Title: Energy savings in buildings applying ASHRAE 55 and regional adaptive thermal comfort models

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Abstract: The building sector plays an important role in energy performance and energy poverty. Decarbonization policies aims to reducing the energy consumption of the built environment, especially using HVAC systems better. Some studies have adopted adaptive thermal comfort models to increase energy savings in winter and summer. However, applying models based on international standards could overestimate setpoint temperatures. This study therefore assesses the potential energy savings by using regional models and quantifies variations with the model of ASHRAE 55-2017. A total of 7 countries and 13 regional models were considered adopting two adaptive strategies: natural ventilation and mixed mode. The results showed that the applicability of a model is not determinant to assess the possible energy saving. Likewise, cooling demand was significantly saved by both regional models and the model of ASHRAE 55 in the warmest countries. However, natural ventilation showed a limited applicability in most countries, with this adaptive strategy being the most applied in warmer months.

Keywords:
Energy saving; Adaptive thermal comfort; Natural ventilation; Adaptive setpoint temperature; Regional models

Acronyms:

AATCM: Application of adaptive thermal comfort model
AC: Air conditioning
CSHD: Cooling saving hourly degrees
GB/T50785: Chinese thermal comfort standard
HSHD: Heating saving hourly degrees
HVAC: Heating, Ventilation and Air-Conditioning
LAL: Lower acceptability limit
LT: Lower applicability threshold of the model
MM: Mixed mode
NV: Natural ventilation
nZEB: Nearly Zero-Energy Building
UAL: upper acceptability limit
UT: Upper applicability threshold of the model
V: Percentage of annual hours applying the model

1. Introduction

Today's society is concerned about high energy consumption and greenhouse gas emissions (World Wildlife Fund, 2014) because habitability conditions in the planet are worsened. There are many sectors responsible for this situation, including construction domain (European Environment Agency, 2018; Stern et al., 2016). The existing built environment has poor energy performance, leading not only to environmental problems, but also to other negative social impacts, such as energy poverty (Bouzarovski and Petrova, 2015; Legendre and Ricci, 2015). Most society's energy and decarbonisation policies aim to reduce the energy consumption of the built environment significantly (European Commission, 2011), with reductions up to 100%.

For this purpose, building technological improvement is usually the main performance action. It focuses on reducing the energy consumption from HVAC (Heating, Ventilation and Air-Conditioning), since this system consumes more energy than other sources, such as electrical household appliances (Golmohamadi et al., 2019) or domestic hot water (Albertí et al., 2019). HVAC system is used to keep appropriate indoor air temperatures to guarantee users' thermal comfort. Their high consumption takes place because of both buildings' poor energy performance (envelope with poor features and old systems) and their inappropriate use. In most countries, buildings were erected before the implementation of the first standards on energy efficiency (Kurtz et al., 2015; Park and Kim, 2017) and consequently, façades did not accomplish the minimum thermal requirements. Therefore, energy saving measures have mainly been focused on adding insulation, enhancing air tightness, and replacing HVAC systems (de Rubeis et al., 2020; Rodrigues et al., 2019).

However, the renovation of the entire built environment, according to decarbonisation policies, could be a challenging task. Attia et al. (2017) showed the drawbacks related to the renovation of building infrastructures in the south of Europe, predominating cooling energy systems. Likewise, rebound effects could reduce the effectiveness of these measures due to users' demands (Galvin and Gubernat, 2016). Along this lines, new actions focused on users' behaviour should be presented. Several studies have shown the great energy saving potential obtained by occupants' awareness. Using HVAC systems appropriately, energy savings and thermal comfort could be achieved without making economic investments (Ghose et al., 2020). In this sense, policies for the use of HVAC systems such as in Japan can be highlighted. In this sense, at the beginning of the 21st century, the Japanese government promoted the "Cool biz" campaign for the use of cool clothing in summer and to be able to have a cooling setpoint temperature of 28 ºC (Indraganti et al., 2013). Recently, the energy crisis due to the Ukraine war has led to the development of energy saving policies based on a more sustainable use of HVAC systems. Along this line, countries like Spain have established that the minimum set temperature is 27 °C in Summer and 19 °C in Winter (Pérez-Carramiñana et al., 2023). These measures have allowed to achieve notable energy savings (Monge Palma et al., 2023), although the thermal comfort of users was not guaranteed. In other words, the implementation of setpoint temperature values was executed from the perspective of energy savings. Given that the use of the HVAC system attempts to ensure the thermal comfort of most users, a common methodology should be established toconsider both energy savings and thermal comfort. In relation to this, adaptive thermal comfort models could be an opportunity.

Recent studies have assessed the possibility of adopting adaptive thermal comfort models to achieve energy savings (Bienvenido-Huertas et al., 2020a; Sánchez-García et al., 2019a). It should be noted that most thermal comfort models are based on the static approaches developed by Fanger (1970), where their respective thresholds are always fixed regardless of outdoor conditions. Moreover, these models were developed in laboratories with the same type of population sample (specifically young male students, without including vulnerable age groups -elderly people or children- (Tejedor et al., 2020)). However, the studies by Nicol and Humphreys (1973), Humphreys (1978, 1975), and Dear and Brager (2002, 2001) showed that users' thermal expectations could change, particularly if they live in spaces with no HVAC systems. Energy saving measures could be focused on the modification of setpoint temperatures and adopting natural ventilation (Sánchez-García et al., 2019b). Regarding to setpoint temperatures, this strategy consists of configuring the thermostat with the thermal comfort thresholds of the adaptive thermal comfort model by means the installation of smart monitoring and control devices for HVAC facilities (Wilson, 2022). As a result, there is a nudge effect in energy demand in comparison with patterns based on static models (Parkinson et al., 2020), and nearly Zero-Energy Building (nZEB) goals could be achieved, In addition, this type of solution would be in line with the European Green Deal (European Commission, 2019) and the Renovation Wave (European Commission, 2020). Hence, the use of regional adaptive models could help to increase the resilience of buildings in front of climate change scenarios. Concerning adaptive natural ventilation, this action decreases thermal loads in summer by introducing external air within thermal comfort thresholds. In this way, it is possible to contribute with free energy (Hiyama and Glicksman, 2015; Omrani et al., 2017) and to avoid the overheating risk in airtight buildings (Heracleous and Michael, 2018).

These aforementioned measures highly depend on outdoor climate conditions. For this reason, their implementation effectiveness has been widely assessed all over the planet (Bienvenido-Huertas et al., 2022, 2021). Until now, some research has been carried out considering either the use of the well-known international adaptive comfort models ASHRAE 55 and EN 16798-1 for the calculation of heating and cooling degree days. Even though the energy saving potential has been promising, studies could vary when considering the changing character of thermal comfort (Chen et al., 2023; Zhang et al., 2017). Several countries have executed their regional adaptive thermal comfort models through standards or research studies (Carlucci et al., 2018). As an example, China has its own adaptive thermal comfort standard, as well as a research that develops different models of adaptive thermal comfort. So, the number of regional or local adaptive comfort models is increasing, adapting to specific types of climate and building use. Using models adapted to the characteristics of each country could impact on the effectiveness of energy saving strategies. However, in the scientific literature, few studies have evaluated energy savings with the use of regional models of adaptive thermal comfort. Most of the studies are based on the use of ASHRAE 55 and EN 16798-1. Therefore, there is a knowledge gap about the potential for energy savings with regional models. Furthermore, existing studies tend to focus on energy savings achieved in case studies (Bienvenido-Huertas et al., 2020a; Sánchez-García et al., 2019a), with limited consideration of climate. There is also a knowledge gap in the influence that the climates of a region can have.

The novelty of this research led to the use of these local approaches instead of common adaptive comfort models to calculate the heating and cooling degree days. Therefore, this study analysed the energy saving potential in 7 countries, considering the regional models of: Australia, Brazil, China, India, Japan, the Netherlands, and Romania. The countries were selected based on the level of development of the adaptive thermal comfort model and the clear indication of its characteristics (model application thresholds, linear correlations, etc.). Two steps were taken: (i) assessment of the energy saving potential obtained by the regional models of each country; (ii) comparative analysis with ASHRAE 55 and quantification of the possible variations in the existing studies. Through this analysis, it was possible to address the knowledge gap of energy savings of the regional models and have a comparison with the most used model in the scientific literature-ASHRAE 55-.

Based on the information reported above, this paper is structured in four sections. Section 2 describes the methodology, briefly explaining the adaptive thermal comfort models of the 7 countries as well as how the dataset was generated. Section 3 discusses the results to understand the existing differences among the regional models. Finally, Section 4 stresses the main contributions.

2. Methodology

2.1. Adaptive thermal comfort models

Thermal comfort models vary upper and lower thermal comfort limits according to the oscillations of the mean outdoor temperature. Nowadays, there are several models designed according to the standards, as well as certain models drew up for some regions (Carlucci et al., 2018). Also, there are three main types of buildings considered in thermal comfort models: (i) naturally ventilated, which are those where occupants can only use natural ventilation to achieve thermal comfort, apart from some other actions such as putting on or taking off clothes, or drinking hot or cold beverages; (ii) air-conditioned, which are those where occupants usually are only allowed to achieve thermal comfort by using active heating and/or cooling systems, and adaptation of the occupant is not generally allowed; and (iii) mixed-mode buildings, where natural ventilation is only used when outdoor temperature is acceptable, otherwise heating or cooling systems are used.

The current research considered the adaptive thermal comfort model of ASHRAE 55 (American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), 2017), as well as the regional models of Australia, Brazil, China, India, Japan, the Netherlands, and Romania (Figure 1). The characteristics of these models are reported below.

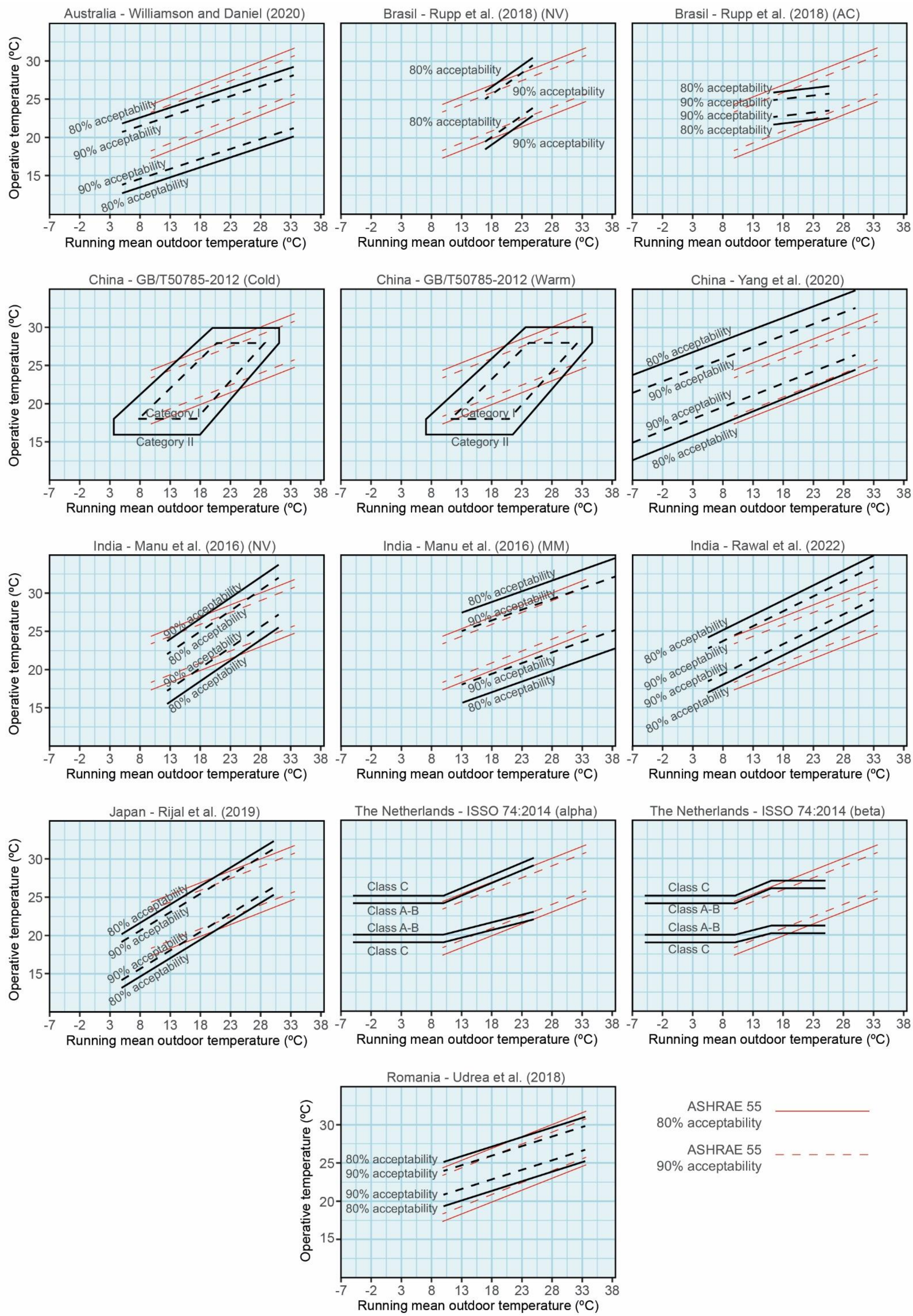

Figure 1. Adaptive thermal comfort models analysed in the study.

2.1.1. ASHRAE 55.

ASHRAE 55 includes the international adaptive thermal comfort model. This standard establishes two categories of acceptability to which various thermal comfort limits are assigned (Figure 1). These limits are established through linear correlations with a mean daily outdoor temperature (Eqs. (1)-(4)), which is known as prevailing mean outdoor temperature or running mean outdoor temperature (Eq. (5)). In addition, the running mean outdoor temperature is useful to know whether the model could be applied, as its value should be between 10 and 33.5 °C. In this case, the model could be applied, and lower and upper limits could be calculated.

$$Upper\ limit\ (80\%\ acc.) = 0.31 \cdot \overline{t_{rm(out)}} + 21.3 \quad [°C] \quad \text{if } 10 \leq \overline{t_{rm(out)}} \leq 33.5 \tag{1}$$

$$Lower\ limit\ (80\%\ acc.) = 0.31 \cdot \overline{t_{rm(out)}} + 14.3 \quad [°C] \quad \text{if } 10 \leq \overline{t_{rm(out)}} \leq 33.5 \tag{2}$$

$$Upper\ limit\ (90\%\ acc.) = 0.31 \cdot \overline{t_{rm(out)}} + 20.3 \quad [°C] \quad \text{if } 10 \leq \overline{t_{rm(out)}} \leq 33.5 \tag{3}$$

$$Lower\ limit\ (90\%\ acc.) = 0.31 \cdot \overline{t_{rm(out)}} + 15.3 \quad [°C] \quad \text{if } 10 \leq \overline{t_{rm(out)}} \leq 33.5 \tag{4}$$

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

Where α is the weight assigned in the calculation, with a value of 0.6 or 0.9 according to the latitude.

2.1.2. Australia

Williamson and Daniel (2020) developed a regional adaptive thermal comfort model for Australia. A database with more than 50,000 instances of case studies was used, visualising the thermal adaptation level of users in residential buildings. The approach of the model was based on the structure proposed by ASHRAE 55, applying the 80 and 90% categories of acceptability (Figure 1). Upper and lower thermal comfort limits are considered for each category according to $\overline{t_{rm(out)}}$. Regardless of the formulation of the correlation, other differences in comparison with the model of ASHRAE 55 is that the applicability range of the model as $\overline{t_{rm(out)}}$ should be between 5 and 33.5 °C.

2.1.3. Brazil

Rupp et al. (2018) designed 2 regional models adapted to office buildings in Brazil. Surveys on thermal comfort were conducted in 3 buildings in Florianópolis (Brazil), obtaining 5,500 surveys that included both natural ventilation (NV) and air conditioning (AC) modes. As a result, 2 different models were developed for each operational mode. Figure 1 show the correlations obtained for the upper and lower limits. Furthermore, 2 thresholds were established according to the percentage of acceptability: 80 and 90%.

2.1.4. China

In this case, 2 thermal comfort models were used (Figure 1): the Chinese thermal comfort standard (GB/T50785) and the model developed by Yang et al. (2020). GB/T50785 was implemented in 2012 to assess the thermoregulation responses in Chinese buildings that operate with natural ventilation. Experts from both the China Academy of Building Research and Chongqing University participated in the study (Li et al., 2014). Field data compiled in 14 significant cities in the country were used, involving all the climate zones of the country. Based on the research, two models were developed according to the climate zone of China (Figure 1): (i) warm and mild climate zones; and (ii) cold climate zones. Two categories are established in each model: Category I is related to an acceptability of 90%, and Category II to an acceptability of 75-90%. Although the graph of the models is different from that of ASHRAE 55, the upper and lower limits are set through relations with mean outdoor temperature.

Likewise, Yang et al. (2020) developed an adaptive thermal comfort model that can be used for regions with dry, dry-hot, and cold climates. For this purpose, surveys were conducted in 10 villages in Turpan (China) between 2011 and 2016. The obtained dataset contains 282 surveys for winter, 249 for spring, and 516 for summer. These data were used to establish two comfort thresholds for both 80 and 90 % acceptability according to $\overline{t_{rm(out)}}$ (Figure 1). $\overline{t_{rm(out)}}$ should be between -7 and 30 °C to apply the model.

2.1.5. India

In the case of India, two regional models were analysed (Figure 1): the models developed by Manu et al. (2016) and the model proposed by Rawal et al. (2022). In Manu et al. (2016), over 6,000 surveys were conducted in office buildings that operate with both NV and mixed mode (MM). As a result, two different models were computed for each operational mode. Comfort limits were established in each model according to the 3 categories of acceptability: 80, 85, and 90%. These models were accepted by the legislators of the country and were included in the National Building Code of India. This study only considered 80 and 90 % acceptabilities to compare them with the model of ASHRAE 55. Figure 1 show the correlations presented for these acceptabilities in each model. Various oscillation ranges were established to apply both models $\overline{t_{rm(out)}}$: between 12.5 and 31 °C for NV, and between 13 and 38.5 °C for MM.

To address the existing gap related to the thermal comfort of residential buildings in India (previous studies only focused on office buildings), Rawal et al. (2022) developed one model for this building type (Figure 1). For this purpose, occupants from 8 cities (Ahmedabad, Bengaluru, Chennai, Delhi, Hyderabad, Kolkata, Mumbai, and Shimla) and5 climate zones were surveyed. Up to 2,000 answers were obtained, including operational modes of NV and MM. Subsequently, two acceptability thresholds were adopted with the dataset. Likewise, $\overline{t_{rm(out)}}$ should oscillate between 5.5 and 33 °C to apply the model.

2.1.6. Japan

Rijal et al. (2019) developed an adaptive thermal comfort model for Japan. The model was developed through 36,144 thermal comfort votes compiled for 4 years in residential buildings in Kanto (Japan). The results allowed to determine thermal comfort limits for the 80 and 90 % acceptabilities (Figure 1). The mean outdoor temperature should be between 5 and 30 °C.

2.1.7. The Netherlands

The Netherlands, like China, has a national adaptive thermal comfort standard: ISSO 74:2014 (Instituut Voor Studie En Stimulering Van Onderzoek, 2014). Based on this, two models were established according to the type of building: (i) Alpha building for samples that operate with NV in summer, and (ii) Beta building for samples whose operation is AC in summer. The models were characterized by taking data from the smart controls and thermal comfort (SCATs) project (McCartney and Nicol, 2002). Likewise, the model suggests 4 thermal comfort classes: Class A for buildings where vulnerable people live, Class B for new buildings, Class C for existing buildings, and Class D for temporary buildings. However, there are 3 classes because the upper and lower limits of Class A and B are the same. This study considered Class A-B and C given their similarity to the acceptabilities of ASHRAE 55 (Figure 1): Class A-B with 90% acceptability, and Class C with 80% acceptability. Figure 1 shows the correlations established by the model for the upper and lower thresholds. It is worth stressing that one characteristic of the thermal comfort limits of the standard is that they vary according to the value of the mean outdoor temperature. There are therefore horizontal sections and sections with slopes. The applicability range of the model is from -5 to 25 °C.

2.1.8. Romania

There is only one regional model developed by Udrea et al. (2018). This model can be used to establish the thermal comfort of buildings that operate with NV in the country. For this purpose, surveys were conducted between 2013 and 2014 in Bucharest (Romania). Based on the results, these authors developed the thermal comfort thresholds for 80 and 90 % acceptabilities (Figure 1). The design of the model is very similar to that of ASHRAE 55, including the fact that the acceptability of the model (i.e. the value range of $\overline{t_{rm(out)}}$) should be between 10 and 33.5 °C.

2.2. Energy saving strategies based on adaptive thermal comfort models

As mentioned in the introduction, energy saving strategies could be focused on applying adaptive thermal comfort models. ASHRAE 55 and EN 16798-1 (formerly EN 15251) certainly states that adaptive comfort models can only be applied in naturally ventilated spaces. Richard de Dear and Gail Brager came to this conclusion in 1998, when they developed the first linear regression adaptive model (de Dear and Brager, 1998), and afterwards the ASHRAE Technical Committee 2.1 in charge of ASHRAE Standard 55. Nevertheless, Thomas Parkinson re-analysed the ASHRAE 55 adaptive model in 2020 using the ASHRAE Global Thermal Comfort Database II, a much larger database of thermal comfort surveys (Parkinson et al., 2020). When indoor temperature was introduced as the independent variable instead of outdoor temperature, a remarkable and consistent adaptive model fitted extremely well across all building types (air-conditioned, naturally-ventilated, and mixed-mode). This prompted a rethinking of the failure of adaptive comfort models in AC and MM buildings. Hence, an adaptation to outdoor climate in those buildings in the 1998 analysis was a correlation with indoor climate. This also leads to assume that it is possible to achieve thermal comfort by means of adaptive setpoint temperatures.

Within this context, a limitation needs to be stated. In this research paper, some of the local models have been built based on thermal sensation votes from a specific region. For instance, the Brazil's local adaptive comfort model was developed based on a thermal sensation questionnaire from Florianópolis area, making it capable of accurately predicting thermal feeling in that region with temperate and humid environment. In addition, the same model has been used throughout the entire of Brazilian territory because there is no comfort model to account for other climate conditions. This has derived to the introduction of a certain error in the estimation of the comfort temperature for those regions with different climate. Similarly, adaptive comfort models are developed in spaces, where a certain activity is carried out: generally, offices or dwellings. Given that behavioural actions to achieve comfort are implicitly considered in the thermal sensation vote (necessary to build the adaptive comfort model), the approaches are only applicable to those climates, types of activity and/or population segmentation (e.j. children, elderly, men, women, etc.) for which they have been developed for. Therefore, using them in a different scenario might lead to the introduction of inaccuracies. However, in order to obtain the closest approximation and considering the high detail of the scenarios and the lack of some of them (e.j. a model for residential spaces in Brasil), the models have been applied regardless the activity, and it is stated as a limitation.

These mentioned strategies aim to reduce the use of HVAC systems, implementing adaptive natural ventilation (Bienvenido-Huertas et al., 2020b) (ventilating when the outdoor temperature is within the adaptive thermal comfort limits) or adaptive setpoint temperatures (Sánchez-García et al., 2019b) (using the respective adaptive thermal comfort limit as setpoint temperature). For adaptive setpoint temperatures, the criterion established by Sánchez-García et al. (2019a) was used. This criterion is based on horizontally increasing the extreme thermal comfort values to always apply a value to the setpoint temperature.

Climate is related to the applicability of these strategies, so their implementation effectiveness was analysed by the models described in Section 2.1 according to the climate of each country. For this purpose, the methodology developed by Bienvenido-Huertas et al. (Bienvenido-Huertas et al., 2021) was executed. This is based on characterising the following variables: percentage of the days with application of the adaptive model, percentage of annual hours using NV, and the saving in hourly heating and cooling degrees. In all models, the prevailing mean outdoor temperature (or running mean outdoor temperature) was obtained through the outdoor temperatures of the previous 7 days.

The application of adaptive thermal comfort model (AATCM) shows the number of days of the year in which $\overline{t_{rm(out)}}$ is within the applicability interval of the model (e.g. between 10 and 33.5 °C with ASHRAE 55) (Eq. (6)). The acceptabilities or categories of the models have the same applicability range (except GB/T50785-2012).

$$AATCM = 100\frac{\sum_{i=1}^{365} d_i}{365}$$
$$d_i = 1 \quad if\ LT \le \overline{t_{rm(out)}} \le UT \qquad (6)$$
$$d_i = 0 \quad if\ \overline{t_{rm(out)}} < LT$$
$$d_i = 0 \quad if\ \overline{t_{rm(out)}} > UT$$

Where d_i is a value of each day of the year obtained by the rules of the equation; LT is the lower applicability threshold of the model (e.g. 10 °C with ASHRAE 55); and UT is the upper applicability threshold of the model (e.g. 33.5 °C with ASHRAE 55).

As for the adaptive NV, the percentage of annual hours applying the model (V) was assessed. The acceptability of each model should be distinguished:

$$\mathrm{V}= \frac{\sum_{i=1}^{8760} h_i}{8760}$$
$$h_i = 1 \quad if\ LAL \le T_{ext,i} \le UAL \qquad (7)$$
$$h_i = 0 \quad if\ T_{ext,i} < LAL$$
$$h_i = 0 \quad if T_{ext,i} > UAL$$

Where h_i is a value of each hour of the year obtained with the rules of the equation; LAL is the lower acceptability limit; UAL is the upper acceptability limit; and $T_{ext,i}$ is the outdoor temperature in the hour i.

The energy saving, resulting fromadaptive setpoint temperatures, was quantified through the difference among the hourly degrees with both adaptive and static setpoint temperatures (i.e. static setpoint temperatures do not depend on the oscillations of the outdoor climate). This assessment was performed for both heating (Eqs. (8)-(10)) and cooling regimes (Eqs. (11)-(13)). The analysis was independently executed for the acceptabilities of each model. Moreover, 5 static setpoint temperatures were adopted for cooling (T_{SC}), as well as 5 static setpoint temperatures for heating (T_{SH}): (i) T_{SC} had values of 23, 24, 25, 26, and 27 °C; and (ii) T_{SH} had values of 19, 20, 21, 22, and 23 °C.

$$SHST_{T_{SH}} = \sum_{i=1}^{8760} (T_{ext,i} - T_{SH}) \cdot X_{SH,i} \qquad (8)$$
$$X_{SH,i} = 1 \quad if\ T_{ext,i} < T_{SH}$$
$$X_{SH,i} = 0 \quad if\ T_{ext,i} \ge T_{SH}$$
$$AHST= \sum_{i=1}^{8760}(T_{ext,i} - LAL) \cdot X_{AH,i} \qquad (9)$$
$$X_{AH,i} = 1 \quad if\ T_{ext,i} > LAL$$
$$X_{AH,i} = 0 \quad if\ T_{ext,i} \le LAL$$
$$HSHD = SHST_{T_{SH}} - AHST \qquad (10)$$
$$SCST_{T_{SC}} = \sum_{i=1}^{8760} (T_{SC} - T_{ext,i}) \cdot X_{SC,i} \qquad (11)$$
$$X_{SC,i} = 1 \quad if\ T_{ext,i} > T_{SC}$$
$$X_{SC,i} = 0 \quad if\ T_{ext,i} \le T_{SC}$$
$$ACST= \sum_{i=1}^{8760}(UAL - T_{ext,i}) \cdot X_{AC,i} \qquad (12)$$
$$X_{AC,i} = 1 \quad if\ T_{ext,i} < UAL$$
$$X_{AC,i} = 0 \quad if\ T_{ext,i} \ge UAL$$
$$HSCD = SCST_{T_{SC}} - ACST \qquad (13)$$

Where $SHST_{T_{SH}}$ is the total annual hourly heating degrees with the value assigned to T_{SH}; $AHST$ refers to the total annual hourly heating degrees with the acceptability of the adaptive thermal comfort model; $HSHD$ corresponds to the heating saving hourly degrees; $SCST_{T_{SC}}$ is the total annual hourly cooling degrees with the value assigned to T_{SC}; $ACST$ is defined as the total annual hourly cooling degrees with the acceptability of the adaptive thermal comfort model; and $CSHD$ is the cooling saving hourly degrees.

2.3. Dataset generation and error assessment

First, hourly climate data were obtained from 19,060 locations divided into several countries. For the current scenario, METEONORM (Meteotest AG, 2023) was used to take the average hourly air temperature data for the period 2000-2019 at each location. It should be pointed out that the climate files obtained with METEONORM are different from those of a Typical Meteorological Year (TMY) (whose monthly values are obtained by selecting the most representative months of a period of several years). In the case of METEONORM, synthetic data is generated for the period analysed based on measurements from different weather stations and stochastic processes. Given its great versatility, it has been widely used in studies from many countries (Kameni et al., 2019; Osman and Sevinc, 2019).

The methodology described in Section 2.2 was applied to each location and for each adaptive thermal comfort model described in Section 2.1. From the total of 19,060 locations, spatial interpolations of these variables were made. The parallel inverse distance weighting (IDW) interpolation algorithm of ArcGIS was applied. The remaining 1,000 locations allowed to test the quality of the estimations of the adaptive variables. The mean absolute percentage error (MAPE) was used (Eq. (14)). Table 1 shows the results obtained by MAPE in each variable. MAPE was always lower than 5%, so the accuracy of the results was guaranteed.

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\frac{|a_i - e_i|}{a_i} \tag{14}$$

Where a_i is the actual value, e_i is the estimated value, and n is the number of observations in the dataset.

Table 1. MAPE values related to each estimated variable.

Variable	MAPE (%)													
	ASHRAE 55-2017	Williamson and Daniel (2020)	Rupp et al. (2018)		GB/T50785-2012		Yang et al. (2020)	Manu et al. (2016)		Rawal et al. (2022)	Rijal et al. (2019)	ISSO 74:2014		Udrea et al. (2018)
			NV	AC	Cold	Warm		NV	MM			Alpha	Beta	
AATCM	0.24	0.30	0.43	0.38	0.12 * 0.06 **	0.14 * 0.09 **	0.04	0.26	0.24	0.07	0.08	0.11	0.11	0.24
V-80	0.34	0.18	0.60	0.45	0.24	0.25	0.35	0.23	0.40	0.36	0.22	0.43	0.40	0.33
V-90	1.14	1.25	1.91	2.15	0.40	0.38	2.50	1.28	2.10	1.64	1.22	1.88	1.81	1.29
AHST-80	0.20	0.46	0.18	0.23	-	-	0.13	0.16	0.45	0.10	0.13	0.34	0.34	0.13
AHCT-80	2.25	1.34	2.76	2.64	-	-	4.00	1.86	2.12	2.54	2.66	2.88	2.16	2.02
AHST-90	0.13	0.63	0.13	0.13	-	-	0.09	0.11	0.65	0.08	0.11	0.16	0.16	0.13
AHCT-90	0.29	0.22	0.58	0.46	-	-	0.35	0.27	0.24	0.36	0.27	0.41	0.39	0.32
SHST19	1.12													
SHST20	0.57													
SHST21	0.39													
SHST22	0.38													
SHST23	0.16													
SCST23	1.99													
SCST24	2.02													
SCST25	3.02													
SCST26	4.64													
SCST27	2.18													

* Category I; ** Category II

After generating and validating the spatial interpolations of each variable, the results were exported. For this purpose, a network with a resolution of one-eighth degree (7.5 arc-minutes) was generated for each country, and subsequently the value of each adaptive variable was calculated for each location. Table 2 indicates the number of locations obtained in each country. The variation of the number depended on the area of each country. It should be highlighted that the variables exported in the locations of each country were those related to ASHRAE 55, the regional application models, and the hourly degrees with static setpoint temperatures.

Table 2. Number of locations per country.

Country	Number of locations analysed
Australia	69,446
Brazil	70,618
China	78,922
India	26,159
Japan	3,742
The Netherlands	464
Romania	2,756

3. Results and discussion

The results of each country were independently analysed and discussed to understand the differences among the models. Annex A includes the spatial representations per country of the variables of adaptive thermal comfort.

3.1. Australia

Australia' climate characteristics provided a different response as regards the applicability of the adaptive thermal comfort model of both ASHRAE 55 and Williamson and Daniel (2020). The percentage of days of the year with the implementation of the models varied among several regions of the country (Figures 2 and 3). ASHRAE 55 obtained an application between 90 and 100% in most of the territory (83%), but the percentage of application was 99.8% with Williamson and Daniel's regional model (Table 3). Likewise, the findings revealed that ASHRAE 55 obtained percentages between 50 and 60%. This disparity implied that the determination coefficient in the applicability of the two models was 7.7% (Figure 2). With the application range of Williamson and Daniel's, running mean outdoor temperature was the most adjusted variable to the climate characteristics of the country. Afterwards, adaptive energy saving strategies (NV and adaptive setpoint temperatures) were analysed. NV focused on assessing the percentage of hours of the year with application of these strategies. The point clouds showed the correlation between the annual percentage of ventilation obtained by both ASHRAE 55 and Williamson and Daniel's model. Determination coefficients were 83.7% for 80% acceptability, and 83.3% for 90% acceptability respectively. Nonetheless, there were differences in the application percentage values, with greater outcomes with Williamson and Daniel's model. This is shown in the distribution analysis and in the percentages of application. For this reason, V-80 designated NV of the 80% acceptability, and V-90 designated NV of the 90% acceptability. Williamson and Daniel's model increased the quartile distribution values of the model of ASHRAE 55 between 5.9 and 13.8%. As for the location percentage is concerned, the regional model obtained greater percentages of application, achieving 2.2% of locations with a percentage of annual hours in the interval of 70-80%. Williamson and Daniel's model was related to better possibilities of applying NV than the model of ASHRAE 55 despite the high correlation between the two variables.

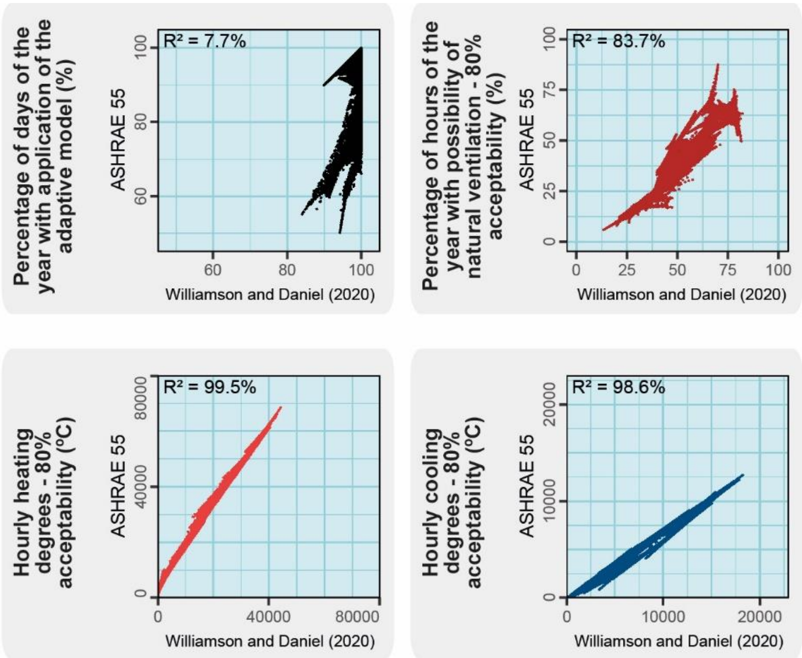

Figure 2. Point cloud comparison between the model of ASHRAE 55 and Australia's regional model (80% acceptability).

Table 3. Matrix with the percentage of locations according to the annual percentages of the variables of application of the adaptive thermal comfort models in Australia.

Variable	Model	Percentage of days/hours of the year of application									
		[0-10%)	[10-20%)	[20-30%)	[30-40%)	[40-50%)	[50-60%)	[60-70%)	[70-80%)	[80-90%)	[90-100%]
AATCM	ASHRAE 55	0.0	0.0	0.0	0.0	0.0	0.2	2.5	4.7	9.5	83.0
	Williamson and Daniel (2020)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	99.8
V-80	ASHRAE 55	0.3	8.0	27.4	35.9	18.8	5.7	3.6	0.2	0.0	0.0
	Williamson and Daniel (2020)	0.0	0.2	4.7	18.2	60.2	9.4	5.2	2.2	0.1	0.0
V-90	ASHRAE 55	1.8	29.1	42.5	19.1	6.8	0.7	0.1	0.0	0.0	0.0
	Williamson and Daniel (2020)	0.0	2.0	14.0	66.4	10.5	5.4	1.8	0.0	0.0	0.0

As for the energy saving expected by using adaptive setpoint temperatures, there was again a high correlation between the results of the model of ASHRAE 55 and Williamson and Daniel's model. Nevertheless, there were discrepancies among the results of both approaches. The point clouds showed that the model of ASHRAE 55 obtained greater hourly heating degrees than Williamson and Daniel's model. As a result, energy saving expectations were different in both models: ASHRAE 55 obtained greater saving in cooling degrees, and Williamson and Daniel's model obtained greater saving in heating degrees. The main reason was focused on the characteristics of the correlation equations suggested by Williamson and Daniel's model in which the operative temperature results are always lower than those obtained by the model of ASHRAE 55. Consequently, Williamson and Daniel's model increased the saving in heating degrees between 71 and 24,278 °C, whereas the saving in cooling degrees decreased between 31 and 5,221 °C. The increase in the saving in heating degrees was greater than the decrease in cooling, but the modifications in the upper limit of the Williamson and Daniel's model should be assessed to obtain better performance in the future. In this case, the progressive increase in cooling demand in the future will imply greater deviation in cooling saving results between the two models, so the possibilities of energy saving with the regional model should be reconsidered through a new definition of the upper limit.

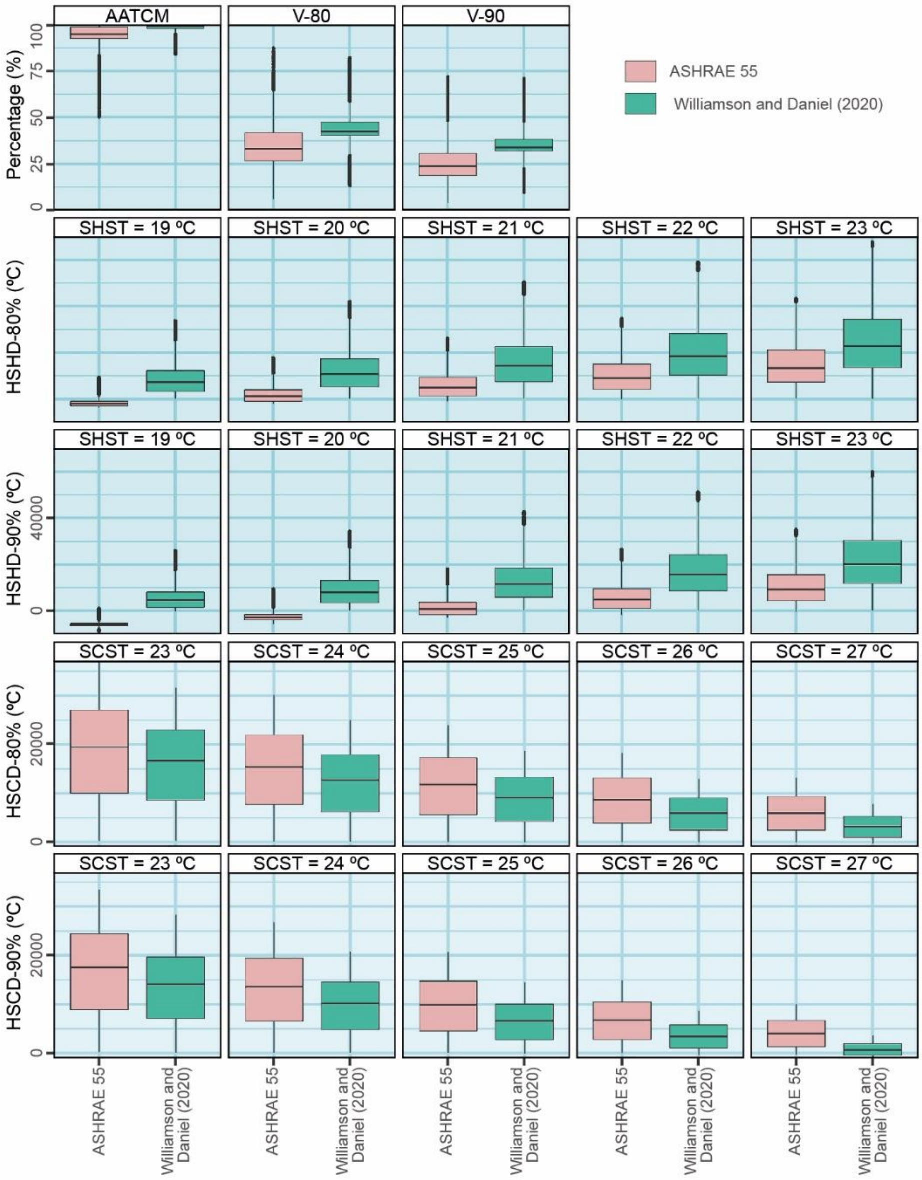

Figure 3. Box plot comparison between the model of ASHRAE 55 and Australia's regional model.

3.2. Brazil

The regional models developed by Rupp et al. (2018) have a very narrow applicability range according to the $\overline{t_{rm(out)}}$ in comparison with ASHRAE 55. As a result, the percentage of days of the year with application of adaptive thermal comfort models greatly varied (Figures 4 and 5): in ASHRAE 55, all locations of the country obtained applications in the interval between 90 and 100% of the days of the year, whereas regional models obtained an interval between 5.3 and 9.7% (Table 4). The remaining locations were divided among the various application intervals, obtaining greater concentration of locations in the lowest interval (between 0 and 10% of the days of the year). Therefore, the regional models developed by Rupp et al. decreased the annual percentage of application of adaptive thermal comfort models, with a determination coefficient of almost 0% in comparison with the percentage relative to ASHRAE 55. Despite this low application, the analysis of the energy saving strategies could vary. There was a similar tendency in NV, since the percentage of annual hours was lower with the regional models. These models presented decreases in the quartile values of their application distributions of NV between 21 and 48% compared to the model of ASHRAE 55. Most locations presented annual percentages of application of NV lower than 30% using regional models, whereas ASHRAE 55 obtained percentages between 50 and 80% according to the category of acceptability.

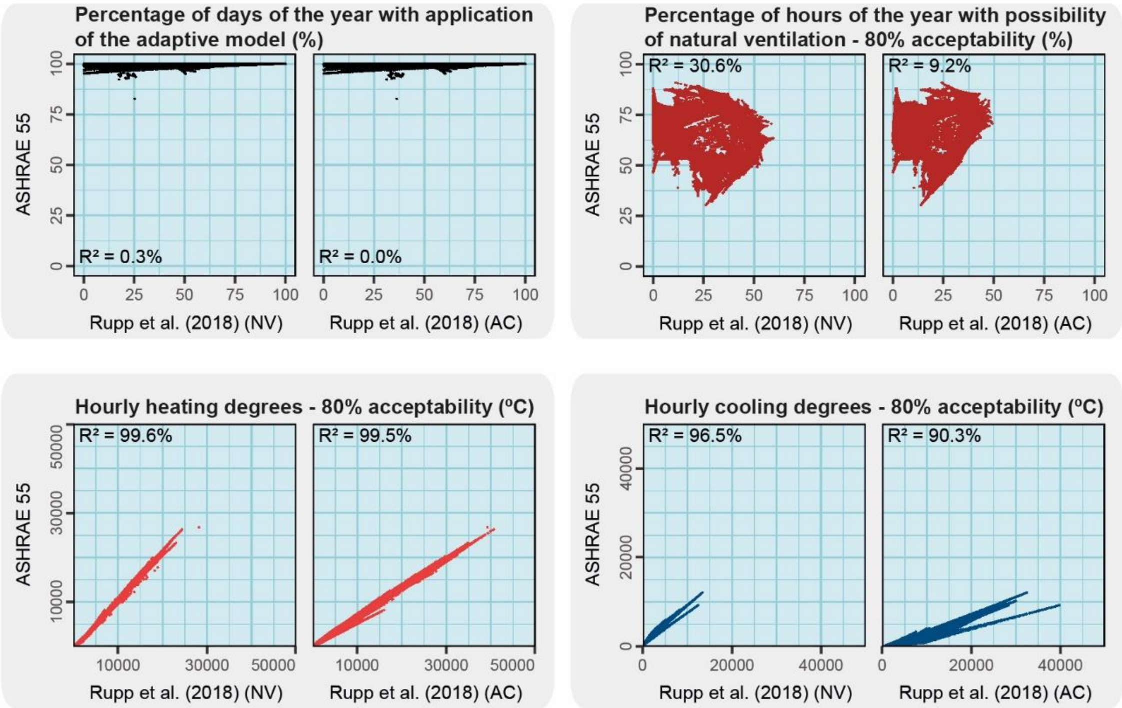

Figure 4. Point cloud comparison between the model of ASHRAE 55 and Brazil's regional models (80% acceptability).

Table 4. Matrix with the percentage of locations according to the annual percentages of the variables of application of the adaptive thermal comfort models in Brazil.

Variable	Model	Percentage of days/hours of the year of application									
		[0-10%)	[10-20%)	[20-30%)	[30-40%)	[40-50%)	[50-60%)	[60-70%)	[70-80%)	[80-90%)	[90-100%]
AATCM	ASHRAE 55	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	Rupp et al. (2018) (NV)	43.5	8.9	8.6	4.1	5.6	6.8	6.7	4.2	6.4	5.3
	Rupp et al. (2018) (AC)	21.5	15.9	9.8	9.6	6.7	5.6	7.2	7.5	6.6	9.7
V-80	ASHRAE 55	0.0	0.0	0.0	4.0	9.0	21.0	30.4	30.0	5.8	0.0
	Rupp et al. (2018) (NV)	50.3	12.8	12.4	10.9	11.4	2.2	0.0	0.0	0.0	0.0
	Rupp et al. (2018) (AC)	38.3	32.4	15.9	11.3	2.1	0.0	0.0	0.0	0.0	0.0
V-90	ASHRAE 55	0.0	0.0	5.4	17.5	28.5	37.4	10.8	0.5	0.0	0.0
	Rupp et al. (2018) (NV)	55.3	15.7	14.5	14.2	0.2	0.0	0.0	0.0	0.0	0.0
	Rupp et al. (2018) (AC)	68.4	27.3	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0

As for the energy saving with the adaptive setpoint temperatures, there was a correlation between the energy demand obtained with both the model of ASHRAE 55 and regional models. However, the outcomes revealed that the two regional models were clearly different: the AC model of Rupp et al. showed greater values of hourly heating and cooling degrees than ASHRAE 55, whereas the results with the NV model were very similar to the model of the international standard. The AC model decreased the distribution quartiles of the hourly heating degrees between 24 and 3,595 °C, as well as hourly cooling degrees between 3,443 and 10,728 °C, whereas the NV model increased the saving in cooling degrees between 524 and 654 °C. Hence, the NV model of Rupp et al. presented energy saving values equal or greater than the model of ASHRAE 55 despite its worst results in the annual percentages of application of the model. It is worth stressing that the best outcomes were obtained with a model developed for buildings with NV (like ASHRAE 55). The assumption suggested for this approach was based on the nudge effect of the setpoint temperatures [34], so the possible limitations when implementing this model should be known. Likewise, the possibility of increasing the oscillation interval of the $\overline{t_{rm(out)}}$should be assessed to implement better the regional models of Rupp et al. Nonetheless, it was remarkable that, with a low percentage of application, the NV model obtained almost the same savings in heating and cooling degrees than the model of ASHRAE 55.

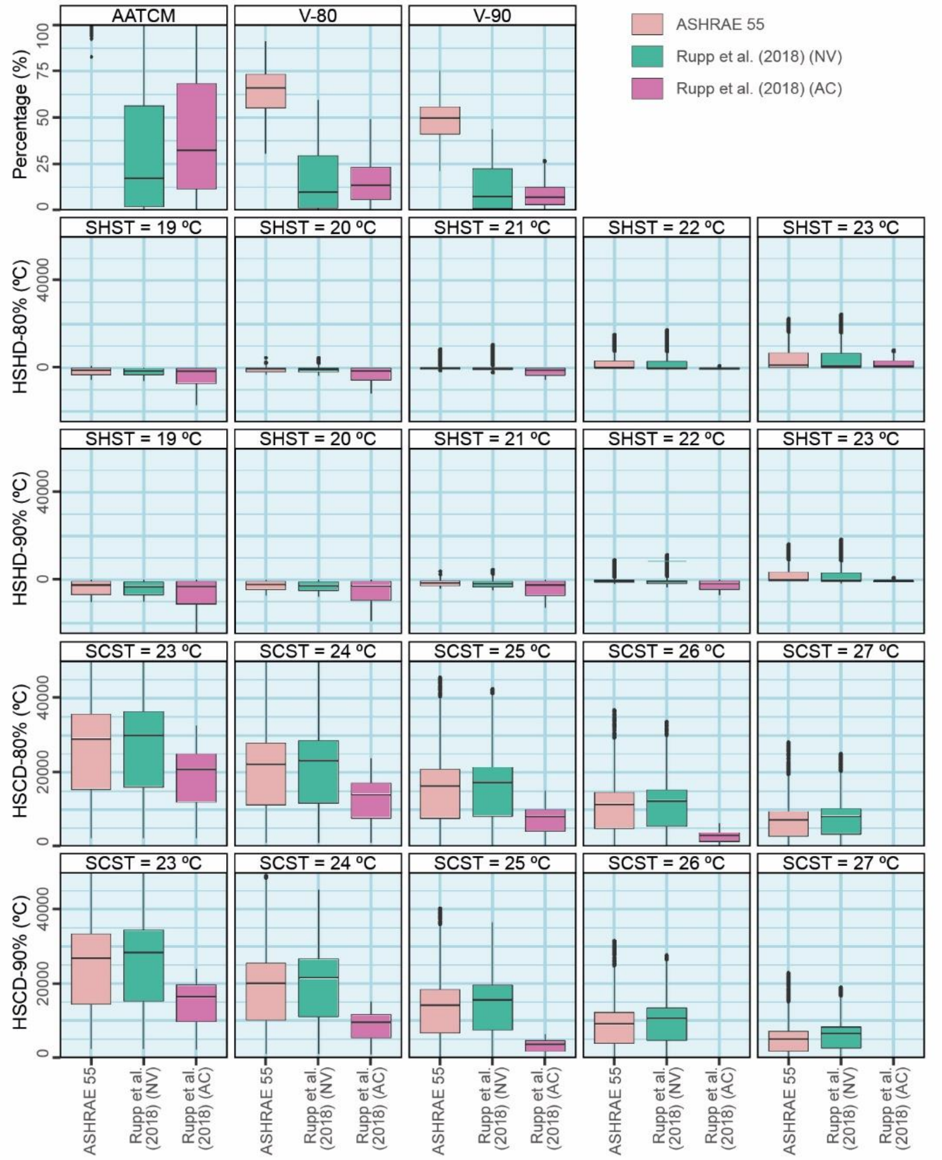

Figure 5. Box plot comparison between the model of ASHRAE 55 and Brazil's regional models.

3.3. China

The applications of adaptive thermal comfort models of China were independently assessed because of the characteristics of the model of the GB/T50785-2012 standard (adaptive setpoint temperatures cannot be applied with this model). Figures 6 and 7 summarises the results obtained with the model of Yang et al. (2020). This model was designed for three zones (dry, dry-hot, and cold), but it was applied in the whole country because of the similarity of the climate in most of the country with the climate application of the model of Yang et al. The percentage of days with application of the adaptive model was analysed, resulting that the model of Yang et al. obtained greater percentages than ASHRAE 55. The findings revealed that 52.3% of the locations of the country presented an application between 90 and 100% of the days of the year with the model of Yang et al., whereas ASHRAE 55 could be executed in only 7.9% of locations (Table 5). Indeed, the lowest application interval obtained by the model of Yang et al. was between 50 and 60%, while the interval of ASHRAE 55 ranged from 0 to 10%. This difference implied that the determination coefficient between the two variables was low. As for NV, the results of both models were very similar. This is shown in the adjustment of the point clouds to the diagonal of the graph and the result distributions (Figure 6). As for the latter, the quartile distribution values presented variations of up to 2%.

Table 5. Matrix with the percentage of locations according to the annual percentages of the variables of application of the adaptive thermal comfort models in China.

Variable	Model	Percentage of days/hours of the year of application									
		[0-10%)	[10-20%)	[20-30%)	[30-40%)	[40-50%)	[50-60%)	[60-70%)	[70-80%)	[80-90%)	[90-100%]
AATCM	ASHRAE 55	0.4	2.1	3.4	8.0	24.1	25.9	12.3	12.0	4.0	7.9
	Yang et al. (2020)	0.0	0.0	0.0	0.0	0.0	0.4	10.0	17.8	19.6	52.3
	GB/T50785-2012 (category I)	0.0	0.2	1.9	6.1	20.1	29.7	22.3	10.2	3.7	5.7
	GB/T50785-2012 (category II)	0.0	0.0	0.0	0.8	8.1	21.7	29.5	14.8	12.0	13.2
V-80	ASHRAE 55	11.6	44.4	25.4	12.1	4.6	1.6	0.4	0.0	0.0	0.0
	Yang et al. (2020)	10.1	35.3	36.8	11.1	4.0	2.0	0.8	0.0	0.0	0.0
	GB/T50785-2012 (category II)	5.5	9.7	48.2	9.2	14.5	6.3	4.6	2.1	0.0	0.0
V-90	ASHRAE 55	20.1	55.4	18.1	5.1	1.2	0.1	0.0	0.0	0.0	0.0
	Yang et al. (2020)	29.6	58.0	8.7	3.0	0.8	0.0	0.0	0.0	0.0	0.0
	GB/T50785-2012 (category I)	12.2	59.5	12.7	10.8	3.9	0.9	0.0	0.0	0.0	0.0

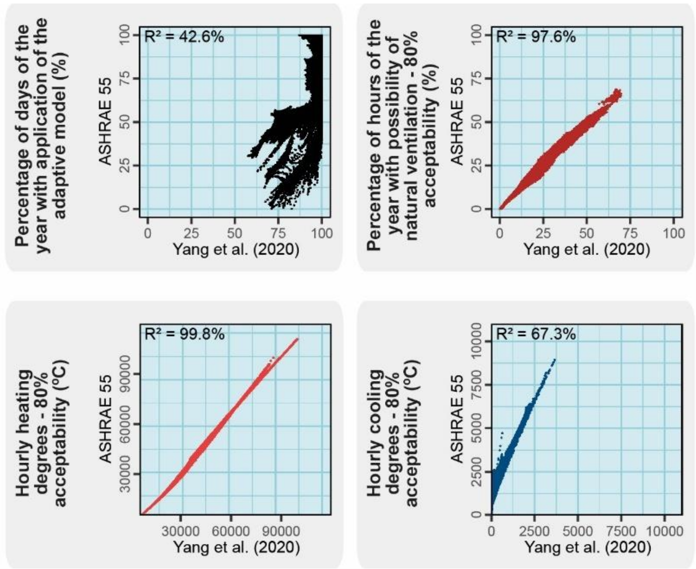

Figure 6. Point cloud comparison between the model of ASHRAE 55 and China's regional model of Yang et al. (2020) (80% acceptability).

The saving in heating and cooling degrees of the two models was different. As for cooling degrees, the model of Yang et al. obtained a greater benefit, with increases in quartiles between 352 and 1,756 °C. As for heating degrees, there were different behaviours according to the location of the country. Nonetheless, the most predominant tendency was an increase in the saving in heating degrees with the regional model, reaching values of 25,692 °C. Thus, the regional model of Yang et al. obtained better performance than ASHRAE 55, except the potential of NV that was similar in both models.

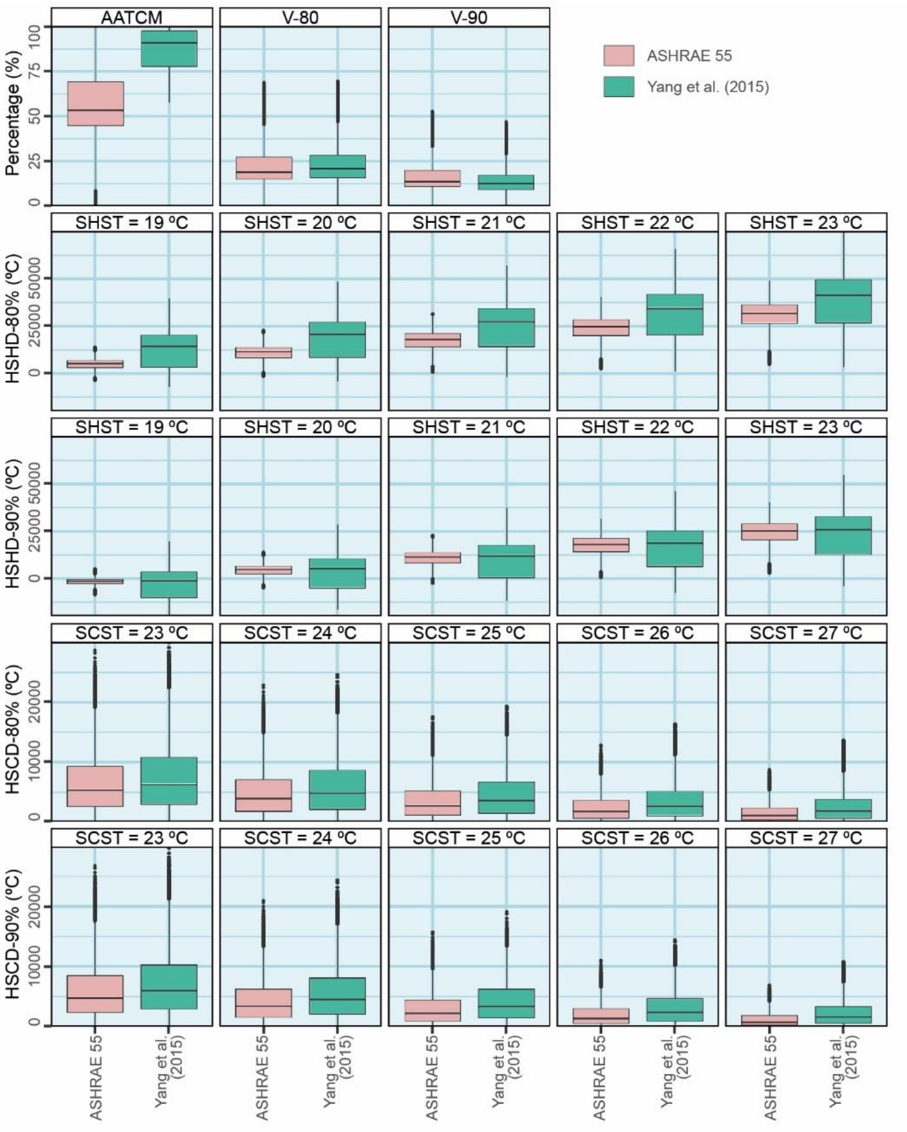

Figure 7. Box plot comparison between the model of ASHRAE 55 and China's regional model (Yang et al. (2020)).

As for the GB/T50785-2012 standard, the analysis only focused on both the percentage of days with application of the model and the possibility of NV. It is worth stressing that the results showed the combined application of options for cold and warm climate according to the climate zones included in [47]. The first variable was independently analysed for the two categories of the standard because they varied the application range of the $\overline{t_{rm(out)}}$. The results showed great similarity between the standard of the country and ASHRAE 55, with determination coefficients of 96.5% in the point clouds (Figure 8). Likewise, the percentage of locations grouped in the intervals of application of the model showed similar results, particularly with Category I of the GB/T50785-2012. With Category II, the possibility of implementing the adaptive thermal comfort model increased, grouping 13.2% of the locations in the application interval between 90 and 100% of the days of the year. This same tendency was observed with NV. It should be pointed out that Category I corresponds to 90% acceptability and Category II corresponds to 75-90% acceptability, so comparisons were made with the equivalent comfort thresholds of ASHRAE 55 (Category II was related to 80% acceptability). The results of the two models were in the same line, although the greatest similarity was noted in Category II (80% acceptability).

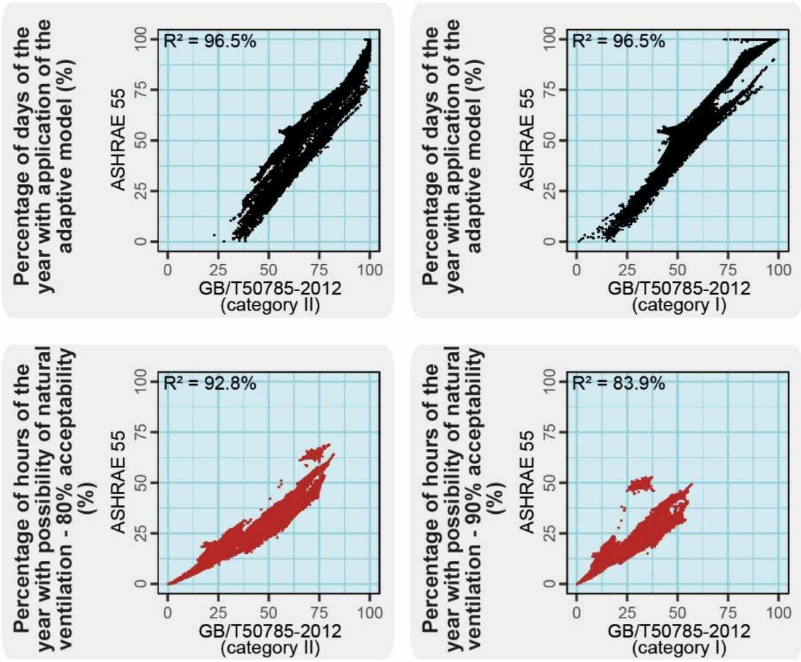

Figure 8. Point cloud comparison between the model of ASHRAE 55 and the models of the GB/T50785-2012 standard in China.

3.4. India

In the case of India, the regional models developed by Rawal et al. (2022) and the two by Manu et al. (2016) were computed. Their application analysis was the same as with the other countries. As for the percentage of days of the year with application of the adaptive thermal comfort model, different results were obtained for the three regional models (Figures 9 and 10). Each model obtained correlations with the applicability of ASHRAE 55 (determination coefficients between 72.2 and 90.2%), but similar application results were not obtained. The most similar model was that proposed by Rawal et al., although the percentage of applicability of the model was slightly lower than that of ASHRAE 55. The NV approach of Manu et al. showed a lower applicability of the model, achieving 22.8% of the locations in the interval between 90 and 100% of the days of the year (Table 6). The other approach by Manu et al. was characterized by a high percentage of applicability, with 93.3% of locations obtaining applications in the interval between 90 and 100% of the days of the year. The same trend was detected in NV, with a greater percentage of hours of the year with the MM of Manu et al. As for heating and cooling degrees, the saving presented various tendencies according to the type of demand. As for heating demand, the models of Manu et al. had very similar results to those resulted from ASHRAE 55, with slightly increases (increases between 41 and 15,655 ℃). In contrast, the results obtained by the model of Rawal et al. were always lower than those obtained by ASHRAE 55, where worse results than the static setpoint temperatures were highlighted. On the other hand, the saving in cooling degrees was very similar in the three regional models. In this regard, very similar saving distributions of hourly cooling degrees were noted with the regional models (with absolute differences between 3 and 3,590 ℃) and 80% of acceptability, whereas in the MM model of Manu et al. had lower saving values in cooling degrees for 90% of acceptability. Nonetheless, the model of Rawal et al. was always characterized by slightly increased value of the saving in cooling degrees in all comparisons. Hence, this model has better operational performance in the warmest seasons. According to the future estimates of the climate of the region, this model could be interesting to reduce cooling energy consumption in the built environment of India.

Table 6. Matrix with the percentage of locations according to the annual percentages of the variables of application of the adaptive thermal comfort models in India.

Variable	Model	Percentage of days/hours of the year of application									
		[0-10%)	[10-20%)	[20-30%)	[30-40%)	[40-50%)	[50-60%)	[60-70%)	[70-80%)	[80-90%)	[90-100%]
AATCM	ASHRAE 55	0.0	0.1	0.2	0.6	0.4	0.4	0.6	1.2	17.4	79.2
	Manu et al. (2016) (NV)	0.0	0.1	0.5	0.5	0.5	1.1	7.9	32.6	34.1	22.8
	Manu et al. (2016) (MM)	0.0	0.1	0.5	0.5	0.4	0.5	0.7	0.9	3.0	93.3
	Rawal et al. (2022)	0.0	0.0	0.0	0.1	0.6	0.5	0.4	3.3	29.3	65.8
V-80	ASHRAE 55	0.7	0.9	1.7	19.7	30.6	35.0	9.5	1.9	0.1	0.0
	Manu et al. (2016) (NV)	0.3	1.0	3.9	14.7	29.6	26.6	18.0	3.5	1.8	0.7
	Manu et al. (2016) (MM)	0.2	0.8	0.6	0.8	1.0	16.2	26.4	39.4	13.3	1.4
	Rawal et al. (2022)	1.0	1.2	3.2	22.6	48.8	16.0	4.8	2.4	0.0	0.0
V-90	ASHRAE 55	1.1	1.4	21.7	45.9	25.2	3.9	0.8	0.0	0.0	0.0
	Manu et al. (2016) (NV)	1.0	7.0	27.1	46.8	14.7	2.7	0.7	0.0	0.0	0.0
	Manu et al. (2016) (MM)	0.7	0.9	1.3	20.0	33.5	33.9	9.1	0.7	0.0	0.0
	Rawal et al. (2022)	1.8	6.6	61.5	25.8	4.1	0.3	0.0	0.0	0.0	0.0

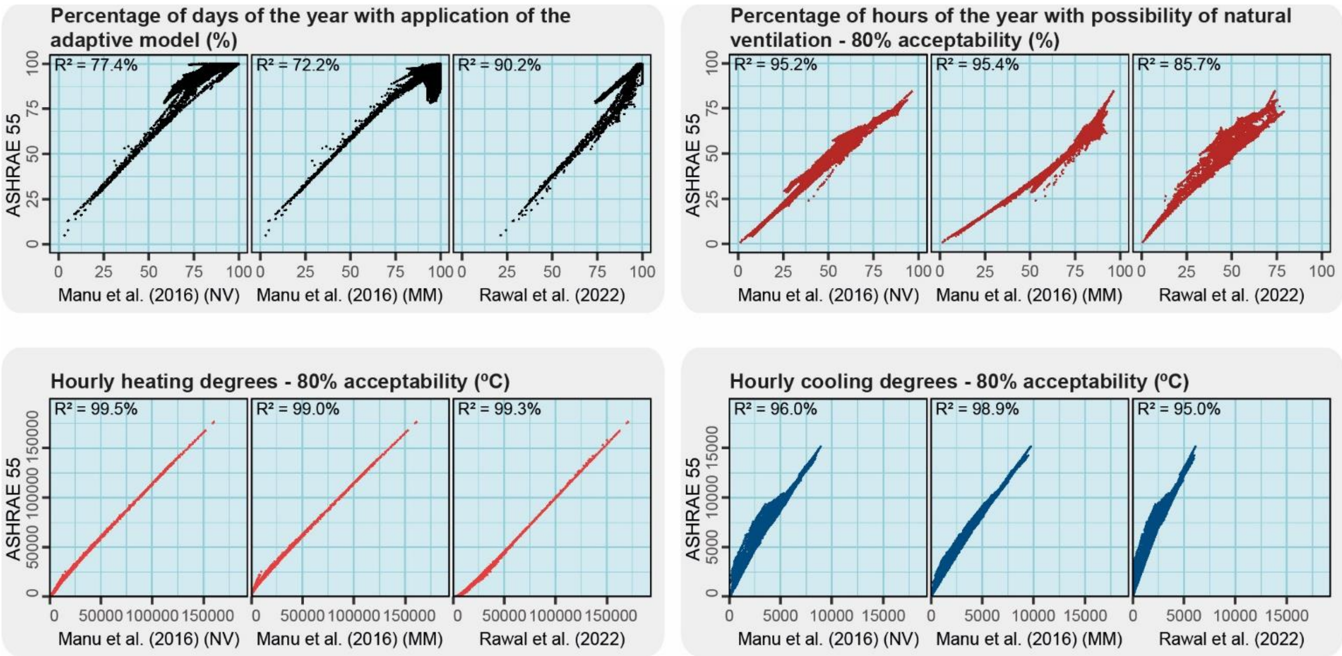

Figure 9. Point cloud comparison between the model of ASHRAE 55 and India's regional models (80% acceptability).

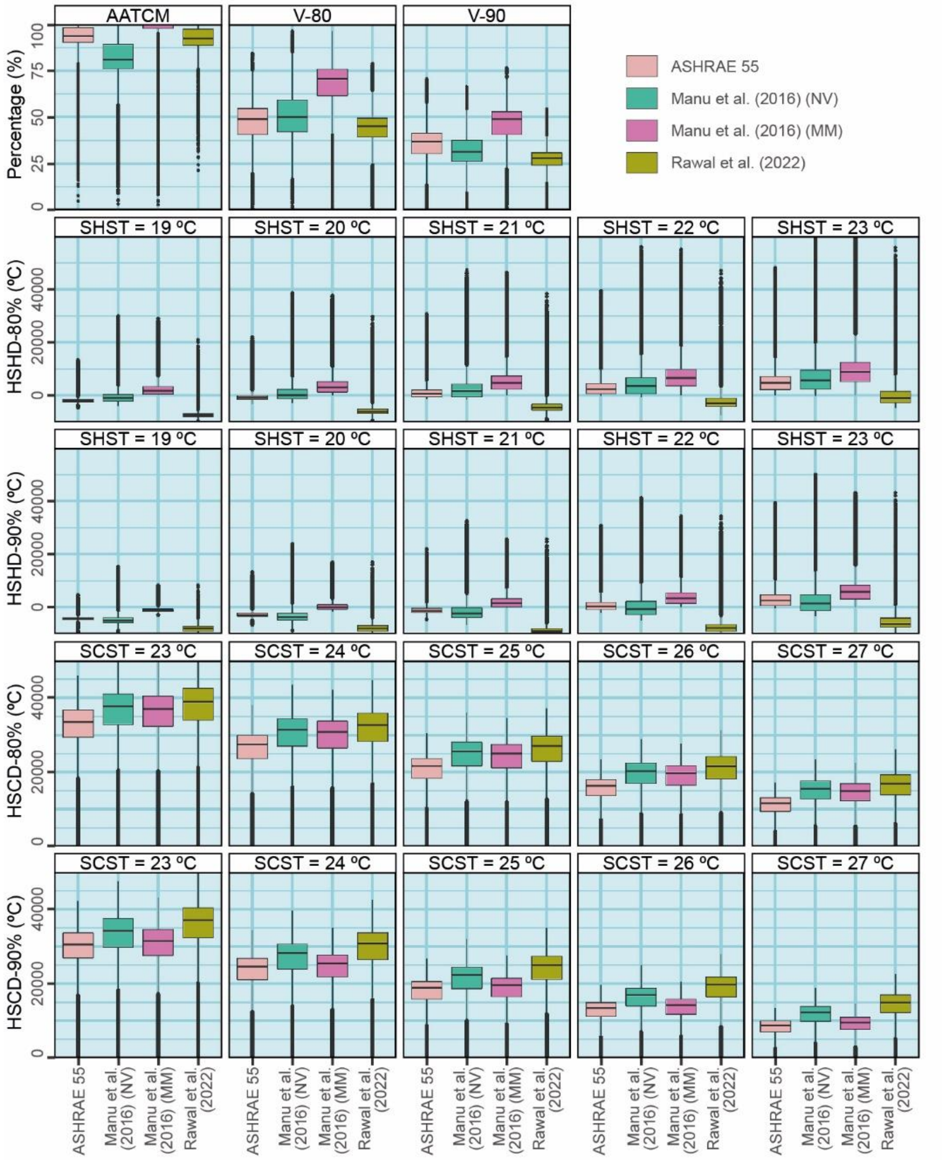

Figure 10. Box plot comparison between the model of ASHRAE 55 and India's regional models.

3.5. Japan

As for Japan, the model developed by Rijal et al. (2019) presented differences in the applicability of the model in comparison with those obtained in ASHRAE 55 (Figures 11 and 12). The possibility of achieving lower values with the $\overline{t_{rm(out)}}$ of the regional model made possible that 45% of locations had an application greater over 80% of the days of the year, in contrast to 1.4% of locations with that application in ASHRAE 55 (Table 7). This difference was also detected in the saving of heating degrees: (i) increases between 178 and 21,808 °C were derived from the regional model in the 80% acceptability; and (ii) increases between 128 and 21,939 °C were obtained with the regional model in the 90% acceptability.

There were similarities between the two models in both the possibility of NV and cooling degrees. As for NV, the percentages of locations grouped according to the intervals of hours of the year presented deviations up to 4.9% for 80% acceptability, and up to 7.9% for 90% acceptability. It is expected that the NV results reported by other studies [58] were like those from the model of Rijal et al. Finally, as for cooling degrees, the distributions with the two models were almost equal, with absolute differences of up to 817 °C.

Table 7. Matrix with the percentage of locations according to the annual percentages of the variables of application of the adaptive thermal comfort models in Japan.

Variable	Model	Percentage of days/hours of the year of application									
		[0-10%)	[10-20%)	[20-30%)	[30-40%)	[40-50%)	[50-60%)	[60-70%)	[70-80%)	[80-90%)	[90-100%]
AATCM	ASHRAE 55	0.0	0.0	0.0	0.1	21.7	24.4	30.8	21.6	0.7	0.7
	Rijal et al. (2019)	0.0	0.0	0.0	0.0	0.0	18.9	12.9	23.3	29.1	15.9
V-80	ASHRAE 55	2.3	27.0	50.6	19.4	0.0	0.5	0.2	0.0	0.0	0.0
	Rijal et al. (2019)	0.6	27.4	47.1	24.3	0.0	0.2	0.5	0.0	0.0	0.0
V-90	ASHRAE 55	21.5	42.7	35.1	0.0	0.7	0.0	0.0	0.0	0.0	0.0
	Rijal et al. (2019)	13.6	48.3	37.4	0.0	0.7	0.0	0.0	0.0	0.0	0.0

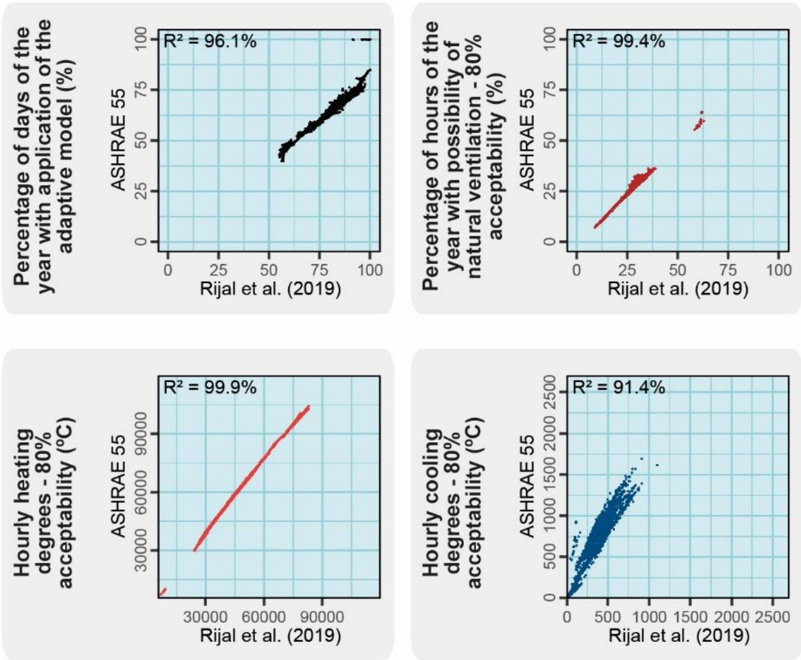

Figure 11. Point cloud comparison between the model of ASHRAE 55 and Japan's regional model (80% acceptability).

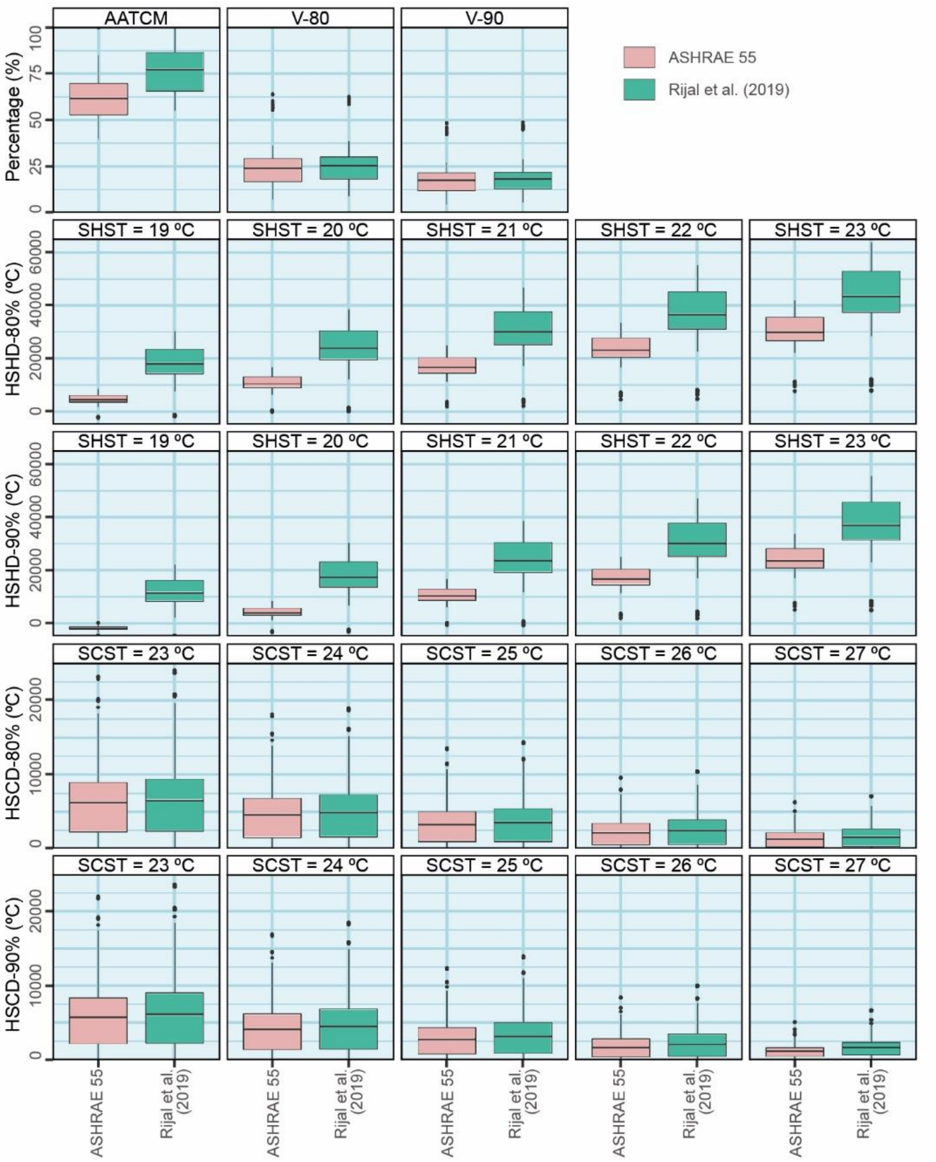

Figure 12. Box plot comparison between the model of ASHRAE 55 and Japan's regional model.

3.6. The Netherlands

The Netherlands, like China, has its national adaptive thermal comfort standard: ISSO 74:2014. This model presents specific characteristics as it horizontally extends upper and lower limits. Therefore, the applicability of ISSO 74:2014 greatly varied, showing an application between 90 and 100% of the days of the year in the whole country (Table 8). The percentages of applicability with the model of ASHRAE 55 oscillated between 40 and 60%. However, it did not mean that the possibilities of energy saving were lower with that standard (Figures 13 and 14). ASHRAE 55 had greater benefits of NV than ISSO 74:2014. The possibilities of NV in the country were concentrated in the summer months, so the design of the model of ASHRAE 55 slightly increased the percentage of annual hours (ventilations up to 20% were obtained with ASHRAE 55, whereas ventilations up to 10% were obtained with ISSO 74:2014). Likewise, the model of ASHRAE 55 had greater saving in heating degrees. It is worth stressing that Classes A-B are related to 90% acceptability, whereas Class C is related to 80% acceptability. Therefore, the saving in heating degrees was greater with the model of ASHRAE 55 (between 10,232 and 11,132 °C). This model presented better performance in terms of greater energy demand in the region. On the other hand, the saving in cooling degrees was very similar with the two models since differences were lower than 115 °C.

The models of ISSO 74:2014 were characterized by a greater applicability throughout the year, but they did not affect energy saving so greatly as ASHRAE 55. Nonetheless, the similarity in the saving in cooling degrees could be interesting with the progressive outdoor temperature rise.

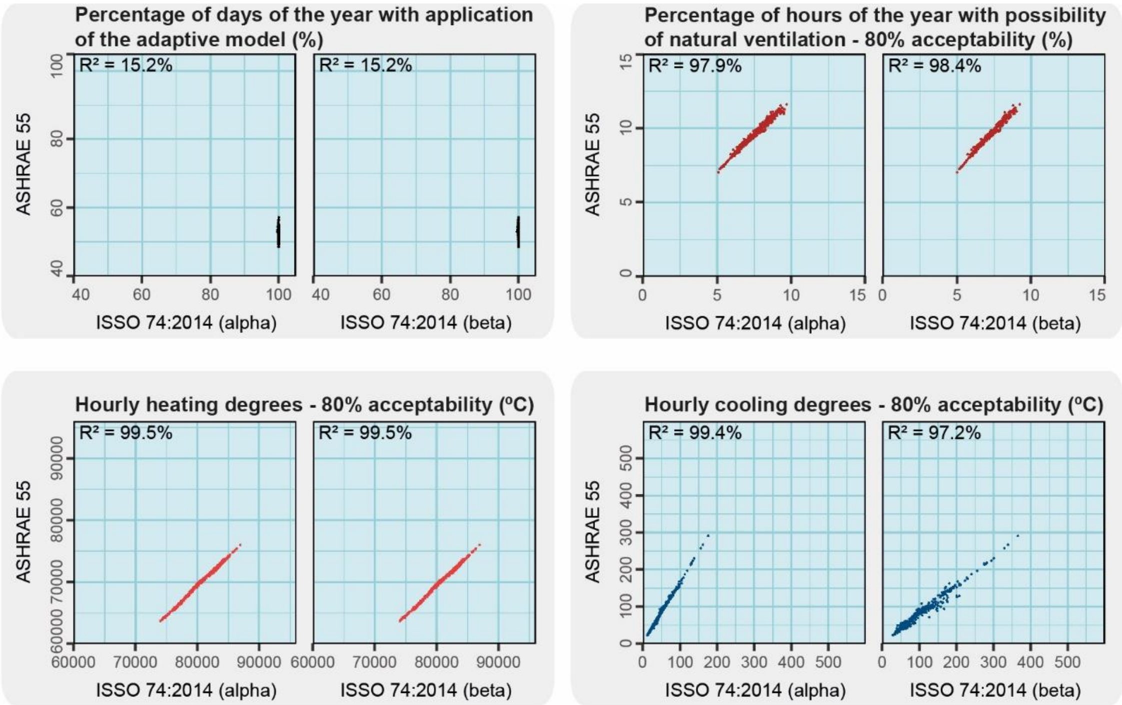

Figure 13. Point cloud comparison between the model of ASHRAE 55 and the models of ISSO 74:2014 in the Netherlands (80% acceptability).

Table 8. Matrix with the percentage of locations according to the annual percentages of the variables of application of the adaptive thermal comfort models in the Netherlands.

Variable	Model	Percentage of days/hours of the year of application									
		[0-10%)	[10-20%)	[20-30%)	[30-40%)	[40-50%)	[50-60%)	[60-70%)	[70-80%)	[80-90%)	[90-100%]
AATCM	ASHRAE 55	0.0	0.0	0.0	0.0	14.7	85.3	0.0	0.0	0.0	0.0
	ISSO 74:2014 (alpha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
	ISSO 74:2014 (beta)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
V-80	ASHRAE 55	62.3	37.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ISSO 74:2014 (alpha)	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ISSO 74:2014 (beta)	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
V-90	ASHRAE 55	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ISSO 74:2014 (alpha)	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ISSO 74:2014 (beta)	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

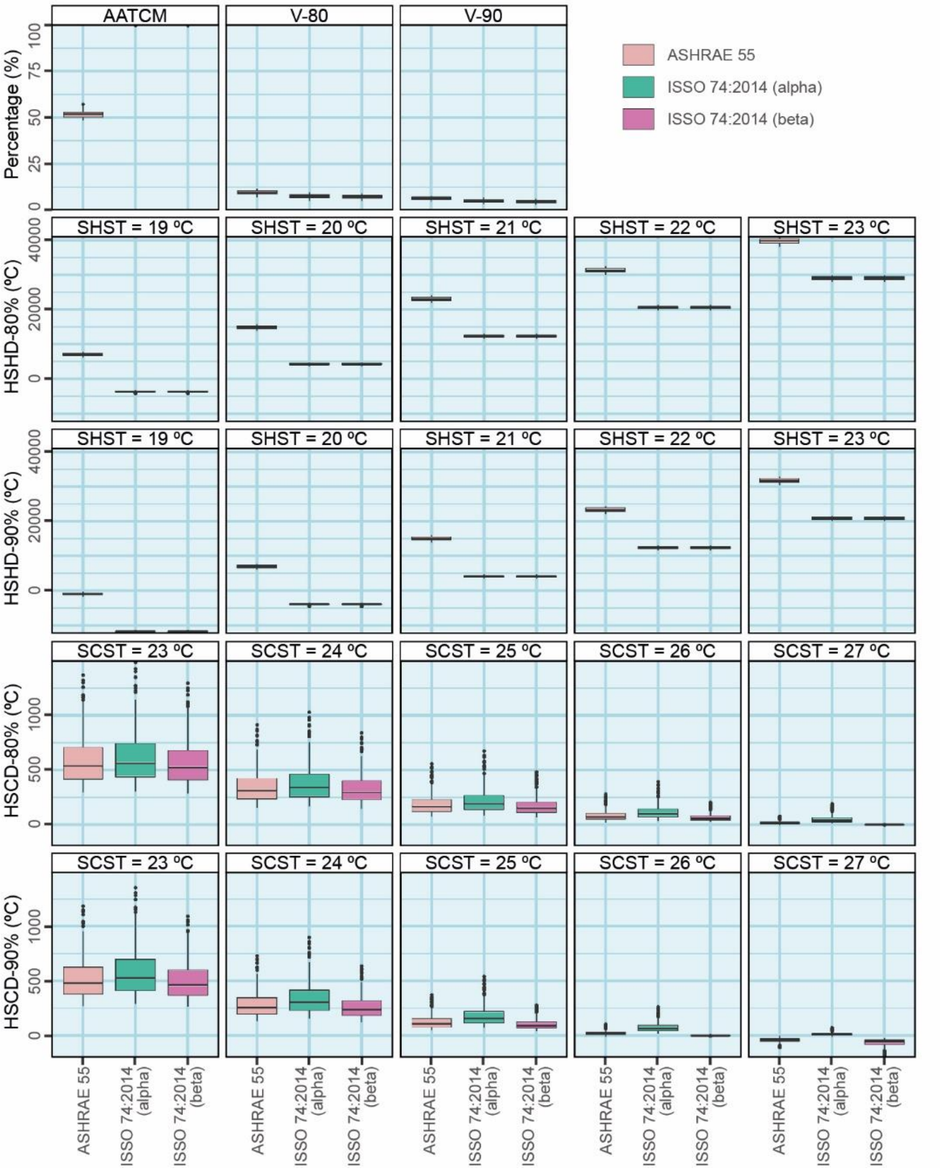

Figure 14. Box plot comparison between the model of ASHRAE 55 and the models of ISSO 74:2014 in the Netherlands.

3.7. Romania

Finally, the possibilities of applying adaptive thermal comfort models in Romania were assessed. Romania has the regional model proposed by Udrea et al. (2018). Its great similarity with the model of ASHRAE 55 is shown in most variables of adaptive thermal comfort (applicability, NV, and saving in cooling degrees). Figures 15 and 16 show the results. The percentages of applicability in the country were in the interval from 30 to 60% of the days of the year (Table 9), whereas NV was up to 20% of the hours of the year (coincident with the summer months). The difference between the two models was observed in the saving of heating degrees: the model of ASHRAE 55 increased the saving in heating degrees between 11,345 and 16,103 °C.

Table 9 Matrix with the percentage of locations according to the annual percentages of the variables of application of the adaptive thermal comfort models in Romania.

Variable	Model	Percentage of days/hours of the year of application									
		[0-10%)	[10-20%)	[20-30%)	[30-40%)	[40-50%)	[50-60%)	[60-70%)	[70-80%)	[80-90%)	[90-100%]
AATCM	ASHRAE 55	0.0	0.2	0.7	3.1	21.5	74.4	0.3	0.0	0.0	0.0
	Udrea et al. (2018)	0.0	0.2	0.7	3.1	21.5	74.4	0.3	0.0	0.0	0.0
V-80	ASHRAE 55	4.7	93.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Udrea et al. (2018)	24.2	75.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
V-90	ASHRAE 55	24.5	75.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Udrea et al. (2018)	99.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

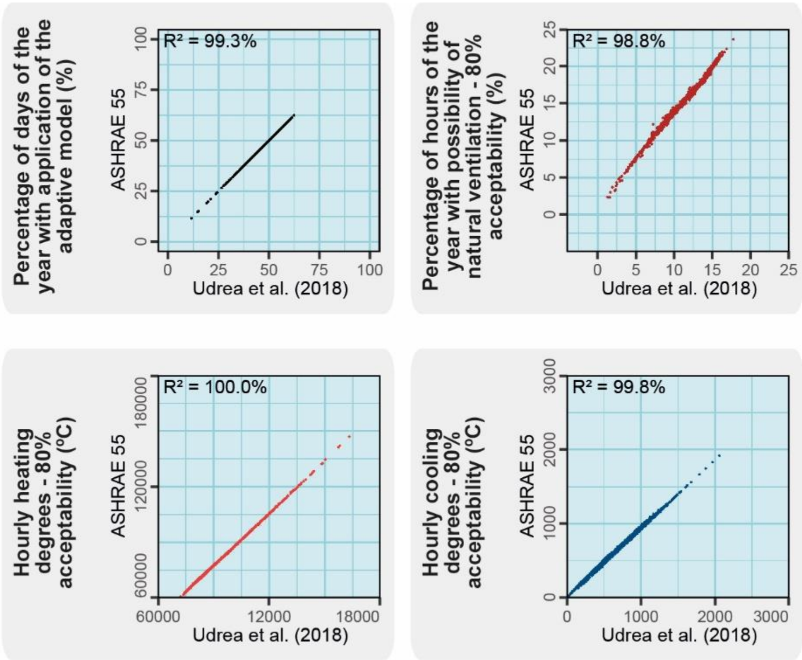

Figure 15. Point cloud comparison between the model of ASHRAE 55 and Romania's regional model (80% acceptability).

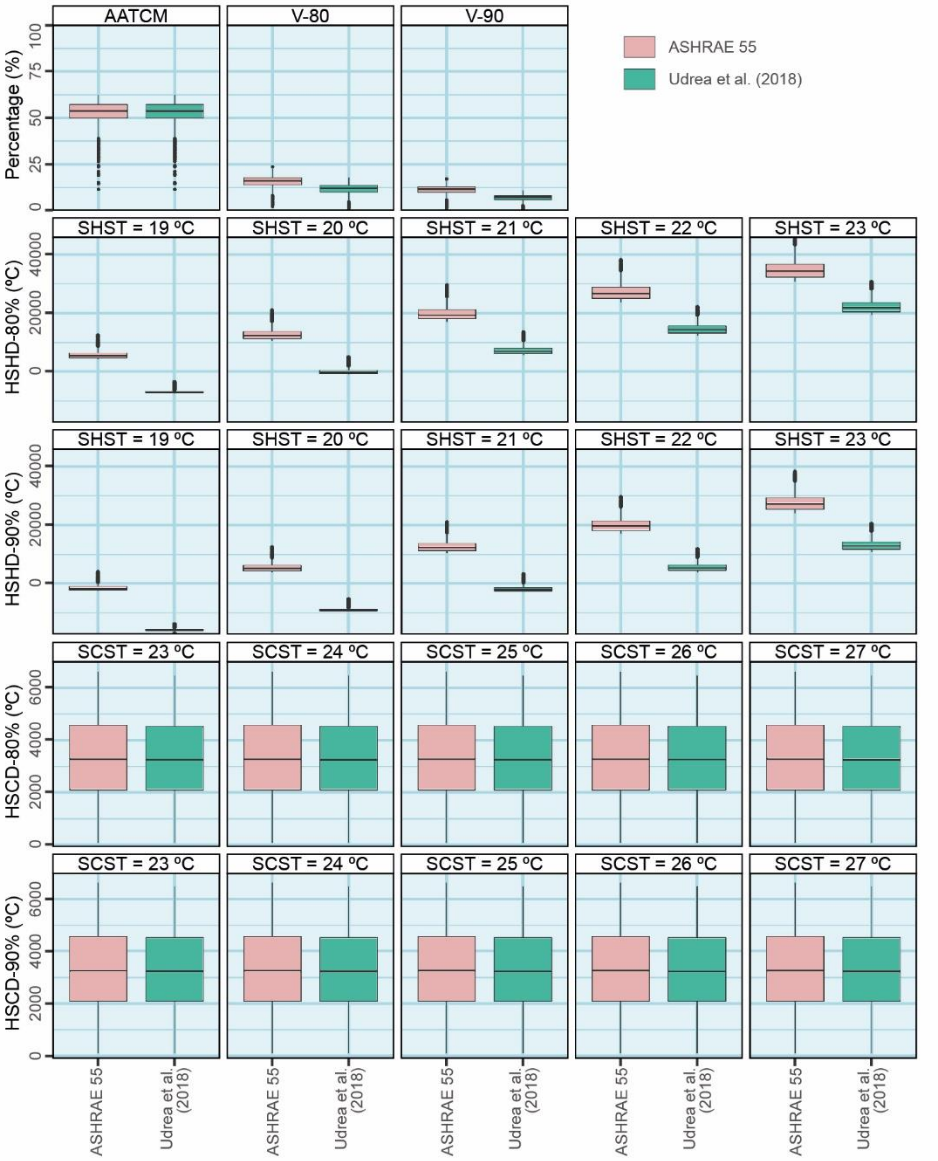

Figure 16. Box plot comparison between the model of ASHRAE 55 and Romania's regional model.

3.8. Discussion

The results have shown a comparative analysis among some regional models and the model of ASHRAE 55 per country. These differences should not be used to establish whether a model is appropriate, but to know the discrepancies between the models adapted to the characteristics of each country and the international model. Nonetheless, some aspects are interesting to observe similar behaviours in other countries. This study aimed to assess the decrease in energy demand with adaptive thermal comfort strategies. Most of the regional models were characterized by having greater applicability than ASHRAE 55. Thus, the models from Australia, China, Japan and India obtained greater application throughout the year. In any case, this did not mean that in the rest of the countries the energy savings obtained with the regional models were lower. This was because no clear relationship was detected in the applicability of the model and the savings obtained. Thus, regional models such as Brazil were characterized by having greater savings in cooling degrees and lower applicability than ASHRAE 55.

Likewise, there was no general trend in the behaviour of degree saving of the model of ASHRAE 55 in comparison with the regional models. The former obtained a more significant saving in the predominant energy demand in some countries (e.g. heating in the Netherlands and Romania, and cooling in Australia), but opposite results were also noted in other countries (e.g. Brazil and Japan). It is worth stressing that the results derived from several regional adaptive thermal comfort models allowed significant savings in heating and cooling degrees compared to static setpoint temperatures, although the energy demand increased in certain cases in the heating mode (e.g., when comparing the saving with respect to a static temperature of 19 ℃). Nonetheless, energy demand was hardly increased by adaptive setpoint temperatures in operational cooling modes (except ISSO 74:2014 in Class C). These results are in line with those reported in previous studies by only applying ASHRAE 55. Indeed, this energy saving measure could be interesting in the future because cooling energy demand will increase. The use of adaptive energy saving approaches will imply a more resilient built environment considering climate change scenarios.

Concerning the role of NV in most countries, low annual percentages of application were highlighted. Only countries under warm climate conditions throughout the year could have benefits. This means that approaches of energy saving with adaptive thermal comfort models should be based on implementing adaptive operational patterns or mixed modes to compensate the low application of NV. Likewise, the differences in the building typology of the models should be pointed out. This study did not assess a specific building type. The analysis focused on the applicability and energy saving potential of each model. However, models could be designed for a certain building type. Along this line, some models are computed for office buildings, and others for residential buildings. Having regional models designed for all building types would allow to optimally adopt of the best strategy. This does not significantly vary savings, as shown by the results of the models of Manu et al. and Rawal et al. in India.

Finally, and in terms of energy policies, both regional models and international adaptive thermal comfort models showed a great energy saving potential and governments should support the respective development and implementation. Most policies on built environment decarbonisation are focused on building refurbishment (including infrastructure and networks of monitoring and control). Nevertheless, several studies have shown the limitations of certain countries to implement up-to-bottom policies based on technological improvement (Attia et al., 2017). Boosting regional models of each country (few countries have today regional models) could push the decarbonisation goals by 2050. In addition, citizens' situation could be enhanced by decreasing both energy poverty cases and energy saving gaps between cold regions (whose performance measures are based on insulation and air tightness) and warm regions.

4. Conclusions

Adaptive thermal comfort models have a wide energy saving potential as the use of HVAC systems is reduced. However, most studies apply the international model of ASHRAE 55. Despite its great scope of action, its thermal comfort thresholds are not always adjusted to users' technical expectations. Therefore, studies and standards are developing models for each country. This research suggested the analysis of the energy savings obtained by the regional models of 7 countries: Australia, Brazil, China, India, Japan, the Netherlands, and Romania. The analysis was based on the applicability of the model, the adaptive natural ventilation, and adaptive setpoint temperatures.

The applicability of regional models could vary compared to ASHRAE 55, no affecting the energy saving. Most regional models had equal or greater energy savings in some adaptive strategies. Likewise, the greatest energy saving potential seemed to be related to the use of adaptive setpoint temperatures. Adaptive natural ventilation is an interesting measure, but low percentages of application were obtained in most combinations of country-regional models. Natural ventilation could play an important role only in countries close to the equator (e.g. Brazil). If not, it will be only used in warmer seasons. On the other hand, adaptive setpoint temperatures presented significant energy savings in all regional models, both for heating and cooling demand, although the potential was greater in the latter. The cooling energy saving obtained with the regional models were satisfactory in comparison with the static setpoint temperatures. The results with the regional models revealed an increasing dissociation of the built environment of each country from great energy consumption and great greenhouse gas emissions.

To conclude, it should be pointed out that the importance of the outcomes as concerns energy policies and further research. The lack of regional models should foster the development of new studies designing them. For this, it is necessary to adopt a subregional approach. Although the use of national approaches facilitates the development of the model, there may be differences between regions. This aspect has been checked in those countries that had several regional models. Users' thermal expectations would be accurately known in a country, and regulatory frameworks would be developed to implement energy saving strategies. Almost no country has a framework of adaptive thermal comfort models applicable to the entire built environment (only office and residential buildings). Nonetheless, further studies should address some limitations related to the results of this study. Given the characteristics of the research, the effect of heat island phenomenon in the applicability of the models in big cities has not been considered. Energy consumption are usually greater in these environments, so energy saving results are expected to vary. Likewise, most energy policies focus on reducing climate change, so the applicability and effectiveness of these models should be assessed in a wider temporary framework. Hence, further studies should address the variations expected with these regional models in terms of climate change. Although the applicability and energy saving potential according to the climate show a great potential, other factors should also be considered when implementing measures (design of the building, urban environment, and so on). In the same way, other researchers should address the effectiveness of implementing regional models in specific case studies. Finally, adaptive thermal comfort models are based on temperature variables. The influence on regional models of other variables, such as relative humidity, should be addressed in future work.

References

Albertí, J., Raigosa, J., Raugei, M., Assiego, R., Ribas-Tur, J., Garrido-Soriano, N., Zhang, L., Song, G., Hernández, P., Fullana-i-Palmer, P., 2019. Life Cycle Assessment of a solar thermal system in Spain, eco-design alternatives and derived climate change scenarios at Spanish and Chinese National levels. Sustain Cities Soc 47, 101467. https://doi.org/10.1016/j.scs.2019.101467

American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), 2017. ASHRAE Standard 55-2017 Thermal Environmental Conditions for Human Occupancy. Atlanta, GA, United States.

Attia, S., Eleftheriou, P., Xeni, F., Morlot, R., Ménézo, C., Kostopoulos, V., Betsi, M., Kalaitzoglou, I., Pagliano, L., Cellura, M., Almeida, M., Ferreira, M., Baracu, T., Badescu, V., Crutescu, R., Hidalgo-Betanzos, J.M., 2017. Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe. Energy Build 155, 439–458. https://doi.org/10.1016/j.enbuild.2017.09.043

Bienvenido-Huertas, D., Pulido-Arcas, J.A., Rubio-Bellido, C., Pérez-Fargallo, A., 2021. Feasibility of adaptive thermal comfort for energy savings in cooling and heating: A study on Europe and the Mediterranean basin. Urban Clim 36. https://doi.org/10.1016/j.uclim.2021.100807

Bienvenido-Huertas, D., Sánchez-García, D., Pérez-Fargallo, A., Rubio-Bellido, C., 2020a. Optimization of energy saving with adaptive setpoint temperatures by calculating the prevailing mean outdoor air temperature. Build Environ 170. https://doi.org/10.1016/j.buildenv.2019.106612

Bienvenido-Huertas, D., Sánchez-García, D., Rubio-Bellido, C., 2022. Influence of the RCP scenarios on the effectiveness of adaptive strategies in buildings around the world. Build Environ 208. https://doi.org/10.1016/j.buildenv.2021.108631

Bienvenido-Huertas, D., Sánchez-García, D., Rubio-Bellido, C., 2020b. Analysing natural ventilation to reduce the cooling energy consumption and the fuel poverty of social dwellings in coastal zones. Appl Energy 279. https://doi.org/10.1016/j.apenergy.2020.115845

Bouzarovski, S., Petrova, S., 2015. A global perspective on domestic energy deprivation: Overcoming the energy poverty–fuel poverty binary. Energy Res Soc Sci 10, 31–40. https://doi.org/10.1016/j.erss.2015.06.007

Carlucci, S., Bai, L., de Dear, R., Yang, L., 2018. Review of adaptive thermal comfort models in built environmental regulatory documents. Build Environ 137, 73–89. https://doi.org/10.1016/J.BUILDENV.2018.03.053

Chen, K., Xu, Q., Leow, B., Ghahramani, A., 2023. Personal thermal comfort models based on physiological measurements – A design of experiments based review. Build Environ 109919. https://doi.org/10.1016/j.buildenv.2022.109919

de Dear, R., Brager, G.S., 2002. Thermal comfort in naturally ventilated buildings: revision to ASHRAE standards 55,. Journal of Energy and Buildings 34, 549–561. https://doi.org/https://doi.org/10.1016/S0378-7788(02)00005-1

de Dear, R., Brager, G.S., 2001. The adaptive model of thermal comfort and energy conservation in the built environment. Int J Biometeorol 45, 100–108.

de Dear, R.J., Brager, G.S., 1998. Developing an adaptive model of thermal comfort and preference. ASHRAE Trans 104, 145–167.

de Rubeis, T., Falasca, S., Curci, G., Paoletti, D., Ambrosini, D., 2020. Sensitivity of heating performance of an energy self-sufficient building to climate zone, climate change and HVAC system solutions. Sustain Cities Soc 61, 102300. https://doi.org/10.1016/j.scs.2020.102300

European Commission, 2020. Renovation wave [WWW Document]. URL (accessed 2.1.23).

European Commission, 2019. A European Green Deal [WWW Document]. URL (accessed 2.1.23).

European Commission, 2011. A Roadmap for moving to a competitive low carbon economy in 2050. Brussels, Belgium.

European Environment Agency, 2018. Final energy consumption by sector and fuel (2016). Copenhagen, Denmark.

Fanger, P.O., 1970. Thermal comfort: analysis and applications in environmental engineering. New York.

Galvin, R., Gubernat, A., 2016. The rebound effect and Schatzki's social theory: Reassessing the socio-materiality of energy consumption via a German case study. Energy Res Soc Sci 22, 183–193. https://doi.org/10.1016/j.erss.2016.08.024

Ghose, A., McLaren, S.J., Dowdell, D., 2020. Upgrading New Zealand's existing office buildings – An assessment of life cycle impacts and its influence on 2050 climate change mitigation target. Sustain Cities Soc 57, 102134. https://doi.org/10.1016/j.scs.2020.102134

Gianfrate, V., Piccardo, C., Longo, D., Giachetta, A., 2017. Rethinking social housing: Behavioural patterns and technological innovations. Sustain Cities Soc 33, 102–112. https://doi.org/10.1016/j.scs.2017.05.015

Golmohamadi, H., Keypour, R., Bak-Jensen, B., Radhakrishna Pillai, J., 2019. Optimization of household energy consumption towards day-ahead retail electricity price in home energy management systems. Sustain Cities Soc 47, 101468. https://doi.org/10.1016/j.scs.2019.101468

Heracleous, C., Michael, A., 2018. Assessment of overheating risk and the impact of natural ventilation in educational buildings of Southern Europe under current and future climatic conditions. Energy 165, 1228–1239. https://doi.org/10.1016/j.energy.2018.10.051

Hiyama, K., Glicksman, L., 2015. Preliminary design method for naturally ventilated buildings using target air change rate and natural ventilation potential maps in the United States. Energy 89, 655–666. https://doi.org/10.1016/j.energy.2015.06.026

Humphreys, M., 1978. Outdoor temperatures and comfort indoors. Building Research and Practice 6, 92. https://doi.org/https://doi.org/10.1080/09613217808550656

Humphreys, M., 1975. Field Studies in Thermal Comfort Compared and Applied.

Indraganti, M., Ooka, R., Rijal, H.B., 2013. Thermal comfort in offices in summer: Findings from a field study under the "setsuden" conditions in Tokyo, Japan. Build Environ 61, 114–132. https://doi.org/10.1016/j.buildenv.2012.12.008

Instituut Voor Studie En Stimulering Van Onderzoek, 2014. ISSO-publicatie 74 Thermische behaaglijkheid.

Kameni, M., Yvon, A., Kalameu, O., Asadi, S., Choudhary, R., Reiter, S., 2019. Impact of climate change on demands for heating and cooling energy in hospitals : An in-depth case study of six islands located in the Indian Ocean region. Sustain Cities Soc 44, 629–645. https://doi.org/10.1016/j.scs.2018.10.031

Kurtz, F., Monzón, M., López-Mesa, B., 2015. Energy and acoustics related obsolescence of social housing of Spain's post-war in less favoured urban areas. The case of Zaragoza. Informes de la Construcción 67, m021. https://doi.org/10.3989/ic.14.062

Legendre, B., Ricci, O., 2015. Measuring fuel poverty in France: Which households are the most fuel vulnerable? Energy Econ 49, 620–628. https://doi.org/10.1016/j.eneco.2015.01.022

Li, B., Yao, R., Wang, Q., Pan, Y., 2014. An introduction to the Chinese Evaluation Standard for the indoor thermal environment. Energy Build 82, 27–36. https://doi.org/10.1016/j.enbuild.2014.06.032

Manu, S., Shukla, Y., Rawal, R., Thomas, L.E., de Dear, R., 2016. Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). Build Environ 98, 55–70. https://doi.org/10.1016/J.BUILDENV.2015.12.019

McCartney, K.J., Nicol, J.F., 2002. Developing an adaptive control algorithm for Europe. Energy Build 34, 623–635.

Meteotest AG, 2023. METEONORM Software.

Monge Palma, R., Sánchez Ramos, J., Guerrero Delgado, M. del C., Palomo Amores, T.R., Romero Rodríguez, L., Álvarez Domínguez, S., 2023. Extending the Thermal Comfort Band in Residential Buildings: A Strategy towards a Less Energy-Intensive Society. Applied Sciences (Switzerland) 13. https://doi.org/10.3390/app13127020

Nicol, J.F., Humphreys, M.A., 1973. Thermal comfort as part of a self-regulating system. Building Research and Practice 1, 174–179. https://doi.org/https://doi.org/10.1080/09613217308550237

Omrani, S., Garcia-Hansen, V., Capra, B.R., Drogemuller, R., 2017. On the effect of provision of balconies on natural ventilation and thermal comfort in high-rise residential buildings. Build Environ 123, 504–516. https://doi.org/10.1016/j.buildenv.2017.07.016

Osman, M.M., Sevinc, H., 2019. Adaptation of climate-responsive building design strategies and resilience to climate change in the hot/arid region of Khartoum, Sudan. Sustain Cities Soc 47. https://doi.org/10.1016/j.scs.2019.101429

Park, K., Kim, M., 2017. Energy Demand Reduction in the Residential Building Sector: A Case Study of Korea. Energies (Basel) 10, 1–11. https://doi.org/10.3390/en10101506

Parkinson, T., de Dear, R., Brager, G., 2020. Nudging the adaptive thermal comfort model. Energy Build 206, 109559. https://doi.org/10.1016/j.enbuild.2019.109559

Pérez-Carramiñana, C., Sabatell-Canales, S., González-Avilés, Á.B., Galiano-Garrigós, A., 2023. Influence of Spanish Energy-Saving Standard on Thermal Comfort and Energy Efficiency Owing to the War in Ukraine: Case Study of an Office Building in a Dry Mediterranean Climate. Buildings 13. https://doi.org/10.3390/buildings13082102

Rawal, R., Shukla, Y., Vardhan, V., Asrani, S., Schweiker, M., de Dear, R., Garg, V., Mathur, J., Prakash, S., Diddi, S., Ranjan, S.V., Siddiqui, A.N., Somani, G., 2022. Adaptive thermal comfort model based on field studies in five climate zones across India. Build Environ 219, 109187. https://doi.org/10.1016/j.buildenv.2022.109187

Rijal, H.B., Humphreys, M.A., Nicol, J.F., 2019. Adaptive model and the adaptive mechanisms for thermal comfort in Japanese dwellings. Energy Build. https://doi.org/10.1016/j.enbuild.2019.109371

Rodrigues, E., Fernandes, M.S., Gaspar, A.R., Gomes, Á., Costa, J.J., 2019. Thermal transmittance effect on energy consumption of Mediterranean buildings with different thermal mass. Appl Energy 252, 113437.

Rupp, R.F., de Dear, R., Ghisi, E., 2018. Field study of mixed-mode office buildings in Southern Brazil using an adaptive thermal comfort framework. Energy Build 158, 1475–1486. https://doi.org/10.1016/j.enbuild.2017.11.047

Sánchez-García, D., Rubio-Bellido, C., del Río, J.J.M., Pérez-Fargallo, A., 2019a. Towards the quantification of energy demand and consumption through the adaptive comfort approach in mixed mode office buildings considering climate change. Energy Build 187, 173–185. https://doi.org/10.1016/j.enbuild.2019.02.002

Sánchez-García, D., Rubio-Bellido, C., del Río, J.J.M., Pérez-Fargallo, A., 2019b. Towards the quantification of energy demand and consumption through the adaptive comfort approach in mixed mode office buildings considering climate change. Energy Build 187, 173–185. https://doi.org/10.1016/j.enbuild.2019.02.002

Stern, P.C., Janda, K.B., Brown, M.A., Steg, L., Vine, E.L., Lutzenhiser, L., 2016. Opportunities and insights for reducing fossil fuel consumption by households and organizations. Nat Energy 1. https://doi.org/10.1038/nenergy.2016.43

Tejedor, B., Casals, M., Gangolells, M., Macarulla, M., Forcada, N., 2020. Human comfort modelling for elderly people by infrared thermography: Evaluating the thermoregulation system responses in an indoor environment during winter. Build Environ 186, 107354. https://doi.org/10.1016/j.buildenv.2020.107354

Udrea, I., Croitoru, C., Nastase, I., Crutescu, R., Badescu, V., 2018. First adaptive thermal comfort equation for naturally ventilated buildings in Bucharest, Romania. International Journal of Ventilation 17, 149–165. https://doi.org/10.1080/14733315.2017.1356057

Williamson, T., Daniel, L., 2020. A new adaptive thermal comfort model for homes in temperate climates of Australia. Energy Build 210, 109728. https://doi.org/10.1016/j.enbuild.2019.109728

Wilson, A., 2022. Revision of the energy performance of buildings directive: Fit for 55 package. European Parliamentary Research Service.

World Wildlife Fund, 2014. Living Planet Report 2014: Species and spaces, people and places. WWF International, Gland, Switzerland. https://doi.org/10.1007/s13398-014-0173-7.2

Yang, L., Fu, R., He, W., He, Q., Liu, Y., 2020. Adaptive thermal comfort and climate responsive building design strategies in dry–hot and dry–cold areas: Case study in Turpan, China. Energy Build 209. https://doi.org/10.1016/j.enbuild.2019.109678

Zhang, N., Cao, B., Wang, Z., Zhu, Y., Lin, B., 2017. A comparison of winter indoor thermal environment and thermal comfort between regions in Europe, North America, and Asia. Build Environ 117, 208–217. https://doi.org/10.1016/j.buildenv.2017.03.006

Annex A

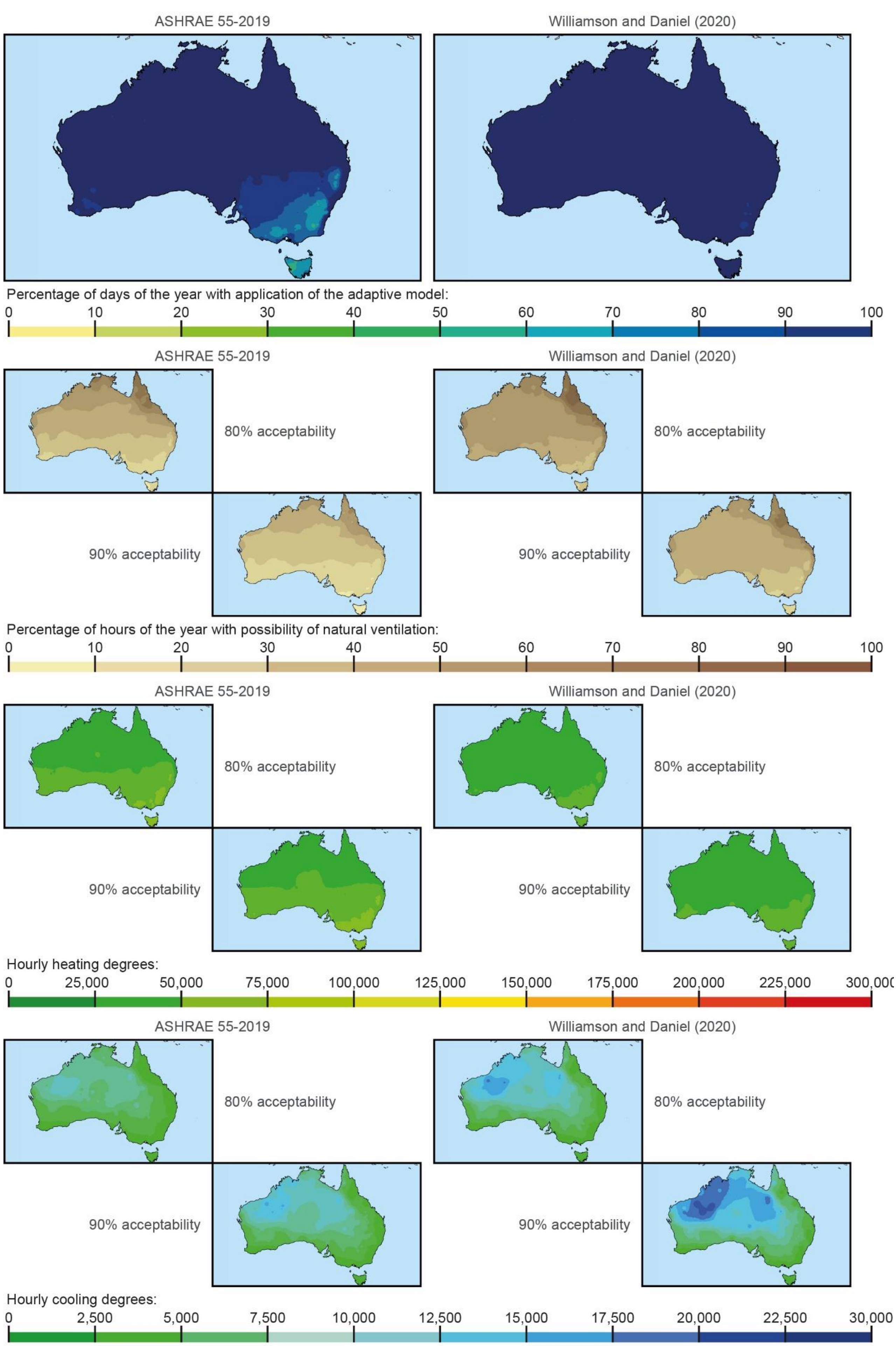

Figure A1. Applicability of the adaptive thermal comfort models in Australia.

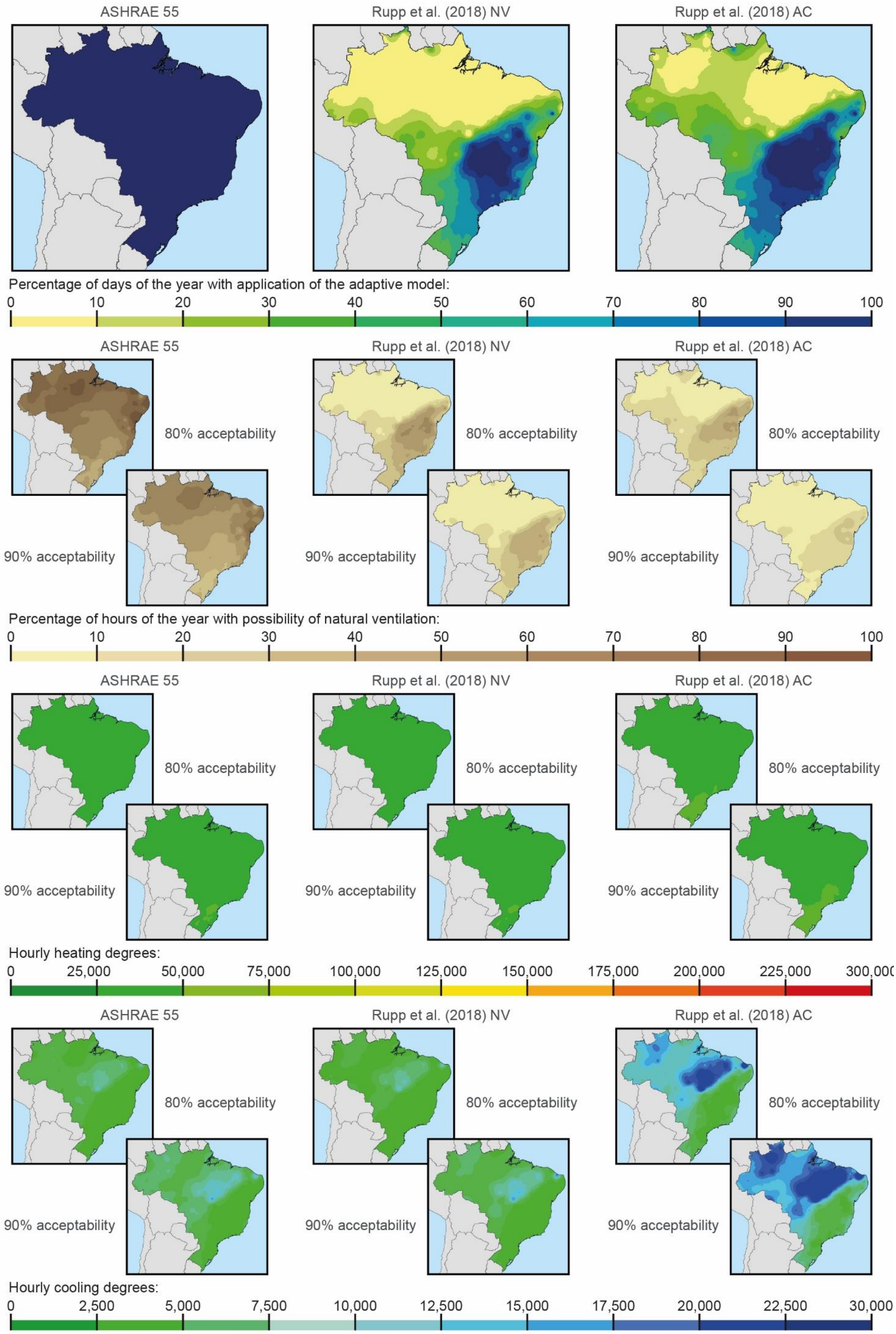

Figure A2. Applicability of the adaptive thermal comfort models in Brazil.

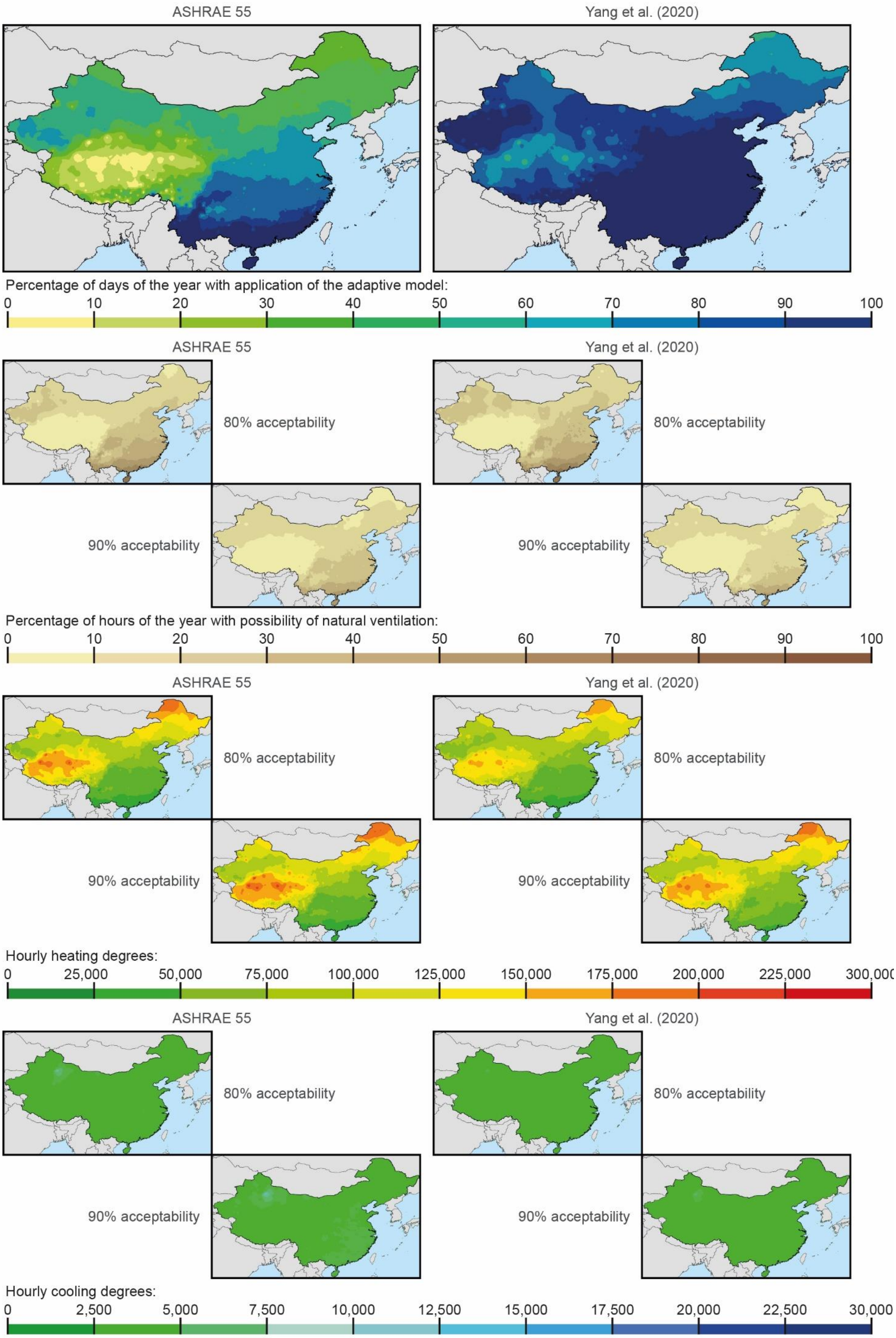

Figure A3. Applicability of the adaptive thermal comfort models in China (ASHRAE 55-2017 and Yang et al. (2020)).

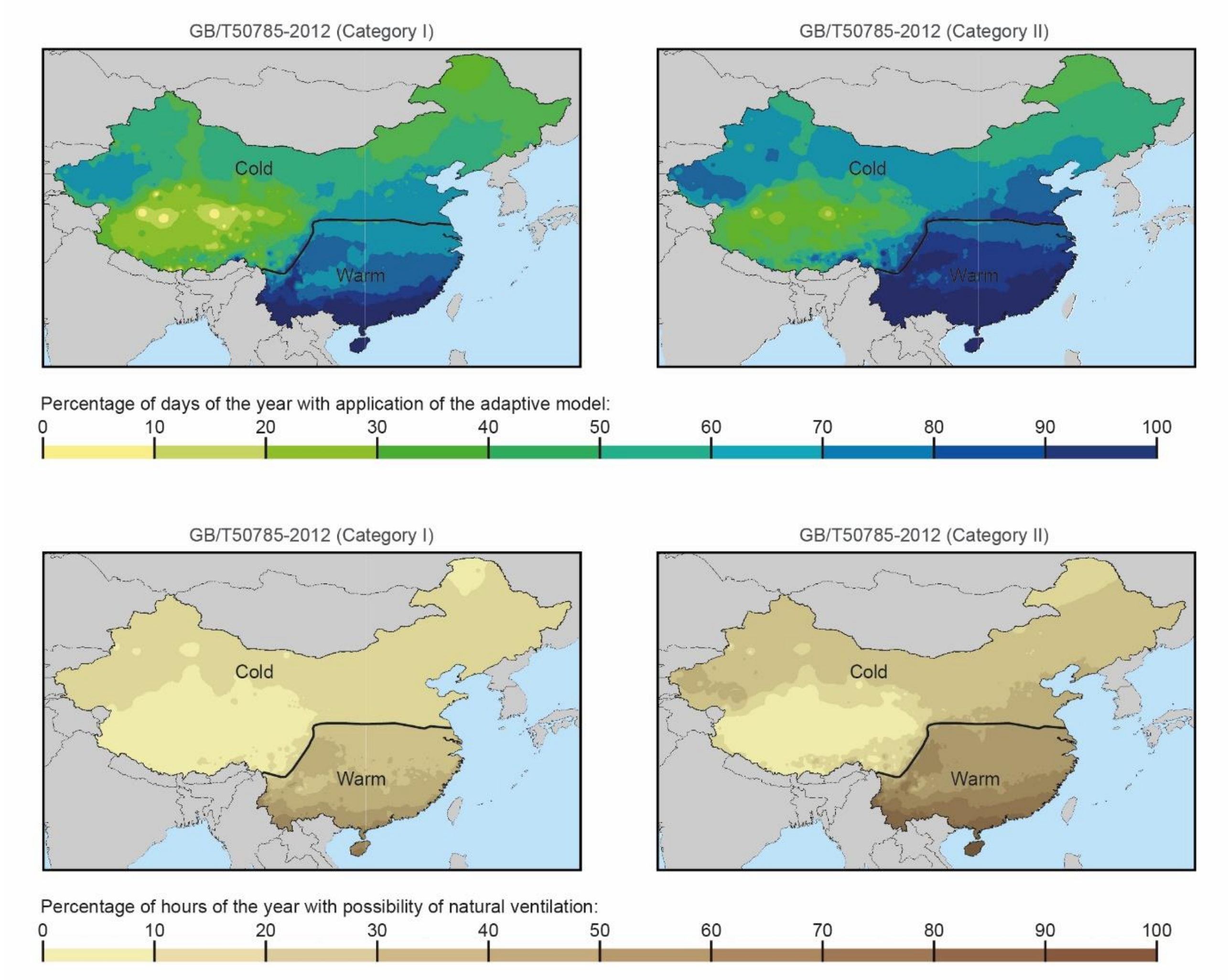

Figure A4. Applicability of the adaptive thermal comfort models of GB/T50785-2012 in China.

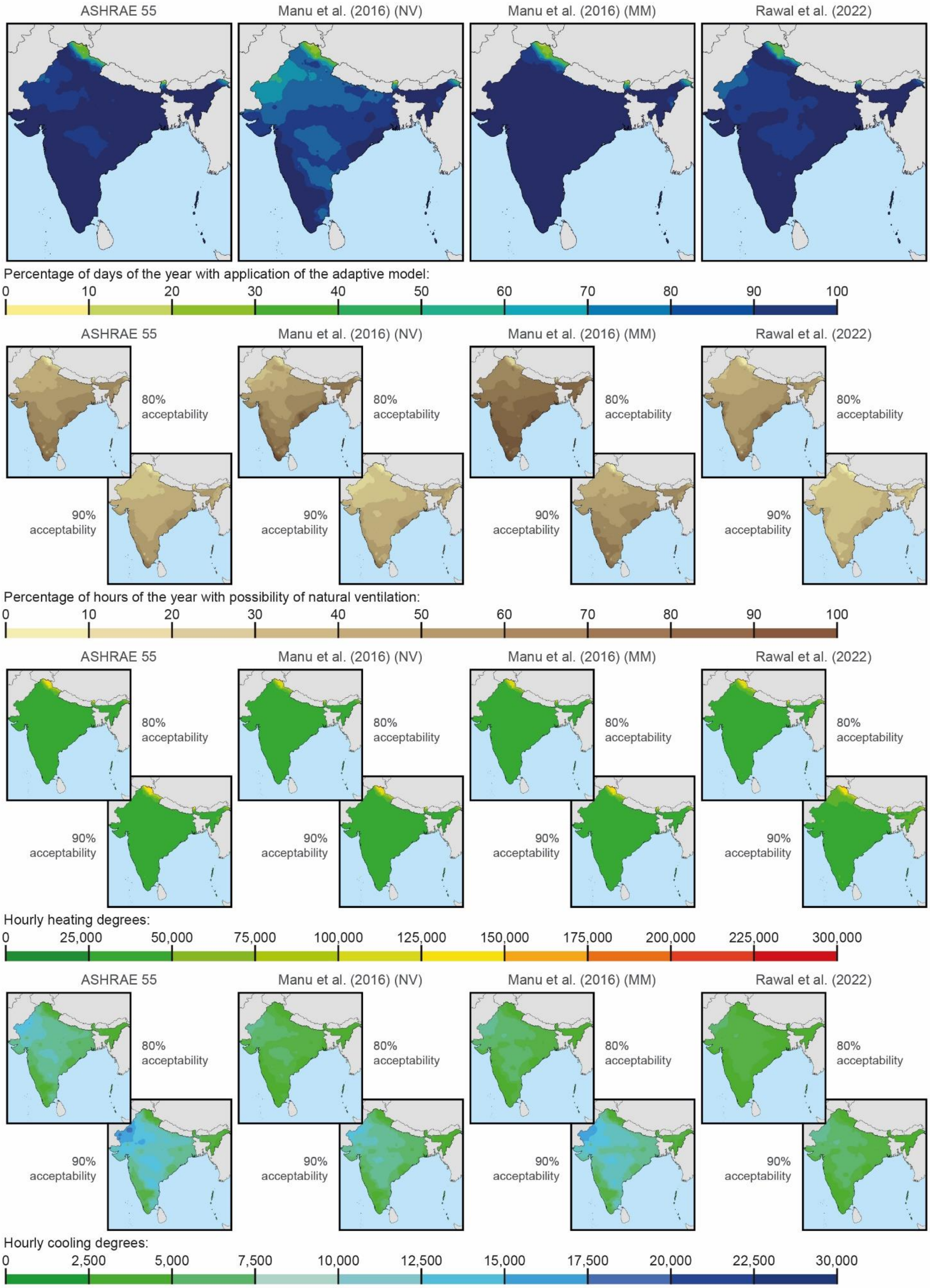

Figure A5. Applicability of the adaptive thermal comfort models in India.

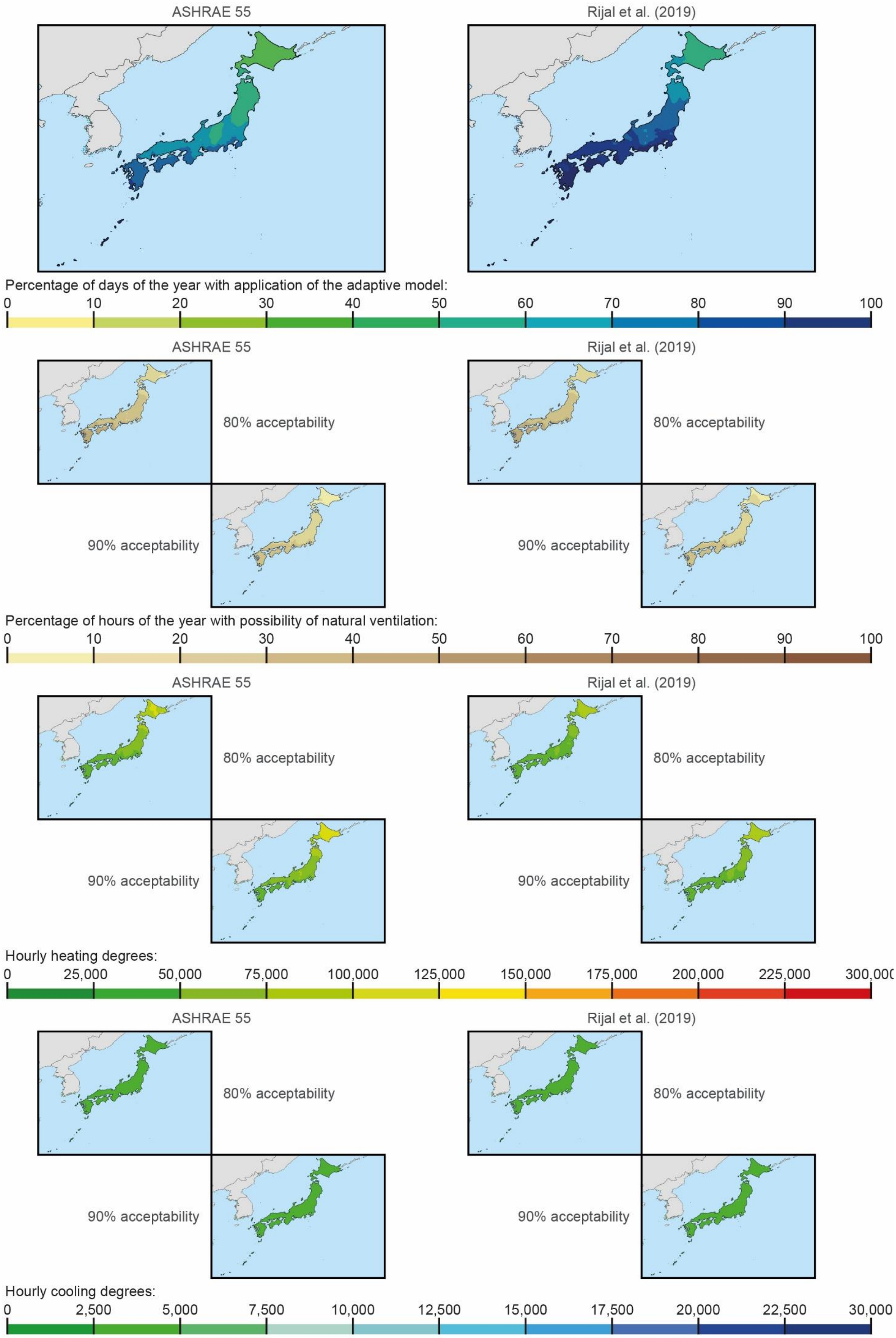

Figure A6. Applicability of the adaptive thermal comfort models in Japan.

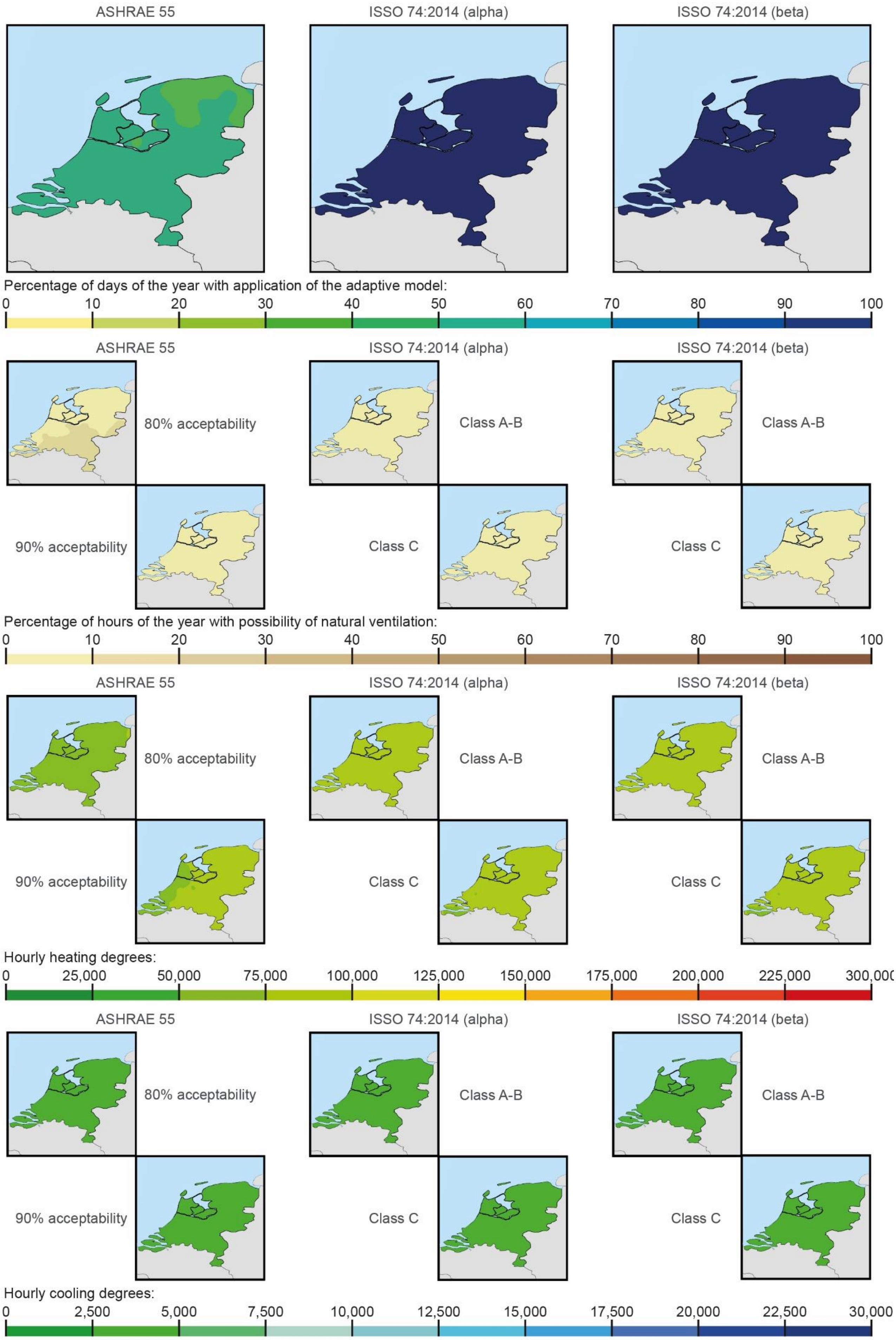

Figure A7. Applicability of the adaptive thermal comfort models in the Netherlands.

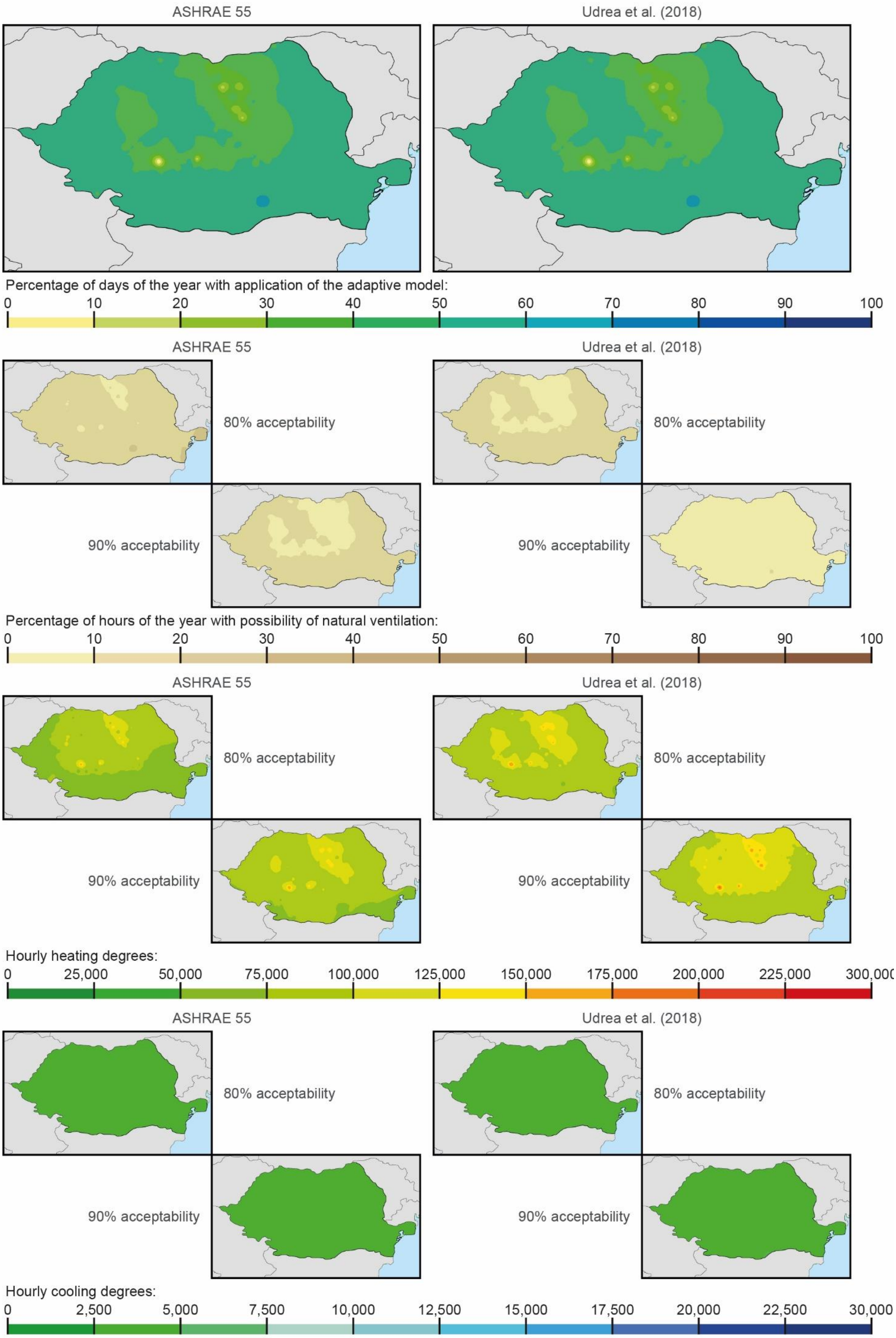

Figure A8. Applicability of the adaptive thermal comfort models in Romania.