Characterising indoor air temperature and humidity in Australian homes

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ABSTRACT

Information about indoor air temperatures in residential buildings is of interest for a range of reasons, e.g. the health and comfort of occupants, energy demand for space heating and cooling. To date there have been few long term studies that measure and characterise indoor air temperatures in Australian homes. New primary research undertaken by the authors measured temperatures in 273 homes over the period 2011 to 2014 in seven climate zones, from Melbourne in the south to Cairns in the north of Australia. Humidity data was also collected in 20 homes. This paper is a description of the data collected and the subsequent analysis.

Indoor temperatures were compared with outdoor temperatures and a mathematical model was fitted to the data. In general, monthly average indoor temperatures were found to be 2°C higher than monthly average outdoor temperatures, apart from periods with consistently cold weather, where the monthly average outdoor temperature was less than 20°C, which were found to have larger differences. The indoor temperature model developed has been compared with data measured by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in 438 homes in three Australian cities. The model developed using project measurements are highly consistent with the CSIRO data.

Further data collection compared indoor and outdoor humidity in 20 houses in Sydney and Melbourne. The indoor humidity ratio was found to be, on average, slightly higher than outdoors, but indoor levels generally track outdoor levels quite closely. This is likely due to the high air exchange rate in most houses.

***Keywords**: Vehicle emissions, tunnel, validation, traffic impact*

INTRODUCTION

Information about indoor air temperatures in residential buildings is of interest for a range of reasons, including those associated with the health and comfort of inhabitants, as well as understanding the drivers of energy demand for heating and cooling. However, to date there have been few long term studies that measure, quantify and characterise indoor temperature conditions in Australian homes. A review of the literature found that there were a number of studies that undertook short term temperature measurements in homes, mainly associated with air quality monitoring or health related issues (*e.g.* AWN Consultants and Team Ferrari Environmental 2004; Galbally *et al.* 2011). However, almost no published studies up to the end of 2013 reported typical indoor air temperature measurements in Australian homes over long periods.

As part of a research project to better understand the energy consumption of household refrigerators in Australian homes, indoor temperatures in 273 homes have been measured over the period 2011 to 2014. The primary aim of the research was to collect better information on typical indoor air temperatures in order to quantify the impact that temperature had on the energy consumption of refrigerators. The majority of the temperature measurements were recorded for long periods, generally for more than six months in each dwelling spanning summer and winter, providing a rich data set for deeper analysis. The sites measured stretch from Melbourne and Gippsland in the south to Cairns in the north of Australia, and consequently cover a diverse range of climates and weather. The research method involved the selection of a large number of households from different socioeconomic backgrounds and in different climates using the snowball recruitment approach. Portable data loggers were installed to measure indoor air temperature and energy consumption of refrigerating appliances.

The air temperature inside a home is likely to depend on a wide range of factors. These include:

- overall climate, diurnal temperature fluctuations, seasonal effects;
- weather, including outdoor air temperatures, wind and solar radiation;
- building envelope, including insulation, thermal mass, glazing performance, glazing orientation, shading and air infiltration;
- use of spacing conditioning equipment such as heating and cooling systems to modify indoor air temperatures to be more comfortable for occupants;
- user-related elements such as occupancy (the times when the occupants are present) affects the operation of space conditioning equipment;
- use of natural ventilation, such as opening and closing of windows;
- zoning: many occupants only heat or cool part of their homes - some parts of many homes are not normally conditioned.

Modelling of indoor air temperatures requires assumptions to be made about each of these variables. In contrast, this paper examines outdoor air temperatures and indoor air temperatures as measured for all 273 sites and develops an empirical mathematical model to estimate average indoor air temperature based on outdoor air temperature. The model developed is then confirmed and refined using an independent data set collected by CSIRO. The final model provides a quantitative estimate of indoor air temperatures in living areas that occur during normal use across many climates. The paper then examines the indoor air humidity in a sample of homes to examine the relationship between outdoor air humidity and indoor air humidity.

METHOD

Primary data sources

The primary data source used for this research was indoor air temperature data that were measured using data loggers for extended periods of time. Households were recruited by the authors as part of a large scale research project on household refrigeration from the following general locations around Australia:

- Cairns area, Far North Queensland: 23 households
- Brisbane metropolitan area, Queensland: 32 households
- Gold Coast, Queensland: eight households
- Byron Bay area, NSW: 11 households
- Sydney metropolitan area, NSW: 71 households
- West Gippsland area (east of Melbourne), Victoria: 72 households
- Melbourne metropolitan area, Victoria: 52 households
- Other locations not included in the above: four households
- Total sites covered: 273 households.

Participating households completed a face-to-face questionnaire that covered broad demographic data, qualitative building shell characteristics and general information on heating and cooling equipment. A battery powered temperature data logger was installed in the living area in each house. The data recording interval was selected to be 10 min. The manufacturer specified range and precision of the temperature measurement instrument are -20°C to +105°C and ±0.5°C (OmegaWatt 2008). A few of these data loggers included measurement of air relative humidity as well as temperature. Raw data was downloaded from each data logger at the end of monitoring. The logger was carefully placed in the living area to avoid any sources or sinks of radiant or sensible heat such as windows, heating or cooling equipment or cooking equipment as well as the refrigerating appliance itself. Generally loggers were affixed to an insulated internal wall at a height of 1.5 m, but this varied depending on the most suitable location available at each site.

Other data sources

Two other important data sources have been used in this research. Firstly, for outdoor air temperature and humidity data, local Bureau of Meteorology (BOM) weather stations were used. Data purchased included dry bulb temperature, wet bulb temperature, relative humidity, dew point temperature and station level air pressure. For the sites listed below, one-minute data for the years 2005 to 2014 was purchased:

- Cairns Airport, BOM Station 031011
- Brisbane (city), BOM Station 040913
- Coolangatta (airport), BOM Station 040717
- Byron Bay, BOM Station 058216 (only available from 1 January 2010)
- Sydney RMO, BOM Station 066062
- Sydney Airport, BOM Station 66037
- Latrobe Valley, BOM Station 085280
- Moorabbin, BOM Station 086077
- Melbourne Airport, BOM Station 086282.

The second key data source was a major study published by CSIRO that evaluated the impact of house star ratings on energy consumption (Ambrose *et al.* 2013). This included long term measurements of indoor air temperatures in 438 Australian homes in three cities over a period of more than one year. One additional data source used was indoor air temperature and humidity measurements collected in selected Melbourne homes over winter in 2013 and 2014 by Sustainability Victoria (McNicol 2015).

Analysis approach

Review of the measured data for hundreds of sites shows that indoor air temperatures change slowly. However, when viewed over a significant period such as a year, there is substantial variation in air temperatures across the seasons, as illustrated in FIGURE 1.

Several different data analysis approaches were examined, such as time-of-day by month and daily average temperatures. The most robust approach to data analysis to generalise across all sites and climates was found to be the examination of monthly average indoor and outdoor air temperatures. The approach has been used to develop the results presented in this paper.

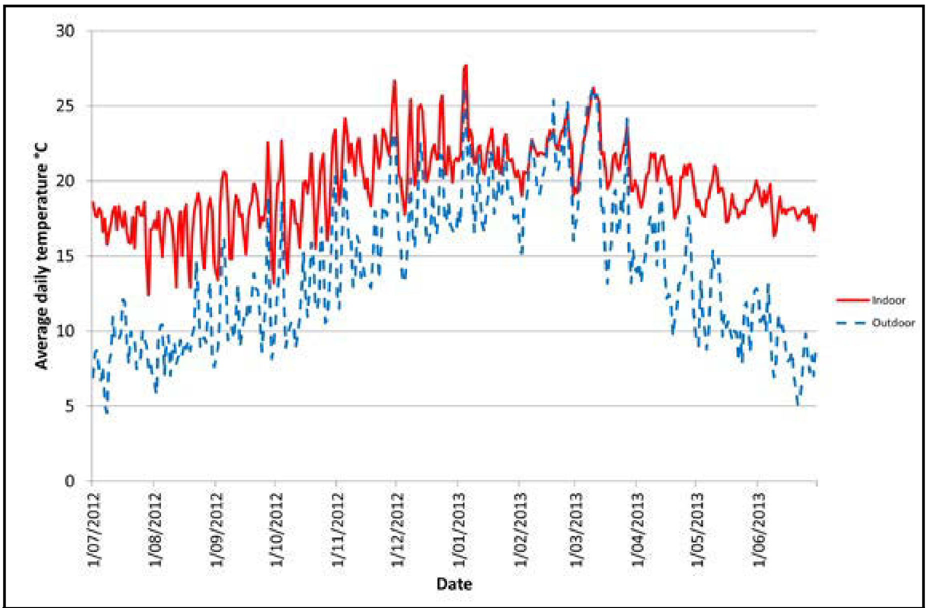

Figure 1. Daily average indoor and outdoor air temperatures for a site in Gippsland, one year.

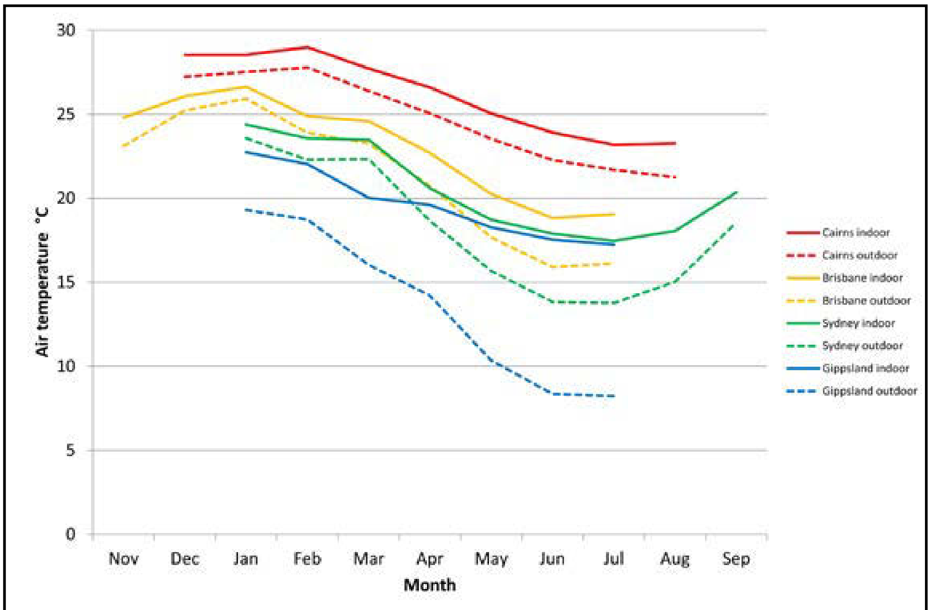

Figure 2. Monthly average air temperatures for selected sites by city/region.

RESULTS AND DISCUSSION

Initial results

Monthly indoor air temperature and monthly outdoor air temperature for a selection of houses was examined in four climates: Cairns, Brisbane, Sydney and Gippsland in Victoria as illustrated in FIGURE 2. These houses were selected for preliminary analysis as they represented 100 sites running in parallel, which allowed seasonal and climate variations to be observed for substantial groups of houses in very different climate zones. It also allowed indoor air temperature data for groups of houses to be averaged as they had common outdoor air temperatures.

There are some important observations that can be made from FIGURE 2. All sites show that outdoor air temperature has a strong influence on indoor air temperature. All sites show that indoor air temperatures are higher (on average) than outdoor air temperatures. For Cairns, Brisbane and Sydney, there is approximately 2°C difference between indoor air temperature and outdoor air temperature during the warmer months (December to February). During colder months (June to August), there is also approximately 2°C difference between indoor air temperature and outdoor air temperature in Cairns. Note that while there are distinct seasonal temperature differences in Cairns as evidenced from the data, locals tend to refer to the period from December to May as the wet season and from June to November as the dry season. For Brisbane, Sydney and Gippsland, there is a significant difference between indoor air temperature and outdoor air temperature during colder winter months (June to August), which is likely to be due to significant levels of space heating. Average indoor air temperature appeared to reach a minimum of about 17°C, irrespective of the outdoor air temperature, although this varied in individual houses.

A more useful way of arranging the large volumes of data available in order to examine the relationship between outdoor air temperature and indoor air temperature in livings spaces is to take the mean data for each of the four climates examined above and to plot these as illustrated in FIGURE 3. Each data point represents one month of average outdoor air temperatures versus one month of indoor air temperatures, where the individual points have been averaged across all houses within the specified climate zone (this ranges from 20 to 40 houses per data point per climate).

This approach offers a more coherent way of considering indoor and outdoor air temperature data across very different climates and seasons as it offers a continuous function across different climate zones. The pattern that emerges is that, on average, indoor air temperatures in living areas are about 2°C warmer than outdoor air temperatures, except when the average monthly outdoor air temperature falls below 20°C. Below an outdoor air temperature of 20°C, there is an increasing divergence between indoor and outdoor air temperatures as outdoor air temperatures decrease. In simple terms, when it gets colder, below the comfort threshold of 20°C, occupants tend to heat more in living areas. It is important to note that these temperature values are monthly average values, so some days and some times of day will be warmer or cooler than the monthly average. The data also suggests that houses in Gippsland, on average, tend to maintain slightly warmer indoor temperatures for the same outdoor air temperature, when compared to Sydney and Brisbane. This is known to be anecdotally true: the colder climate in Victoria means that houses have more insulation and have more serious heating systems (Energy Efficient Strategies 2008, Australian Bureau of Statistics 2014).

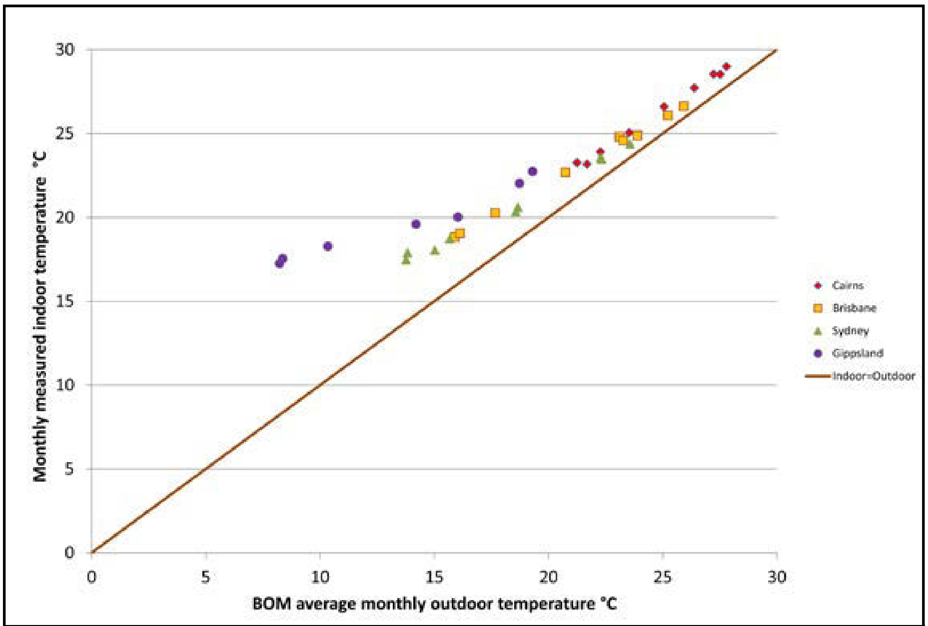

Figure 3. Monthly average air temperatures for living areas for four climates – average of all households for each climate (100 sites)

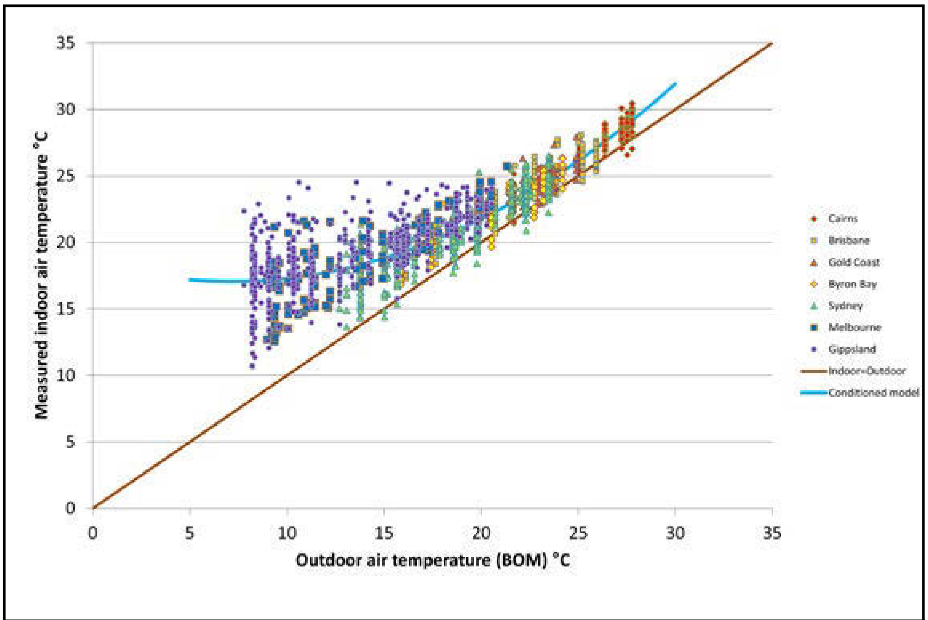

Figure 4. Matched monthly average indoor and outdoor air temperatures for living areas, all sites and all climates (273 sites) – preliminary model

Detailed results

Indoor air temperature data was collected at 273 sites around Australia; of these 251 covered a period of six months or more (more than 95% of the data) representing an average of 7.5 months per site. Data for a specific month for each site were cross matched with outdoor air temperatures from the closest BOM station so the length of time where data were available for a specific site was of less importance in this phase of the analysis, as each monthly data pair for each house is considered individually. When the data were filtered to remove non-living areas and outdoor measurements, a total of 1835 matched pairs of monthly average indoor living area air temperature and BOM monthly average outdoor air temperature were obtained. This is illustrated in FIGURE 4 with a separate legend entry for each climate. Each data point on this figure represents one month of average outdoor air temperature and one month of average indoor air temperature at a single site.

FIGURE 4 reveals considerably more information about the differences between individual houses when compared to climate averages shown in FIGURE 3. The range of indoor air temperatures (warmest minus coldest) is about 4°C for most climates where the monthly average outdoor air temperature is above 20°C. This range expands as outdoor temperatures get colder: at a monthly average outdoor air temperature of 8°C, which is somewhat colder than Melbourne would normally experience in winter, the range in indoor average monthly air temperatures increases to about 11.5°C (warmest minus coldest in the sample). There is a significant minority of houses in Melbourne and Gippsland (around 15%) that keep their living areas over 20°C throughout winter, irrespective of the outdoor air temperature. The bulk of households have a pattern of heating that result in a monthly indoor average air temperature of 16°C to 19°C when the outdoor temperature is 10°C.

This approach provides a method to predict typical indoor air temperatures in living areas. The value of this approach is that it uses data on outdoor air temperatures, which are readily available from agencies such as BOM. It also provides reliable estimates of average or typical indoor air temperatures that are likely across a very wide range of climates, which is useful for energy policy makers and health analysts. It is an estimate of actual temperatures that are likely to occur and does not require any assumptions regarding the building or the household. However, the indoor air temperature at any particular site will depend on a range of factors as noted previously, such as building shell performance, occupancy and use of space conditioning equipment. For the 100 sites located in four climates zones that have been subjected to intensive parallel analysis, it is possible to estimate the likely range in average monthly indoor air temperatures across all sites in each climate for each month, calculated as the standard deviation of mean monthly temperatures for each house. FIGURE 5 provides an approach to estimating the variation in indoor mean air temperatures across all sites.

A curve was fitted through the data in FIGURE 4 as follows:

$$t_i = 0.0285t_o^2 - 0.409t_o + 18.53$$

(Equation 1) (R^2 = 0.816)

where t_o is the average monthly outdoor air temperature (°C) for the site and t_i (°C) is the expected average monthly indoor air temperature in the living area. The data suggests that heating occurs below an outdoor monthly average air temperature of 20°C as there is a divergence between outdoor air temperature and indoor air temperature. Splitting the data into a nominal heating component, with an average monthly outdoor air temperature below 20°C (quadratic), and a cooling component, with an average monthly outdoor air temperature above 20°C (linear), did not result in an improved correlation coefficient. A continuous function to cover all outdoor temperatures (within the limits of the available data) also has advantages.

Similarly, a curve was fitted through the data in FIGURE 5 as follows:

$$z = 0.00578t_o^2 - 0.283t_o + 4.22$$

(Equation 2) (R^2 = 0.861)

where z is the standard deviation of the range of indoor mean air temperatures in living areas across all sites for a given outdoor air temperature and x is as given in Equation 1.

Further investigations revealed that the use of data collected at one-minute, 30-min or 60-min intervals had no impact on the calculated monthly standard deviation of measured temperature readings where complete data sets were available for the whole month. This is illustrated in TABLE 1, which shows a single 1-min data set that has been converted to average temperature readings ranging from 1-min to 1-day intervals, with the standard deviation for the month calculated on each converted data set. This suggests that recording of temperature data at 60-min intervals or less will produce consistent results.

Validation of the approach using CSIRO data and fine tuning of data

The initial model developed in the previous section was based on data collected from 273 sites. In 2013, CSIRO published a major study that evaluated the impact of house star ratings on energy consumption (Ambrose *et al.* 2013). This included long term measurements of indoor air temperatures in 438 Australian homes in three cities over a period of more than one year, primarily located in and around Brisbane, Adelaide and Melbourne.

The CSIRO study focused on newer homes, with nearly all houses in the sample being constructed after 2004. The objective of that study was to evaluate the impact of house star rating on the heating and cooling energy consumption in order to establish whether more efficient building shells resulted in lower energy consumption for space conditioning. This involved data logging of house energy consumption, as well as collection of indoor air temperature data in all participating households. Within each of the three broad climates (Brisbane, Adelaide and Melbourne) each household was allocated to a BOM weather station that best represented the local outdoor weather conditions. A total of 14 different BOM weather stations were used, with five around Melbourne (including one at Geelong), five around Adelaide (including Mt Lofty and one at Mt Gambier) and four around Brisbane as shown in TABLE 2.

The data provided by CSIRO included monthly average indoor air temperature measurements and the associated BOM weather data, grouped by BOM weather station. Monthly indoor temperature data was available from November 2011 to March 2013 (details of the source data are given in Ambrose *et al.* 2013). This data was configured to allow a comparable analysis to that undertaken in the previous section. Only aggregated average data for all participant houses for each BOM station was provided: there was no separation of house data by star rating, size or demographics and no data for individual houses were provided. Altogether, this data set provided an additional 234 pairs of monthly indoor and outdoor air temperature data spread across 438 participating households. This data is plotted in FIGURE 6. The spread of data is naturally much less as each point represents a group of houses (from 4 to 85 houses, depending on the climate).

The first observation was that the line of best fit for the CSIRO houses and the initial conditioned model developed from the 273 sites (all data), as shown in FIGURE 6, are very similar for colder temperatures (outdoor air temperatures below 15°C) and for warmer temperatures (outdoor air temperatures above 23°C). The CSIRO houses are, on average, about one degree warmer where outdoor air temperatures are in the range 17°C to 21°C.

The CSIRO study actively recruited participants in newer houses that were rated as four stars or five stars under the NatHERS house rating scheme. The houses in the CSIRO sample had a mean build year of 2007. In contrast, the sample of 273 houses was effectively a random selection of the

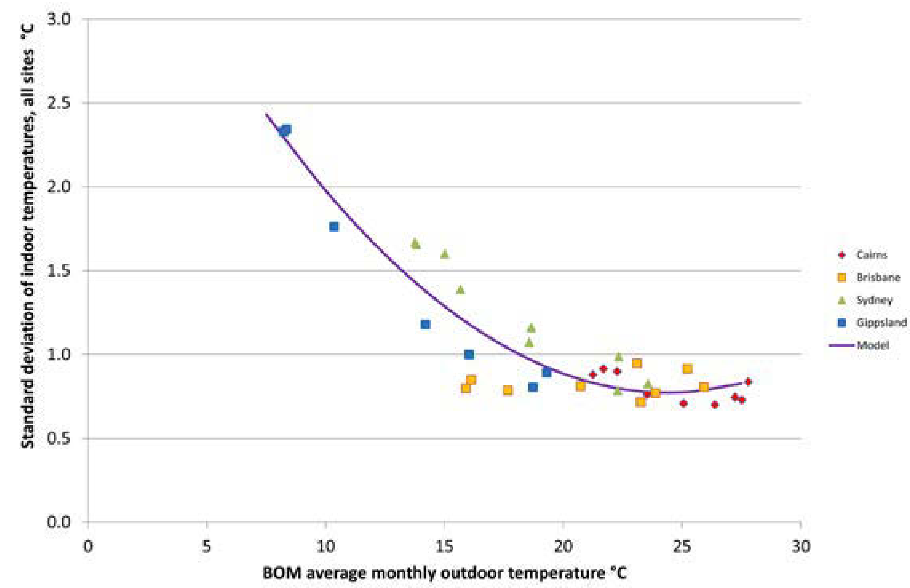

Figure 5. Standard deviation of average indoor air temperature across all sites, by month and climate.

Month	Average Dry Bulb °C	Std Dev 1 min interval °C	Std Dev 10 min interval °C	Std Dev 30 min interval °C	Std Dev 60 min interval °C	Std Dev 180 min interval °C	Std Dev 1 day interval °C
2013-01	21.1	5.44	5.44	5.44	5.45	5.37	3.65
2013-02	22.6	5.10	5.09	5.08	5.08	5.02	3.40
2013-03	21.4	5.88	5.88	5.88	5.87	5.82	4.78
2013-04	16.5	3.62	3.62	3.61	3.60	3.54	2.24
2013-05	13.7	3.60	3.60	3.59	3.59	3.53	2.51
2013-06	11.0	3.30	3.29	3.29	3.28	3.22	1.96
2013-07	11.8	3.37	3.37	3.36	3.35	3.30	2.57

Table 1: Monthly standard deviation calculations for weather data in Melbourne.

total stock of dwellings in Australia, with a mean build year of 1965. Survey information collected by the authors during field monitoring recorded the year of construction for 221 of the sample of 273 houses. The data in Figure 4 was re-analysed into several cohorts as follows:

- Older houses (built before 1991) – 136 houses
- Intermediate houses (built between 1991 and 2005) – 64 houses
- Newer houses (built after 2005) – 21 houses.

These cohorts were selected after a trial analysis of many different break points where the indoor temperature distributions were examined. Originally, houses prior to 1950 and from 1951 to 1990 were separately examined, but these appeared to have almost exactly the same indoor conditions, so were subsequently amalgamated. Wall and ceiling insulation became mandatory in 1991 in Victoria so this was a logical cohort. Analysis of the data certainly showed that average indoor air temperatures become increasingly warmer as the construction date progresses past 1990. Most states had building shell efficiency requirements from 2006 under the Building Code of Australia, which formed another logical cohort that also aligned closely with the CSIRO sample. The intermediate houses were found to have somewhat warmer indoor temperatures than older houses across all outdoor conditions and the newer houses were found to have virtually identical indoor air temperatures to the CSIRO sample for outdoor temperatures ranging 15°C to 26°C. The very new houses from the author sample at an outdoor temperature 10°C showed warmer indoor air temperatures than the CSIRO sample, but this can be explained by the fact that only 3 new houses (in the sample of 21 newer houses) experienced outdoor temperatures at or below 10°C, so the discrepancy is likely to be caused by bias in the very small sample for this temperature. The CSIRO sample had 141 houses that experienced outdoor air temperatures of 10°C or below, so this is a much more robust data set at these lower outdoor air temperatures. This effectively proves that average indoor air temperatures are likely to be driven to some extent by the age of the building shell and that the CSIRO and author data sets are entirely consistent. The results of the analysis are shown in Figure 7 and the resulting final equations are set out in Table 3.

Access to the CSIRO data for this research has validated the approach used to estimate indoor air temperatures. Both data sets, while representing very different types of dwellings, are highly consistent when examined across the seasons over a range of climates and when broken into comparable cohorts. The analysis illustrates that average indoor air temperatures in living areas increase gradually for newer buildings.

CSIRO analysis in Ambrose *et al.* (2013) has confirmed that the energy consumption for heating is strongly correlated with building performance, so comparable indoor conditions in older homes will be associated

Nominal City	Climate	BOM Station	Participants
Melbourne	Moorabbin	86077	14
Melbourne	Scoresby	86104	19
Melbourne	Melbourne Airport	86282	42
Melbourne	Laverton	87031	36
Melbourne	Breakwater (Geelong) *	87184	4
Adelaide	Edinburgh	23083	41
Adelaide	Kent Town	23090	85
Adelaide	Mount Lofty	23842	17
Adelaide	Noarlunga	23885	24
Adelaide	Mount Gambier *	26021	8
Brisbane	Amberley AMO	40004	10
Brisbane	Archerfield Airport	40211	50
Brisbane	Brisbane	40913	53
Brisbane	Redcliffe	40958	35
All	14 weather stations		438

Table 2: List of climates and participants covered by CSIRO study.

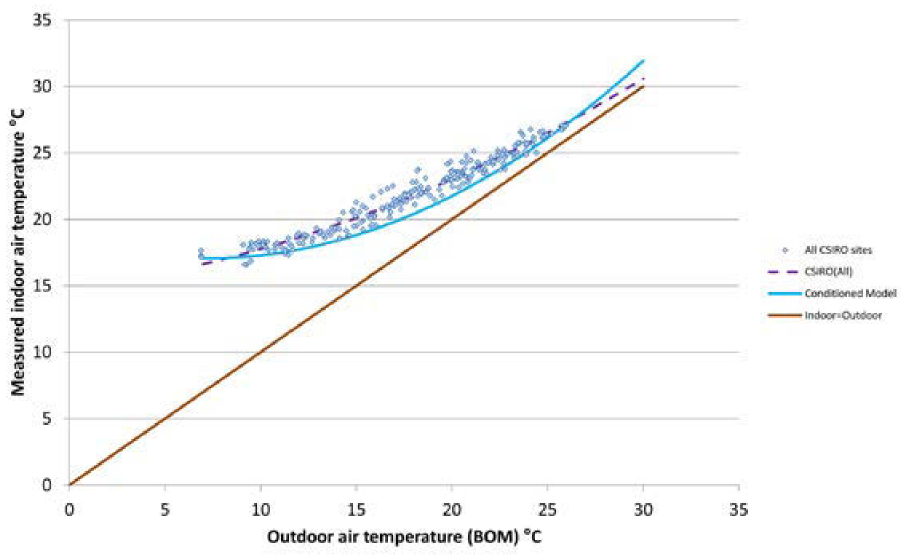

Figure 6. Matched monthly average indoor and outdoor air temperatures for CSIRO sites.

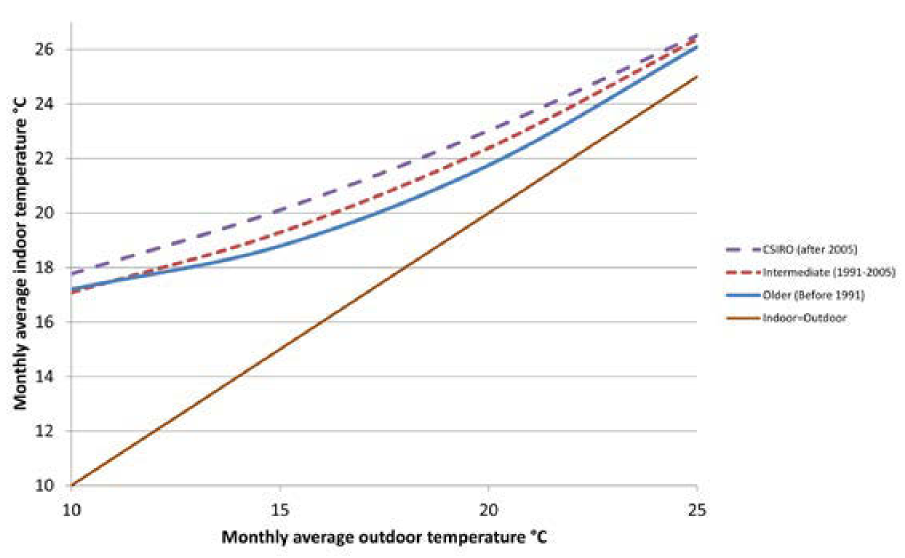

Figure 7. Final model of average monthly indoor air temperature as a function of outdoor air temperature by building cohort.

in higher levels of space heating energy consumption for houses, especially those with poorly performing building shells. Based on an analysis of the building stock of Australian homes, the average star rating in 2007 was less than 2 stars (Energy Efficient Strategies 2008) and the energy consumption could be expected to be 60% higher in order to maintain comparable indoor conditions.

INDOOR HUMIDITY DATA

Indoor air humidity is a topic of some interest as this can affect human comfort. Excess air humidity and condensation can also promote the growth of fungi and pathogens, which can be a health hazard (Prezant *et al.* 2008). To examine the relationship between indoor air humidity and outdoor air humidity in homes, long term data for 20 sites was examined.

There are many different ways of defining air humidity, which is the quantity of water vapour in the air. Each has advantages and disadvantages in terms of analysis, depending on the objective. Some common parameters used to specify humidity and water vapour are wet bulb temperature, dew point temperature, relative humidity and humidity ratio (ASHRAE 2013). It is important to note that these metrics are just different ways of measuring the quantity of water vapour in air and they may be interchangeable, depending on the application.

Relative humidity is the term that is most familiar to most people as this is a parameter that is often quoted in weather reports. It is one parameter that provides a broad indicator of human comfort and can drive the growth of pathogens. However, as a measure of moisture content in the air, relative humidity is difficult to analyse over long periods as it changes with the air temperature (dry bulb), which itself is changing continually. The most relevant measure of humidity for this type of analysis, where indoor and outdoor values are directly compared, is humidity ratio, as this is a direct measure of the mass of water vapour in the dry air and the parameter is independent of the air (dry bulb) temperature. The results using humidity ratio can be converted to relative humidity for a given dry bulb temperature if that is more relevant for specific applications. The humidity ratio of air inside of homes could be higher than outside due to water vapour emitted by occupants, plants as well as human activities such as cooking. The humidity ratio of the air inside of homes could also be affected by the use of air conditioners: refrigerative air conditioners will reduce the humidity ratio of air inside of homes while evaporative air conditioners will increase the humidity ratio. Unflued gas heaters could also increase indoor humidity ratio.

TenWolde and Pilon (2007) set out a range of likely sources of water vapour in a typical home. One of the main sources of water vapour is the occupants themselves, estimated to be around 50 g per hour per adult at rest from transpiration (sweating) and respiration combined (1.2 kg per 24 hours). Other sources include pets, indoor plants, showers and bathing, cooking and cleaning, clothes washing and drying and water vapour emitted from foundations. TenWolde and Pilon (2007), together with Glass and TenWolde (2009), estimate total water vapour production rates in the range of 6 kg to 12 kg of water vapour load per day from all sources for a range of typical houses in the USA. Given that Australian houses are smaller than those in the USA, an example where water vapour production was 5 kg per day for an average house of 180 m^2 floor area and a ceiling height of 2.5 m (representing 450 m^3 of air) would be the equivalent of approximately 11 g of water vapour per cubic metre of air, or an increase in humidity ratio of around 9.75 g/kg dry air per day. Given that outdoor humidity ratio values are typically in the range 5 g/kg to 12 g/kg, this would equate to a huge increase of air moisture content over time if there was little air exchange with outdoors.

A critical factor that will impact on the resulting indoor air humidity ratio is the air exchange rate. The estimated stock average natural air change rate for Victorian homes is 1.9 air changes per hour, with the average being about 2.0 for pre-1990 houses (Sustainability Victoria 2014). Measurements in 116 homes with unflued gas heaters in Sydney, Canberra and Melbourne estimated an average natural air change rate of 1.1 air changes per hour using CO_2 depletion rates, with values ranging from 0.2 to 3.8 (AWN Consultants & Team Ferrari Environmental 2004) with the results for each house being somewhat dependent on weather conditions during measurement (especially wind speed and direction). With these rates of air exchange in homes, the indoor humidity ratio would be expected to be only slightly above the outdoor humidity ratio, even in cases with high levels of water vapour production indoors from occupant activities and other sources. If the outdoor air humidity ratio increases, then the indoor air humidity ratio would increase with some lag, depending on rate of air exchange. Similarly, if the outdoor air humidity ratio decreases, then the indoor air humidity ratio would be expected to decrease with some lag. Values of 0.35 air changes per hour are qualitative considered to be good from an energy perspective (Department of Industry 2013), but it appears that few houses in Australia currently fall into that category. An international review of air exchange rates found that many countries recommend a minimum of 0.3 to 0.5 air exchanges per hour in order to minimise health impacts (Lajoie *et al.* 2007), but it also notes that a downward trend in air exchange rate is being driven by energy efficiency.

Seven months of daily data for the Gippsland site is illustrated in FIGURE 8. This house has no air conditioning and the building shell rates 6 stars under NATHERS. The outdoor air humidity ratio is quite variable, especially through spring months (September to November), but the indoor air humidity ratio closely tracks the outdoor humidity ratio. The indoor air humidity ratio is usually higher, especially in winter when all windows and doors are closed during heating. The indoor air humidity ratio can be higher than outdoors when the outdoor levels are dropping rapidly, as there is some lag effect for air exchange to occur.

It is important to note that, while humidity ratio values tend to change fairly slowly over a period of hours, it can be quite variable from day to day. FIGURE 9 illustrates the monthly average humidity ratio for

Building Cohort	*a*	*b*	*c*	R^2
Older – before 1991	0.0275	-0.3700	18.152	0.8035
Intermediate – 1991 to 2005	0.0179	-0.0072	15.367	0.9318
CSIRO (all after 2004)	0.0115	0.1809	14.805	0.9573

Table 3: Quadratic coefficients for final indoor air temperature model by building cohort.

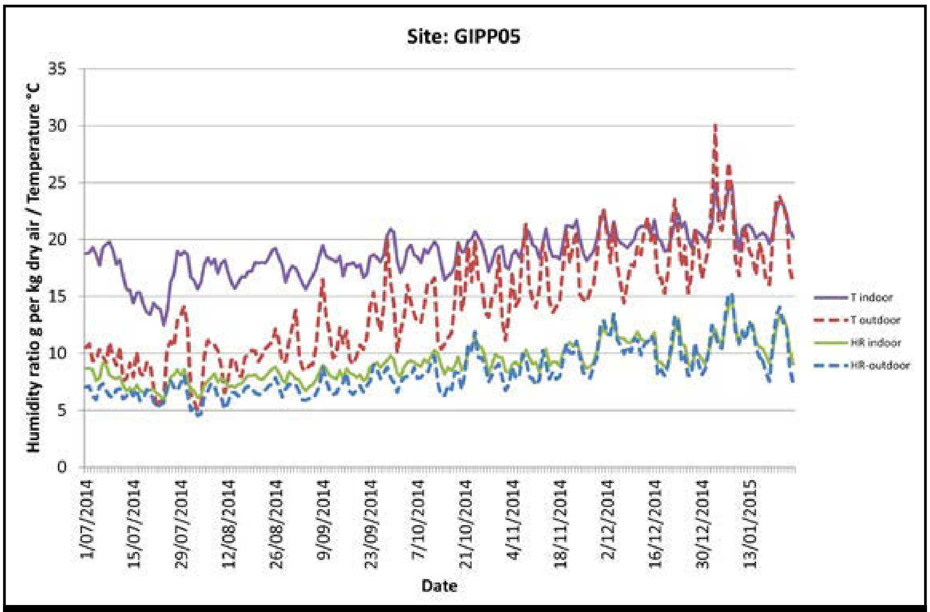

Figure 8. Daily indoor and outdoor air temperature and humidity ratio for the Gippsland site.

Sydney in 2014 along with the daily average values for the same year. This illustrates the typical monthly seasonal pattern in humidity ratio as well as the day-to-day volatility, which will impact on indoor conditions.

To assess the difference in indoor and outdoor humidity ratio in homes, a range of monitoring data was compiled. Ten of the sites were measured by the authors and ten of the sites had data provided by Sustainability Victoria as part of another project on building shell performance. The Sydney and Gippsland sites had separate data loggers recording indoor and outdoor air temperature and relative humidity data in parallel. This was converted to humidity ratio using psychrometric software (Chemicalogic 2015) and using air pressure readings from the nearest BOM site. This software uses formulations that comply with *ASHRAE Handbook - Fundamentals* (ASHRAE 2013). A summary of the key monitoring results for all 20 houses is included in TABLE 4.

The main observation from this data is that the indoor humidity ratio is generally very similar to, but slightly higher than, the outdoor humidity ratio. The maximum difference observed was about 3 g per kg of dry air when averaged over a month for a home in Melbourne built within the last 5 years. In terms of seasonal differences, the difference between indoor and outdoor humidity ratio is generally higher in winter than summer. This is expected, as houses will generally have all windows and doors closed in winter (June to August), whereas in summer (December to February) during milder weather, many houses have doors and windows open.

The Sydney houses on average had very similar readings for indoors and outdoors in summer. This reflects both more ventilation as well as more active use of refrigerative air conditioners, which were present in these particular houses. Periods of air conditioner use supressed the indoor humidity ratio noticeably. For some summer months in some Sydney houses the indoor humidity ratio values were as much as 0.5 g/kg lower than the outdoor value. On average, the expected difference between indoor and outdoor humidity ratio for Sydney and Melbourne houses is typically:

- 0.4 g/kg higher indoors in summer in Melbourne (range 0.2 to 0.6 g/kg dry air)
- no difference between indoor and outdoor in summer in Sydney (range –0.5 to +0.5 g/kg dry air)

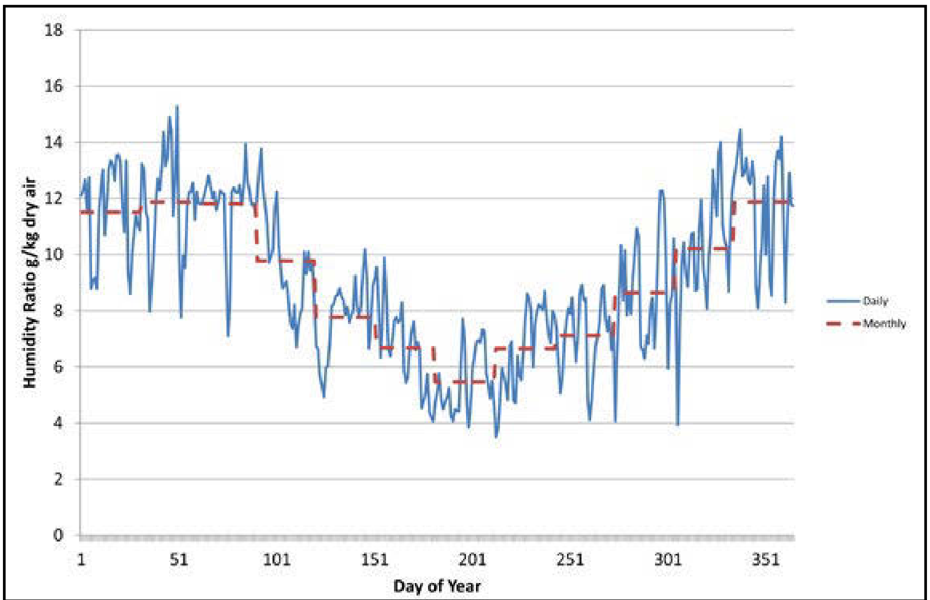

Figure 9. Daily and monthly average air humidity ratio for Sydney BOM in 2014.

Site	Period	Days	Summer outdoor humidity ratio g/kg	Indoor-outdoor difference humidity ratio g/kg	Winter outdoor humidity ratio g/kg	Indoor-outdoor difference humidity ratio g/kg	Dew point temp °C outdoor summer	Dew point temp °C indoor summer	Dew point temp °C outdoor winter	Dew point temp °C indoor winter
SYD-H08	2013-14	406	12.4	-0.1	7.3	0.8	17.1	17.0	9.0	10.7
SYD-H74	2013-15	690	12.3	-0.4	7.1	0.9	16.9	16.5	8.5	10.5
SYD-H24	2013-15	689	12.3	0.0	7.0	1.1	16.8	16.8	8.3	10.6
SYD-H28	2013-15	691	11.3	0.6	6.9	0.8	15.5	16.5	8.1	10.0
GIPP05	2014-15	223	10.5	0.4	6.5	1.1	14.2	14.9	7.3	9.6
MEL51	2010-11	179	9.5	0.4	6.0	1.3	12.5	13.3	6.2	8.9
MEL52	2010-11	174	9.6	0.6	6.0	1.0	11.4	13.7	5.5	8.2
MEL53	2010	88	9.5	0.5	6.0	0.5	12.2	13.2	6.2	7.4
MEL54	2010-11	138	10.0	0.4	6.1	0.5	13.3	14.1	6.3	7.6
MEL55	2010-11	179	9.6	0.3	5.7	0.7	12.4	13.2	5.5	7.2
MEL81	2013	107	No data	No data	5.9	1.8	No data	No data	5.9	9.8
MEL82	2013	63	No data	No data	6.0	1.4	No data	No data	6.1	9.4
MEL83	2013	69	No data	No data	5.7	1.4	No data	No data	5.3	8.6
MEL84	2013	72	No data	No data	5.8	3.0	No data	No data	5.6	11.8
MEL85	2013	84	No data	No data	5.8	2.7	No data	No data	5.6	11.3
MEL86	2014	125	No data	No data	6.0	1.5	No data	No data	6.2	9.6
MEL87	2014	119	No data	No data	6.4	1.4	No data	No data	7.3	10.4
MEL88	2014	124	No data	No data	6.4	1.3	No data	No data	7.3	10.2
MEL89	2014	126	No data	No data	6.0	1.3	No data	No data	6.2	9.0
MEL90	2014	115	No data	No data	6.0	2.0	No data	No data	6.2	10.5

Table 4: Summary of long term indoor and outdoor air humidity data for 20 sites.

- 1.5 g/kg higher indoors in winter in Melbourne (range 0.5 to 3.0 g/kg dry air)
- 0.9 g/kg higher indoors in winter in Sydney (range 0.8 to 1.1 g/kg dry air)
- The Gippsland home was comparable to Melbourne values for summer and winter.

Detailed daily data by time-of-day was reviewed at each site. Some regular activities such as cooking can appear as a systematic increase in the indoor humidity ratio in some houses at certain times of the day. The use of refrigerative air conditioners appears to reduce the indoor humidity ratio by up to 1.5 g moisture per kg of dry air when in use. The use of evaporative air conditioners appears to increase the indoor humidity ratio by up to 2 g moisture per kg of dry air when in use. These tend to have small effects on monthly averages unless usage extends for very long periods.

The conclusion regarding indoor humidity in homes is that the outdoor humidity ratio is a very good predictor of the indoor humidity ratio, although outdoor humidity ratio can be quite variable due to rapid changes in weather. The average indoor humidity ratio can be estimated as the outdoor levels plus a small adjustor, depending on the climate and season. Houses in warmer climates tend to have more natural ventilation and so this is reflected as lower differences between indoor and outdoor humidity ratio. The use of refrigerative air conditioners can reduce the indoor humidity ratio below the outdoor level. In general terms, the differences in indoor-outdoor humidity ratio are small when the scale of day-to-day variations in humidity ratio are considered. However, in winter in Victoria, an increase of 1 g moisture per kg of dry air is around a 15% increase in the total water vapour load in the indoor air, which also increases the dew point temperature by around 2°C.

CONCLUSIONS

Analysis of the field data collected from 273 homes has led to the development of a mathematical model to estimate the expected range of indoor temperatures found in living areas in a wide range of climate zones within Australia. Importantly, the model uses outdoor temperature data as the predictive variable, so it can be applied to any household where there is consistent long term weather data in Australia, within the range of climates examined. Along with CSIRO data from a larger monitoring program, a series of equations have been developed to estimate indoor air temperature as a function of outdoor air temperature and building age. Development of a robust model of this kind, based on observed data, is important as estimation of air temperature in living areas is of interest to a wide range of analysts, including health and energy practitioners. The model meets the overall objective of being able to predict indoor air temperatures in order to estimate energy consumption for refrigeration appliances and space heating and cooling equipment. The value of this analysis over and above most modelling approaches is that it provides a quantitative assessment of indoor air temperatures that actually occur in livings areas in Australian homes and is not dependent on a range of assumptions or estimates for modelling.

However, despite the value of the analysis, there are some limitations with respect to the data and what can be extracted from it. No measurements were made of the use of space heating and cooling equipment, so there is little information on what factors may have influenced indoor temperatures. While some data was collected on the number of residents normally living in each household, occupancy was not monitored. Some qualitative information on the building shell was collected (mostly in terms of the perceptions of the residents) but no quantitative data on building shell performance was collected. While these additional parameters would have been of great interest for this type of analysis, they are also very costly to collect and would have increased the project costs by more than an order of magnitude. Ambrose *et al.* (2013) do look at these issues in some depth, but that study only covers newer homes.

While the paper does not examine the issue of energy consumption, the model developed in fact provides a solid benchmark for the calibration of a range of indoor simulation and energy models so that they more accurately reflect the range of normal use in households. The paper does provide a quantitative approach to estimate the range of indoor air temperatures in homes, but it does not explain the drivers of indoor air temperatures. This is an area where further research would be valuable. A wide range of climates were examined and found to be valid, but there may be limitations in more extreme climates such as hot deserts and tropical areas like Darwin, where the findings may not be applicable. The results may not apply to very atypical building shells and occupant behaviours.

A detailed analysis was also undertaken of indoor humidity measurements in 20 houses. This found that the indoor air humidity ratio was strongly linked to outdoor air humidity ratio but that indoor values were typically slightly higher. A range of factors such as the presence of occupants, occupant activities and the use of air conditioners were found to have an influence on the expected indoor humidity ratio, but generally these impacts were found to be small and relatively short lived when compared to the influence of outdoor humidity ratio. There is good evidence that the air exchange rate in typical homes is quite high and that water vapour generated by users is unlikely to accumulate. The trend towards very tightly sealed homes, driven by energy efficiency, may increase indoor air humidity issues in the future unless minimum ventilation rates are maintained.

This paper has examined a range of primary data sources and has developed some robust approaches to estimating indoor air temperature and humidity conditions in homes. The analysis undertaken in this paper is new and unique in Australia.

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