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What the Indoor Air Temperatures in Houses in Three Australian Cities Tell Us

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Abstract: This study analysed over 1.8 million measurements of air conditioner power consumption and indoor/outdoor air temperatures in 129 houses in Adelaide, Brisbane and Melbourne from 2012 to 2014. It was found that the preferred indoor air temperature range, at which occupants are most unlikely to operate air conditioners, increases for warmer local climates. In each city, the air conditioner switch on and off indoor temperatures, and the indoor temperatures when air conditioner is in operation can be grouped into three prevailing outdoor temperature ranges: the low range, the shoulder range and the high range. Occupants are not very tolerant at the low and high temperature ranges, while they are more adaptive with the shoulder temperature range. This finding supports the simplified static thermostat setting approach used in the *AccuRate* software for house energy rating, though the existing thermostat settings should be adjusted with more research in understanding thermal comfort and air conditioner operation behaviours in residential houses.

Keywords: thermal comfort; thermostat settings; triggering temperature; residential buildings

1. Introduction

In recent years, energy consumption in the residential sector, which accounts for 11% of Australian total energy consumption, has been relatively flat or in decline (DOEE, 2017). This has been partially attributed to the adoption of more energy efficient housing (DOEE, 2017). Since 1993, Australian state and territory governments and building regulators gradually introduced the Nationwide House Energy Rating Scheme (NatHERS) in order to improve the energy efficiency of residential buildings. In supporting the scheme, a dynamic building simulation software *AccuRate* is used for NatHERS star rating for houses to demonstrate compliance with Australian building code energy efficiency requirements.

The *AccuRate* software was developed by coupling a frequency response building thermal model and a multi-zone ventilation model for energy requirement calculation of residential buildings (Walsh & Delsante, 1983; Ren & Chen, 2010; Delsante, 2005). Taking into account the local climate and building fabrics, *AccuRate* automatically switches the building operation between mechanical air conditioning and natural ventilation operation when natural ventilation satisfies occupant thermal comfort and calculates hourly heating and cooling energy requirement over a period of one year. Then, *AccuRate* assigns the house a NatHERS star rating based on the calculated heating and cooling energy requirement.

For the calculation of building heating and cooling energy requirement, the thermostat settings are commonly set according to standards such as ASHRAE 55-2013 (ASHRAE, 2013) for achieving the required occupant thermal comfort indoor environment. The heating and cooling thermostat settings used in *AccuRate* are specified in the Protocol for House Energy Rating Software (ABCB, 2006). For living spaces, a heating thermostat setting of 20°C is used. For sleeping spaces, a heating thermostat setting of 18°C from 7:00 to 9:00 and 16:00 to

24:00, and 15°C from 24:00 to 7:00. The cooling thermostat is set equal to the neutral temperature of January (the middle month of the summer in the southern hemisphere) for the corresponding climate zone. It is also assumed that cooling is triggered when indoor air temperature is 2.5°C above the neutral temperature which corresponds to 90% acceptability of the ASHRAE adaptive thermal comfort model (de Dear & Brager, 1998; ASHRAE, 2013). The cooling thermostat settings, although not exactly corresponding to the ASHRAE adaptive comfort model (ASHRAE, 2013), are based on the understanding that acceptable thermal conditions vary with the local climates.

The thermostat settings can significantly affect the calculation of the heating and cooling energy requirement and thus impact on whether or not a house design obtains building approval. James et al (1996) simulated a typical house in three Florida cities and showed that cooling energy can be reduced over 20% per °C increase in the thermostat temperature. Manning et al (2007) evaluated experimentally a pair of identical twin houses at the Canadian Centre for Housing Technology and showed that cooling energy reduction can be over 10% per °C increase in the thermostat temperature. Recently, using *AccuRate* simulations, Ren & Chen (2017) demonstrated that relaxing the cooling triggering temperature from 2.5°C to 3.5°C above the neutral temperature (corresponding to 80% acceptability of the ASHRAE adaptive comfort model) reduces 40% of the calculated space cooling energy requirement in regions with a hot summer climate and wide diurnal temperature swing (e.g. Alice Springs) for a heavyweight double brick cavity construction house. For a high set lightweight weatherboard house, such a relaxing in the cooling triggering temperature can result in 25% reduction in the cooling energy requirement and a 2 star increase in tropical regions (e.g. Darwin). Large reductions over 95% in heating and cooling energy requirements were also reported by Shiel et al (2017) using *AccuRate* simulations for a house in Adelaide by relaxing both the heating and cooling triggering temperatures and the thermostat temperatures.

It is clear that both the triggering and thermostat set point temperatures used in *AccuRate* can have different, yet sometimes significant, impact on the calculated heating and cooling requirement for different house construction types in different climates. For example, by extending the cooling triggering temperature from 2.5°C to 3.5°C above the neutral temperature, light weight constructions become easier to pass the building energy efficient regulation requirements in tropical regions in comparison with heavyweight constructions (Ren & Chen, 2017). On the other hand, by decreasing the heating thermostat set temperature, heavyweight construction houses become easier to pass the regulation requirements in certain climates (Beckett et al, 2017). Consequently, the triggering temperature and thermostat set point temperature in *AccuRate* play important roles in construction types of the residential building sector in Australia. However, so far, it is still a question as to how well these thermostat settings reflect the thermal comfort and the real heating and cooling operations in Australian houses.

The existing ASHRAE adaptive thermal comfort model defines acceptable indoor conditions for free run buildings when vote casts are within the three central categories of comfort scale (slightly cool, neutral or slightly warm). For common naturally ventilated building designs, the ASHRAE standard specifies that the allowable indoor operative temperature shall be determined using the 80% acceptability limits. The ASHRAE adaptive thermal comfort model was established based on empirical data mainly from office buildings (de Dear, 1998) whose occupants are relatively restricted in their adaptive measures and perceived control of the environment in comparison with those in residential buildings.

Direct application of the ASHRAE adaptive model to residential buildings has been questioned by previous studies (Peters et al, 2009; Lomas and Kane, 2013; Daniel, 2015; Kim et al, 2016; Alshaikh & Roaf, 2016; Nicol, 2017). Nicol (2017) examined the records from different research groups on indoor temperatures and comfort in residential buildings in Japan, England, Saudi Arabia, Russia, China, Australia, Belgium, Denmark, Portugal and New Zealand. A common finding of these studies is that in residential houses, whether heated, cooled or free running (FR), the comfort temperature range is generally wider than the corresponding range in ASHRAE standard due to residential occupants' wider adaptive options, perceived control etc. However, the width of the comfort temperature range and the slope for the regression line between the neutral temperature and the prevailing mean outdoor air temperature are not consistent among studies. An indoor operative temperature range from 7 to 14°C was reported by different researchers (Kim et al, 2016; Nicol, 2017). For the regression line between the neutral temperature and the prevailing mean outdoor air temperature, some reported a steep slope of around 0.5, 0.6 (Daniel, 2015; Nicol, 2017). Some gave a slope of below 0.3 (Kim et al, 2016) and even below 0.1 (Alshaikh & Roaf, 2016).

In summary, so far, studies on thermal comfort and heating and cooling operation in residential buildings are insufficient to form credible methodology for determining the adequate thermostat settings for energy efficient building designs and energy ratings. More research is needed. The current study aims at adding to the understanding of the indoor temperatures in heated and cooled Australian houses through analysing measurements of air conditioner (A/C) power consumption and indoor/outdoor air temperatures in 129 houses in Adelaide, Brisbane and Melbourne from 2012 to 2014.

2. Data collections

To investigate the impact of the NatHERS house energy efficiency regulation on Australian residential buildings, the Australian Government commissioned CSIRO to do a survey and monitoring study in Brisbane, Adelaide and Melbourne in 2012. These three cities have different climates: Brisbane (warm humid summer, mild winter), Adelaide (warm temperate) and Melbourne (mild temperate) respectively. Half-hour electricity consumption data was collected using direct monitoring of electricity at the switchboard for 64, 66 and 59 houses in Brisbane, Adelaide and Melbourne respectively for 9 months from the beginning of June 2012 to the end of February 2013. The monitoring was continued after February 2013 to allow follow-up studies. Temperature measurements at the living areas were also taken at 30 minute intervals using Thermochron temperature sensor/data logger which has an accuracy of ±1°C within the temperature range from -30 °C to +70 °C. The temperature sensors were installed at locations where direct sunlight was avoided.

All the houses were built between 2001 and 2011. Among these monitored houses, 129 houses (21 in Melbourne, 49 in Adelaide and 59 in Brisbane), which have at least one reverse cycle air conditioner installed, were chosen for this study, because these 129 houses have dedicated electric circuits for air conditioners. Between June 2012 and August 2014, a total of 1.86 million sets of half hour measurements were collected on A/C electricity consumption and living room air temperature for the 129 houses. The majority of these measurements were taken between the beginning of June 2012 to the end of February 2013. For each house, the air temperatures of the nearest Bureau of Meteorology (BoM) weather station were obtained as the outdoor air temperature. For details of the monitoring methodology, please refer to Ambrose et al (2013).

3. Results and discussions

The A/C power consumption measurements were analysed to find the A/C switch on and switch off time. A/C switch on is determined by a power consumption jump from zero or a low standby power consumption, while A/C switch off is judged by a power consumption drop to zero or a low standby power consumption. The indoor temperature at the beginning of the power jump is taken as the A/C switch on indoor temperature, $T_{switchon}$. Similarly, the A/C switch off indoor temperature, T_{off} was taken at the beginning of a power consumption drop. The indoor temperatures between the A/C switch on and switch off is the indoor temperature when A/C is in operation, i.e., $T_{operation}$.

3.1. A/C operation hours

Figure 1 shows the probability of using A/C in each hour of the day through the whole monitoring period for the three cities. It is seen that occupants are more likely to use A/C from 5pm to 10pm, less in the morning and lowest probability of using A/C during the sleeping hours from 11pm to 6 am. This trend is more obvious in Adelaide which has the highest probability of using A/C, followed by Melbourne. Brisbane has the lowest probability of A/C usage. The high occupancy rate during the late afternoon and evening hours is believed to contribute to this pattern of A/C usage.

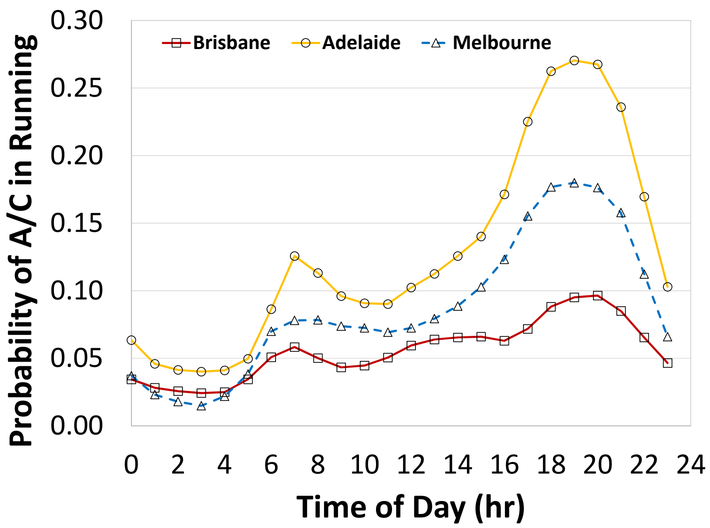


Figure 1. A/C "in running" probability at different time of the day in Brisbane, Adelaide and Melbourne

Figure 2 shows the outdoor air temperature distributions for the period from June 2012 to February 2013 for Brisbane, Adelaide and Melbourne. The relatively mild weather explains the lowest A/C usage in Brisbane. Figure 3 shows the probability distributions for different indoor temperatures in the 49 houses in Adelaide at different hours of the day. As expected, due to the diurnal outdoor temperature and solar radiation changes, many low indoor temperatures occur during sleeping hours, while most high indoor temperatures occur from the late afternoon to the early evening. Consequently, the high summer temperature in Adelaide results in the high probability of A/C operation in the late afternoon and evening which coincide with high house occupancy rate. The low A/C usage during sleeping hours seen in Figure 1 is believed due to the fact that sleeping in a cold indoor environment is relatively acceptable in comparison with sleeping in a hot indoor environment.

Although in average, the winter temperature in Melbourne is lower than that in Adelaide and Brisbane (refer to Figure 2), A/C is not normally used for space heating in

Melbourne. 15 out of the 21 houses in Melbourne were mainly heated by gas heaters, while 54 out of the 59 houses in Brisbane and 45 out of the 49 houses in Adelaide used A/C for space heating. This explains that the probability of A/C operation in Melbourne houses are lower than that in Adelaide during the sleeping hours from 11pm to 6 am.

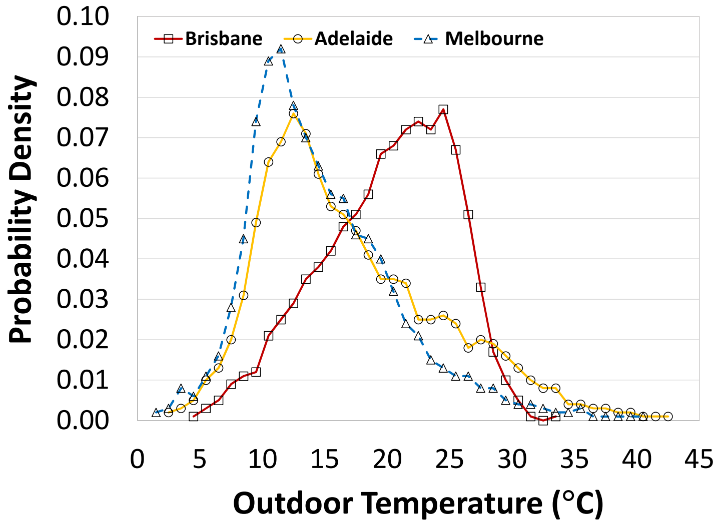


Figure 2. Outdoor temperature distribution from June 2012 to February 2013 for three cities

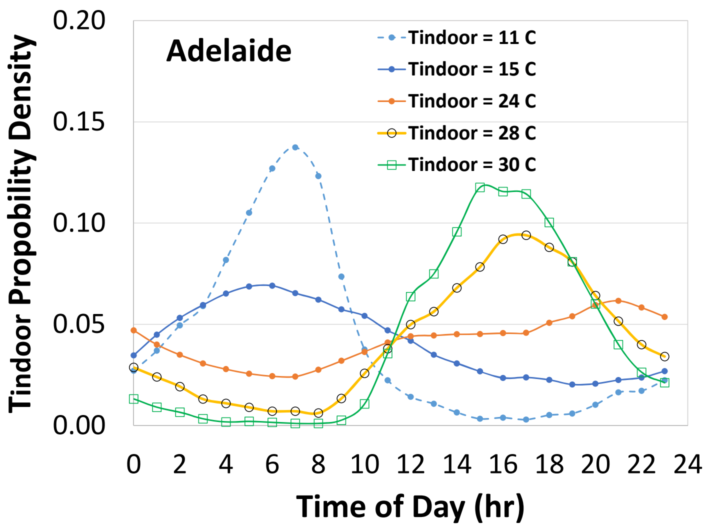


Figure 3. Indoor temperature distribution at different time of the day in all the houses in Adelaide

3.2. A/C switch on temperatures

When A/C is switched on, it means that the occupants would like to change the current indoor thermal condition which is most likely unsatisfactory. Figure 4 shows the probability of A/C switch on when the houses are at different indoor air temperatures. This probability is the number of A/C switch on at one specified indoor temperature divided by the total number of half hour records when the house is at this same indoor temperature. Figure 4 does not include the lowest and highest indoor temperatures experienced in the houses in each city, because switch on events for these extreme indoor temperatures are too low (less than 10). It is seen that A/C is most unlikely to be switched on at around 20-22.5°C, 21.5-24°C and 23.5-

26°C indoor temperatures in Melbourne, Adelaide and Brisbane. These temperature range around 20°C to 26°C is arguably the most preferred temperature range or the easiest temperature range for thermal adaption by the majority of the populations in buildings with heating and cooling (de Dear et al, 1997). These preferred temperature ranges increase with the average outdoor temperatures, which suggests thermal adaptation to the local climate.

Since many low indoor temperatures occur during sleeping hours (refer to Figure 3), this period has the lowest probability of A/C operation. This may explain that the switch on curve at low indoor temperatures in Figure 4 is not as decisive as the curve at high indoor temperatures which often occur during late afternoon and evening when occupants are awake and active. The probability of A/C switch on increases rapidly at high indoor temperatures above the preferred temperature ranges.

It is noted that the 80% and 90% acceptability limits of the ASHRAE adaptive thermal comfort model are set at 2.5°C and 3.5°C apart from the neutral temperature. It implies that statistically, the dissatisfactory rate increases approximately 100% for each °C increase in the difference between the indoor temperature and the neutral temperature at least for the temperature difference range between 2.5 and 3.5°C. In other words, statistically, the probability of A/C switch on is likely to increase rapidly with the increase in this temperature difference.

Figure 5 again shows the probability of A/C switch on when the houses is at different indoor air temperatures for the three cities respectively. However, in Figure 5, each curve is at a fixed running average outdoor temperature $T_{\text{runningaverage}}$, which is the mean temperature for the previous seven days. Due to small number of data points, the plots are scattered. The neutral temperatures calculated based on the ASHRAE adaptive thermal comfort model, i.e., Eq. (1), are also included for references.

$$T_{neutral} = 17.8 + 0.31T_{runningaverage} \qquad (1)$$

At low $T_{\text{runningaverage}}$, heating is the main function for the A/C operation. When $T_{\text{runningaverage}}$ is high, cooling is the main function for the A/C operation. The trend for heating is difficult to see perhaps again due to the fact that many low indoor temperatures occur during sleeping hours. For cooling, Figure 5 fails to show the trend that the probability of A/C switch on increases rapidly with an increase in the difference between the indoor temperature and the neutral temperature. For example, in Adelaide, there is no significant difference in the probability of A/C switch on for an indoor temperature at 28°C when $T_{\text{runningaverage}}$ is at 20°C, 23°C and 26°C which correspond to the temperature differences of 4.0°C, 3.1°C and 2.1°C. In Brisbane, the same can be found for an indoor temperature at 29°C when $T_{\text{runningaverage}}$ is at 23°C and 26°C which correspond to the temperature differences of 4.1°C and 3.1°C. Similar trends can be observed in Melbourne when $T_{\text{runningaverage}}$ is at 20°C and 23°C for the indoor temperatures from 25°C and 30°C. It is understood that the neutral temperatures calculated using Eq. (1) may be not suitable for residential houses (Nicole, 2017; Kim et al, 2016). Although there are around 4000 A/C switch on events in Melbourne, 15000 in Adelaide and 8000 in Brisbane, when divided into around 25 T_{switchon} and around 15-25 $T_{\text{runningaverage}}$ bins, the number of measurements for the data points in Figure 5 can still be limited. Nevertheless, these results suggests that the switch on of A/C is not a strong function of $T_{\text{runningaverage}}$ for cooling. In fact, for cooling, Figure 5 shows that the probability of A/C switch on is more related to the indoor temperature.

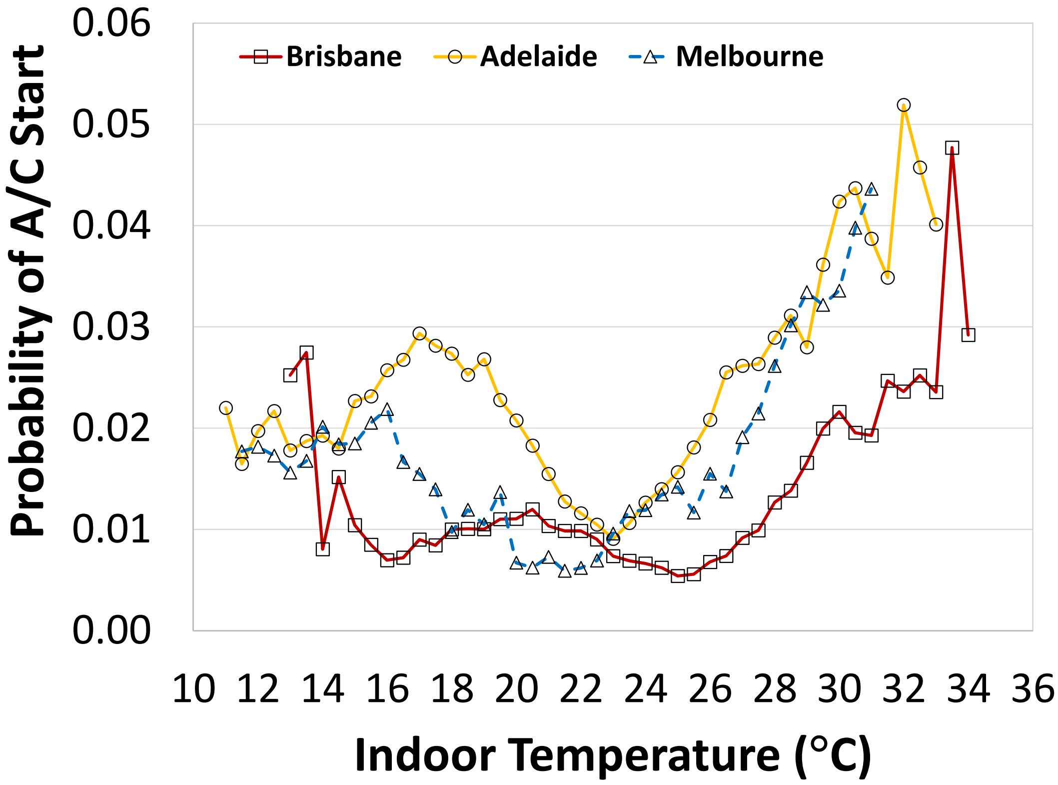


Figure 4. A/C "switch on" probability at different indoor air temperature in Brisbane, Adelaide and Melbourne

Figure 6 shows the relationship between the indoor air temperatures when A/C is switched on, i.e., $T_{switchon}$, and $T_{runningaverage}$ in Brisbane, Adelaide and Melbourne respectively. For each city, the left side plot shows the correlation including all the data points in the whole range of the running average outdoor temperature (referred to as single range plot hereafter). The right side plot shows the correlations if the running average outdoor temperature is divided into three ranges, the low range, the shoulder range and the high range (referred to as three range plot hereafter). These ranges are 10.1 - 15.5°C, 15.6 - 22.8°C, 22.9 - 27.5°C for Brisbane; 4.9 - 12.7°C, 12.8 - 22.0°C, 22.1 - 30.4°C for Adelaide; and 7.0 - 12.8°C, 12.9 - 19.5°C, 19.6 - 27.2°C for Melbourne respectively.

It was found that for the single range plot, the correlation slopes between $T_{switchon}$ and $T_{runningaverage}$ are between 0.63 and 0.74 for the three cities. However, for the three range plot, the correlation slopes between $T_{switchon}$ and $T_{runningaverage}$ are between 0.02 and 0.37 for the three cities for the low and the high ranges. Especially for Adelaide and Melbourne, the correlation slopes are all below 0.28 for the low and the high ranges. For the shoulder ranges, the correlation slopes are high at around 1.0 for the three cities. Figure 6 suggests that occupants are not very tolerant at the low and the high $T_{runningaverage}$ ranges, while they are more adaptive with the shoulder $T_{runningaverage}$ range which is a transition from relatively cold to hot outdoor air temperatures. This low tolerance at the low and the high $T_{runningaverage}$ range can be more clearly seen by the flat median (50-percentile) $T_{switchon}$ values at the low and the high $T_{runningaverage}$ ranges in the single range plots in Figure 6.

Figure 7 shows the relationship between $T_{switchon}$ and $T_{runningaverage}$ after combining all the data from the houses in the three cities. Similar to Figure 6, three ranges of the $T_{runningaverage}$ can be found. The correlation slope is 0.66 for single range plot, while they are 0.11, 0.89 and 0.24 for the low (4.9 – 13.0°C), shoulder (13.1 – 23.0°C) and the high ranges (23.1 – 30.4°C) respectively.

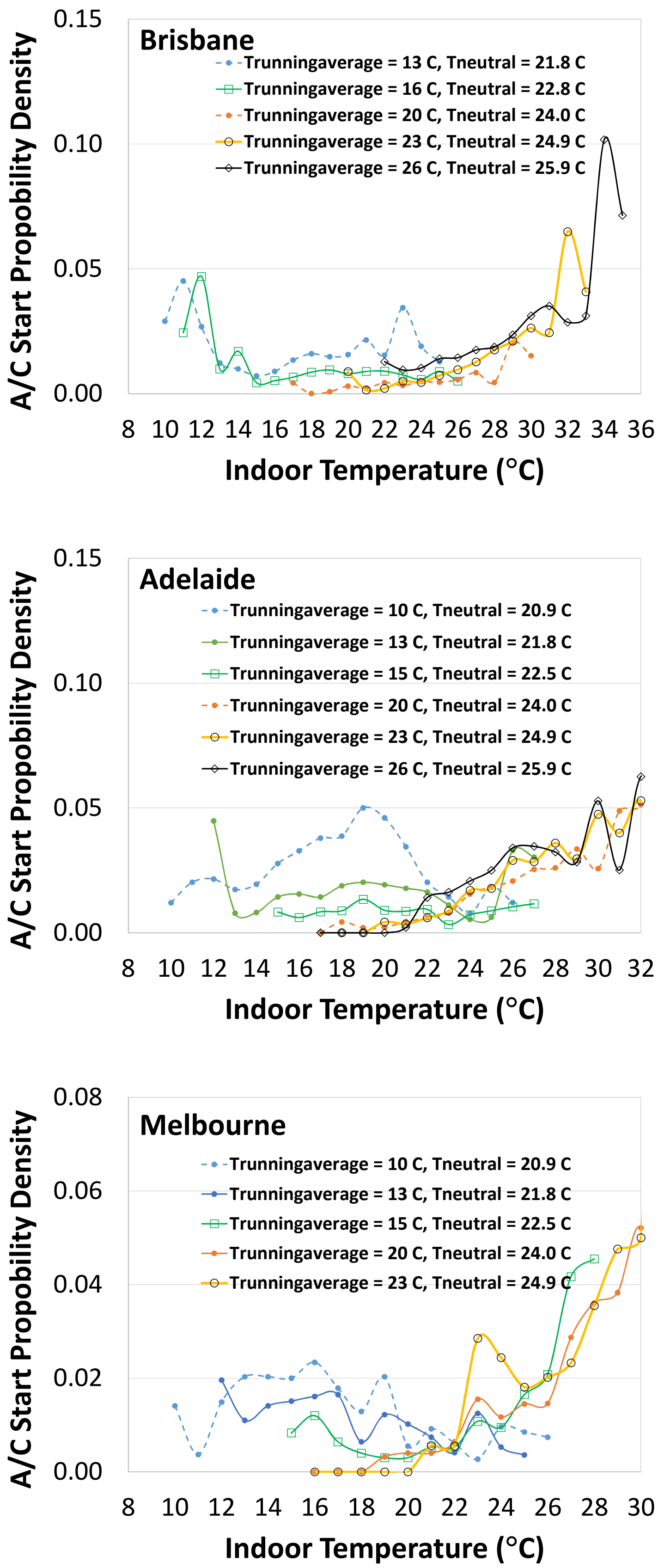


Figure 5. A/C "switch on" probability at fixed running outdoor average temperature at different indoor air temperature in Brisbane, Adelaide and Melbourne

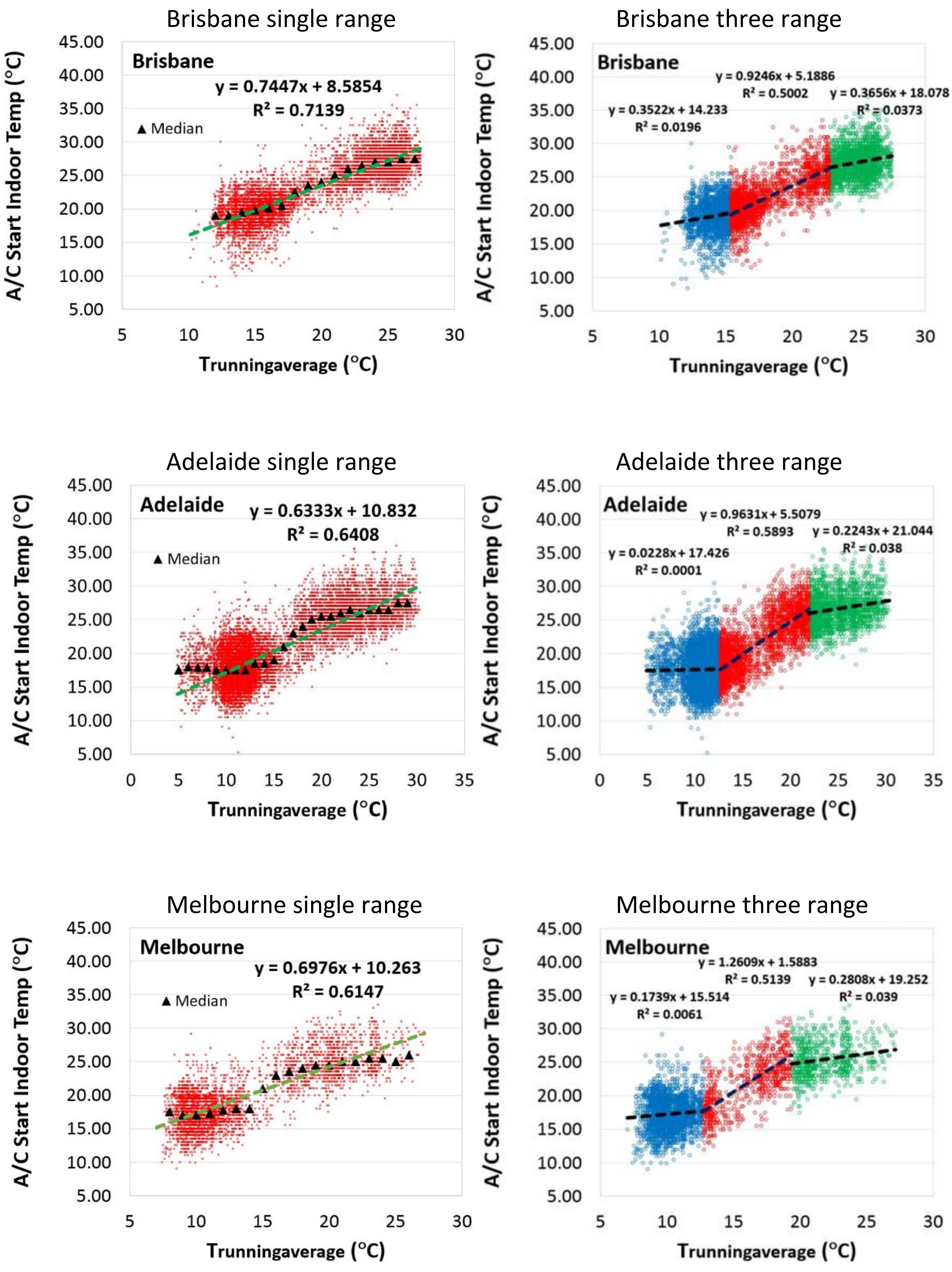
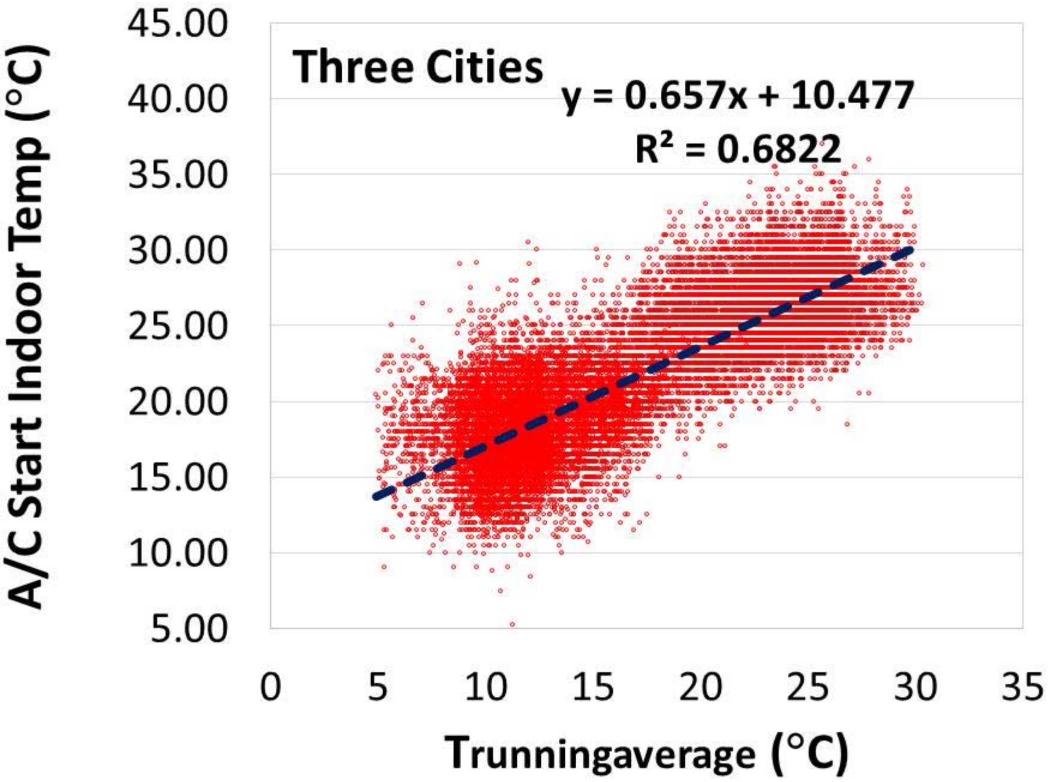
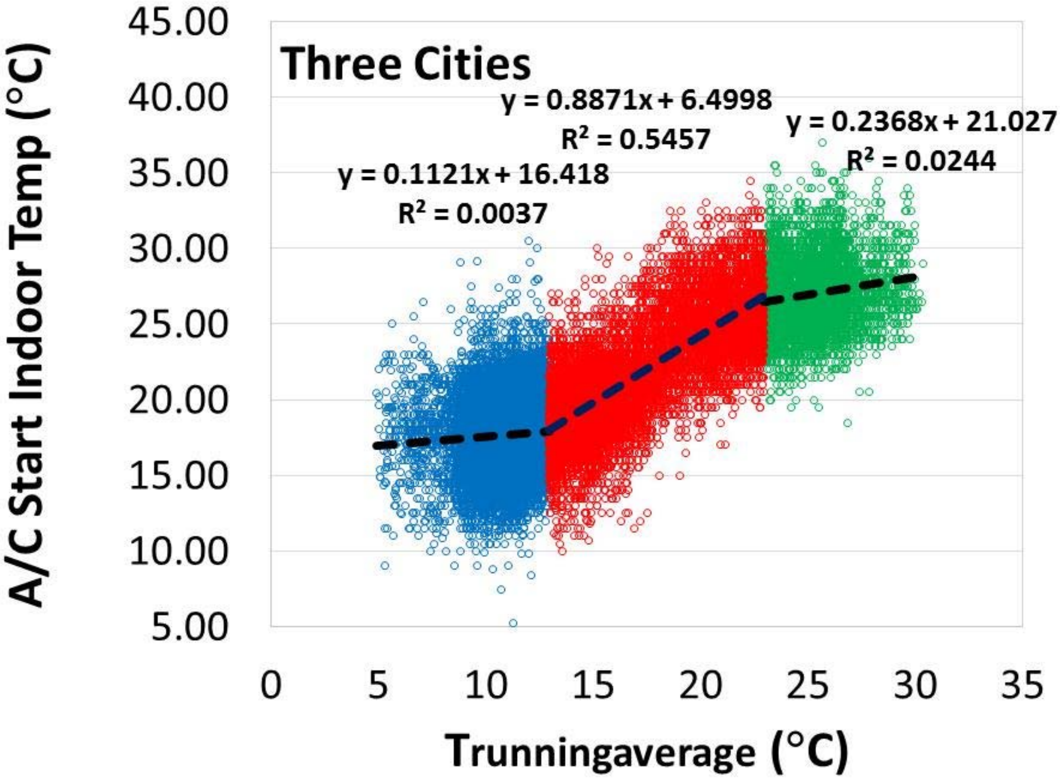


Figure 6. A/C "switch on" indoor air temperature at different running outdoor average temperature in Brisbane, Adelaide and Melbourne



(a)



(b)

Figure 7. A/C “switch on” indoor air temperature at different running outdoor average temperature using data from all the three cities: (a) single range plot; (b) three range plot.

3.3. A/C switching off temperatures

A/C may be switched off when the occupants judge the indoor environment can maintain comfortable without A/C running, or when the occupants leave the air conditioned space or the house. Kim et al (2016) discussed the A/C switch off indoor temperature (T_{off}) and considered that it may be a good approximation of occupants' comfort temperature. Figure 8 shows the relationship between T_{off} and $T_{\text{runningaverage}}$ for Brisbane, Adelaide and Melbourne respectively. The left side shows the single range plot and the right side shows the three range plot. The single range plots also include the neutral temperature T_{neutral} calculated by Eq. (1) based on the ASHRAE adaptive thermal comfort model.

It is seen that, in general, the correlations for the three cities are not far from the neutral temperature predicted by the ASHRAE adaptive thermal comfort model. The slightly higher correlation slopes from the measured T_{off} in comparison with T_{neutral} may be due to several factors: 1) occupants do not heat or cool the living room to the neutral temperature since slightly cold (during heating) and slightly warm (during cooling) are acceptable; 2) the A/C capacity is not sufficient to heat or cool the living room to the neutral temperature; 3) due to the cost of running A/C at high capacity, and so on. Similar to A/C switch on, Figure 8 again shows the existence of three $T_{\text{runningaverage}}$ ranges: a low, a shoulder and a high range for each climates. At the low and the high ranges, the occupants have less tolerance to the thermal environment, while the occupants are more adaptive in the shoulder range.

3.4. The relationship between A/C switch on and A/C operation indoor temperatures

Figure 9 shows the relationship between the average T_{switchon} and the average A/C operation indoor temperature $T_{\text{operation}}$ for each house in winter and summer in Brisbane, Adelaide and Melbourne respectively. It is seen that occupants operate houses in significantly wide ranges of average heating and cooling indoor temperatures. For heating, this was from 12 to 25 °C. For cooling, it was from 22 to 31°C. It is also seen that the average T_{switchon} and the average $T_{\text{operation}}$ are well correlated. It means that occupants who switch on A/C at low indoor temperatures prefer running A/C at low indoor temperatures. The opposite is true that occupants who switch on A/C at high indoor temperatures prefer running A/C at high indoor temperatures.

Figure 10 shows the relationship between a house's average T_{switchon} in the winter and its corresponding average T_{switchon} in the summer for all the houses in the three cities. Figure 11 shows the relationship between the average $T_{\text{operation}}$ in winter and summer for the three cities. Figures 10 and 11 suggest that there is no relationship between occupants' winter cool sensation and their summer warm sensation. This means that an occupant who prefers running A/C at a relatively high indoor temperature in summer does not mean the occupant will prefer running A/C at a relatively high or low indoor temperature in winter.

3.5. A/C operation indoor temperature band

Figure 12 shows the living room temperature when A/C is running as a function of $T_{\text{runningaverage}}$: minimum, maximum, 95-, 50-, and 5-percentiles for the houses in the three cities. It is seen that except those low $T_{\text{runningaverage}}$ where the measurements are sparse and the shoulder $T_{\text{runningaverage}}$ range, the median (50%) indoor temperature are relatively flat for cooling and heating. This trend is similar to that reported by Peeters et al. (2009) for Belgian dwellings. Figure 12 also includes the neutral temperature line for the ASHRAE adaptive model, i.e. Eq. (1). It is interesting to see that the median indoor temperatures when A/C is in operation for the three cities are spread around the ASHRAE adaptive model line, except that the median indoor temperatures flatten out at the low and high $T_{\text{runningaverage}}$ ranges.

Combining the findings above for T_{off}, the indoor temperature clouds during A/C operation may suggest that occupants' thermal comfort in the heated and cooled houses in these three cities may be not far from the ASHRAE adaptive model, however, there are obviously limits existing at the low and high $T_{runningaverage}$ ranges.

Table 1 lists the average median indoor temperature, the 80-percentile (from 10-percentile to 90-percentile) and the 90-percentile temperature (from 5-percentile to 95-percentile) bands for the three cities for heating and cooling respectively. In the brackets in Table 1, the positive value is the upper band and the negative value is the lower band. It is seen that the median heating indoor temperatures are between 20.0 and 21.2°C. In general, the temperature band for heating is wider than that for cooling. This is in agreement with that reported by Peeters et al. (2009) for Belgian dwellings. In average, the 80-percentile indoor air temperature bands are 7.3°C and 6.2°C for heating and cooling respectively. The 90-percentile indoor air temperature bands are 9.3°C and 7.8°C for heating and cooling respectively which is within the ranges reported by Nicol (2017) for residential buildings.

Table 1. average median indoor temperature and 80-, 90-percentile temperature bands when A/C runs

	Average Median Temperature [ºC]		**Average 80% percentile band [ºC]**		**Average 90% percentile band [ºC]**	
	Heating	**Cooling**	**Heating**	**Cooling**	**Heating**	**Cooling**
Brisbane	**21.2**	**27.1**	**7.7(4.1,-3.6)**	**6.2(2.9,-3.3)**	**9.8(5.2,-4.6)**	**7.8(4.0,-3.8)**
Adelaide	**20.6**	**26.1**	**7.1(2.8,-4.3)**	**6.1(3.4,-2.7)**	**9.0(3.7,-5.3)**	**7.8(4.4,-3.4)**
Melbourne	**20.0**	**26.1**	**7.0(3.2,-3.8)**	**6.2(3.2,-3.0)**	**9.0(4.0,-5.0)**	**7.9(4.1,-3.8)**

3.6. Implications for energy efficient building regulations

The findings of the current study may have several implications to the development and improvement on the regulations of Australian house energy efficiency in terms of occupant thermal comfort and A/C operation assumptions. It is very likely that the existing static thermostat setting approach will continue to be used in the *AccuRate* software for house energy rating in Australia for the foreseeable three to five years. The findings in this study that occupants are relatively not thermally tolerant and the $T_{switchon}$, $T_{operation}$, T_{off} are relatively flat at the low and high $T_{runningaverage}$ ranges do support such simplifications before a more reliable dynamic thermostat setting approach can be established.

Table 2 lists the average median $T_{switchon}$, $T_{operation}$, T_{off} for heating and cooling for the three cities. In the brackets are the existing assumed thermostat settings in *AccuRate* for house energy rating calculations. For heating, the thermostat of 20°C in the living room appears reasonable for Melbourne, but is about 0.6°C and 1.2°C lower for Adelaide and Brisbane respectively. However, the heating switch on temperatures in Adelaide and in Melbourne in the existing *AccuRate* software for living room is too high and a switch on indoor temperature of around 17.5°C may be more adequate. For cooling, the average median cooling switch on temperature are around 0.5°C lower than the currently assumed values for the three cities. However, the median indoor temperatures, when A/C is running which may be considered as the real thermostat set point, are about 1.5°C above the currently assumed values for the three cities. Of course, it is arguable whether it is adequate to use the average median $T_{switchon}$ and $T_{operation}$ for setting the A/C triggering indoor temperature and the thermostat set point temperature. Further research is needed.

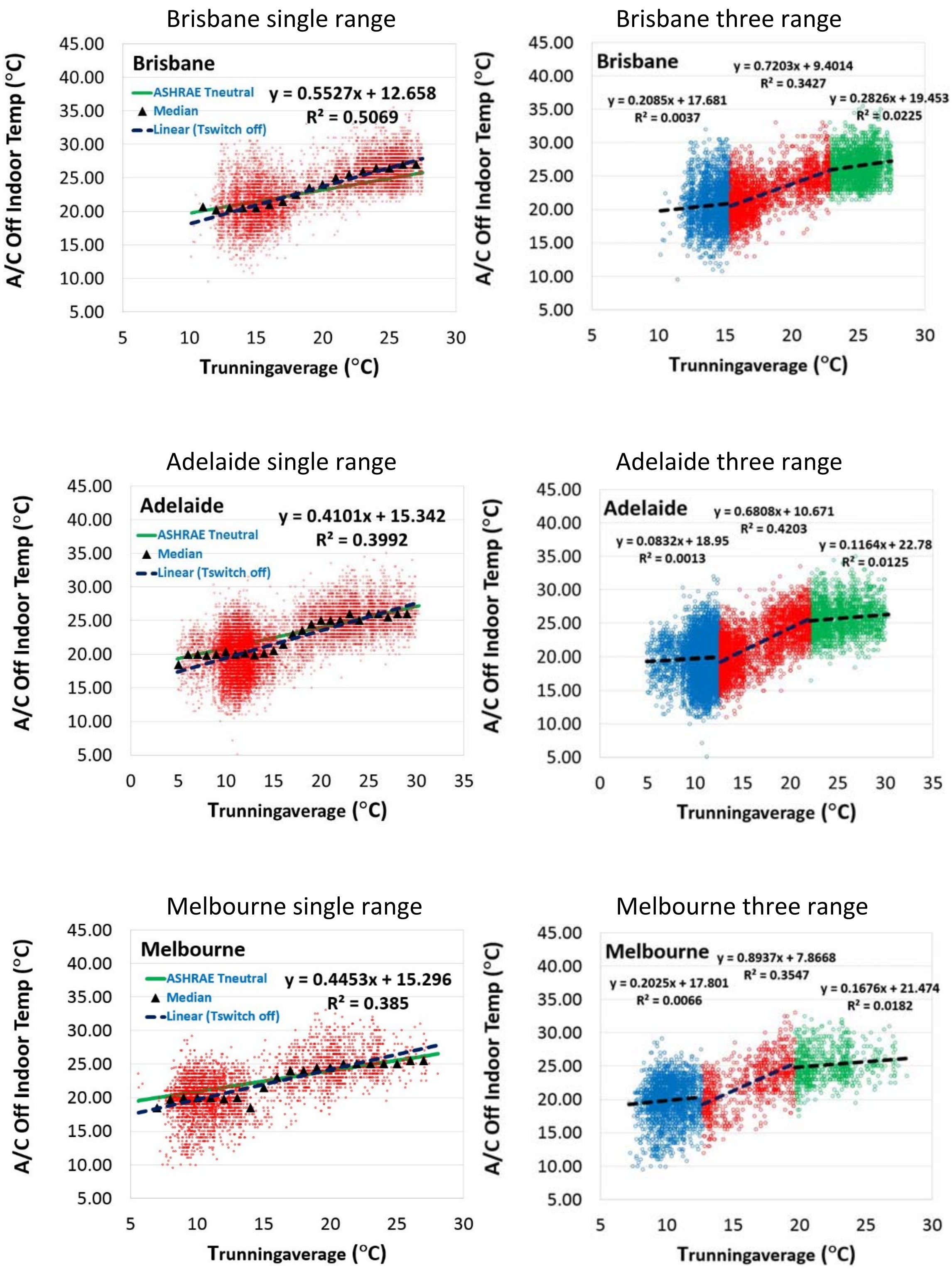


Figure 8. A/C "switch off" indoor air temperature at different running outdoor average temperature in Brisbane, Adelaide and Melbourne

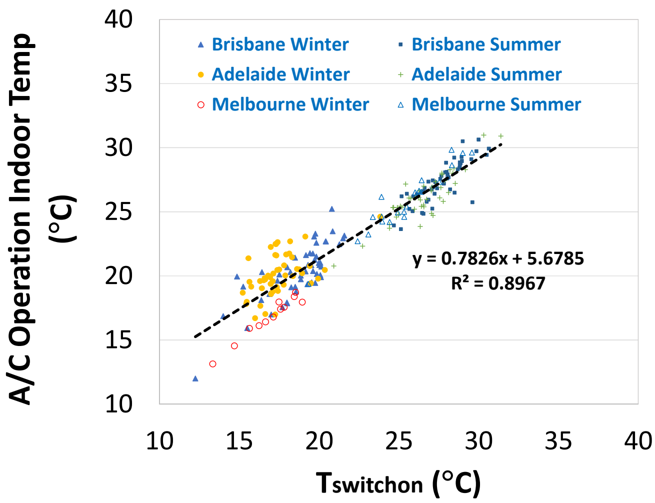


Figure 9. Relationship between the average A/C switch on indoor temperature and the average A/C operation indoor air temperature for each house in winter and summer

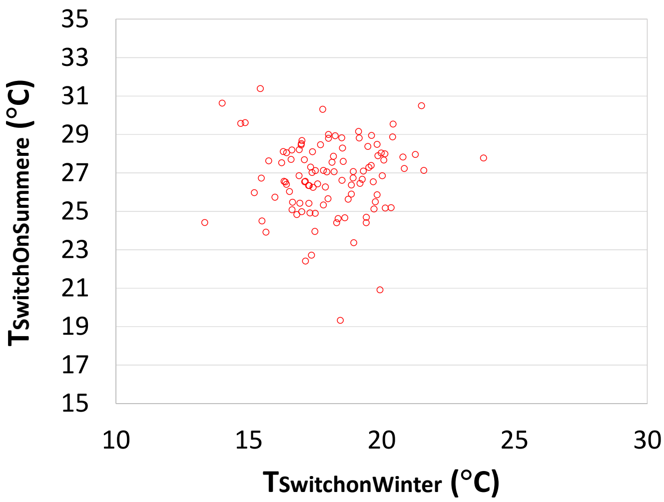


Figure 10. Relationship between A/C "switch on" indoor air temperatures in the winter and summer for the three cities

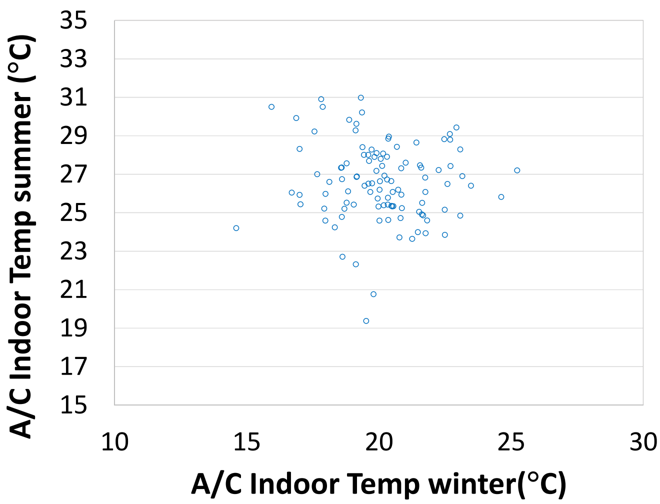


Figure 11. Relationship between A/C operation indoor air temperatures in the winter and summer for the three cities

Table 2. average median $T_{switchon}$, $T_{operation}$, T_{off} for heating and cooling for the three cities (In the brackets are the existing assumed thermostat settings in *AccuRate* for house energy rating calculations)

	Average Median $T_{switchon}$ [ºC]		**Average Median $T_{operation}$ [ºC]**		**Average Median T_{off} [ºC]**	
	Heating	**Cooling**	**Heating**	**Cooling**	**Heating**	**Cooling**
Brisbane	**19.5(20.0)**	**27.6(28.0)**	**21.2(20.0)**	**27.1(25.5)**	**20.5(20.0)**	**27.1(25.5)**
Adelaide	**17.7(20.0)**	**26.8(27.5)**	**20.6(20.0)**	**26.1(25.0)**	**20.1(20.0)**	**26.1(25.0)**
Melbourne	**17.2(20.0)**	**26.2(26.5)**	**20.0(20.0)**	**26.1(24.0)**	**19.9(20.0)**	**25.6(24.0)**

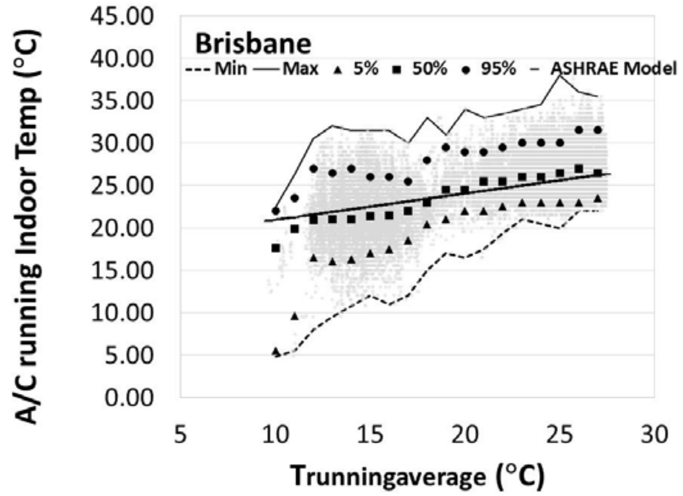
It is noted that the current research only provide one angle of the understanding of thermal comfort and occupants' A/C operation behaviours in houses. The study has at least the following limitations:

1. The number of houses investigated are limited and data points are not enough as can be seen in Figure 5;
2. Measurements were only taken for air temperatures in the living room. Indoor relative humidity, mean radiant temperatures and air movement velocity were not measured. Further, indoor temperatures in bedrooms are likely different from those in living rooms;
3. Thermal comfort surveys were not carried out in this study.

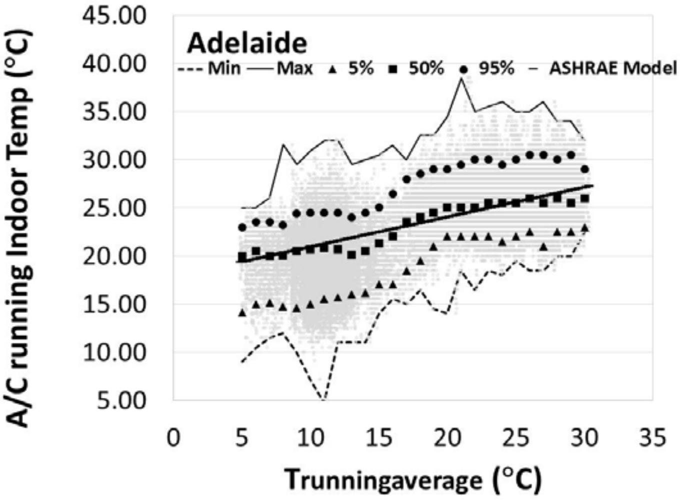
Considering the importance of thermal comfort and A/C operation in house energy efficiency regulation development, further research is needed to validate and improve the understanding in both occupants' thermal comfort and A/C operation behaviours in Australian residential houses.

4. Conclusions

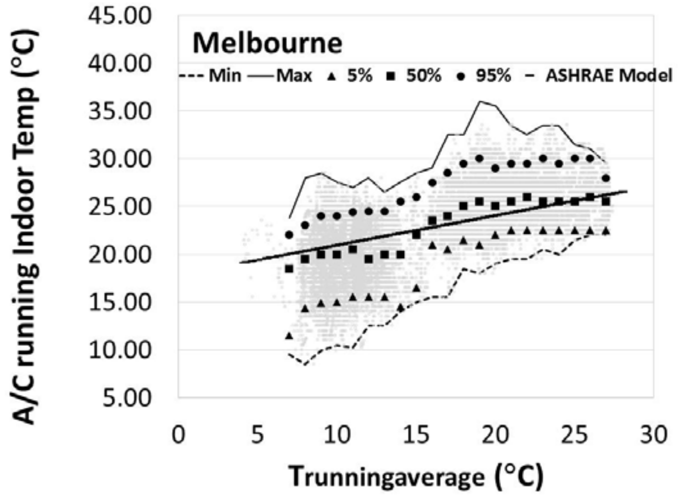
This study analysed over 1.8 million measurements of air conditioner power consumption and indoor/outdoor air temperatures in 129 houses in Adelaide, Brisbane and Melbourne from 2012 to 2014. It was found that A/C is most unlikely to be switched on at around 20-22.5°C, 21.5-24°C and 23.5-26°C indoor temperature ranges in Melbourne, Adelaide and Brisbane respectively. This is in line with thermal adaption to the local climates. In each climate, the A/C switch on indoor temperatures, the A/C switch off indoor temperatures and the A/C in operation indoor temperatures can be grouped into three $T_{runningaverage}$ ranges: the low range, the shoulder range and the high range. Occupants are not very tolerant at the low and high $T_{runningaverage}$ ranges, while they are more adaptive with the shoulder temperature range. Findings in this study support the simplified static thermostat setting approach used in *AccuRate*, though the existing thermostat settings should be adjusted. More research is required for better understanding thermal comfort and A/C operation behaviours in residential houses for developing building regulations for more comfortable and energy efficient housing in Australia.



(a) Brisbane



(b) Adelaide



(c) Melbourne

Figure 12. Living room temperature when A/C in running as a function of $T_{runningaverage}$: minimum, maximum, 95-, 50-, and 5-percentiles

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