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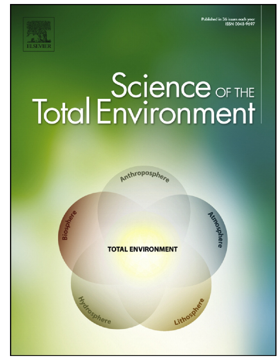

Seasonal temperature patterns and durations of acceptable temperature range in houses in Brisbane, Australia

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PII: S0048-9697(19)32170-9
DOI: https://doi.org/10.1016/j.scitotenv.2019.05.145
Reference: STOTEN 32306

To appear in: *Science of the Total Environment*

Received date: 14 February 2019
Revised date: 8 May 2019
Accepted date: 11 May 2019

Seasonal temperature patterns and durations of acceptable temperature range in houses in Brisbane, Australia

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Abstract

A paradigm shift to the use of indoor rather than outdoor temperature to estimate the exposure risk of low and high temperatures is vital for better prediction of temperature health effects and timely health warnings, and will also assist in understanding the influence of temperature on energy consumption and comfort. This study aimed to quantify the percentage of hours during the year that indoor temperature (living room) was in the extended comfort band (18–28^{o}C) of a subtropical climate, and identify the diurnal pattern of indoor temperatures in different seasons. Data used was collected in a previous study on the association between indoor and outdoor temperature. A k-shape cluster analysis resulted in two clusters of indoor temperature patterns for both weekdays and weekends. A bimodal pattern was identified during the cool season and a flat top pattern for the warm season, with many variations at weekends. These patterns can be attributed to the influence of cooling and heating processes depending on the season as well as occupancy, occupants' interference, and building materials. During the intermediate season, a sinusoidal pattern was observed for both weekdays and weekends because occupants likely relied on outdoor temperature conditions which were similar to those expected indoors without heating or cooling devices. The percentage of hours in which the indoor temperature of the houses ranged within the extended comfort band was 72–97% throughout the year, but for the coldest and hottest months it was 50–75%. These findings show that Brisbane residents are at possible risk of exposure to cold and hot temperatures due to the poor thermal performance of houses, and confirm that there is no standard indoor temperature pattern for all houses.

Keywords: Indoor temperature, thermal comfort, residential houses, temperature pattern, temperature sensors, k-shape algorithm cluster analysis

1. Introduction

The impact of outdoor temperature (low and high) on human health has been well documented by studies in the field of epidemiology and environmental science (Barnett and Morawska 2015; Gasparrini et al. 2015; Bunker et al. 2016; Basu et al. 2015; Wang et al. 2017; Zeka et al. 2014). The association between temperature and many health effects is usually non-linear (U- or J-shaped) with increased risks for both hot and cold temperatures (Barnett and Morawska 2015). Health impacts of outdoor temperature include respiratory, cardiovascular, and cerebrovascular deaths (Phung et al. 2016; Onozuka and Hagihara 2017; Zhang et al. 2018; Basu 2009), as well as diseases including hand, foot, and mouth diseases (Cheng et al. 2018; Zhang et al. 2016). Additionally, morbidities linked to outdoor temperature include increased emergency hospital admissions, occupational accidents, and food poisoning (Ito, Akahane and Imamura 2018; Stephen and Barnett 2016; Xiang et al. 2015; Wang et al. 2013; Qiu et al. 2015). Adults over the age of 65 years and infants are generally most susceptible to the health effects of outdoor temperature (Basu and Ostro 2008; Xu et al. 2012; Basu et al. 2015). The World Health Organization (WHO) recommended indoor air temperature in residential settings to protect health to be within the range between 18–24^{o}C, while the extended comfort band in a subtropical climate was proposed to range between 18–28^{o}C (Tuohy et al. 2011; Miller, Buys and Bell 2012) (WHO, 1987).

The exposure risk of outdoor temperature is estimated by using data that are available from a network of meteorological stations (Basu 2009), while indoor temperature data are scarce (particularly in households). The use of outdoor temperature data from meteorological stations as a surrogate for 24-hour exposure contributes to inconsistency in epidemiological risk estimation, because meteorological stations are fixed to a location, whereas humans have geographically varying activity patterns. Other factors include differences in microclimate as a result of being indoors, varying vegetation cover, and urban heat island and urban albedo effects (Tomlinson et al. 2011; Zhang et al. 2011; Bernhard et al. 2015). Personal exposure investigations have shown that humans spend most of their time indoors, especially the vulnerable (infants, sick, and disabled); thus, indoor temperature is the most appropriate measure of exposure to low/high temperatures (Klepeis 2001). The scarcity of indoor temperature data has meant that outdoor temperature is used to estimate 24-hour exposure (Ormandy and Ezratty 2012). Indoor temperature is more difficult to collect because it involves placing monitors inside households.

A common temperature measure that best estimates low or high temperature health effects in all locations has not been found, and even the best estimate in the same location can vary annually. The difficulty in determining this measure has been attributed to the inaccuracy in risk assessment as a result of the use of outdoor temperature in place of indoor temperature. Studies have therefore reported the need to focus on indoor temperature for better prediction of temperature health effects and timely health warnings (Barnett 2015).

Indoor temperature is also monitored to investigate human thermal comfort, household energy consumption, and the thermal efficiency of buildings (Hong et al. 2009; Al-ajmi and Loveday 2010; Kavgic et al. 2012; Lomas and Kane 2013). Energy consumption in houses in developed countries contributes to 40% of world energy demand as a result of the use of heating, ventilation, and air conditioning (HVAC) and other services (refrigeration, cooking, and lighting) (Heller et al. 2015). The energy demand in houses is expected to increase on average by 1.4% per year, and is influenced by population and economic growth (International Energy Outlook, 2016).

In south-east Queensland, where Brisbane is the capital city, it is estimated that to house an additional two million people by 2041, about 794,000 more dwellings need to be built (The Queensland Cabinet and Ministerial Directory, 2018). Thus, in the near future, energy consumption is likely to increase, given that over 49% of existing houses use air conditioning for cooling (ABS, 2014). Moreover, in summer 2017, south-east Queensland exceeded the highest ever daily demand on the electricity network, as occupants resorted to air conditioners during a week-long heatwave (Swanston, 2018).

The changing climate, the impact of low and high temperatures, and the increasing energy demand mean that it is important to examine indoor temperatures, particularly in residential settings. This information on indoor temperature would aid the building industry in housing design and construction and encourage the reform of existing policies to meet expected thermal comfort. Further, such information would be important in assessing the risk of extreme temperature exposure to humans and in supporting energy demand models.

This study aimed to use indoor (living room) temperature data already collected during our previous study on the relationship between indoor and outdoor temperature in warm and cool seasons (Asumadu-Sakyi et al. 2019) to:

I. identify the diurnal pattern of indoor temperature in different seasons;
II. quantify the percentage of hours during the year that indoor temperature was in the extended comfort band (18–28°C) in a subtropical climate, and the implications for extreme temperature exposure, thermal comfort, and energy consumption.

Our previous study developed a new model to quantify the association between indoor temperature in households and the immediate surrounding outdoor temperature and identified factors driving the association. The model predicted that on average, a 1oC increase in outdoor temperature resulted in a 0.4oC increase in indoor temperature during both the cool and warm seasons. This association was moderately influenced by the age of house, building material, roof material, and insulation. While our previous study quantified the association between the indoor temperature in households and the immediate surrounding outdoor temperature, the present study focused on indoor temperature, in particularly to gain better understanding of extreme temperature exposure and energy consumption in houses.

2. Method

2.1 Climate of the study area

The study was set in Brisbane (27° 28' S, 153° 1' E), Queensland, which has a subtropical climate. Mean annual minimum and maximum daily temperatures are 16.0°C and 26.6°C. Winter (June to August) has long-term mean minimum and maximum temperatures of 11.2°C and 21.4°C. Summer (December to February) has long-term mean minimum and maximum temperatures of 21.3°C and 29.3°C. General variability in Brisbane's temperature is minimal compared with that of other regional capitals of Australia due to the city's closeness to the warm ocean current (DEHP, 2016; BOM, 2017; Tourism Australia, 2018).

2.2 Outdoor temperature measured by the Bureau of Meteorology

Mean monthly outdoor temperature data were requested from three Bureau of Meteorology (BOM) stations and are presented in Table 1.

Table 1 Mean monthly outdoor temperatures between May 2017 and May 2018 from three Bureau of Meteorology stations in Brisbane

Location	Temperature (ºC)	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Archerfield Airport	Max	24.8	22.6	22.8	25.0	28.3	27.4	27.3	30.8	32.5	30.4	29.1	27.9	22.6
	Min	12.9	10.6	7.5	8.2	12.0	17.9	16.4	19.7	20.3	20.2	19.7	16.0	8.5
Brisbane Central Business District (CBD)	Max	24.7	22.8	22.9	24.7	27.3	27.0	27.0	30.7	31.8	29.9	28.7	27.8	24.8
	Min	15.1	12.9	10.3	10.9	14.2	18.8	17.7	20.8	21.6	21.2	20.8	18.0	13.9
Brisbane Airport	Max	23.6	22.2	21.7	23.3	25.7	25.5	26.0	29.1	30.5	28.7	27.6	26.6	23.8
	Min	14.4	12.0	9.2	10.3	13.4	18.5	17.3	20.6	21.2	20.8	20.5	17.7	13.1

2.3 Indoor and outdoor measurements

The data collection process was described in our previous study (Asumadu-Sakyi et al. 2019, under review). Briefly, the study involved field measurement of indoor (living room) temperature in 77 houses (49 slab-on-ground [SOG] and 28 Queenslanders, a local architectural style) varying in building materials, types, and with their locations shown in Figure 1. Initially, ninety-four houses were selected, located in 49 residential suburbs across the city of Brisbane (Fig. 1). These houses were 80 detached houses (51 SOG and 29 Queenslanders), 11 semi-detached and 3 apartments, a distribution that was consistent with that of Brisbane's housing stock. We focused on the detached houses because the sample size of this type of house was sufficiently large for the analysis. However, we were compelled to exclude four houses from the analysis during the cool season and three houses during the warm season because of missing data. An SOG detached house was defined as a single or two-story house with a concrete slab as a foundation that stands within its grounds and includes private open space, while a Queenslander house is a stand-alone house constructed with single-skin timber walls, a corrugated iron roof and suspended timber floors on timber or concrete stumps (BCC, 2011; Osborne 2014; http://www.househistories.org/qld-house-designs-1887-1920). The Queenslander houses in this study had been renovated previously to provide internal wall sheeting. Houses were recruited by electronic mail through Queensland University of Technology's media office and social media (Facebook), as well as through social and family networks by word of mouth. Occupants had to be 18 years or older, plan to be in the house for at least one year, and agree to participate. Information on housing characteristics such as house types, construction materials, heating and cooling options, and cooking systems, was collected through a questionnaire. The housing characteristics are summarized in Table A.3.

Houses were grouped as non-air conditioned (non-AC) or air conditioned (AC) depending on the presence or absence of space heating or cooling devices. The presence of an HVAC system in this climate does not necessarily mean that the system is regularly used. Data on the actual running times and set point temperatures of such systems in use in the houses were not collected, as we anticipated that device operation times would be identified from the recorded indoor temperature patterns.

The study procedure complied with the QUT Human Research Ethics standard conditions (approval number 1700000192).

Temperature sensors (Maxim Integrated DS1921 Hygrochron iButton and Labjack Digit TL sensors) were installed in indoor (living room) and outdoor areas of houses to monitor temperature simultaneously and continuously every 30 minutes from May 2017 to May 2018. The Maxim Integrated DS1921 Hygrochron iButton has an accuracy of ± 1^{o}C; an operating temperature of –40^{o}C to +85^{o}C and, at a setting of 30 minute intervals, has a storage capacity of approximately 2,048 readings (see Table A.1 for specifications). The Labjack Digit TL sensors have a memory capacity for 260,000 readings; an accuracy of ± 1^{o}C, and a measurement range of –35^{o}C to +85^{o}C (see Table A.2 for specifications). At a recruited house, sensors were installed by the investigator on the inner wall of the living room, away from children and sources of heat, and at a location where it would not be moved.

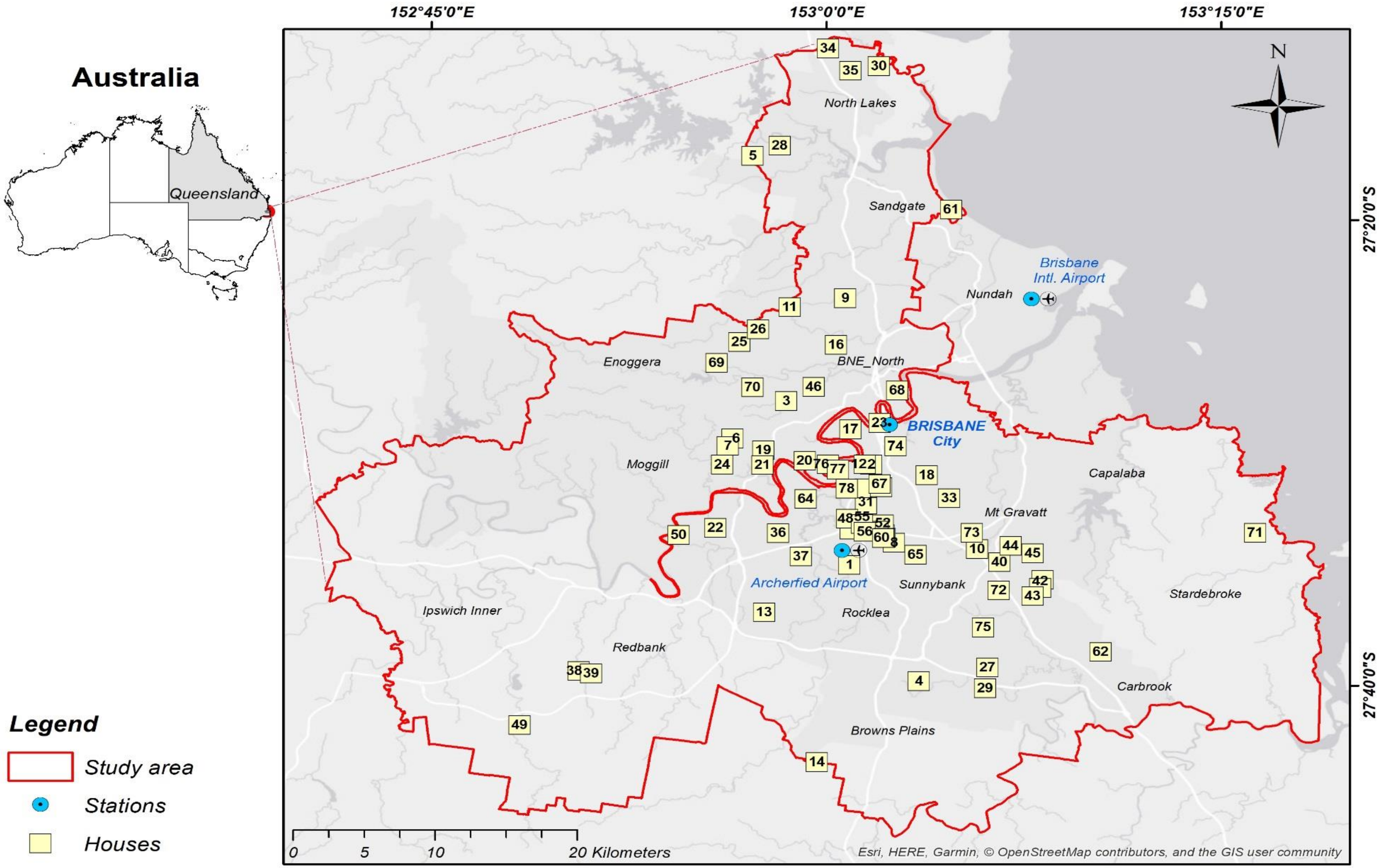


Figure 1 Map of the study area with the locations of the houses and the three meteorological stations marked.

2.3 Data preparation

Temperature data were downloaded into Microsoft Excel 2013 and then loaded into R statistical software (R Core Team 2018). R is a language and environment for statistical computing (R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/). Initial checks were made for missing values and outliers. Descriptive statistics for the indoor data are shown in Table A.4. Outdoor temperature data from the BOM were used for season selection by visual inspection; thus, the months of June to August were selected to represent the cool season, and December to February to represent the warm season. September to November and March to May were selected as representing intermediate seasons.

2.4 Statistical technique

The k-shape clustering algorithm was used to identify patterns in the indoor temperature of all houses during the intermediate seasons and only air conditioned houses during the cool and warm seasons. This method was chosen because it uses a scalable iterative refinement procedure that generates homogenous and well-separated clusters, and is an efficient and accurate clustering approach for time series data (Paparrizos and Gravano 2015).

The percentage of hours that the indoor temperature remained within the extended comfortable band (18–28^{o}C) was calculated. The comfort band was derived based on the adaptive comfort equations (equations 1 and 2) (Tuohy et al. 2011; Miller et al. 2018) that incorporate the mean monthly outdoor temperature of the hottest (January) and coldest (July) months as well as an acceptance level. The analysis was to quantify and compare the thermal performance of the living rooms of the houses in terms of percentage annual hours.

$$T_n = 17.8 + 0.31 \times T_{om}(January) \pm 2.5\ ℃ \qquad (1)$$

$$T_n = 17.8 + 0.31 \times T_{om}\ (July) \pm 3.5\ ℃ \qquad (2)$$

Where T_n: thermal neutrality; T_{om}: mean outdoor temperature.

3. Results

3.1 Data

Temperature was measured in 100% of the houses, but data was available for only 96% due to unforeseen circumstances such as discontinued participation and loss of measuring devices. Therefore H12, H33 and H38 are not included in the analysis.

3.2 Indoor temperature

The median annual indoor temperature of the houses was 24.0°C (IQR: 21.2–26.4°C), which was within the annual 'acceptable' temperature range (extended comfort band) of 18–28°C for this climate. However, only 59% of the houses were within the World Health Organization (WHO) recommended indoor air temperature range of 18–24°C for residential settings.

Indoor temperature in the houses varied by month as shown in Figure 2, particularly during the cool and warm seasons. For the cool season, the median indoor temperature was 19.8°C (IQR: 18.0–21.5°C), while for the warm season it was 26.6°C (IQR: 25.2–28.5°C). Indoor temperatures were similar by type of house and by construction material. For Queenslanders, the median indoor temperature was 24.0°C (IQR: 21.5–26.5°C) and for SOG houses, it was 24.0°C (IQR: 21.0–26.3°C). For houses constructed of brick, the median indoor temperature was 24.0°C (IQR: 21.4–26.5°C), for concrete it was 23.6°C (IQR: 21.0–25.8°C), and for lightweight materials it was 24.0°C (IQR: 21.0–26.4°C).

Variation in indoor temperatures in the houses during the intermediate seasons was minimal. Median indoor temperature between September and November was 23.6°C (IQR: 21.9–25.5°C), while between March and May it was 23.5°C (IQR: 21.5–25.5°C). Indoor temperatures were similar to outdoor temperatures from September to November (22.0°C; IQR: 19.4–25.0°C; mean: 22.3°C) and from March to May (21.9°C; IQR: 19.0–24.5°C; mean: 21.8°C), suggesting that occupants mostly use natural means (opening of windows) to maintain comfort during these seasons.

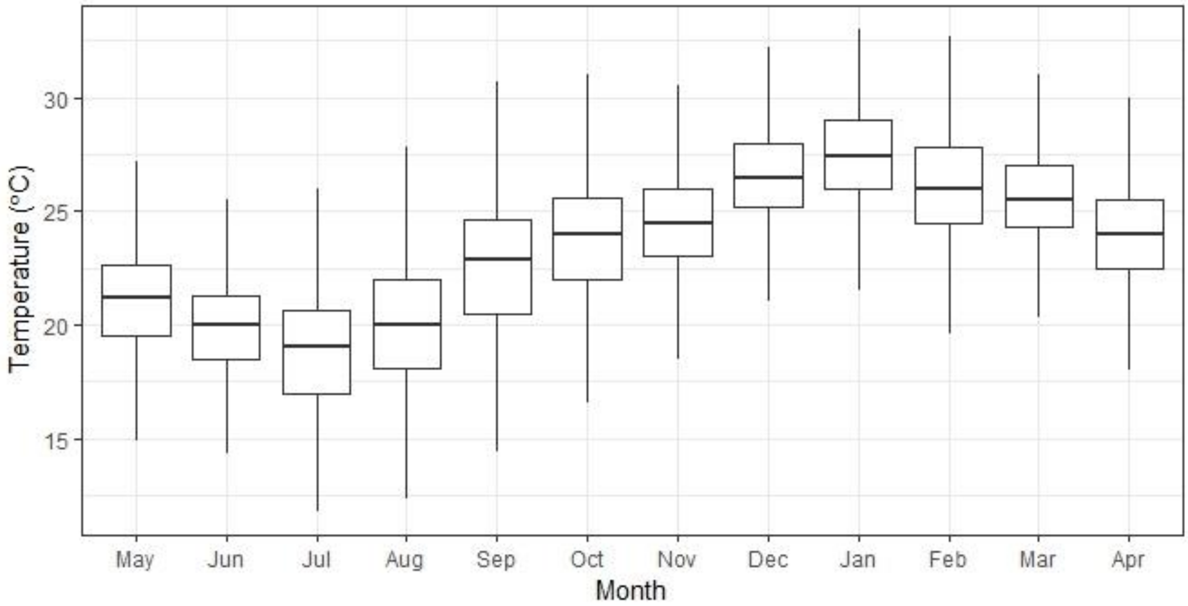


Figure 2 Boxplots of indoor temperatures by month for all the houses (May 2017 to May 2018).

3.3 Diurnal pattern of indoor temperature

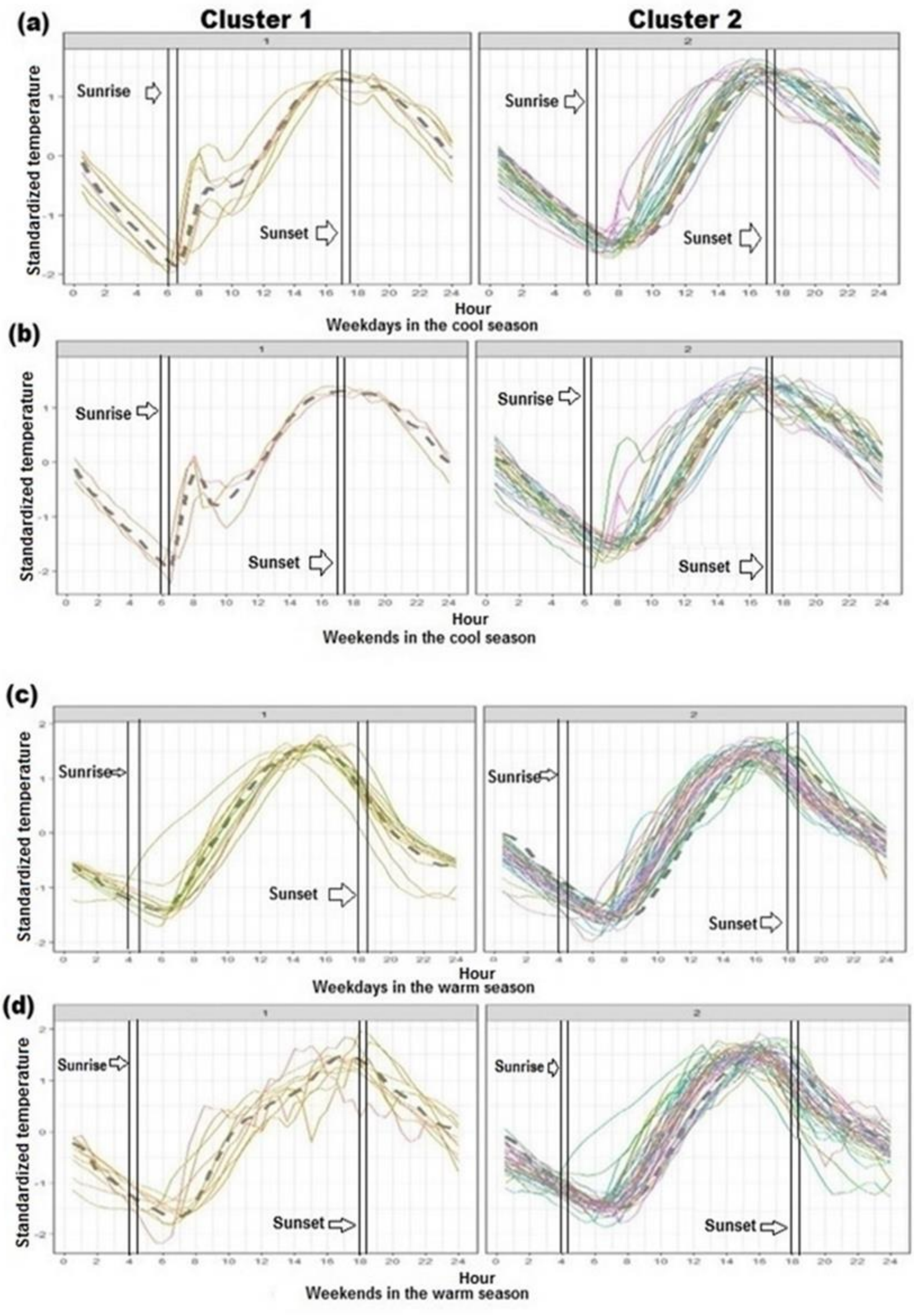
The k-shape clustering analysis resulted in two clusters of hourly mean indoor temperatures (1 and 2) both for weekdays (Monday to Friday) and weekends (Saturday to Sunday) during the cool, warm and intermediate seasons, as presented in Figures 3 and 4. Information on the distribution of building characteristics in the identified clusters is also found in Tables 2 and 3. As mentioned earlier, house types were SOG and Queenslander, while construction materials included brick veneer, concrete and lightweight materials (timber). The presence of roof insulation was categorized as ‘Yes’ or ‘No’. In all seasons, cluster 2 contained many more houses than cluster 1. Houses found in cluster 2 were predominantly SOGs constructed of lightweight materials (timber) with roof insulation. The higher numbers of SOGs in our sample may have contributed to the observed skew in the number of houses contained in each cluster. The identified clusters are graphically represented in Figures 3 and 4.

Table 2 Houses in clusters 1 and 2 according to building characteristics during cool and warm seasons and weekends/weekdays

	Cool season				**Warm season**			
Building characteristics	**Weekday**		**Weekend**		**Weekday**		**Weekend**	
	Cluster				**Cluster**			
	1	**2**	**1**	**2**	**1**	**2**	**1**	**2**
House type								
SOG	3	18	1	18	11	27	8	30
Queenslander	3	7	2	8	3	12	1	14
Construction material								
Brick veneer	3	10	1	12	7	16	5	18
Concrete	0	1	0	1	3	1	0	4
Lightweight	3	14	2	13	4	22	4	22
Roof insulation								
Yes	5	22	3	22	10	35	9	36
No	1	3	0	4	4	4	0	8

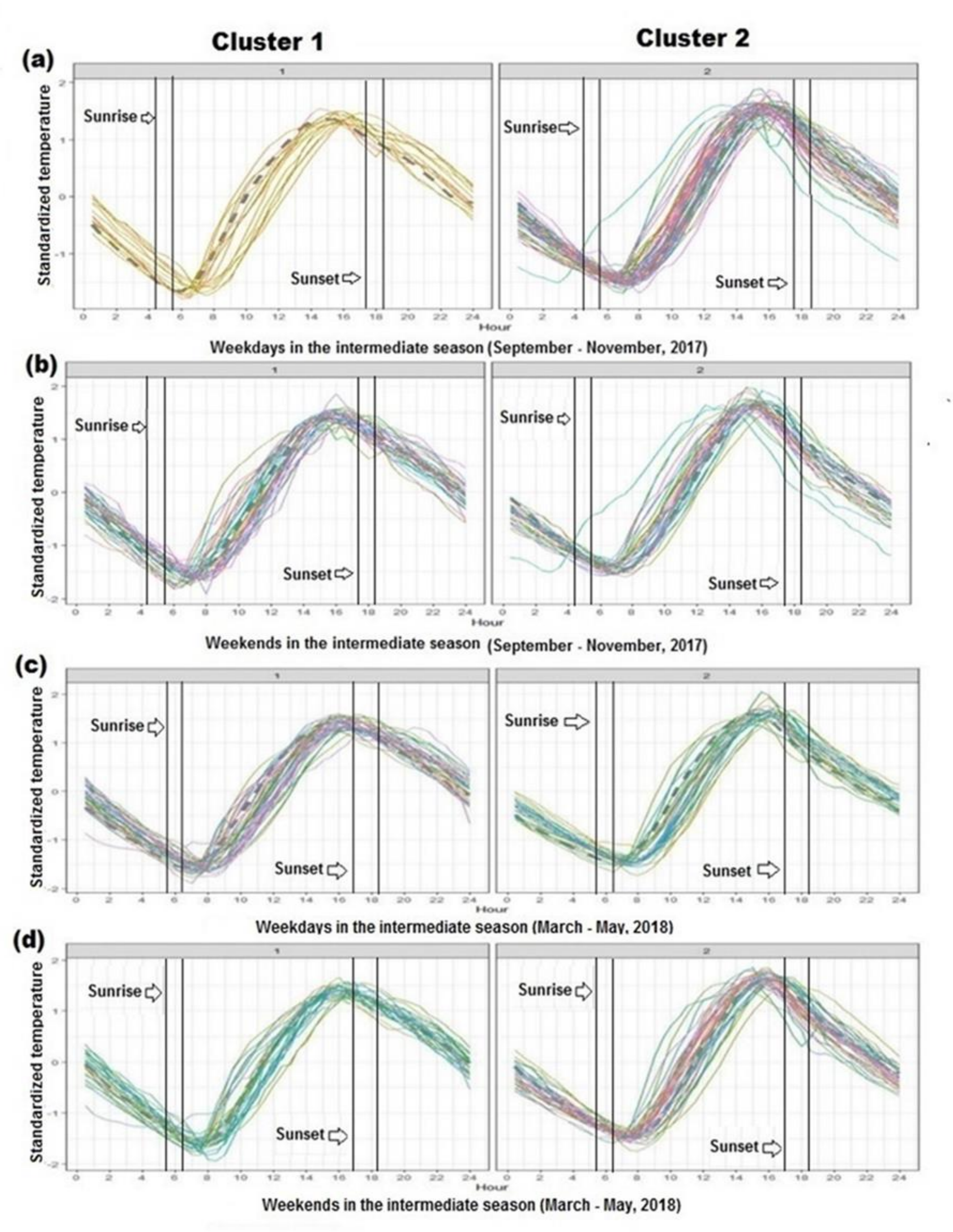
Table 3 Houses in clusters 1 and 2 according to building characteristics during intermediate seasons and weekends/weekdays

	Intermediate seasons							
	September–November 2017				**March–May 2018**			
Building characteristics	**Weekday**		**Weekend**		**Weekday**		**Weekend**	
	Cluster				Cluster			
	1	**2**	**1**	**2**	**1**	**2**	**1**	**2**
House type								
SOG	10	33	24	19	23	20	18	24
Queenslander	4	22	12	14	15	10	10	15
Construction material								
Brick veneer	6	22	16	12	14	14	9	18
Concrete	1	2	1	2	1	2	1	2
Lightweight	7	31	19	19	23	14	18	19
Roof insulation								
Yes	13	42	34	22	34	22	26	29
No	1	13	2	11	4	8	2	10



Note: The peak in temperature occurs at different locations in relation to the period of sunset.

Figure 3 Two clusters of diurnal indoor temperature patterns for weekdays and weekends during the cool season (a, b) and the warm season (c, d). Each panel represents a cluster.



Note: The peak in temperature occurs at different locations in relation to the period of sunset.

Figure 4 Two clusters of diurnal mean indoor temperature patterns for weekdays and weekends during intermediate seasons (September–November 2017) (a and b) and (March–May 2018 (c and d). Each panel represents a cluster.

During the cool season, the hourly mean indoor temperature for weekdays (Figure 3a) in cluster 1 decreased steadily to a minimum between 00:00 and 6:00, then increased steeply between 6:00 and 8:00, followed by a decrease between 9:00 and 10:00. It then increased steeply after 10:00 to a maximum between 14:00 and 16:00, and decreased gradually again. Two peaks were observed in the trend around the hours of 08:00 and 19:00, exhibiting a bimodal pattern. In contrast, the hourly mean indoor temperature trend in cluster 2 reached peaks in the evening between 18:00 and 22:00.

Hourly mean indoor temperature patterns in both clusters for weekends during the cool season (Figure 3b) were comparable to each other in that a single peak was observed around 08:00. This differed from the weekday patterns. In both clusters (1 and 2) for weekends, the hourly mean indoor temperature decreased steadily to a minimum between 00:00 and 6:00, then increased steeply between 6:00 and 8:00, followed by a decrease between 9:00 and 10:00. It then increased steeply after 10:00 to a maximum between 14:00 and 16:00, and decreased again between 20:00 and 23:00.

During the warm season, the hourly mean indoor temperature pattern in clusters 1 and 2 noted for weekdays (Figure 3c) were analogous to each other, but differed when the temperature decreased in the evenings. In cluster 1, the hourly mean indoor temperature decreased steadily to a minimum between 00:00 and 6:00, then constantly increased after 6:00 to a maximum at around 16:30, then decreased steadily again between 17:00 and 23:00. Houses in cluster 2 exhibited a similar trend to cluster 1 over most of the day, except for a steeply decreasing trend between 18:00 and 23:00. The hourly mean indoor temperature patterns for weekdays in both clusters showed flat-top patterns, particularly around the period when the maximum temperature was observed. In both clusters, the hourly mean indoor temperature patterns occasionally peaked between 18:00 and 20:00.

During weekends in the warm season (Figure 3d), hourly mean indoor temperature patterns in clusters 1 and 2 were irregular and distinctly different to those noted during the weekdays. Much variation was observed in the patterns, especially in cluster 1, as the hourly mean indoor temperature increased to a maximum (around 16:30) and decreased again (18:00 to 23:00).

The hourly mean indoor temperature pattern noted in the houses during the intermediate season (September to November 2017) was sinusoidal in both clusters as shown in Figure 4a and b. During weekdays, the hourly mean indoor temperature in both clusters decreased steadily to a minimum between 00:00 and 8:00, then increased steeply to a maximum between 14:00 and 16:00. It further decreased again between 17:00 and 23:30. The trend in the hourly mean indoor temperature in cluster 2 was similar to the trend in cluster 1. However, the decreasing trend noted between 17:00 and 23:30 was gradual in cluster 2, unlike the sharp decrease in cluster 1. The hourly mean indoor temperature pattern observed in both clusters at weekends was analogous to that on weekdays, although there was much variation in the patterns.

During the intermediate season (March to May 2018), the hourly mean indoor temperature pattern in both clusters for weekdays and weekends was sinusoidal (Figure 4c and d) and was similar to the hourly mean indoor temperature pattern observed in the other intermediate season (September to November 2017) as seen in Figure 4a and b.

3.4 Total number of hours during the year in/outside the comfort band

The thermal performance of the living rooms of the houses in terms of the percentage of hours during the year in the extended comfort band (18–28ºC) is summarized in Table A.5. A graphical representation of the thermal performance of the living room of each house in descending order is presented in Figure 5. The indoor temperature in the living rooms of the houses were within the extended comfort band range for most of the year (72–97%). Visual inspection of Figure 5 shows that as the percentage of hours within the extended comfort band range decreased, the percentage of hours at which temperatures were lower or higher than the extended comfort band increased. Houses with a smaller extended comfort band period are exposing occupants to temperature extremes that may impact on their health if the duration of the exposure is prolonged.

The percentage of hours in the extended comfort band varied by month, as shown in Figure 6. The longest comfort band period occurred in April and the shortest in July. The extended comfort band period increased in months in which the outdoor temperature conditions were more comfortable (intermediate seasons – March, April, May, September, October, November), and thus it was comparable between house type, construction material, and roof insulation as shown in Figure 6. In contrast, the extended comfort band period decreased during the cool (June, July, August) and warm (December, January, February) months (50–75%); therefore, it varied considerably between house type, construction material, and roof insulation (Figure 6). The longest_extended comfort band period was observed in an SOG concrete-constructed house (H69), while the shortest was in a Queenslander (H17).

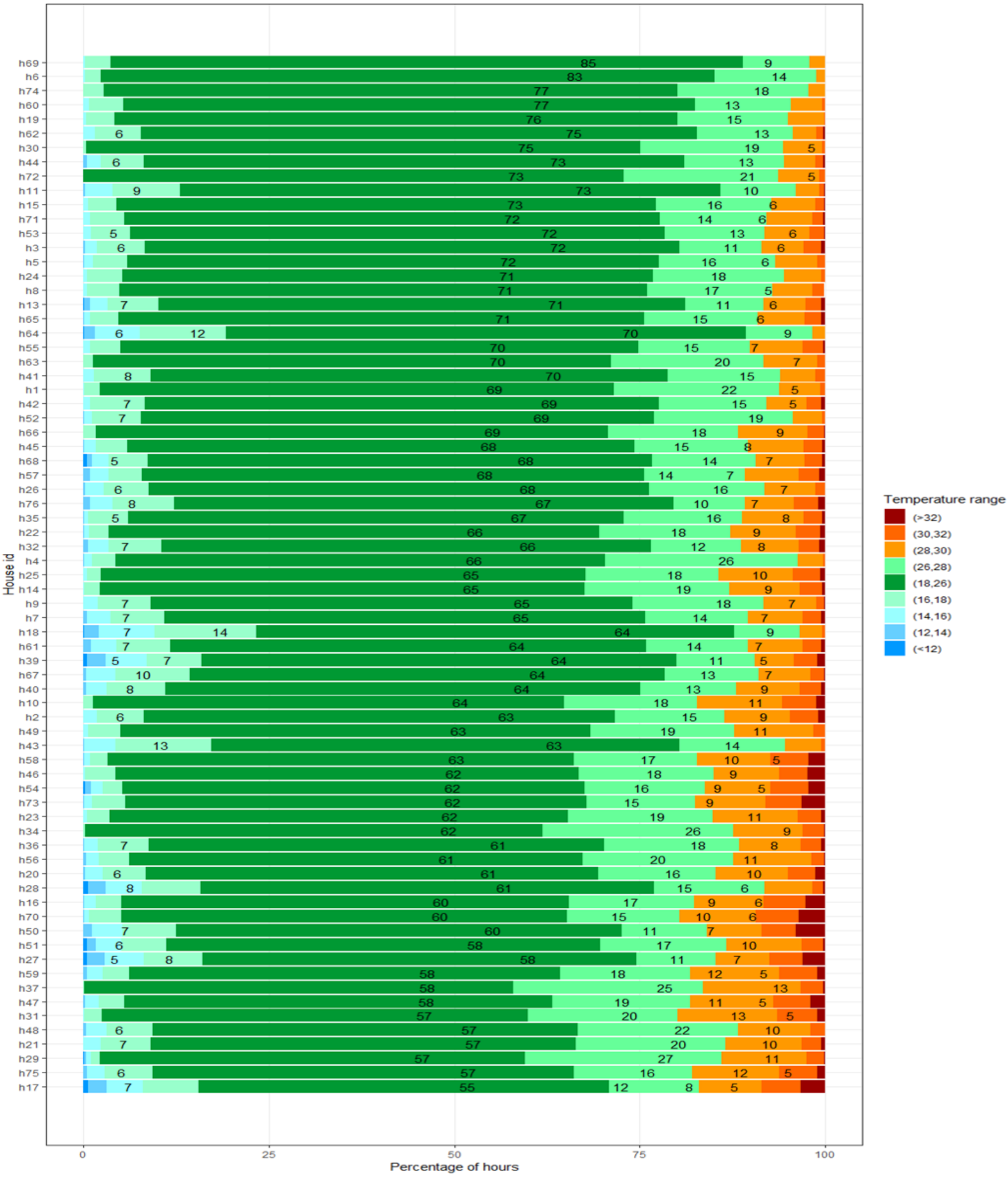


Figure 5 Percentage of hours during the year in different temperature ranges (May 2017 to May 2018).The two shades of green representing the temperature range of 18–28^{o}C show the number of hours within the extended comfort band. The blue sections represent the number

of hours colder than the extended comfort band, while the orange and red sections represent the number of hours warmer than the extended comfort band.

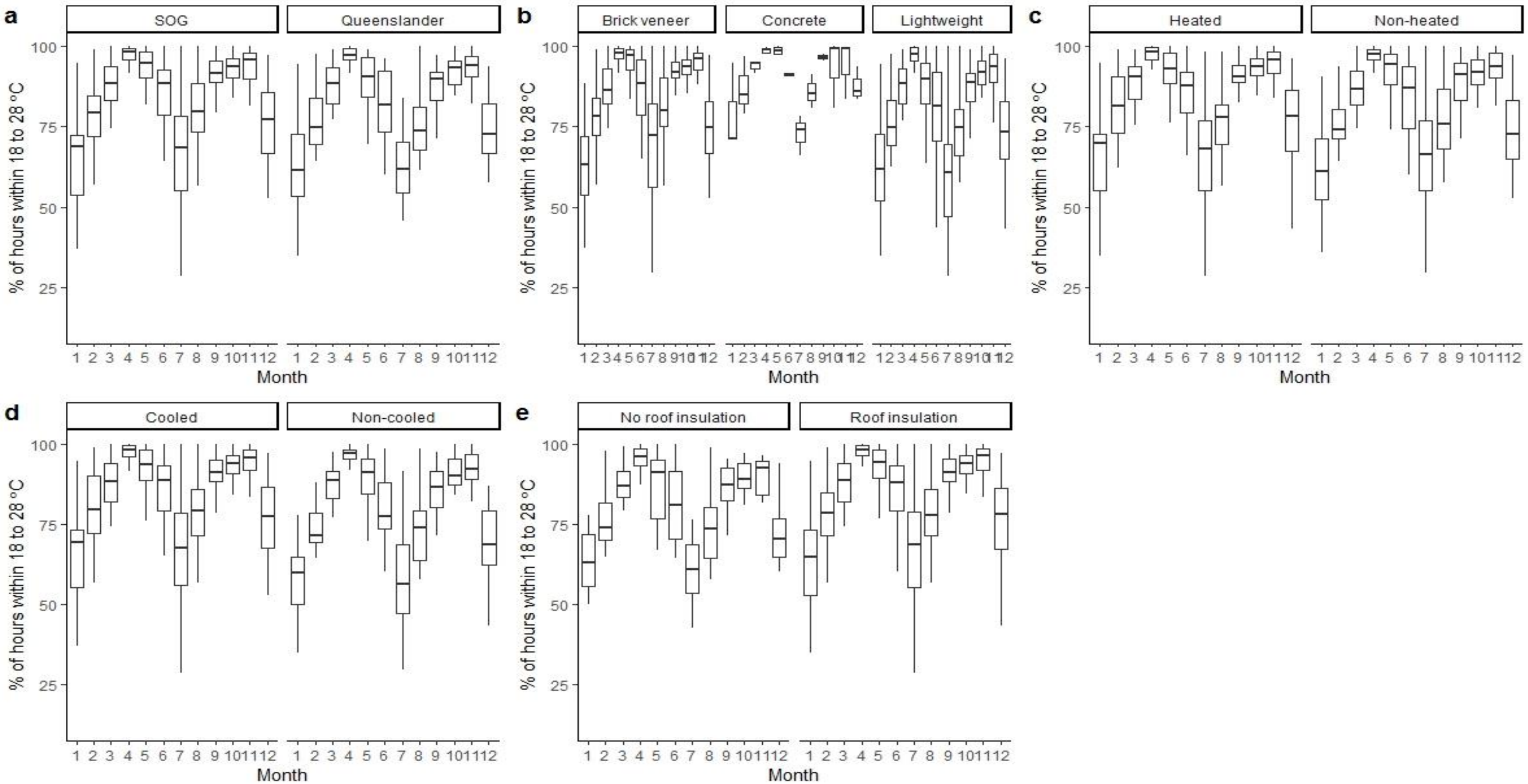


Figure 6 Boxplots of the percentage of hours within the extended comfort band by month and house type (a), construction material (b), air conditioned houses – heating (c), air conditioned houses – cooling (d), and roof insulation (e).

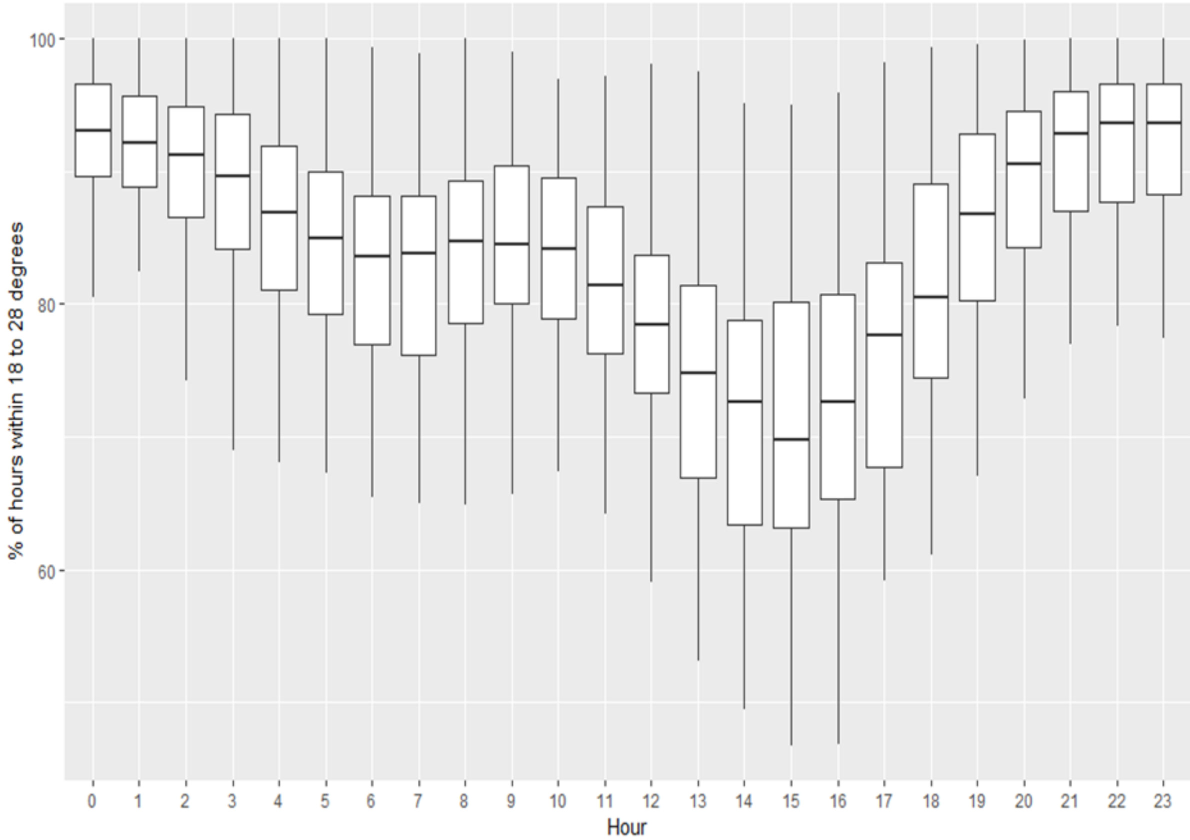


Figure 7 Boxplot of the percentage of hours within the extended comfort band by hour.

The hours inside the comfort band increases during the period that people are likely to be home and awake (17:00 – 23:00) (Figure 7), and this could be attributed to cooking by occupants and/or the use of cooling/heating devices/opening of windows to achieve to prefer indoor thermal condition.

4.0 Discussion and conclusion

This study used the data collected for a year in our previous study on indoor and outdoor temperature (immediate surroundings) of residential houses in Brisbane to identify diurnal patterns in indoor temperatures during different seasons, as well as to quantify the number of hours during the year at which the indoor temperature ranged within the extended comfort band (18–28^{o}C) in a subtropical climate. We also discussed the implications for extreme temperature exposure, thermal comfort, and energy consumption.

The k-shape cluster analysis performed on the indoor temperature dataset resulted in two different clusters of temperature patterns both at weekdays and weekends of the seasons considered. During weekdays in the cool season, bimodal patterns in the hourly mean indoor temperatures of cluster 1 and cluster 2 (Figure 3a) resulted from the use of heaters, either because the occupants may have been older or may have felt the cold, or because they may have had a higher income and could afford to use a heater. This was similar to the pattern of indoor temperatures reported by Huebner et al. in their study on temperature profiles in the living rooms of houses in the United Kingdom. For example, cluster 1 suggests the following: the house cools down in line with the outdoor temperature drop overnight (between 00:00 and 6:00); people turn on heating appliances when they rise, but only use them for a short time (until they go to work/school) (between 6:00 and 8:00), and once the heater is turned off, the inside temperature again drops a little in line with the outdoor temperature (between 9:00 and 10:00); houses receive some passive solar heating (e.g. sun in the windows) and/or are responding to the general warming of the outdoor temperature (as Brisbane winters are generally clear and sunny). The indoor temperature pattern also shows whether (and explains how) heating devices are used depending on occupancy and the occupants' preferences. The pattern also indicates that during the week, the occupancy of housing is much more homogenous; whereas on weekends it is not. This could account for the different patterns during weekdays and weekends. Occupant behavior has been related to variations in heating patterns (Gill et al. 2010).

During the warm season, the patterns shown by the hourly mean indoor temperature trend between 16:00 and 18:00 on weekdays in both clusters (Figure 4a and b) were attributed to the use of HVAC systems for cooling to attain preferred indoor temperatures, because the outdoor temperatures during that period reach the maximum. The trend shows that the indoor temperature increases during the day after 8:00 in line with the outdoor temperature (i.e. by passive solar heating); people turn on the HVAC system for cooling (between 16:00 and 20:00) because houses are likely to be occupied, before they go to sleep (but likely not overnight). The pattern observed at weekends was similar to that of weekdays over most of the day, but with much variation after noon (12:00). As mentioned above, the patterns suggest that it is feasible to assume that the use of cooling devices is influenced by occupancy and the occupants' preferences; and occupancy of houses is homogenous during the week, but not during weekends, as seen in Figure 4a and b. For example, the differing temperatures may be a result of occupants not being home (and therefore the house heating up as a response to the outdoor temperature); or of occupants being home but not putting on the air conditioning (opening doors and windows instead), or working outside in the garden. The influence of occupant behaviour on indoor thermal conditions has been reported by other studies (Andersen et al. 2009; Fabi et al. 2012; Daniel, Soebarto and Williamson 2015)

The sinusoidal pattern observed in the hourly mean indoor temperature trend in the clusters for weekdays and weekends during the intermediate seasons (March to May; September to November) (Figure 4c and 4d; Figure 4a and 4b) could be related to occupants' reliance on outdoor temperature conditions, as temperatures are similar to what is expected indoors without the use of heating or cooling devices. This is feasible as the difference between the mean daily outdoor and indoor temperatures in these months was 1.6^{o}C. Occasional peaks and differences in evening patterns seen on weekdays may be linked to the impact of the thermal mass characteristics of the houses as mentioned above, and may indicate specific days that were hotter or colder than the monthly means.

The hourly mean indoor temperature patterns identified in the houses show that space heating and cooling practices in these houses is carried out at certain periods of the day, rather than over a 24-hour period. This has important implications for energy consumption by the building stock as global warming occurs. That is, as the increase in outdoor temperature reduces demand for heating during the cool season, it could lead to an increase in demand for cooling during the warm season. Moreover, the identified indoor temperature patterns show that the heating and cooling in houses vary; thus, to represent these patterns with a single standard pattern, as assumed by energy models, would introduce some inaccuracy as emphasized by other studies (Hughes et al. 2013; Huebner et al. 2014). In addition, the patterns show that the indoor temperatures in houses are very similar in seasons when cooling or heating is not required. Heating and cooling patterns were impacted to varying degrees, depending on the season, the building materials, the day of the week, and the time of day. The latter two could indicate an occupant-related influence. The former two may indicate both the impact of the building materials and the occupants. Therefore, energy models need to take building typologies into account as well as occupancy-related factors. Not covered in this paper, but equally important, is how heating and cooling is provided. In the United Kingdom and other European countries, for example, winter heating is provided by gas. As climate change is leading to more summer overheating, cooling will likely be provided by electricity, so the impact of summer cooling could be immense in terms of the size of the electricity network and its ability to meet demand. In Brisbane, houses are cooled mostly by electricity, especially at night. However, during the day cooling is likely to be provided by rooftop photovoltaics (PVs) because Australia has the highest proportion of households with rooftop PVs globally (16.5%). Further uptake of PVs would likely reduce pressure on the electricity network. For example, the 5 kW PV predominantly used in Australian households produces an average of 21 kWh of energy daily in Brisbane, amounting to about 630 kWh of energy during the hottest month (January). Thus, given that average energy consumption in air conditioned houses in Brisbane during January was 233–409 kWh (Law et al. 2014), this amount of energy would be sufficient for cooling during summer, although it may depend on other factors.

Quantification of the hours during the year in the extended comfort band presents quantitative information on the thermal performance of the main living room of the houses, as well as the indoor temperatures experienced by occupants. For most hours of the year, the living rooms of the houses were in the extended comfort band, which was comparable to the findings reported by Miller et al.; however, the number of hours decreased and varied considerably depending on the studied housing characteristics during the coldest and hottest months (Figure 6). A decrease in the thermal performance of living rooms is associated with the houses' energy performance, which is in turn influenced by the housing characteristics (building envelope) and is reflected in the differences in the hours during the year in the extended comfort band. However, the hours during the year in the extended comfort band will be influenced by the time that participants occupied the living rooms because occupants adjust the room temperature to feel comfortable. Collecting such data was outside the scope of this study, we recommend it for any further studies on this topic. Approximately 80% of Australia's houses, which are mostly detached houses (80%), were built prior to the introduction of energy efficiency regulations in 2003. Although the energy efficiency regulations have undergone periodic reforms (in 2006 and 2010), the level of energy efficiency in houses built since their introduction is reported to be uncertain in terms of regulatory expectations (Berry and Marker 2015). The poor thermal performance of the living room in the houses during the coldest and hottest months has possible implications for the health of occupants if they do not use an HVAC system and are therefore exposed to low or high temperatures for prolonged periods. There are also energy infrastructure and energy consumption/cost implications if occupants use heating or cooling to keep the temperature within the 'safe' zone. Thus, not using an HVAC system has health implications; while the use of an HVAC system has energy (and therefore greenhouse gas emission) implications. Reforms in energy efficiency standards are needed, particularly in improving the building stock to both decrease the risk of exposure to extreme temperatures for residents, and decrease the reliance on artificial heating/cooling systems.

Our sample does not fully represent all house types in Brisbane, so we cannot claim to have identified all types of indoor temperature patterns in all seasons, or the determined energy performance of all houses because only living room temperature was monitored and we did not collect data on occupants' behaviour. Given that the studied predominant housing characteristics exerted only a minor influence on indoor temperature patterns, further studies on a bigger scale would be needed to detail the links between the indoor temperature pattern and house features. Further, the households in the study were identified through university social media and snowball sampling, so most of the houses were likely in reasonably good condition, which may mean the results underestimate temperature fluctuations in poorer quality housing. The findings of this study are relevant to the housing stock in this climate (i.e. subtropical), and the behavior patterns of occupants are likely to be very different in other climates; therefore, similar investigations would be beneficial and should be conducted in different types of climate and environment. Moreover, future studies should include information such as socio-economic status, types of wall, floor insulation and types of fuel used in households in their analysis to enhance understanding of the results.

In conclusion, the study quantified indoor temperatures experienced by occupants in terms of the hours during the year in the extended comfort band (18–28ºC), and identified diurnal patterns of indoor temperatures during different seasons in Brisbane houses in a subtropical climate. The implications of temperature exposure to humans and energy consumption in houses was also investigated.

Acknowledgments

We would like to thank all the study participants who volunteered their houses for the study; their kind gesture is much appreciated.

Declaration of interest: none

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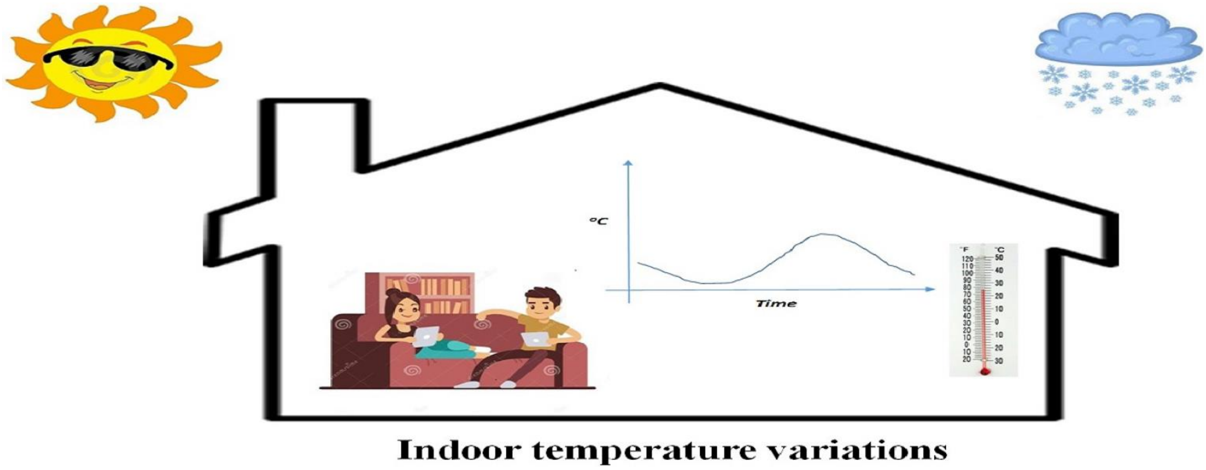
Graphical abstract



Highlights

- Diurnal (hourly) patterns of indoor (household) temperature were identified.
- Household temperature was in the extended comfort band (18–28 ^{o}C) most of the year.
- Hourly patterns differed by season, occupant behaviour and building materials.
- Temperature was outside of 18–28^{o}C more often during coldest and hottest months.
- Patterns were modified by use of HVAC (Heating, ventilation, and air conditioning).