RESEARCH

Can commercial buildings cope with Australian bushfires? An IAQ analysis

ARIANNA BRAMBILLA
CHRISTHINA CANDIDO
MARCO FILIPPO SANGIORGIO
OZGUR GOCER
KENAN GOCER

**Author affiliations can be found in the back matter of this article*

ABSTRACT

The Australian 2019/20 summer witnessed an extraordinary bushfire season characterised by unprecedented duration, geographical reach and impact. The aftermath of the bushfires includes increased health-related implications on people due to short and long exposure to poor air quality. The current advice from the Australian authorities in such events is to remain indoors, as it was assumed indoor air quality (IAQ) is healthy. This paper examined that assumption and presents the case study of an office building in Canberra subjected to the 2019/20 bushfires, responding to the need of understanding the ability of air-conditioning buildings to cope with such unprecedented and extreme weather events. Measured data for indoor concentration of CO_2, PM_{10} and $PM_{2.5}$ recorded a prolonged period of concerning levels, as well as extreme concentration peaks. This poses a significant risk to the occupants' health. The values showed peaks up to 12 times higher for PM_{10} and 24 times higher for $PM_{2.5}$ than the recommended critical thresholds. The infiltration factor and protection performance analysis suggest that old filtering systems and low airtightness levels are not optimal in protecting the indoor environment from outdoor air pollutants.

PRACTICE RELEVANCE

Results show that the concentration of the outdoor pollutant significantly exceeded thresholds for a prolonged time, posing a health risk to the population. The case study presented has been partially able to protect its occupants thanks to the heating, ventilation and air-conditioning (HVAC) response, but this brings up the concern about all those spaces where mechanical ventilation may not be installed or have the same filtering system. Evidence provided here calls for an urgent update of the protection agenda to account for extreme weather events with regard to the diverse indoor built environments, because relying on the mechanical ventilation system is no more sufficient to provide healthy and safe environments.

CORRESPONDING AUTHOR:
Arianna Brambilla
School of Architecture, Design and Planning, University of Sydney, Sydney, NSW, Australia
arianna.brambilla@sydney.edu.au

KEYWORDS:
air pollution; building performance; buildings; bushfire; indoor air quality; public health

TO CITE THIS ARTICLE:
Brambilla, A., Candido, C., Sangiorgio, M. P., Gocer, O., & Gocer, K. (2021). Can commercial buildings cope with Australian bushfires? An IAQ analysis. *Buildings and Cities*, 2(1), pp. 583–598. DOI: *https://doi.org/10.5334/bc.87*

1. BACKGROUND

The Australian 2019–20 bushfire season is now known as the 'black summer' (Vardoulakis *et al.* 2020b). This refers to a series of extreme bushfire events that started in June 2019 and declared contained only in March 2020. A combination of an unprecedented extended period of high temperatures and drought contributed to the increase of magnitude and duration of bushfires and their subsequent impacts (Yu *et al.* 2020). It is estimated that the fire burnt around 18.6 million ha, with catastrophic consequences to fauna and flora along with significant environmental and economic losses to affected areas. Indeed, the fires destroyed 5900 buildings, threatened the wildlife population due to habitat loss and caused at least 34 fatalities, exceeding any prior bushfire event (Jolly *et al.* 2015; Ladds *et al.* 2017).

However, the hidden impact of bushfire lies in the indirect costs associated with the adverse health of bushfire smoke haze, such as increased morbidity and increased hospitalisations, which have been estimated to be around A$1.95 billion for the 2019–20 Australian bushfire (Johnston *et al.* 2021). Even short-term exposures to smoke haze can exacerbate respiratory conditions, such as asthma and eye irritation, while long-term exposures can impact the cardiovascular system leading to myocardial infarction and cardiac arrest (Reid *et al.* 2016; Brown 2018; Cheong *et al.* 2019; Hu *et al.* 2018), increase in psychological disorders and adverse birth outcomes (Cascio 2018; Finlay *et al.* 2012; Karthikeyan *et al.* 2006).

A significant factor that must be considered when assessing the risks associated with bushfires smoke relates to the broad geographical extension where the health impacts may be observed (Adam *et al.* 2021). The smoke can cover areas hundreds of kilometres away from the actual bushfire zone, reaching major urban centres and, consequently, representing a potential health hazard for millions of people and becoming a significant issue for the public health system (Dennekamp & Abramson 2011).

Unfortunately, it is unlikely, though, those events from 2019–20 will be one-off considering the current trends (Vardoulakis *et al.* 2020b), as the 2019–20 events only confirmed the warning of previous research predicting an amplification of the global risk of bushfire because of climate change (Yu *et al.* 2020; Jones *et al.* 2013). Indeed, the observation of the global fires from 1979 to 2013 highlighted that the length of the bushfire season has been prolonged by up to 20% during this period (Jolly *et al.* 2015), indicating an increasing trend of more frequent and more severe bushfire events (Keywood *et al.* 2013; Flannigan *et al.* 2009). Following this tendency, the number of days characterised by an extreme risk of bushfire will increase by 15–70% by 2050 and by more than 100% by 2100 (Jones *et al.* 2013). Thus, understanding the implications and the impacts of bushfires on the economy, environment and health is of utmost importance to assess the suitability of the current strategies adopted to reduce the health risk during such events. Australian bushfires highlighted the urgent need for an inquiry into the effectiveness of buildings in protecting occupants from exposure to poor air quality. This paper presents the case study of an office building in Canberra subjected to the 2019–20 bushfires to evaluate the ability of mechanical ventilation systems in providing healthy indoor air quality (IAQ).

1.1 BUSHFIRE, AIR POLLUTION AND COMMERCIAL BUILDINGS

Wildfires are widely recognised as a significant source of air pollution (Johnston *et al.* 2012). The international literature shows that a significant percentage of outdoor pollution generated during bushfire events can infiltrate indoor environments (Barn *et al.* 2008; Chen *et al.* 2016; Sharma & Balasubramanian 2017; Kearney *et al.* 2014; Zhou *et al.* 2015), which is a finding common to the Australian building stock (Reisen *et al.* 2019).

Despite the lack of strong evidence, the current public health recommendation to curb the impact on people during bushfire events is to remain indoors (Reisen *et al.* 2019). This strategy relies on the assumption that buildings can protect people against pollutants infiltration. Indeed, when windows and doors are closed, the rate of infiltration is reduced, depending on the level of airtightness of the construction itself (Adam *et al.* 2021). Recently, several studies focused on residential buildings performance (Zhang & Stewart 2020; Rajagopalan & Goodman 2021; Shrestha *et al.* 2019; Fisk & Chan 2017). However, considering that people spend one-third of their time at the workplace, the common assumption that air-conditioned commercial buildings can protect their occupants from particulates and other pollutants, especially during extended smoke events, should be investigated. Offices must also be able to offer a safe and healthy environment, protecting their occupants from hazardous outdoor pollution.

Commercial buildings are more likely to rely on mechanical ventilation, offering the potential to prevent pollutants' infiltration. A strategy that can be adopted is to apply positive pressurisation of the indoors by increasing air intake above the exhaust and, hence, reducing infiltration for the outdoors (Davison *et al.* 2021). However, this may not be possible in all cases, increasing the reliance on filters.

Filtering systems can potentially aid in reducing the circulation of particulate matter (PM) and pollutants from bushfires in the indoor environment (Barn *et al.* 2016). In standard heating, ventilation and air-conditioning (HVAC) systems, the filters are placed in the return-air ducts, and they only function when the system is in operation. Thus, during bushfire events, the HVAC needs to be constantly switched on during the occupation to allow for adequate PM filtrations (Joseph *et al.* 2020). The efficiency of the filters in removing the PM from the air is expressed through their minimum efficiency reporting values (MERV) from 1 to 16 (ASHRAE 2017). The higher the MERV ratings, the more efficient is the filter, with high-efficiency particulate air (HEPA) filters being categorised as MERV 16. They have been proved to be more effective at reducing indoor PM concentrations (ASHRAE 2017). Further, ultrafine particles can be efficiently filtered by special air filters with high gas permeance and low-pressure drop (Wang *et al.* 2017, 2018). HEPA filters, however, are usually employed in healthcare or industrial settings (Joseph *et al.* 2020), with MERV filters more likely to be installed in standard commercial buildings.

However, the literature presents contradicting findings on the efficiency of MERV filters during extreme bushfire events. Studies on the IAQ during the 2013 Singapore haze episode demonstrate that mechanical ventilation systems with MERV 7 filters have been unable to offer adequate protection from the outdoor PM, with an estimated removal efficiency of 30% for particles with diameters < 0.1 μm (Chen *et al.* 2016). Contrarily, some evidence shows that either fan-coil units equipped with high-grade filters (Cao *et al.* 2016) or portable air cleaners (Stauffer *et al.* 2020) may be effective in removing indoor PM.

These findings indicate that filter efficiency is key for reducing the indoor concentrations of pollutants that originated outdoors. However, conclusive evidence and research on the commercial sector are still lacking, which represents a significant gap that prevents the generation of informed management strategies.

The ability of the built environment to protect from outdoor pollutions must be considered and evaluated through a holistic approach. Furthermore, remaining indoors is a strategy that becomes less effective if the smoke haze lingers for consecutive days (Brown 2018), as the quality of the indoor air is also severely affected during non-hazy days (Sharma & Balasubramanian 2019). When the high levels of air pollutants persist over weeks, it is impractical and also introduces several side issues. Keeping the windows closed may result in lower air exchange, but can lead to building overheating, higher levels of indoor humidity, higher CO_2 concentrations and accumulation of $PM_{2.5}$ trapped indoors (Vardoulakis *et al.* 2020a; Reisen *et al.* 2019). When a mechanical ventilation system is available, the high reliance on HVAC for air filtering leads to increased energy consumption (Joseph *et al.* 2020). It is widely recognised that these extreme weather events are exacerbated by climate change, in both magnitude and frequency (Vardoulakis *et al.* 2020b). Thus, increased use of HVAC systems would lead to increased carbon emissions with implications for climate change mitigation, resulting in a vicious cycle that may be difficult to interrupt while preserving people's health.

1.2 SCOPE

The majority of the research aimed at analysing and evaluating the suitability of the current health advice in cases of extreme bushfire events has focused on residential buildings. Few projects consider commercial building case studies, mainly testing ad hoc filtration systems. A lack of evidence exists on the ability of office buildings to protect their occupants from outdoor pollution using the mechanical ventilation systems already in place.

During the 2019–20 events, the public health recommendation to stay indoors was a very clear response to poor air quality conditions found outdoors. However, a lack of data supports the assumption that IAQ conditions delivered by buildings were *actually* safe during the extreme events of 2019–20 because much of the attention was placed on thresholds found outdoors and not indoors. This study provides measured data about the performance of the Australian built environment under extreme weather events based on the case study of a governmental building in Canberra during the 'black summer'. This analysis relies upon the monitored indoor concentration of CO_2, PM_{10} and $PM_{2.5}$ and it investigates the ability of the indoor environment to cope with the prolonged and extreme outdoor smoke conditions. Considering the likelihood of this event being repeated as a result of climate change, it is important to understand how buildings coped.

The ultimate goal of the analysis is to understand the resilience of the built environment to future events, informing the next generation of health advice and management strategies to be adopted during extreme weather events.

2. METHODS

This research showcases the performance of a governmental office building before and during the 2019–20 bushfires season, from December 2019 to February 2020. The building is located in Canberra, one of the locations hardly hit by the smoke haze during the 'black summer'. The case study is a fully occupied two-storey mixed-use building, with spaces used for laboratories and offices, and it hosts approximately 450 workers, when fully occupied. The construction technique and architectural design represent the average Australian office building. The building is equipped with a central mechanical HVAC system, estimated to be 15 years old, without a dedicated air filtration stage before the mixing plenum. The HVAC is equipped with F5 filters (AS 1324.1-2001; Australian Standard 2001), corresponding to a grade MERV 8–9. During the bushfire events, the ventilation system was promptly set on the heavy filtration of outdoor air, but it was not possible to set small pressurisation of the indoor environment, achieved through lower return air volume and higher outside air volume. Hence, the only active protection from outdoor air pollutants infiltration was offered by the filters. This makes the case study highly relevant because it represents the case of an average office building equipped with a relatively old HVAC system, and not optimally operated, offering the possibility to evaluate the protection offered by the system envelope/HVAC.

2.1 INDOOR POLLUTANTS THRESHOLDS

The air pollutants concentrations thresholds are indicated by the National Environment Protection Measure for Ambient Air Quality (Air NEPM) (ADEE 2016) and reported in the *Indoor Air Quality Handbook*, a publication released by the Australian Building Code Board (ABCB) to provide construction industry participants with non-mandatory advice and guidance on specific topics (ABCB 2018).

2.1.1 CO_2

CO_2 is a natural chemical component of the atmosphere and non-toxic in low concentrations; in standard conditions, the average CO_2 outdoor level in the air is around 400 ppm (ABCB 2018). CO_2 is formed and released in the atmosphere by biological and natural processes, such as respiration, decay processes and volcanos, but also by anthropogenic activities, such as fossil fuel combustion. The latter is the primary source of CO_2 in outdoor environments, while indoor is usually dominated by human metabolic functions. A high concentration of CO_2 can cause headaches, dizziness, confusion, dyspnoea, disorientation, hypertension and ultimately loss of consciousness (ABCB 2018).

CO_2 is often used as a driving parameter for mechanical ventilation and to monitor indoor occupancy. ASHRAE Standard 62.1-2019 recommends a maximum CO_2 level of 1000 ppm to maintain IAQ (ASHRAE 2019), but the National Construction Code of Australia further reduces it to 850 ppm over an eight-hour period (ABCB 2013). This level is based on an increment of 450 ppm above the background CO_2 concentration, representing an adequately ventilated building (ABCB 2018).

In this study, CO_2 concentrations were used to understand the occupancy of the building and to estimate the mechanical ventilation adopted based on daily values.

2.1.2 PM_{10} and $PM_{2.5}$

Airborne particles are referred to as particulate matters (PMs), and they include dust, dirt, sand, smoke and liquid droplets, with varying sizes and visibility. They are usually grouped based on their size, dividing between (ABCB 2018):

- coarse particle PM_{10}: diameter < 10 μm
- fine particles $PM_{2.5}$: diameter < 2.5 μm
- ultrafine particles: diameter < 0.1 μm.

These types of pollutants can be produced by natural processes or anthropogenic activities. Bushfires and dust storms are among the first, and they are the most relevant for the Australian context due to the natural wildfires and the dust transported from the arid central regions.

The WHO (2009) set the yearly thresholds based on the lowest level associated with a relative increment of lung cancer mortality, which is $PM_{2.5}$ 25 μg/m^3 and PM_{10} 50 μg/m^3. A recent study concluded that $PM_{2.5}$ levels four times higher than this value may induce up to 6% of daily all-cause mortality, 5% of cardiovascular mortality and 6% of respiratory mortality (Liu *et al.* 2019). Another recent investigation found a linear correlation between $PM_{2.5}$ and mortality from lung cancer; indeed, it reported that for every 10 μg/m^3 increment in fine particle concentration, there is an increased risk of death of 8% (Pope *et al.* 2002).

In Australia, air quality thresholds defined by the Air NEPM (ADEE 2016) had been updated in 2016 to include both the annual and the daily limits as reported in ***Table 1***.

Table 1 PM_{10} and $PM_{2.5}$ limits as defined by the National Environment Protection Measure for Ambient Air Quality (Air NEPM).

Source: ADEE (2016).

POLLUTANT	THRESHOLD (μg/m^3)	AVERAGING PERIOD	ALLOWABLE EXCEEDANCE
PM_{10}	50	24 h	Exceptional event rule: an exceptional event is a fire or dust occurrence that adversely affects air quality at a particular location; causes an exceedance of one-day average standards in excess of normal historical fluctuations and background levels, and is directly related to bushfire, jurisdiction-authorised hazard-reduction burning or continental-scale windblown dust
	25	1 year	
$PM_{2.5}$	25	24 h	
	8	1 year	

The 2016 revision also started a process for the reduction of the $PM_{2.5}$ limits to 20 μg/m^3 (24 h) and 7 μg/m^3 (one year) to be achieved by 2025, and to develop a population exposure metric that could be nationally consistent and agreed between the different territorial jurisdiction.

2.2 MEASUREMENTS

The monitored parameters include indoor and outdoor, CO_2, $PM_{2.5}$ and PM_{10}, measured at 1.5 m above the floor. The accuracy of the device is reported in ***Table 2***. The sensors used in this study are part of a commercial monitoring unit (SE-100 Sensedge), which is accurately calibrated by the manufacturer.

Each room of the building was equipped with a monitoring device, placed in the centre of the area with careful consideration of the displacement regarding supply air diffusers. This study presents the monitored data of an open-plan office area located on the ground floor, because it is representative of a more consistently and homogenously occupied floor across the monitoring period.

Table 2 Technical data of the sensors used in the monitoring campaign: sensor types, accuracy, resolution and range are reported.

	SENSOR TYPE	ACCURACY	RESOLUTION	RANGE
CO_2	Non-dispersive infrared	±3% ± 50 ppm	1 ppm	400–2000 ppm
PM_{10}	Light-scattering (350 nm)	±10% (< 30 ± 3 μg/m^3)	1 μg/m^3	1–100,030 μg/m^3
$PM_{2.5}$	Light-scattering (350 nm)	±10% (< 30 ± 3 μg/m^3)	1 μg/m^3	1–100,030 μg/m^3

The data were collected at one-minute intervals throughout the bushfire season. In January, the indoor device was switched off for the first 15 days, while the rest of the series does not present gaps of more than 15 consecutive minutes, which allowed us to build a complete time series of hourly averages. The gap does not influence the analysis, because the findings are based on the difference between indoor and outdoor concentrations rather than comparing the monthly trends.

3. RESULTS AND DISCUSSION

3.1 CO_2

Figure 1 shows that the outdoor CO_2 levels were consistently above the standard value of 400 ppm for the whole bushfire season, with a significant peak during January, when the CO_2 concentration increases by almost a factor of 2. The Australian Capital Territory (ACT) Emergency Service Agency (ESA) officially declared the end of the bushfire season on 31 March 2020, but the emergency was under control by February. ***Figure 1*** reveals that the levels of outdoor CO_2 dropped to the normal value as soon as the bushfire was extinguished, indicating that the possible harm for humans in these events is directly related to the presence of the pollutant's source. Although the recorded CO_2 concentration indoors is high, the value never exceeded the critical threshold of 850 ppm as an eight-hour averaged value (ABCB 2013). CO_2 levels never achieved a concerning value to be considered a primary source of harm for human health. ***Figure 1*** also reports that the indoor CO_2 concentrations were constantly above the outdoor levels, which can be expected as CO_2 is also

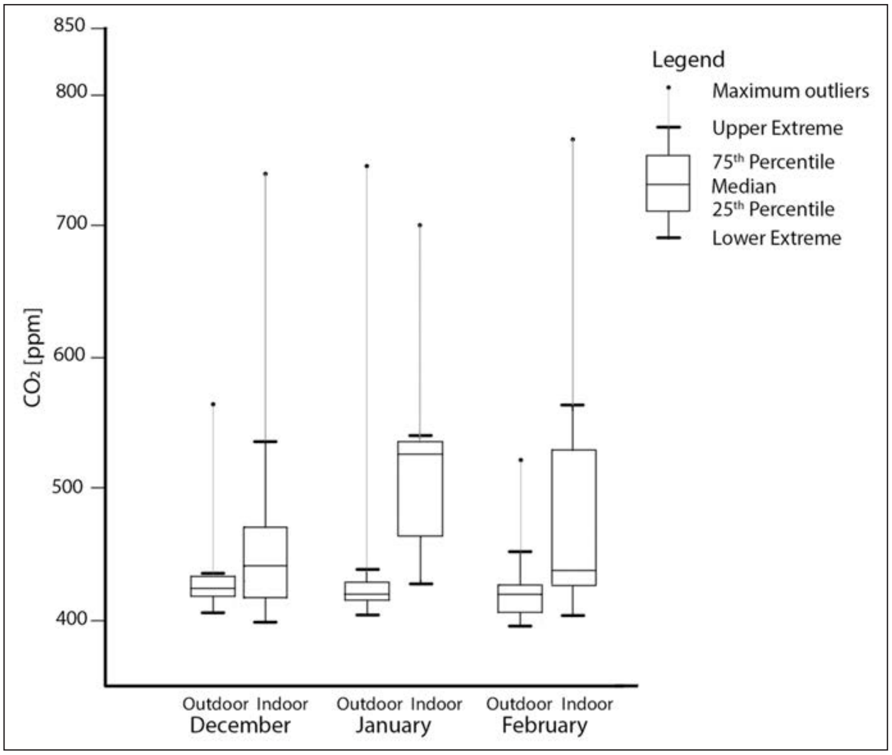


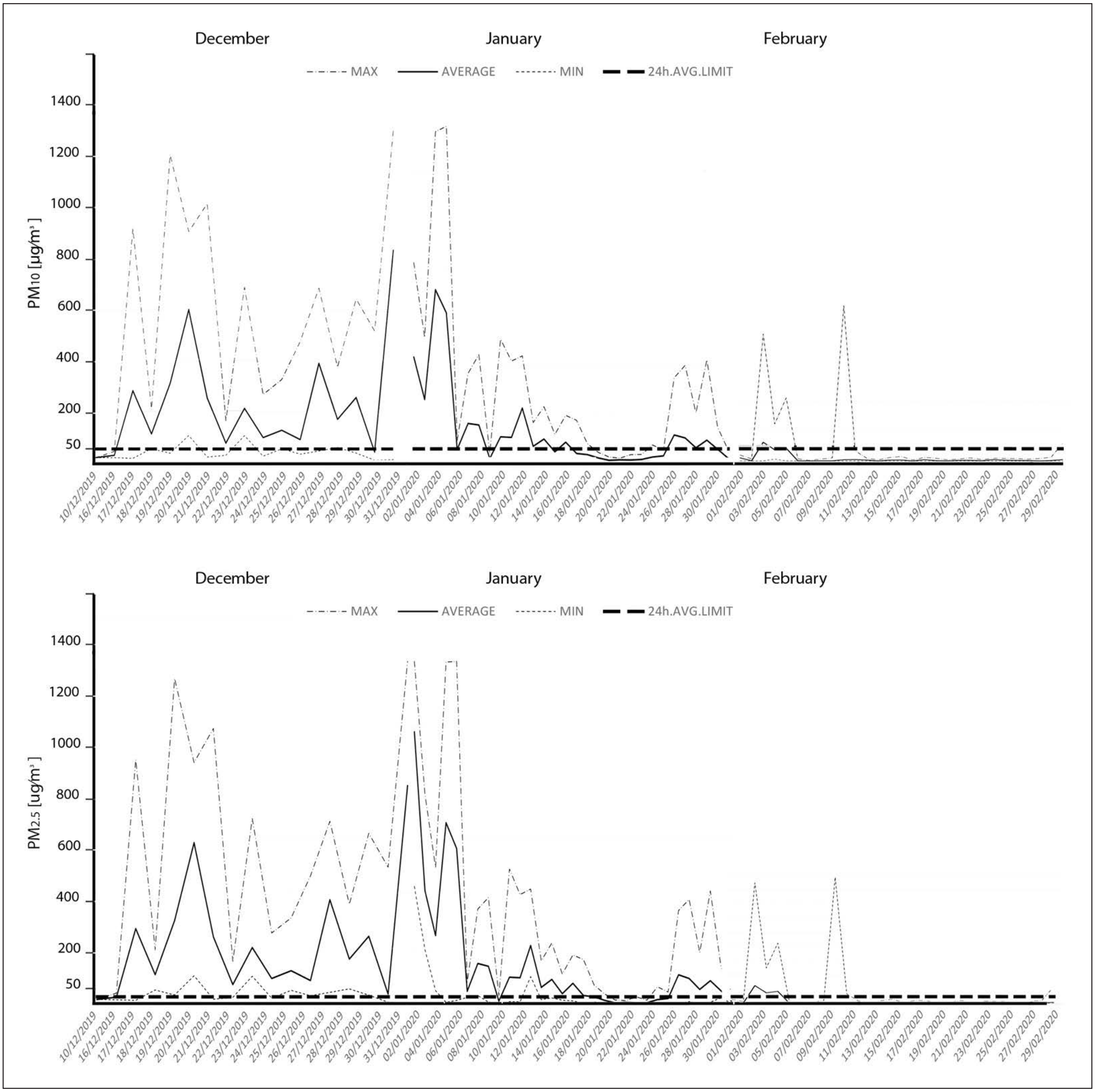
Figure 1: Box plot graph of the monthly indoor and outdoor CO_2 concentrations, December 2019–February 2020.

produced by human respiration and is the main driver for ventilation in buildings. In this case, however, it is possible to notice a discrepancy with the outdoor data. Indeed, the highest outdoor CO_2 median values are reported toward the end of the bushfire season, while it seems the opposite indoors, even if the building has been occupied for most of the bushfire season. These trends are determined by use of the mechanical ventilation in the system, which has been used at its maximum capacity to compensate for the smoke infiltration through the envelope.

3.2 PM_{10} AND $PM_{2.5}$

The concentration of PM in the air is usually expressed through two indicators: the coarse and the fine PM, respectively, PM_{10} and $PM_{2.5}$. In the case study presented here, trends observed for the two PM indicators are similar; however, the magnitude and frequency of the thresholds' exceedances must be analysed separately to identify the possible source of health risks and HVAC resilience. ***Figure 2*** shows the outdoor PM concentration during the monitoring period, alongside the maximum and minimum monitored values and the acceptable thresholds.

Figure 2: Outdoor PM_{10} (above) and $PM_{2.5}$ (below) daily average, maximum and minimum values, December 2019–February 2020.



The air pollutants concentrations exceeded the yearly thresholds previously indicated. Although the Air NEPM quality standard (ADEE 2016) admits an exceptional exceedance of the limit, it is still unclear what are its long-term consequences. The 2019–20 bushfire season was unusually long, and PM concentrations outdoors have been consistently above the thresholds for more than two consecutive months. Concerning levels of both PM_{10} and $PM_{2.5}$ have been detected during the whole summer, with December being the worst month. The daily thresholds are set on the 24 h averages and, during this month, the detected values ranged cyclically from just above the recommended limit to 12 times higher for PM_{10} and 24 times higher for $PM_{2.5}$ (approximately 600 μg/m^3 in both cases). However, looking at the peak values, the situation appears even more severe, with PM_{10} peaks up to 24 times and $PM_{2.5}$ peaks up to 48 times higher than the limits (approximately 1200 μg/m^3). This trend is observed to continue in January and mid-February when most of the fires were contained, but it asks the question about the health effects of long-term and cyclical exposure to a high concentration of air pollutants combined with short-term exposure to extremely high concentrations. Indeed, the lack of an hourly indication on critical PM concentrations limits the possibility to identify the possible issues at a finer scale and, consequently, to define a more suitable strategy to reduce harmful exposures. This issue is also acknowledged by the Environmental Protection Agency of the State of Victoria (EPA), which states that:

> there is currently no national standard for the one-hour PM_{10} average, and it uses the value 80 μg/m^3 to trigger a 'poor' air quality category.
>
> (EPA 2019)

This can also indicate the magnitude of the issue, as PM_{10} has exceeded this level for more than one consecutive month.

Figure 3 shows a summary of the indoor and outdoor monthly $PM_{2.5}$ values recorded. As shown in ***Figure 2***, $PM_{2.5}$ and PM_{10} are very similar, hence the first can be used as a proxy for the second, and the same conclusions apply.

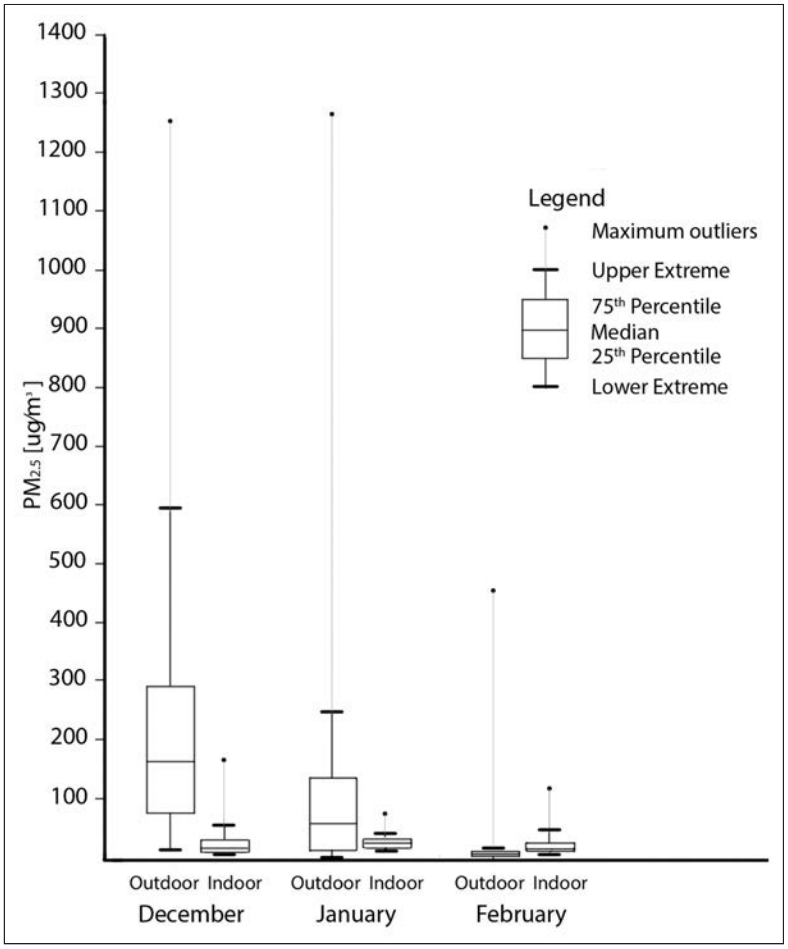


Figure 3: Box plot graph of the monthly outdoor and indoor concentration of $PM_{2.5}$, December 2019–February 2020.

The first observation regards the scale of the values: outdoor concentrations reached peaks up to 10 times higher than measured values indoors, indicating that the building offered a certain degree of protection from the extreme and most severe moments. Considering the outdoor concentrations, it is possible to notice a difference in the month with the highest peaks and the highest average. The highest peaks were observed during January, but the month with the highest average concentration is December. This may be due to the partial failure of the monitoring system, even if the outdoor data indicate that December has been the worst month for long periods of outdoor exposure, and January posed an increased pressure on the buildings to resist air pollutants' infiltration thereby keeping indoor conditions acceptable.

Figure 4 shows the PM_{10} and $PM_{2.5}$ indoor concentrations in regard to the outdoor average during the extreme peak observed in December.

One of the major issues related to the presence of PM_{10} and $PM_{2.5}$ is the persistence of these pollutants in the air because they generally take a long time to settle. Rain may help the process, but Australian summers are generally hot and dry, preventing water from settling or dissolving the particles. The fine and light nature of PM_{10} and $PM_{2.5}$ makes it very easy for these pollutants entrained into the air by wind or disturbances consequently entering buildings through infiltrations, openings and ventilation systems. This is clearly seen in the delay of the peaks.

The daily limits for PM_{10} and $PM_{2.5}$, respectively 50 and 28 $\mu g/m^3$ (ADEE 2016), are exceeded. This indicates that the building and the ventilation strategy have not been able to provide an adequate level of protection during teak events. Outdoor levels reached everyday peaks up to 1200 $\mu g/m^3$, except for the 20th, where it ranged consistently between 150 and 200 $\mu g/m^3$. From ***Figure 4*** it is possible to notice that indoor trends do not follow the outdoors. Indeed, indoor peaks are observed during the night-time, which poses pressure on the HVAC systems in the morning, just before working hours. These night-time peaks are due to the ventilation schedule employed in commercial buildings, where the HVAC system is usually switched off during non-working hours. However, the data monitored during the bushfire question the suitability of these energy-efficient measures during extreme events, where constant ventilation of the indoor spaces is required. The high values detected during 20 December are consistent with the delay identified previously, which not only indicates that the building has a slower reaction time (peak of the precedent day), but also that the building and the mechanical system have difficulties in coping with constant pressure, given by the lower but steadier outdoor value detected on the same day.

3.3 STATISTICAL ANALYSIS AND INFILTRATION MODELLING

To better assess the ability of the building to provide a healthy indoor environment, the particle infiltration factor (F_{inf}) and protection effectiveness (PE) are calculated. The particle infiltration factor is averaged daily, dividing occupied and unoccupied hours. The hourly averaged concentration of pollutants has been used to determine the hours of occupancy, which are assumed to correspond to the hours where the HVAC system was in operation. A multiple linear regression is used to determine the coefficient of penetration of outdoor particles (a_1) and the coefficient decay of indoor particles (a_2) (Barn *et al.* 2008; Switzer & Ott 1992), following the equation:

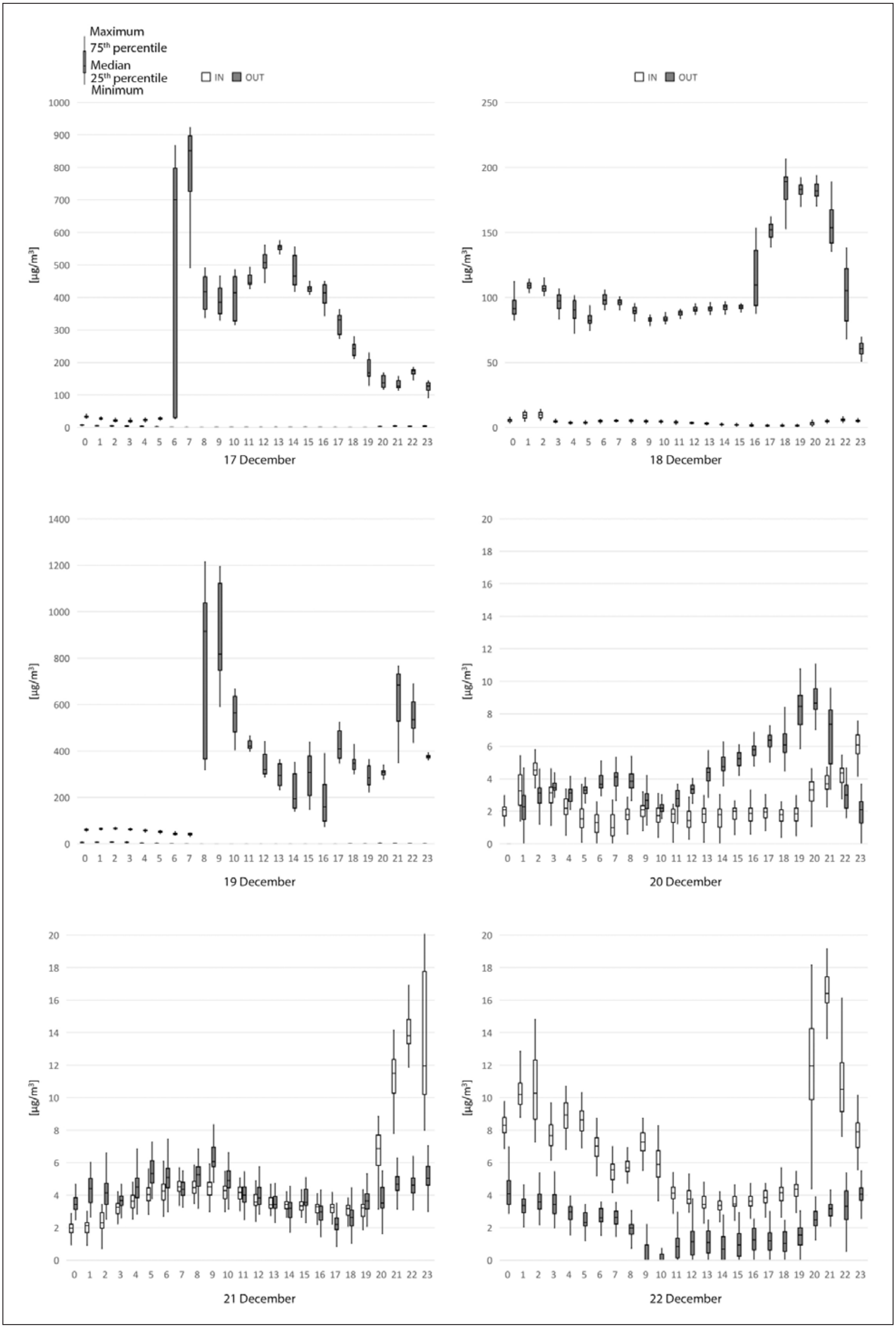
$$C_{in} = a_1\left(C_{\text{out}}\right)_t + a_2\left(C_{\text{in}}\right)_{t-1} + S_i \tag{1}$$

where C_{in} is the concentration of PM indoors; C_{out} the concentration of PM outdoors; and S_{i} the indoor PM generation, assumed to be null. Based on (1), the infiltration factor F_{inf} has been determined as:

$$F_{\text{inf}} = a_1/\left(1 - a_2\right) \tag{2}$$

F_{inf} for occupied and unoccupied hours is equal to 0.36 and 0.50. respectively, which means that the infiltration rate is higher during the unoccupied hours when the HVAC system is off. This result is easily understandable because the calculation accounts for the filtering system by assessing the rate of the air pollutants' concentration. These values appear to be aligned with the literature: in a comparative study the seasonal infiltration factor was calculated for 21 homes with and without HEPA filters (Barn *et al.* 2008), resulting in F_{inf} ranging from 0.61 to 0.28 without filters, and from 0.19 to 0.10 when HEPA filters were installed. The results of the presented case study support the literature, with F_{inf} higher when there is a filtering system in place.

Figure 4: Indoor and outdoor daily concentration of PM_{10} and $PM_{2.5}$, 17–21 December 2019.



Further, these values can be used to calculate the factor PE, expressed as a percentage:

$$PE = \left(F_{\text{in}}\left(\text{unoccupied}\right) - F_{\text{in}}\left(\text{occupied}\right)\right) / F_{\text{inf}}\left(\text{unoccupied}\right) = 100 * \left(0.5 - 036\right) / 0.5 = 28\% \qquad (3)$$

This value represents the efficacy of the system building and HVAC to protect indoor occupants from outdoor pollutants' infiltration, and it accounts for the filters' efficiency and the envelope's airtightness. Indeed, PE depends on both the ability of the HVAC system to filter the pollutant penetrated indoors and the ability of the envelope to reduce this penetration. Hence, PE can be a good indicator of the overall building performance, which, in this case, shows a capacity to reduce by 28% the air pollutants' infiltration. Compared with a more sophisticated filtering system, this value is lower than the average (Barn *et al.* 2008). However, it reflects a typical Australian case, where the HVAC system installed is estimated to be 15 years old and the airtightness of the envelope is not optimal (Ambrose & Syme 2017). This prompts a new question about the necessity to expand the research on bushfire responses and intervention strategies to a broader cohort of buildings, accounting for different ages, quality, design, operational and construction practices.

A multiple regression analysis was also conducted to predict the relationship between outdoor $PM_{2.5}$ and CO_2 (independent variables) and indoor $PM_{2.5}$ data (dependent variables) for unoccupied and occupied hours (***Table 3***).

Table 3 Multiple regression analyses of the relationship between indoor $PM_{2.5}$ and outdoor $PM_{2.5}$ and CO_2 data for occupied and unoccupied hours.

TIME PERIOD	INDEPENDENT VARIABLE	R^2	B	t	p	STANDARD ERROR
Unoccupied hours	$PM_{2.5}$ outdoor	0.23	0.62	36.97	0	0.017
	CO_2 outdoor		23.07	48.13	0	0.479
Occupied hours	$PM_{2.5}$ outdoor	0.14	0.058	34.89	0	0.002
	CO_2 outdoor		0.003	12.50	0	0.000

The multiple regression analyses predict the relationship between outdoor $PM_{2.5}$ and CO_2 values, and this correlation is found to be statistically significant (R^2 ranked 0.23, $p < 0.0005$ for unoccupied hours; 0.14, $p < 0.0005$ for occupied hours). The R^2 values show that there is a stronger relationship between outdoor and indoor variables during the unoccupied hours compared with occupied ones. This might be since, when the HVAC system was switched off, the windows were kept closed, leaving uncontrolled infiltration as the only exchange between the indoor and outdoor environments. However, during the occupied hours when the HVAC system is active, the analysis shows a weak relationship between the dependent and independent variables. In this case, it is the performance of the filters to determine whether the relationship between the variable is weak or strong. Accordingly, the multiple regression analysis confirms the infiltration models.

3.4 SUMMARY OF THE RESULTS

In this study a commercial building in Canberra (AU) was monitored during the extreme bushfire events of 2019–20. The results show the following:

- Indoor CO_2 levels do not constitute a source of harm for the occupants' health during extreme bushfire events, mainly due to the high reliance on the mechanical ventilation system, preferred over natural ventilation to protect the indoors and left active for all the occupied hours as a response to the high filtration needs.
- Indoor $PM_{2.5}$ and PM_{10} have shown similar trends, hence one can be used as a proxy for the other. The main reason is the filtering system: the case study is equipped with F5 filters, which can capture particles with diameters < 1 μm, thus showing a similar efficacy for both air pollutants.
- Outdoor PM consistently exceeded the acceptable thresholds (ADEE 2016) for the whole monitoring period, with averages up to 12 (PM_{10}) and 24 ($PM_{2.5}$) times higher than the limits, and peak values up to 24 (PM_{10}) and 48 ($PM_{2.5}$) times higher, indicating a serious health hazard for both long exposures and peak values.

- Indoor PM shows a delay in the peaks, indicating that the air pollutants take time to settle and that the filtering system had issues in coping with prolonged high pollution levels.
- Indoor PM limits have been consistently close to the limit, with exceedance during the peak days registered in December, which supports the questions about the effects of mixed exposure (prolonged period combined with extremely high peaks) on human health.
- The F_{inf} values are 0.36 and 0.50 for occupied and unoccupied periods, respectively; the difference is mainly due to HVAC operations, which has been able to filter the air pollutants. However, the PE offered by the envelope and the HVAC is estimated to be only 28%, which reflects a situation where old filtering systems and low airtightness levels are not optimal at protecting the indoor environment from outdoor air pollutants.
- The multiple regression analyses indicated a stronger relationship between indoor $PM_{2.5}$ and outdoor $PM_{2.5}$ and CO_2 values ($R^2 = 0.23$, $p < 0.0005$) for unoccupied hours than occupied hours ($R^2 = 0.14$, $p < 0.0005$) as a result of the filtering performance of the HVAC system.

4. CONCLUSIONS

The 2019–20 Australian bushfire season has prompted unprecedented recorded pollutant concentrations outdoors and indoors, posing a significant threat to human health. The severity and duration of the bushfire season have also placed extreme pressure on buildings and their heating, ventilation and air-conditioning (HVAC) systems to cope with such environmental stress and protect against the smoke for a prolonged period of time. This study contributes to the discussion about the ability of our indoor environments to cope with extreme weather events. It reports on indoor air quality (IAQ): measured levels of indoor air pollutants (such as $PM_{2.5}$ and PM_{10}) detected in an office building during the Australian bushfire season of 2019–20.

Monitored levels of indoor air pollutants, such as CO_2, PM_{10} and $PM_{2.5}$, have been compared with the outdoor levels and recommended thresholds to understand the health risks posed on the population during this period. The findings show that concentrations of outdoor air pollutants consistently exceeded the indicated thresholds for more than two consecutive months, with peaks up to 24 and 48 times higher than considered safe limits, indicating a significant high health risk. Besides, it was observed that indoor PM_{10} and $PM_{2.5}$ concentrations also exceeded the thresholds. The particle infiltration factor (F_{inf}) and protection effectiveness (PE) calculations indicated that the infiltration system was working effectively when unoccupied and occupied periods are compared, with an overall efficiency of the system envelope and filter up to 39%. The multiple regression analyses showed that outdoor $PM_{2.5}$ and CO_2 concentrations had a higher impact on indoor $PM_{2.5}$ concentration during the unoccupied hours.

Furthermore, the indoor environment shows a delay in the peaks, suggesting that air pollutants had difficulty settling and, most likely, that they accumulate indoors, further aggravated by the small air exchange with the outdoors. These statistically significant findings highlighted the importance of HVAC and infiltration system, especially under these extreme weather conditions. The high concentration of indoor air pollutants during unoccupied hours overthrows the common assumptions that trivialise the envelope air leakage in office buildings.

The current health policy recommends the public to stay indoors during extreme hazy days, which strongly relies on the assumption that the indoors is healthier and more efficient in protecting from air pollutants. However, Australian buildings are generally leaky and without a mechanical ventilation system. If HVAC is installed, occupants are less prepared and lack instruction on how to manage it during such extreme weather events. According to the results, the monitored office building could reduce high levels of air pollutants, but the concerning prolonged concentration of air pollutants questions the general approach currently adopted.

Considering that the likelihood of these extreme events is increasing due to climate change, understanding how buildings behaved during this period is of utmost importance to identify a suitable strategy to reduce the health risks associated with fire-related air pollutants.

Future research should aim to investigate the performance of a broader set of buildings, drawing on the knowledge and insights gained from this analysis.

The results from this paper suggest that:

- the built environment is not equipped to cope with the duration and magnitude such as those from the Australian bushfire season of 2019–2020
- the evidence exposes the unreliability of the current health advice
- urgent actions and a thorough rethinking are needed in relation to the protection that buildings should provide (especially IAQ) during extreme events associated with climate change.

ACKNOWLEDGEMENTS

The authors thank Alex Ellerman and AETMOS for sharing the data analysed in this paper.

AUTHOR AFFILIATIONS

Arianna Brambilla *orcid.org/0000-0002-8494-7861*
School of Architecture, Design and Planning, The University of Sydney, Sydney, NSW, Australia
Christhina Candido *orcid.org/0000-0002-1966-657X*
Faculty of Architecture, Building and Planning, University of Melbourne, Melbourne, VIC, Australia
Marco Filippo Sangiorgio *orcid.org/0000-0002-8924-5869*
Baxter srl, Meda (MB), Italy
Ozgur Gocer *orcid.org/0000-0002-3978-440X*
School of Architecture, Design and Planning, The University of Sydney, Sydney, NSW, Australia
Kenan Gocer *orcid.org/0000-0002-4862-4993*
Faculty of Engineering and Architecture, Beykoz University, Istanbul, Turkey

COMPETING INTERESTS

The authors have no competing interests to declare. C.C. is a member of this journal's editorial board, which is on a voluntary basis.

FUNDING

This research was conducted without additional funding.

REFERENCES

ABCB. (2013). *National construction code series volume 1: Building code of Australia 577 2013, class 2 to 9 buildings*. Australian Building Code Board (ABCB). **https://ncc.abcb.gov.au**

ABCB. (2018). *Indoor air quality handbook*. Australian Building Code Board (ABCB). ***https://www.abcb.gov.au/Resources/Publications/Education-Training/Indoor-air-quality***

Adam, M. G., Tran, P. T. M., Bolan, N., & **Balasubramanian, R.** (2021). Biomass burning-derived airborne particulate matter in Southeast Asia: A critical review. *Journal of Hazardous Materials*, 407, 124760. DOI: *https://doi.org/10.1016/j.jhazmat.2020.124760*

ADEE. (2016). *National air quality standards*. Australia Department of Environment and Energy (ADEE). ***https://soe.environment.gov.au/theme/ambient-air-quality/topic/2016/national-air-quality-standards***

Ambrose, M., & **Syme, M.** (2017). Air tightness of new Australian residential buildings. *Procedia Engineering*, 180, 33–40. DOI: ***https://doi.org/10.1016/j.proeng.2017.04.162***

ASHRAE. (2017). *ASHRAE Standard 52.2: Method of testing general ventilation air-cleaning devices for removal efficiency by particle size*. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). ***https://www.ashrae.org/File%20Library/Technical%20Resources/COVID-19/52_2_2017_COVID-19_20200401.pdf***

ASHRAE. (2019). *ASHRAE Standard 62.1-2019: Ventilation for acceptable indoor air quality*. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). ***https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2***

Australian Standard. (2001). *AS 1324.1-2001: Air filters for use in general ventilation and airconditioning. Application, performance and construction*. Australian Standard. *https://www.saiglobal.com/PDFTemp/Previews/OSH/as/as1000/1300/13241.pdf*

Barn, P., Larson, T., Noullett, M., Kennedy, S., Copes, R., & **Brauer, M.** (2008). Infiltration of forest fire and residential wood smoke: an evaluation of air cleaner effectiveness. *Journal of Exposure Science & Environmental Epidemiology*, 18(5), 503–511. DOI: *https://doi.org/10.1038/sj.jes.7500640*

Barn, P. K., Elliott, C. T., Allen, R. W., Kosatsky, T., Rideout, K., & **Henderson, S. B.** (2016). Portable air cleaners should be at the forefront of the public health response to landscape fire smoke. *Environmental Health*, 15(1), 1–8. DOI: *https://doi.org/10.1186/s12940-016-0198-9*

Brown, S. K. (2018). Bushfires and indoor built environments. *Indoor and Built Environment*, 27(2), 145–147. DOI: *https://doi.org/10.1177/1420326X18758095*

Cao, Q., Chen, A., Zhou, J., & **Chang, V. W. C.** (2016). Performance evaluation of filter applications in fan-coil units during the 2015 Southeast Asian haze episode. *Building and Environment*, 107, 191–197. DOI: *https://doi.org/10.1016/j.buildenv.2016.08.004*

Cascio, W. E. (2018). Wildland fire smoke and human health. *Science of the Total Environment*, 624, 586–595. DOI: *https://doi.org/10.1016/j.scitotenv.2017.12.086*

Chen, A., Cao, Q., Zhou, J., Yang, B., Chang, V. W. C., & **Nazaroff, W. W.** (2016). Indoor and outdoor particles in an air-conditioned building during and after the 2013 haze in Singapore. *Building and Environment*, 99, 73–81. DOI: *https://doi.org/10.1016/j.buildenv.2016.01.002*

Cheong, K. H., Ngiam, N. J., Morgan, G. G., Pek, P. P., Tan, B. Y.-Q., Lai, J. W., Koh, J. M., Ong, M. E. H., & **Ho, A. F. W.** (2019). Acute health impacts of the Southeast Asian transboundary haze problem—A review. *International Journal of Environmental Research and Public Health*, 16, 3286. DOI: *https://doi.org/10.3390/ijerph16183286*

Davison, G., Barkjohn, K. K., Hagler, G. S., Holder, A. L., Coefield, S., Noonan, C., & **Hassett-Sipple, B.** (2021). Creating clean air spaces during wildland fire smoke episodes: Web Summit summary. *Frontiers in Public Health*, 9, 70. DOI: *https://doi.org/10.3389/fpubh.2021.508971*

Dennekamp, M., & **Abramson, M. J.** (2011). The effects of bushfire smoke on respiratory health. *Respirology*, 16(2), 198–209. DOI: *https://doi.org/10.1111/j.1440-1843.2010.01868.x*

EPA. (2019). *PM10 particles in the air*. Environmental Protection Agency, Victoria (EPA). *https://www.epa.vic.gov.au/for-community/environmental-information/air-quality/pm10-particles-in-the-air*

Finlay, S. E., Moffat, A., Gazzard, R., Baker, D., & **Murray, V.** (2012). Health impacts of wildfires. *PLoS Currents Disasters*, 2 November, Edition 1. DOI: *https://doi.org/10.1371/4f959951cce2c*

Fisk, W. J., & **Chan, W. R.** (2017). Health benefits and costs of filtration interventions that reduce indoor exposure to PM 2.5 during wildfires. *Indoor Air*, 27(1), 191–204. DOI: *https://doi.org/10.1111/ina.12285*

Flannigan, M. D., Krawchuk, M. A., de Groot, W. J., Wotton, B. M., & **Gowman, L. M.** (2009). Implications of changing climate for global wildland fire. *International Journal of Wildland Fire*, 18(5), 483–507. DOI: *https://doi.org/10.1071/WF08187*

Hu, Y., Fernandez-Anez, N., Smith, T. E. L., & **Rein, G.** (2018). Review of emission from smouldering peat fires and their contribution to regional haze episodes. *International Journal of Wildland Fire*, 27, 293–312. DOI: *https://doi.org/10.1071/WF17084*

Johnston, F. H., Borchers-Arriagada, N., Morgan, G. G., Jalaludin, B., Palmer, A. J., Williamson, G. J., & **Bowman, D. M.** (2021). Unprecedented health costs of smoke-related PM 2.5 from the 2019–20 Australian megafires. *Nature Sustainability*, 4(1), 42–47. DOI: *https://doi.org/10.1038/s41893-020-00610-5*

Johnston, F. H., Henderson, S. B., Chen, Y., Randerson, J. T., Marlier, M., DeFries, R. S., … & **Brauer, M.** (2012). Estimated global mortality attributable to smoke from landscape fires. *Environmental Health Perspectives*, 120(5), 695–701. DOI: *https://doi.org/10.1289/ehp.1104422*

Jolly, W., Cochrane, M., Freeborn, P. *et al.* (2015). Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, 6, 7537. DOI: *https://doi.org/10.1038/ncomms8537*

Jones, R. N., Young, C. K., Handmer, J., Keating, A., Mekala, G. D., & **Sheehan, P.** (2013). *Valuing adaptation under rapid change*. National Climate Change Adaptation Research Facility, Gold Coast. *https://apo.org.au/node/34095*

Joseph, G., Schramm, P. J., Vaidyanathan, A., Breysse, P., & **Goodwin, B.** (2020). *Evidence on the use of indoor air filtration as an intervention for wildfire smoke pollutant exposure*. *https://www.cdc.gov/air/wildfire-smoke/socialmedia/Wildfire-Air-Filtration-508.pdf*

Karthikeyan, S., Balasubramanian, R., & **Iouri, K.** (2006). Particulate air pollution from bushfires: Human exposure and possible health effects. *Journal of Toxicology and Environmental Health, Part A*, 69(21), 1895–1908. DOI: *https://doi.org/10.1080/15287390600751264*

Kearney, J., Wallace, L., MacNeill, M., Héroux, M. E., Kindzierski, W., & **Wheeler, A.** (2014). Residential infiltration of fine and ultrafine particles in Edmonton. *Atmospheric Environment*, 94, 793–805. DOI: *https://doi.org/10.1016/j.atmosenv.2014.05.020*

Keywood, M., Kanakidou, M., Stohl, A., Dentener, F., Grassi, G., Meyer, C. P., … & **Burrows, J.** (2013). Fire in the air: Biomass burning impacts in a changing climate. *Critical Reviews in Environmental Science and Technology*, 43(1), 40–83. DOI: *https://doi.org/10.1080/10643389.2011.604248*

Ladds, M., Keating, A., Handmer, J., & **Magee, L.** (2017). How much do disasters cost? A comparison of disaster cost estimates in Australia. *International Journal of Disaster Risk Reduction*, 21, 419–429. DOI: *https://doi.org/10.1016/j.ijdrr.2017.01.004*

Liu, C., Chen, R., Sera, F., Vicedo-Cabrera, A. M., Guo, Y., Tong, S., … & **Valdes Ortega, N.** (2019). Ambient particulate air pollution and daily mortality in 652 cities. *New England Journal of Medicine*, 381(8), 705–715. DOI: *https://doi.org/10.1056/NEJMoa1817364*

Pope, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & **Thurston, G. D.** (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Journal of the American Medical Association*, 287(9), 1132–1141. DOI: *https://doi.org/10.1001/jama.287.9.1132*

Rajagopalan, P., & **Goodman, N.** (2021). Improving the indoor air quality of residential buildings during bushfire smoke events. *Climate*, 9(2), 32. DOI: *https://doi.org/10.3390/cli9020032*

Reid, C. E., Brauer, M., Johnston, F. H., Jerrett, M., Balmes, J. R., & **Elliott, C. T.** (2016). Critical review of health impacts of wildfire smoke exposure. *Environmental Health Perspectives*, 124(9), 1334–1343. DOI: *https://doi.org/10.1289/ehp.1409277*

Reisen, F., Powell, J. C., Dennekamp, M., Johnston, F. H., & **Wheeler, A. J.** (2019). Is remaining indoors an effective way of reducing exposure to fine particulate matter during biomass burning events?. *Journal of the Air & Waste Management Association*, 69(5), 611–622. DOI: *https://doi.org/10.1080/10962247.2019.1567623*

Sharma, R., & **Balasubramanian, R.** (2017). Indoor human exposure to size-fractionated aerosols during the 2015 Southeast Asian smoke haze and assessment of exposure mitigation strategies. *Environmental Research Letters*, 12(11), 114026. DOI: *https://doi.org/10.1088/1748-9326/aa86dd*

Sharma, R., & **Balasubramanian, R.** (2019). Assessment and mitigation of indoor human exposure to fine particulate matter (PM2.5) of outdoor origin in naturally ventilated residential apartments: A case study. *Atmospheric Environment*, 212, 163–171. DOI: *https://doi.org/10.1016/j.atmosenv.2019.05.040*

Shrestha, P. M., Humphrey, J. L., Carlton, E. J., Adgate, J. L., Barton, K. E., Root, E. D., & **Miller, S. L.** (2019). Impact of outdoor air pollution on indoor air quality in low-income homes during wildfire seasons. *International Journal of Environmental Research and Public Health*, 16(19), 3535. DOI: *https://doi.org/10.3390/ijerph16193535*

Stauffer, D. A., Autenrieth, D. A., Hart, J. F., & **Capoccia, S.** (2020). Control of wildfire-sourced PM2.5 in an office setting using a commercially available portable air cleaner. *Journal of Occupational and Environmental Hygiene*, 17(4), 109–120. DOI: *https://doi.org/10.1080/15459624.2020.1722314*

Switzer, P., & **Ott, W.** (1992). Derivation of an indoor air averaging time model from the mass balance equation for the case of independent source inputs and fixed air exchange rates. *Journal of Exposure Analysis and Environmental Epidemiology*, 2(2), 113–135. *https://www.osti.gov/biblio/5638493*

Vardoulakis, S., Jalaludin, B. B., Morgan, G. G., Hanigan, I. C., & **Johnston, F. H.** (2020a). Bushfire smoke: Urgent need for a national health protection strategy. *Medical Journal of Australia*, 212(8), 349–353. *https://www.mja.com.au/system/files/issues/212_08/mja250511.pdf*. DOI: *https://doi.org/10.5694/mja2.50511*

Vardoulakis, S., Marks, G., & **Abramson, M. J.** (2020b). Lessons learned from the Australian bushfires: Climate change, air pollution, and public health. *JAMA Internal Medicine*, 180(5), 635–636. DOI: *https://doi.org/10.1001/jamainternmed.2020.0703*

Wang, L. Y., Liya, E. Y., Lai, J. Y., & **Chung, T. S.** (2018). Developing ultra-high gas permeance PVDF hollow fibers for air filtration applications. *Separation and Purification Technology*, 205, 184–195. DOI: *https://doi.org/10.1016/j.seppur.2018.05.036*

Wang, L. Y., Yong, W. F., Liya, E. Y., & **Chung, T. S.** (2017). Design of high efficiency PVDF-PEG hollow fibers for air filtration of ultrafine particles. *Journal of Membrane Science*, 535, 342–349. DOI: *https://doi.org/10.1016/j.memsci.2017.04.053*

WHO. (2009). *WHO guidelines for indoor air quality: dampness and mould*. World Health Organization (WHO).

Yu, P., Xu, R., Abramson, M. J., Li, S., & **Guo, Y.** (2020). Bushfires in Australia: A serious health emergency under climate change. *The Lancet Planetary Health*, 4(1), e7–e8. DOI: *https://doi.org/10.1016/S2542-5196(19)30267-0*

Zhang, F., & **Stewart, R.** (2020). Indoor air quality in South East Queensland dwellings during 2019–2020 bushfires. In A. Ghaffarianhoseini *et al.* (Eds.), *Conference Proceedings: Imaginable Futures: Design Thinking, and the Scientific Method*. *54th International Conference of the Architectural Science Association 2020* (pp. 610–619). Architectural Science Association (ANZAScA). *https://research-repository.griffith.edu.au/bitstream/handle/10072/402678/Zhang463203-Published.pdf?sequence=5*

Zhou, J., Chen, A., Cao, Q., Yang, B., Chang, V. W. C., & **Nazaroff, W. W.** (2015). Particle exposure during the 2013 haze in Singapore: Importance of the built environment. *Building and Environment*, 93, 14–23. DOI: *https://doi.org/10.1016/j.buildenv.2015.04.029*

TO CITE THIS ARTICLE:
Brambilla, A., Candido, C., Sangiorgio, M. P., Gocer, O., & Gocer, K. (2021). Can commercial buildings cope with Australian bushfires? An IAQ analysis. *Buildings and Cities*, 2(1), pp. 583–598. DOI: *https://doi.org/10.5334/bc.87*

Submitted: 06 November 2020
Accepted: 02 June 2021
Published: 29 June 2021

COPYRIGHT:
© 2021 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See *http://creativecommons.org/licenses/by/4.0/*.

Buildings and Cities is a peer-reviewed open access journal published by Ubiquity Press.