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Using setpoint temperatures based on adaptive thermal comfort models: The case of an Australian model considering climate change

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ABSTRACT

It has recently become clear that using adaptive thermal comfort models to determine setpoint temperatures is a successful energy-saving method. Global models like ASHRAE 55 and EN16798-1 have been used in recent experiments using adaptive setpoint temperatures. This work, however, has taken a different route by concentrating on a region-specific Australian adaptive comfort model. The goal is to compare the energy implications of the use of setpoint temperatures based on the Australian local comfort model compared to the worldwide adaptive ASHRAE 55 model to highlight the significance of choosing the most fitting comfort model for making accurate predictions. All of Australia's climate zones are taken into account, as well as mixed-mode building operation scenarios, current and future scenarios, namely the years 2050 and 2100 for Representative Concentration Pathways (RCP) 2.6, 4.5, and 8.5. It has been found that the Australian-model-based adaptive setpoint temperatures taking into account mixed-mode significantly lowers energy demand when compared to the ASHRAE 55 adaptive model (average energy-saving value of 63 %). Considering climate change, the Australian model has an average energy demand of 13–26 kW h/m^2·year, and an average increase of 1–13 kW h/m^2·year. In the case of ASHRAE 55 model, energy demand decreases in future scenarios and average values range between 3 and 11 kW h/m^2·year. Therefore, setting setpoint temperatures in accordance with the Australian regional adaptive comfort model is a very efficient method for energy conservation. These differences raise awareness on the importance of the selection of the appropriate adaptive thermal comfort model.

1. Introduction

1.1. Overview

Because the circumstances on the earth are worsening, modern civilization is concerned about increasing energy use and greenhouse gas emissions [1]. This scenario is caused by a variety of industries, including the building industry [2,3]. Due to the current built environment's low energy performance, there are other issues outside merely environmental ones, such energy poverty [4,5]. The majority of societal energy and decarbonization plans seek to drastically cut the built environment's energy use [6], with savings of up to 100 % [7–9].

Building technical advancement is often the primary performance activity for this objective. It primarily focuses on lowering the energy consumption of Heating, Ventilation and Air-Conditioning (HVAC) systems because these systems use more energy than other sources, such electrical home appliances [10]. In order to ensure consumers' thermal comfort, HVAC systems are employed to maintain optimum indoor temperature [11]. Their excessive energy consumption is a result of both the use of very restrictive setpoint temperatures and low energy performance of the buildings (poor envelope features and outdated systems). The latter is because buildings were constructed before to the adoption of the first energy efficiency requirements, which affects the built environment in most nations [12–15]. Therefore, the majority of energy-saving efforts to date have been concentrated on retrofits such as upgrading HVAC systems, improving air tightness, and adding insulation [16–18].

However, it could be difficult to technologically update the entire built environment by the dates set by decarbonization laws. In addition, technological advancement can be constrained. Limitations in building technical refurbishment in southern Europe, with a focus on cooling

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Nomenclature

Acronym	*Description*
AC	Air-conditioned
accim	Adaptive-Comfort-Control-Implemented Model
ACCIS	Adaptive-Comfort-Control-Implementation Script
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
CZ	Climate Zone
EPW	EnergyPlus Weather file
GHG	Greenhouse Gas
HVAC	Heating, Ventilation and Air-Conditioning
MM	Mixed-mode
NV	Naturally-ventilated
PCS	Personal Comfort Systems
PMV	Predicted Mean Vote
RCP	Representative Concentration Pathways
T_{rm}	Prevailing Mean Outdoor Temperature

energy demand, were demonstrated by Attia et al. [19]. Additionally, rebound effects[1] may lessen the impact of these measures when consumers' demand rises in response to HVAC systems [20]. Therefore, it is necessary to propose new user-centred actions.

Recently, the use of adaptive setpoint temperatures, which are setpoint temperatures that take the values of the upper and lower adaptive thermal comfort limits, have been presented. These adaptive setpoints can be used to make sure all hourly temperatures fall within the adaptive thermal comfort zone by the use of the HVAC system. The first iteration of adaptive comfort regression models published by de Dear and Brager in 1998 [21] used an independent variable based on mean prevailing outdoor temperature. Their results showed that naturally ventilated (NV) buildings held linear regression models more consistently than air-conditioned (AC) spaces, with occupants of the latter showing only minor temperature adaptability. As such, de Dear and Brager and subsequently ASHRAE Standard 55 concluded that adaptive comfort models were exclusively relevant to naturally ventilated buildings. Consequently, the first adaptive comfort standard ASHRAE Standard 55 in 2004 [22] explicitly limited its scope of application to naturally ventilated spaces where no heating or cooling systems could be used. Since then, adaptive comfort models have been generally based on field studies, which have been mostly carried out in dwellings and residential spaces without air-conditioning units, where occupants were free to take any actions they needed in order to adapt to the indoor environment [23,24]. However, Parkinson et al. [25] re-analysed the first ASHRAE adaptive models on the enlarged set of data found in ASHRAE Global Thermal Comfort Database II [26] in 2020, and discovered that all building types (AC, NV, and MM) shared a consistently good fit to the same adaptive model when the mean indoor temperature was used as the independent variable instead of the outside temperature, as in the initial ASHRAE adaptive comfort standard. This prompted a re-examination of the low correlation in MM and AC buildings related to the adaptive comfort models. The correlation of neutral (or comfort) temperature and outdoor temperature found in the 1998 paper [21] turned out to be a correlation between the neutral temperature and indoor temperature, which, in turn, was highly dependent of outdoor temperature in the NV section of the database. Therefore, adaptive setpoint temperatures in the current project have been based on the evidence provided by recent studies [25,27] showing that occupants tend to adapt to the indoor thermal environment to which they are exposed, regardless of whether it is delivered by natural ventilation, fans, or air-conditioning units. This revelation prompts us to apply adaptive thermal comfort in air-conditioned spaces by means of adaptive setpoint temperatures.

The adjustment of setpoint temperatures has been widely used and studied as an energy saving strategy. Some examples can be found in Table 1. However, all these studies considered static or Predicted-Mean-Vote-based (PMV) setpoint temperatures. On the other hand, there are also studies which have considered the use of setpoint temperatures based on adaptive comfort models, which can be found in Table 2, as well as other studies in which the energy saving potential of using adaptive comfort models have been studied [28,29].

Adaptive setpoint temperatures have been developed within the framework of the Python package "accim" (which stands for Adaptive-Comfort-Control-Implemented Model) [43]. In this framework, adaptive comfort setpoint temperatures were applied to building energy performance simulation models in order to analyse the energy savings

Table 1
Research studies in which the adjustment of PMV-based or static setpoints have been investigated.

Authors	Research	Results	Citation
Li et al.	Developed demand response dynamic room temperature setpoints based on heat balance equations with thermal comfort model as constraint	Under the presumption of guaranteeing thermal comfort, the dynamic temperature setpoint scenario may reduce electricity consumption by 2.8 % and operational expenses by 3.73 %	[30]
Zhang et al.	Assessed the impact of a footwarmer in an office	Using Personal Comfort Systems for heating permitted relaxation of the ambient space HVAC setpoint by 2 °C, resulting in energy savings of 38 %–75 %. The energy saved from HVAC is significantly greater than the power consumption of the footwarmers	[31]
Heidarinejad et al.	Examined the impact of Personalized Conditioning, such as Phase Change Materials portable systems for possible energy, cost, and CO2 emission reductions	For older buildings, the savings from the extended setpoint can reach 21.8 %, compared to 16.5 % for newer midrise apartment complexes	[32]
Ling et al.	Used 40 people to measure thermal comfort by gathering subjective input. Energy simulations were conducted in 7 cities with Personal Comfort Systems	Raising the setpoint by 2.6 °C might result in HVAC system savings of 10–70 % depending on the city	[33]
Wang et al.	Investigated five different energy-saving measures using 32 scenarios in a 35-storey office building in Hong Kong	Raising the indoor temperature setpoint is the most economical strategy to reduce energy use, with potential savings of over 10 % when the cooling setpoint temperature is increased from 23 to 26 °C	[34]
Thyer et al.	Found that raising indoor air temperature set-points by 1.5 °C in Australia allowed savings of 13 % with no appreciable expenses or effects on occupant thermal comfort	Savings of 13 % with no appreciable expenses or effects on occupant thermal comfort	[35]

[1] the decrease in expected benefits from new technology that improve resource usage efficiency as a result of behavioural or other systemic reactions.

Table 2
Research studies in which the use of adaptive setpoint temperatures have been investigated.

Authors	Research	Results	Citation
Wang et al.	Investigated six HVAC system management techniques based on multiple types of thermostats (always on, based on schedule, and driven by occupancy), as well as fixed setpoint and adaptive control types	Adaptive setpoints can save costs by 14 %–54 %	[36]
Sánchez-García et al.	Explored the usage of adaptive setpoint temperatures in scenarios with changing climatic conditions to reduce the energy consumption of office buildings	Daily adjustment of adaptive setpoint temperatures provided energy demand reductions ranging from 63 to 52 % depending on the climate scenario	[37]
Kramer et al.	Reduced the heating setpoint temperature of a museum to match the value of the lower limit of the adaptive comfort zone, based on a comfort standard developed by Van der Linden et al. [38]	A 74 % reduction in energy consumption	[39]
Dhaka et al.	Examined how a fixed and adaptive thermostat schedule would affect energy saving in a university dormitory building in a hot, humid area of India	A 40 % reduction in energy use was possible with the use of adaptive setpoint temperatures	[40]
Sánchez-García et al.	Studied the use of adaptive setpoint temperatures in Japan	Energy savings ranging from 29 to 52 % in full air-conditioning mode, and from 33 to 78 % in mixed-mode	[41]
Sánchez-García et al.	Explored the use of adaptive setpoint temperatures in Brazil	Energy-saving values ranging from 52 to 58 % with mixed-mode	[42]

compared to the base-case of static setpoint temperatures based on the PMV [37]. The process of applying adaptive setpoint temperatures has been done using different methods: from the most basic, which used monthly setpoint temperatures within separate simulation of each month and the subsequent merger of the results [44], to more advanced strategies, such as the use of schedules in EnergyPlus with the previous calculation of the daily adaptive comfort limits in a worksheet [45], until the latest and more advanced method, which consists of the use of the Adaptive-Comfort-Control-Implementation Script (ACCIS) computational approach [46,47] integrated on the software.

Adaptive comfort models can be used to propose strategies to reduce energy demand considering occupants climate adaptability. Standards like EN 16798–1:2019 [48] and ASHRAE 55–2020 [49] that consider the interactions of the user with the building contain such models. The Smart Controls and Thermal Comfort [50] (SCATs, Europe) and ASHRAE's RP-884 [21] project (carried out in several locations around the world), respectively, served as the foundation for the creation of the standards. The results of this study showed that, in terms of user comfort, there is a link between the ambient outdoor temperature and the comfortable indoor operative temperature. However, in case of EN16798-1, the comfort model is based on a small amount of data gathered at outdoor temperatures higher than 25 °C. This is due to the fact that just two sample buildings in Greece had data under these circumstances, whereas the remainder of the sample is made up of countries in colder climates (e.g., United Kingdom). In other words, the results are confined, and the model's application is restricted when deployed to warm locations, especially when the effects of climate change are taken into account [51,52].

In this sense, international models do not consider certain peculiarities of some climates and their close relationship with the local culture, which also have an impact on thermal sensation. For this reason, the number of local adaptive comfort models proliferated recently, developed for countries with hot arid weather such as Pakistan [53], Iran [54], Tunisia [55] and Qatar [56]; hot and humid climates such as India [57–60], Colombia [61], Brazil [62] and Mexico [63], colder weathers such as the Netherlands [38], Romania [64] and China [65–68], temperate climates as Japan [69–71] and Spain [72,73], and subtropical climates, such as those for Australia [74,75]. Some of these models have also led to standards, such as GB/T 50,785 [76] for China, ISSO 74 [77, 78] for the Netherlands, and India [79]. Further, considering thermal sensation is subjective and it depends on gender [80] and age [81] among other human factors, different thermal comfort models can also vary depending on the building typology and the people occupying them, such as hospitals [82], shelters [83], dormitories [84], prefab construction site offices [85] or workshops [86] and primary schools [87].

1.2. Research gap

In this research, the local adaptive comfort model used to set the adaptive setpoint temperatures was developed by de Dear et al. [74] for the subtropical climate of Sydney, Australia. In that study, adaptive comfort behaviours, right-here-right-now thermal comfort perceptions, indoor and outdoor thermal environmental factors, and spatiotemporal patterns of air conditioning use by homeowners were all documented. A total of 4867 air-conditioning usage events and 1525 comfort questionnaire were registered over the two-year monitoring period for the longitudinal research design, which comprised a sample of 42 residences.

The use of adaptive setpoint temperatures has already been studied considering international standards, namely ASHRAE 55 and EN16798-1. However, the energy implications of the use of adaptive setpoints based on local comfort models remain uncertain for many countries and climates including Australia, which is what this research intends to explore, and therefore composes the originality statement. This knowledge gap leads to the research questions, which are:

- Is natural ventilation capable of providing an acceptable indoor thermal environment in the selected locations in present and future scenarios?
- How would impact the use of adaptive setpoint temperatures based on the Australian local model and ASHRAE 55 on energy demand?
- How would impact the climate change on the energy demand?

1.3. Objectives

To answer these questions, this study compares the energy demand from employing setpoint temperatures based on the Australian local adaptive comfort model to that generated from using the international ASHRAE 55 adaptive comfort model, to raise awareness on the importance of selecting the most representative comfort model for the predictions. In order to examine the potential for mixed-mode energy savings, building energy simulations are carried out across the nation for the 8 climate zones under present-day and future climate change scenarios, based upon Representative Concentration Pathways (RCP) for the years 2050 and 2100. Section 2 describes the methodology, which is broken down into the description of the building case study and the description of the Australian comfort model. The findings are reviewed in Section 3 while taking into account naturally-ventilated building operating mode, mixed-mode building operating mode and the future scenarios influenced by climate change, to lastly present the limitations of the study separately for the building energy model and adaptive thermal comfort models. After that, Section 4 presents the conclusions.

2. Methodology

The methodology used for this present research is shown in Fig. 1. Firstly, it is based on the Australian model for residential spaces and the use of accim, both developed prior to this study in their respective research frameworks. Secondly, the methodology starts with the selection of representative cities for each climate zone, in order to obtain the EPW files for present scenario, and later, for future RCP scenarios (refer to Section 2.1). Concurrently, information from the 2021 Housing data summary of Australian Bureau of Statistics' Census of Population and Housing was analysed in order to carry out a residential building energy model representative for Australia (refer to Section 2.2). Then, the adaptive setpoint temperatures for the Australian model (refer to Section 2.3) were implemented, as well as ASHRAE 55 adaptive model (refer to Section 2.4) to be used as comparison baseline. Finally, the simulations were run and the results analysed.

2.1. Climate zones in Australia

Australia's territory is divided into 8 climatic zones, according to the National Construction Code [88] (Fig. 2). Since all climate zones are considered in this study, a specific city for each of them was selected in order to obtain an hourly weather file for a Typical Meteorological Year (EPW). To be consistent with the existing literature [89], the selected cities are shown in Table 3. Also, the years 2050 and 2100 for the Representative Concentration Pathways future climate scenarios RCP2.6, RCP4.5, and RCP8.5 for the were taken into consideration to determine the possibility of local adaptive setpoint temperatures in future scenarios under the impact of climate change. An RCP is a trajectory of greenhouse gas (GHG) concentrations (not emissions). For the 2014 IPCC Fifth Assessment Report (AR5), four research and modelling approaches were employed. Various climatic scenarios are depicted in the pathways, all of which are thought to be feasible given the level of GHG emissions in the years to come. RCP scenarios are named after a range of radiative forcing levels possible for the year 2100 (respectively, 2.6, 4.5, 6, and 8.5 W/m^2). The versatility of RCPs lies in their ability to incorporate both stringent mitigation efforts, such as those outlined in the 2.6 W/m^2 scenario, and more business-as-usual projections, as seen in the 8.5 W/m^2 scenario. This comprehensive approach enables a thorough exploration of potential future climates, taking into account uncertainties in socio-economic development, technological advancements, and policy implementations. As a result, RCPs provide a nuanced and adaptable framework that enhances our understanding of the complex interplay between human activities and climate change. Meteonorm has been used to generate climate data for each of the seven settings. The EnergyPlus weather (EPW) data of the places chosen in the climate change scenario may be obtained using this program, comprising 8325 weather stations.

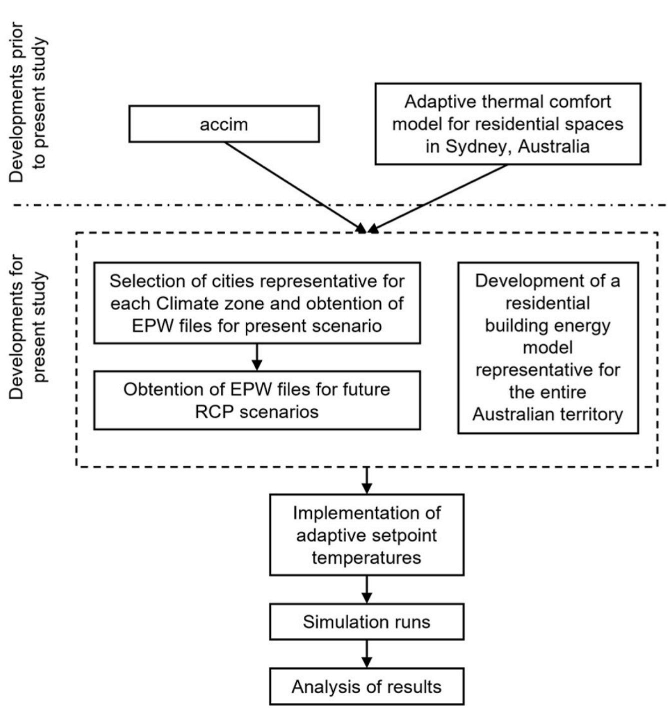

Fig. 1. Flowchart for the development of the present study.

Given the variety of climates in Australia, this study and the location's selection have made it possible to determine the acceptability of locally adjusted setpoint temperatures for the various climates as well as the potential for energy savings. The annual average outdoor temperatures in present scenario range from 8 °C in Thredbo (Climate zone (CZ) 8), the coldest climate zone, to 27.3 °C in Darwin (CZ1), the warmest climate zone. Also, each climate zone is impacted by climate change slightly differently. In Darwin, the increase in yearly mean outdoor dry-bulb air temperature varies from 0.5 to 3.3 °C depending on the RCP scenario and year, whereas it varies from 0.8 to 5.1 °C in Alice Springs, with a difference of around 1.8 °C in the RCP8.5-2100 scenario (Fig. 3). This large increase in the RCP8.5 and year 2100 can also be observed in Fig. 3, where the average minimum and maximum monthly outdoor temperatures clearly exceed all others in all climate zones. The variation of the monthly mean outdoor temperatures in each RCP scenario and year can be observed in Table A1, in Appendix A.

2.2. Case study

With the purpose of providing simulation results representative of the entire Australian territory, information from the 2021 Housing data summary of Australian Bureau of Statistics' Census of Population and Housing [90] have been obtained. Firstly, the most representative building type was analysed. Although there are policy efforts moving towards a higher density housing supply [91], the detached houses are the most prevalent, with more than 7 million dwellings, roughly 70 % of the total dwellings (Fig. 4). Secondly, the most representative dwelling size was identified. To do so, the average floor area of new residential dwellings in Australia [92] was obtained, and an average floor area between 230 and 245 m^2 was considered a representative value. Finally, and also related to the size of the building, the 61 % of dwellings have 3 bedrooms or more, therefore a number of 3 or 4 bedrooms was considered to be representative (Table 4). It's important to consider that heating and/or cooling can account for 20–50 % of energy used in Australian homes, depending on the climate zone [93]. This variation highlights the need for simulations that account for geographic differences.

Based on such details, an exemplar dwelling was sought for use in the case study (Fig. 5a). This dwelling is a separate house, has a ground floor area of 234.84 m^2 and 4 bedrooms. Then, the building energy model was developed (Fig. 5b) using DesignBuilder and EnergyPlus as calculation engine, considering the dwelling has been designed and built to meet the current Australian Building Construction Code. As with many other construction codes around the world, the minimum requirements for energy performance varies, depending on climate zone. Therefore, in order to provide consistent results, these variations have been considered in the modelling of the building envelope (Table 5). All openings are sliding windows and doors, which has been represented in the model considering 50 % openable glazed areas. Infiltrations have been modelled using a Designbuilder-predefined medium quality crack setting, which results in reference crack conditions considering 20 °C as the reference temperature, 101,320 Pa as barometric pressure and 0.005 kgWater/kgDryAir as the reference humidity ratio. Finally, regarding mixed-mode operation, the following conditions must be satisfied to open the window separately for each zone:

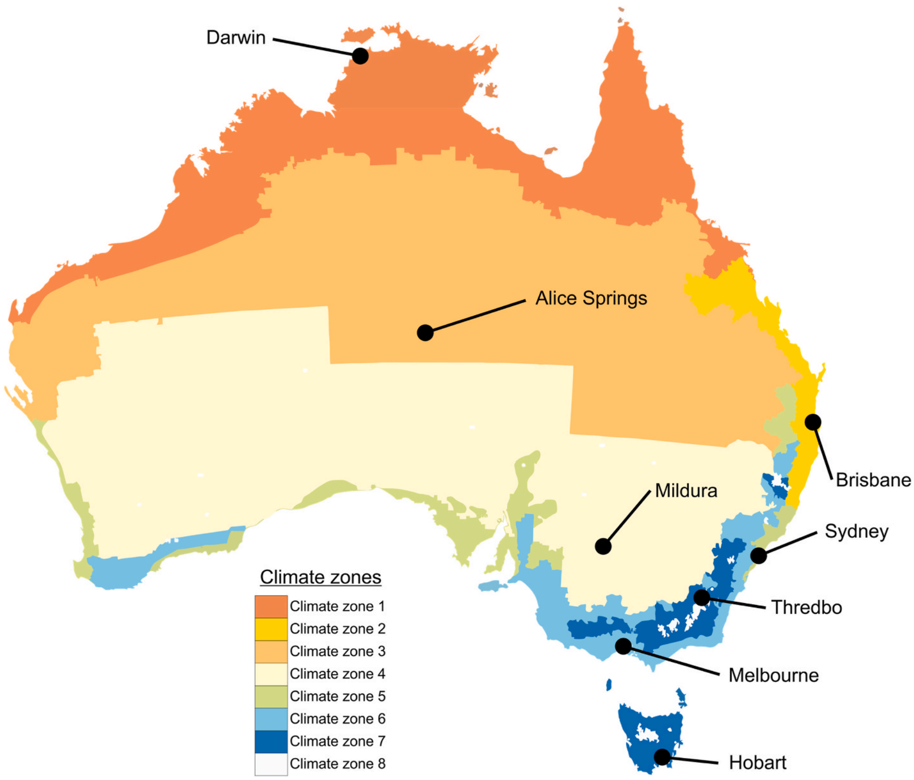

Fig. 2. Climate zones of Australia.

Table 3
Selected city for each climate zone.

Climate Zone - City	Latitude	Longitude	Koppen-Geiger climate zone	Koppen-Geiger climate zone description
CZ1-Darwin	−12.45	130.833	Aw	Tropical wet and dry or savanna climate
CZ2-Brisbane	−27.47	153.023	Cfb	Temperate oceanic climate or subtropical highland climate
CZ3-Alice Springs	−23.7	133.87	BWh	Hot desert climate
CZ4-Mildura	−34.183	142.15	BSk	Cold semi-arid climate
CZ5-Sydney	−33.873	151.205	Cfb	Temperate oceanic climate or subtropical highland climate
CZ6-Melbourne	−37.814	144.963	Cfb	
CZ7-Hobart	−42.881	147.325	Cfb	
CZ8-Thredbo	−36.504	148.306	Cfb	

- no heating and no cooling are needed
- outdoor temperature < min outdoor temperature (controlled with argument, but unlimited in this case)
- outdoor temperature < operative temperature
- wind speed < max wind speed (controlled with argument, but unlimited in this case)
- operative temperature < cooling setpoint temperature
- operative temperature > ventilation setpoint temperature (usually equal to the neutral or comfort temperature)

2.3. Description of the local adaptive comfort model for sydney Australia

Up until recently, EN 16798–1 and ASHRAE 55 were the only two international comfort standards that were included in accim. The Australian local adaptive comfort model for residential spaces [74] was selected from the several options because of its substantial sample size of 1500 thermal sensation votes collected from 42 residences. The main differences between the Australian and ASHRAE 55 adaptive models are summarised in Table 6. In case of the Australian model, the range of applicability is limited to Prevailing Mean Outdoor Temperatures (T_{rm}, Eq. (1)) between 8 and 27 °C. In that case, an offset of ±4.5 °C from the comfort temperature (Eq. (2)) can be used to establish the 80 % acceptability comfort limits and, ultimately, adaptive setpoint temperatures (Eqs. (3) and (4)). Both Australian local and ASHRAE 55 global comfort models are compared in Fig. 6. ASHRAE 55 adaptive model has been fitted to data from a more diverse suite of climates, and therefore the applicability range is wider (10–33.5 °C). In the Australian model, the 80 % permissible temperature range was around 2 °C larger than that recommended by the ASHRAE 55 adaptive model. However, comfort temperature was shifted downwards colder interior temperatures by an average value of 2 °C (ranging from 1.6 to 2.4 °C) in comparison with ASHRAE 55 adaptive model, therefore revealing that people are more tolerant to, or more adapted to, colder interior temperatures.

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

$$\textit{Comfort temperature} = T_{rm} * 0.26 + 16.75\ (^{\circ}C) \tag{2}$$

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

$$\textit{Upper limit}\ (80\%\ \textit{acceptability}) = T_{rm} * 0.26 + 16.75 + 4.5\ [^{\circ}C]\ (8^{\circ}C \leq T_{rm} < 27^{\circ}C) \tag{3}$$

$$\textit{Lower limit}\ (80\%\ \textit{acceptability}) = T_{rm} * 0.26 + 16.75 - 4.5\ [^{\circ}C]\ (8^{\circ}C \leq T_{rm} < 27^{\circ}C) \tag{4}$$

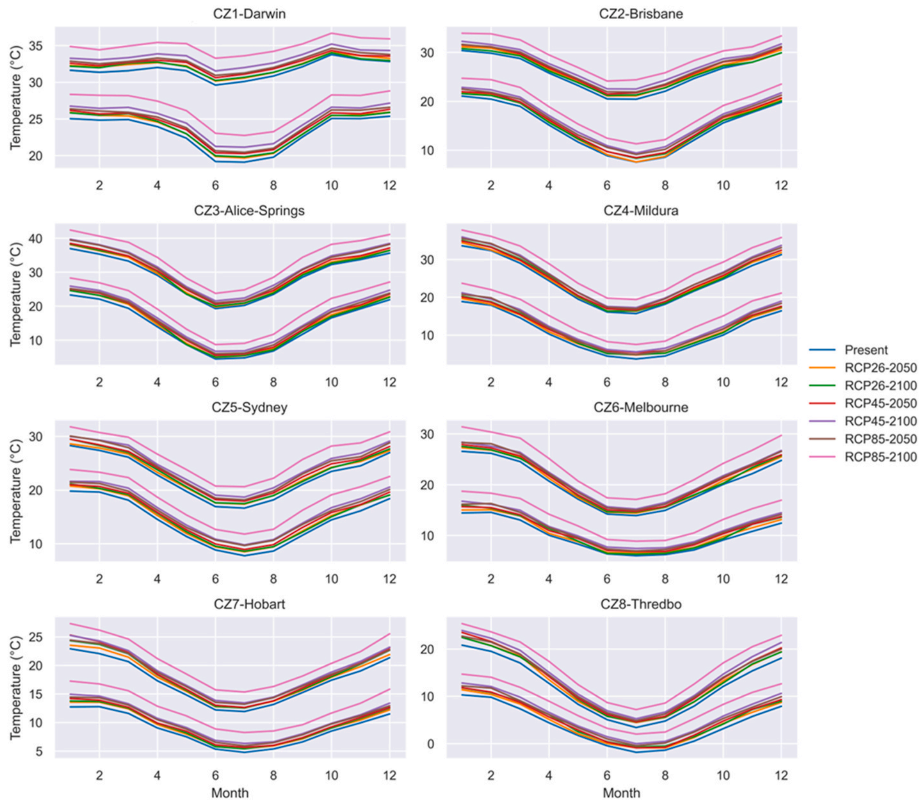

Fig. 3. Evolution of the maximum and minimum monthly average temperatures in future climate scenarios.

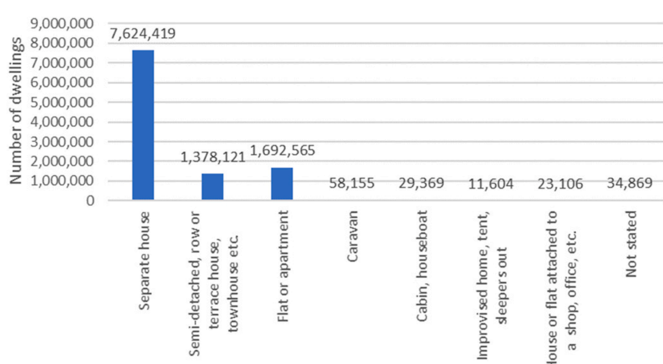

Fig. 4. Number of dwellings in Australia by type according to Australian Bureau of Statistics' Census of Population and Housing: Housing data summary, 2021 [90].

2.4. Comfort models considered in this study

In this section, the comfort models to be used in this study are explained, and the setpoint temperatures for each are shown in Table 7. The comfort model whose energy saving potential is analysed is the Australian local adaptive comfort model developed by de Dear [74], considering the 80 % acceptability levels, in which setpoint temperatures are horizontally extended when applicability limits are not met.

In order to assess the Australian local adaptive comfort model energy performance, the ASHRAE 55 adaptive model has been selected as an alternative reference comfort model for comparison to highlight the significance of choosing the most fitting comfort model for making accurate predictions. In that case, the 80 % acceptability levels are considered, and setpoint temperatures are also horizontally extended when T_{rm} falls outside applicability limits.

3. Results and discussion

In the first sub-section, the levels of thermal comfort in all climate zones and climate scenarios have been studied in naturally ventilated mode, that is, without any HVAC system at all. In the second sub-section, the energy efficiency of the setpoint temperatures based on the Australian adaptive local comfort model has been investigated considering mixed mode, wherein when outdoor conditions are adequate, natural ventilation takes precedence over using the HVAC system. If not, the HVAC system is turned on and the windows are closed. Finally, the third subsection also looks at how energy use is affected by climate change.

The dwelling has been modelled room by room, and therefore, each room has different energy needs. The results related to energy consist of the sum of the energy needs of all rooms, while those related to temperature consist of the average of all mixed-mode-conditioned rooms. Given the adaptive setpoints are calculated from the adaptive comfort limits, the setpoints are the same in all conditioned rooms, and therefore the average represents a very accurate picture of the indoor temperatures of the building.

3.1. Levels of thermal comfort in naturally ventilated mode

Before the analysis of the energy implications from the use of adaptive setpoint temperatures, it is necessary to understand the levels of thermal comfort that can be achieved in naturally-ventilated mode to fully understand the extent to which the HVAC systems are needed in each climate zone and climate scenario. Fig. 7 shows a heatmap of the percentage of hours in which operative temperature falls within the comfort zone. In present scenario, the Australian adaptive model suits very well to the climates of Brisbane, Mildura, Sydney, Melbourne and Hobart (98 %, 97 %, 98 %, 98 % and 94 % comfortable hours). On the other hand, the ASHRAE 55 model suits better than the Australian model in Darwin and Alice Springs (99 and 95 % against 36 and 70 %

Table 4
Dwelling structure by number of bedrooms in Australia according to Australian Bureau of Statistics' Census of Population and Housing: Housing data summary, 2021 [90].

Dwelling type	Count of occupied private dwellings					
	None (includes studio apartments or bedsitters)	One bedroom	Two bedrooms	Three bedrooms	Four bedrooms or more	Not stated
Separate house	15,302	80,047	561,236	2,928,132	3,103,476	315,115
Semi-detached, row or terrace house, townhouse with one storey	2976	58,871	297,330	235,244	36,527	46,585
Semi-detached, row or terrace house, townhouse with two or more storeys	1679	27,843	144,523	277,973	78,104	30,463
Flat or apartment in a one or two storey block	6158	84,334	210,842	64,246	8767	32,811
Flat or apartment in a three-storey block	4744	57,844	201,046	40,819	2629	20,635
Flat or apartment in a four to eight storey block	6294	84,830	203,698	51,416	2652	23,689
Flat or apartment in a nine or more-storey block	5898	81,385	145,976	36,822	1907	21,205
Flat or apartment attached to a house	356	3406	6296	3071	3088	2020
Caravan	13,979	22,816	4125	2372	1847	11,163
Cabin, houseboat	2187	8546	7540	1671	653	6433
Improvised home, tent, sleepers out	1597	1579	483	447	395	7101
House or flat attached to a shop, office, etc.	502	3498	6804	4405	2104	1958
Not stated	3752	8365	6145	5250	4470	5905

Fig. 5. Single-family detached dwelling used as a case study.

respectively), but suits slightly worse in Mildura, Melbourne and mainly Hobart (84 %, 85 % and 74 % against 97 %, 98 %, and 94 %). The reason of this resides on the higher upper applicability limit of ASHRAE 55: given the upper applicability limit is higher in ASHRAE 55 (33.5 °C compared to 27 °C), the highest acceptable temperature in ASHRAE 55 is 32 °C, higher than the Australian model, in which it is 28.3 °C. As a result of this, ASHRAE 55 suits better to hot climates in Australia, while the Australian model suit better to mild and cool climates.

This difference in applicability limits is something to bear in mind when considering climate change. ASHRAE 55 is better suited to handle warmer temperatures, therefore, reductions in comfortable hours are larger in case of the Australian model: for instance, in case of Brisbane, Mildura and Sydney, these are reduced respectively to 65, 69 and 85 % in RCP8.5-2100. Fig. 8 shows the impact of climate change on the operative temperature, where the comfort zone is moved towards higher temperatures until RCP8.5-2100, in which Australian model's upper applicability limit of 27 °C is exceeded and comfort limits are flattened.

Table 5
Thermal properties of the envelope.

Construction type	U-value (W/m2·K)				SHGC
	External wall	Ground floor	Roof	Window	
Climate zone 1 - Darwin	0.3	0.5	0.32	0.3	0.057
Climate zone 2 - Brisbane	0.71	0.5	0.24	0.3	0.074
Climate zone 3 - Alice Spring	0.3	0.5	0.24	0.3	0.062
Climate zone 4 - Dubbo	0.35	0.5	0.24	0.3	0.097
Climate zone 5 - Sydney	0.71	0.5	0.24	0.3	0.122
Climate zone 6 - Melbourne	0.35	0.44	0.21	0.3	0.153
Climate zone 7 - Hobart	0.35	0.5	0.21	0.3	0.187
Climate zone 8 - Thredbo	0.26	0.3	0.15	0.3	0.234

SHGC: Solar Heat Gain Coefficient

Table 6
Key parameters for ASHRAE 55 and Australian adaptive comfort models.

Model	ASHRAE 55 model	Australian model
Field study location	Worldwide	Wollongong/Sydney (Australia)
Indoor environmental conditioning	NV	AC
Upper applicability limit (°C)	33.5	27
Lower applicability limit (°C)	10	8
80 % acceptability limits offset (°C)	±3.5	±4.5
Neutral temperature linear equation (°C)	T_{rm}*0.31 + 17.8	T_{rm}*0.26 + 16.75

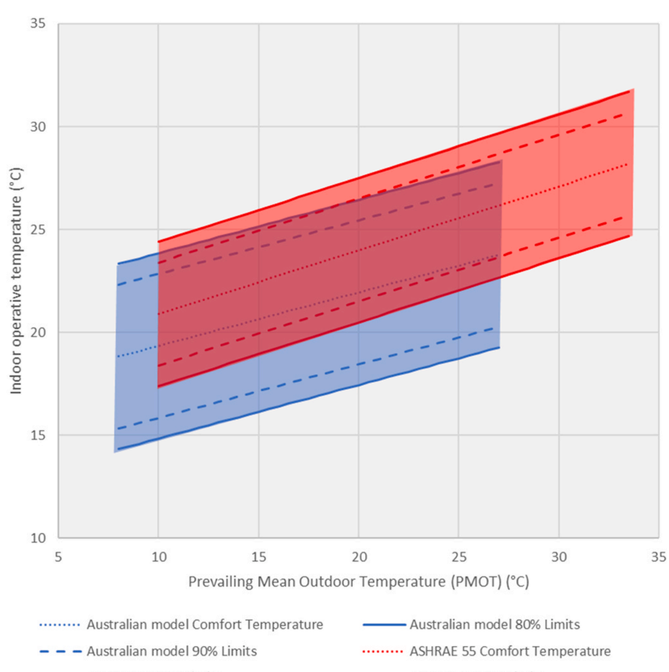

Fig. 6. Adaptive comfort model developed for Sydney (Australia) [74] compared to the ASHRAE 55 global adaptive comfort model [49].

Table 7
Setpoint temperatures of the comfort models used in this study.

Setpoints	Cooling setpoint temperature (°C)			Heating setpoint temperature (°C)		
	T_{rm} < ACSTall	ACSTall < T_{rm} < ACSTaul	ACSTaul < T_{rm}	T_{rm} < AHSTall	AHSTall < T_{rm} < AHSTaul	AHSTaul < T_{rm}
ASHRAE 55	10*0.31 + 17.8 +3.5	T_{rm}*0.31 + 17.8 +3.5	33.5*0.31 + 17.8+3.5	10*0.31 + 17.8 −3.5	T_{rm}*0.31 + 17.8 −3.5	33.5*0.31 + 17.8–3.5
Australian	8*0.26 + 16.75 +4.5	T_{rm}*0.26 + 16.75 +4.5	27*0.26 + 16.75 +4.5	8*0.26 + 16.75 −4.5	T_{rm}*0.26 + 16.75–4.5	27*0.26 + 16.75 −4.5

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.

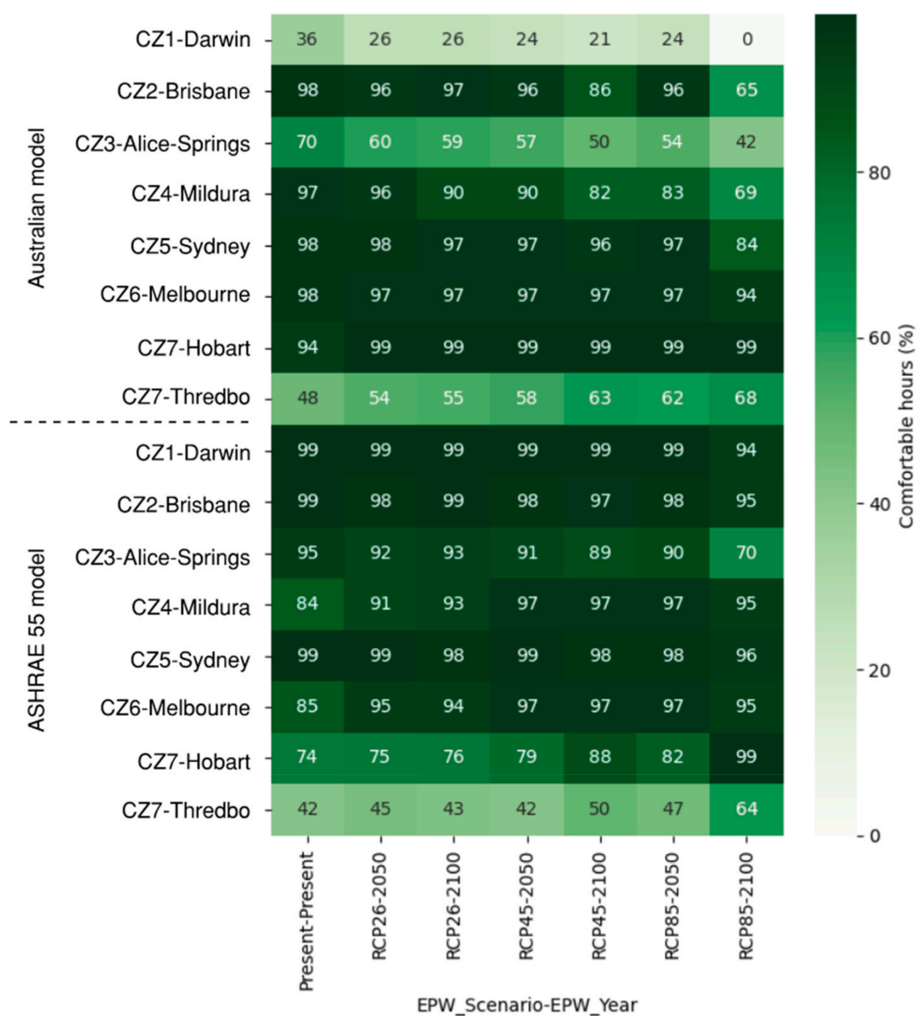

Fig. 7. Percentage of hours falling inside of Australian model and ASHRAE 55 thermal comfort zones.

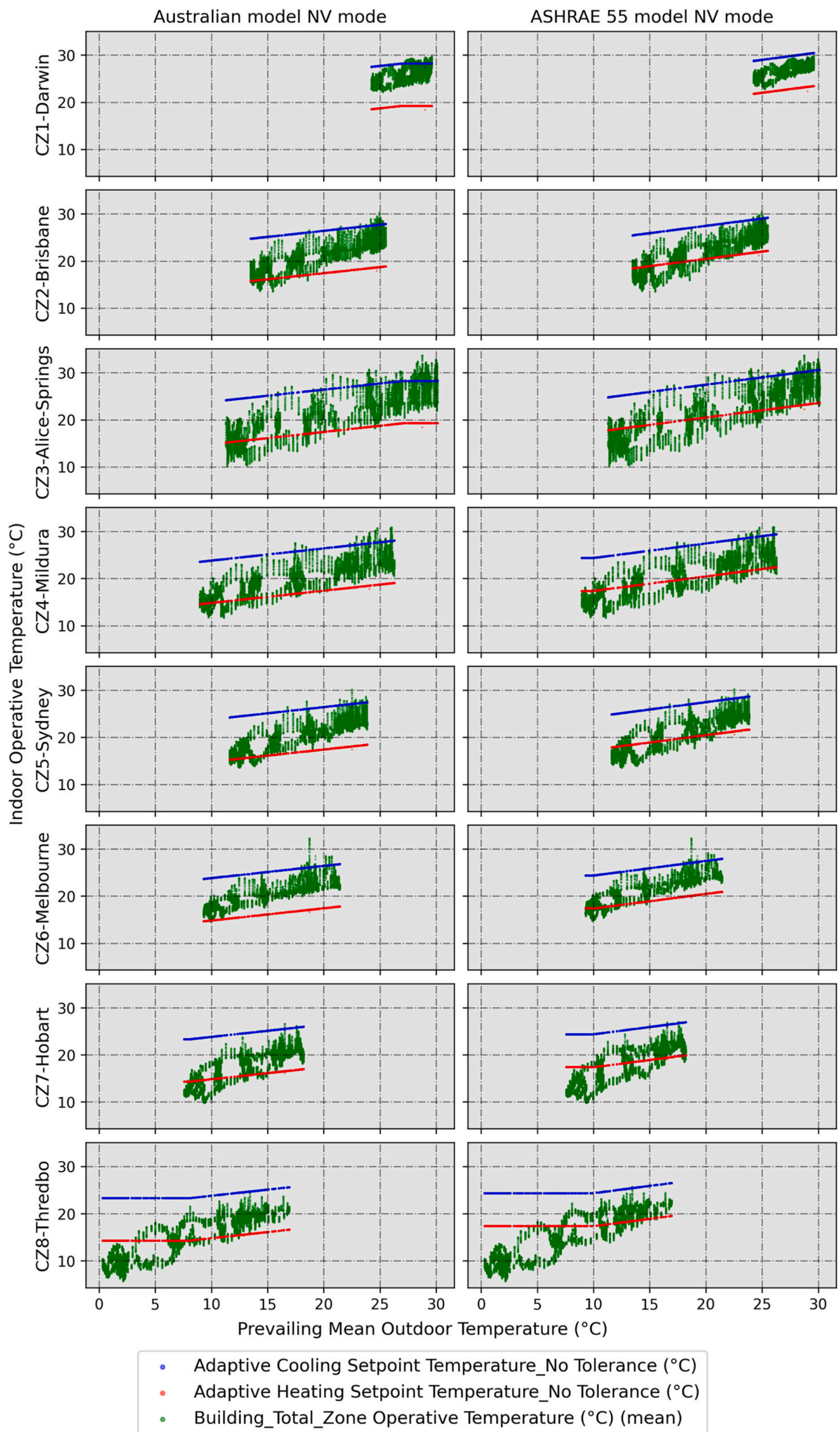

Fig. 8. Operative temperature in the evolution of future climate change scenarios in Sydney in naturally ventilated mode (i.e. without HVAC system).

Table 8
Values of energy demand.

Energy demand	Model	CZ1-Darwin	CZ2-Brisbane	CZ3-Alice-Springs	CZ4-Mildura	CZ5-Sydney	CZ6-Melbourne	CZ7-Hobart	CZ8-Thredbo	Average
Cooling Energy Demand	Australian	6.3	2.5	13.1	2.8	1.5	3.3	0.1	0.1	3.7
(kWh/m^2·year)	ASHRAE55	0.0	0.8	4.9	1.4	0.7	2.9	0.1	0.1	1.3
Heating Energy Demand	Australian	0.0	2.4	10.9	5.7	2.3	0.3	14.8	38.4	9.4
(kWh/m^2·year)	ASHRAE55	0.0	19.5	33.6	30.1	19.1	6.6	44.9	71.6	28.0
Total Energy Demand	Australian	6.3	4.9	24.0	8.5	3.8	3.6	14.9	38.5	13.0
(kWh/m^2·year)	ASHRAE55	0.0	20.3	38.5	31.5	19.8	9.4	45.0	71.8	30.0

3.2. Energy savings in present scenario

Building energy simulations were performed with mixed-mode for each setpoint behaviour and climatic zone combination, with the results reported in Table 8. Considering the average of the values for all climate zones, adaptive setpoints based on the ASHRAE 55 adaptive model had the lowest demand in cooling mode (1.3 kW h/m^2·year), slightly smaller than the Australian adaptive model (3.7 kW h/m^2·year). However, in heating mode, The Australian adaptive model had a lower demand (9.4 kW h/m^2·year) than ASHRAE 55 adaptive model (28.2 kW h/m^2·year). This is reflected in the total energy demand, where the Australian model had a lower demand (13.1 kW h/m^2·year), than the ASHRAE 55 adaptive model (29.5 kW h/m^2·year).

Table 9 helps to understand better these relationships. This research investigates the energy saving potential of the use of adaptive setpoint temperatures based on the Australian local adaptive model compared to ASHRAE 55 adaptive model, therefore the Australian adaptive model was given primary consideration, and ASHRAE 55 adaptive model was contrasted with it. Therefore, Table 9 displays the numbers as a percentual variation (1-(Australian/ASHRAE55)) and a difference (ASHRAE55 - Australian) from the Australian adaptive model. As previously noted, ASHRAE 55 adaptive model had a lower demand in cooling mode, particularly in hottest weather conditions. Although the comfort zone threshold is wider in the Australian model (9 °C) compared to ASHRAE 55 (7 °C), the wider applicability limits in ASHRAE 55 (33.5 °C compared to 27 °C) results in higher temperatures for the cooling setpoint. Therefore, the energy demand is lower and the energy performance is better. This is especially true, in Alice Springs and Darwin, where hottest temperatures have similar values. In case of the heating mode, the Australian adaptive model provides reductions in all cases ranging from 46 to 100 %. Overall, i.e. considering the total energy demand, the average energy savings compared to the ASHRAE 55 adaptive model are 63 %. The Australian adaptive model provides reductions in total energy demand in all climate zones, except for Darwin, in which energy demand increases 6.3 kW h/m^2·year compared to ASHRAE 55 adaptive model.

The lower energy demand of ASHRAE 55 adaptive model in hot climates and the Australian adaptive model in cold climates are partially due to the suitability of their applicability limits [74]. This can be seen in Fig. 9, which shows the behaviour of the different setpoint temperatures in all models and climate zones in present scenario. Also, when it is compared to Fig. 8, it can be observed that all the hourly temperatures fall within the thermal comfort zone. ASHRAE 55 and Australian adaptive models setpoints become flat at the hot end at 33.5 °C and 27 °C in T_{rm}, reaching the cooling setpoints 31.7 °C and 28.3 °C respectively at their highest. However, on the cold end, these become flat at 10 °C and 8 °C in T_{rm}, and the heating setpoints reach 24.4 °C and 23.3 °C respectively at their lowest.

3.3. Impact of climate change

The effects of rising outdoor temperatures were examined for all climate zones, taking into account the various setpoint temperature behaviours and the RCP2.6, RCP4.5, and RCP8.5 scenarios for the years 2050 and 2100. Table 10 shows the total energy demand in present and future scenarios (colour-shaded in yellow) as well as the increase or decrease of every future scenario compared to present scenario (colour-shaded in red for increases and green for decreases). The greatest increases take place in the Australian adaptive model, in which the average energy demand increases across the climate change scenarios ranging between 0 and 13 kW h/m^2·year, and the ASHRAE 55 adaptive model is better suited for future scenarios, as it results in an average energy demand reduction ranging from 3 to 11 kW h/m^2·year. However, the model with the lowest energy demand considering present and future scenarios is the Australian adaptive model, since the average energy demand ranges between 13 and 26 kW h/m^2·year, compared to ASHRAE 55 adaptive model, in which average energy demand ranges between 30 and 18 kW h/m^2·year.

From the point of view of climate zones, climate change has different energy implications. Fig. 10 shows the general trend for Hobart and Thredbo decreases, since cold temperatures are predominant in those climates; in case of Darwin and Alice Springs, the general trend increases, since hot temperatures are predominant; finally, in all other climate zones the increase in cooling and decrease in heating energy demands roughly compensate each other, and the energy demand varies in smaller ranges. However, there is some exception to be remarked consistently with the insights from Tables 9 and 10, which relates to the lower demand of ASHRAE 55 adaptive model mainly in Darwin but also, although to a smaller extent, in Alice Springs. The results are not fully comparable to other previous research [94] since location and therefore climates are different, however, the main trends of heating decrease and cooling increase remain similar [95].

3.4. Limitations

3.4.1. Building energy model

Building energy modelling, while a powerful tool for predicting energy usage and thermal comfort, has inherent limitations that must be acknowledged:

- Natural ventilation airflows: Predicting natural ventilation airflows is a complex task with many variables. These variables include meteorological factors such as the location of the weather station, wind speed and direction, and the average surface pressure

Table 9
Energy saving as a percentage and difference variation.

Energy demand	Comparison	Units	CZ1-Darwin	CZ2-Brisbane	CZ3-Alice-Springs	CZ4-Mildura	CZ5-Sydney	CZ6-Melbourne	CZ7-Hobart	CZ8-Thredbo	Average
Cooling Energy Demand	1-(Australian/ASHRAE55)	%	–	−228 %	−169 %	−107 %	−121 %	−17 %	−27 %	28 %	−92 %
	ASHRAE55 - Australian	kWh/m^2·year	−6.3	−1.8	−8.2	−1.5	−0.8	−0.5	0.0	0.0	−2.4
Heating Energy Demand	1-(Australian/ASHRAE55)	%	–	88 %	67 %	81 %	88 %	96 %	67 %	46 %	76 %
	ASHRAE55 - Australian	kWh/m^2·year	0.0	17.1	22.7	24.5	16.8	6.3	30.1	33.2	18.8
Total Energy Demand	1-(Australian/ASHRAE55)	%	–	76 %	38 %	73 %	81 %	62 %	67 %	46 %	63 %
	ASHRAE55 - Australian	kWh/m^2·year	−6.3	15.3	14.5	23.0	16.0	5.8	30.1	33.3	16.5

coefficient. Additionally, the unpredictable behaviour of occupants in terms of when and how much they open or close windows adds another layer of complexity. This behaviour is not deterministic and can vary from room to room. Lastly, the aerodynamics of the airflow around windows, which depends on the window type, the wind's angle of attack, and the degree to which the window is open, also introduces uncertainty into the model. In this case, the necessity to open or close the windows is evaluated each timestep of the simulation, independently of the time of the day. That means, even at nighttime, windows are opened or closed as many times as needed, which is not a very realistic window behaviour. This behaviour has been normalised to some extent by modulating the open fraction, which is calculated using a linear equation dependent of the difference between indoor and outdoor temperatures.

- Modelling assumptions: The model is based on a number of assumptions, such as constant indoor air temperature, which may not always hold true in real-world scenarios. These assumptions can significantly impact the results.
- Sensitivity to input parameters: The model's predictions are highly sensitive to input parameters. Small changes in these parameters can lead to significant variations in the predicted outcomes.
- Lack of real-world validation: The model's predictions have not been validated against real-world data. This limits the confidence that can be placed in the model's predictions.
- Inherent uncertainties: These uncertainties stem from the simplifications and assumptions made in the model, as well as the variability and uncertainty in the input data.

By acknowledging these limitations, we aim to provide a more balanced and realistic view of the model's capabilities and the confidence that can be placed in its predictions.

3.4.2. *Adaptive thermal comfort models*

As a result, the current analysis is firstly limited on the assumption that occupants will adapt to air-conditioned environmental temperature fluctuations similarly to how they would in a naturally ventilated space. Secondly, and similar to this, the Australian local adaptive comfort model, which covers climate zone 5, was created based on thermal sensation surveys conducted in the adjacent cities of Sydney and Wollongong (humid subtropical climate). The same model has been used throughout the entire Australian territory since it is the best approximation because there is no other comfort model to account for all different climates. There is only one other adaptive comfort model for Australia developed by Williamson et al. [75], however it was also developed based on thermal comfort surveys collected in the areas of Perth (CZ5), Adelaide (CZ5), Sydney (CZ5), and Melbourne (CZ6). Moreover, similarities between linear regressions in Williamson and de Dear et al. models (T_{rm}*0.26 + 15.9 in Williamson's and T_{rm}*0.26 + 16.75 in de Dear's) serve to strengthen the validity of the adaptive model adopted for the current analysis. This may also be a limitation of the study since it is anticipated that there may be some discrepancies when using a local comfort model created for a subtropical region in, for example, a warmer tropical location. Thirdly, the Australian adaptive model is based on air-conditioned dwellings, while ASHRAE 55's is entirely based on naturally-ventilated buildings. Therefore, occupants from Australian model's buildings were acclimatized to air-conditioned indoor environments, while occupants from ASHRAE 55 model's building had a wider acceptable temperature threshold. Finally, the adaptive comfort theory supports that people will adapt to the increasing temperatures from future climate scenarios, at least to some extent. However, how they will and to what extent still remain uncertain. Therefore, in the absence of comfort models specifically developed for future scenarios, the linear regressions for present scenario have been used instead. That means, the adaptation to future increasing temperatures due to climate change has not been considered and certain errors have been introduced, restricting the ability to

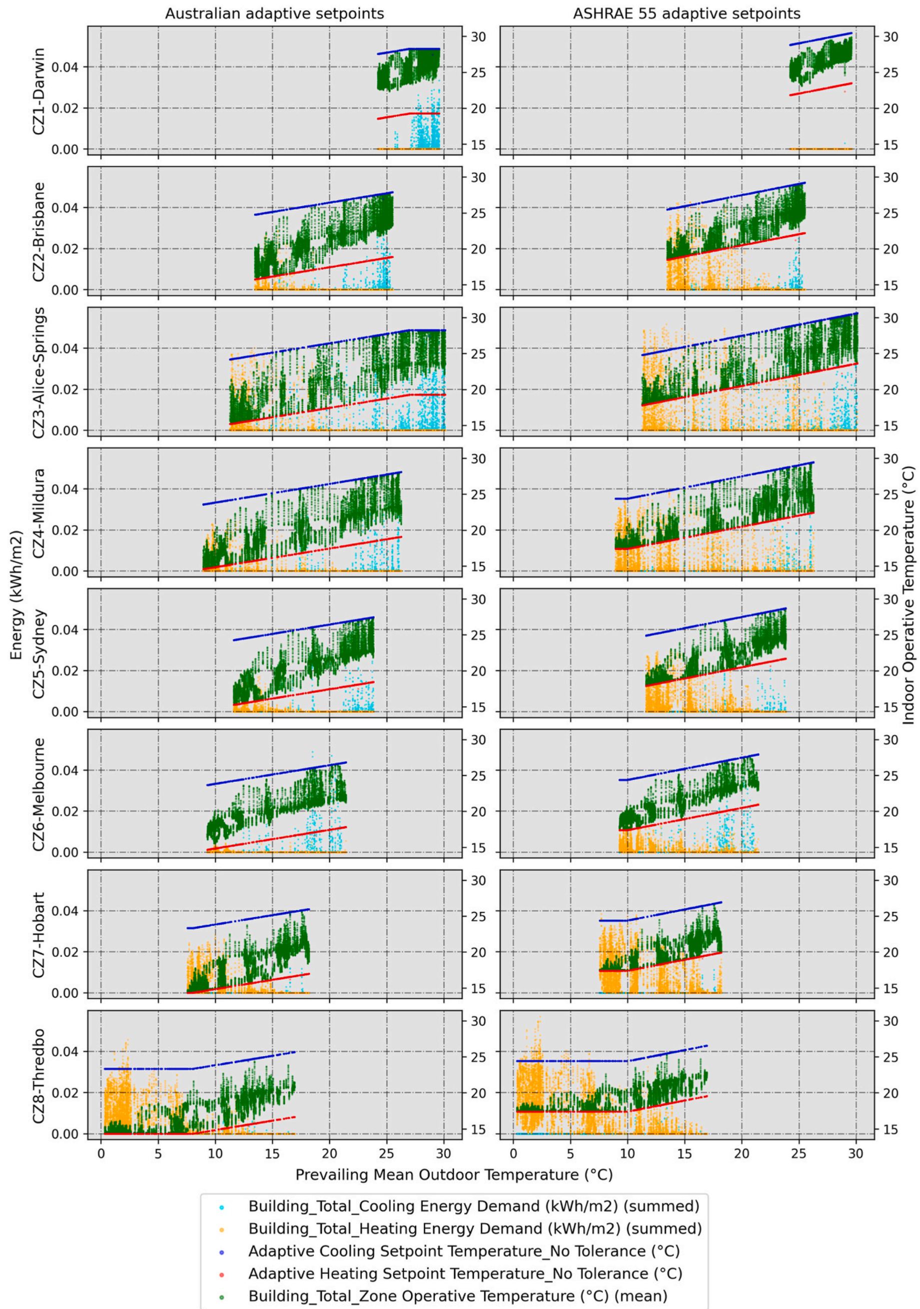

Fig. 9. Thermal comfort zones in all models and climate zones in present scenario.

Table 10
Total energy demand variation in the climate change scenarios.

		Total Energy Demand (kWh/m²·year)														
		Values								Increase or decrease from Present scenario						
Model	Climate zone	Present	RCP26 2050	RCP26 2100	RCP45 2050	RCP45 2100	RCP85 2050	RCP85 2100	Average	RCP26 2050 - Present	RCP26 2100 - Present	RCP45 2050 - Present	RCP45 2100 - Present	RCP85 2050 - Present	RCP85 2100 - Present	Average
Australian local adaptive	CZ1-Darwin	6	13	14	19	34	24	75	**27**	7	7	13	28	18	68	**24**
	CZ2-Brisbane	5	7	5	6	9	7	23	**9**	2	1	1	4	2	18	**5**
	CZ3-Alice-Springs	24	29	29	30	37	34	61	**35**	5	5	6	13	10	37	**13**
	CZ4-Mildura	8	8	8	7	8	8	11	**9**	-1	0	-1	0	0	3	**0**
	CZ5-Sydney	4	4	4	4	5	4	12	**5**	0	0	0	1	1	8	**2**
	CZ6-Melbourne	4	4	4	5	5	5	12	**5**	0	1	1	2	2	8	**2**
	CZ7-Hobart	15	11	12	11	9	10	5	**10**	-3	-3	-4	-6	-5	-10	**-5**
	CZ8-Thredbo	38	33	32	30	23	27	13	**28**	-6	-7	-8	-15	-12	-26	**-12**
	Average	**13**	**14**	**13**	**14**	**17**	**15**	**26**	**16**	**1**	**0**	**1**	**3**	**2**	**13**	**3**
ASHRAE 55 adaptive	CZ1-Darwin	0	0	0	0	0	0	4	**1**	0	0	0	0	0	4	**1**
	CZ2-Brisbane	20	18	16	16	13	15	13	**16**	-2	-4	-5	-7	-6	-7	**-5**
	CZ3-Alice-Springs	38	38	38	36	35	36	38	**37**	-1	0	-2	-3	-2	-1	**-2**
	CZ4-Mildura	32	28	28	26	24	26	18	**26**	-3	-4	-5	-7	-6	-13	**-6**
	CZ5-Sydney	20	16	16	15	11	13	9	**14**	-3	-4	-5	-8	-7	-11	**-6**
	CZ6-Melbourne	9	9	9	9	8	8	10	**9**	0	-1	-1	-2	-1	1	**-1**
	CZ7-Hobart	45	38	38	36	32	33	20	**35**	-7	-7	-9	-13	-12	-24	**-12**
	CZ8-Thredbo	72	63	61	60	49	55	33	**56**	-9	-10	-12	-23	-17	-39	**-18**
	Average	**30**	**26**	**26**	**25**	**22**	**23**	**18**	**24**	**-3**	**-4**	**-5**	**-8**	**-6**	**-11**	**-6**

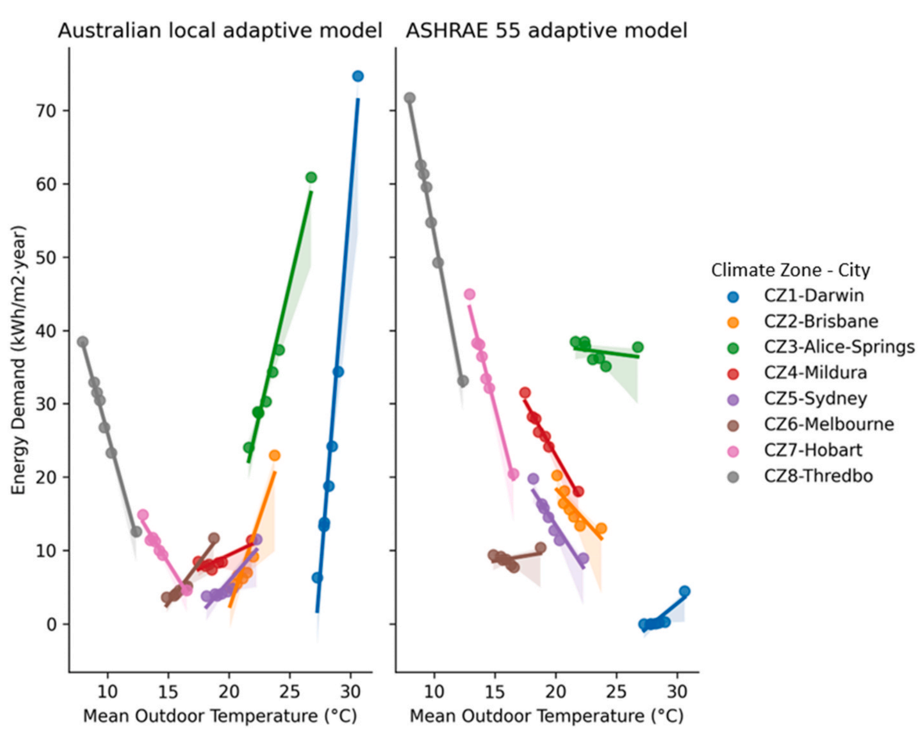

Fig. 10. Linear regressions for results in present and future scenarios in climate zones and models.

estimate comfort in future circumstances. Given that humans could withstand higher temperatures, taking thermal adaptation into account would likely result in higher adaptive cooling setpoint temperatures and potentially higher energy savings.

4. Conclusions

Adaptive setpoint temperatures, or setpoint temperatures based on adaptive comfort models, have gained recognition as a major energy-saving technique lately, since they give energy demand reductions essentially without any installation expense. International models EN16798-1 and ASHRAE 55 have been taken into account in studies based on adaptive setpoint temperatures up until this point, which have served as the framework for the Python package “accim” (which stands for Adaptive-Comfort-Control-Implemented Model). Nonetheless, this research examines the energy impacts of employing local or regional comfort models, specifically an Australian local adaptive comfort model, by contrasting it with the effects of using the ASHRAE 55 adaptive model. Building energy simulations were also carried out in each of the 8 climate zones while taking into account the years 2050 and 2100 for the Representative Concentration Pathways scenarios RCP2.5, RCP4.5, and RCP8.5 in order to comprehend the effects of climate change on energy across the country in the present and future. As a result, the following points can be concluded:

- employing adaptive setpoint temperatures derived from the Australian local model leads to significant energy conservation in comparison to the adaptive model proposed by ASHRAE 55 (with a 63 % decrease).
- When climate change is considered, the Australian model also has the lowest energy demand (since average energy demand values range between 13 and 26 kW h/m^2·year), although the trend for future scenarios is increasing, with average values between 1 and 13 kW h/m^2·year. Oppositely, this trend in case of the ASHRAE 55 model is decreasing, with average values ranging between 3 and 11 kW h/m^2·year.

Hence, utilizing setpoint temperatures derived from the Australian local adaptive comfort model emerges as an exceptionally effective approach for conserving energy. Also, this study emphasizes the importance of using a suitable adaptive comfort model for thermal comfort and energy predictions, which otherwise, might lead to inaccuracies and discrepancies in energy demand. Nonetheless, it is important to note that this study assumes individuals would acclimate to air-conditioned surroundings just as they would to naturally ventilated spaces, though this aspect requires deeper exploration. Additionally, the comfort model from Australia, analysed in this research, was initially designed for Sydney’s climate. Given the absence of a more fitting comfort model for other Australian climates, it has been extended for application across all climatic zones. These two constraints offer suggestions for prospective research directions, which might focus on a comprehensive exploration of thermal perception incorporating adaptive setpoint temperatures, and the creation of thermal comfort models suitable for the other Australian climates. Considering the interconnectedness of adaptive thermal comfort and energy-related challenges, these discoveries could be valuable information for decision making and potentially steer forthcoming advancements in Australian social housing, factoring in climate change and the diverse climatic zones, akin to initiatives undertaken in Chile [96]. Closely related to this, adaptive comfort models have been recently used to mitigate energy poverty cases [97], which could be extrapolated to similar circumstances in Australia.

CRediT authorship contribution statement

Daniel Sánchez-García: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **David Bienvenido-Huertas:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Jorge Martínez-Crespo:** Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis. **Richard de Dear:** Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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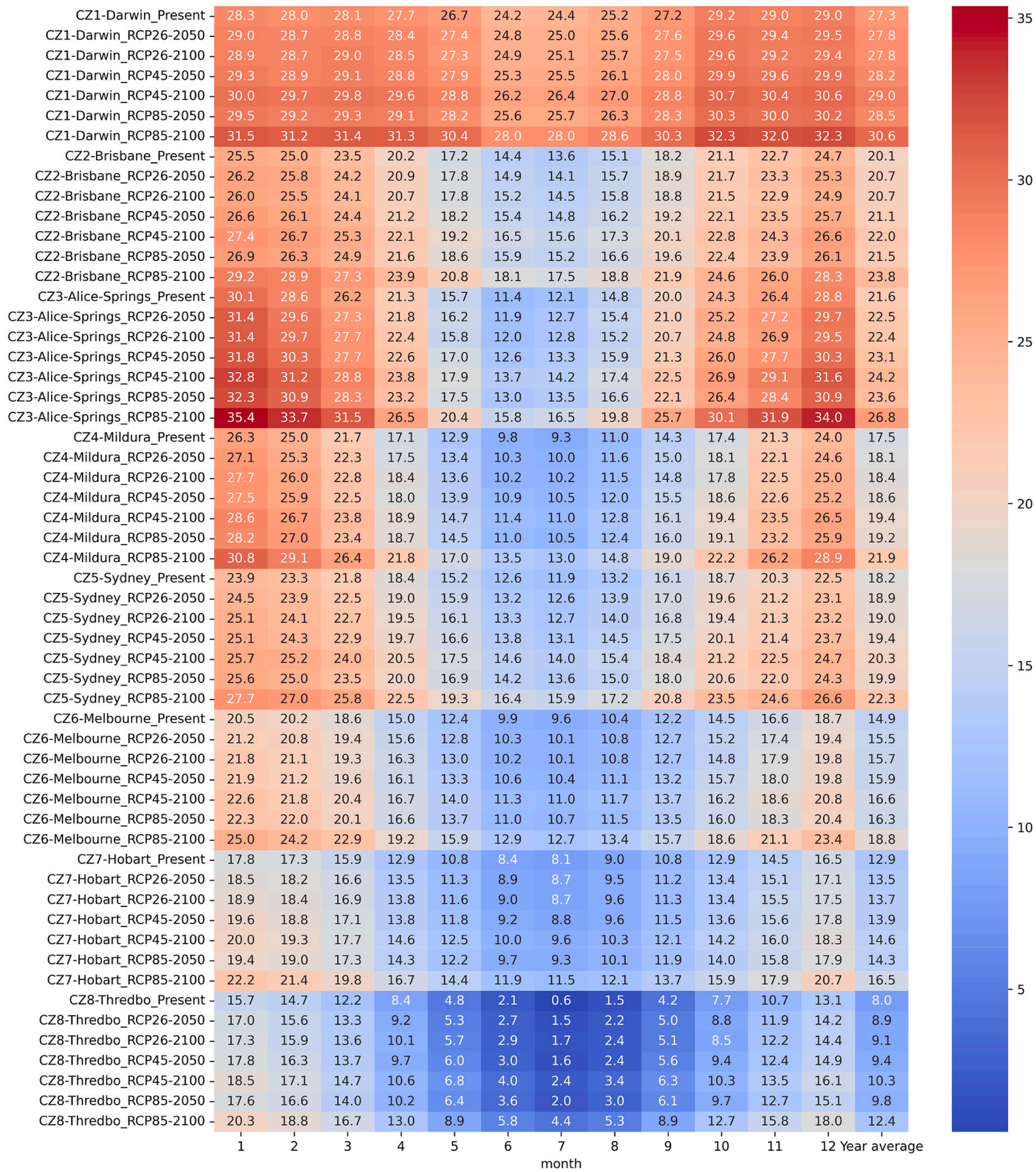
Appendix A

Table A1
Average monthly outdoor temperature in each city for present and future climate scenarios



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