# Indoor air quality in South East Queensland dwellings during 2019-2020 bushfires

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**Abstract:** Australia has experienced the longest bushfire season in 2019–2020 summertime. This study investigates the indoor air quality, represented by indoor air temperature, relative humidity, $PM_{2.5}$ concentration and $CO_2$ concentration, in 16 Brisbane and 5 Gold Coast residential buildings from Dec 2019 to Feb 2020. Results demonstrated that in general, IAQ conditions were not seriously affected by the bushfire, except a few days in December 2019. The indoor and outdoor $PM_{2.5}$ concentrations were very close during normal building ventilation conditions; however, the indoor to outdoor ratio can range widely between 0.21 and 7.50 during bushfire days under minimal ventilation conditions. Staying indoors with windows and doors closed might not always bring benefits during bushfire events, as internally generated fine particulates might exacerbate the level of pollution indoors.

**Keywords:** Indoor air quality; South East Queensland; residential buildings; bushfire season.

## 1. Introduction

Australia has experienced the longest bushfire season from September 2019 to March 2020. As of 9th March 2020, the fires burnt an estimated 18.6 million hectares of land (Burton, 2020). Over 5,900 buildings (including 2,779 homes) were destroyed across the country (O'Mallon and Tiernan, 2020). Bushfires also have indirect costs, mainly resulting from the population exposure to atmospheric particulate matter (PM) with a diameter less than 2.5 µm ($PM_{2.5}$), which can penetrate deep into the respiratory system (Vardoulakis *et al.*, 2020). Taking Brisbane and Gold Coast as an example, Table 1 lists the monthly maximum 24-hour average $PM_{2.5}$ concentrations in South Brisbane and Southport monitoring stations from March 2019 to February 2020. The annual average $PM_{2.5}$ concentration during the same period was 9.9 µg/m$^3$ for South Brisbane, and 8.5 µg/m$^3$ for Southport (The State of Queensland, 2020). Because of the bushfire, the 24-hour average $PM_{2.5}$ concentrations in both locations have exceeded the National Environment Protection Measure for Ambient Air Quality (Air NEPM) advisory standards (25 µg/m$^3$ for 24-hour average) (Keywood et al., 2016) in September, November, and December 2019. Previous research demonstrates that bushfire smoke is associated with increased risks of hospitalization and emergency department visits due to respiratory diseases and infections (Dennekamp and Abramson, 2011), increased cardiovascular morbidity, and psychological disorders (Finlay et al., 2012).

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Table 1: Monthly maximum 24-hour average $PM_{2.5}$ concentrations (µg/$m^3$) in Brisbane and Gold Coast, March 2019 to February 2020 (The State of Queensland, 2020).

| | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| South Brisbane, Brisbane | 17.1 | 10.2 | 12.5 | 14.3 | 24.8 | 12.9 | **36.1** | 18.0 | **124.8** | **75.3** | 18.5 | 12.5 |
| Southport, Gold Coast | 9.7 | 6.2 | - | 9.3 | **27.1** | 18.9 | **39.0** | 10.1 | **95.8** | **64.1** | 16.7 | 10.4 |

(Numbers in bold denote values that have exceeded the 24-hour average $PM_{2.5}$ concentrations of 25 µg/$m^3$ regulated in Air NEPM advisory standards)

To reduce the adverse health impacts, Queensland government and public health research studies (Queensland government, 2020; Jalaludin *et al.*, 2020; Vardoulakis *et al.*, 2020) advise residents to stay indoors and minimise the transfer of outdoor air to the inside by closing windows and doors where possible. However, the effectiveness and feasibility of staying indoors is questioned by recent studies (Reisen *et al.*, 2019; Jalaludin *et al.*, 2020; Vardoulakis *et al.*, 2020; Yu *et al.*, 2020). For one reason, most residential houses are not equipped with air purifiers or air conditioning systems with high-efficiency filters. Hence, outdoor pollutants can still penetrate houses, and indoor and outdoor concentrations of fine particles are often very close (Yu *et al.*, 2020; Liu *et al*., 2018). For another reason, staying indoors may be impractical or ineffective during longer periods of bushfire events (Vardoulakis *et al.*, 2020).

Although there is a large amount of IAQ studies in residential buildings all around the world (e.g. Morawska et al., 2001; Molloy et al., 2012; Yassin et al., 2012; Liu et al., 2018), few study has focused on IAQ in residential buildings during bushfire events, probably due to the unpredictable nature of these events. With the recent development of low-cost environmental sensors, it is now feasible to deploy large-scale IAQ monitoring in an extended period in which extreme weather events are likely to occur, e.g. during the summer bushfire season, and so on.

This study aims to explore the indoor air quality, represented by indoor air temperature, relative humidity, $CO_2$ concentration, and $PM_{2.5}$ concentration in South East Queensland (SEQ) dwellings from Dec 2019 to Feb 2020, which coincided with the 2019–2020 Australian bushfire season. The objectives are to report residential IAQ conditions during the bushfire season and compare indoor and outdoor $PM_{2.5}$ concentrations during a bushfire day and a normal day.

# 2. Methods

## 2.1. Locations of the study

This study was carried out in Brisbane and Gold Coast. Brisbane has a humid subtropical climate (Köppen climate classification: Cfa) (Brisbane Climate, 2020) with hot, wet summers and moderately dry, moderately warm winters. Being 66 kilometres south-southeast of Brisbane and immediately north of the border with New South Wales, Gold Coast also features a humid subtropical climate with the Köppen classification of Cfa. However, Gold Coast has slightly cooler summers and slightly warmer winters than Brisbane.

## 2.2. Participating dwellings

Twenty-one dwellings—16 in Brisbane and 5 in Gold Coast—were recruited from multiple avenues, including email broadcast to all Griffith University students and staff, paid advertisements in local newspapers, and word of mouth within social and family networks. To be eligible, participants needed to reside in Brisbane or Gold Coast areas, and planned to stay in the same dwelling during the monitoring period. Participants received a small compensation at the end of the project if they finish all required research activities. All research protocols have been approved by the Griffith University Human Research Ethics Committee.

Characteristics of the dwellings and the participating households can be seen in Table 2. Most dwellings (76.2%) are detached houses with one or two storeys. The ages of the buildings range between 7 and 100 years old, with an average of 28.5 years. The total floor areas range between 59 $m^2$ and 385 $m^2$, with an average of 227 $m^2$. All dwellings are occupied by families, with an average number of 3 occupants per dwelling. About 88.9% of dwellings are insulated. All dwellings have air-conditioning systems installed, among which 28.6% adopts ducted air-conditioning systems, and 71.4% adopts split systems. No dwelling has air purifier installed.

Table 2: Characteristics of the participants' dwellings.

| **Dwelling type** | **Value** |
|---|---|
| Detached house | 16 (76.2%) |
| Semi-detached townhouse | 3 (14.3%) |
| Apartment | 2 (9.5%) |
| **Dwelling characteristics** | |
| Average age of the dwelling (yrs) | 28.5 |
| Average floor area ($m^2$) | 227 |
| Average number of occupants per dwelling | 3 |
| Percentage of dwellings with insulation (%) | 88.9 |
| Percentage of dwellings with air-conditioning (%) | 100 |
| Percentage of dwellings with air purifiers (%) | 0 |

## 2.3. IAQ measurements

The field monitoring campaign started from 4th Dec 2019 and ended on 29th Feb 2020. The indoor air temperature, relative humidity, $PM_{2.5}$ concentration, and $CO_2$ concentration in 21 households have been continuously monitored via the Qingping IAQ sensors during the monitoring period. Qingping IAQ monitor is a commercial-grade low-cost IAQ monitor. Its performance specification is listed in Table 3. All 21 devices have been calibrated against Testo 480 for air temperature, relative humidity, and $CO_2$ readings.

Table 3: The performance specification of IAQ monitor.

| Category | Range | Resolution | Accuracy |
|---|---|---|---|
| Air Temperature, °C | -10–50 | 0.1 | ±0.5 °C |
| Relative Humidity, % | 0–100 | 0.1 | ±5% |
| $PM_{2.5}$, μg/$m^3$ | 0–999 | 0.1 | ±10% |
| $CO_2$, ppm | 400–9999 | 1 | ±15% |

Qingping IAQ monitors were placed in participants' living rooms, where occupants spend most of their time during the day. The devices were positioned in well-ventilated locations, away from heat emitting sources, direct sunlight, or excessive moisture exposure. Monitors connected to residents' Wi-

Fi and a mobile APP which allowed the long-distance real-time visualization of the data. Data were recorded in 15 min intervals and stored in the cloud. During researchers' first visit to participants' dwellings, participants were required to complete a background questionnaire regarding dwelling and demographic features, general comfort perceptions, daily activities, and behaviors, etc.

### 2.4. Data preparation and analysis

All data were first screened for significant outliers. To ensure the quality of data, Liu *et al.* (2018) have removed $PM_{2.5}$ concentrations higher than 800 µg/m$^3$ from the database. This study adopted the same method to remove the extreme $PM_{2.5}$ readings. Depending on the Wi-Fi connection quality in each dwelling, IAQ monitors sometimes went offline, thus the IAQ data might not be continuously monitored. When calculating the daily average values for all measured IAQ parameters, those days with less than 12 hours of recorded data were removed from the dataset.

To facilitate comparisons between indoor and outdoor parameters, the outdoor air temperature, relative humidity, and $PM_{2.5}$ concentration data from the closest monitoring stations were acquired from the Queensland government website (https://apps.des.qld.gov.au/air-quality/download/) and matched *post hoc* with the corresponding indoor climate observations. Brisbane's outdoor data were retrieved from South Brisbane monitoring station, and outdoor weather data of Gold Coast were retrieved from the Southport monitoring station. To calculate the acceptable indoor temperature range using the adaptive thermal comfort model (de Dear *et al.,* 2018), the required daily maximum and minimum air temperature data were obtained from the closest Bureau of Meteorology stations. The prevailing mean outdoor air temperature was calculated as the weighted running mean of last seven day's outdoor daily air temperatures.

The differences between the daily average indoor and outdoor $PM_{2.5}$ concentrations were examined by the independent t-test. The significance level was set at $p < 0.05$. All data analyses were carried out in SPSS (Version 26).

## 3. Results and discussions

### 3.1. IAQ conditions during the monitoring period

#### *3.1.1. Indoor air temperature and relative humidity*

Figure 1 plotted the indoor and outdoor daily average air temperature in 16 Brisbane and 5 Gold Coast dwellings during the monitoring period. The outdoor air temperature in Gold Coast was generally 1–2 °C lower than that in Brisbane. However, the indoor air temperatures were similar in both locations, which typically ranged between 26 °C and 30 °C. de Dear *et al.* (2018) has developed an adaptive thermal comfort model for residential buildings based on field monitoring in 43 dwellings in Sydney. Figure 1 also plotted the upper and lower 80% acceptability limits based on this residential adaptive model. The average indoor temperatures in Brisbane and Gold Coast dwellings frequently exceeded the upper 80% acceptability limits during the monitoring period. The percentage of exceedance was 44.3% in Brisbane and 57.5% in Gold Coast. This finding aligned with the participants' respondence in the background questionnaires, where 66.7% of participants have chosen "too hot during summer" as their main concerns of thermal comfort in their dwellings. Although 90.5% of dwellings have air-conditioning installed in the living rooms, the AC units were not frequently used for cooling. As reported in the background surveys, 61.9% of dwellings utilized cross ventilation in living rooms all the time.

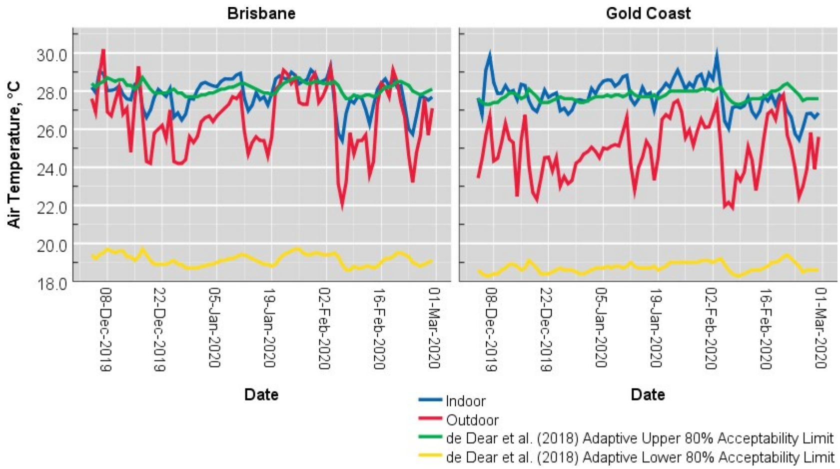



Figure 1 The indoor and outdoor daily average air temperature in 16 Brisbane and 5 Gold Coast dwellings during the monitoring period, compared with de Dear *et al.* (2018) residential adaptive comfort 80% acceptability limits

Figure 2 plots the indoor and outdoor daily average relative humidity in 16 Brisbane and 5 Gold Coast dwellings during the monitoring period. The outdoor relative humidity in Gold Coast was slightly higher than that in Brisbane. Indoor relative humidity levels were similar in both locations, typically ranging between 50% and 80% in summertime. High humidity is known to facilitate mould growth. In the background surveys, 23.8% of participants have reported mould in their dwellings.

### *3.1.2. Indoor $CO_2$ concentration*

Figure 3 plots the 24h average indoor $CO_2$ concentration in 16 Brisbane and 5 Gold Coast dwellings during the monitoring period, where the boxes represent the 25th and 75th percentiles, and the whiskers represent the 5th and 95th percentiles. The mean $CO_2$ concentration for all dwellings were below 500 ppm, and the 95th percentile for most dwellings were below 800 ppm, indicating good ventilation in the living rooms. In the background surveys, 61.9% of participants reported that their living rooms were cross ventilated all the time; only 4.8% of participants never utilized cross ventilation in the living rooms. When being asked "how many windows do you usually open to ventilate the living area", 52.4% of participants have selected three or more windows.

### *3.1.3. Indoor $PM_{2.5}$ concentration*

Figure 4 illustrates the 24h average indoor and outdoor $PM_{2.5}$ concentration in Brisbane and Gold Coast dwellings during the monitoring period. The 24h average outdoor $PM_{2.5}$ concentration in both locations were normally below 10 μg/m$^3$. Due to the bushfire, the 24h average outdoor $PM_{2.5}$ concentration in Brisbane between 5th Dec and 9th Dec exceeded the Air NEPM threshold (25 μg/m$^3$), with the highest daily concentration occurring on 7th Dec at 74.1 μg/m$^3$, almost three times the guideline value.

Similarly, the 24h average outdoor $PM_{2.5}$ concentration in Gold Coast between 4th Dec and 9th Dec exceeded the Air NEPM threshold, with the highest daily concentration occurring on 8th Dec at 58.5 μg/m$^3$. Figure 4 shows that the indoor $PM_{2.5}$ concentration in two locations generally followed the outdoor trend but displayed slightly different patterns in Brisbane and Gold Coast. In Brisbane, the indoor $PM_{2.5}$ concentration was consistently lower than its outdoor counterpart, whereas in Gold Coast, there seemed to be no discernible difference between indoor and outdoor values.

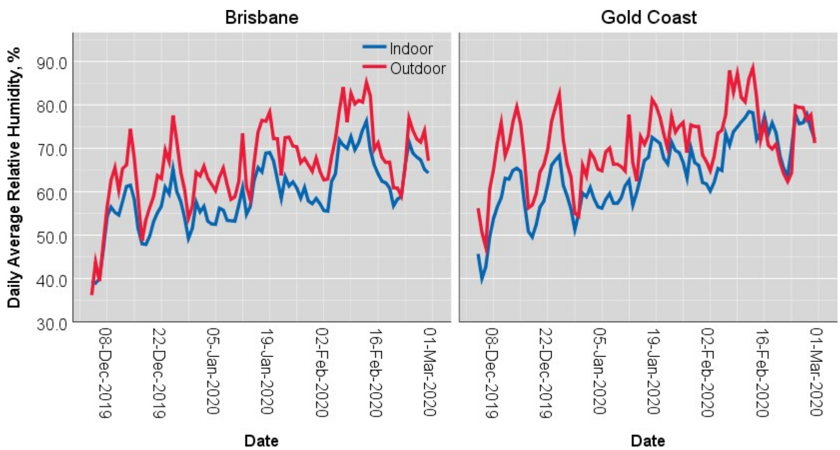



Figure 2 The indoor and outdoor daily relative humidity in 16 Brisbane and 5 Gold Coast dwellings during the monitoring period

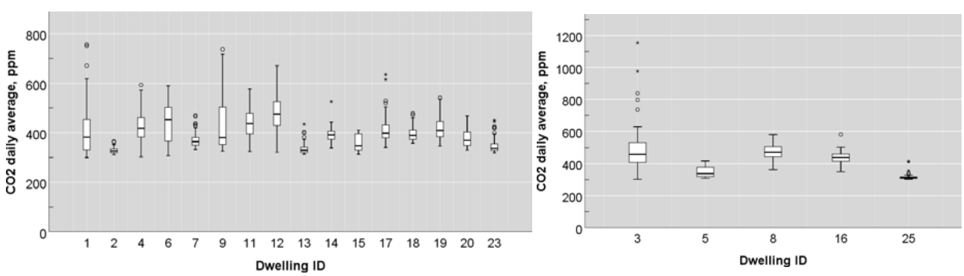



Figure 3 Boxplot of 24h average indoor $CO_2$ concentration in 16 Brisbane and 5 Gold Coast dwellings during the monitoring period

Independent t-tests were adopted to examine the differences between the 24h average $PM_{2.5}$ concentrations indoors and outdoors in Brisbane and Gold Coast. The results were reported in Table 4. In both locations, the 24h average indoor $PM_{2.5}$ concentration was lower than the corresponding outdoor value. This difference was statistically significant in Brisbane (M=-3.28, p=0.01), but not significant in Gold Coast (M=-1.72, p=0.22).

To understand the impact of bushfire on the outdoor and indoor $PM_{2.5}$ concentrations and the indoor-to-outdoor (I/O) ratio, a typical bushfire day (7th Dec, 2019) and a typical normal day (29th Feb, 2020) were selected during the monitoring period in Brisbane for comparison. Figure 5 plots the hourly average indoor and outdoor $PM_{2.5}$ concentration and the I/O ratio in two scenarios. During a typical bushfire day (Figure 5a), the hourly outdoor $PM_{2.5}$ concentration displayed a drastic range between 6.4 and 157.6 μg/m$^3$ with an average concentration of 74.1 μg/m$^3$, while the hourly indoor concentration were much more stable, with a range of 31.4 to 62.0 μg/m$^3$. The I/O ratio fluctuated between 0.21 to 7.50, with a mean level of 1.55. During a typical normal day (Figure 5b), outdoor $PM_{2.5}$ concentration fluctuated between 4 and 8.4 μg/m$^3$ with an average level of 6.1 μg/m$^3$, which was 1/40 of the maximum outdoor $PM_{2.5}$ concentration during the bushfire. The indoor concentration ranged between 1.4 and 5.0 μg/m$^3$, and the I/O ratio ranged between 0.18 and 1.03, with a mean level of 0.54.

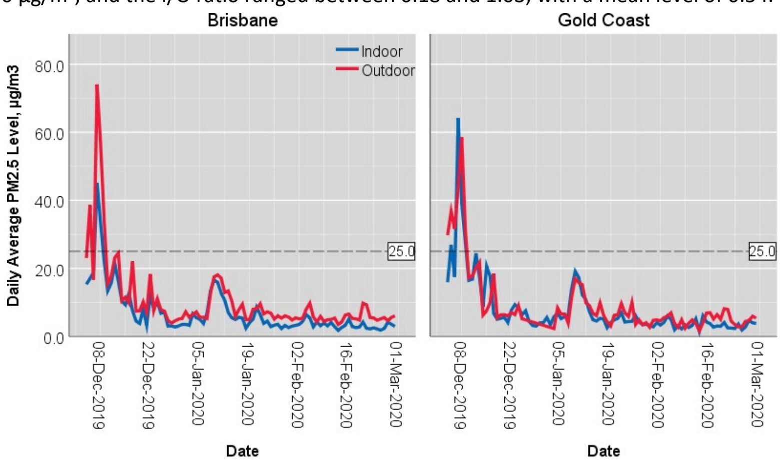
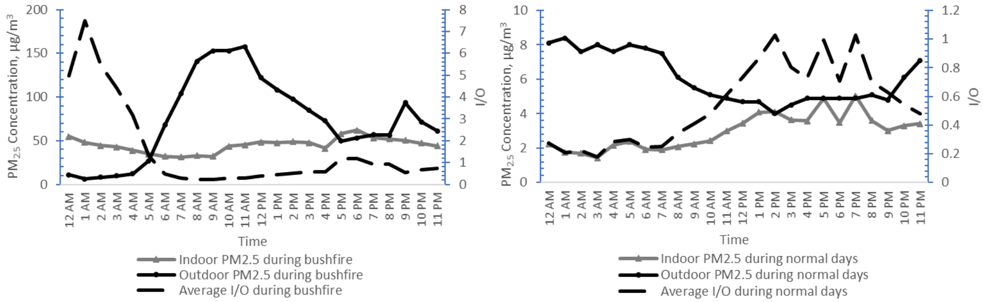



Figure 4 The indoor and outdoor 24h average $PM_{2.5}$ concentration in 16 Brisbane and 5 Gold Coast dwellings during the monitoring period

Table 4: Comparison of indoor and outdoor 24h average $PM_{2.5}$ concentration in Brisbane and Gold Coast during the monitoring period.

| Location | Mean Difference | Std. Error | Sig. (2-tailed) | BCa 95% Confidence Interval | |
|---|---|---|---|---|---|
| | | | | Lower | Upper |
| Brisbane | -3.28 | 1.35 | 0.01* | -6.12 | -0.60 |
| Gold Coast | -1.72 | 1.38 | 0.22 | -4.35 | 1.00 |

(*p < 0.05)




a) A typical bushfire day in Brisbane b) A normal day in Brisbane

Figure 5 Average indoor $PM_{2.5}$ concentration in relation to outdoor concentration in Brisbane during 1) a typical bushfire day when average outdoor concentration was 74.1 µg/m$^3$; 2) a normal day when average outdoor concentration was 6.1 µg/m$^3$

## 4. Discussions

$PM_{2.5}$ pollution is generally not an issue in Australia (Paton-Walsh *et al.*, 2019). The modelled annual average $PM_{2.5}$ concentration in Australian urban areas is approximately 8 µg/m$^3$, which is lower than values in nations with higher population densities, such as UK (12 µg/m$^3$), Germany (14 µg/m$^3$), and China (59 µg/m$^3$) (World Health Organization, 2016). However, there are occasions when the 24h average $PM_{2.5}$ concentration exceeds the 25 µg/m$^3$ threshold in Australian cities, mostly during bushfires or hazard reduction burns (Paton-Walsh *et al.*, 2019). During bushfire events, the temporary values of I/O ratio could range widely (0.21–7.50), however, the average ratios were close to 1 (1.55). Table 4 revealed that during the 3-month bushfire season, the average differences between the indoor and outdoor $PM_{2.5}$ concentration in both Brisbane and Gold Coast were less than 5 µg/m$^3$. Although the differences were statistically significant in Brisbane, the actual indoor concentration might be closer to the outdoor level given the accuracy of the low-cost IAQ sensors (Liu *et al.*, 2018). The similarity of indoor and outdoor $PM_{2.5}$ concentration has been reported by many previous residential IAQ studies (e.g. Morawska *et al.*, 2001; Massey *et al.*, 2012; Liu *et al.*, 2018).

Finding in this study also challenges the idea of staying indoors during bushfires as a measure to prevent the adverse health impact, even with doors and windows closed. Figure 6 plots the hourly average $CO_2$ concentration in Brisbane dwellings during the same days as in Figure 5. The average $CO_2$ level was much higher between 12AM and 3PM during the bushfire day compared with the normal day, indicating reduced ventilation during bushfire events. This could well explain the distinct trend of $PM_{2.5}$ concentration indoors and outdoors during this period in Figure 5a. Nevertheless, the average $CO_2$ level was similar between 3PM and 11PM during the bushfire and the normal day, indicating similar ventilation conditions. This was also evidenced by the I/O ratio being close to 1 after 3PM in Figure 5a. However, the daily average indoor $PM_{2.5}$ concentration during the bushfire day was 55% higher than its outdoor counterparts, indicating that closing doors and windows during bushfire events may not always bring benefits. It effectively prevented outdoor pollutions from coming indoors, meanwhile prevented the internally generated fine particulates from dissipating. Therefore, the average indoor pollution level might even exceed the outdoor level.

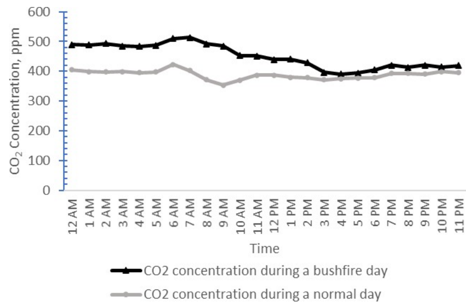



Figure 6 Average indoor $CO_2$ concentration in Brisbane households during a typical bushfire day and a normal day

## 5. Conclusions

This study investigates the indoor air quality in South East Queensland dwellings during the Dec 2019–Feb 2020 Australian bushfire season. The following conclusions can be drawn.

- During the monitoring period, 44.3% of days in Brisbane and 57.5% of days in Gold Coast exhibited indoor air temperatures that exceeded the residential adaptive comfort model's upper 80% acceptability limit. The indoor relative humidity typically ranges between 50% and 80% in both locations. The indoor 24h average $CO_2$ concentration in all dwellings was below 500 ppm.
- Throughout the monitoring period, the indoor 24h average $PM_{2.5}$ concentration in Brisbane was significantly lower than its outdoor counterpart ($p < 0.05$); this difference was not statistically significant in Gold Coast. However, the indoor and outdoor $PM_{2.5}$ concentrations were very close during normal building ventilation conditions.
- During a typical bushfire day, the hourly I/O ratio of $PM_{2.5}$ concentration can range between 0.21 and 7.50 due to reduced ventilation, with a daily average of 1.55. Staying indoors with windows and doors closed might not effectively protect occupants from fine particulates during bushfires.

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