Determination of the association between indoor and outdoor temperature in selected houses and its application: a pilot study

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Abstract

Quantitative information on indoor temperature is important for understanding the impacts of temperature on building energy consumption, human health and comfort, however, such information is scarce. Additionally, extraction of useful information from existing indoor temperature data is hindered by varying study designs. The study aims to: simultaneously monitor indoor and outdoor temperature of selected houses and to develop a model describing their relationship; and analyse the potentials and limitations of the model towards understanding the association between indoor and outdoor temperature. Temperature sensors were installed in 15 houses in Brisbane, Australia, to monitor at intervals of 30 min over the winter of 2016. The linear mixed-effects model which we developed performed well and predicted that on average, 1^{o}C increase in outdoor temperature resulted in an increase of 0.4^{o}C ± 0.05^{o}C in indoor temperature. While the sample size of the study is relatively small, our model is expected to perform with any sample sizes particularly with large sample. Application of our indoor/outdoor temperature modelling will facilitate understanding the influence of temperature on energy consumption in households and human health. Such information is imperative towards future comfortable and low energy homes.

Keywords: Indoor temperature, outdoor temperature, residential settings, temperature sensors, linear mixed effects model

1. Introduction

Epidemiological studies that associate exposure to low and high temperatures with human health mostly use outdoor temperature values from meteorological stations since this data is readily available (Basu, 2009; Gasparrini et al., 2015; Guo et al., 2016). Exposure risk assessments should include measurements in microenvironments (such as houses) where humans spend most of their time, however, such an approach is rarely used in epidemiological studies because of the lack of indoor temperature data, especially in residential settings. In most locations in the world as well as where the study was conducted (Australia), people spend around 90% of their time indoors (Daniel and Baker, 2017). The use of outdoor temperature as a surrogate for 24-hour exposure will incur errors in estimating risk due to the temperature differences between outdoor and various indoor microenvironments, such as homes and workplaces (Basu, 2009). This deficiency has been highlighted by the World Health Organization (WHO), as well as by other studies (Barnett, 2015; Bernhard et al., 2015), and is attributed to the challenge of attaining statistically significant sample sizes and non-standardised protocols for data collection (Ormandy & Ezratty, 2012).

The indoor temperature is monitored to assess human thermal comfort in homes as well as household energy consumption and the thermal efficiency of houses (Adunola, 2014; de Dear et al., 2013; Hu, Yoshino, & Zhou, 2012; Kamar, Kamsah, Tap, & Salimin, 2012; Kavgic et al., 2012; Paravantis & Santamouris, 2015; Pisello, Santamouris, & Cotana, 2013; Wang, Zhang, Zhao, & He, 2010; Willand, Ridley, & Pears, 2016). Indoor temperature monitoring is typically conducted by individual scientific studies, using portable and deployable instrumentation and a variety of approaches, depending on the aims of the particular investigation. Studies which involve indoor temperature have used a variety of devices, such as HOBO U12-011 Temperature/Relative Humidity Data Logger (Onset Corporation; Bourne, MA, USA) (Nguyen, Schwartz, & Dockery, 2014), the La Crosse Technology Instant Transmission Plus Weather Station (Adunola, 2014) and Thermochron iButton devices DS1921G (Willand et al., 2016). The generated indoor temperature data are not easily accessible and available to the public as compared to outdoor temperature data. This is monitored continuously at meteorological stations and with robust instruments for the purpose of real time or periodic reporting; data archiving and accessibility. The design of the studies which measure indoor temperature differ in sampling duration, characteristics of houses recruited and mainly depend on the aim of the research (Anderson, Carmichael, Murray, Dengel, & Swainson, 2013). For example, thermal comfort studies have a characteristic of short duration sampling (Al-ajmi & Loveday, 2010; Humphreys, Nicol, & Raja, 2007) while that of thermal efficiency and household energy consumption are typically longer (over one year)(Rojas, Wagner, Suschek-Berger, Pfluger, & Feist, 2015). Nature of the study designs have contributed to the difficulty in using the data for broader purposes (outside of the original investigation aims). Although measured indoor temperature data are scarce worldwide, some large scale dataset do exist (for example the National Renewable Energy Laboratory indoor temperature in American homes and the Energy Follow Up Survey of the English Housing Survey (Booten et al., 2017; Hulme, Beaumont, & Summer, 2013)).

Previous studies have investigated the association between indoor and outdoor temperature to bridge the gap of lack of indoor temperature data through field measurements (Nguyen & Dockery, 2016; Nguyen et al., 2014; White-Newsome et al., 2012). Nguyen et al. (2014) compared average indoor temperature measured in 16 homes in Greater Boston with outdoor temperatures monitored at Boston Logan weather station during a one-year study. This study found that at warmer outdoor temperatures there is a strong correlation ($r = 0.91$) between indoor and outdoor temperatures, but this correlation was much weaker in cooler conditions (r = 0.40). It was also reported by a study conducted in Kuwait that there was no relationship between indoor and outdoor temperature when air conditioning was used by the occupants (Al-ajmi & Loveday, 2010). Additionally, these temperature (indoor and outdoor) relationship studies utilized daily temperature data sets from nearby airport station or central location as the outdoor temperature of their study area, rather than immediate proximity of the buildings, thus adding additional uncertainty. The main problem arises from the fact that by only using external data, we are not able to quantify the impact of building characteristics on temperature-related morbidity and mortality as a single external temperature value will mask potential geospatial variations resulting from the heterogeneity of indoor environments (Basu, 2009; Zhang et al., 2011). However, population in urban settings may be at a higher risk to temperature exposure than rural areas due to urban heat island (UHI) effect. Vegetation or tree covers converted into paved surfaces and buildings as part of city development results in less shade and moisture to keep urban areas cool (US E.P.A 2015)(Dwivedi, Khire, Mohan, & Shah, 2018; Knowlton et al., 2007; Santamouris, 2007; Tan et al., 2010; Vardoulakis, Karamanis, & Mihalakakou, 2014).

Consequently, there is minimal data on indoor temperature and it is difficult to extract useful information even if they are available. Thus, the need to measure indoor and outdoor temperature data primarily in residential settings to develop a new model to estimate the influence of outdoor temperature on indoor temperature and to analyse the strengths and limitations of the model towards understanding the association between indoor and outdoor temperature . The empirical data acquired would be of importance for understanding human thermal comfort and support energy demand models for the building stock. Therefore, the aims of this study were to:

(1) simultaneously monitor indoor and outdoor temperature of selected houses and to utilize these data to develop a new model to estimate the effect of outdoor temperature influence on indoor temperature.; and

(2) to analyse the potentials and limitations of the model towards understanding the association between indoor and outdoor temperature. This a critical information towards future comfortable and low energy houses.

2. Methods

The study had two stages: 1) laboratory assessment of temperature sensors to evaluate their performance, and 2) field measurements of indoor and outdoor temperatures in selected residential settings.

2.1 Laboratory assessment of temperature sensors

The Labjack-Digit Temperature Light Humidity (TLH) Sensor (Sahasra Electronics, INDIA) (Figure 1) was selected based on experts' advice, affordability, simplicity in operation, memory size and long battery life. The general specification of the Labjack-Digit TLH is presented in Table A.1.

[Figure 1 near here]

The laboratory assessment of the Labjack was conducted in a test chamber at the International Laboratory for Air Quality and Health (ILAQH), Queensland University of Technology (QUT). This is a sealed chamber with a dimension of 60 cm × 60 cm × 150 cm (L × W × H) with three sampling windows, spacious enough to accommodate all the evaluated sensors and two Mercury (Hg) thermometers. An electrical blow heater was used to increase the temperature of the chamber to 50°C. The colder temperatures (3°C) were achieved by placing the entire set-up within a large refrigerator. The door was opened at regular intervals to read the mercury thermometers. The mean readings on the Labjacks are shown with the respective standard deviations against the mean value reported by the two mercury thermometers in [Figure 3]. The consistency between the readings (slope = 1.00) together with the strong linear relationship (R^2=1.00) indicates that the Labjacks were providing reliable readings of temperature.

2.2 Field measurements

The fifteen houses included in this pilot study were located across different residential suburbs of the city of Brisbane (27° 28' S, 153° 1' E), Queensland, Australia as presented in [Figure 2]. These houses were occupied predominantly by students, at the International Laboratory for Air quality and Health (ILAQH), Queensland University of Technology (QUT). The selection of houses was based upon occupancy of houses for a period of at least six months and voluntary participation. The houses varied in style, construction material, age and design as shown by their characteristics presented in Table 1 and Table A.2. The climate of Brisbane is subtropical. The daily mean outdoor temperature during this study (winter months, June – August) ranged between 13.1 – 21.5 °C (June), 12.3 – 22.5 °C (July), and 11.8 – 23.0 °C (August) (BOM, 2017). Indoor and outdoor temperature measurements were conducted simultaneously and continuously in the selected houses from 1 June to 31 August 2016. Each house was provided with two labelled (indoor and outdoor) Labjack-Digit temperature sensors to be placed in the living room and the immediate outdoor surroundings. An instruction guide on how to place the temperature sensors at the respective sampling areas and how to download logged data onto computers was given to the participants. The same approach of asking participants to install sensors has been used by Nguyen, J. L., & Dockery, D. W. (2016).

The Labjack-Digit TLH Sensors were configured to record average indoor and outdoor temperature readings every 30 min. This sampling interval enabled the sensors to store logged data into its memory as well as consume less power to prolong its battery life throughout the study period. This sampling interval is not, however, intrinsic to this method, and may be shortened by the use of higher capacity batteries. For the indoor measurements, sensors were placed on the inner wall of living rooms (i.e. not an external wall); away from any source of heat and where they would not be moved. Outdoor temperature sensors were located at a safe place at the south side of the houses to avoid direct sunlight. To check whether the sensors were properly installed, the residents were asked to email photos of the installed sensors. Photos of temperature sensors installed both indoor and outside of three of the houses are shown in [Figure A.2].The downloaded logged data were emailed to the study team every fortnight. Participants were sent weekly reminders to submit their data via email. This process provided continuous data as well as information on the logging state of the sensors.

[Figure 2 near here]

[Table 1 near here]

2.3 Data processing

The raw data were exported into Microsoft Excel 2016 and R statistical computing software (version 3.3.3: R Foundation for Statistical Computing, Vienna, Austria) was used to inspect missing values, anomalies and for statistical analysis. Outliers in outdoor temperature data were defined as temperature readings either five times greater than mean maximum or less than mean minimum outdoor temperature reported by the Bureau of Meteorology, Australia. Descriptive statistics such as means, medians, standard deviations and 95% confidence intervals were used to summarize the indoor and outdoor temperature data acquired as presented in Table A.3. Indoor and outdoor temperatures were time-matched for each house.

2.4 Statistical analysis and modelling

Time series plots were used to identify diurnal temperature trends for individual houses and to compare their variability. The difference in the means of outdoor and indoor temperatures and their standard deviations were calculated to quantify diurnal variations in outdoor and indoor temperatures at the houses. A linear mixed-effects model with a random intercept to control for non-independent data from individual houses was used as defined in equation (1) to examine the extent to which outdoor temperature influenced indoor temperature.

$$I_{i,t} \sim \beta_{i,o} + \beta_{i,1} O_{i,t} + \boldsymbol{\alpha}\, H_{i,t} + \varepsilon_{i,t} \qquad (1)$$

Where:

$I_{i,t}$: *indoor temperature (°C)*

($\beta_{i,o}$): *random intercept (°C)*

($\beta_{i,1}$) : *random slope*

α : *estimated effect of the hour of the day*

$H_{i,t}$: *hour of day (hrs),*

$O_{i,t}$: *outdoor temperature (°C)*

ε : *error*

The dependent variable $I_{i,t}$ which is the indoor temperature measured in house *i* at time *t;* ε is the error term which is assumed to have a constant variance, and be serially independent and normally distributed. The two independent variables were the time-matched continuous outdoor temperature readings $O_{i,t}$, and hour of day as a categorical variables with 24 levels and reference time of midnight. We assumed the effect of outdoor temperature on indoor temperature would vary by house using a random slope ($\beta_{i,1}$). We also assumed the average indoor temperature would vary by house using a random intercept ($\beta_{i,o}$). These assumptions are based on our prior knowledge that temperatures inside homes in Brisbane on the same day can be very different depending on the behaviour of occupants, and the surroundings of the homes and building materials. The identified building characteristics of the houses were not used as variables in the model because our small sample size was insufficient for group comparison, but such data could be used in larger samples to identify average differences in indoor temperatures due to house characteristics. As part of the identified building characteristics, we collected data on whether the houses have heating and cooling system but not the exact time periods when occupants used them. However, based on the indoor and outdoor temperature profiles of the houses, we could infer when mechanical space conditioning was used in the houses; there was a small proportion of the houses where this happened. .

The model is comparable to that developed by (Oraiopoulos, Kane, Firth, & Lomas, 2017) to predict overheating in UK houses and also has the advantage of addressing the longitudinal structure of temperature data. A linear mixed effects model was used because the data are longitudinal with repeated results from the same house (Diggle, Heagerty, Liang, & Zeger, 2002). A random intercept per house was used to adjust for correlation and also to account for differences in the average temperature between individual houses. A mixed model also allowed us to use a random slope for each house, which meant that we could model a varying effect of outdoor temperature on indoor temperature. This is very important because houses (and their occupants) are likely to differ in how they respond to changing outdoor temperatures. An added advantage of this method is that we were able to plot the random intercepts and slopes for houses in order to identify unusual houses and patterns by housing characteristics.

3. Results

3.1 Laboratory assessment

The relationship between the mean Labjack-Digit TLH Sensor temperatures versus the readings of the mercury thermometer is shown in [Figure 3]. The line of best fit is linear with the equation $y = 0.9975x + 0.0582$ and $R^2 = 1.00$. The R^2 value (1.00) depicts the strong correlation between the Labjack-Digit TLH Sensors readings and that of the Hg thermometer with marginal error. The laboratory assessment results agreed quantitatively with the specifications of the Labjack-Digit TLH Sensor specifications as presented in Table A.2.

[Figure 3 near here]

We concluded that temperature readings acquired with the Labjack-Digit (TLH) temperature sensors are reliable.

3.2 Temperature profiles

Mean indoor temperature in the houses ranged from 16.6 to 25.1 ^{o}C, and mean outdoor temperatures from 15.0 to 21.5 ^{o}C. The mean indoor temperatures did not vary substantially with the month of measurements but varied significantly with the type of houses. A minimum indoor temperature of 9.6 ^{o}C was recorded in H3 (Queenslander: a single detached house constructed with timber and iron (Osborne 2014)) located in an inner suburb of Brisbane. The maximum indoor temperature of 29.3 ^{o}C was recorded in H10 (an apartment: a dwelling within a group of self-contained dwellings in a building up to three or more storeys in height (Brisbane City Council and the Queensland Government 2011, 5)) in a western (inland) suburb of Brisbane. Neither H3 nor H10 were artificially heated. As expected, the mean outdoor temperature at all the houses corresponded with the long-term winter temperatures of Brisbane reported by the Bureau of Meteorology over the period June to August (June (13.1 – 21.0 ^{o}C), July (12.3 – 22.5 ^{o}C), August (11.8 – 23. 0 ^{o}C) (BOM, 2017)). The mean indoor temperature range of 18.2 – 23.4 ^{o}C obtained in 11 of the houses was within to the World Health Organization (WHO, 1984) recommended indoor temperature range of 18 – 24 ^{o}C (Ormandy & Ezratty, 2012), but that of H4 was lower (16.8 to 17.2 ^{o}C) while that of H8 was higher (24.7 to 25.1 ^{o}C).

Temperature trends of indoor and outdoor temperatures for all houses from June to August are presented in Figure A.1. Time series of outdoor temperatures had a clear diurnal trend corresponding to the rise and fall of the Sun, except for H9. The different outdoor temperature trend identified in H9 was attributed to a sensor installed at the southeast side of the house instead of the south side as directed. This resulted in the maximum outdoor temperature recorded at H9 occurring close to sunrise (when sensors would have been subjected to direct solar radiation). In general, outdoor temperature decreased steadily between 00:00 and 6:00, then increased steeply to its maximum between 13:00 to 14:00 and decreased again between 15:00 to 23:00.

The indoor temperature trends in most of the houses were S-shaped while in some houses were flat. Indoor temperature followed their corresponding outdoor temperature in some houses as shown in the trends for H3, H4, H5 but was not so for other houses as shown in Figure. A.1.1 (H1 (June)) and Figure. A.1.35 (H12 (June)). The difference in the temperature trends in these houses has been attributed to the use of Air-conditioners (AC) (heating) and portable heaters by occupants, which influenced indoor temperature.

To compare temperature trends of heated (Air-conditioned (AC)) and non-heated (non-AC) houses, we chose Figure 4 and Figure 5 as representative examples of temperature trends in heated and non-heated houses. In non-heated homes, indoor temperature trends were similar to outdoor temperature trend as indoor temperature lagged after the outdoor temperature with a marginal difference in temperature at different times. The variations in the lag time is attributed to the building envelope of the houses, which includes insulation, glazing and building material used (Cheng, Ng, & Givoni, 2005; Gregory, Moghtaderi, Sugo, & Page, 2008; Sadineni, Madala, & Boehm, 2011). The building envelope characteristics of the house also dictate to what extent the indoor temperature trend in non-heated house flattens.

Conversely, in Figure 5, the trend in indoor temperature was distinctively different from that of outdoor temperature because of the use of air-conditioning for heating purposes. The indoor temperature trend was almost flat. Also, given that the temperature variation in Figure 5 is so small (24 ± 1 ^{o}C), it seems feasible the H7 had a heating set point at around 23 – 24 ^{o}C. The shape of indoor temperature trends identified for the heated houses in this study was similar to that observed by Huebner et al. (2014)) in their study on temperature trends in the living room of 275 dwellings in the UK.

[Figure 4 and 5 near here]

3.3 Difference in diurnal temperatures

Computed differences in mean outdoor and indoor temperatures measured at the houses within the 24-hour cycle are presented in Table 2. The difference calculated was grouped by houses without heating (non-AC) and those heated (AC). In both groups of houses, the differences were greater in the mornings (00:00 – 7:00) and night (18:00 – 23:00) which are the times when houses are most likely to be occupied. This difference may be due to lower outdoor temperature, similar to Hamilton et al. (2017)) findings and the building envelope of the houses. Factors such as type of insulation, glazing and thermal mass influence heat flux between the external and internal environment. For example, houses with high thermal mass (concrete, brick) such as H1, H, H8, H10 had higher indoor temperature both in the morning and the evening because the thermal mass effect limits variations in indoor temperature (higher minimums and lower maximums). The thermal mass and insulation of non-heated houses also contributed to the marginal difference between 8:00 – 17:00. Hence, around midday when the outdoor temperature is high, light weight construction (timber) may heat quickly (if there is solar access) up, thereby increasing the indoor temperature faster as compared to houses with thermal mass (Cheng et al., 2005). Among the non-heated houses, we noticed that houses of the same types had similar temperature difference such as the case of H3 and H5 (Queenslander) as well as H8 and H10 (Apartments). The similarities are likely due to the related nature of the building envelope. For the heated houses, the significant difference in outdoor and indoor temperature was broadly governed by building envelope of the house, behaviour of occupants and the use of air-conditioning for heating purposes. The high temperature difference observed in H7 was due to the use of air-conditioning throughout the study period, as indicated by the occupant. The high standard deviation values associated with the difference in outdoor and indoor temperature between hours of 8:00 – 17:00 is related to temporal variations in outdoor temperature because of non-uniform solar radiation caused by factors such as cloud cover.

[Table 2 near here]

3.4 Influence of outdoor temperature on indoor temperature

The output of the linear mixed-effect model with a random intercept, as described in equation (1), is presented in Table 3.

[Table 3 near here]

The random slope (β_1) denotes to what degree outdoor temperature (independent variable) influences indoor temperature in the houses (dependent variable) for each outdoor temperature increase. On average, each increase in outdoor temperature of (1 ^{o}C) for all the houses is associated with an increase of their indoor temperature by 0.39 ^{o}C (95% C.I = 0.29 – 0.48). There was a large variability between houses in the effect of outdoor temperature [Figure 6]. In three houses H3 (β = 0.68), H4 (β = 0.57), H5 (β = 0.72) the indoor temperature had a much stronger dependency on the outdoor temperature. These houses were non-heated; constructed mainly of timber; and may have, had the least insulation.

[Figure 6 near here]

The plot [Figure 7] shows the estimated effect of the hour of the day on the indoor temperature after adjusting for the outdoor temperature. So we do not estimate that the indoor temperature is around 2 degrees colder at 11am, rather it is 2 degrees colder than expected given the outdoor temperature. In other words, the outdoor temperature is having less effect at this time of day, and has a stronger effect during the hours of 7pm to 1am where the estimated effect of the hour of the day is close to zero.

[Figure 7 near here]

4. Discussion and Conclusion

This study simultaneously monitored indoor and outdoor temperature (in immediate surroundings) using calibrated sensors (data loggers) in selected houses. It used the acquired data to develop a model to quantify the relationship between temperature (indoor and outdoor) in households as well as explore the information on temperature towards understanding the local residential thermal comfort. The method used for temperature measurement is similar to that used by Magalhães, Leal, and Horta (2016)). They measured living room and bedroom temperatures of households as well as the outdoor temperature of immediate surrounding of schools close to the selected houses with temperature sensors to predict and characterize indoor temperatures in residential buildings in Northern Portugal. In our study, data was acquired from 13 houses out of the 15 recruited because of the loss of installed sensors during measurements representing 15% data loss as compared with other studies which had loss rate of 33%, 41% and 42% (Lomas & Kane, 2013; Vellei et al., 2016). The minimal loss rate could be due to the check put in place and the simplified installation guide. The loss of sensors data from some was due to the relocation of occupants as most of them were students. Residents co-operated well with the task of placing of sensors in their homes; downloading of logged data onto their computers and emailing it to us every fortnight until completion of the study.

Our analysis of the acquired data led to the development of a model which determined the extent outdoor temperature influences indoor temperature in homes. This also provided insight into indoor and outdoor temperature trend of the houses; and variation in diurnal temperatures.

Applying the linear mixed-effect model with a random intercept to control for non-independent data for each house on the data obtained presents a systematic and quantitative approach to determine the extent outdoor temperature influenced indoor temperature in each house. The result of the modelling is that changes in outdoor temperature had a direct impact on indoor temperature, but this varied greatly between houses. This is demonstrated by the varying slopes shown in Figure 6, where the largest slope was 0.72 indicating a strong association between outdoor and indoor temperature, and the smallest slope was 0.22, showing a much weaker association between outdoor and indoor temperature. Thus, outdoor temperature is a major contributor to indoor temperature and therefore impacts occupants' thermal comfort as well as mitigation options. Other studies that predicted indoor temperatures in naturally ventilated houses also reported varying results (Krüger & Givoni, 2004, 2008; Ogoli, 2003). Krüger & Givoni, 2004 reported that maximum, average and minimum indoor temperatures in naturally ventilated houses in Curitiba, Brazil strongly correlated to their corresponding outdoor temperatures in the summer and winter seasons. As mentioned earlier, Nguyen et al. (2014) observed in an indoor and outdoor measurement campaign in 16 homes of Greater Boston, that at warmer outdoor temperature, there is a strong correlation (r = 0.90) compared to a weaker correlation (r = 0.40) at cooler temperature conditions. The above mentioned studies were conducted in different climates, thus, the relationship between indoor and outdoor temperature may be location specific. This technique can be applied to projects with larger sample size as the accuracy in predictions improve with more data and would contribute to the understanding of the association between indoor and outdoor temperature in different type of houses. The model is applicable in every setting, regardless of how much time people spend indoors at home. Also, this statistical method would aid modellers to predict indoor temperature as a function of outdoor temperature, thereby reducing the scarcity in indoor temperature data.

Indoor and outdoor temperature trends for the non-heated houses were similar, indicating that there was a strong influence of outdoor temperature and building envelope (insulation, glazing and building material used) on indoor temperature. The use of air-conditioning and building envelope determined the trend in indoor temperature for the heated houses. In such cases, this resulted in significant difference in indoor and outdoor temperature trends. The flat trend of indoor temperature seen in the heated houses was analogous to that observed in living rooms of houses in the UK during a heating season in a study on living room temperature profiles (Huebner et al., 2014).The trend of indoor temperature in the heated houses provided information on occupant's heating set-point, which influences thermal comfort perception and energy consumption in households (Fabi, Andersen, & Corgnati, 2013; Papadopoulos, 2007). Human thermal comfort is more sensitive to indoor temperature set-point variations during heating season as compared to that of cooling (Kazanci & Olesen, 2013). Knowledge of variation in indoor temperature set-point is vital for calculation of energy need for cooling and heating purposes. The difference in diurnal temperature (outdoor and indoor) of both the heated and non-heated houses within a 24hour cycle provided knowledge on the period that indoor temperature was greater than outdoor temperature. Also, the variation observed in the heated houses indicates that indoor temperature preference varies among houses and is influenced by occupants lifestyle (Gill, Tierney, Pegg, & Allan, 2010). Hence, existing energy modules differ as residents did not follow predefined heating patterns (Huebner et al., 2013). Such information is vital in designing thermal regulation systems for the building stock (mainly residential settings).

Previous studies have compared indoor temperature to outdoor temperature from nearby meteorological stations which may not be a representation of outdoor temperatures of houses as noted by (Zhang et al., 2011). In this study, we associated indoor temperature in houses with their immediate outdoor temperature. However, it should be noted that the study was limited by small sample size and may not be a representative of all houses in Brisbane. Therefore, caution must be taken when applying the results to a bigger population. Also, situations beyond our control, such as moving of study participants, contributed to the abrupt end of measurements in two of the houses. This study was carried out in Brisbane, Australia, the location of the research team. As an extension of this study, it is intended to apply the model to data from about 100 houses varying in type and surrounding to quantify the effect of building characteristics on the association between indoor and outdoor temperature.The applied outcomes of the study are:

- It presents a non-invasive, empirical, continuous and simultaneous approach of monitoring indoor and outdoor temperature with limited data losses;
- It offers a statistical model to estimate the effect of outdoor temperature on indoor temperature as houses are likely to differ in how they respond to outdoor temperature;The model also can accommodate building characteristics as variables thereby could predict how they influence indoor temperature;
- An advantage of this model is that, we can identify unusual houses and patterns by house characteristics from plots of the random intercepts and slopes for houses
- .

In summary, indoor and outdoor temperature of selected houses was monitored to generate data and develop a model to estimate the influence of outdoor temperature on indoor temperature. Lastly the potentials and limitations of the model towards understanding the association between indoor and outdoor temperature were explored.

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Appendices

Table A.1: Specification of Labjack Digit-Temperature Light Humidity (TLH) Sensor

Specification	Details
Enclosure dimensions (H × W)	60 mm × 21mm
Circuit board dimensions (L × W × H)	40 mm × 17 mm × 9 mm
Memory	260,000 readings
Logging rate	10s, 30s, 1min, 10min, 30min, 1h, 6h
Alarms	2x user-defined
LED indicators	Green, Red
Battery life	3 Years@ 25°C and 1min logging rate
Battery type	3V lithium, factory replaceable
Software	Free, Windows and Mac
Communication	USB
Real-time clock	±2 seconds per day
Memory-Wrap	No
Single /Multi-Use	Multi-use
Conformal Coating	Yes
Operating Temperature	-35 °C to +85 °C (-31°F to +176 °F)
Waterproof Enclosure	Yes, IP68
Temperature resolution	0.067 °C
Temperature accuracy	1 °C
Operating Relative humidity	10 to 90 %
Relative humidity accuracy	± 5 %
Relative humidity resolution	0.75 %

Table A.2: Characteristics of the 15 houses investigated

I.D	Type of House	Construction material	Ceiling material	Roof material	Roof construction	Age of house	Number of separate bedrooms	Type of kitchen oven/stove	Use of Extraction fan over oven/stove	Heating system used in winter	Cooling system used in summer
H1	Detached (two storey)[a]	Timber, brick, plasterboard	Plaster	Metal	Pitched	old	3	Electric	Yes	Portable electric heater	Natural ventilation
H2	√	Timber, brick, plasterboard, concrete	Plaster	Tile	Pitched	5 yrs	3	Electric	Yes	Air-conditioned	Ceiling fan, Natural ventilation
H4	√	Timber	Timber	Metal	Pitched	27 yrs	5	Electric	Yes	No heating	Air-conditioned, Natural ventilation
H7	√	Timber	Timber	Metal	Flat	old	1	Electric	Yes	Air-conditioned	Air-conditioned
H12	√	Timber, brick	Timber, Plaster, Metal	Metal	pitched	30 yrs	4	Gas	Yes	Air-conditioned	Air-conditioned, ceiling fan, Portable fan, natural ventilation
H6	Detached (single storey)	Timber, brick	Timber	Tile	Pitched	2 yrs	3	Gas	Yes	No heating	Air-conditioned, Portable fan

H14	√	Timber	plaster	Metal	Pitched	old	6	Electric	Yes	No heating	Ceiling fan, natural ventilation
H3	Queenslander[b]	Timber	Timber	Metal	Pitched	old	7	Electric	No	No heating	Portable fan
H5	√	Timber	Timber	Metal	Pitched	90 yrs	5	Gas	Yes	No heating	Ceiling fan
H13	√	Timber	Timber	Tile	Pitched	10 yrs	5	Gas	Yes	No heating	Ceiling fan
H9	Townhouse[c]	Timber, concrete, plasterboard	Plaster	Tile	Pitched	20 yrs	7	Gas	Yes	Air-condition	Air-conditioned
H11	√	Timber	Timber, Plaster, Metal	Metal	Pitched	old	9	Electric	No	No heating	Natural ventilation
H8	Apartment[d]	Concrete, Plasterboard	Plaster	Fibro	Flat	2 yrs	3	Electric	Yes	No heating	Air-conditioned
H10	√	Concrete	Plaster	Metal	Flat	New	2	Gas	Yes	No heating	Portable fan
H15	√	Concrete	Plaster	Metal	Pitched	old	2	Gas	Yes	Air-conditioned	Air-conditioned

Table A.3: Summary statistics of outdoor and indoor temperature readings obtained at the investigated houses over the period of June to August

I.D	**Type of house**	**Indoor temperature (°C)**					**Outdoor temperature (°C)**				
		Min.	Median	Max.	Mean (sd)	95% C.I	Min.	Median	Max.	Mean (sd)	95% C.I
H1	Detached (two storey)	15.5	19.9	24.5	19.9 (1.5)	19.8, 19.9	6.4	16.3	25.8	16.3 (3.5)	16.1, 16.5
		15.8	19.4	26.2	19.6 (1.9)	19.5, 19.7	6.3	16.1	28.0	16.0 (4.1)	15.6, 16.2
		16.1	19.9	23.7	20.1 (1.4)	19.9, 20.0	7.7	16.4	26.1	16.3 (4.1)	16.1, 16.6
H2		15.9	21.4	26.3	21.2 (1.8)	21.1, 21.3	7.0	16.7	32.4	17.0 (3.4)	16.8, 17.2
		16.7	20.8	28.1	21.0 (2.1)	20.8, 21.1	6.8	16.5	34.4	17.3 (5.0)	17.0, 17.5
		17.8	21.0	25.3	21.0 (1.5)	20.9, 21.1	8.6	16.7	35.0	17.5 (4.9)	17.3, 17.8
H4		10.0	17.2	22.2	16.8 (2.3)	16.7, 16.9	5.9	15.7	24.0	15.6 (3.1)	15.4, 15.7
		11.8	16.3	24.8	16.6 (2.3)	16.5, 16.7	6.4	15.6	26.5	15.5 (3.4)	15.3, 15.7
		12.3	17.2	22.7	17.2 (1.8)	17.1, 17.3	7.6	15.9	24.4	15.8 (3.3)	15.6, 16.0
H7		16.3	23.4	25.9	23.2 (1.4)	23.1, 23.3	8.3	17.3	32.9	17.7 (3.8)	17.5, 17.9
		17.6	23.5	28.9	23.4 (1.7)	23.3, 23.5	9.4	17.1	35.1	18.0 (4.6)	17.7, 18.2
		17.1	23.5	27.0	23.3 (1.5)	23.2, 23.3	10.4	17.4	32.0	18.3 (4.5)	18.1, 18.5
H12		14.1	18.6	23.2	18.5 (1.5)	18.4, 18.6	3.3	15.2	26.4	15.3 (3.8)	15.1, 15.6
		14.5	18.0	24.9	18.2 (1.8)	18.1, 18.3	4.9	15.0	27.3	15.0 (4.4)	14.7, 15.2
		15.0	18.4	23.1	18.5 (1.5)	18.4, 18.5	5.8	14.9	26.2	15.2 (4.5)	15.0, 15.4
H6	Detached (Single storey)	16.3	20.2	24.8	20.1 (1.4)	20.1, 20.2	2.9	16.4	27.4	16.5 (4.4)	16.2, 16.7
		16.0	19.8	27.3	19.9 (1.8)	19.8, 20.0	4.4	15.6	31.6	16.0 (5.2)	15.7, 16.3

		16.8	20.1	25.1	20.3 (1.3)	20.2, 20.3	5.7	16.0	30.8	16.7 (5.4)	16.5, 17.0
H3	Queenslander	9.6	18.4	26.5	18.2 (2.8)	18.1, 18.4	7.2	16.9	31.2	17.1 (3.7)	16.9, 17.3
		16.7	20.8	28.1	21.0 (2.1)	20.8, 21.1	6.8	16.5	34.4	17.3 (5.0)	17.0, 17.5
		12.9	19.4	26.3	19.6 (2.8)	19.0, 19.3	9.9	17.3	29.9	17.7 (4.3)	17.5, 18.0
H5		11.2	19.0	25.7	18.8 (2.5)	18.7, 18.9	7.8	17.4	26.5	17.4 (3.1)	17.3, 17.6
		12.8	18.8	28.3	19.0 (2.8)	18.9, 19.2	9.3	17.3	28.9	17.5 (3.5)	17.3, 17.7
		12.4	19.1	25.1	18.9 (2.6)	18.8, 19.1	10.3	17.9	26.7	18.0 (3.4)	17.8, 18.1
H13		15.9	19.6	24.0	19.6 (1.3)	19.5, 19.6	6.6	16.5	25.2	16.6 (3.6)	16.5, 16.8
		15.6	19.3	25.9	19.4 (1.6)	19.3, 19.5	7.0	16.4	28.9	16.5 (4.0)	16.3, 16.7
		16.4	19.5	23.7	19.5 (1.2)	19.4, 19.6	8.0	16.4	27.2	16.7 (4.1)	16.5, 17.0
H9	Townhouse	14.9	20.3	25.0	20.1 (1.8)	20.0, 20.2	7.5	17.7	41.4	18.1 (4.2)	17.9, 18.3
		15.6	19.8	27.9	20.0 (2.0)	19.9, 20.1	8.9	17.4	36.1	18.2 (4.5)	18.0, 18.5
		16.7	20.3	24.8	20.3 (1.6)	20.3, 20.4	10.3	17.8	31.6	18.4 (4.1)	18.2, 18.6
H11		14.8	19.8	23.8	19.5 (1.7)	19.4, 20.0	8.8	17.3	29.0	17.4 (3.2)	17.3, 17.6
		16.4	19.4	26.6	19.7 (1.8)	19.6, 19.6	9.6	17.0	32.8	17.7 (3.8)	17.5, 17.9
		17.1	19.9	23.3	20.0 (1.2)	19.9, 20.0	11.4	17.1	28.5	17.8 (3.6)	17.6, 18.0
H8	Apartment	22.4	25.1	27.0	25.0 (0.8)	25.0, 25.1	12.8	20.7	44.9	21.3 (3.9)	21.1, 21.5
		23.3	25.0	27.6	25.1 (0.9)	25.0, 25.1	15.1	20.9	41.6	21.5 (3.5)	21.3, 21.7

	23.1	24.6	26.5	24.7 (0.7)	24.6, 24.7	15.5	20.7	27.3	20.9 (2.3)	20.7, 21.0
H10	13.0	19.6	26.4	19.5 (2.1)	19.3, 19.6	6.1	16.3	27.0	16.4 (3.4)	16.3, 16.6
	14.4	19.3	29.3	19.6 (2.6)	19.4, 19.7	6.3	16.2	28.8	16.4 (4.0)	16.2, 16.6
	15.6	20.3	25.3	20.3 (2.0)	20.2, 20.4	8.3	16.3	25.7	16.5 (3.4)	16.3, 16.7

Figure A.1. Temperature profiles observed in indoor and outdoor temperature readings for all the investigated individual houses

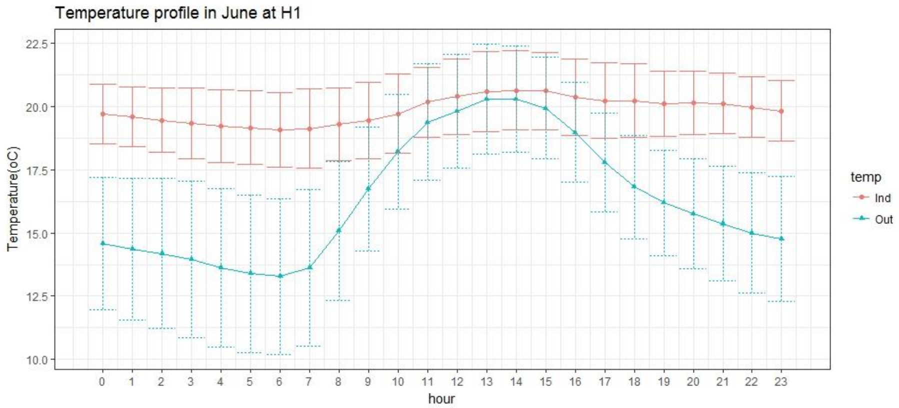

Fig. A.1.1. Temperature profile for the month of June at H1

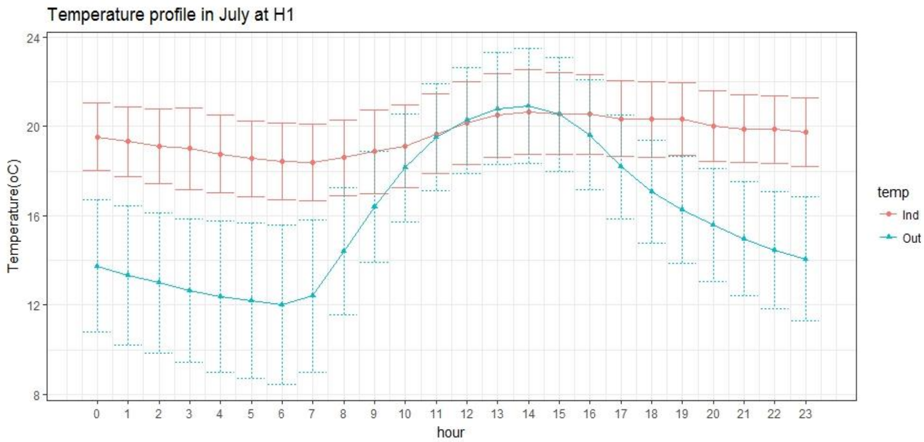

Fig. A.1.2. Temperature profile for the month of July at H1

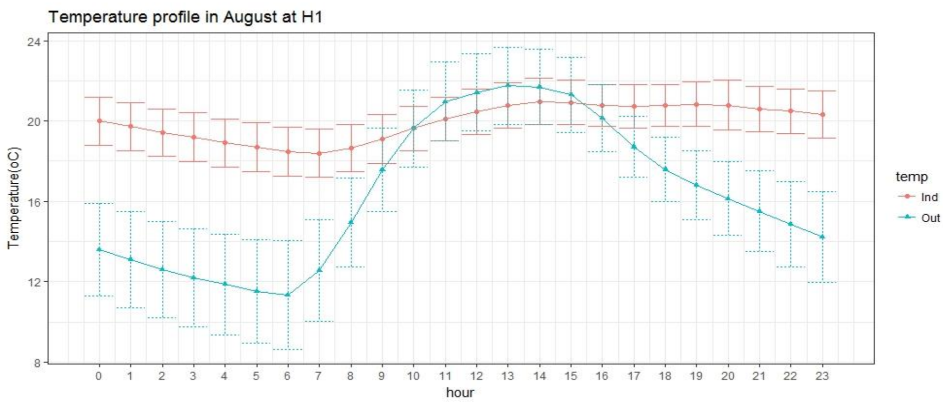

Fig. A.1.3. Temperature profile for the month of August at H1

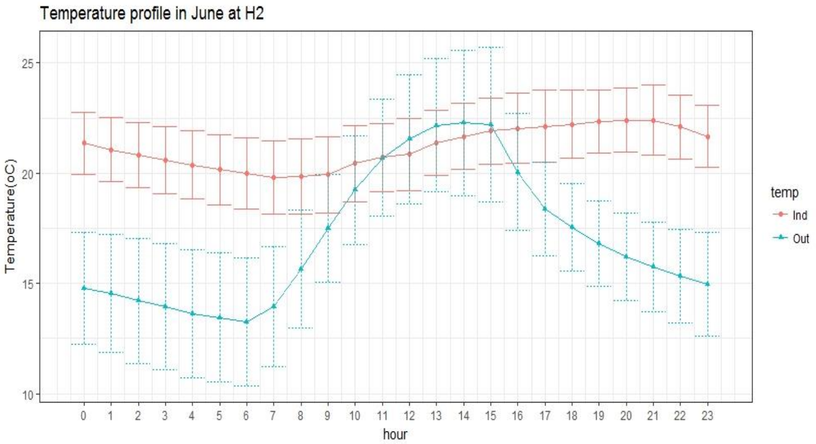

Fig. A.1.4. Temperature profile for the month of June at H2

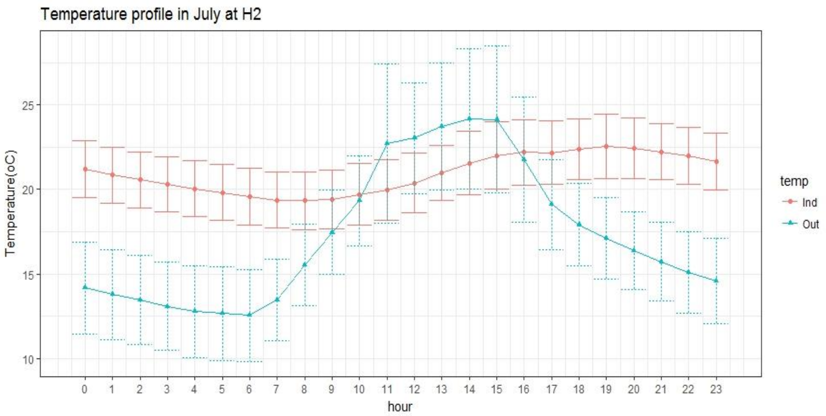

Fig. A.1.5. Temperature profile for the month of July at H2

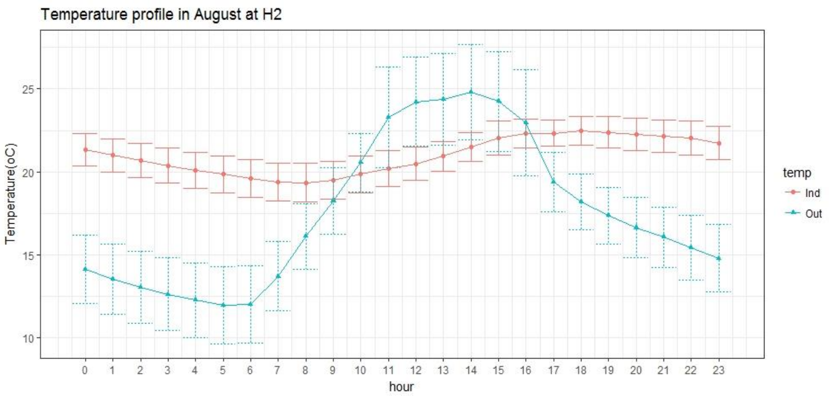

Fig. A.1.6. Temperature profile for the month of August at H2

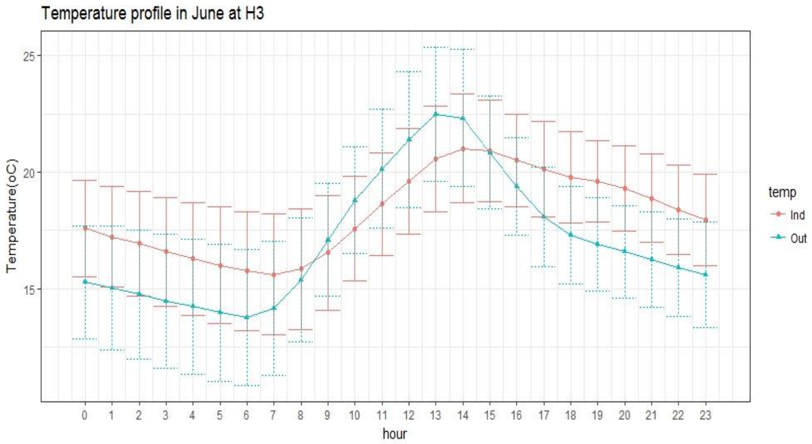

Fig. A.1.7. Temperature profile for the month of June at H3

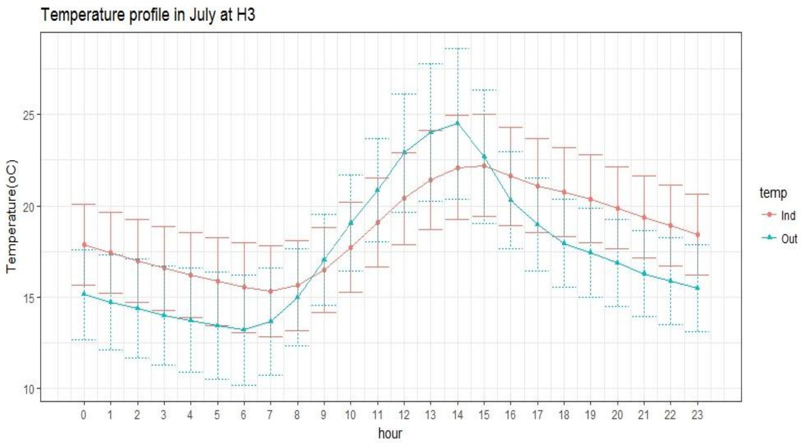

Fig. A.1.8. Temperature profile for the month of July at H3

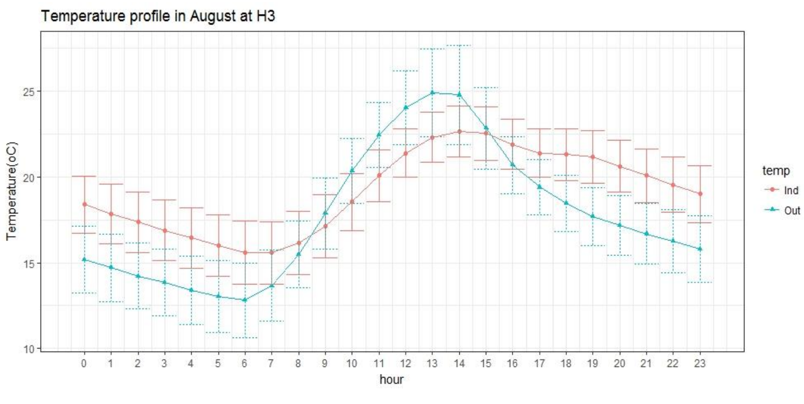

Fig. A.1.9. Temperature profile for the month of August at H3

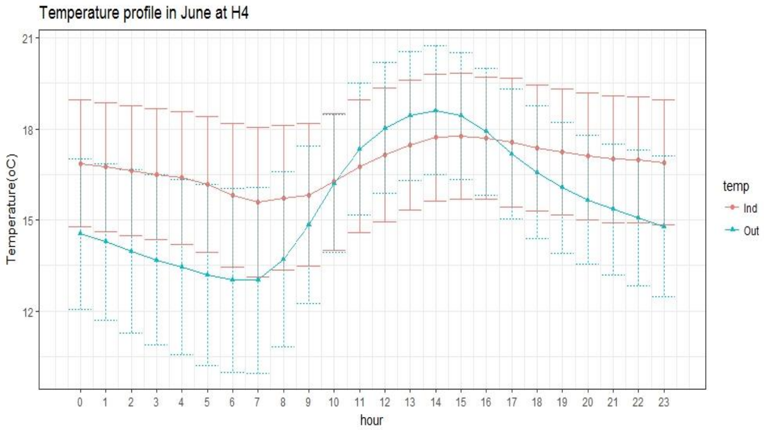

Fig. A.1.10. Temperature profile for the month of June at H4

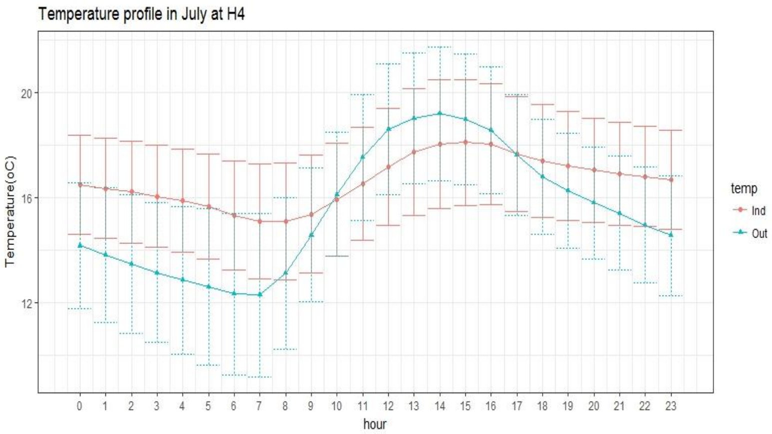

Fig. A.1.11. Temperature profile for the month of July at H4

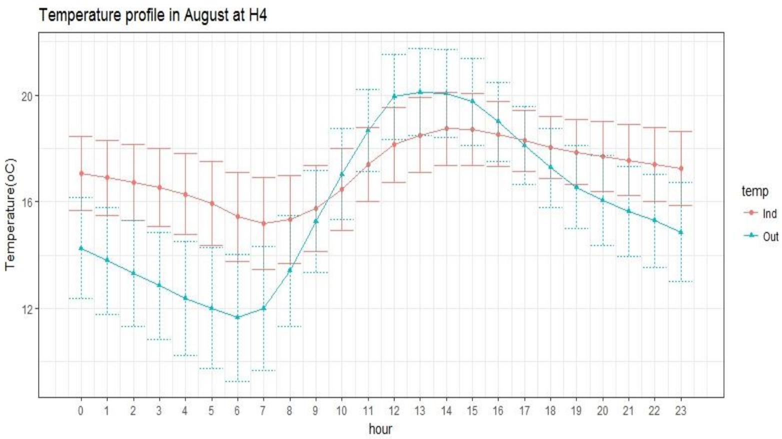

Fig. A.1.12. Temperature profile for the month of August at H4

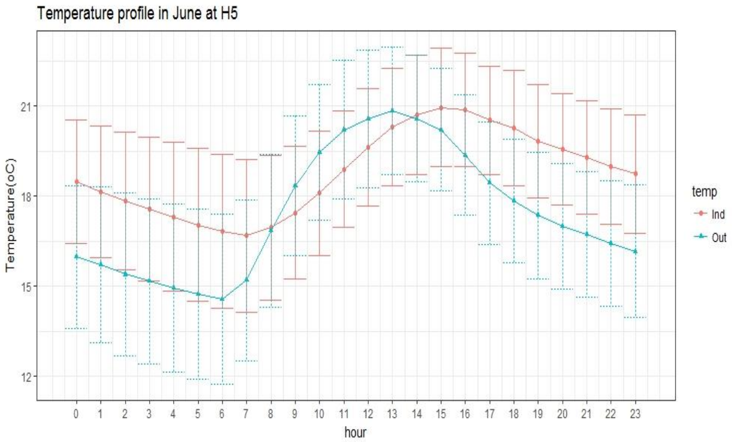

Fig. A.1.13. Temperature profile for the month of June at H5

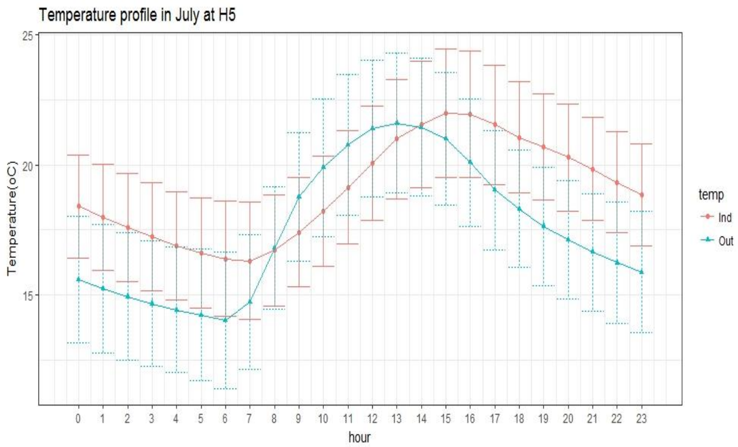

Fig. A.1.14. Temperature profile for the month of July at H5

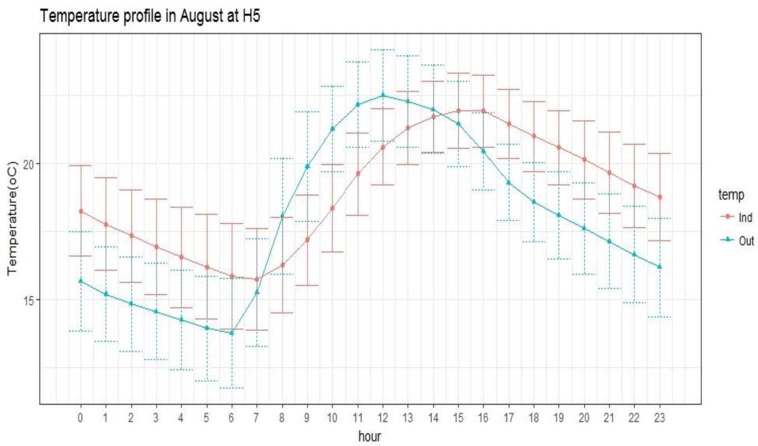

Fig. A.1.15. Temperature profile for the month of August at H5

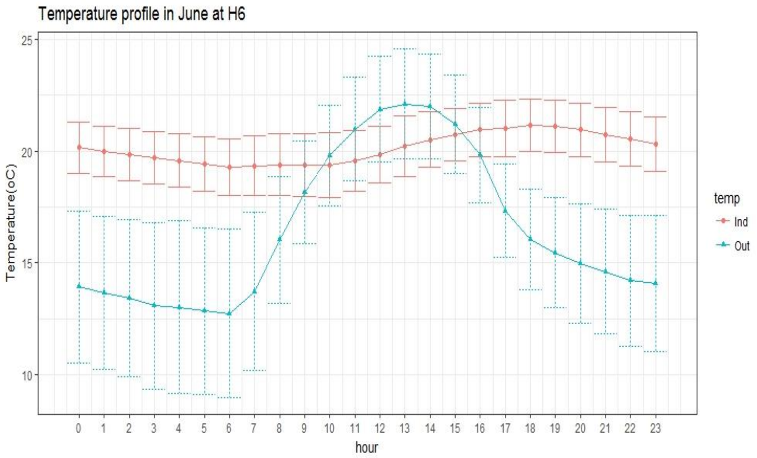

Fig. A.1.16. Temperature profile for the month of June at H6

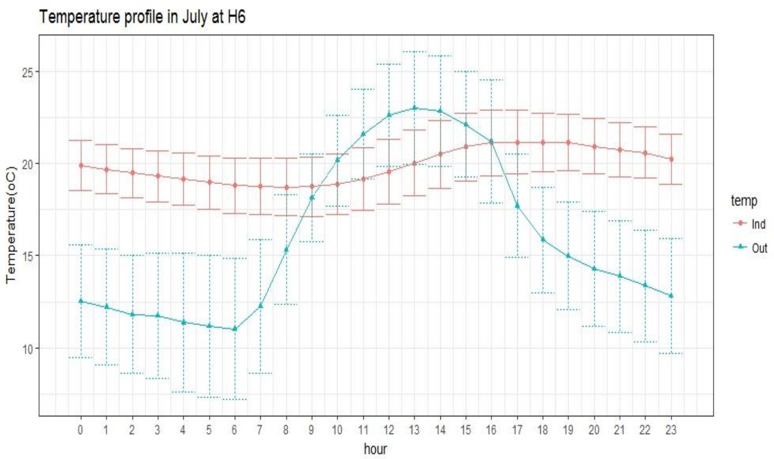

Fig. A.1.17. Temperature profile for the month of July at H6

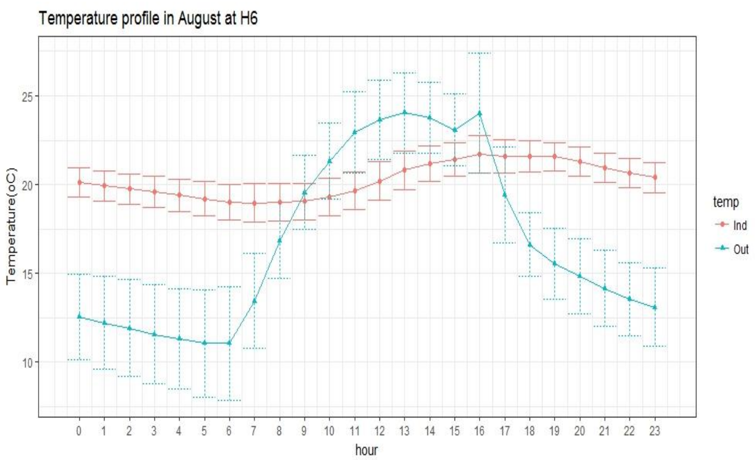

Fig. A.1.18. Temperature profile for the month of August at H6

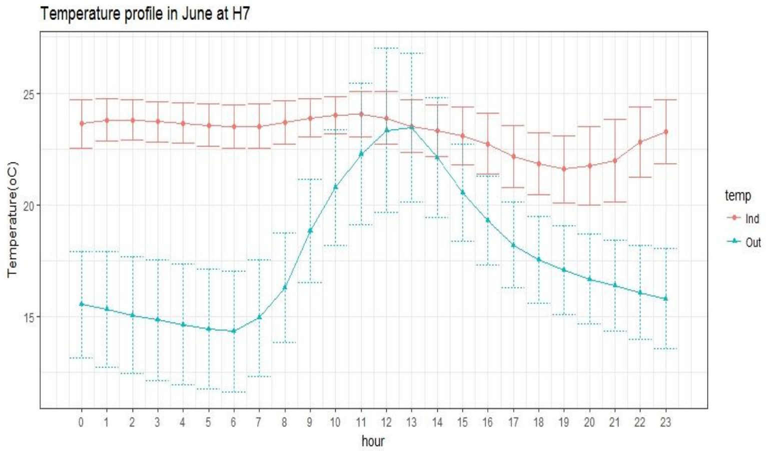

Fig. A.1.19. Temperature profile for the month of June at H7

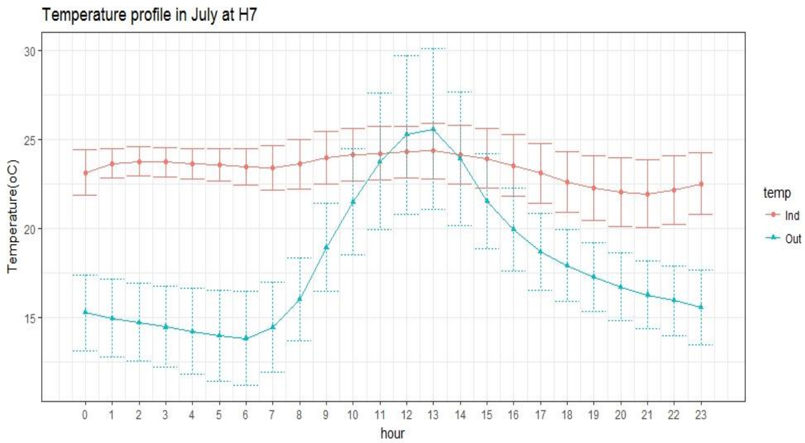

Fig. A.1.20. Temperature profile for the month of July at H7

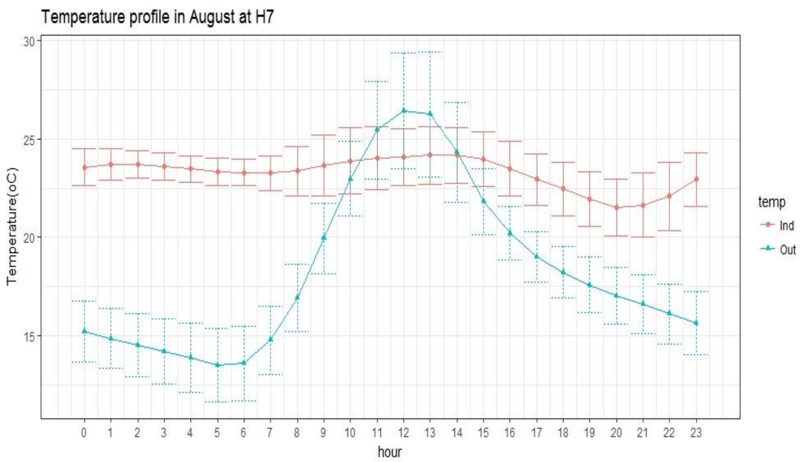

Fig. A.1.21. Temperature profile for the month of August at H7

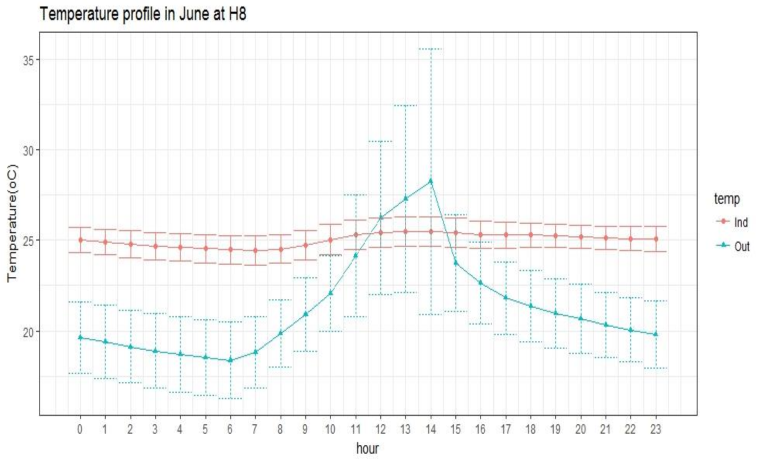

Fig. A.1.22. Temperature profile for the month of June at H8

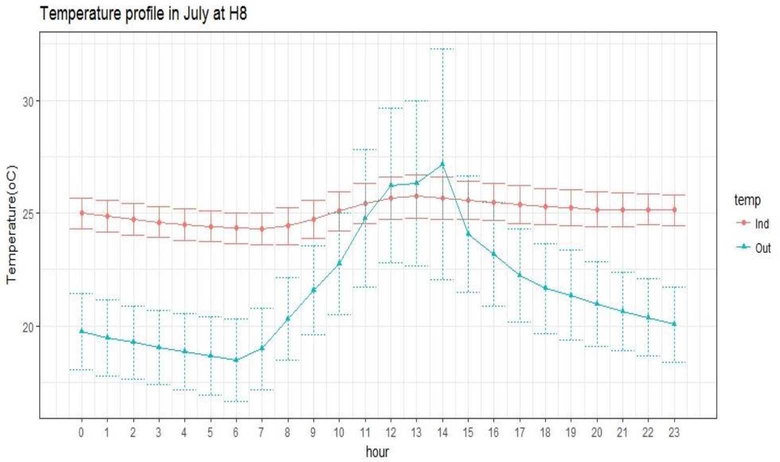

Fig. A.1.23. Temperature profile for the month of July at H8

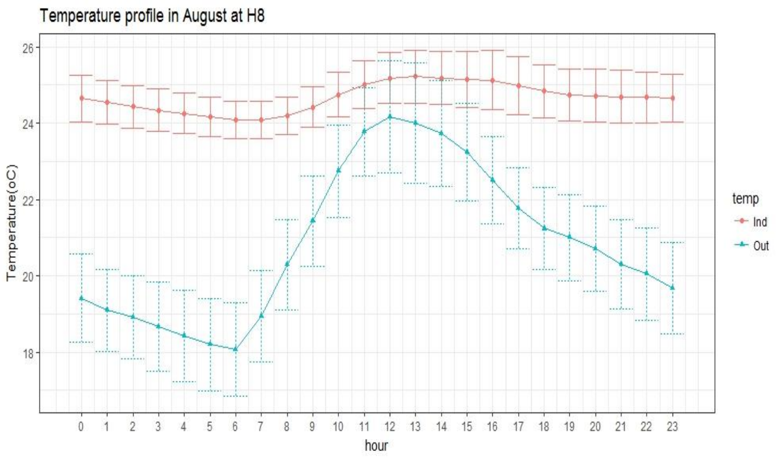

Fig. A.1.24. Temperature profile for the month of August at H8

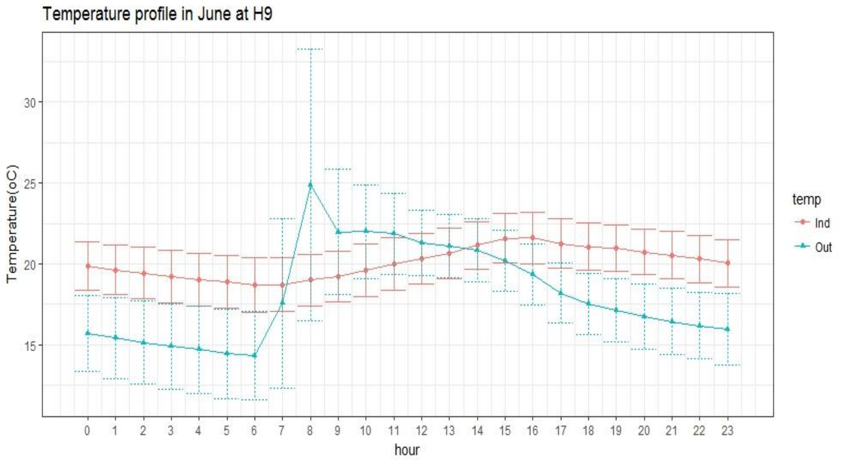

Fig. A.1.25. Temperature profile for the month of June at H9

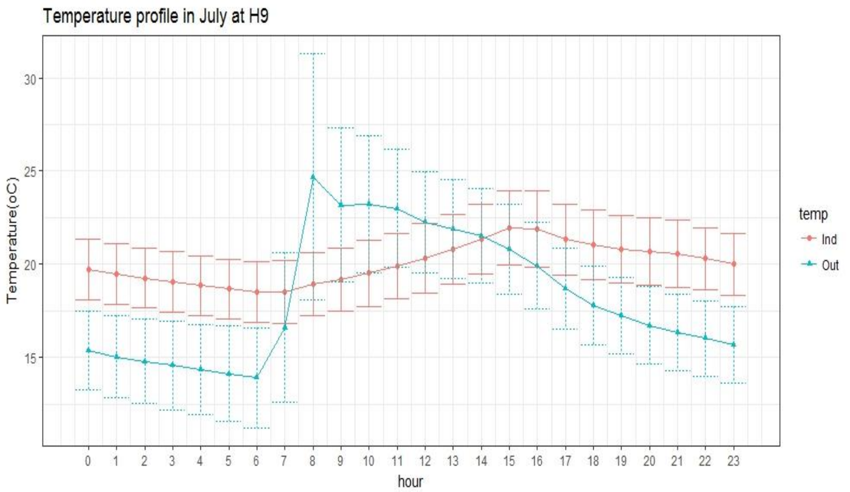

Fig. A.1.26. Temperature profile for the month of July at H9

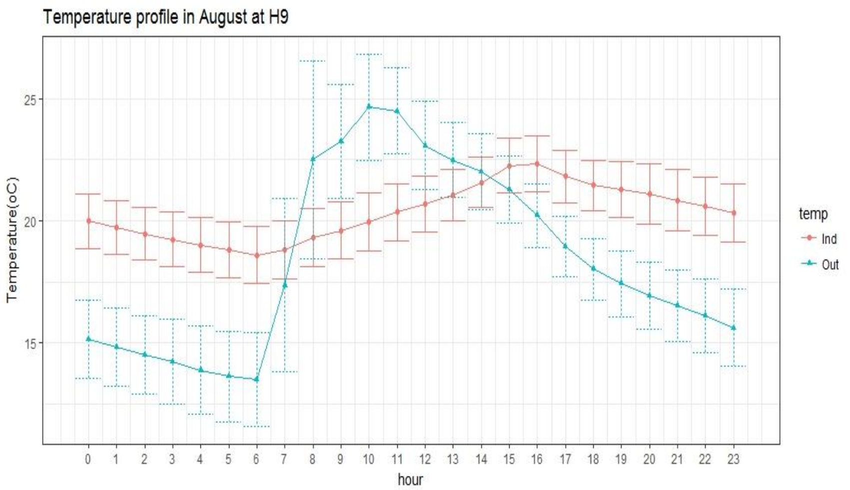

Fig. A.1.27. Temperature profile for the month of August at H9

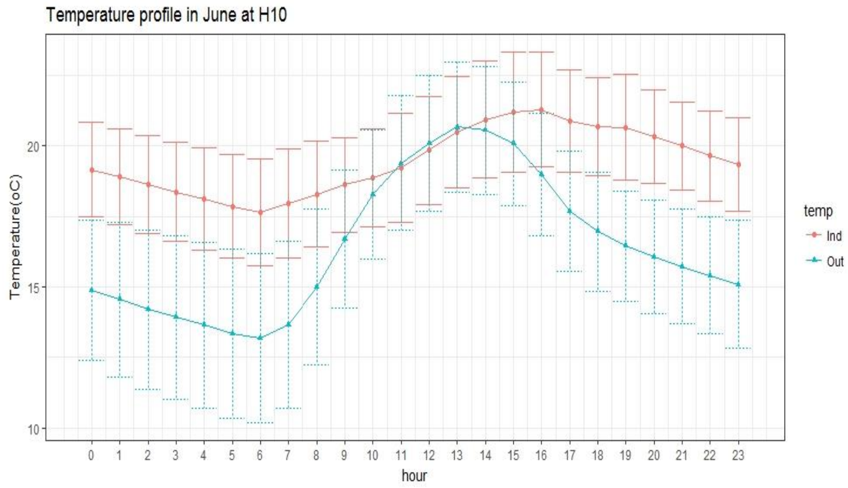

Fig. A.1.28. Temperature profile for the month of June at H10

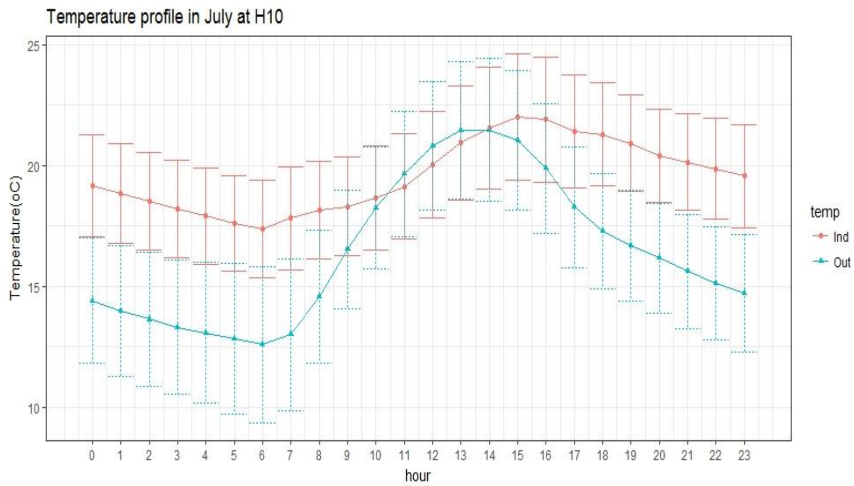

Fig. A.1.29. Temperature profile for the month of July at H10

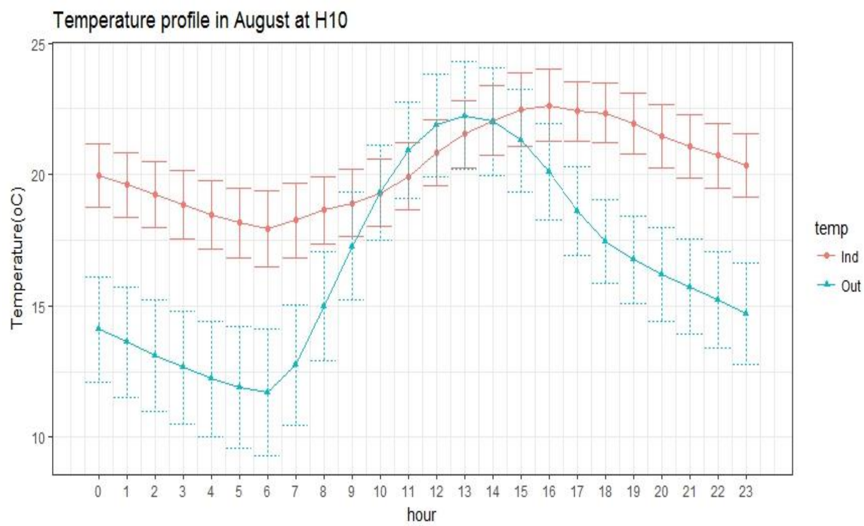

Fig. A.1.30. Temperature profile for the month of August at H10

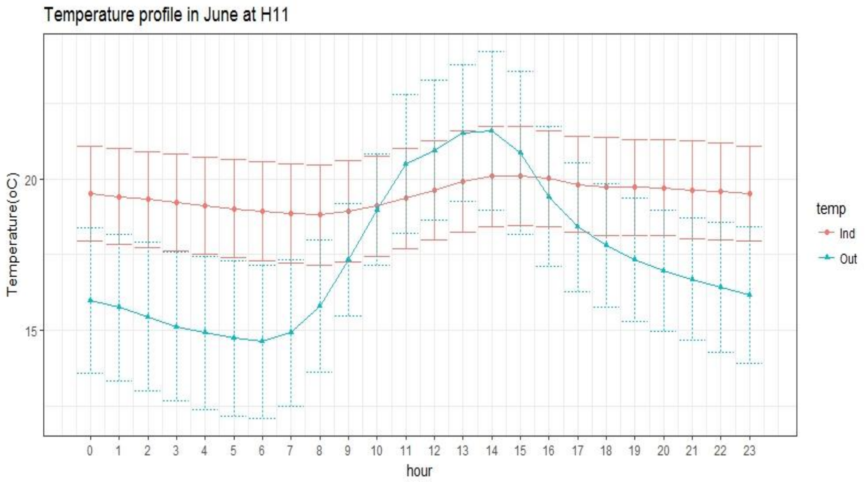

Fig. A.1.31. Temperature profile for the month of June at H11

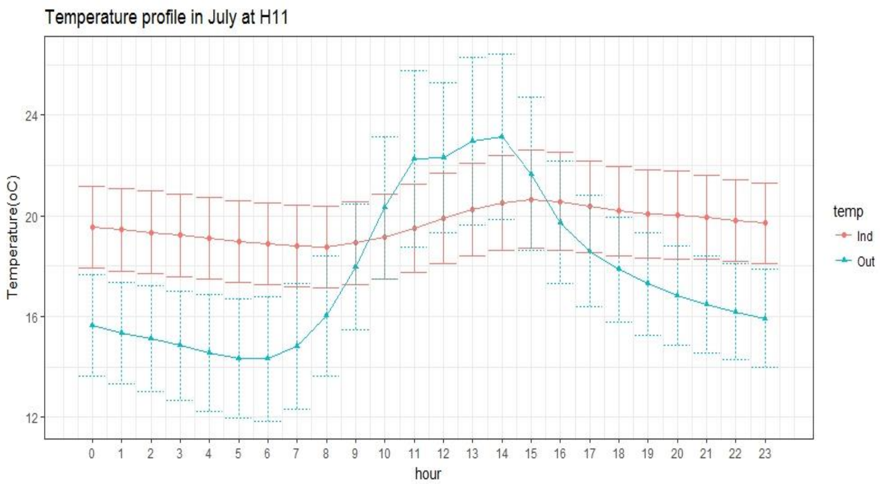

Fig. A.1.32. Temperature profile for the month of July at H11

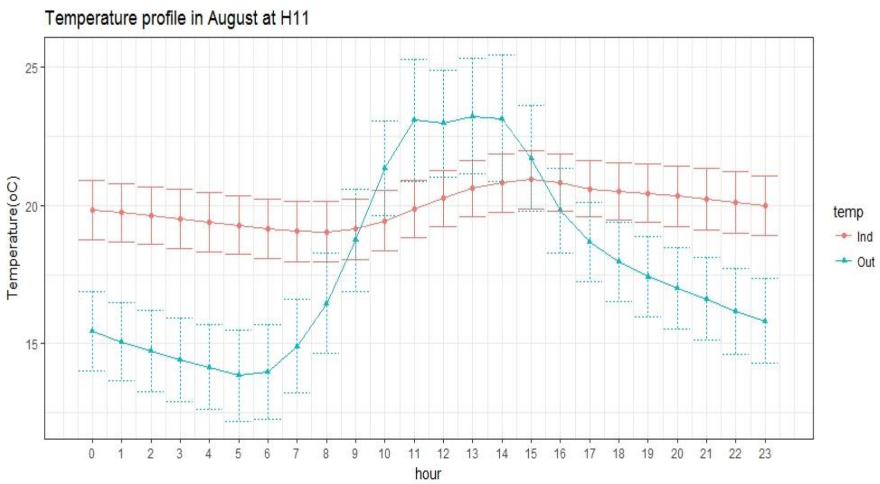

Fig. A.1.33. Temperature profile for the month of August at H11

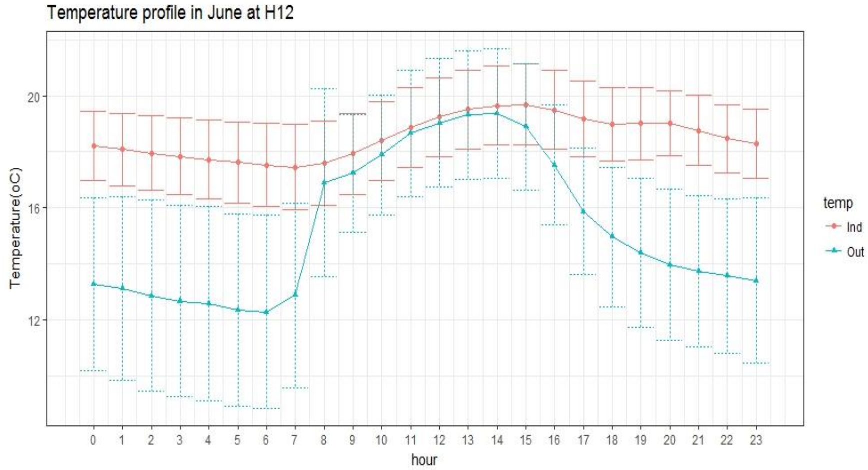

Fig. A.1.34. Temperature profile for the month of June at H12

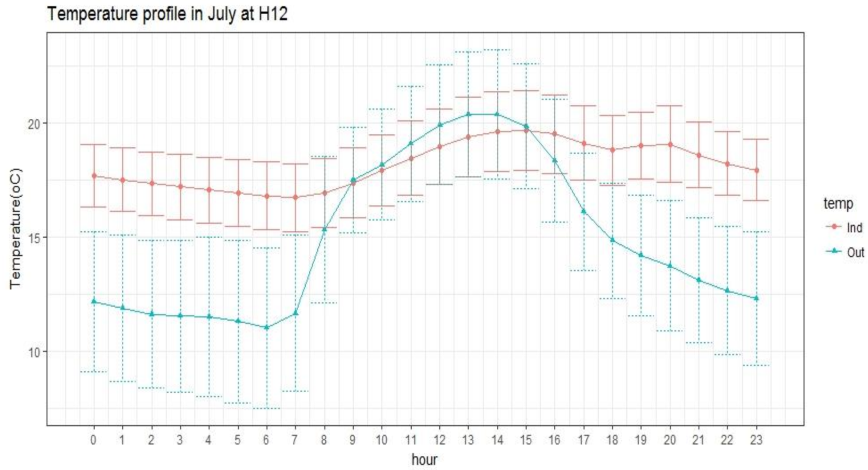

Fig. A.1.35. Temperature profile for the month of July at H12

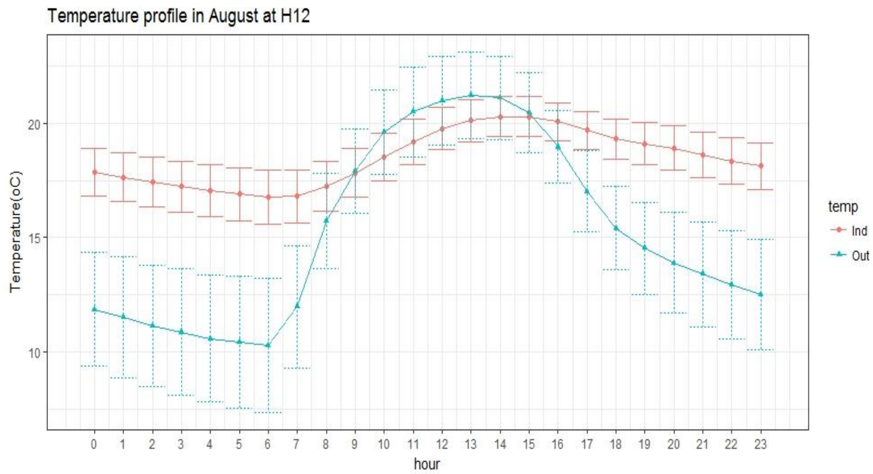

Fig. A.1.36. Temperature profile for the month of August at H12

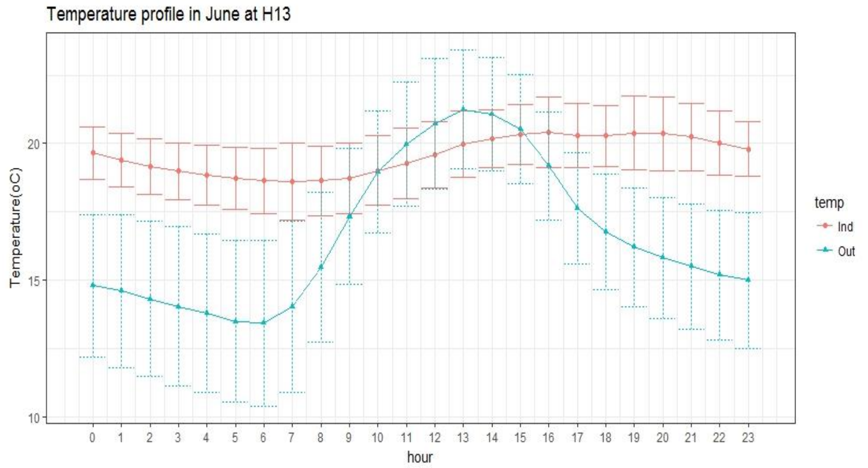

Fig. A.1.37. Temperature profile for the month of June at H13

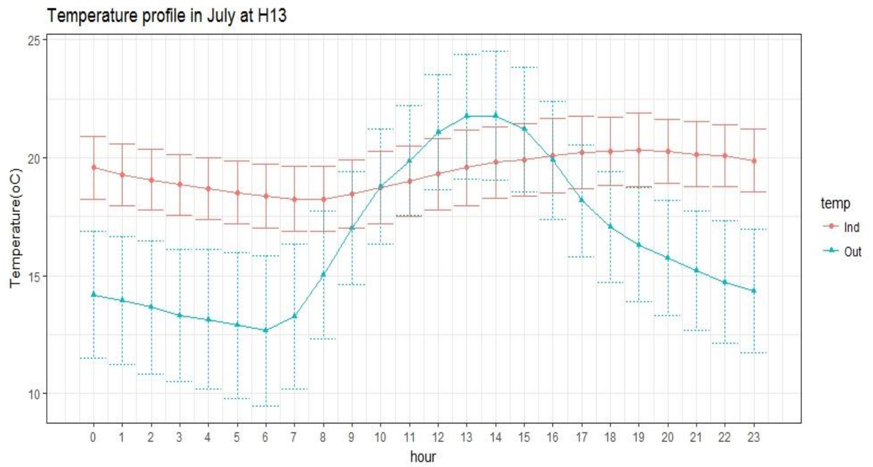

Fig. A.1.38. Temperature profile for the month of July at H13

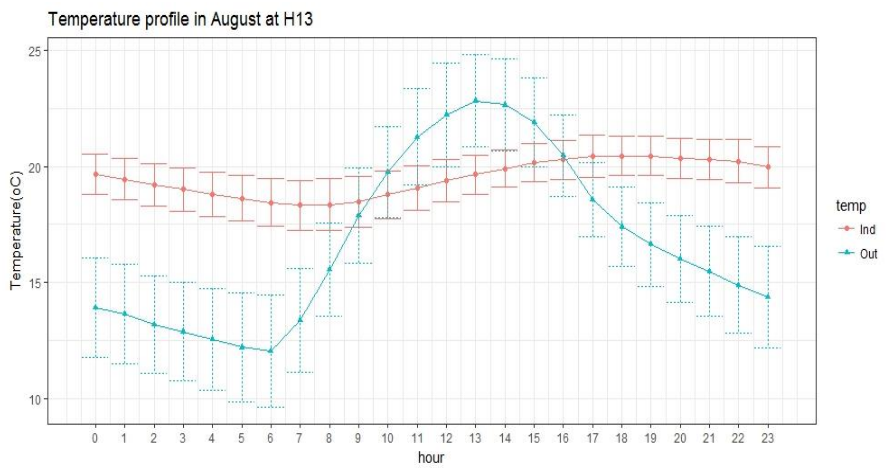

Fig. A.1.37. Temperature profile for the month of August at H13

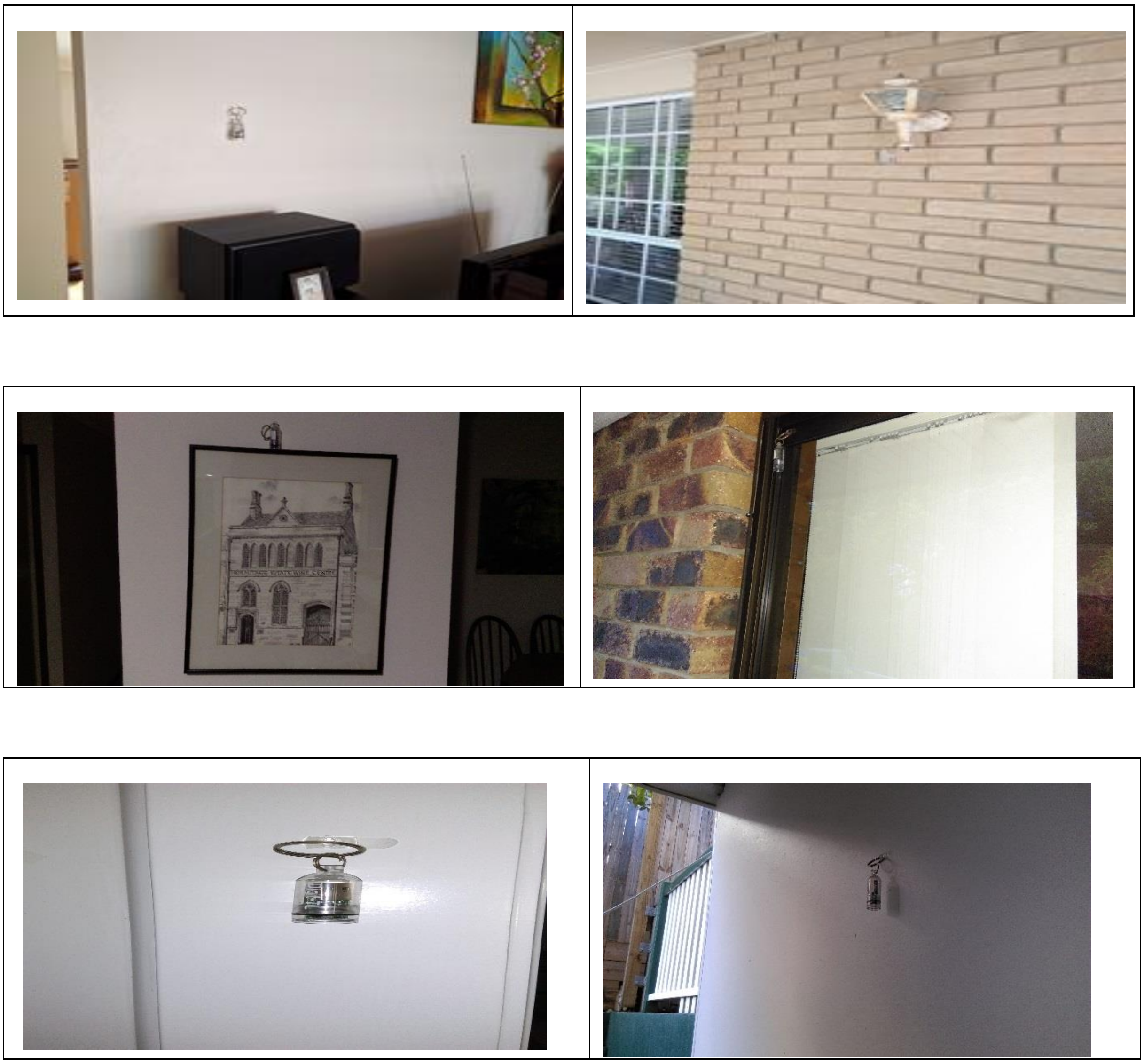

Fig. A.2 Photos of temperature sensors installed both indoor and outside of three of the houses