Title: Assessing the energy saving potential of using adaptive setpoint temperatures: the case study of a regional adaptive comfort model for Brazil in both the present and the future

Abstract

It has been found in recent years that using setpoint temperatures based on adaptive thermal comfort models is a successful method of energy conservation. Recent studies using adaptive setpoint temperatures incorporate international models from ASHRAE Standard 55 and EN16798-1. This study, however, has instead considered a regional Brazilian adaptive comfort model. This study investigates the energy demand arising from the use of a local Brazilian comfort model in order to assess the energy implications from the use of the worldwide ASHRAE Standard 55 adaptive model and various fixed setpoint temperatures. All of Brazil's climate zones, full air-conditioning, mixed-mode building operating modes, present-day climate change scenarios, and future scenarios—specifically Representative Concentration Pathways (RCP) 2.6, 4.5, and 8.5 for the years 2050 and 2100—have all been taken into account in building energy simulations. The use of adaptive setpoint temperatures based on the Brazilian local model considering mixed-mode has been found to significantly reduce energy consumption when compared to static setpoint temperatures (average energy-saving values ranging from 52 to 58%) and the ASHRAE 55 adaptive model (average values ranging from 15 to 21%). Considering climate change and the mixed-mode Brazilian model, the overall energy demand for the three groups of climatic zones (annual average outdoor temperatures ≤ 21°C, > 21 and ≤ 25°C and > 25°C) ranged between 2% decrease and 5% increase, 4% and 27% increase, and 13% and 45% increase, respectively. It is concluded as a consequence that setting setpoint temperatures based on the Brazilian local adaptive comfort model is a very efficient energy-saving method.

Keywords: adaptive thermal comfort; building energy simulation; energy efficiency; climate change; adaptive setpoint temperatures; local comfort model

Highlights

- Adaptive setpoint temperatures are based on a Brazilian local model instead of international standards
- Energy savings for mixed-mode ranged from 52 to 58% and from 15 to 21% compared respectively to the Brazilian regulations and ASHRAE 55 adaptive model
- Climate change increased average energy demand up to 45% depending on the RCP scenario and year

1. Introduction

The integration of homes' resilience into reduced energy usage has been proposed until now using adaptive comfort models. Standards like EN 16798-1:2019 (European committee for standardization, 2019) and ASHRAE 55-2020 (ASHRAE Standard 55-2020 Thermal Environmental Conditions for Human Occupancy, 2020) are used to implement those models, which take into consideration the users' interaction with the environment. The standards were built based on the Smart Controls and Thermal Comfort (SCATs) and ASHRAE RP-884 initiative, respectively. The results of these studies showed that, in terms of user comfort, the operative temperature and the outside temperature are related (R. de Dear & G.S. Brager, 2002).

Different adaptive thermal comfort models were recently built to overcome the weaknesses of the global models. The EN 16798-1:2019 standard states that the comfort standard has been built based on a limited quantity of data collected for outdoor dry-bulb temperatures higher than 25°C. This is because, out of all the participating nations, only two buildings in Greece had data under these conditions, while the rest of the sample is made up of colder-climate nations (e.g., United Kingdom and France). Therefore, when this model is used to warm regions, the results are constrained and the model's applicability is limited, especially when the consequences of climate change are taken into consideration (Barbosa et al., 2015; Sánchez-García et al., 2018). In order to recognise the peculiarity of each region, many national standards, including GB/T 50785 ((GB/T 50785-2012) Evaluation Standard for Indoor Thermal Environment in Civil Buildings, 2012) from China and ISSO 74 (ISSO-Publicatie 74 Thermische Behaaglijkheid, 2004; ISSO-Publicatie 74 Thermische Behaaglijkheid, 2014) from the Netherlands, have been developed. Based on the cold, warm, and mild climate zones, two unique models were constructed for the Chinese standard. Also, China has constructed specific models for certain places (Yang et al., 2020a). With regards to the Dutch standard, the second edition from 2014 (Boerstra et al., 2015) focuses on developing interior settings that fit into one of four categories of acceptability using both global databases and local research with a variety of upper and lower boundaries. Although conducting in-depth studies for various building applications or understanding actual living circumstances is not new, it has become a global trend as a result of the growth of numerous adaptive comfort field studies in recent years. These studies, for example, have been conducted for regions like Pakistan (Nicol & Roaf, 1996), Iran (Heidari & Sharples, 2002), China (Mui & Chan, 2003; Wang et al., 2010; Yang et al., 2015, 2020b), Tunisia (Bouden & Ghrab, 2005), Japan (Rijal et al., 2013, 2017, 2019a), Australia (R. de Dear et al., 2018; Williamson & Daniel, 2020), Qatar (Indraganti & Boussaa, 2018), India (Dhaka et al., 2015; Indraganti et al., 2014; Manu et al., 2016; Rawal et al., 2022; S. Thapa, 2020; S. Thapa et al., 2018; S. Thapa & Indraganti, 2020), Colombia (García et al., 2019), Mexico (López-Pérez et al., 2019), Romania (Udrea et al., 2018), building uses like hospitals (Yau & Chew, n.d.), shelters (R. Thapa et al., 2018), dormitories (Wu et al., 2019), prefab construction site offices (Fu et al., 2020) or workshops (Kumar et al., 2020), or aimed to a specific gender or age like young children in primary school (Haddad et al., 2016), females (S. Thapa, 2020) and older residents (Jiao et al., 2020).

The energy needs of a building are considerably influenced by the inclusion of adaptive comfort models (Yang et al., 2014). In order to minimize energy usage, setpoint temperatures have been changed in various research: (i) a study carried out for an airport in Egypt's hot, dry environment, with a particular emphasis on the HVAC systems' performance (Abdallah et al., 2021). The study discovered that increasing the thermostat setpoint temperature from 25 to 27 °C can result in a decrease of 24.5% in HVAC energy consumption during the hot season; (ii) Saleh N. Al-Saadi found out that, by modifying the thermostat setpoint, installing a timer to enforce an optimal operating schedule for the HVAC system, and recommending a setback thermostat setpoint, it is possible to cut energy use and costs by 29.4% and 26.4%, respectively (Al-Saadi, 2021); (iii) another study used setpoint temperatures based on different energy efficiency regulations and comfort standards. It was found that by shifting the heating-cooling setpoints' range from 18-24°C to 20-26°C, 12% savings may be realized without sacrificing comfort (Abdul Mujeebu & Bano, 2022). Perhaps, one of the most recent occasions in which setpoint temperatures have been adjusted to save energy occurred in August 2022, when some Governments, such as the Greek and Spanish, limited the heating and cooling setpoint temperatures to 19 and 27°C as measures focused to the independence of natural gas – Danish government also implemented energy-saving measures limiting the heating setpoint of public office buildings at 19°C. However, the setpoint temperatures used in most of the above-mentioned studies were static or based on the Predicted Mean Vote (PMV) index.

On the other hand, adaptive comfort models are only suited for areas running under natural ventilation (or non-cooled/non-heated areas), under the specifications of ASHRAE 55 and EN16798-1, although certain explanations must be made. In 1998, de Dear and Brager released the first version of their adaptive comfort regression models, using an outside climate meter as the independent variable. They discovered that although naturally ventilated (NV) spaces exhibited a significantly adaptive comfort model, air-conditioned (AC) spaces showed barely any thermal adaptation. As a result, de Dear and Brager and subsequently ASHRAE TC 2.1 (charged for developing Standard 55) arrived at the initial conclusion in 1998 that adaptive comfort models were only applicable to naturally ventilated buildings (R. J. de Dear & Brager, 1998). The 1998 research lacked sufficient data on mixed-mode (MM) buildings to make a conclusive statement about them since there were so few MM building records in the original RP-884 database. Yet in 2020, Parkinson et al. conducted a new analysis of the original ASHRAE adaptive models based on a larger database (Parkinson et al., 2020). When the interior temperature was utilized as the independent variable instead of outside temperature, a consistent adaptive model fitted exceptionally well across all building types, including AC, NV, and MM. This led to a reexamination of the adaptive comfort models' shortcomings in MM and AC buildings. The 1998 results could only be reconciled with the 2020 reanalysis by admitting that there is an exceptionally strong correlation between interior and external climates in NV spaces. Because of this, what the 1998 study believed to be an adaptation to the external environment in some buildings was actually a connection with the internal climate, which was linked to the outdoor climate. The fact that it is feasible to develop statistically significant adaptive comfort models for cooling operations in air-conditioned office buildings has also been confirmed by another study (Yun et al., 2016). This suggests that employing adaptive setpoint temperatures might help attain thermal comfort.

Therefore, in recent years, a number of studies have examined the benefits and drawbacks of adaptive setpoint temperatures in comparison to models based on the PMV in order to demonstrate how they affect energy usage. Following are a few examples of such studies: (i) Sánchez-García et al. (Sánchez-García et al., 2019) investigated how adaptive setpoint temperatures may be used in situations of changing climatic conditions in an effort to lower the energy demand for office buildings. Depending on the climatic scenario examined by the authors, the daily change of setpoint temperatures lowered the demand and total HVAC consumption by 63 to 52% and 61 to 51%, respectively; (ii) Holmes and Hacker (Holmes & Hacker, 2007) examined how the adaptive thermal comfort technique was used in different governmental buildings around the United Kingdom in both the present and the future; (iii) Kramer et al (Kramer et al., 2015) lowered the heating setpoint temperature of a museum to the lower limit of the comfort zone of the model created by Van der Linden et al (van der Linden et al., 2006), lowering the energy usage by 74%; (iv) the impact of a fixed and adaptive thermostat schedule on energy conservation of a university hostel building in a hot, humid region of India was investigated in a research by Dhaka et al. (Dhaka et al., 2012); the results showed that a 40% decrease in energy use was feasible; and (vi) the study of the use of adaptive setpoint temperatures based on a local comfort model developed by Hom Bahadur Rijal for Japan (Rijal et al., 2019b). Another study achieved energy savings that ranged between 29 and 52% and 33 and 78% respectively in full air-conditioning and mixed-mode operations (Sánchez-García, Bienvenido-Huertas, et al., 2023).

As a result, the interest in the adaptive setpoint temperatures as an energy-saving measure, originally entitled as the framework Adaptive-Comfort-Control-Implemented Model (ACCIM) (Sánchez-García et al., 2019), has recently increased. Nonetheless, to finally run building energy simulations in EnergyPlus software considering adaptive setpoint temperatures, a tedious and error-prone process needed to be previously carried out: (i) the calculation of the adaptive comfort limit values for a certain climate and a certain scenario, (ii) the creation of the Schedule:Compact objects that would contain the daily values of the setpoint temperatures, and (iii) the selection of the EnergyPlus Weather (EPW) file. However, that process needed to be repeated depending on the number of combinations of adaptive setpoint temperatures and EPWs, which were numbered over dozens. Therefore, a computational approach was developed to automate this process: the Adaptive-Comfort-Control-Implementation Script (ACCIS) (Sánchez-García et al., 2021; Sánchez-García, Martínez-Crespo, et al., 2023b). ACCIS could be added to the Input Data File (IDF), which is the EnergyPlus building energy model, however, some conditions related to the internal EnergyPlus workflow needed to be met. Finally, to improve the usability features and make it usable by professionals without a programming background, ACCIS was nested in a Python library called 'accim' (Sánchez-García, 2021a).

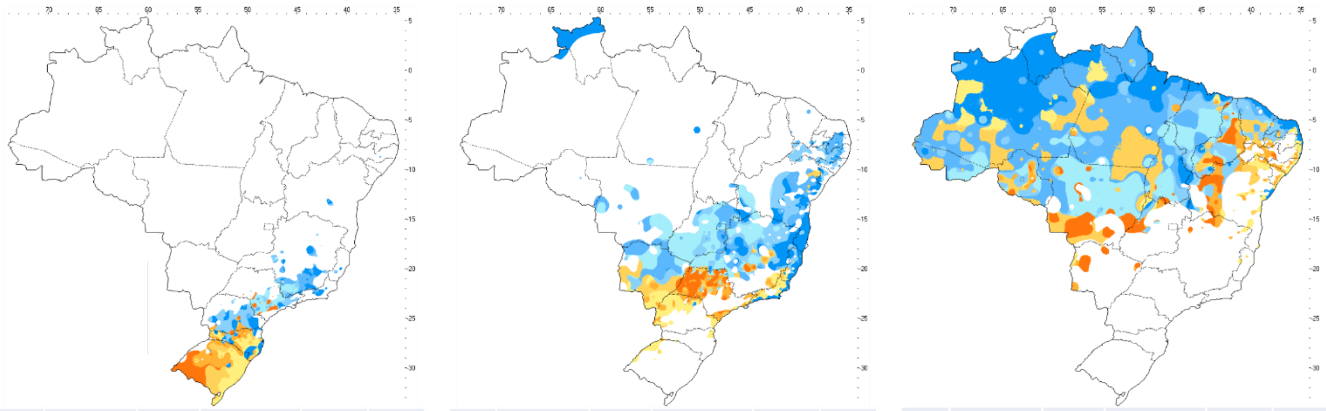
Until recently, only international comfort models and standards were available to be used in ACCIM; however, a recent update has included a number of local comfort models (Sánchez-García, Martínez-Crespo, et al., 2023a), including an adaptive local comfort model that was developed for Brazil's climatic conditions (area of Florianópolis) and mixed-mode office buildings (Rupp et al., 2018). Therefore, this model is considered in this paper as a baseline to be compared with the ASHRAE 55 international adaptive comfort model and the national regulation ABNT NBR 16401-2 Standard (ANBR 16 401: Instalações de Ar-Condicionado - Sistemas Centrais e Unitários. Parte 2: Parâmetros de Conforto Térmico, 2008) static setpoint temperatures. This model was developed to shed light on whether natural ventilation or air-conditioning modes should be considered separately in mixed-mode office buildings and whether adaptive thermal comfort is applicable to both operation modes. It was based on a field study that consisted of roughly 5500 thermal sensation questionnaires answered by the occupants of three buildings in both naturally ventilated and air-conditioned modes of operation along the four seasons, in the city of Florianópolis (temperate and humid climate), at the south of Brazil. Also, considering its important energy saving potential (Daaboul et al., 2018; Kim & de Dear, 2021), mixed-mode ventilation is assessed in this study.

The aim of this paper is to study the energy savings obtained from using adaptive setpoint temperatures based on Brazilian local adaptive comfort models against the international ASHRAE 55 adaptive comfort model and static setpoint temperatures specified in the Brazilian regulations. The novelty of this paper resides in the use of a local adaptive comfort model for Brazil instead of international thermal comfort standards. Building energy simulations have been performed across the country, for the 24 climate zones considering present and future weather under the effect of climate change, namely the Representative Concentration Pathways (RCP) for years 2050 and 2100, in which mixed-mode energy saving potential is tested. In Section 2, where there is also a description of the building case study, the methodology for this study is explained, a description of how the Python library 'accim' was updated to incorporate the Brazilian local adaptive model and a discussion of how 'accim' was used are also included. The findings are discussed in Section 3 while taking the fully air-conditioned and mixed-mode building operating modes into account, as well as the future weather under the influence of climate change. The conclusions are then presented in Section 4.

2. Methodology

2.1. Climate zones in Brazil

Until recently, the territory of Brazil was divided into 8 climate zones, called Bioclimatic Zones (ZB), as stated in the first thermal performance code for social interest housing NBR 15220 (ABNT NBR 15220-3: Desempenho Térmico de Edificações. Parte 3: Zoneamento Bioclimático Brasileiro e Diretrizes Construtivas Para Habitações Unifamiliares de Interesse Social, 2005), approved in 2005. However, the climate zones of Brazil has been revised and, currently, the number of zones has increased to 24 zones (Roriz, 2014). Those new climate zones are the outcome of the analysis of the temperatures at the different regions of Brazil, depending on (i) the annual average temperature (AAT), which divides the zones in 3 groups (GC01 to GC08, GC09 to GC16 and GC17 to GC24), (ii) the standard deviation of the monthly mean of the average daily temperature (SD(MAT)), (iii) the annual average temperature amplitude (AATA) and finally (iv) the standard deviation of the monthly average temperature amplitude (SD(MATA)) (Roriz, 2014). Therefore, in order to analyse the energy consumption as a result of using adaptive setpoint temperatures, a city has been chosen for each climate zone. Figure 1 shows the location and extent of the 24 climate zones, and Table 1 shows the basic information about the city selected for each one, as well as the bioclimatic zone which each city previously belonged to.



AAT	SD(MAT)	AATA	SD(MATA)	Group	Color
AAT ≤ 21.0	≤3.0	≤11.1	≤1.0	1	
			>1.0	2	
		>11.1	≤1.6	3	
			>1.6	4	
	>3.0	≤10.2	≤0.7	5	
			>0.7	6	
		>10.2	≤0.9	7	
			>0.9	8	

AAT	SD(MAT)	AATA	SD(MATA)	Group	Color
21.0 < AAT ≤25.0	≤2.1	≤10.6	≤1.0	9	
			>1.0	10	
		>10.6	≤1.4	11	
			>1.4	12	
	>2.1	≤11.9	≤1.1	13	
			>1.1	14	
		>11.9	≤2.1	15	
			>2.1	16	

AAT	SD(MAT)	AATA	SD(MATA)	Group	Color
25.0 < AAT	≤1.1	≤9.6	≤1.0	17	
			>1.0	18	
		>9.6	≤1.8	19	
			>1.8	20	
	>1.1	≤10.7	≤1.2	21	
			>1.2	22	
		>10.7	≤1.6	23	
			>1.6	24	

AAT: Annual Average Temperature
SD(MAT): Standard deviation of the Monthly Average Temperature
AATA: Annual Average Temperature Amplitude
SD(MATA): Standard Deviation of Monthly Average Temperature Amplitude

Figure 1. Climate zones of Brazil (Roriz, 2014).

Table 1. Selected cities.

City name/State	Latitude	Longitude	Koppen-Geiger Classification	Climate Zone (GC)	Bioclimatic Zone (ZB)
Florianópolis/SC	-27.593	-48.553	Cfb	GC01	ZB3
Curitiba/PR	-25.43	-49.272	Cfb	GC02	ZB1
Ponta Grossa/PR	-25.095	-50.162	Cfa	GC03	ZB2
Toledo/PR	-24.714	-53.743	Cfa	GC04	ZB4
Pelotas/RS	-31.772	-52.343	Cfa	GC05	ZB2
Porto Alegre/RS	-30.033	-51.23	Cfa	GC06	ZB3
Chapecó/SC	-27.096	-52.618	Cfa	GC07	ZB3
Santa Maria/RS	-29.684	-53.807	Cfa	GC08	ZB2
Niterói/RJ	-22.883	-43.104	Cfa	GC09	ZB5
Brasília/DF	-15.794	-47.883	Aw	GC10	ZB4
Marília/SP	-22.214	-49.946	Cfa	GC11	ZB7
Goiânia/GO	-16.681	-49.256	Aw	GC12	ZB6
Rio de Janeiro/RJ	-22.908	-43.196	Cfa	GC13	ZB8
Dourados/MS	-22.221	-54.806	Cfa	GC14	ZB3
Campinas/SP	-22.901	-47.057	Cfa	GC15	ZB3
Rio Brilhante/MS	-21.8	-54.541	Cfa	GC16	ZB7
Bélem/PA	-1.456	-48.504	Am	GC17	ZB8
Macapá/AP	0.033	-51.065	Am	GC18	ZB8
Cruzeiro do Sul/AC	-7.631	-72.67	Am	GC19	ZB8
Palmas/TO	-10.189	-48.334	Aw	GC20	ZB8
Aracaju/SE	-10.917	-37.05	Af	GC21	ZB8
Feira de Santana/BA	-12.267	-38.967	Aw	GC22	ZB8
Picos/PI	-7.077	-41.467	BSh	GC23	ZB7
Cuiabá/MT	-15.596	-56.097	Aw	GC24	ZB7

In order to study the impact of climate change on the local adaptive setpoint temperatures, future scenarios were considered. Those scenarios are the Representative Concentration Pathways (RCP), and EPW files for those have been generated with Meteonorm. These scenarios are described as routes to emphasize that they are internally coherent collections of time-dependent force predictions rather than final scenarios. They can be distinguished by their extensions' approximation of the radiative forcing (measured in W/m²) in 2100 or at stabilization beyond 2100 in comparison to pre-industrial levels. The four RCP scenarios are RCP2.6 (the lowest, also known as RCP3-PD), which peaks at 3.0 W/m² and then declines to 2.6 W/m² in 2100, RCP4.5 (the medium-low), RCP6.0 (the medium-high), which stabilize at 4.2 and 6.0 W/m² respectively after 2100, and RCP8.5 (the highest), which rises to 8.3 W/m² in 2100 (Collins et al., 2013). In this paper, RCP2.6, 4.5 and 8.5, for the years 2050 and 2100 were studied.

Table 2 shows the impact of climate change on the outdoor temperatures. In the case of the climate zones GC01 to GC08, the average increase ranges from 0.59°C in RCP2.6 year 2050 to 4.07°C in RCP8.5 year 2100, while in case of the climate zones GC09 to GC16 and GC17 to GC24 the average increase ranges from 0.88 to 5.01°C and 0.79 to 4.83°C respectively. As a result, the average outdoor temperature in the worst case scenario (i.e. RCP8.5 year 2100) is estimated to be 24.27, 28.02 and 31.93°C, respectively.

Table 2. Annual average outdoor temperature.

		Scenario												
		Present	RCP26_2050		RCP26_2100		RCP45_2050		RCP45_2100		RCP85_2050		RCP85_2100	
Climate zone	City	Present (°C)	Temperature (°C)	Increase from Present (°C)	Temperature (°C)	Increase from Present (°C)	Temperature (°C)	Increase from Present (°C)	Temperature (°C)	Increase from Present (°C)	Temperature (°C)	Increase from Present (°C)	Temperature (°C)	Increase from Present (°C)
GC01	Florianópolis	20.88	21.56	0.68	21.64	0.76	21.82	0.94	22.68	1.80	22.09	1.21	24.17	3.28
GC02	Curitiba	18.79	19.57	0.78	19.61	0.83	20.03	1.24	21.30	2.51	20.40	1.61	23.33	4.54
GC03	Ponta Grossa	18.38	19.04	0.66	19.04	0.66	19.62	1.24	20.94	2.56	19.99	1.61	22.95	4.57
GC04	Toledo	21.89	22.42	0.53	22.52	0.63	23.19	1.30	24.56	2.67	23.62	1.73	26.92	5.03
GC05	Pelotas	19.93	20.46	0.52	20.40	0.47	20.84	0.90	21.66	1.72	21.05	1.12	23.05	3.11
GC06	Porto Alegre	20.42	20.95	0.52	21.02	0.60	21.44	1.02	22.45	2.03	21.60	1.18	24.08	3.66
GC07	Chapecó	20.19	20.66	0.47	20.76	0.58	21.35	1.16	22.59	2.41	21.74	1.55	24.77	4.58
GC08	Santa Maria	21.11	21.70	0.58	21.61	0.50	22.18	1.06	23.24	2.13	22.42	1.31	24.92	3.81
Average GC01 to GC08		**20.20**	**20.79**	**0.59**	**20.83**	**0.63**	**21.31**	**1.11**	**22.43**	**2.23**	**21.61**	**1.42**	**24.27**	**4.07**
GC09	Niterói	24.14	25.07	0.92	25.02	0.87	25.22	1.08	26.46	2.31	25.72	1.57	28.38	4.24
GC10	Brasília	21.82	22.93	1.11	22.92	1.10	23.54	1.72	24.91	3.09	23.86	2.04	27.19	5.37
GC11	Marília	22.23	22.97	0.75	23.05	0.82	23.55	1.32	24.99	2.76	24.01	1.78	27.49	5.27
GC12	Goiânia	22.09	23.05	0.96	23.03	0.93	23.56	1.46	25.04	2.95	24.15	2.05	27.48	5.39
GC13	Rio de Janeiro	23.97	24.89	0.92	24.85	0.88	25.13	1.16	26.28	2.31	25.54	1.57	28.12	4.15
GC14	Dourados	24.11	25.04	0.93	24.94	0.83	25.49	1.38	27.02	2.91	25.98	1.87	29.67	5.56
GC15	Campinas	21.29	21.98	0.69	21.94	0.65	22.54	1.25	23.93	2.64	22.96	1.68	26.14	4.85
GC16	Rio Brilhante	24.44	25.16	0.72	25.02	0.58	25.82	1.39	27.22	2.79	26.19	1.75	29.73	5.29
Average GC09 to GC16		**23.01**	**23.89**	**0.88**	**23.85**	**0.83**	**24.36**	**1.34**	**25.73**	**2.72**	**24.80**	**1.79**	**28.02**	**5.01**
GC17	Bélem	26.70	27.53	0.83	27.47	0.77	27.96	1.26	28.95	2.25	28.30	1.60	30.68	3.98
GC18	Macapá	27.75	28.66	0.91	28.46	0.71	29.18	1.44	30.44	2.69	29.59	1.84	32.79	5.04
GC19	Cruzeiro do Sul	27.04	27.83	0.79	27.72	0.69	28.44	1.40	29.69	2.65	28.95	1.92	32.65	5.62
GC20	Palmas	29.80	30.50	0.70	30.57	0.77	31.35	1.54	32.93	3.13	31.87	2.06	35.51	5.71
GC21	Aracaju	25.44	26.27	0.84	26.59	1.15	26.78	1.35	27.74	2.30	27.08	1.64	29.48	4.05
GC22	Feira de Santana	25.13	25.98	0.84	26.14	1.01	26.32	1.19	27.45	2.31	26.73	1.59	29.34	4.20
GC23	Picos	28.20	28.83	0.63	28.98	0.78	29.59	1.39	30.78	2.59	29.72	1.52	32.64	4.44
GC24	Cuiabá	26.72	27.48	0.76	27.35	0.63	28.03	1.31	29.41	2.68	28.62	1.90	32.32	5.59
Average GC17 to GC24		**27.10**	**27.88**	**0.79**	**27.91**	**0.81**	**28.46**	**1.36**	**29.67**	**2.58**	**28.86**	**1.76**	**31.93**	**4.83**

2.2. Case study

The selected case study is a representative building model of a Brazilian detached (social) house based on the study of Triana et al. (Triana et al., 2015). The house is composed of a kitchen/living room, two bedrooms and a bathroom (WC), totaling roughly a total net area of 40m^2 and a gross floor area of 45m^2 (Figure 2). A detailed description of the representative building model may be found in Triana et al. (Triana et al., 2015). The considered building materials follow the minimum thermal performance requirements of the Brazilian NBR 15575-1 Standard (ABNT NBR 15575-1: Edificações Habitacionais — Desempenho - Parte 1: Requisitos Gerais, 2021) and can be seen in Table 3. The house was considered to be occupied by four people and occupation was modelled according to the NBR 15575-1. Internal thermal loads were in accordance with NBR 15575-1, i.e. 5 W/m^2 for lighting and 120 W for equipment in the living room during occupation. The HVAC system consists of a Variable Refrigerant Flow (VRF) system, with an Energy Efficiency Ratio of 2.00 and a Coefficient of Performance of 2.10.

It is important to highlight that the selected building model represent a range of social houses that have been built across Brazil mainly due to a government program (Triana et al., 2015), regardless of the climate zone. Thus, our intention in this work is not to suggest more appropriate building components for each climate zone, nor to promote the adoption of such representative building throughout Brazil, but rather to assess the current and future thermal performance of the existing selected building model for different climate zones.

Table 3. Thermal properties of building components.

Building component	Composition	Thermal conductivity (W/m.K)	Solar absorptance	Solar factor
Walls	Concrete block	1.75	0.58	-
Roof*	Clay tile roof	0.65	0.65	-
	Concrete ceiling	1.75	0.50	-
Floors	Concrete	1.75	0.50	-
Windows	Single-glass	-	-	0.87

* For seven cities (Rio de Janeiro, Belém, Macapá, Cruzeiro do Sul, Palmas, Aracaju and Feira de Santana) that belonged to the Bioclimatic Zone 8 (Table 1), it was added above the ceiling a layer of thermal insulation with a thermal resistance of 0.67 m^2.k/W, following NBR 15575-1.

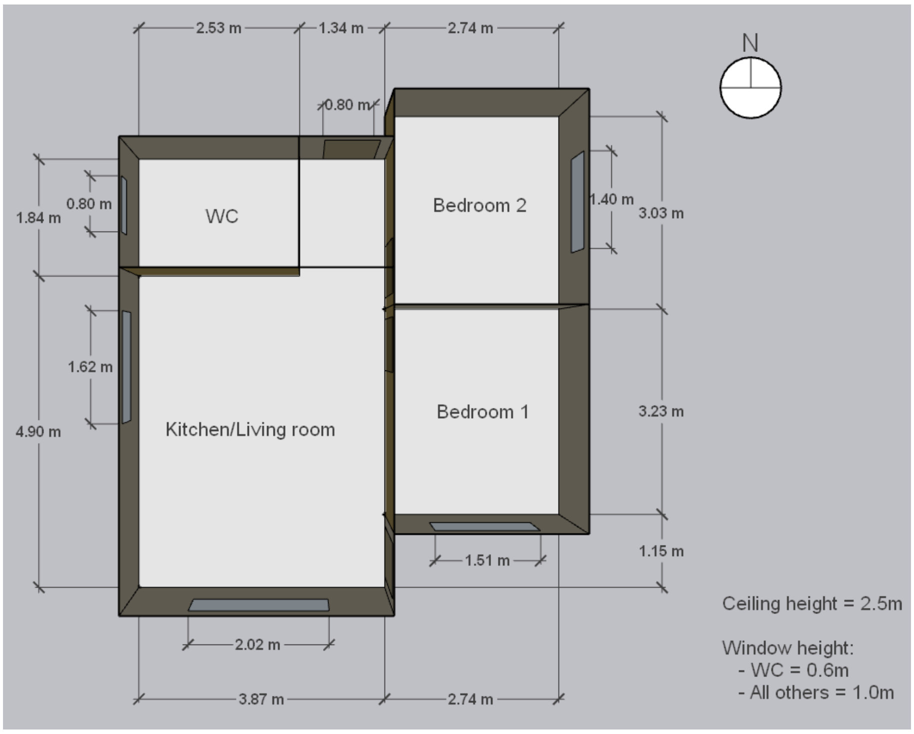


Figure 2. Floor plan of the studied detached (social) house.

2.3. Inclusion of the Brazilian local adaptive model in accim

Until recently, mainly only international comfort standards were available in accim: EN 16798-1 and ASHRAE 55. However, multiple local comfort models have been added and published with the recent release of version 0.3.0, among those the Brazilian local adaptive comfort model for naturally ventilated spaces developed by Rupp et al. (Rupp et al., 2018). This model has been chosen based on its high reliability, since it draws on roughly 5500 thermal sensation votes gathered from three buildings.

Depending on the adaptive standard, different weighted mean outdoor temperatures are used to construct adaptive comfort models. The Prevailing Mean Outdoor Temperature (PMOT) (Eq. 1), in accordance with the ASHRAE 55 framework, will be employed in this case as the baseline for comparison with the local adaptive model.

The linear regression method is used to derive the comfort temperature equation (Figure 3), which takes PMOT as an input (Eq. 2).

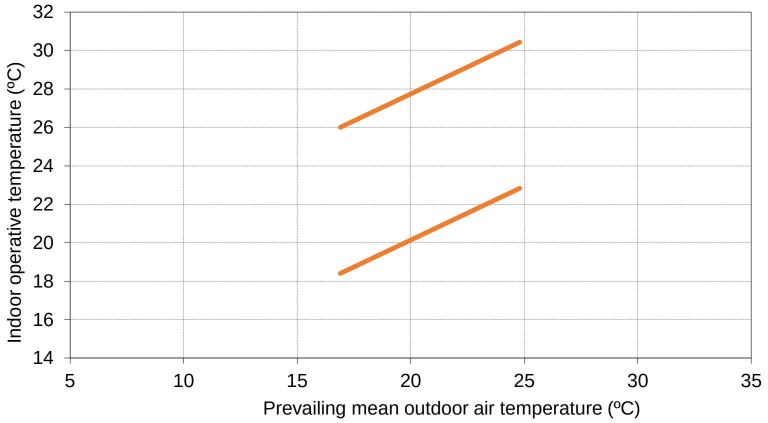


Figure 3. Acceptability ranges of the Brazilian local adaptive comfort model by Rupp et al. (Rupp et al., 2018).

$$PMOT = (T_{ext,d-1} + 0.8T_{ext,d-2} + 0.6T_{ext,d-3} + 0.5T_{ext,d-4} + 0.4T_{ext,d-5} + 0.3T_{ext,d-6} + 0.2T_{ext,d-7})/3.8 \quad [C] \tag{1}$$

$$Comfort\ temperature = \text{PMOT} * 0.56 + 12.74\ (°C) \tag{2}$$

Where $T_{ext,d-1}$ is the mean outdoor air temperature of the previous day to the day in question, $T_{ext,d-2}$ the mean outdoor air temperature of the day before that, and so on.

According to the research article, the local adaptive comfort model could confidently provide accurate thermal comfort predictions when the PMOT falls in the range from 16.9 to 24.8°C in the case of the NV mode, therefore constituting the applicability limits of the comfort model. When it is applicable, the comfort limits and subsequently adaptive setpoint temperatures can be calculated considering an offset of ±3.8°C and ±2.8°C from the comfort temperature for 80 and 90% of acceptability, respectively (Eqs. 3-6).

$$Upper\ limit\ (80\%\ acceptability) = \text{PMOT} * 0.56 + 12.74 + 3.8\ [°C] \qquad (16.9°C \leq \text{PMOT} < 24.8°C) \tag{3}$$

$$Lower\ limit\ (80\%\ acceptability) = \text{PMOT} * 0.56 + 12.74 - 3.8\ [°C] \qquad (16.9°C \leq \text{PMOT} < 24.8°C) \tag{4}$$

$$Upper\ limit\ (90\%\ acceptability) = \text{PMOT} * 0.56 + 12.74 + 2.8\ [°C] \qquad (16.9°C \leq \text{PMOT} < 24.8°C) \tag{5}$$

$$Lower\ limit\ (90\%\ acceptability) = \text{PMOT} * 0.56 + 12.74 - 2.8\ [°C] \qquad (16.9°C \leq \text{PMOT} < 24.8°C) \tag{6}$$

After the definition of all necessary information, accim was updated to include the Brazilian local adaptive model. The most important function of accim is the ACCIS, which consists of a number of EnergyManagementSystem sensors, actuators and program objects, among which there is a program called 'SetAST' (i.e. Set Adaptive Setpoint Temperatures). This program essentially sets the values of the adaptive comfort limits to the heating and cooling setpoint temperature actuators mainly based on three arguments: 'ComfStand', 'CAT' and 'ComfMod'. All available settings for the Brazilian adaptive local model depending on these three arguments are shown in Table 4. These arguments are explained below so that this research can be replicable using a different case study:

- The argument ‘ComfStand’ is used to select the comfort standard or model. Currently, there is a total amount of 21 available comfort models in accim, including the Brazilian adaptive model for naturally ventilated spaces which takes the number 15.
- The argument ‘CAT’ is used to select the occupant expectations (i.e. acceptability levels). In this case, entering the numbers 80, 90 or both indicates accim which occupant expectations are meant to be used (80% or 90% acceptability, respectively).
- The argument ‘ComfMod’ is used to select the behaviour of the setpoint temperatures. When the value 0 is entered, the user indicates accim that setpoint temperatures are static, in the case of the Brazilian adaptive model, based on the ABNT NBR 16401-2 Standard (ANBR 16 401: Instalações de Ar-Condicionado - Sistemas Centrais e Unitários. Parte 2: Parâmetros de Conforto Térmico, 2008). Otherwise, when values 1, 2 or 3 are entered, the comfort model selected at ComfStand is used as long as it is applicable (i.e. 16.9°C ≤ PMOT < 24.8°C). However, when it is not, different behaviours are applied:
    - In case of 1, the static model of the ABNT NBR 16401-2 Standard is used
    - In case of 2, the static model of the ISO 7730 (ISO, 2005) is used
    - In case of 3, the static model is based on the horizontal extension of the adaptive comfort limits (Eqs. 3 to 6, but replacing PMOT with 16.9 and 24.8)

Table 4. Setpoint temperature values for the Brazilian adaptive local model as a function of parameters ComfStand, CAT and ComfMod, and applicability limits.

ComfStand	CAT	ComfMod	Cooling setpoint temperature (°C)			Heating setpoint temperature (°C)		
			PMOT ≤ 16.9	16.9≤PMOT<24.8	PMOT > 24.8	PMOT ≤ 16.9	16.9≤PMOT<24.8	PMOT > 24.8
15	80	0		23.5 (WS) or 25.5 (SS)			21 (WS) or 22.5 (SS)	
		1	23.5	PMOT*0.56+12.74 +3.8	25.5	21	PMOT*0.56+12.74 -3.8	22.5
		2	25	PMOT*0.56+12.74 +3.8	27	19	PMOT*0.56+12.74 -3.8	22
		3	16.9*0.56+12.74 +3.8	PMOT*0.56+12.74 +3.8	24.8*0.56+12.74 +3.8	16.9*0.56+12.74 -3.8	PMOT*0.56+12.74 -3.8	24.8*0.56+12.74 -3.8
	90	0		23 (WS) or 25 (SS)			21.5 (WS) or 23 (SS)	
		1	23	PMOT*0.56+12.74 +2.8	25	21.5	PMOT*0.56+12.74 -2.8	23
		2	24	PMOT*0.56+12.74 +2.8	26	20	PMOT*0.56+12.74 -2.8	23
		3	16.9*0.56+12.74 +2.8	PMOT*0.56+12.74 +2.8	24.8*0.56+12.74 +2.8	16.9*0.56+12.74 -2.8	PMOT*0.56+12.74 -2.8	24.8*0.56+12.74 -2.8

PMOT: Prevailing Mean Outdoor Temperature; WS: Winter Season; SS: Summer Season

2.4. Use of accim

The tool has been updated maintaining its ease of use. For replicability purposes, the needed commands are explained as follows: considering Python 3.9 and EnergyPlus 9.0 or newer have been installed, if accim has not been installed yet, the user needs to open a CMD terminal and type ‘pip install accim’; (i) afterwards, the first step is opening a CMD terminal pointing at a path, where at least an IDF is located; (ii) secondly, execute Python by typing ‘python’ or ‘py’; and finally, (iii) typing the following two lines of code:

```
from accim.sim import accis
accis.addAccis()
```

The tool will then request input from the user on the settings for the output IDF files it will create. The published documentation (Sánchez-García, 2021b) thoroughly explains how to give the necessary arguments when invoking the method. For instance, the following has been this study's code:

```
from accim.sim import accis
accis.addAccis(
```

```
    ScriptType='vrf_mm',
    SupplyAirTempInputMethod='temperature difference',
    TempCtrl='temperature',
    Output_keep_existing=False,
    Output_type='standard',
    Output_freqs=['hourly'],
    EnergyPlus_version='22.1',
    ComfStand=[2, 15],
    CAT=[80],
    ComfMod=[0, 3],
    HVACmode=[0, 2],
    VentCtrl=[0],
    VSToffset=[0],
    MinOToffset=[50],
    MaxWindSpeed=[50],
    ASTtol_start=0.1,
    ASTtol_end_input=0.1,
    ASTtol_steps=0.1
    )
```

2.5. Comfort models considered

In order to assess the energy performance of Brazil's local adaptive comfort model, two alternative reference comfort models have been selected for comparison, which are listed in Table 5: ASHRAE 55 (in the table, selected when ComfStand = 2, CAT = 80 and ComfMod = 3), considering the horizontal extension of the limits out of the applicability range, as it is the only adaptive comfort model used globally, and the ABNT NBR 16401-2 Standard (in the table, selected when ComfStand = 15, CAT = 80 and ComfMod = 0), in order to provide a reference of static setpoint temperatures required by a Brazilian standard.

Table 5. Comfort models considered in this study.

ComfStand	CAT	ComfMod	Cooling setpoint temperature (°C)			Heating setpoint temperature (°C)		
			PMOT < ACSTall	ACSTall < PMOT < ACSTaul	ACSTaul < PMOT	PMOT < AHSTall	AHSTall < PMOT < AHSTaul	AHSTaul < PMOT
2	80	3	10*0.31+17.8 +3.5	PMOT*0.31+17.8 +3.5	33.5*0.31+17.8 +3.5	10*0.31+17.8 -3.5	PMOT*0.31+17.8 -3.5	33.5*0.31+17.8 -3.5
15	80	0		23 (WS) or 25 (SS)			21.5 (WS) or 23 (SS)	
		3	16.9*0.56+12.74 +3.8	PMOT*0.56+12.74 +3.8	24.8*0.56+12.74 +3.8	16.9*0.56+12.74 -3.8	PMOT*0.56+12.74 -3.8	24.8*0.56+12.74 -3.8

PMOT: Prevailing Mean Outdoor Temperature;
ACSTall: Adaptive Cooling Setpoint Temperature applicability lower limit; ACSTaul: Adaptive Cooling Setpoint Temperature applicability upper limit;
AHSTall: Adaptive Heating Setpoint Temperature applicability lower limit; AHSTaul: Adaptive Heating Setpoint Temperature applicability upper limit;
WS: Winter Season; SS: Summer Season.

3. Results and discussion

The energy saving potential of the setpoint temperatures based on Brazil's adaptive local comfort model was investigated at the first and second sub-sections while considering two different building operations: full air-conditioning mode, in which no natural ventilation is allowed, and mixed-mode, in which natural ventilation is prioritized over the use of the HVAC system when outdoor conditions are suitable. Otherwise, windows are closed and the HVAC system is employed. The impact of climate change on the energy saving potential and ventilation was also explored in the third sub-section.

In order to improve the clarity and readability of the results, the combination of settings was coded based on Table 6.

Table 6. Coded names for each combination of setpoint temperatures and operation mode.

ComfStand	CAT	ComfMod	HVACmode	Setpoint temperatures	Operation mode	Coded name

2	80	3	0	ASHRAE 55	Full air-conditioning mode	ASH_Adap_AC
15	80	0	0	ABNT NBR 16401-2 Standard	Full air-conditioning mode	BRA_Stat_AC
		3	0	Brazilian adaptive local model	Full air-conditioning mode	BRA_Adap_AC
			2	Brazilian adaptive local model	Mixed-mode	BRA_Adap_MM

3.1. Heating and cooling energy demand in the present scenario

Building energy simulations were run for each combination of setpoint behaviour and climate zone considering full air-conditioning mode, whose results are shown in Table 7. Cells were color-shaded in blue, red and yellow for the cooling, heating and total energy demand depending on the values. Energy demand was significantly higher in BRA_Stat_AC than the rest in all climate zones, as a result of the use of static setpoint temperatures, while it was lower in BRA_Adap_MM, as a result of the use of adaptive setpoint temperatures based on the Brazilian adaptive model coupled with the mixed-mode operation. Therefore, the main focus was set on BRA_Adap_MM, while all other settings were compared to it. Averaging the values obtained in climate zones GC01 to GC08 (average outdoor temperature less than 21°C), GC09 to GC16 (average outdoor temperature between 21 and 25°C) and GC17 to GC24 (average outdoor temperature greater than 25°C), the values for BRA_Adap_MM were respectively 245, 328 and 536 kWh/m² for cooling energy demand; 267, 170 and 36 kWh/m² for heating energy demand; and 512, 499 and 572 kWh/m² for total energy demand.

Table 7. Absolute values of energy demand.

Climate zone	Cooling Energy Demand (kWh/m²·year)				Heating Energy Demand (kWh/m²·year)				Total Energy Demand (kWh/m²·year)			
	BRA_Adap_AC	BRA_Stat_AC	ASH_Adap_AC	BRA_Adap_MM	BRA_Adap_AC	BRA_Stat_AC	ASH_Adap_AC	BRA_Adap_MM	BRA_Adap_AC	BRA_Stat_AC	ASH_Adap_AC	BRA_Adap_MM
GC01-Florianopolis	302	731	362	225	169	239	201	178	470	970	563	403
GC02-Curitiba	273	587	293	206	257	393	316	268	530	980	608	474
GC03-Ponta-Grossa	312	626	329	231	267	421	326	279	579	1047	655	510
GC04-Toledo	412	914	484	358	217	262	237	225	629	1176	721	582
GC05-Pelotas	264	655	319	208	289	397	323	298	553	1052	642	506
GC06-Porto-Alegre	293	704	352	237	261	351	288	270	554	1055	639	507
GC07-Chapeco	288	671	339	234	306	401	336	315	594	1072	676	549
GC08-Santa-Maria	308	741	356	264	292	374	326	300	600	1115	683	564
Average GC01 to GC08	**306**	**704**	**354**	**245**	**257**	**355**	**294**	**267**	**564**	**1058**	**648**	**512**
GC09-Niteroi	413	965	497	345	82	87	73	89	495	1052	570	434
GC10-Brasilia	408	865	478	335	175	210	178	182	583	1075	656	518
GC11-Marilia	394	904	478	319	178	187	176	187	572	1091	654	505
GC12-Goiania	409	864	483	336	176	201	171	183	585	1065	654	519
GC13-Rio-de-Janeiro	408	953	491	344	91	97	83	97	498	1050	574	441
GC14-Dourados	397	974	481	358	202	186	195	208	599	1160	677	566
GC15-Campinas	303	718	358	237	209	255	227	217	512	974	585	454
GC16-Rio-Brilhante	392	970	484	355	195	182	182	200	587	1152	666	555
Average GC09 to GC16	**390**	**902**	**469**	**328**	**163**	**176**	**161**	**170**	**554**	**1077**	**629**	**499**
GC17-Belem	528	1282	630	500	14	1	10	15	542	1283	639	515
GC18-Macapa	550	1343	609	536	9	1	9	10	559	1343	618	547
GC19-Cruzeiro-do-Sul	696	1475	787	679	33	11	31	35	729	1486	818	714
GC20-Palmas	742	1615	721	737	5	0	17	6	748	1616	738	743
GC21-Aracaju	397	1058	506	337	54	22	33	58	451	1080	539	395
GC22-Feira-de-Santana	356	969	454	295	50	26	32	54	406	995	486	349
GC23-Picos	675	1495	721	658	17	3	24	18	693	1498	745	676
GC24-Cuiaba	576	1323	667	548	86	51	75	89	662	1374	742	637
Average GC17 to GC24	**565**	**1320**	**637**	**536**	**34**	**14**	**29**	**36**	**599**	**1334**	**666**	**572**

These values were translated into energy savings in Table 8, which shows the values as a difference from BRA_Adap_MM (X – BRA_Adap_MM) as well as a percentual variation (1-(BRA_Adap_MM / X). Again, cells were color-shaded depending on the value, considering reductions in energy demand in green and increases in red. Considering the averaged values for the climate zones, the energy savings of BRA_Adap_MM compared to BRA_Stat_AC were 52, 54 and 58% for total energy demand. Compared to ASH_Adap_AC, these values decreased to 21, 21 and 15% respectively for the three groups of climate zones, although these are still significant energy savings. Also, results show there were some cases in which heating energy demand slightly increased for BRA_Adap_MM. Most of them took place in the climate group GC17 to GC24, especially for the GC24, compared to BRA_Stat_AC with an increase of 39 kWh/m². Also, there were some increases in heating energy demand compared to ASH_Adap_AC, and even an increase in total energy demand in GC20, which is the hottest one, which is due to the differences in applicability limits of the models. For instance, while in case of ASHRAE 55, these are 10 to 33.5°C, in case of the Brazilian adaptive model these are 16.9 to 24.8°C. Therefore, in case of the hottest hours, the PMOT exceeds 24.8°C and becomes static, while for ASHRAE 55, it remains adaptive until 33.5°C, therefore reaching a higher cooling setpoint temperature.

Comparing BRA_Adap_MM to BRA_Adap_AC is where the potential of mixed-mode under natural ventilation operation can be analysed since the only difference between these two settings is that natural ventilation is not allowed for BRA_Adap_AC, while it is allowed for BRA_Adap_MM when certain conditions are met, as previously explained in Method section. Regarding the energy savings in cooling operation, the average values were 20, 16 and 6% for each climate zone group (GC01 to CG08, GC09 to GC 16 and GC17 to GC24), ranging respectively from

13 to 26%, 9 to 22% and 1 to 5%, with some exceptional cases of 15 and 17%. Therefore, as expected, the performance of mixed-mode is highly dependent on the climate, although important energy savings can be achieved in the most favorable climate zones. However, these performances were reduced considering there were some heating energy demand increases due to the excessive introduction of cold air, being the average values respectively 4, 5 and 5%, and therefore, the total energy saving potential of mixed-mode was reduced to the average values of 9, 10 and 5% respectively.

Table 8. Energy savings as a difference and percentage variation.

Climate zone	Energy savings compared to BRA_Adap_AC (%; kWh/m²·year)						Energy savings compared to BRA_Stat_AC (%; kWh/m²·year)						Energy savings compared to ASH_Adap_AC (%; kWh/m²·year)					
	Cooling		Heating		Total		Cooling		Heating		Total		Cooling		Heating		Total	
	1-(BRA_Adap_MM/BRA_Adap_AC)	BRA_Adap_AC - BRA_Adap_MM	1-(BRA_Adap_MM/BRA_Adap_AC)	BRA_Adap_AC - BRA_Adap_MM	1-(BRA_Adap_MM/BRA_Adap_AC)	BRA_Adap_AC - BRA_Adap_MM	1-(BRA_Adap_MM/BRA_Stat_AC)	BRA_Stat_AC - BRA_Adap_MM	1-(BRA_Adap_MM/BRA_Stat_AC)	BRA_Stat_AC - BRA_Adap_MM	1-(BRA_Adap_MM/BRA_Stat_AC)	BRA_Stat_AC - BRA_Adap_MM	1-(BRA_Adap_MM/ASH_Adap_AC)	ASH_Adap_AC - BRA_Adap_MM	1-(BRA_Adap_MM/ASH_Adap_AC)	ASH_Adap_AC - BRA_Adap_MM	1-(BRA_Adap_MM/ASH_Adap_AC)	ASH_Adap_AC - BRA_Adap_MM
GC01-Florianopolis	25%	76	-5%	-9	14%	67	69%	505	26%	61	58%	567	38%	137	12%	23	28%	160
GC02-Curitiba	25%	67	-4%	-11	11%	56	65%	381	32%	125	52%	506	30%	87	15%	47	22%	134
GC03-Ponta-Grossa	26%	81	-4%	-12	12%	69	63%	396	34%	142	51%	537	30%	99	14%	47	22%	146
GC04-Toledo	13%	54	-3%	-7	7%	47	61%	556	14%	38	50%	594	26%	126	5%	12	19%	139
GC05-Pelotas	21%	56	-3%	-9	8%	47	68%	447	25%	99	52%	546	35%	111	8%	25	21%	136
GC06-Porto-Alegre	19%	56	-4%	-9	8%	47	66%	467	23%	81	52%	548	33%	115	6%	18	21%	132
GC07-Chapeco	19%	55	-3%	-9	8%	46	65%	437	21%	86	49%	523	31%	106	6%	21	19%	127
GC08-Santa-Maria	14%	43	-3%	-8	6%	36	64%	476	20%	74	49%	551	26%	92	8%	27	17%	118
Average GC01 to GC08	20%	61	-4%	-9	9%	52	65%	458	24%	88	52%	546	31%	109	9%	28	21%	137
GC09-Niteroi	16%	68	-8%	-7	12%	61	64%	621	-2%	-2	59%	619	31%	152	-22%	-16	24%	136
GC10-Brasilia	18%	73	-4%	-7	11%	65	61%	530	13%	28	52%	558	30%	143	-3%	-4	21%	138
GC11-Marilia	19%	75	-5%	-9	12%	67	65%	586	0%	0	54%	586	33%	159	-6%	-10	23%	149
GC12-Goiania	18%	74	-4%	-7	11%	67	61%	529	9%	18	51%	547	31%	148	-7%	-13	21%	135
GC13-Rio-de-Janeiro	16%	64	-7%	-7	12%	58	64%	609	0%	0	58%	609	30%	147	-17%	-14	23%	133
GC14-Dourados	10%	39	-3%	-6	6%	33	63%	616	-12%	-22	51%	594	26%	123	-6%	-12	16%	110
GC15-Campinas	22%	67	-4%	-9	11%	58	67%	482	15%	38	53%	520	34%	121	4%	10	22%	131
GC16-Rio-Brilhante	9%	37	-3%	-5	5%	32	63%	615	-10%	-18	52%	597	27%	129	-10%	-18	17%	111
Average GC09 to GC16	16%	62	-5%	-7	10%	55	64%	573	2%	5	54%	579	30%	140	-8%	-10	21%	131
GC17-Belem	5%	28	-8%	-1	5%	27	61%	782	-1368%	-14	60%	768	21%	129	-61%	-6	19%	124
GC18-Macapa	2%	13	-6%	-1	2%	13	60%	806	-1442%	-9	59%	797	12%	72	-6%	-1	12%	72
GC19-Cruzeiro-do-Sul	2%	16	-4%	-1	2%	15	54%	795	-216%	-24	52%	772	14%	108	-13%	-4	13%	104
GC20-Palmas	1%	5	-3%	0	1%	5	54%	878	-1210%	-5	54%	873	-2%	-16	67%	11	-1%	-5
GC21-Aracaju	15%	60	-7%	-4	12%	56	68%	720	-162%	-36	63%	685	33%	168	-75%	-25	27%	144
GC22-Feira-de-Santana	17%	61	-8%	-4	14%	57	70%	674	-106%	-28	65%	646	35%	159	-70%	-22	28%	137
GC23-Picos	3%	18	-4%	-1	2%	17	56%	837	-420%	-15	55%	823	9%	64	24%	6	9%	69
GC24-Cuiaba	5%	28	-4%	-3	4%	25	59%	775	-76%	-39	54%	737	18%	119	-19%	-14	14%	104
Average GC17 to GC24	6%	29	-5%	-2	5%	27	60%	784	-625%	-21	58%	762	17%	100	-19%	-7	15%	94

The comparison of hourly energy demand values is shown in Figure 4. The energy demand of BRA_Adap_MM is plotted in x-axis, while the energy demand resulting from the other models is plotted in the y-axis, and the dashed lines represent the 50% and 25% reduction and increase references compared to BRA_Adap_MM. In this case, three reference climate zones were chosen: GC01, since it is the climate zone for what the Brazilian adaptive model was developed and, although it does not belong to the temperate climate zones group, the energy demand values were similar, and GC07 and GC20, since the highest heating and cooling energy demand values for BRA_Adap_MM were respectively found in those climate zones. Consistently with the results from the previous tables, the highest energy savings were achieved when compared to BRA_Stat_AC, especially for the cooling mode, while these energy savings were reduced compared to ASH_Adap_AC.

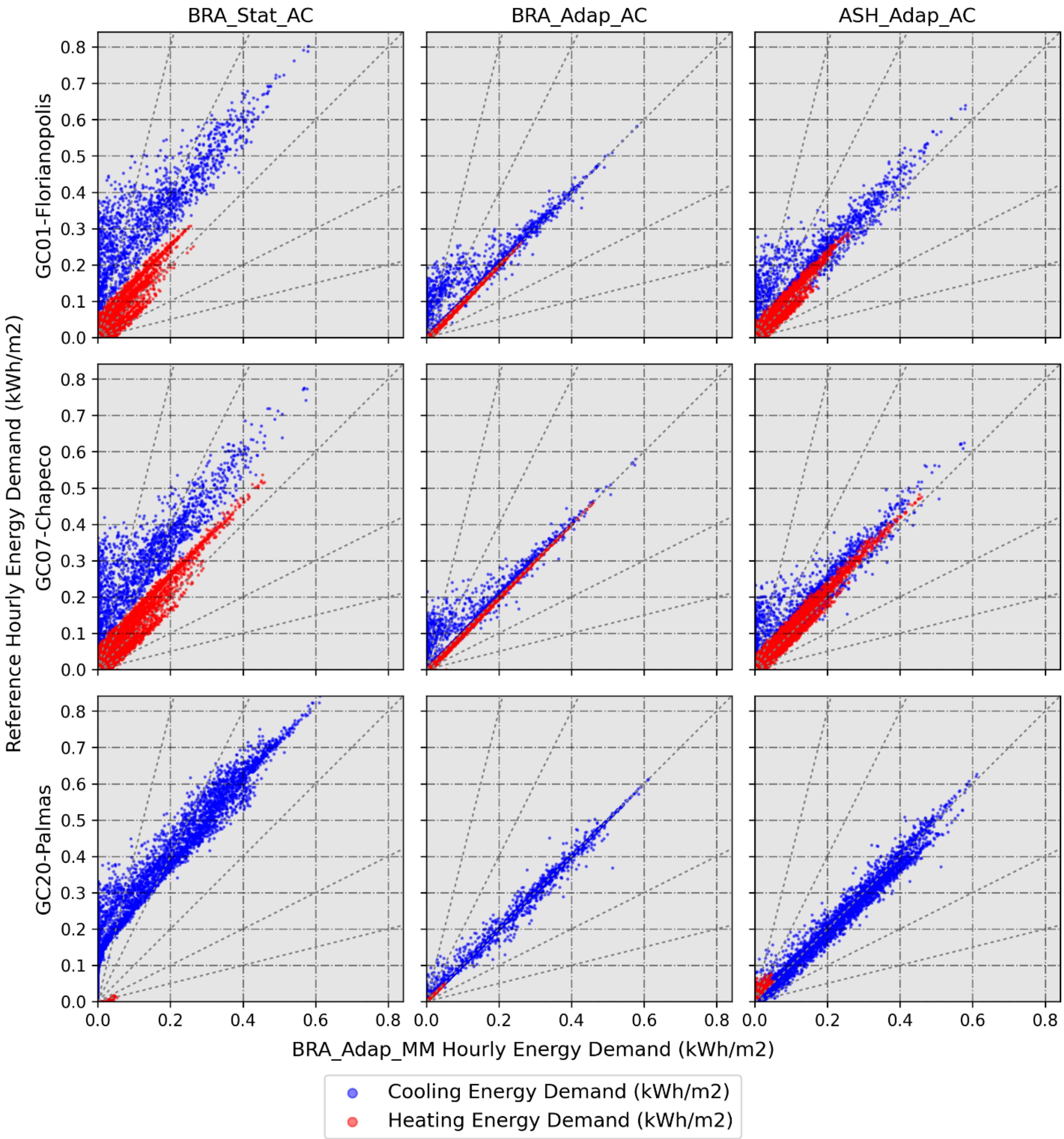


Figure 4. Full air-conditioning energy performance compared to BRA_Adap_MM.

The results explained so far consider that hourly operative temperatures fall within thermal comfort limits (either adaptive or static), as shown in Figure 5. This figure shows the behaviour of the setpoint temperatures when applicability limits were exceeded: in the case of BRA_Adap_MM, in GC01-Florianópolis, the applicability limits were exceeded in both extremes, and therefore adaptive setpoint temperatures were horizontally extended from those points on; in GC07-Chapeco, only the lower applicability limit was exceeded, and in case of GC20-Palmas, the distribution of temperatures completely exceeded the upper applicability limit, and therefore adaptive setpoint temperatures were horizontal for the whole year; in case of ASH_Adap_AC, the applicability range (10 to

33.5°C) is wider than the Brazilian adaptive model, and therefore ASHRAE 55 remained applicable for the whole year in all climates; in case of BRA_Stat_AC, the change from heating to cooling season took place at 20°C.

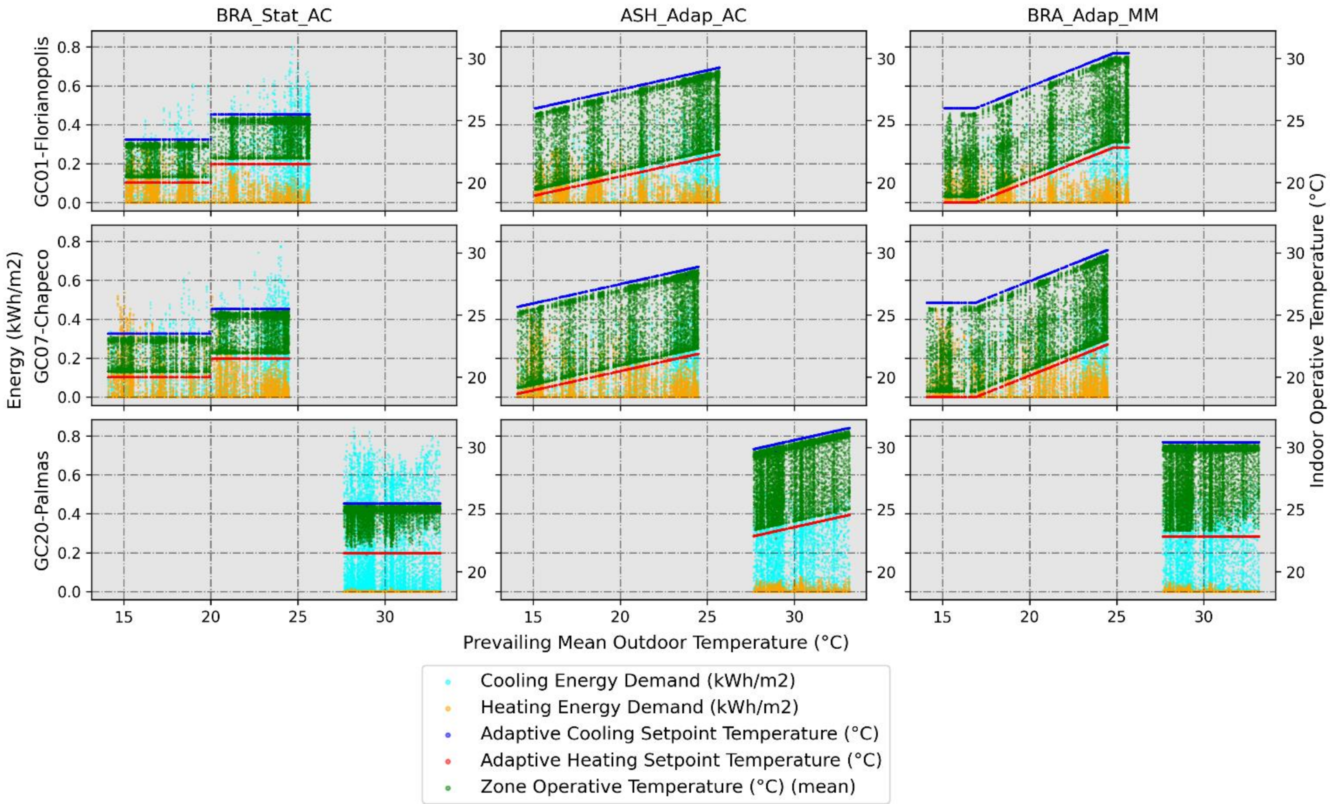


Figure 5. Simulated hourly operative temperature and energy demand.

3.2. Impact of the climate change

The impact of the increasing outdoor temperatures was studied for all climate zones, considering the RCP scenarios RCP2.6, RCP4.5 and RCP8.5 in years 2050 and 2100, as well as the different setpoint temperature behaviours, as shown in Figure 6. The impact of climate change was more severe in the case of BRA_Stat_AC, where total energy demand values ranged from 1150 to 1250 kWh/m²·year in most of the RCP scenarios, except RCP4.5 2100, when total energy demand almost reached 1400 kWh/m²·year, and RCP8.5 2100, when it increased reaching almost 1600 kWh/m²·year. The ASHRAE 55's energy demand (around 650 kWh/m²·year) was slightly greater than the Brazilian model in both full air-conditioning (around 600 kWh/m²·year) and mixed-mode (around 550 kWh/m²·year) except for RCP8.5 2100. In this case, the temperature increase would have caused that the PMOT at a greater number of hours falls in the range 24.8 to 33.5°C, where ASHRAE 55 is still applicable, but the Brazilian model is not. As a result, in that range ASHRAE 55's cooling setpoints would be higher than the Brazilian model, therefore achieving a lower energy demand.

Figure 6. Total energy consumption depending on the climate zone and scenario.

The variation of total energy demand in the evolution of the future scenarios for BRA_Stat_AC, ASH_Adap_AC, BRA_Adap_AC and BRA_Adap_MM is shown respectively in Tables 9 to 12, where total energy demand values were color-shaded in yellow, and the increases and reductions of energy demand compared to the present scenario were highlighted respectively in red and green. (i) In case of BRA_Stat_AC (Table 9), the average values for GC01 to GC08 showed an increase in energy demand within up to 2% except for both RCP4.5 and RCP8.5 in year 2100, when the increase reached respectively 3 and 8%; regarding the average values for GC09 to GC16 and GC17 to GC24, these increasing trends remained similar, although the values are alarming; in case of GC09 to GC16, the range was 5 to 8%, and the top values at RCP4.5 and 8.5 2100 were respectively 14% and 28%; in case of GC17 to GC24, the range was 9 to 16%, and the top values 23% and 37%. In the temperate climates (GC01 to GC08), some decreases were found as the temperatures increased, ranging up to 4%. Although these reductions seemed to be beneficial, they were insignificant when compared to other effects of climate change, and therefore should not be considered as a favorable impact. This trend changed for the warm and hot climates, where no decrease can be found. (ii) In the case of ASH_Adap_AC (Table 10), the decreases in energy demand in temperate climates were accentuated. In fact, the average values of GC01 to GC08 showed some reductions in energy demand, although these were still little variations compared to the present scenario, ranging up to 3%. In case of the average values of GC09 to GC16, the energy demand increased ranging from 1 to 3%, except for RCP4.5 and RCP8.5 in year 2100, when, again, top values of 7 and 14% increases were found; and finally, the average values of GC17 to GC24 showed an increase within the range of 8 to 10%, with the exception of 17 and 28% for the same scenarios. (iii) In the case of BRA_Adap_AC (Table 11), the increase and decrease trends in energy demand were very similar to ASH_Adap_AC, however the values slightly differed. With regards to the average values for GC01 to GC08, the energy demand varied within the range of 4% decrease to 1% increase. Regarding the average values of GC09 to GC16, energy demand increased ranging from 2 to 4%, with the exception of the RCP4.5 and RCP8.5 scenarios in year 2100, when energy demand increased up to 9 and 21% respectively. Following a similar trend, these values were worsened in GC17 to GC24, where the increase ranged from 11 to 18%, and the top values were 27 and 42%. (iv) In the case of BRA_Adap_MM (Table 12), the increase and decrease percentages were very similar to the full air-conditioning mode. However, if BRA_Adap_MM and BRA_Adap_AC average total energy demands are compared, average reductions of 44 and 42 kWh/m²·year are found for climates GC01 to GC08 and GC09 to GC16 respectively. In case of the climates GC17 to GC24, the average reduction in energy demand decreases to 10 kWh/m²·year due to the lower performance in hot climates. The distribution of energy demand values is shown in Figures 7 and 8, which show the most usual energy demand values gather around 500 kWh/m²·year, with barely any value exceeding 1500 kWh/m²·year. However, in future scenarios, values larger than 1500 kWh/m²·year are more frequent, although the median still stays around 500 kWh/m²·year. Lastly, in RCP8.5-2100, the median moves to higher values around 750 kWh/m²·year, since it is the most severe scenario. The reason behind this increase in energy demand is certainly the increasing outdoor temperatures due to climate change. The trend shown in Figure 8, consistent with the analysis in the previous sections, depicts an increase in all RCPs in years 2050 and 2100 compared to the present scenario, easily visible in the latter.

Table 9. Variation of total energy demand along climate change scenarios for BRA_Stat_AC.

Climate zone	Total Energy Demand (kWh/m²·year)												
	Present	RCP26_2050	RCP26_2100	RCP45_2050	RCP45_2100	RCP85_2050	RCP85_2100	1-(Present/RCP26_2050)	1-(Present/RCP26_2100)	1-(Present/RCP45_2050)	1-(Present/RCP45_2100)	1-(Present/RCP85_2050)	1-(Present/RCP85_2100)
GC01-Florianopolis	970	979	1003	961	997	966	1034	1%	3%	-1%	3%	0%	6%
GC02-Curitiba	980	1005	1016	978	991	970	1023	2%	4%	0%	1%	-1%	4%
GC03-Ponta-Grossa	1047	1035	1046	1030	1038	1038	1061	-1%	0%	-2%	-1%	-1%	1%
GC04-Toledo	1176	1190	1196	1220	1306	1240	1504	1%	2%	4%	10%	5%	22%
GC05-Pelotas	1052	1007	1049	1040	1036	1007	1061	-4%	0%	-1%	-2%	-4%	1%
GC06-Porto-Alegre	1055	1066	1075	1082	1091	1059	1141	1%	2%	2%	3%	0%	8%
GC07-Chapeco	1072	1069	1094	1076	1105	1094	1199	0%	2%	0%	3%	2%	11%
GC08-Santa-Maria	1115	1107	1122	1120	1152	1110	1226	-1%	1%	0%	3%	0%	9%
Average GC01 to GC08	**1058**	**1057**	**1075**	**1063**	**1089**	**1061**	**1156**	**0%**	**2%**	**0%**	**3%**	**0%**	**8%**
GC09-Niteroi	1052	1141	1149	1113	1258	1169	1476	8%	8%	5%	16%	10%	29%
GC10-Brasilia	1075	1120	1124	1132	1232	1142	1433	4%	4%	5%	13%	6%	25%
GC11-Marilia	1091	1138	1150	1140	1245	1169	1485	4%	5%	4%	12%	7%	27%
GC12-Goiania	1065	1106	1089	1108	1209	1124	1439	4%	2%	4%	12%	5%	26%
GC13-Rio-de-Janeiro	1050	1138	1139	1106	1235	1156	1450	8%	8%	5%	15%	9%	28%
GC14-Dourados	1160	1244	1228	1251	1427	1302	1738	7%	6%	7%	19%	11%	33%
GC15-Campinas	974	994	998	983	1055	1004	1238	2%	2%	1%	8%	3%	21%
GC16-Rio-Brilhante	1152	1215	1208	1255	1415	1287	1744	5%	5%	8%	19%	10%	34%
Average GC09 to GC16	**1077**	**1137**	**1136**	**1136**	**1260**	**1169**	**1500**	**5%**	**5%**	**5%**	**14%**	**8%**	**28%**
GC17-Belem	1283	1427	1377	1496	1638	1510	1932	10%	7%	14%	22%	15%	34%
GC18-Macapa	1343	1517	1486	1601	1842	1655	2303	11%	10%	16%	27%	19%	42%
GC19-Cruzeiro-do-Sul	1486	1634	1611	1691	1919	1771	2438	9%	8%	12%	23%	16%	39%
GC20-Palmas	1616	1744	1751	1888	2178	1949	2701	7%	8%	14%	26%	17%	40%
GC21-Aracaju	1080	1195	1251	1258	1388	1276	1635	10%	14%	14%	22%	15%	34%
GC22-Feira-de-Santana	995	1112	1152	1151	1306	1178	1566	11%	14%	14%	24%	16%	36%
GC23-Picos	1498	1595	1630	1713	1916	1723	2240	6%	8%	13%	22%	13%	33%
GC24-Cuiaba	1374	1488	1474	1536	1747	1610	2208	8%	7%	11%	21%	15%	38%
Average GC17 to GC24	**1334**	**1464**	**1466**	**1542**	**1742**	**1584**	**2128**	**9%**	**9%**	**13%**	**23%**	**16%**	**37%**

Table 10. Variation of total energy demand along climate change scenarios for ASH_Adap_AC.

Climate zone	Total Energy Demand (kWh/m²·year)												
	Present	RCP26_2050	RCP26_2100	RCP45_2050	RCP45_2100	RCP85_2050	RCP85_2100	1-(Present/RCP26_2050)	1-(Present/RCP26_2100)	1-(Present/RCP45_2050)	1-(Present/RCP45_2100)	1-(Present/RCP85_2050)	1-(Present/RCP85_2100)
GC01-Florianopolis	563	556	577	545	550	541	541	-1%	2%	-3%	-2%	-4%	-4%
GC02-Curitiba	608	622	634	606	602	595	585	2%	4%	0%	-1%	-2%	-4%
GC03-Ponta-Grossa	655	640	652	635	634	644	615	-2%	0%	-3%	-3%	-2%	-7%
GC04-Toledo	721	720	719	721	742	731	790	0%	0%	0%	3%	1%	9%
GC05-Pelotas	642	604	632	623	605	593	579	-6%	-2%	-3%	-6%	-8%	-11%
GC06-Porto-Alegre	639	635	642	648	623	619	622	-1%	0%	1%	-3%	-3%	-3%
GC07-Chapeco	676	668	684	670	664	672	661	-1%	1%	-1%	-2%	-1%	-2%
GC08-Santa-Maria	683	663	668	655	646	642	652	-3%	-2%	-4%	-6%	-6%	-5%
Average GC01 to GC08	**648**	**638**	**651**	**638**	**633**	**630**	**631**	**-2%**	**0%**	**-2%**	**-3%**	**-3%**	**-3%**
GC09-Niteroi	570	600	607	573	628	599	681	5%	6%	1%	9%	5%	16%
GC10-Brasilia	656	680	684	680	712	677	757	3%	4%	3%	8%	3%	13%
GC11-Marilia	654	676	682	662	696	671	755	3%	4%	1%	6%	2%	13%
GC12-Goiania	654	674	658	668	697	660	750	3%	1%	2%	6%	1%	13%
GC13-Rio-de-Janeiro	574	606	607	576	622	598	681	5%	5%	0%	8%	4%	16%
GC14-Dourados	677	705	694	690	752	711	806	4%	2%	2%	10%	5%	16%
GC15-Campinas	585	583	590	565	585	575	634	0%	1%	-3%	0%	-2%	8%
GC16-Rio-Brilhante	666	677	679	688	722	690	805	2%	2%	3%	8%	3%	17%
Average GC09 to GC16	**629**	**650**	**650**	**638**	**677**	**647**	**734**	**3%**	**3%**	**1%**	**7%**	**3%**	**14%**
GC17-Belem	639	704	665	729	765	715	847	9%	4%	12%	16%	11%	25%
GC18-Macapa	618	688	676	713	789	720	934	10%	9%	13%	22%	14%	34%
GC19-Cruzeiro-do-Sul	818	884	873	889	976	912	1129	8%	6%	8%	16%	10%	28%
GC20-Palmas	738	778	781	822	925	828	1175	5%	6%	10%	20%	11%	37%
GC21-Aracaju	539	583	607	604	641	598	703	8%	11%	11%	16%	10%	23%
GC22-Feira-de-Santana	486	537	554	549	597	547	656	10%	12%	11%	19%	11%	26%
GC23-Picos	745	781	795	815	881	813	984	5%	6%	9%	15%	8%	24%
GC24-Cuiaba	742	791	784	790	860	808	1006	6%	5%	6%	14%	8%	26%
Average GC17 to GC24	**666**	**718**	**717**	**739**	**804**	**743**	**929**	**8%**	**7%**	**10%**	**17%**	**10%**	**28%**

Table 11. Variation of total energy demand along climate change scenarios for BRA_Adap_AC.

Climate zone	Total Energy Demand (kWh/m²·year)												
	Present	RCP26_2050	RCP26_2100	RCP45_2050	RCP45_2100	RCP85_2050	RCP85_2100	1-(Present/RCP26_2050)	1-(Present/RCP26_2100)	1-(Present/RCP45_2050)	1-(Present/RCP45_2100)	1-(Present/RCP85_2050)	1-(Present/RCP85_2100)
GC01-Florianopolis	470	465	485	457	470	456	484	-1%	3%	-3%	0%	-3%	3%
GC02-Curitiba	530	541	551	526	522	514	512	2%	4%	-1%	-2%	-3%	-4%
GC03-Ponta-Grossa	579	559	569	552	550	562	536	-4%	-2%	-5%	-5%	-3%	-8%
GC04-Toledo	629	628	629	637	676	649	764	0%	0%	1%	7%	3%	18%
GC05-Pelotas	553	512	543	534	518	504	506	-8%	-2%	-3%	-7%	-10%	-9%
GC06-Porto-Alegre	554	550	554	563	540	531	563	-1%	0%	2%	-3%	-4%	2%
GC07-Chapeco	594	582	595	582	580	583	597	-2%	0%	-2%	-2%	-2%	0%
GC08-Santa-Maria	600	581	586	575	575	565	619	-3%	-2%	-4%	-4%	-6%	3%
Average GC01 to GC08	**564**	**552**	**564**	**553**	**554**	**546**	**573**	**-2%**	**0%**	**-2%**	**-2%**	**-4%**	**1%**
GC09-Niteroi	495	529	537	505	574	535	665	6%	8%	2%	14%	8%	26%
GC10-Brasilia	583	598	601	595	621	591	692	3%	3%	2%	6%	1%	16%
GC11-Marilia	572	587	594	577	615	585	715	3%	4%	1%	7%	2%	20%
GC12-Goiania	585	595	579	588	609	576	688	2%	-1%	1%	4%	-2%	15%
GC13-Rio-de-Janeiro	498	537	538	510	569	534	662	7%	7%	2%	12%	7%	25%
GC14-Dourados	599	633	624	622	711	650	845	5%	4%	4%	16%	8%	29%
GC15-Campinas	512	507	513	492	505	497	567	-1%	0%	-4%	-1%	-3%	10%
GC16-Rio-Brilhante	587	601	608	620	680	627	841	2%	3%	5%	14%	6%	30%
Average GC09 to GC16	**554**	**573**	**574**	**564**	**611**	**574**	**709**	**3%**	**4%**	**2%**	**9%**	**3%**	**21%**
GC17-Belem	542	632	591	672	747	672	911	14%	8%	19%	27%	19%	41%
GC18-Macapa	559	660	641	707	842	732	1107	15%	13%	21%	34%	24%	49%
GC19-Cruzeiro-do-Sul	729	817	802	844	983	888	1289	11%	9%	14%	26%	18%	43%
GC20-Palmas	748	820	828	906	1081	938	1414	9%	10%	18%	31%	20%	47%
GC21-Aracaju	451	500	524	528	586	528	714	10%	14%	14%	23%	14%	37%
GC22-Feira-de-Santana	406	459	473	472	540	479	661	12%	14%	14%	25%	15%	39%
GC23-Picos	693	754	772	819	946	824	1140	8%	10%	15%	27%	16%	39%
GC24-Cuiaba	662	729	720	743	861	777	1134	9%	8%	11%	23%	15%	42%
Average GC17 to GC24	**599**	**671**	**669**	**711**	**823**	**730**	**1046**	**11%**	**11%**	**16%**	**27%**	**18%**	**42%**

Table 12. Variation of total energy demand along climate change scenarios for BRA_Adap_MM.

Climate zone	Total Energy Demand (kWh/m²·year)												
	Present	RCP26_2050	RCP26_2100	RCP45_2050	RCP45_2100	RCP85_2050	RCP85_2100	1-(Present/RCP26_2050)	1-(Present/RCP26_2100)	1-(Present/RCP45_2050)	1-(Present/RCP45_2100)	1-(Present/RCP85_2050)	1-(Present/RCP85_2100)
GC01-Florianopolis	403	406	431	404	422	405	454	1%	7%	0%	4%	1%	11%
GC02-Curitiba	474	485	494	474	473	461	472	2%	4%	0%	0%	-3%	0%
GC03-Ponta-Grossa	510	489	498	486	489	494	487	-4%	-2%	-5%	-4%	-3%	-5%
GC04-Toledo	582	585	587	601	650	619	753	0%	1%	3%	10%	6%	23%
GC05-Pelotas	506	468	497	493	483	467	476	-8%	-2%	-3%	-5%	-8%	-6%
GC06-Porto-Alegre	507	511	512	525	506	494	539	1%	1%	3%	0%	-3%	6%
GC07-Chapeco	549	539	552	543	547	542	575	-2%	1%	-1%	0%	-1%	5%
GC08-Santa-Maria	564	544	549	543	547	536	597	-4%	-3%	-4%	-3%	-5%	6%
Average GC01 to GC08	**512**	**503**	**515**	**509**	**515**	**502**	**544**	**-2%**	**1%**	**-1%**	**0%**	**-2%**	**5%**
GC09-Niteroi	434	477	489	459	540	493	646	9%	11%	6%	20%	12%	33%
GC10-Brasilia	518	540	541	541	578	542	669	4%	4%	4%	10%	4%	23%
GC11-Marilia	505	528	537	520	574	532	695	4%	6%	3%	12%	5%	27%
GC12-Goiania	519	533	517	530	565	524	667	3%	0%	2%	8%	1%	22%
GC13-Rio-de-Janeiro	441	486	492	466	534	493	642	9%	10%	5%	17%	11%	31%
GC14-Dourados	566	608	598	596	696	629	838	7%	5%	5%	19%	10%	32%
GC15-Campinas	454	449	454	438	458	444	537	-1%	0%	-4%	1%	-2%	16%
GC16-Rio-Brilhante	555	573	581	598	666	606	836	3%	4%	7%	17%	8%	34%
Average GC09 to GC16	**499**	**524**	**526**	**518**	**576**	**533**	**691**	**5%**	**5%**	**4%**	**13%**	**6%**	**27%**
GC17-Belem	515	627	581	676	759	675	927	18%	11%	24%	32%	24%	44%
GC18-Macapa	547	664	642	714	855	742	1111	18%	15%	23%	36%	26%	51%
GC19-Cruzeiro-do-Sul	714	815	801	851	1001	900	1300	12%	11%	16%	29%	21%	45%
GC20-Palmas	743	821	828	911	1085	942	1415	10%	10%	18%	32%	21%	47%
GC21-Aracaju	395	455	481	492	564	496	713	13%	18%	20%	30%	20%	45%
GC22-Feira-de-Santana	349	410	426	428	514	443	654	15%	18%	19%	32%	21%	47%
GC23-Picos	676	744	766	817	951	824	1145	9%	12%	17%	29%	18%	41%
GC24-Cuiaba	637	712	701	729	856	766	1135	10%	9%	13%	26%	17%	44%
Average GC17 to GC24	**572**	**656**	**653**	**702**	**823**	**724**	**1050**	**13%**	**13%**	**19%**	**31%**	**21%**	**45%**

Figure 7. Distribution plot of the total energy demand depending on climate scenarios and zones

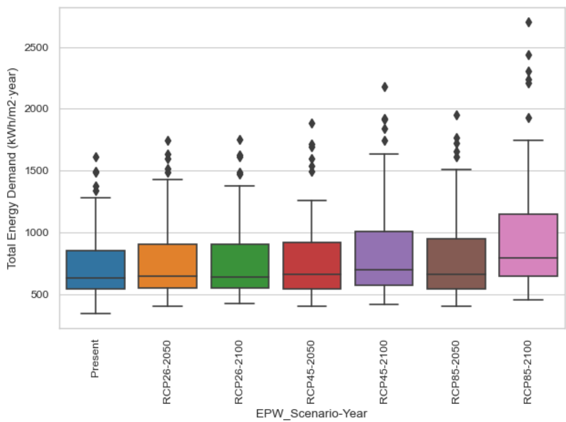


Figure 8. Distribution of total energy demand values in present and future scenarios

Although the use of mixed-mode seemed to have had a moderate impact on energy consumption, the air change rate were counted to a great extent. Figure 9 shows the mean hourly change rate at every hour in summer months (December to March) at GC01-Florianópolis, GC07-Chapecó and GC20-Palmas for present and every future scenario. Coherently with the nature of each climate, in GC07-Chapecó (zone with highest heating demand needs), the outdoor temperature generally allowed for higher air change rates, ranging up to 50 ach, while in GC01-Florianópolis (temperate zone), the air change rates ranged up to 30 ach, and finally in GC-20-Palmas (zone with highest cooling demand needs), these air change rates were reduced to a maximum of roughly 17 ach. Also, air change rates in present scenario generally outstand above all other scenarios, translated into higher values. At the bottom can be generally found the RCP8.5-2100 scenario, since the increasing temperatures led to the decreased use of natural ventilation. Also, a valley due to the increasing outdoor temperature in daytime, and two peaks in air change rates are found: in case of GC01, those peak values took place around 9 and 18 hours; in case of GC07, around 10 and 19 hours; and, in case of GC20, around 8 and 19 hours. The latter is especially severe in RCP8.5 2100, since hardly any natural ventilation was allowed. Therefore, Figure 9 clearly shows the decrease in the ventilation opportunities, which will be very important in future scenarios to help reduce the energy consumption, but at the same time will be scarce as the scenarios evolve.

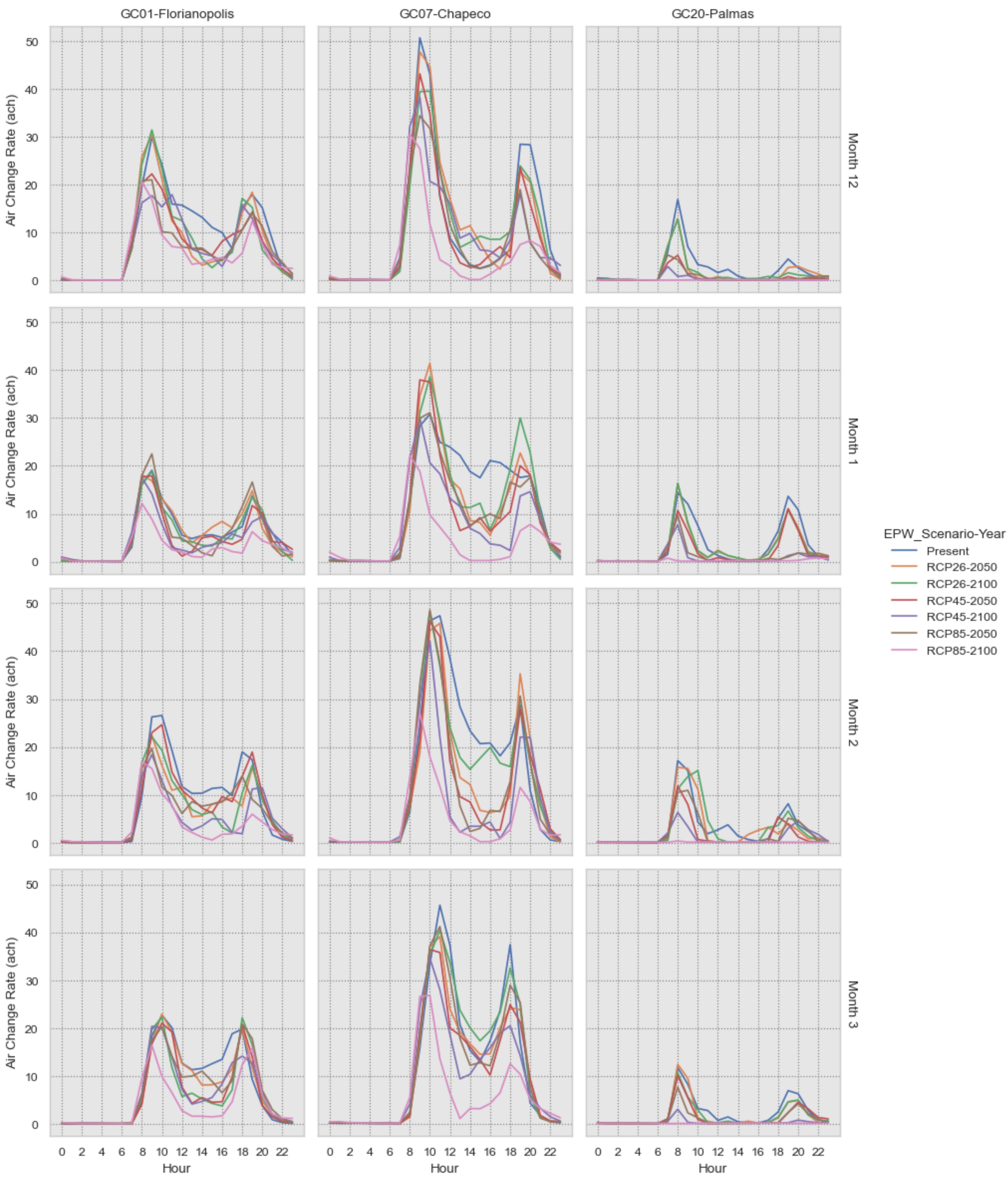


Figure 9. Mean air change rate values depending on time in summer months.

3.3. Limitations of the study

This study has a number of limitations. Firstly, according to current thermal comfort research, the human body adjusts to naturally ventilated, cooled and heated rooms differently. A recent study, however, discovered that regardless of whether an indoor climate is naturally ventilated or air-conditioned, inhabitants often tend to adapt to it (Parkinson et al., 2020). This study consequently assumes that people would adjust to the air-conditioned environment as if it were naturally ventilated, even though this is a research topic that undoubtedly needs additional investigation and is therefore indicated as a limitation. Secondly, the Brazilian local adaptive comfort model has been built based on thermal sensation questionnaire in the region of Florianópolis (temperate and humid climate), and therefore is able to confidently predict the thermal sensation in that climate, covering climate zones GC01 to GC08. However, since there is still no other comfort model to capture all other climates, the same model has been applied across the whole Brazilian territory, which is the closest approximation available. This is also considered as a study limitation since it is expected that there may be some inconsistencies when employing a local comfort model developed for a subtropical region in, for instance, a warmer tropical region. Thirdly, the use of the buildings case study to develop the Brazilian adaptive model (i.e. offices) and the building case study used in this research (i.e. social dwelling) differs. However, metabolic rate in the office was sedentary (similar to residential spaces) and office participants were free to change their clothing and take different actions to adapt to the indoor environment, therefore it is not considered a major limitation. Finally, since the adaptation to rising temperatures has not been considered, the capacity to estimate adaptive thermal comfort levels for future situations is limited. If thermal adaptation were taken into account, it is expected that the adaptive setpoint temperatures would be greater than those actually forecast since people would find higher temperatures bearable. This might result in larger energy savings. For instance, Figure 10 shows the operative temperatures for the case study in naturally ventilated mode in GC01-Florianópolis, in present and future scenarios. As expected, the capabilities of natural ventilation are closely related to the climate, and in this case, roughly 49% of hours fall outside the comfort zone in the present scenario, which even increases to 57% considering future scenarios.

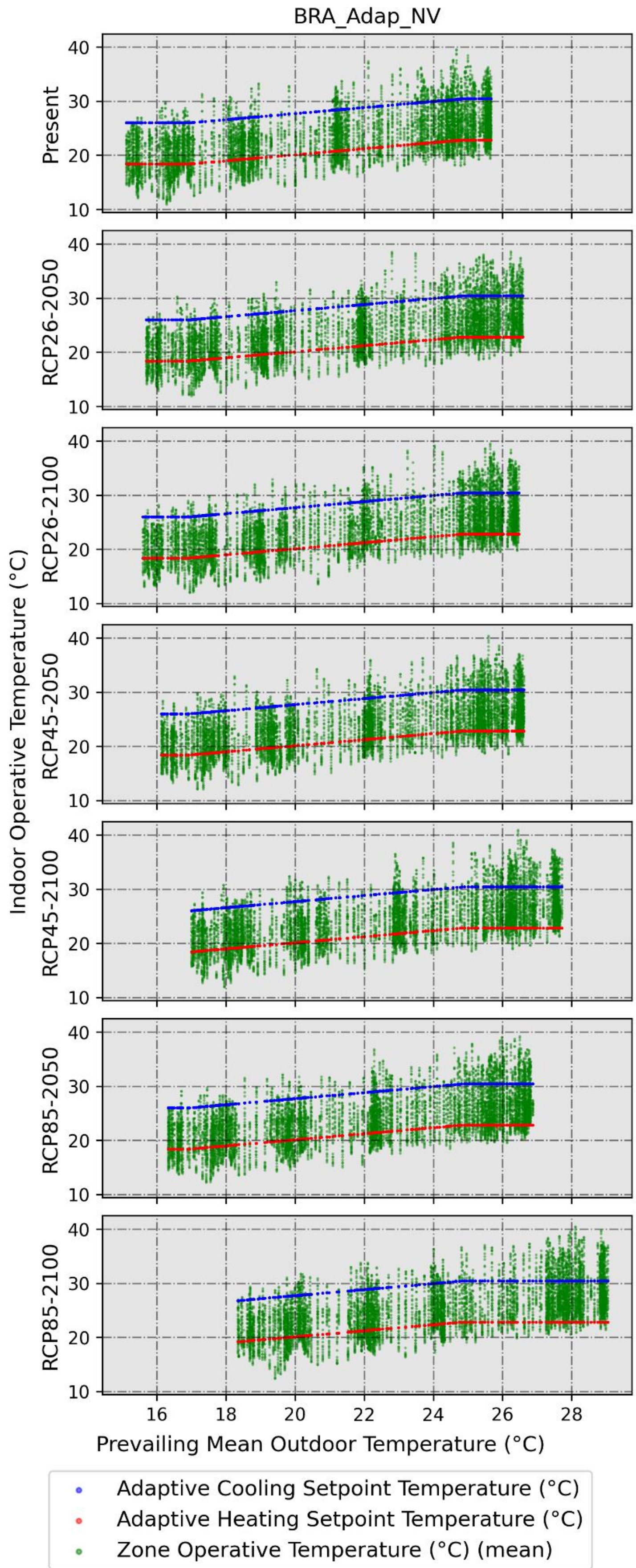


Figure 10. Indoor operative temperatures considering the Brazilian adaptive comfort model without HVAC system.

4. Conclusions

Recently, more flexible setpoint temperatures based on adaptive comfort models (i.e. adaptive setpoint temperatures) have been identified as an important energy saving strategy, since they provide reductions in energy demand with negligible investment cost, while keeping similar or improved occupant comfort. Studies based on adaptive setpoint temperatures have considered EN16798-1 and ASHRAE 55 international models so far, which have made up the framework of the Adaptive-Comfort-Control-Implemented Model (ACCIM). However, this study analyses the energy implications of using regional or local comfort models, namely a Brazilian adaptive local comfort model, by comparing them with those resulting from the use of the ASHRAE 55 adaptive model and static setpoint temperatures suggested by Brazilian regulations. The Brazilian adaptive local model was studied considering both the full air-conditioning and mixed-mode operations. Also, in order to understand the energy implications across the country and consider future scenarios under the influence of climate change, building energy simulations were performed in each of the 24 climate zones and considering the Representative Concentration Pathways scenarios RCP2.5, RCP4.5 and RCP8.5 in years 2050 and 2100.

To do so, the Brazilian model was included in the Python-based software tool named 'accim', which allows to easily transform EnergyPlus building energy models with PMV-based setpoint temperatures into adaptive setpoint temperatures. This tool adds the Adaptive-Comfort-Control-Implementation Script to the EnergyPlus building energy model (i.e. IDF file), which is essentially an EnergyManagementSystem script that overrides the values of the thermostat schedules based on the requirements specified by the user.

Results of our work have shown that the use of adaptive setpoint temperatures based on the Brazilian local model provides important energy savings compared to the static setpoint temperatures (average values ranging from 47 to 55%), and the ASHRAE 55 adaptive model (average values ranging from 11 to 13%). Mixed-mode have provided moderate additional energy savings to the full air-conditioning mode, since the average values of energy savings ranged from 5% to 10%. Considering climate change and the mixed-mode Brazilian model, the overall energy demand for the three groups of climatic zones (annual average outdoor temperatures ≤ 21°C, > 21 and ≤ 25°C and > 25°C) ranged between 2% decrease and 5% increase, 4% and 27% increase, and 13% and 45% increase, respectively.The adoption of setpoint temperatures based on the Brazilian local adaptive comfort model is therefore found to be a very efficient energy-saving method. In properly designed mixed-mode buildings, natural ventilation is maximized, and cooling/heating should be used only when the thresholds of the adaptive model are exceeded. International adaptive comfort models (i.e. ASHRAE 55 or EN16798-1) are normally applied in practice in the absence of local models. This work has shown the potential for additional energy savings by implementing a local adaptive model in comparison with ASHRAE 55 global model, which highlights the application value of using local adaptive models to reduce greenhouse gas emissions in buildings.

Findings should be interpreted taking into consideration the following limitations. This study makes the assumption that individuals would adapt to the air-conditioned environment in the same way they would to one that is naturally ventilated, even though this is a topic that clearly needs further investigation. Also, the Brazilian model studied in this paper was originally developed for office buildings in the climate of Florianópolis, in the South region of Brazil. However, considering there is still no other comfort model more suitable for residential buildings or for the other climates of Brazil, it has been applied across all climate zones for the case study building (i.e. detached house). These limitations provide hints for future lines of investigation, which could be oriented to the in-depth study of the thermal sensation considering adaptive setpoint temperatures, as well as the development of thermal comfort models for the remaining climates of Brazil and residential settings and the validation of the energy results in an actual building, rather than a simulation model. Given the close relationship of adaptive thermal comfort and energy poverty, these findings might help to guide future developments of social housing in Brazil which consider climate change and the different climate regions, similarly to those carried out in Chile (Pérez-Fargallo et al., 2017, 2018). Also, the findings remark the urgent need to improve the envelope of the studied building according to the climate context (i.e. social housing employed at a Brazilian national level) and to maximize the performance of mixed-mode operation with the purpose of preparing it to be climate-resilient and contribute to mitigate the effects of climate change.

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