climates, obtaining a maximum application in the latitudes closer to the equator. Nevertheless, the study presented limitations in the accuracy obtained by the results as it was conducted at a global scale.

For this reason, it was deemed necessary to continue this study, this time focusing on specific geographic locations. Japan is a challenging case of study for a series of reasons. First, it tops as the 5th largest CO2 emitter in the world although it is the 10th by population and the 61st by surface (Database., 2014). Second, this country features a variety of warm climates, ranging from warm oceanic (Cfa) to warm (Dfa) and temperate continental climates (Dfb and DwB). With the exception of the Northern territories of Hokkaido, the climate of this country generally features cold winters and hot humid summers. Third, predicted climate change scenarios foresee tendencies for this country in relation to normal and abnormal climate events: average temperatures are expected to raise in Japan more than the world average, especially in Northern latitudes, and the number of days with temperatures over 30°C and 35°C is expected to increase, especially in Southern island and Western Japan. Fourth, the pattern of abnormal climate events, i.e. storm surges, typhoons and heavy snowfalls, will shift within its territory (Environment et al., 2018). Fifth, the distribution of the population is heavily irregular and concentrated around the Taiheiyō Belt, a large conurbation that stretches for around 1.000 km and one third of the total surface of Japan, concentrating around 60% of the population and 70% of the economic output of the country (－少子高齢化時代の地域活性化検討委員会, 2005). Regarding this country, research pertaining to this topic can be classified into two main areas: adaptive thermal comfort and climate change.

Regarding the first one, studies have mainly focused on the assessment of adaptive thermal comfort in existing buildings. Rijal et. al (2019) surveyed 244 residents in the Kantō region for 4 years and suggested that their comfort temperature under free running conditions would be around 17.6°C in winter and 27°C in summer. Other study focused on office building where the setsuden (energy saving) campaign was enforced after the Fukushima disaster; air conditioners were off during summer season and workers were allowed to wear light shirts instead of suits; it was found out that workers felt comfortable around 27°C, although the temperature was over 28°C in 50% of the buildings, as they were not equipped with fans (Indraganti et al., 2013b). Other authors have focused on concrete strategies, such as the natural and artificial ventilation. A study by Imagawa et. al (2019) clarified that, under summer conditions, residents tend to use the combination of fan use and window opening, rather than a combination of fan and air conditioners for achieving thermal comfort.

The influence of climate change in the built environment has also been researched from a concrete perspective; studies have dealt mainly with the change in cooling and heating loads in tertiary facilities. A study estimated the cooling and heating load in office buildings located nationwide taking as a base the meteorological data form the period 1991-2018; that data was used to extrapolate these scenarios into the future and found that cooling load will increase in many cities, whereas heating load will experience a rise in only a few (Isozaki & Takeda, 2019); these results agree with other study that foresee an increase in the average monthly temperatures in Tokyo; in January the average will rise from 5 to 8°C and, in summer, from 25 to 30°C (江守正多 & 住明正, 2004). Taking as a base this study, other authors also foresee an increase in the peak cooling load in office buildings for the next 50 and 100 years (明, 2006). Another study conducted in an office facility in Yokohama predicts a rise in the primary energy consumption around 120% in the future, mainly because of the cooling loads (Kim, Ito, Yoshida, & Sadohara, 2019); in a similar fashion, another study clarified that sensible and latent cooling loads of a typical house in Tokyo would rise in 2030 if compared with the current scenario, due to the change in climate conditions (Arima et al., 2016). These predictions are based either on a policy document published by the Japanese Government: Database for policy decision making for future climate change (d4PDF) (*Database for policy decision making for future climate change*, 2015) or on self-generated data that compiles past information from climate trends (Arima et al., 2016). However, other studies have adopted a different approach, using the IPCC A2 scenario to assess the increment of energy consumption and CO2 emissions of office buildings across the whole territory of Japan (Shibuya & Croxford, 2016).

It is evident that, despite adaptive thermal comfort and climate change have been attracting interest from the scientific community, research on these topics are somewhat disconnected. Indeed, adaptive thermal comfort finds application in Japanese climate, especially in Mid and Western Japan during summer season; however, studies about climate change in the build environment are rather focused on the change of pattern in energy consumption and CO_2 emissions for both heating and cooling, disregarding the potential of the adaptive theory to provide comfort without increasing the energy usage.

That situation calls for a specific research on the effect of climate change on the applicability of adaptive thermal comfort in this territory. It should also be mentioned that no location in Japan was included in the database used to compile the ASHRAE Standard-55 and thus this country is not represented in this adaptive comfort model (Indraganti et al., 2013b), giving support to the need of this study. This research brings novelty on the field in two aspects: first, it aims at clarifying the feasibility of the adaptive comfort model in current and future climate scenarios in Japan. The feasibility will be assessed in terms of the two adaptive strategies of such model: natural ventilation and adaptive setpoint temperatures for heating and cooling; the timespan will cover the current scenario, which will be the base case (2020), and the future scenarios (2050 and 2100). Second, this study is not focused on a single case-study, but on the whole Japanese territory, providing a general perspective of the country and highlighting differences across different regions. Besides, since no specific building typology will be covered by this study, the conclusions are expected to have a wide application.

According to former studies by the authors (Bienvenido-Huertas, Rubio-Bellido, Pérez-Fargallo, et al., 2020) and the scientific corpus, it seems evident that climate change might exert an influence on the feasibility of the adaptive comfort model in this country; however, it is not clear how this influence will be, and that is precisely the research question that this study strives to answer. It is hypothesised that this model will find application especially in the Central and Western Japan, which is part of the Taiheiyō Belt that includes big urban areas, such as Tōkyō, Yokohama, Nagoya, Kyōto, Ōsaka, Kōbe, and Fukuoka. Colder areas such as the Northern regions of Aomori, Sendai, and especially Hokkaidō, are expected to need special considerations. However, it should be mentioned that, due to the lack of specific studies on this topic and the variability of climates across Japan, it is rather difficult to make an educated guess on the effect of climate change on the feasibility of the adaptive comfort model.

To answer these questions, this research is organised into the following steps: (i) Section 2 describes a detailed description of the methodology of this research. This section summarises the adaptive thermal comfort model from ASHRAE 55 and the adaptive strategies considered, the obtaining of climate data and the scenarios considered, and the analysis method used; (ii) Section 3 includes and discusses the results, and is divided into three subsections per each aspect analysed: application potential of the adaptive thermal comfort model, percentage of hours using natural ventilation, and hourly saving of heating and cooling degrees. Each subsection analyses both the current scenario and climate change scenarios throughout the 21st century; and (iii) Section 4 includes the main conclusions of this research.

2. Methodology

2.1. Adaptive thermal comfort model from ASHRAE 55-2017

Today there are many adaptive thermal comfort models, some of them included in standards (ASHRAE, 2017; Ministry of Housing and Urban-Rural Development (China), 2012; European Committee for Standardization, 2007) and others in research studies carried out in Chile (Pérez-Fargallo et al., 2018), Mexico (López-Pérez et al., 2019) or India (Tewari, Mathur, Mathur, Kumar, et al., 2019), among others. The model included in ASHRAE 55-2017 is among the most used (ASHRAE Standard 55-2017 Thermal Environmental Conditions for Human Occupancy, 2017). This standard could be considered as an international implementation of an adaptive thermal comfort model, since it was developed with data from various countries (Carlucci et al., 2018). This model could therefore be applied in different regions of the world.

ASHRAE 55-2017 establishes two different typologies of adaptive thermal comfort models according to the percentage of acceptability: 80 and 90%. Upper and lower limits of the models are determined by the prevailing mean outdoor air temperature ($\overline{t_{pma(out)}}$) (see Eq. (1)). This temperature is a weighted average of daily external temperatures ($T_{ext,d}$) according to a value α (which could be of 0.6 for mid-latitude climates) and in a period between 7 and 30 days. To calculate the limits of the model, Eqs. (2) and (3) should be used for the 80% acceptability and Eqs. (4) and (5) for the 90%

acceptability, provided that $\overline{t_{pma(out)}}$ ranges between 10 and 33.5°C (see Figure 1). Out of these limits, HVAC systems should be used to maintain suitable conditions in the interior. As Eqs. (2) – (5) show, the main difference of both categories of acceptability is in the thermal comfort limits: in the 80% acceptability, the amplitude between upper and lower limits is broader than in the 90% acceptability, which means that users' thermal expectations of the 90% acceptability are greater than in that of the 80%. Unlike the study conducted at a global level which only considered the category of 80% as it is related to a greater energy saving with adaptive strategies (Bienvenido-Huertas, Rubio-Bellido, Pérez-Fargallo, et al., 2020), two adaptive thermal comfort models were considered for this study.

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

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

$$Lower\ limit\ (80\%\ acceptability) = 0.31 \cdot \overline{t_{pma(out)}} + 14.3 \quad [ºC] \tag{3}$$

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

$$Lower\ limit\ (90\%\ acceptability) = 0.31 \cdot \overline{t_{pma(out)}} + 15.3 \quad [ºC] \tag{5}$$

Energy saving strategies based on adaptive thermal comfort models consist of two aspects: (i) use of natural ventilation in the hours in which the external temperature is within the lower and upper limits of the adaptive thermal comfort model; and (ii) the thermal conditioning of internal spaces when they could not be ventilated by using adaptive setpoint temperatures (i.e., setpoint temperatures adapted to the limit values of the adaptive thermal comfort model). If the prevailing mean outdoor air temperature is greater than 33.5°C or lower than 10°C, a fixed value should be used for setpoint temperatures, corresponding to the limits of the adaptive model (see Figure 1) (Sánchez-García, Bienvenido-Huertas, et al., 2019).

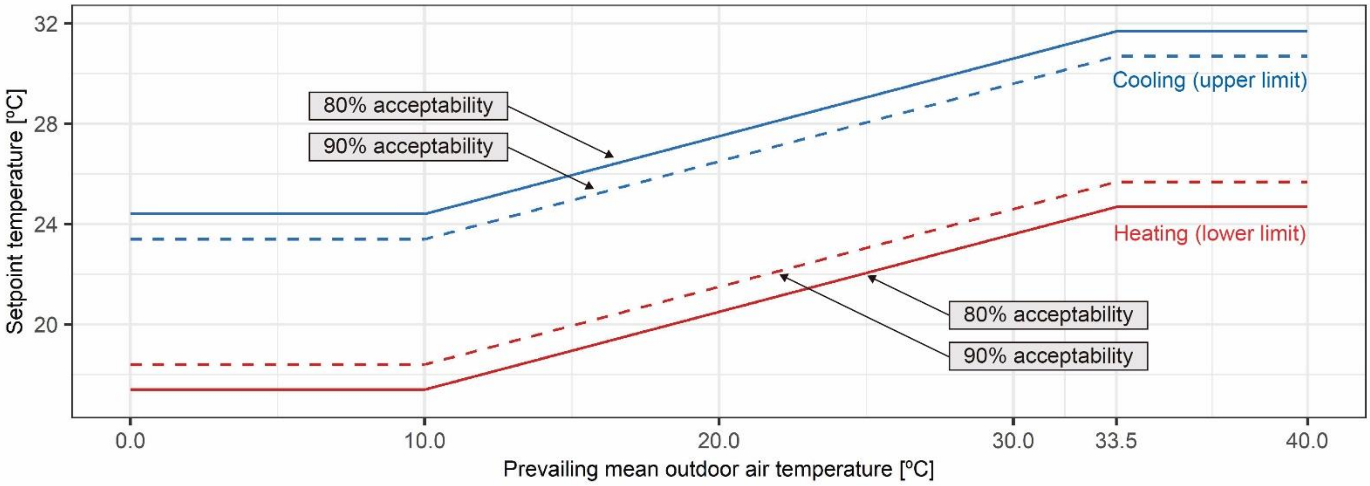

Figure 1. Setpoint temperatures for the adaptive thermal comfort models from ASHRAE 55: with an 80% (continuous line) and a 90% (discontinuous line) acceptability. The red line corresponds to the limit for the operation of heating systems, and the blue line to the limit for the operation of cooling systems.

2.2. Obtaining climate data

For this study, 500 locations across the country were analysed (Figure 2). These locations were selected based on the most important cities in each of the 8 regions of the country. Thus, cities such as Tokyo and Sapporo, among others, were selected. Regarding climate data, they were obtained from the METEONORM database, which provided for 500 locations across the country. METEONORM is a software made up of 8,325 weather stations distributed all over the world, whose use has been endorsed by various research studies (Bellia et al., 2015; Hatwaambo et al., 2009; Kameni et al., 2019; Osman & Sevinc, 2019). For each location in Japan, meteorological data was downloaded from this database. Based on these data, hourly temperature values were obtained in any location using a stochastic model (METEONORM, 2019). Then, climate data were generated in the current scenario and in the 3 climate change scenarios included in the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic & Swart, 2000): A1B, A2, and B1. The use of these scenarios to predict the energy performance of buildings in the future has been widely recognized by several studies (Jylhä et al., 2015; Kameni et al., 2019; Nik et al., 2016; C. Rubio-Bellido et al., 2017). The differences among these scenarios depend on the estimations of growth of countries and the increase of temperatures:

- Scenario B1 describes a convergent world with the same global population, which reaches its peak by the mid of the century and is declined since then, but rapidly changing the economic structures towards an economy of services and information by introducing clear and effective technologies. Global solutions are stressed for the economic, social, and environmental sustainability, including the improvement of equity, but without additional climate initiatives. It is the most favourable climate change scenario presented by the IPCC, with a possible increase of temperatures between 1.1 and 2.9°C by the end of the 21st century.
- Scenario A1B describes a world similar to that of the scenario B1, with a rapid growth until the mid of the 21st century and a progressive decrease from 2050. The main underlying issues are the convergence among regions, developments of capacities, and the increase of cultural and social interactions, with a significant reduction of regional differences in the income per capita. Technological change in the energy sector has a balance between renewable and non-renewable sources. It is a medium-high climate change scenario, with a possible increase of temperatures between 1.7 and 4.4°C by the end of the 21st century.
- Scenario A2 represents a very heterogeneous world, stressing the self-sufficiency and the preservation of local identities, with a constant increase of population. The economic development is mainly focused on the region, and the economic growth per capita and technological change are more fragmented and slower than in the other scenarios. It is one of the most unfavourable climate change scenarios, with a possible increase of temperatures between 2 and 5.4°C by the end of the 21st century.

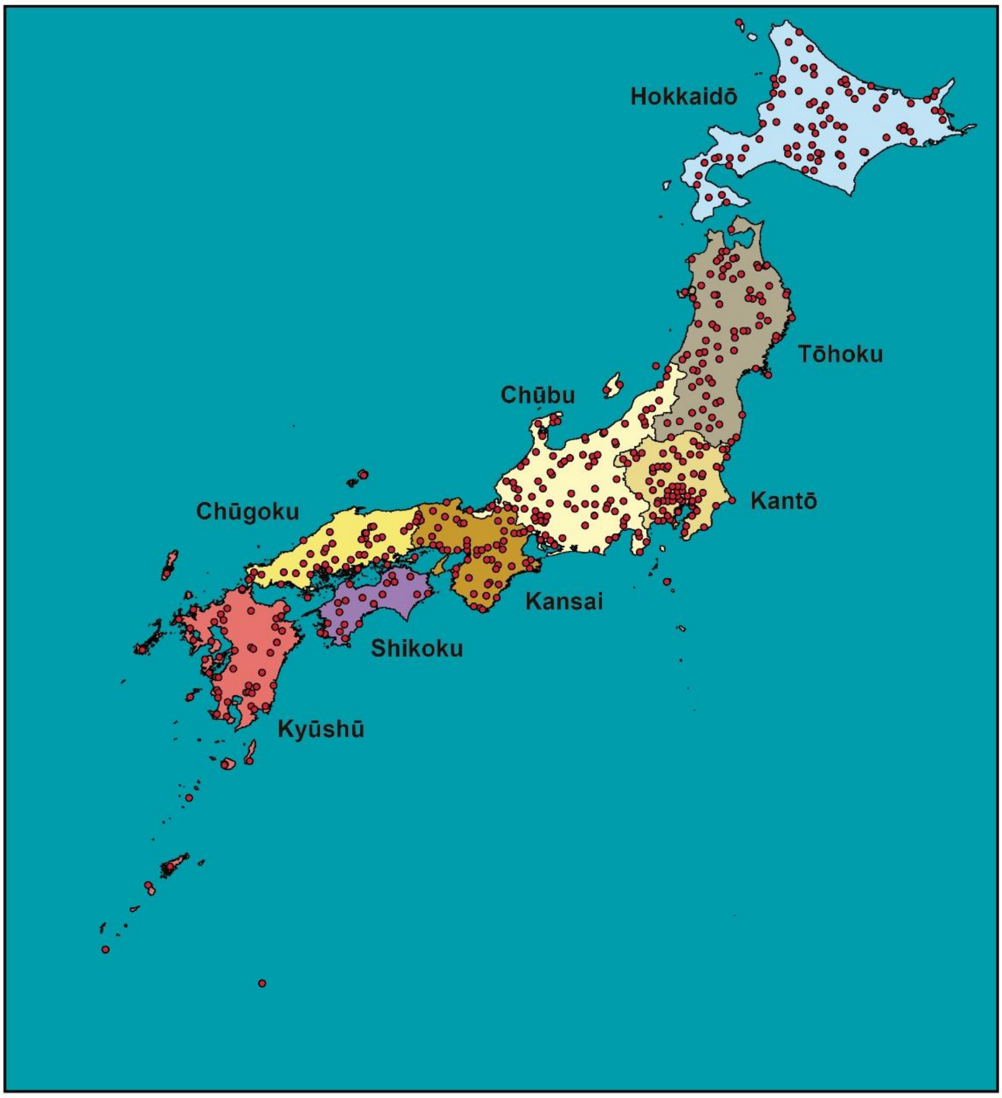

Figure 2. The regions of Japan and location of the 500 points used in this study.

It is important to highlight that these projections predict the average values with respect to the climatic variables that most influence the energy performance of a building (e.g., the external temperature), but don't predict extraordinary natural phenomena such as hurricanes or floods (Carlos Rubio-Bellido et al., 2016). Likewise, it is not possible to determine precisely what will be the most probable projection in the future (Nematchoua et al., 2019). For this reason, it is necessary to evaluate the possible variations that adaptive strategies can present in different future scenarios. To precisely know the possible evolutions of the application of adaptive thermal comfort models, external temperature data were compiled from each decade of the 21st century. Thus, hourly data were obtained for the years 2030, 2040, 2050, 2060, 2070, 2080, 2090 and 2100 in each of the climate change scenarios (A1B, A2, and B1).

2.3. Analysis process

The analysis process of the research consisted in assessing the possibilities to apply adaptive strategies and their effectiveness. Three aspects were evaluated: first, the application of the adaptive comfort model, and second and third, the possibility to apply both strategies of such model: natural ventilation and adaptive setpoint temperatures for heating and cooling.

To assess the application of adaptive thermal comfort models, the criterion included in ASHRAE 55-2017 was followed as it indicates that the comfort model could be used when $\overline{t_{pma(out)}}$ is between 10 and 33.5°C. It is worth stressing that, for this case, it is not necessary to distinguish between the 80 and 90% acceptability as both categories follow the same criterion. The $\overline{t_{pma(out)}}$ was determined by using data from the 15 previous days and with a α-value of 0.6, thus determinig the percentage of days of the year in which the adaptive thermal comfort model could be applied ($PDAAM$):

$$PDAAM = \frac{\sum_{i=1}^{365} d_i}{365} \qquad d_i = 1 \quad if\ 33.5 \geq \overline{t_{pma(out)}} \geq 10 \tag{6}$$

where d_i is a value assigned to each day of the year. If the $\overline{t_{pma(out)}}$ is between 10 and 33.5°C, then a value of 1 is assigned, and a value of 0 is assigned when such condition is not fulfilled.

Regarding adaptive strategies, the analysis was carried out at an hourly scale. For the natural ventilation, the number of annual hours in which the external temperature was within the thermal comfort limits of the category of 80 and 90% acceptability was assessed. For this purpose, a criterion similar to that of Eq. (6) was followed:

$$PHNV = \frac{\sum_{i=1}^{8760} h_i}{8760} \qquad h_i = 1 \quad if\ Upper\ acceptability\ daily\ limit \geq T_{ext,i} \geq Lower\ acceptability\ daily\ limit \tag{7}$$

where $PHNV$ is the percentage of hours in which adaptive natural ventilation strategies are applicable [%]; and h_i is a value assigned to each hour of the year. If the hourly external temperature is within the limits of acceptability, then a value of 1 is assigned, and a value of 0 is assigned when such condition is not fulfilled.

The possibility of using adaptive setpoint temperatures was assessed through the saving of heating and cooling degrees achieved with respect to use patterns of static setpoint temperatures (i.e., setpoint temperatures constantly used throughout the year). This type of setpoint temperatures is today the most usual behaviour guideline of users. Adaptive setpoint temperatures were determined according to the limits obtained by the model of 80% acceptability (Eqs. (2)-(3)) and for the model of 90% acceptability (Eqs. (4)-(5)). For the configurations of static setpoint temperatures, 3 temperatures were selected for cooling (25, 26, and 27°C) and 3 for heating (20, 21, and 22°C), following the same criterion of the previous research (Bienvenido-Huertas, Rubio-Bellido, Pérez-Fargallo, et al., 2020). Through these configurations of static and adaptive setpoints, different saving values of cooling and heating degrees were obtained:

$$T_{AH,i} = Lower\ acceptability\ daily\ limit \tag{8}$$

$$T_{AC,i} = Upper\ acceptability\ daily\ limit \tag{9}$$

$$StaticCD_R = \sum_{i=1}^{8760} (T_{SC,R,i} - T_{ext,i}) \cdot X_{CS} \qquad X_{CS} = 1\ if\ T_{ext,i} > T_{SC,R,i} \tag{10}$$

$$AdaptiveCD = \sum_{i=1}^{8760} (T_{AC,i} - T_{ext,i}) \cdot X_{CA} \qquad X_{CA} = 1\ if\ T_{ext,i} > T_{AC,i} \tag{11}$$

$$SCDH_R = StaticCD_R - AdaptiveCD \tag{12}$$

$$StaticHD_R = \sum_{i=1}^{8760} (T_{ext,i} - T_{SH,R,i}) \cdot X_{HS} \qquad X_{HS} = 1\ if\ T_{ext,i} < T_{SH,R,i} \tag{13}$$

$$AdaptiveHD = \sum_{i=1}^{8760} (T_{ext,i} - T_{AH,i}) \cdot X_{HA} \qquad X_{HA} = 1\ if\ T_{ext,i} < T_{AH,i} \tag{14}$$

$$SHDH_R = StaticHD_R - AdaptiveHD \tag{15}$$

where $T_{AH,i}$ is the hourly value of adaptive setpoint temperature for heating in an i-hour [°C]; $T_{AC,i}$ is the hourly value of adaptive setpoint temperature for cooling in an i-hour [°C]; $StaticCD_R$ is the annual sum of difference degrees between hourly static setpoints for cooling and the external hourly temperature [°C]; $T_{SC,R,i}$ is the hourly value of static setpoint temperature for cooling in an i-hour [°C]; $AdaptiveCD$ is the annual sum of difference degrees between hourly adaptive setpoints for cooling [°C] and the external temperature; $SCDH_R$ is the annual saving of cooling degrees [°C]; $StaticHD_R$ is the annual sum of the difference degrees between hourly static setpoints for heating and the external temperature [°C]; R is the reference value selected for static setpoint temperatures. Regarding heating temperatures, R has values of 20, 21, and 22°C, and as for 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 [°C]; $T_{ext,i}$ is the hourly value of external temperature in an i-hour [°C]; $AdaptiveHD$ is the annual sum of difference degrees between hourly adaptive setpoints for heating [°C] and the external temperature; $SHDH_R$ is the annual saving of heating degrees [°C]; and X_{HS}, X_{HA}, X_{CS}, X_{CA} are logic values whose value will be 1 when the condition provided by equations is fulfilled, and 0 when not. This approach was identical both for adaptive setpoints of 80% and of 90% acceptability.

Finally, as data from this study are presented by maps following colour codes, it was necessary to interpolate data for those locations not having nearby weather stations. These spatial analyses were conducted with the Geographic Information System (GIS), by using the parallel inverse distance weighting (IDW) interpolation algorithm (Watson & Philip, 1985). IDW considers that values spatially unknown are more influenced by close than distant points. Raster files could be developed by this algorithm, thus analysing the zones obtained.

3. Results and discussion

This Section includes and discusses the results obtained in the research. In addition, readers are recommended to consult the figures included in Annex A to obtain greater spatial information about the variations of the adaptive thermal comfort models in the different climate change scenarios. In this regard, all figures related to 2030, 2050, and 2100 are represented in such Annex.

3.1. Application of the adaptive thermal comfort models

First, the possibilities to apply the adaptive thermal comfort models from ASHRAE 55 were analysed. As Section 2 mentions, the fundamental requirement to apply these models is that $\overline{t_{pma(out)}}$ has a value between 10 and 33.5°C. For this reason, the analysis of the 500 locations in Japan determined the possibilities of application in the various scenarios analysed.

Climate conditions in Japan make possible to apply adaptive models today (Figure 3), since approximately 97% of the country obtained a percentage of application greater than 40%. Most low percentages of application (> 50%) were obtained in the Hokkaido Island and in some places of Aomori and Iwate Prefectures (characterised by a Dfb climate according to the Köppen-Geiger climate classification (Rubel & Kottek, 2010)). In this regard, some of the most important cities of the country, located in the Taiheiyō Belt, present percentages of application greater than 60% of the days of the year: the Kyōto-Ōsaka-Kōbe conurbation, with a percentage greater than 60%; and the Greater Tōkyō area, with a percentage greater than 70%.

It is also important to stress that there is a small percentage of the country presenting suitable climate conditions to apply the adaptive model throughout the year. The adaptive model could be applied during 80% of the year or more in approximately 2% of the territory, mainly in the islands in the south of Japan (e.g., The Ryukyu Islands or Okinawa). These results are in accordance with that obtained by the overall study, in which percentages of application greater than 90% of the days of the year were obtained in other regions of the world nearer to the equator.

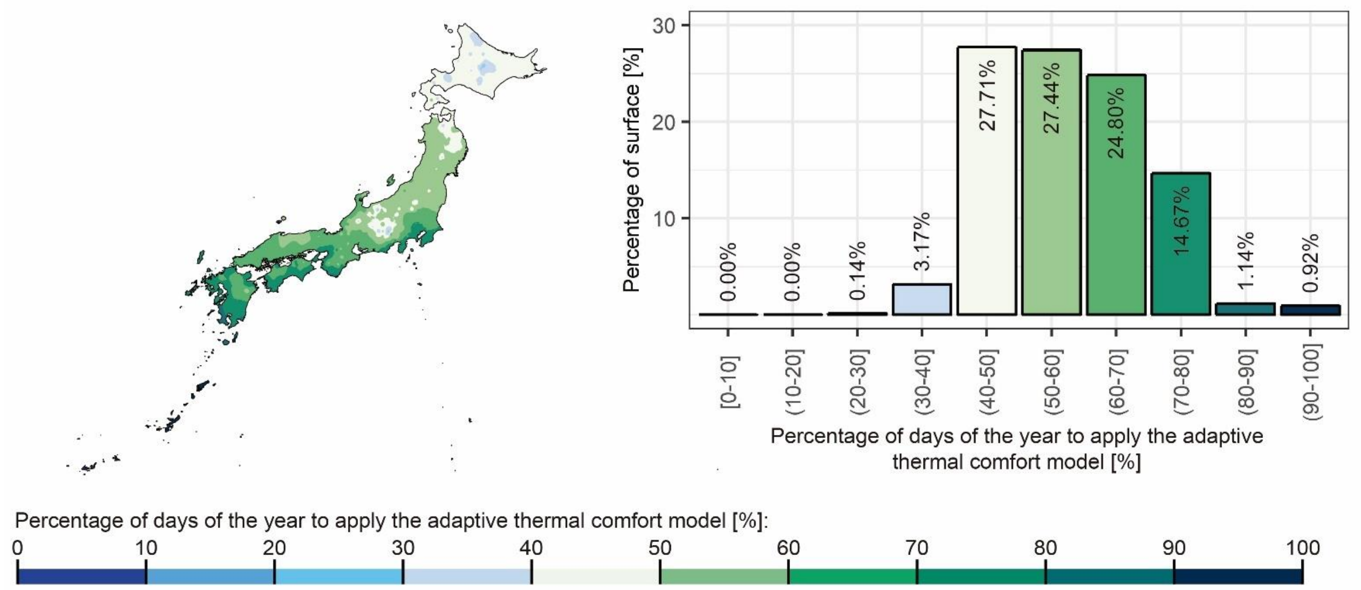

Figure 3. Percentage of days of the year to apply the adaptive thermal comfort model in Japan in the current scenario. The percentage of surface per application ranges throughout the year is also indicated.

However, future climate change scenarios would vary the possibilities of application in the various zones of Japan (Figure 4). The different climate change scenarios increase the possibilities to apply adaptive thermal comfort models. There is a downward tendency in the percentages of application lower than 70%, whereas the percentages of application greater than 70% group zones with the lowest percentages of application. It was also found that scenarios A1B and A2 presented a similar linear tendency throughout the 21st century, stressing a small increase in surface of the application between 60 and 70% in the year 2080 due to the unification of zones with lower applications.

Although the 3 scenarios tend to a better application of these models by the end of the 21st century (2100), the own characteristics of each scenario lead to climate change scenarios contributing more than others to the use of these models. In this regard, the scenario A2 achieved the greatest percentage of surfaces with a high application (greater than 80%): the scenario A2 achieved a percentage of the surface of Japan of 14.12%; the scenario A1B, a 10.44%; and the scenario B1, a 6.36%. Likewise, in the lowest range of percentages of application (between 30 and 50%), the scenario A2 obtained the lowest surface (9.01%), whereas the percentage was greater in the other two scenarios (16.50% in A1B and 23.83% in B1).

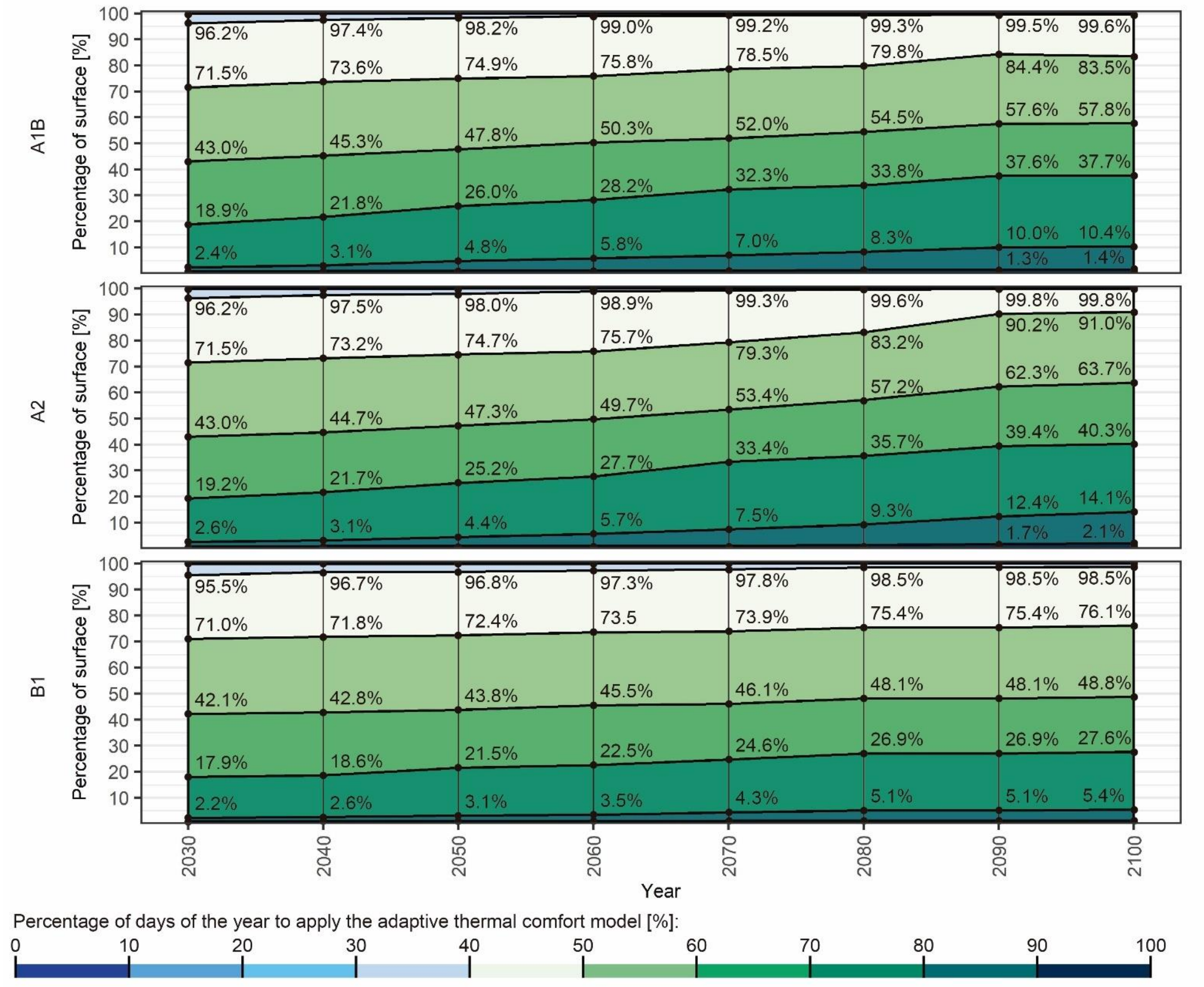

Figure 4. Evolution of the percentages of the days of the year with application of the adaptive thermal comfort model in the 3 climate change scenarios in Japan throughout the 21st century.

3.2. Natural ventilation strategies

After analysing the possibilities to apply the adaptive thermal comfort models in the regions of Japan, the possibility to thermally adapt the internal spaces of buildings by natural ventilation was assessed. For this purpose, the hours of the year in which the external temperature was between the lower and upper limit of the adaptive model were hourly analysed. Likewise, both limit typologies established by ASHRAE 55 were analysed: 80% acceptability and 90% acceptability.

First, the results related to the current scenario are discussed (Figure 5). The possibilities to use ventilation strategies were never greater than 70%. In this regard, only a very low percentage of surface of the country (lower than 1%) achieved a percentage of application between 40 and 70% by using the model of 80% acceptability. These zones are most of the island territory in the south of Japan. The application of natural ventilation strategies in Japan presents therefore a possibility of application lower than 40% in most of the territory, stressing the application between 20 and 30% which virtually includes half of the country.

In this regard, it is crucial to consider users' thermal expectations to condition internal spaces, since using the model of 90% acceptability instead of that of 80% acceptability generates significant variations in the possibilities to apply ventilation strategies. The use of a model of 90% acceptability implies that almost 50% of the country could use the natural ventilation strategies between 10 and 20% of the hours of the year, instead of between 20 and 30% (80% acceptability) (Figure 5).

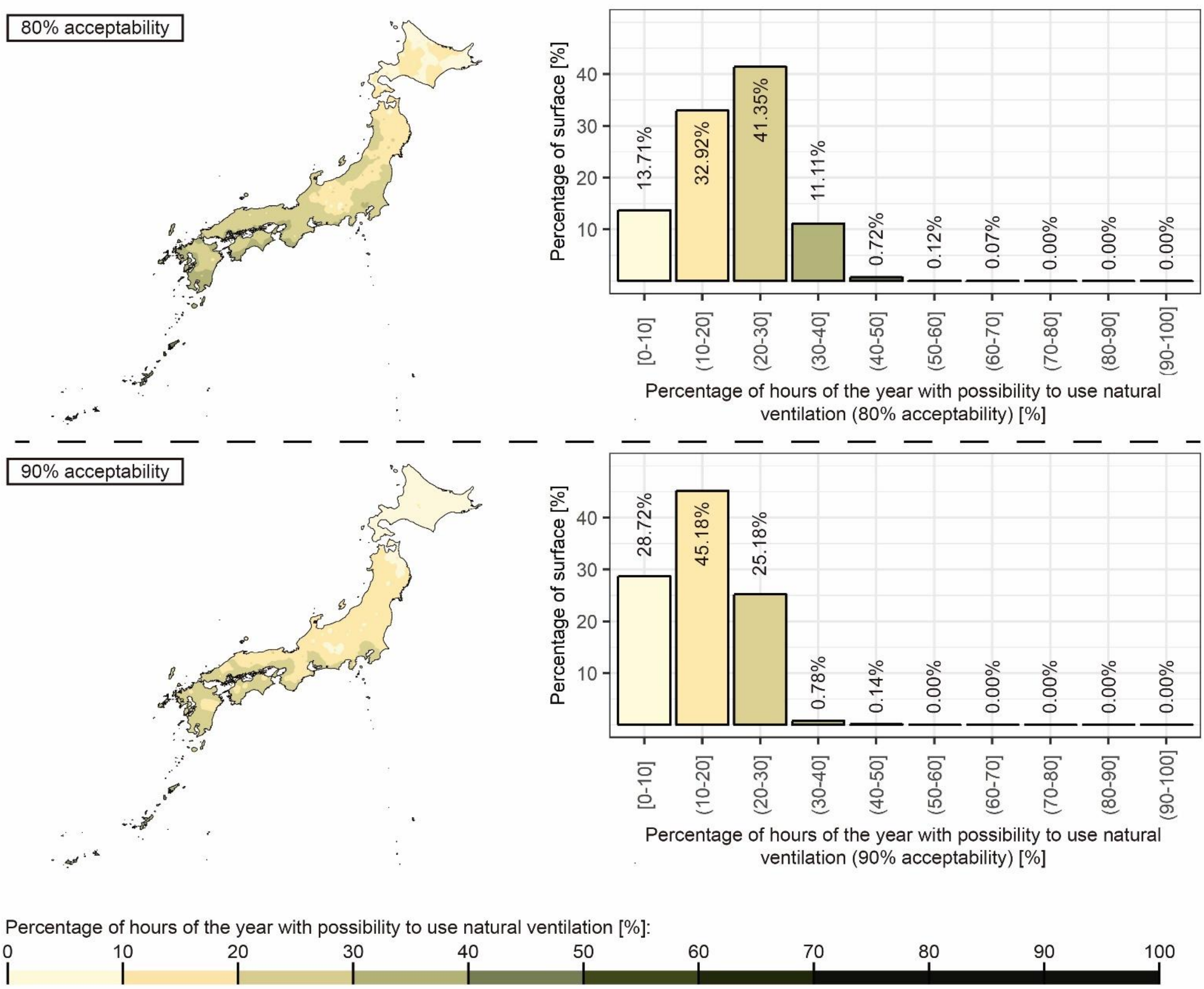

Figure 5. Percentage of hours of the year with the possibility to use natural ventilation strategies in Japan in the current scenario. The results are distinguished according to the acceptability model considered (80 and 90%). The percentage of surface per application ranges throughout the year is also indicated.

As with the possibilities to apply adaptive thermal comfort models from ASHRAE 55, future climate change scenarios imply a variation in the number of hours of the year with possibilities to naturally ventilate buildings.

Firstly, in the model of 80% of acceptability, the rise of external temperatures increased in turn the number of hours in which buildings could be ventilated, and such number was greater in the most unfavourable climate change scenarios (Figure 6). The scenario A2 obtained the greatest surface of the country in which buildings could be ventilated during more time: in the year 2100, the scenario A2 obtained that the application range between 30 and 40% of the hours of the year will be applied in 32.84% of the surface of the country, whereas in A1B in 28.40%, and in B1 in 19.26%. The lowest application range also decreased, from 13.71% of the surface in the current scenario to 0.56% in A1B, 0.33% in A2, and 5.14% in B1. In addition, there is again a similar behaviour tendency between scenarios A1B and A2, although the own characteristics of the latter contribute to greater possibilities to ventilate buildings naturally.

Secondly, the use of the model of 90% acceptability in future climate change scenarios presented the same tendency as in the current scenario: the possibilities to apply the natural ventilation strategies in the country were reduced. In this regard, the comparison between the possibilities of application of the model of 80 and 90% acceptability shows that the increase of thermal expectations increases low percentages of application and reduces the others. So, the minimum and maximum average differences in the 3 climate change scenario throughout the 21st century by increasing the acceptability of the thermal model by 90% were as follows: (i) in the application range between 0 and 10%, the surface increased between 9.36 and 16.56%; (ii) in the application range between 10 and 20%, the surface increased between 13.47 and 19.08% (iii) in the application range between 20 and 30%, the surface decreased between 0.89 and 20.26%; and (iv) in the application range between 30 and 70% , the surface decreased between 0.01 and 0.63%.

These results therefore show that, although climate conditions in Japan do not contribute to a high number of years of the year in which buildings could be naturally ventilated according to the adaptive model, the rise of external temperatures will in turn increase the possibilities to use these strategies. However, it is essential that users have thermal expectations adopting an adaptive thermal comfort model with broader limits, since models with a lower amplitude between lower and upper limits (such as the model of 90% acceptability) reduce the possibilities to apply ventilation strategies in the country.

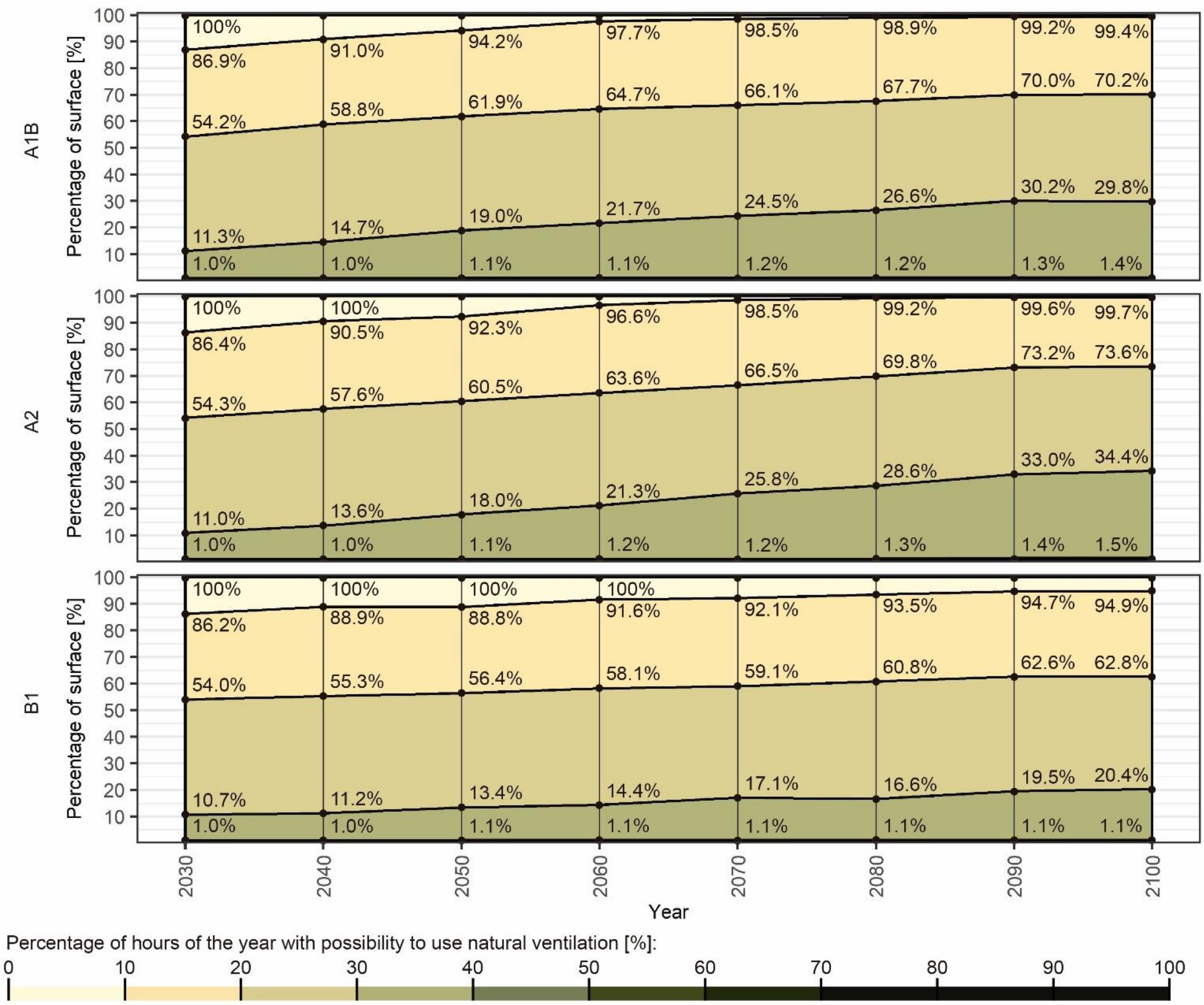

Figure 6. Evolution of the percentages of the hours of the year with the possibility to use natural ventilation strategies in the 3 climate change scenarios in Japan throughout the 21st century (80% acceptability).

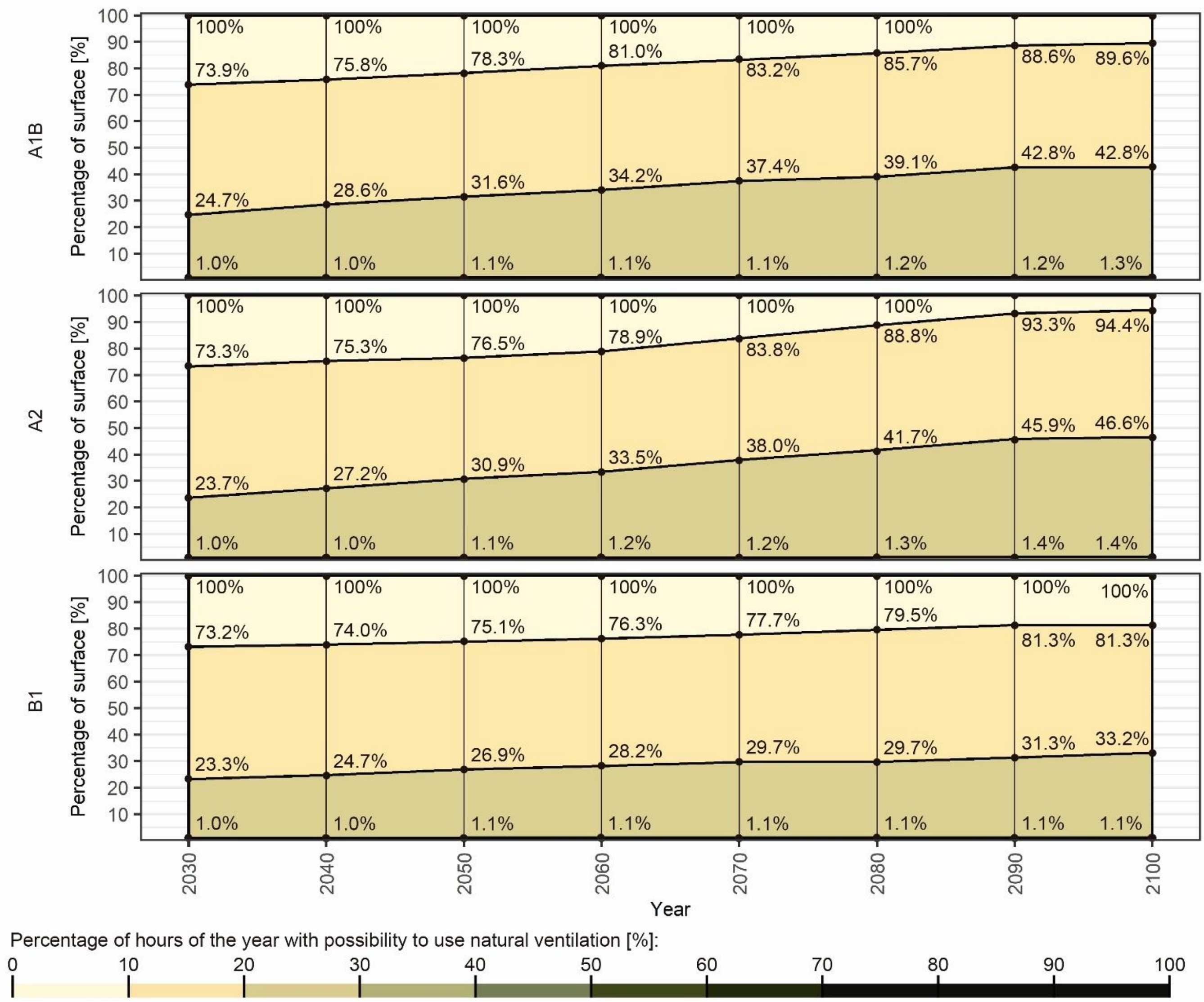

Figure 7. Evolution of the percentages of the hours of the year with the possibility to use natural ventilation strategies in the 3 climate change scenarios in Japan throughout the 21st century (90% acceptability).

3.3. Strategies of adaptive setpoint temperatures

Finally, the potential of using adaptive setpoint temperatures was analysed in the two thermal comfort models from ASHRAE 55. For this purpose, the saving of heating and cooling degrees obtained by adaptive setpoint temperatures was hourly assessed with respect to the different static setpoint temperatures used throughout the year: (i) 20, 21, and 22 for heating, and (ii) 25, 26, and 27 for cooling. The analysis was conducted for the model of 80% acceptability, and then the variations obtained by using the model of 90% acceptability were assessed. It is worth stressing that in those regions with a low application (e.g., the Hokkaido Island), the use of adaptive setpoint temperatures was mainly based on the use of the heating temperature obtained in the limit value of 10°C (see Figure 1).

With respect to the saving of heating degrees, the use of adaptive setpoint temperatures achieved considerable savings in all the scenarios considered (Figure 8). In this regard, the saving of heating degrees obtained very similar results in the different years and periods of climate change. The differences obtained were according to the reference value considered for the static setpoint temperature: (i) for the static setpoint temperature of 20°C, savings between 19 and 20,870°C were achieved; (ii) for the static setpoint temperature of 21°C, savings between 888 and 29,602°C; and (iii) for the static setpoint temperature of 22°C, savings between 2,720 and 38,329°C. These results showed the great potential of using adaptive setpoint temperatures for heating systems, as even in the assumption of using an effective static setpoint temperature (i.e., a temperature of 20°C), considerable savings of heating degrees are achieved. Although the tendency of saving heating degrees was similar throughout the 21st century, as the century was advancing, the saving of heating degrees could be reduced. This was the result of the climate change scenario being considering, which generated a lower demand. This aspect is shown by the violin plots included in Figure 9, which represent the distributions obtained in the hourly saving of heating degrees in 2050 and 2100. The distributions between scenarios A1B and A2 were very similar and virtually had the same saving values in the whole Japanese territory, whereas the scenario B1 was characterised by having a greater concentration of instances in the upper side of the distribution. The reason was that a greater heating demand would be required in buildings due to lower external temperatures than that of scenarios A1B and A2.

So, in a scenario with a lower increase of external temperatures, the use of adaptive setpoint temperatures would slightly increase the saving of heating degrees with respect to the most unfavourable scenarios. Also, the evolution of climate change scenarios reduces the saving of heating degrees. This aspect is found in the differences of the densities of distributions of the violin plots from 2050 and 2100. In this regard, some details could be highlighted, such as the concentration of values around 30,50°C of the scenario A2 in 2050 with respect to a static setpoint temperature of 22°C, which becomes to be concentrated around 28,000°C in 2100.

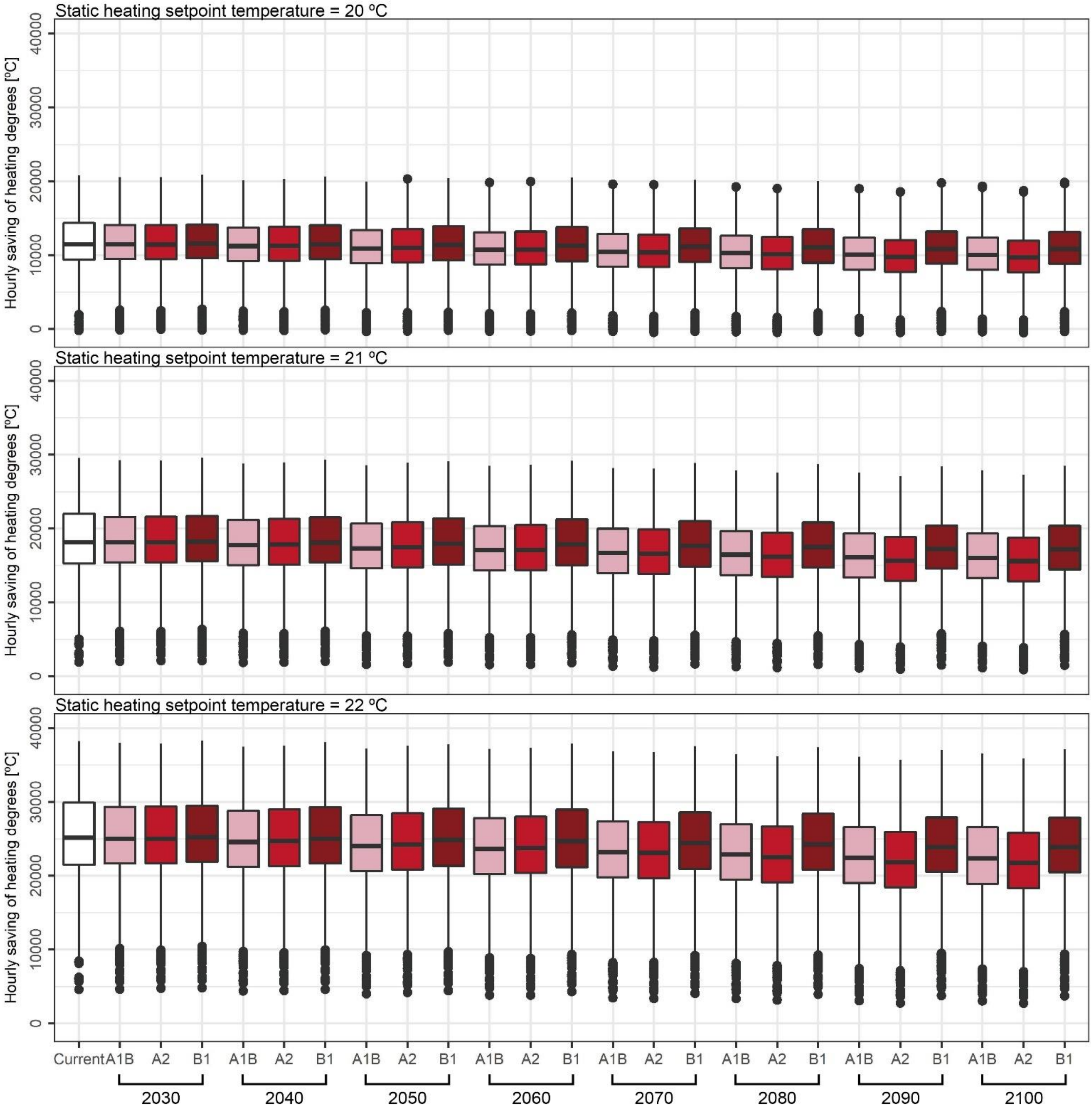

Figure 8. Comparison of the hourly distribution of the saving of heating degrees by using adaptive setpoint temperatures (model of 80% acceptability) with respect to the 3 configurations of static setpoint temperatures in all the time scenarios considered in the research.

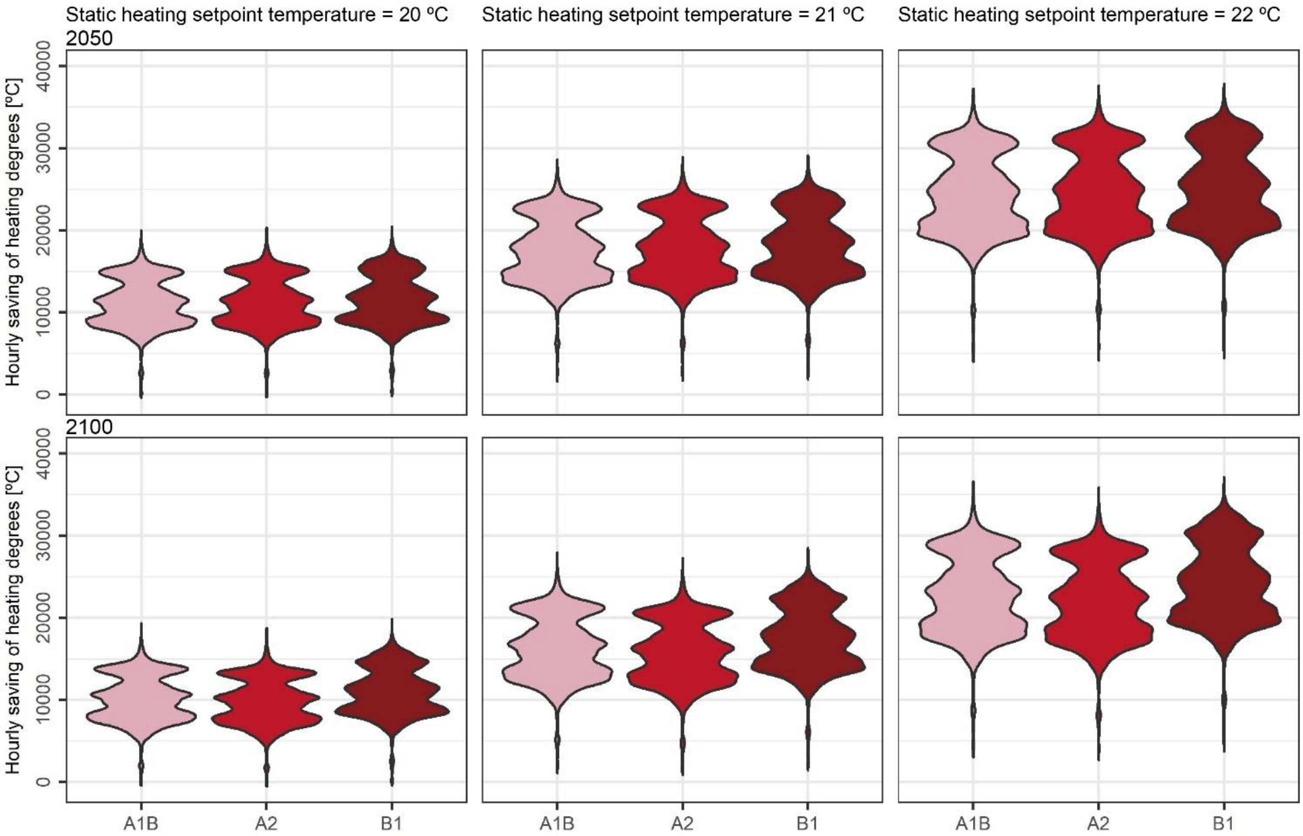

Figure 9. Violin plots with the variations of the hourly distribution of the saving of heating degrees by using adaptive setpoint temperatures (model of 80% acceptability) with respect to the 3 configurations of static setpoint temperatures in 2050 and 2100.

This progressive decrease of the hourly saving of heating degrees of the Japanese building stock had the opposite effect in the saving of cooling degrees. Firstly, the saving of cooling degrees progressively increased in the results estimated for the 21st century (Figure 10). In general terms, the saving of cooling degrees is lower than that obtained of heating degrees due to the climate of Japan, characterised by temperatures usually generating a heating demand greater than a cooling demand. For this reason, saving results ranging between the following values were obtained in the current scenario: (i) for the static setpoint temperature of 25°C, savings between 3and 9,024°C were achieved; (ii) for the static setpoint temperature of 26°C, savings between 1 and 6,1871°C; and (iii) for the static setpoint temperature of 27°C, savings between 0 and 4.049°C. However, adaptive setpoint temperatures reduced cooling degrees in most approaches of the research, except in cold zones, such as the region of Hokkaido, in which cooling degrees increased.

In addition, the potential to use adaptive setpoint temperatures for cooling is mainly related to the progressive external temperature rise, which will generate a greater cooling demand. In this regard, the use of adaptive setpoint temperatures achieved greater savings in the scenario A2 with respect to the other scenarios (Figures 10 and 11), due to the progressive increase of distributions of the saving values obtained. The saving of cooling degrees increased in 2100 with respect to that obtained in 2050 (Figure 11), thus showing the most appropriate behaviour guidelines that Japanese users should adopt to guarantee an adequate performance of buildings in the hottest hours.

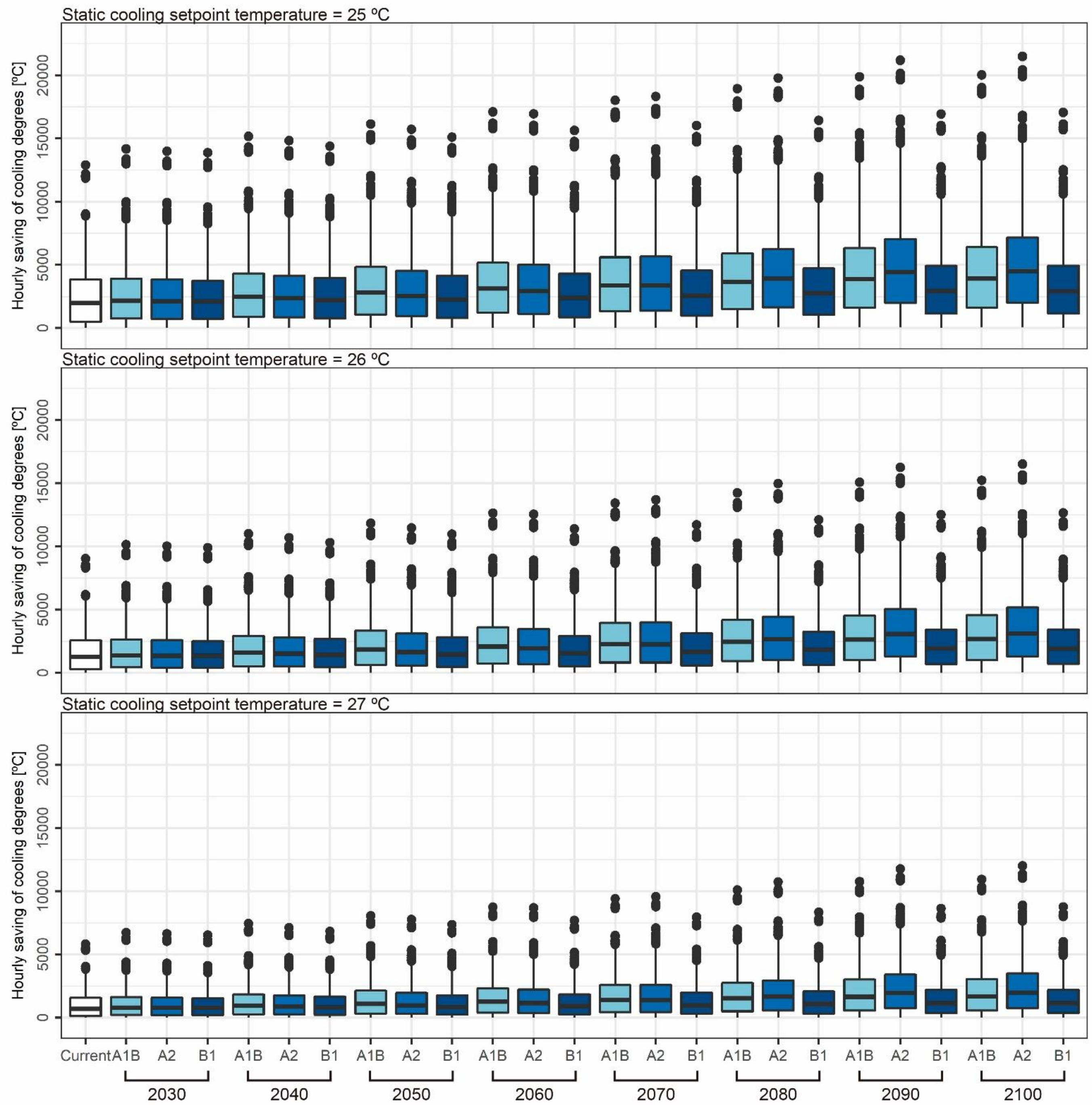

Figure 10. Comparison of the hourly distribution of the saving of cooling degrees by using adaptive setpoint temperatures (model of 80% acceptability) with respect to the 3 configurations of static setpoint temperatures in all the time scenarios considered in the research.

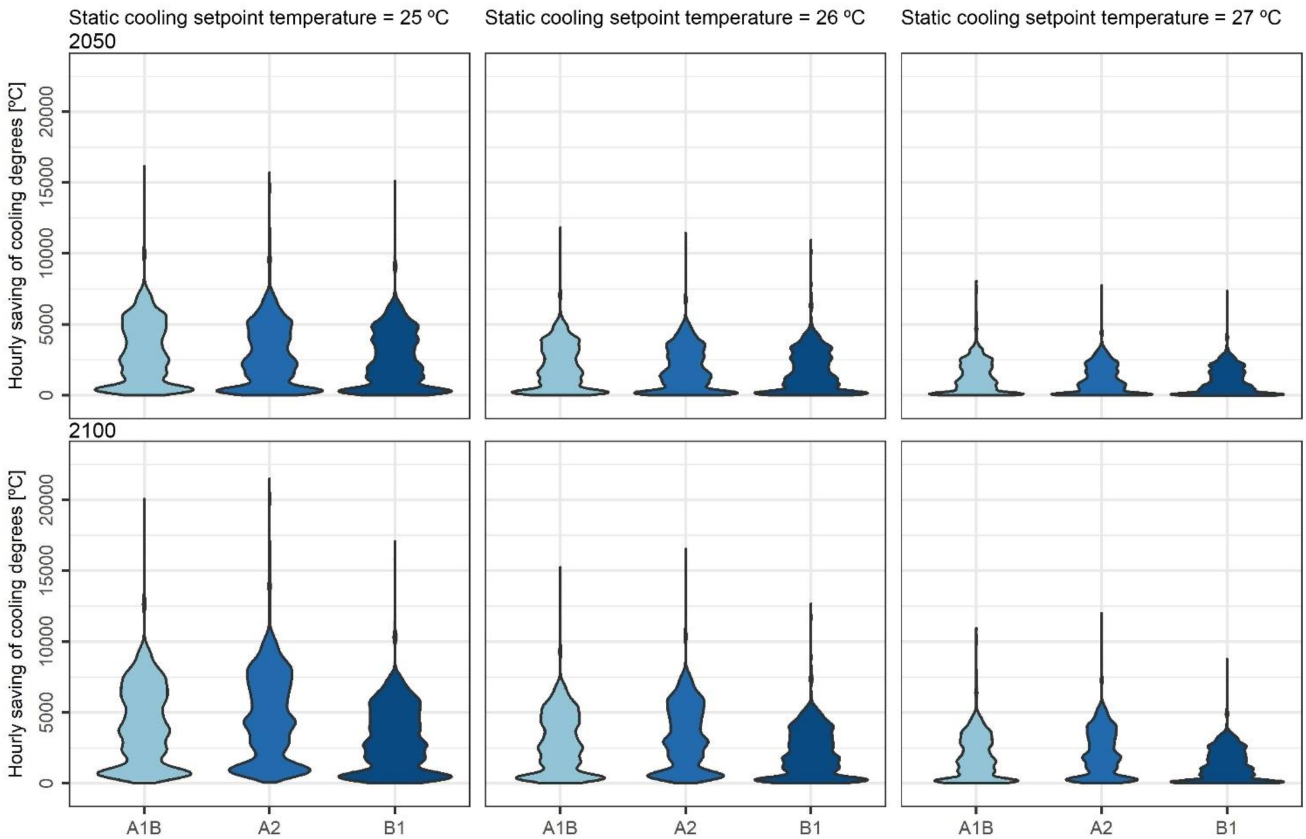

Figure 11. Violin plots with the variations of the hourly distribution of the saving of heating degrees by using adaptive setpoint temperatures (model of 80% acceptability) with respect to the 3 configurations of static setpoint temperatures in 2050 and 2100.

Furthermore, the increase of users' thermal expectations with the model of 90% acceptability directly influenced the hourly saving of heating and cooling degrees. Table 1 summarises the increases obtained in the saving of degrees by using the model of 80% acceptability instead of that of 90%. As can be seen, increasing the limits of the adaptive thermal comfort model by 1°C strongly affected the saving of heating and cooling degrees in the whole Japanese territory. In this regard, the increase in the saving values of degrees presented the same tendency analysed in Figures 8-11, with a progressive decrease of heating degrees and an increase of cooling degrees. As for the latter, the increase of the upper limit could mean that, by the end of the 21st century, a greater maximum saving between 545 and 1,248 was obtained with respect to that obtained in the current scenario. The use of adaptive setpoint temperatures therefore allows important savings of heating and cooling degrees to be achieved.

However, the effectiveness of this energy saving measure will also depend on users' thermal expectation level. The combination of these approaches of internal spaces thermal comfort with others, such as the installation of photovoltaic cells and the cogeneration (Ishii et al., 2010; Wu et al., 2016; Yuan et al., 2016), would significantly reduce the greenhouse gas emissions related to the building sector in Japan.

Table 1. Increase ranges of the hourly saving of heating and cooling degrees by using the model of 80% acceptability instead of the model of 90% acceptability. Minimum and maximum values are represented.

Period	Year	Increase range of the hourly saving of degrees [°C]			
		Hourly saving heating degrees		Hourly saving cooling degrees	
		Min	Max	Min	Max
Current		2,689	8,669	0	1,079
A1B	2030	2,671	8,643	0	1,288
	2040	2,525	8,560	0	1,427
	2050	2,432	8,519	3	1,538
	2060	2,298	8,552	3	1,652

	2070	2,187	8,491	5	1,786
	2080	2,147	8,481	8	1,951
	2090	2,022	8,450	6	2,076
	2100	1,962	8,497	7	2,100
A2	2030	2,646	8,568	0	1,258
	2040	2,515	8,571	1	1,319
	2050	2,463	8,559	1	1,474
	2060	2,309	8,560	2	1,683
	2070	2,207	8,456	3	1,811
	2080	2,091	8,422	9	2,077
	2090	1,880	8,399	10	2,234
	2100	1,897	8,400	8	2,327
B1	2030	2,716	8,631	1	1,227
	2040	2,578	8,636	1	1,289
	2050	2,561	8,599	0	1,398
	2060	2,465	8,618	0	1,467
	2070	2,448	8,600	1	1,522
	2080	2,360	8,650	1	1,596
	2090	2,319	8,616	0	1,634
	2100	2,332	8,583	0	1,624

4. Conclusions

Following previous research by the authors (Bienvenido-Huertas, Rubio-Bellido, Pérez-Fargallo, et al., 2020), this is the first comprehensive study of its kind to assess the effect of climate change on the feasibility of the adaptive comfort model in the whole Japanese territory. A previous study by Shibuya & Croxford (2016) analysed three selected locations nationwide, representative of the extreme climates of Japan, but did not address the issue as in this study. Large amounts of data have been generated and presented not only in graphs and tables, but also in maps that allow the most affected regions of the country to be easily identified. The most relevant conclusions of this study are related to the applicability of the adaptive model itself, as well as of the two main strategies that it comprises: natural ventilation and adaptive setpoint temperatures.

In general, it can be said that future climate outlines a favourable scenario for the feasibility of such model. Areas of Japan where this model finds application between 40 and 80% of the year will essentially remain the same; however, the surface where the applicability falls between 60 and 80% will generally increase at the expense of those with an applicability between 40 and 60%. Areas with very low or very large percentages of application seemed to remain marginal in all scenarios. Therefore, according to this study, the applicability of this model across the Japanese territory might be influenced, albeit to a moderate degree. Nonetheless, it is important to mention regional differences: heavy built-up areas such as the Taiheiyō Belt will not see remarkable changes, whereas North-Easter areas, such as Hokkaidō and Tōhoku might be clearly influenced under the different scenarios.

Natural ventilation seems not to play an important role, not in current nor in future scenarios, with percentages of application thorough the year below 40% in the great majority of the cases. Slight differences were found depending on the percentage of acceptability, but overall, the figures are basically the same. Once again, the regions of Hokkaidō and Tōhoku in North-Western Japan are expected to see the more significant changes in future scenarios.

The potential savings both for heating and cooling degrees depending on the adaptive setpoint temperatures pave the way for a fruitful discussion. Indeed, a rise in temperatures seems to bring larger savings for heating rather than cooling in the Japanese territory, which might lead to a wrong conclusion: in the event that Japanese climate would be warmer in the future, the overall energy used for keeping buildings warm or cool could stay the same or even be reduced. However, additional information extracted from the maps could lead to different conclusions. Regarding heating degrees, substantial savings could be achieved in the coldest regions of Japan (Hokkaidō, Tōhoku, and parts of Chūbu) for all scenarios. However, the potential saving of cooling degrees, despite being remarkably lower than its counterpart, is of greater importance for the purpose of this study. This is because the areas with a greater potential for savings lay on the Taiheiyō Belt, a heavily urbanised area where around 60% of the Japanese population (i.e., around 76 million people) live (ー少子高齢化時代の地域活性化検討委員会, 2005).

The results from this study might be of use in explaining the general trend followed by previous research; besides, despite this study might be the first one of its kind, its results can be supported by other studies that have dealt with similar topics. In the introduction, it was mentioned that researchers seemed to have focused on cooling loads rather than heating loads (ISOZAKI & TAKEDA, 2019) , with studies dealing with building in the Kantō region (Arima et al., 2016; Kim et al., 2019). The present research adds to the understanding of this issue and confirms the necessity of conducting more research specifically focused on the effect of climate change in the cooling strategies, including of course adaptive comfort models, in this specific region of Japan.

This leads to a discussion about the importance of refining this kind of studies. Despite the authors consider that this study provides with insightful conclusions, it should be mentioned that there were limitations that should be overcome in future research.

First, there is an evident gap between the previous research that was mentioned in the introduction, whose conclusions were based on single case-studies, and a study of this kind, which bring results on the basis of large-scale simulations. Therefore, future research should be oriented towards small and mid-scaled studies. Thus, future studies will be oriented to the individual analysis of the most frequent types of buildings in the country and the impact of the use of adaptive energy saving strategies. Furthermore, this would allow establishing bioclimatic design charts of the use of HVAC systems for interior spaces, similar to studies carried out in other countries, such as India (Tewari, Mathur, & Mathur, 2019; Tewari, Mathur, Mathur, Loftness, et al., 2019).

Second, this study drew conclusions considering the percentage of the area of Japan where the adaptive comfort model might find application. Despite it was mentioned at some point of the manuscript, this study does not provide with conclusions with regard to the percentage of population affected by the future changes in the feasibility of the model; however, it gave some hints regarding the gap between the highly populated areas (Taiheiyō Belt) and extense but underpopulated regions, such as Hokkaidō and Tōhoku. Therefore, future studies should assess the impact of the application of such models in relation with the affected population, as authors did in previous research at a worldwide scale (Bienvenido-Huertas, Rubio-Bellido, Pérez-Fargallo, et al., 2020).

These two main limitations might be overcome in a future study that features a model with a better resolution and that assess the impact of climate change with respect to the population. In the case of Japan, the greater Tokyō area and the cities in the Taiheiyō Belt will deserve special attention because of effect that a sprawled, heavily urbanised and populated area may exert on the temperature distribution. Previous research has shown that the rapid and intense urbanisation process that Tokyō experienced since 1868 have had an influence on the average temperatures (a rise of 3°C during the period 1901-2015) and also suggested that it might exert some influence on the number of foggy days and the urban rainfall (Matsumoto et al., 2017). For those reasons, the authors consider that future studies should address this issue in an urban-regional scale. In concrete, it is suggested that the prevailing mean-outdoor temperature for future mid-scaled models should be adjusted considering the urban heat island phenomenon. Likewise, it is necessary to carry out a control of the variation of the real temperatures with respect to the future estimates analysed. For this reason, the analysis of the evolution of temperature throughout the country in the coming years will determine which projection is best adjusted in 2030.

Summing up, this study has provided with valuable information about the feasibility of the adaptive comfort model and its strategies at a national scale for Japan. Remarkable differences have been found between regions, and the conclusions shed light on the direction that not only new, but also extant buildings, should follow to provide a comfortable environment while containing the energy used in heating and cooling, paving the way for a more sustainable future for the building industry in this country.

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Annex A

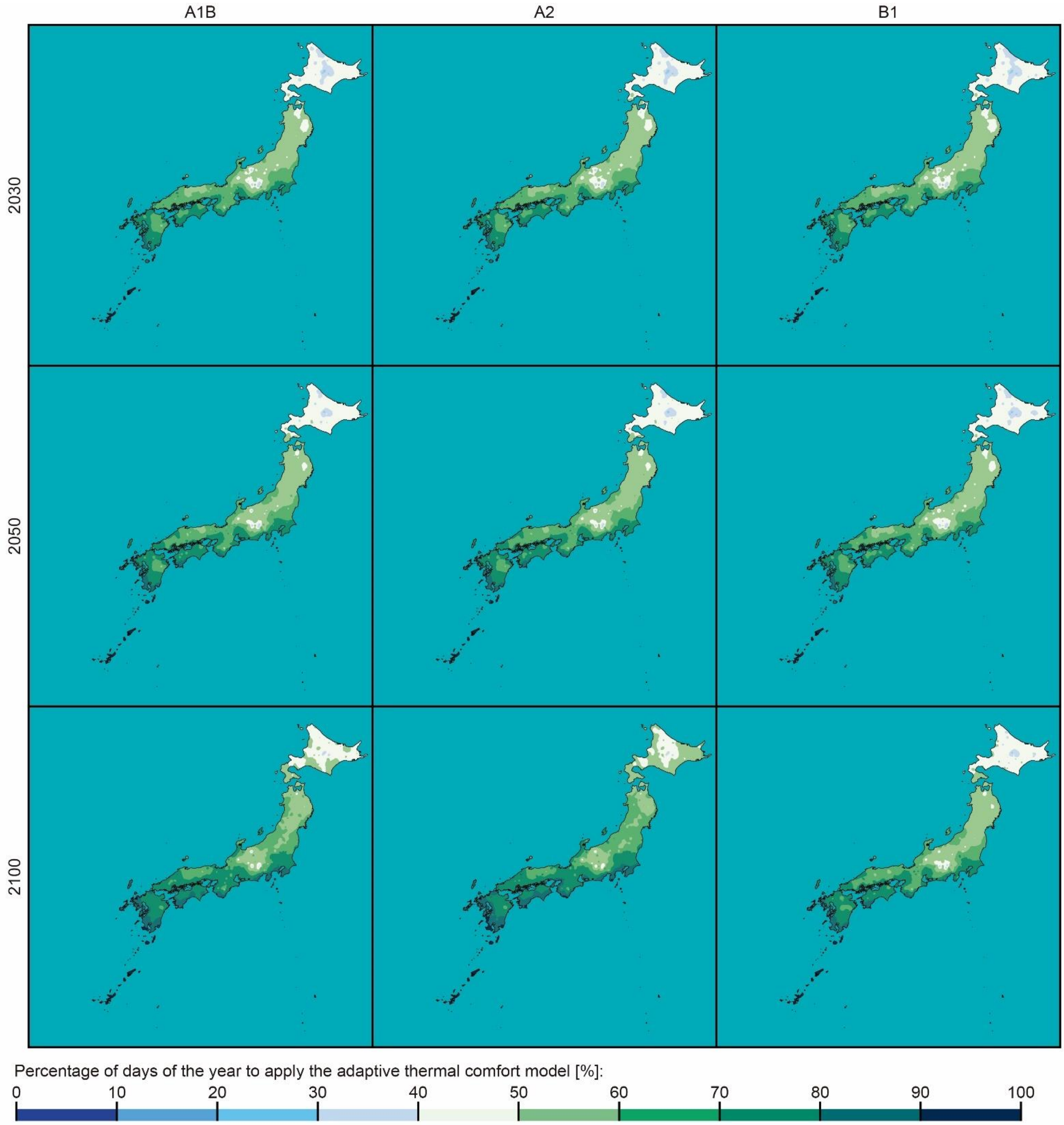

Figure A1. Percentage of days of the year with the application of the adaptive thermal comfort model in Japan in future climate change scenarios in 2030, 2050, and 2100.

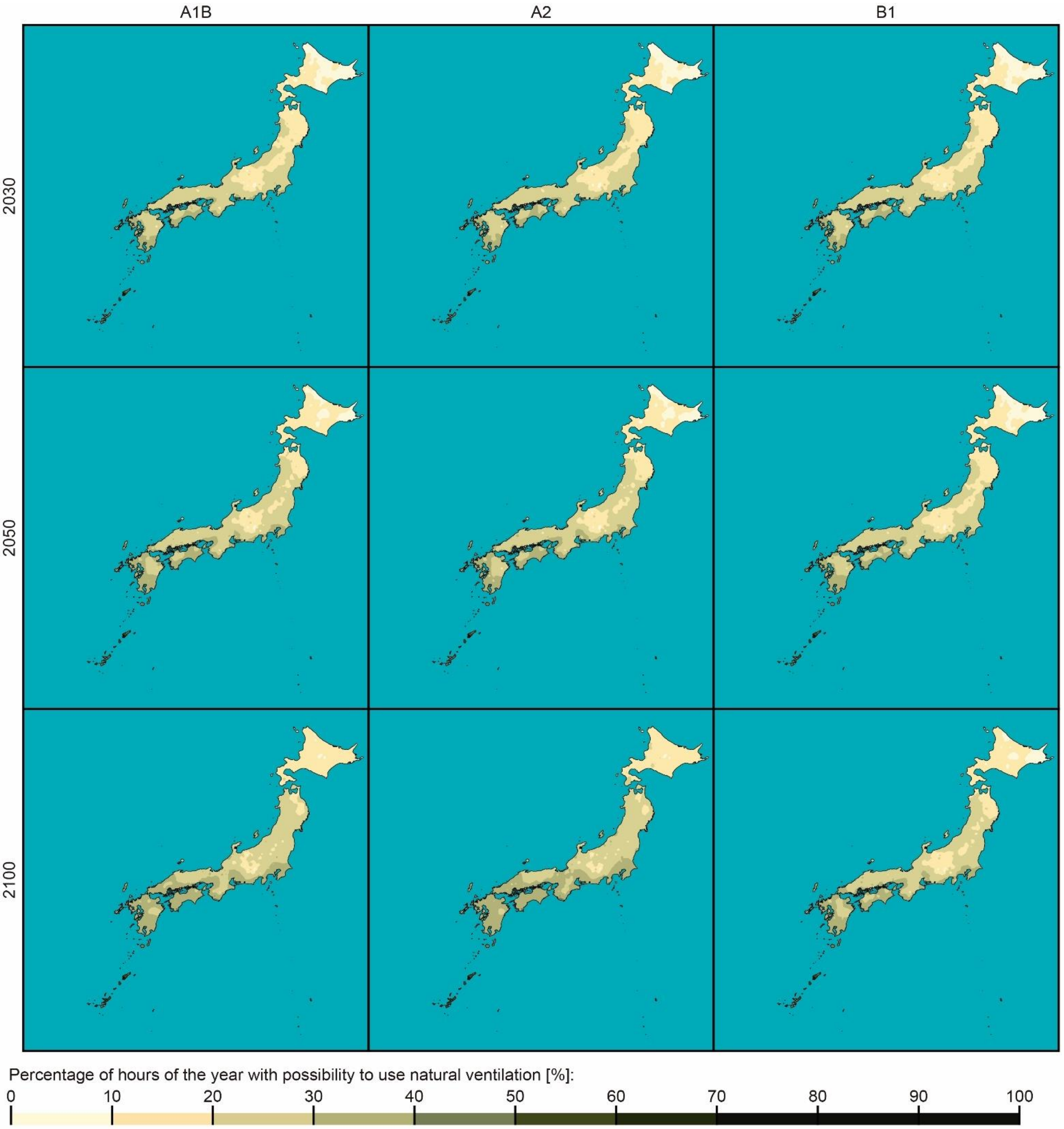

Figure A2. Percentage of days of the year with the possibility of using natural ventilation strategies Japan in future climate change scenarios in 2030, 2050, and 2100 (80% acceptability).

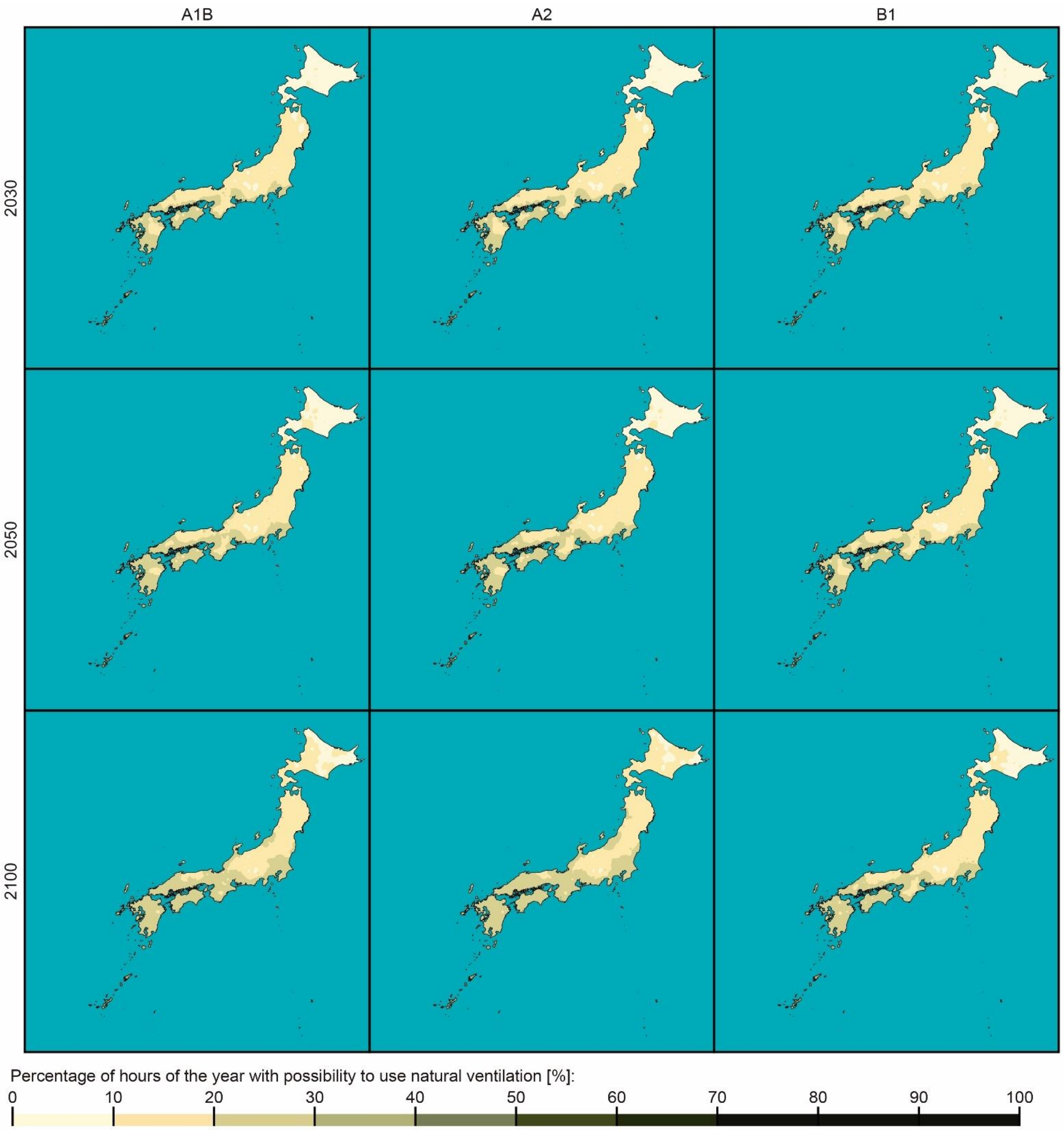

Figure A3. Percentage of days of the year with the possibility of using natural ventilation strategies Japan in future climate change scenarios in 2030, 2050, and 2100 (90% acceptability).

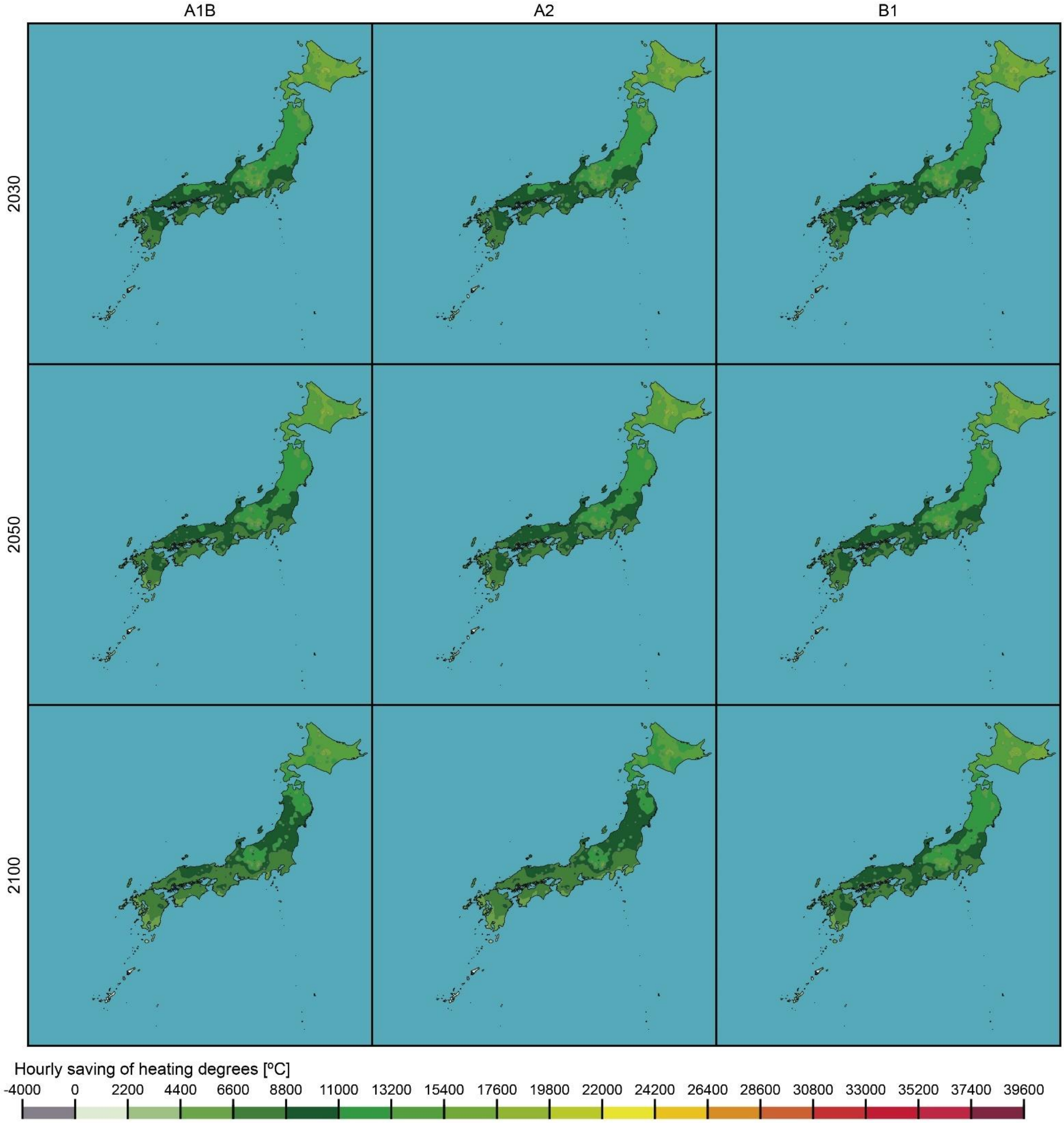

Figure A4. Comparison of the hourly saving of heating degrees by using adaptive setpoint temperatures with respect to static setpoint temperatures of 20°C in Japan in 2030, 2050, and 2100 (80% acceptability).

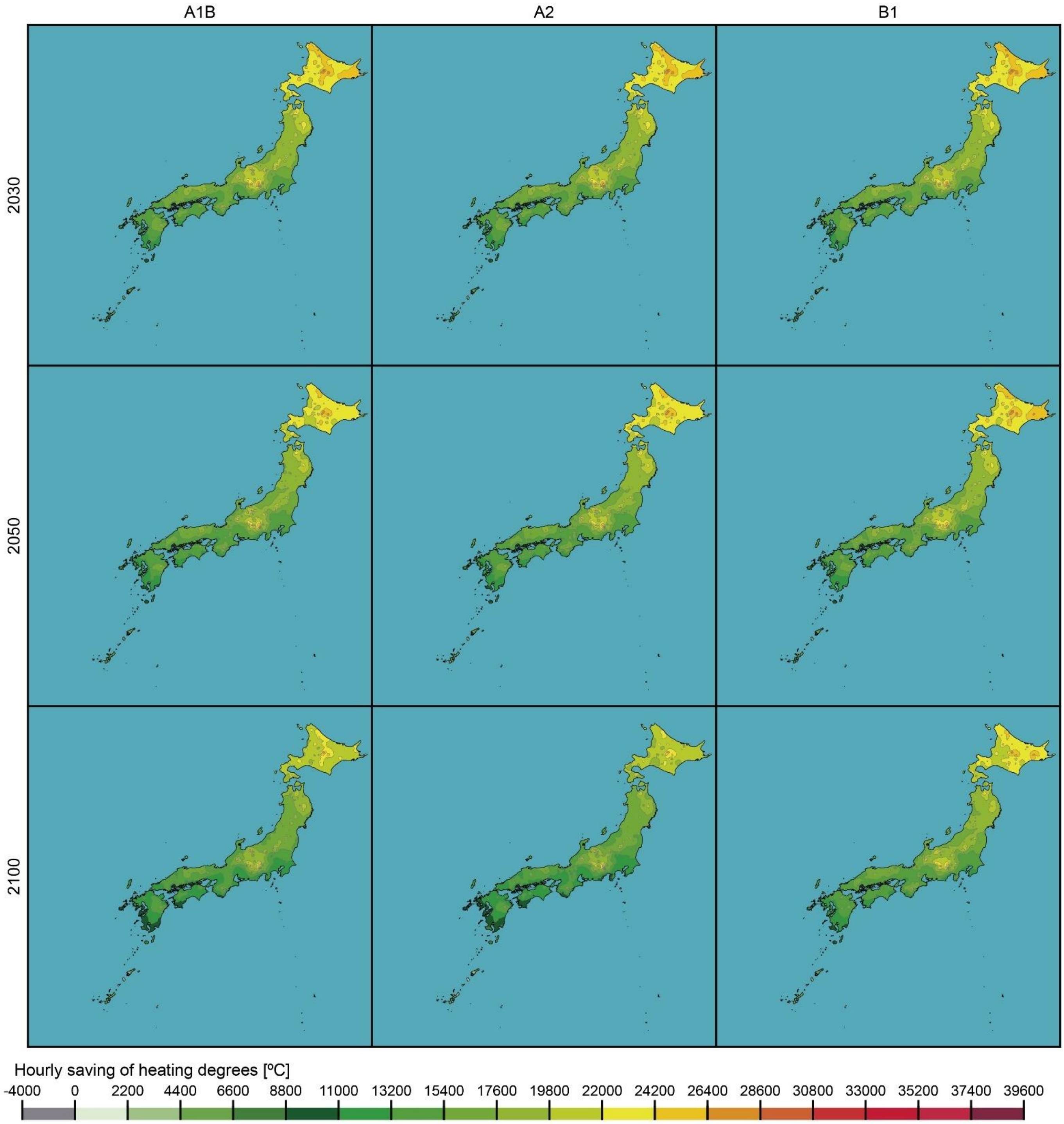

Figure A5. Comparison of the hourly saving of heating degrees by using adaptive setpoint temperatures with respect to static setpoint temperatures of 21°C in Japan in 2030, 2050, and 2100 (80% acceptability).

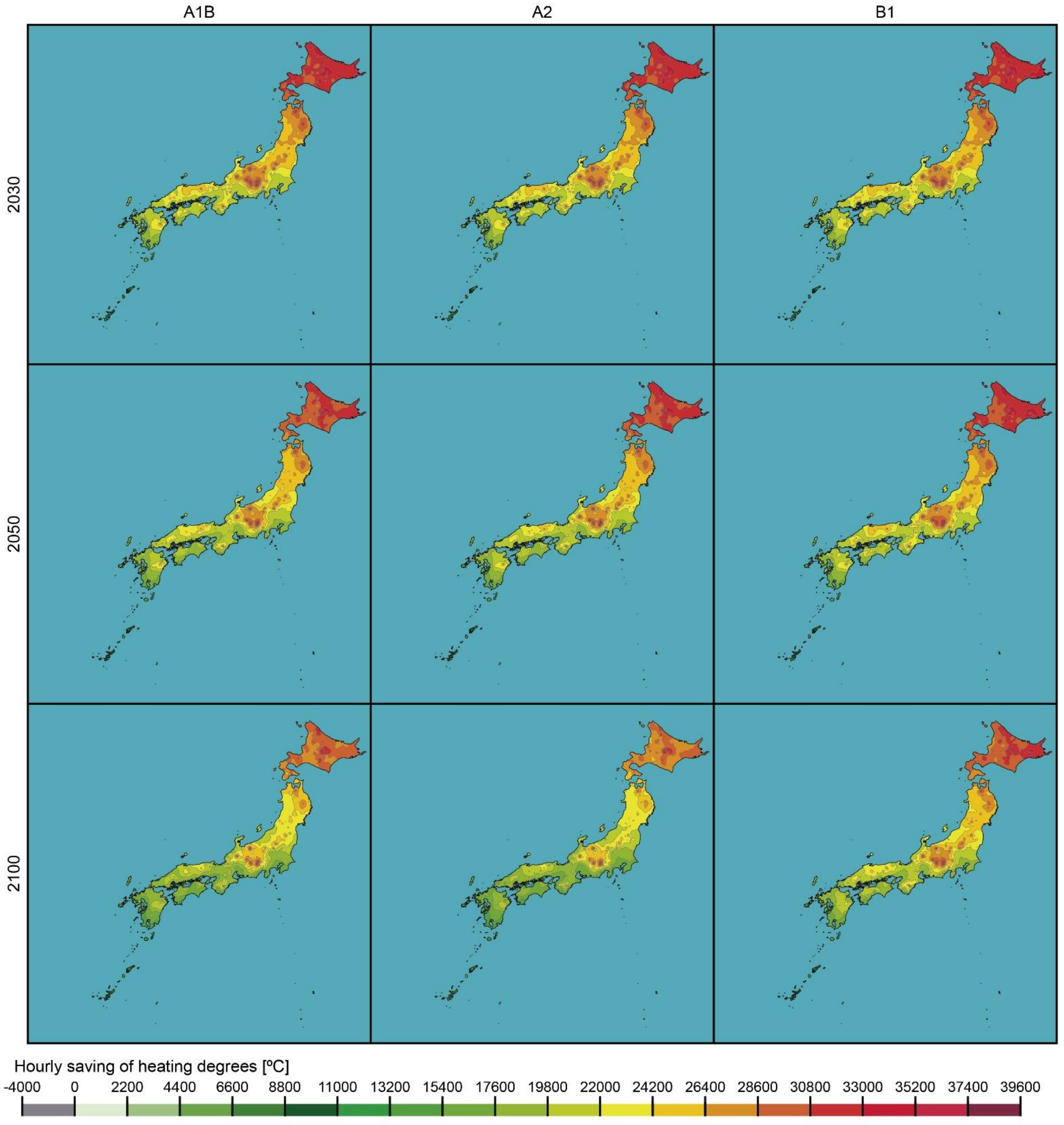

Figure A6. Comparison of the hourly saving of heating degrees by using adaptive setpoint temperatures with respect to static setpoint temperatures of 22°C in Japan in 2030, 2050, and 2100 (80% acceptability).

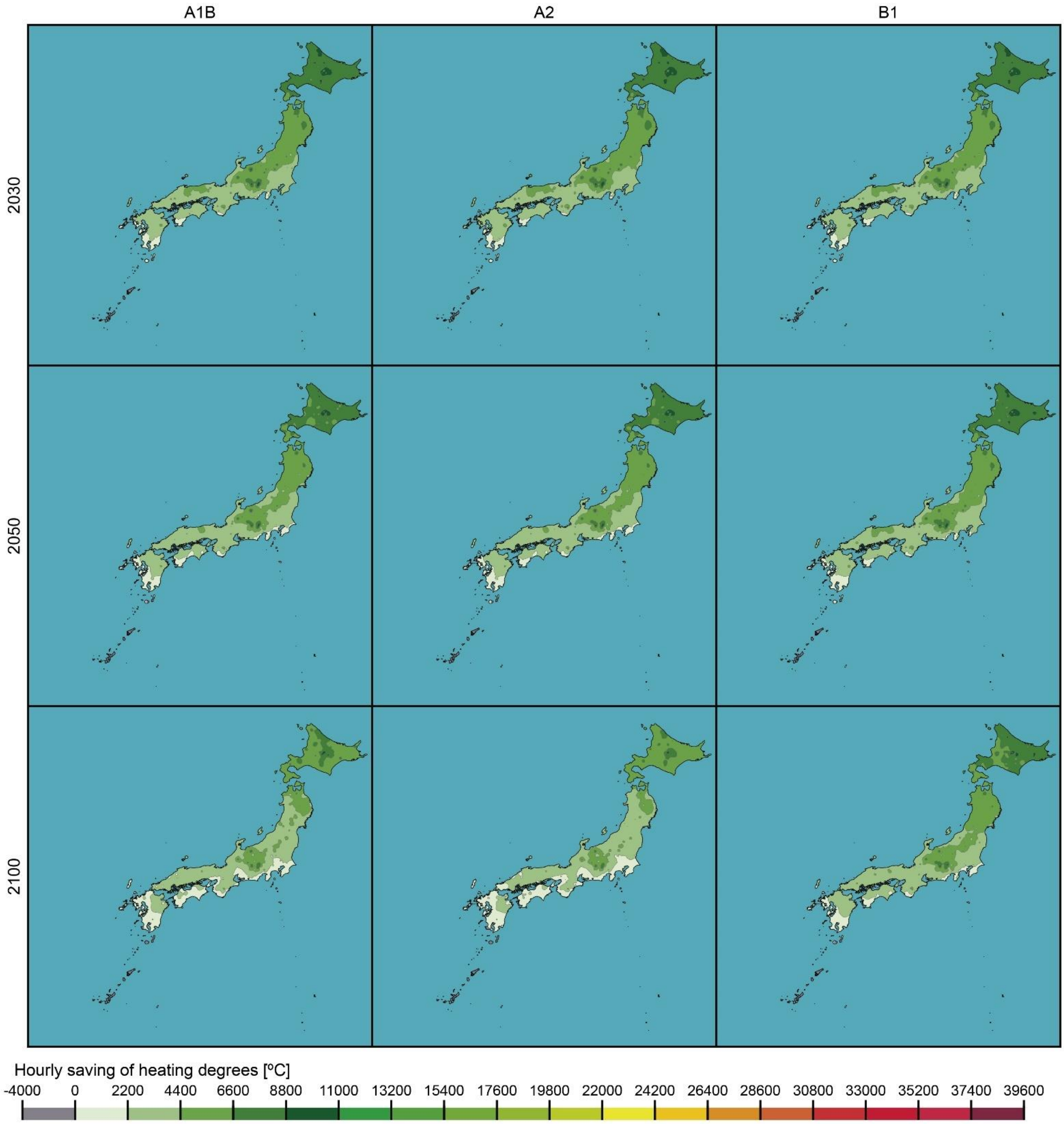

Figure A7. Comparison of the hourly saving of heating degrees by using adaptive setpoint temperatures with respect to static setpoint temperatures of 20°C in Japan in 2030, 2050, and 2100 (90% acceptability).

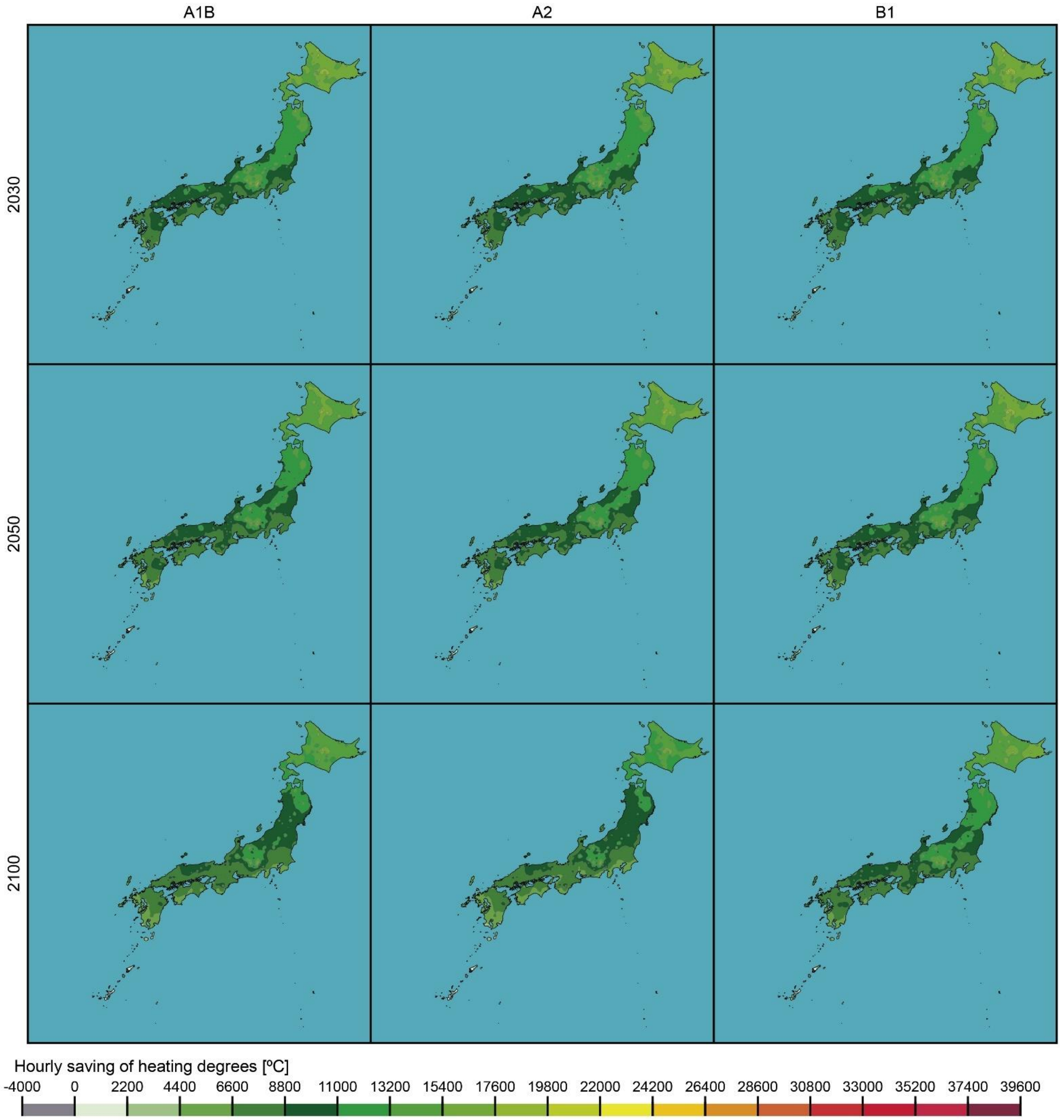

Figure A8. Comparison of the hourly saving of heating degrees by using adaptive setpoint temperatures with respect to static setpoint temperatures of 21°C in Japan in 2030, 2050, and 2100 (90% acceptability).

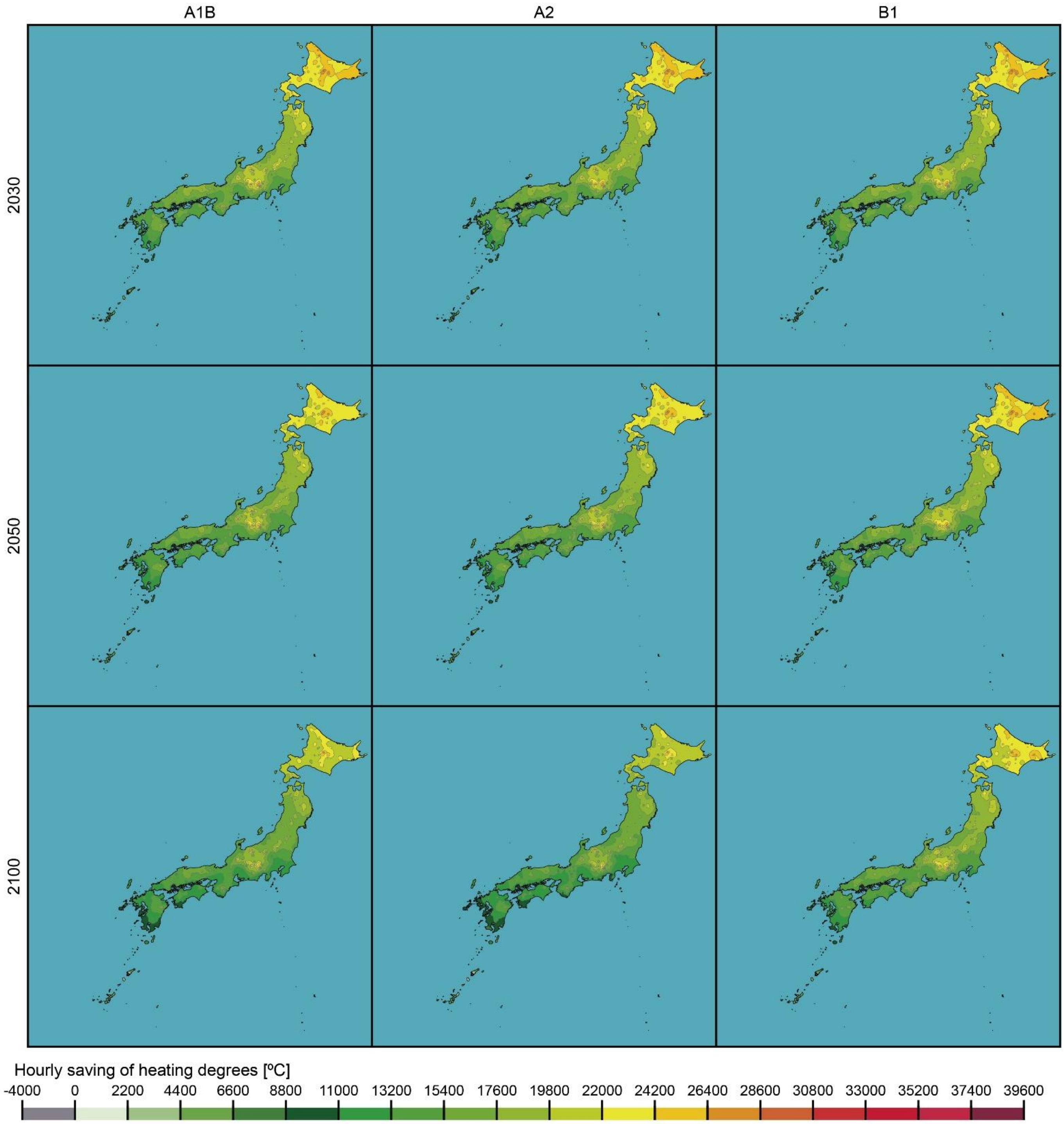

Figure A9. Comparison of the hourly saving of heating degrees by using adaptive setpoint temperatures with respect to static setpoint temperatures of 22°C in Japan in 2030, 2050, and 2100 (90% acceptability).

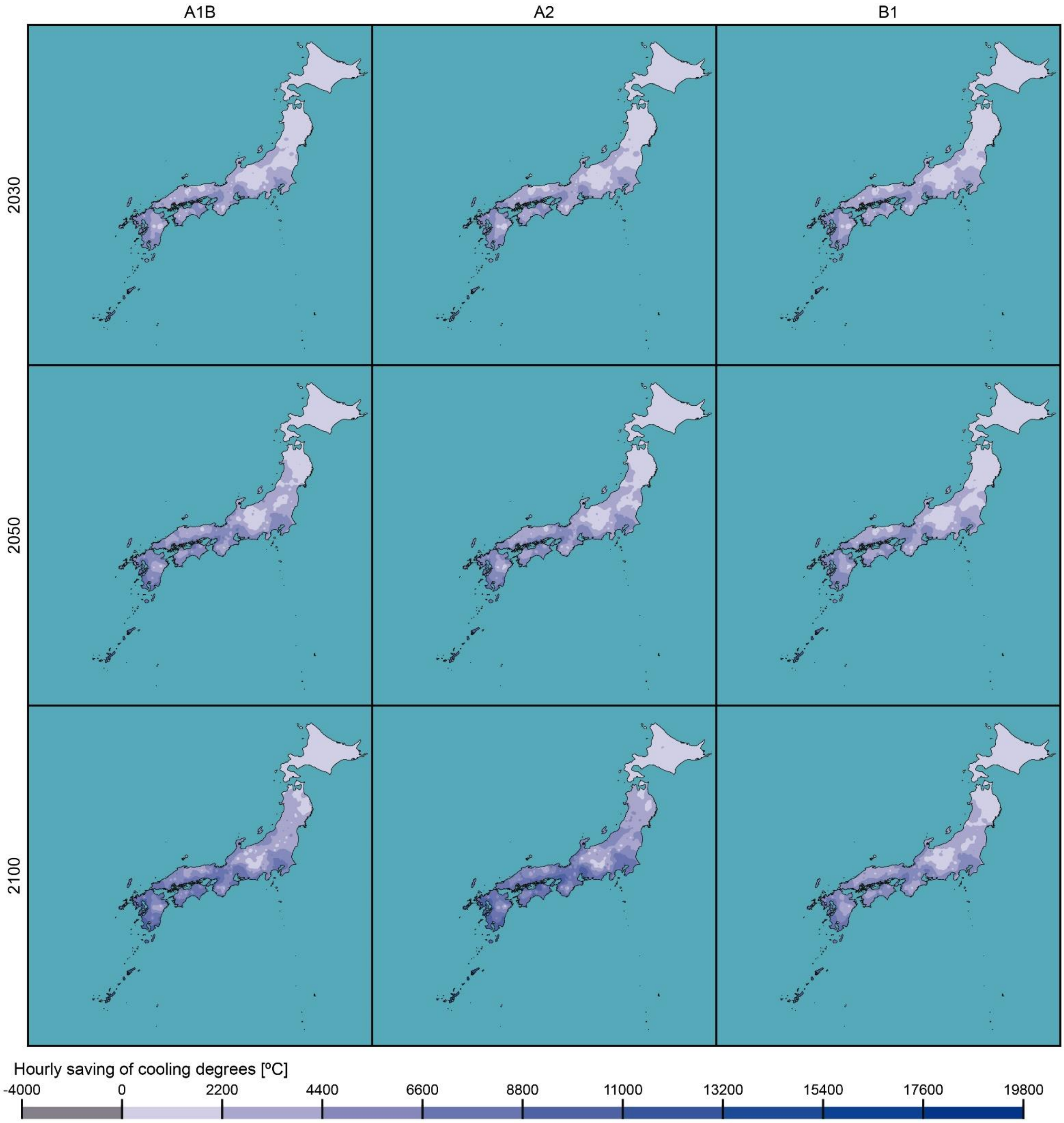

Figure A10. Comparison of the hourly saving of cooling degrees by using adaptive setpoint temperatures with respect to static setpoint temperatures of 25°C in Japan in 2030, 2050, and 2100 (80% acceptability).

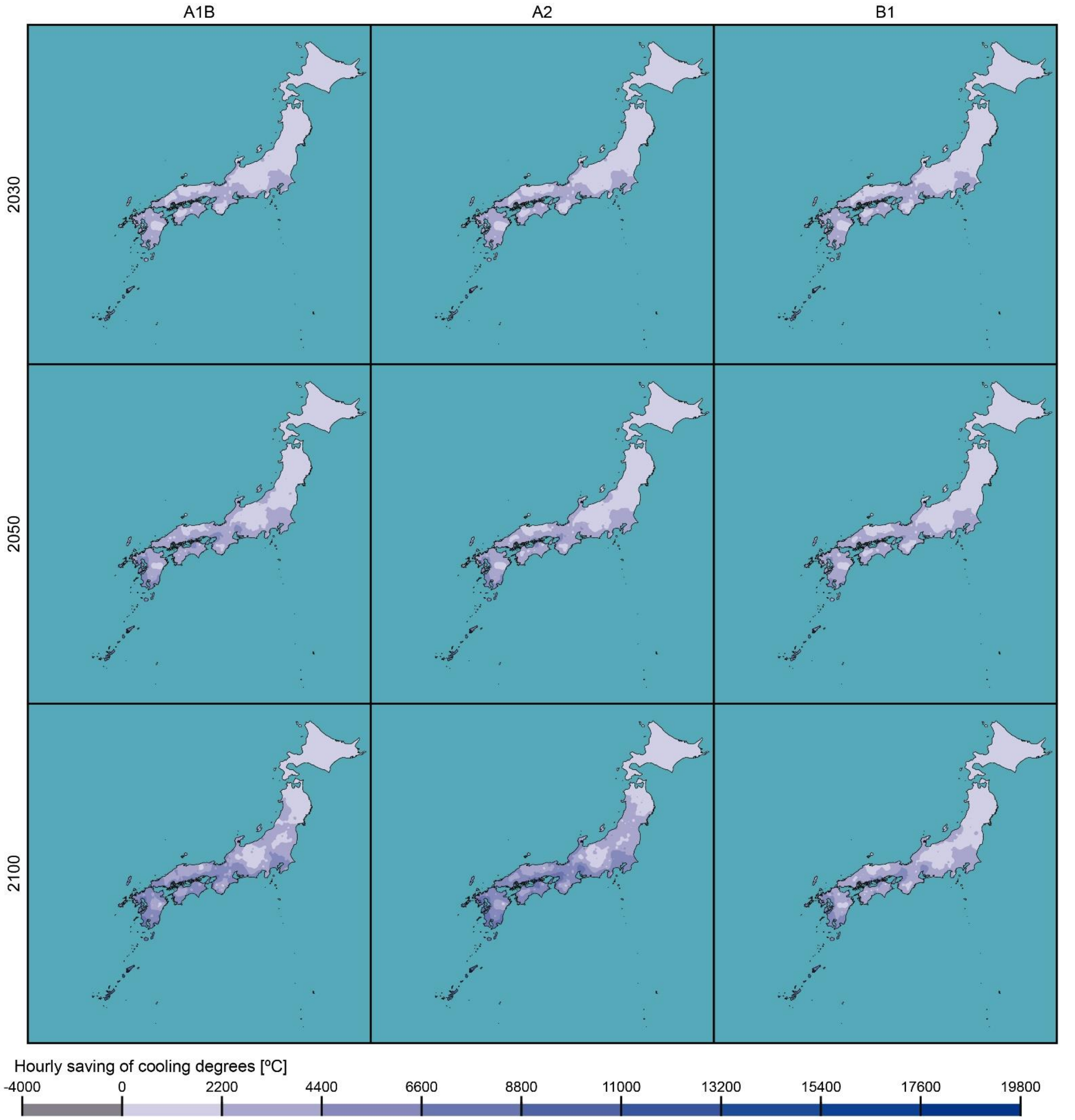

Figure A11. Comparison of the hourly saving of cooling degrees by using adaptive setpoint temperatures with respect to static setpoint temperatures of 26°C in Japan in 2030, 2050, and 2100 (80% acceptability).

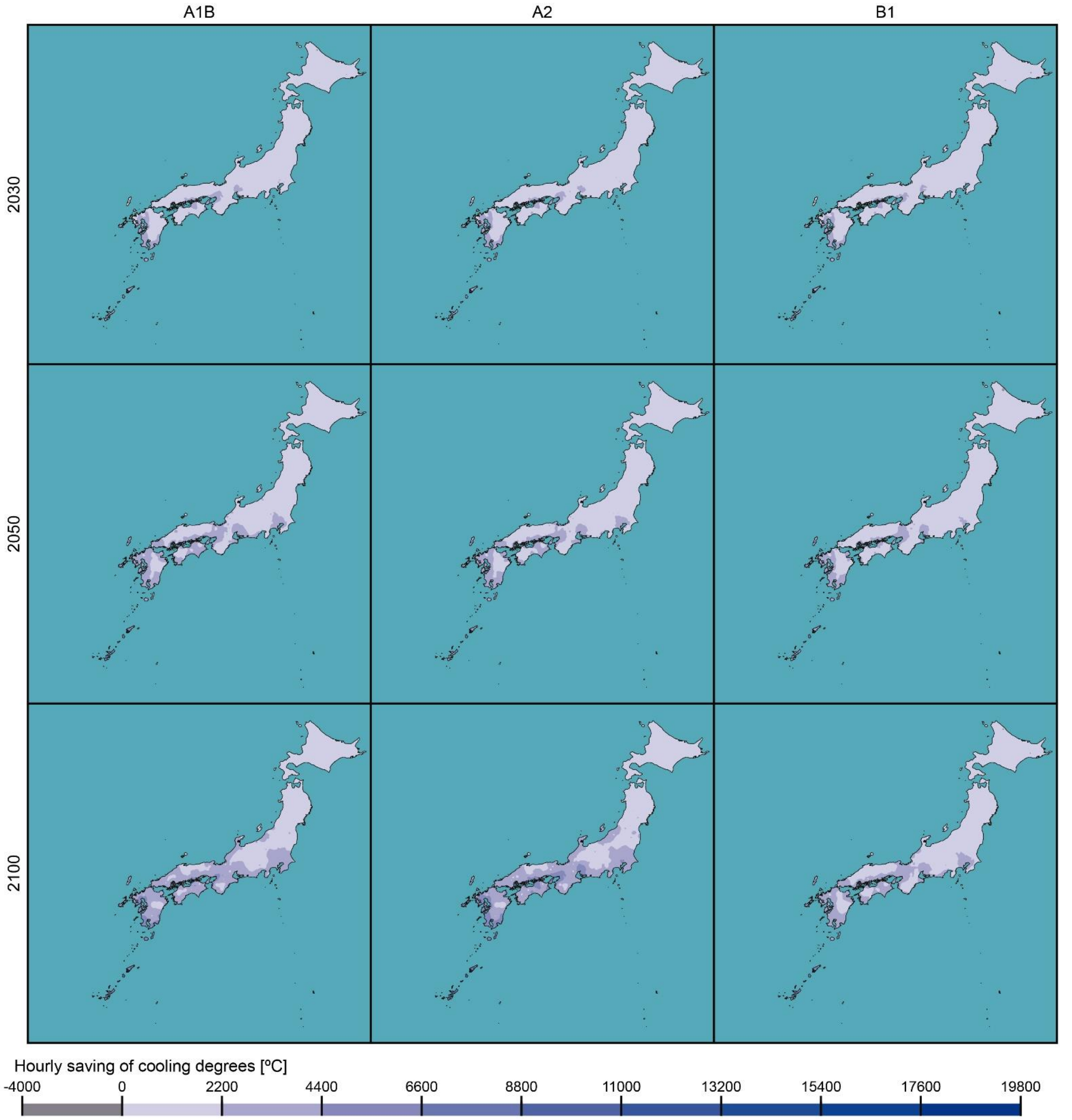

Figure A12. Comparison of the hourly saving of cooling degrees by using adaptive setpoint temperatures with respect to static setpoint temperatures of 27°C in Japan in 2030, 2050, and 2100 (80% acceptability).

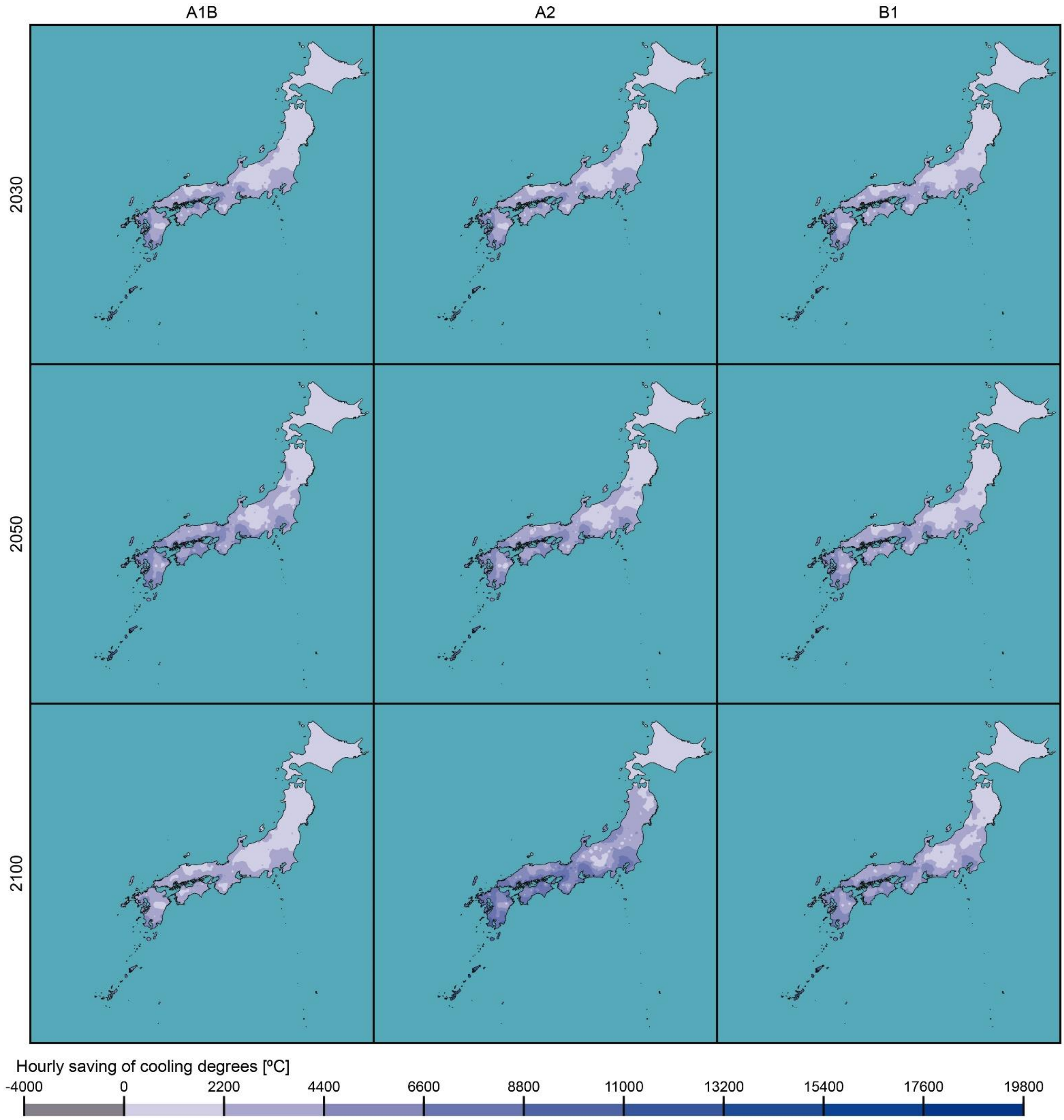

Figure A13. Comparison of the hourly saving of cooling degrees by using adaptive setpoint temperatures with respect to static setpoint temperatures of 25°C in Japan in 2030, 2050, and 2100 (90% acceptability).

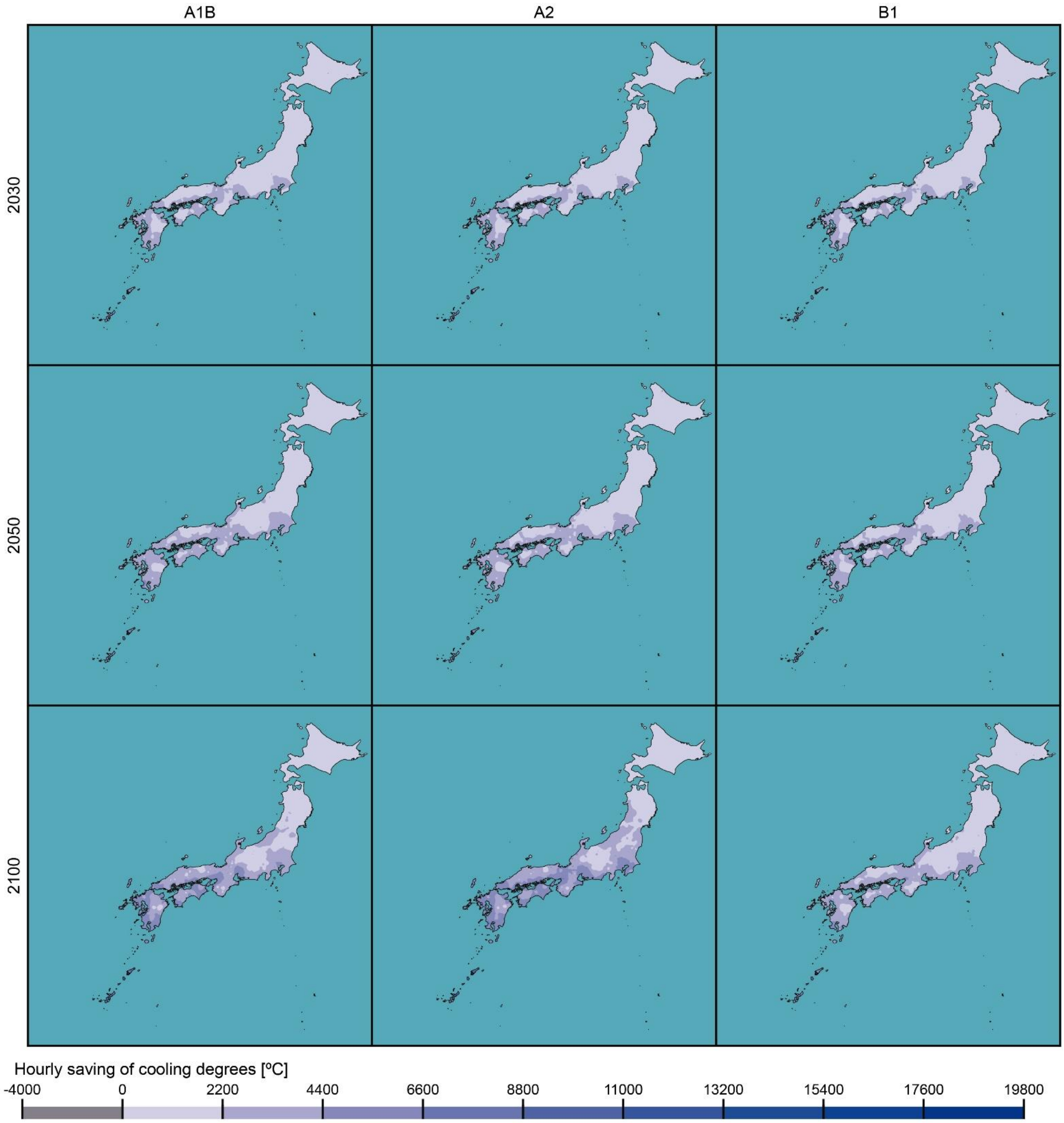

Figure A14. Comparison of the hourly saving of cooling degrees by using adaptive setpoint temperatures with respect to static setpoint temperatures of 26°C in Japan in 2030, 2050, and 2100 (90% acceptability).

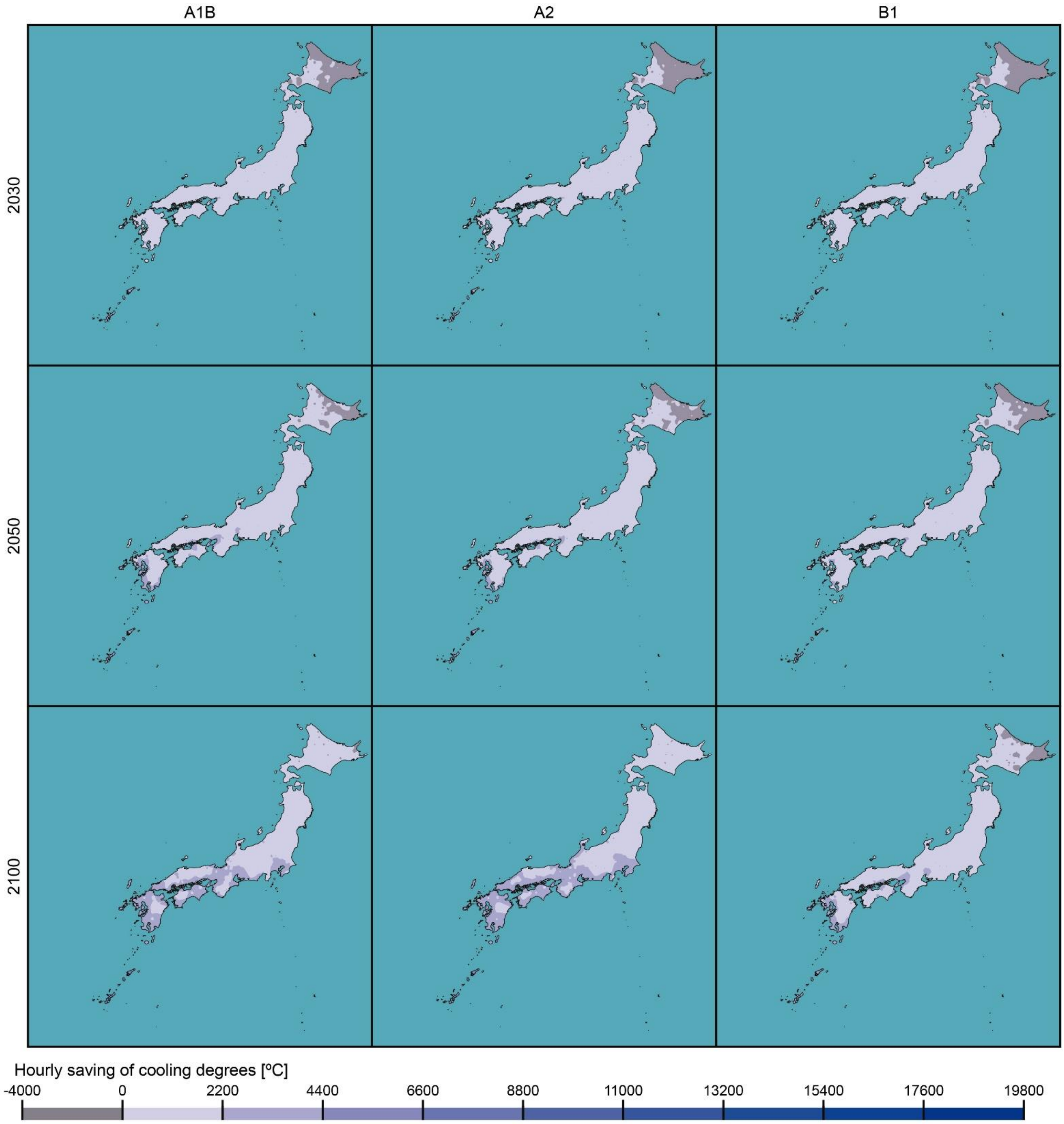

Figure A15. Comparison of the hourly saving of cooling degrees by using adaptive setpoint temperatures with respect to static setpoint temperatures of 27°C in Japan in 2030, 2050, and 2100 (90% acceptability).