Is remaining indoors an effective way of reducing exposure to $PM_{2.5}$ during biomass burning events?

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Abstract

Bushfires, prescribed burns and residential wood burning are a significant source of fine particles ($PM_{2.5}$) affecting the health and well-being of many communities. Despite the lack of evidence, a common public health recommendation is to remain indoors assuming that the home provides a protective barrier against ambient $PM_{2.5}$. The study aimed to assess to what extent houses provide protection against peak concentrations of outdoor $PM_{2.5}$ and whether remaining indoors is an effective way of reducing exposure to $PM_{2.5}$. The effectiveness of this strategy was evaluated by conducting simultaneous week-long indoor and outdoor measurements of $PM_{2.5}$ at 21 residences in regional areas of Victoria, Australia.
During smoke plume events, remaining indoors protected residents from peak outdoor $PM_{2.5}$ concentrations, but the level of protection was highly variable ranging from 12-76%. Housing stock (e.g. age of the house) and ventilation (e.g. having windows/doors open or closed) played a significant role in the infiltration of outdoor $PM_{2.5}$ indoors. The results also showed that leaving windows and doors closed once the smoke plume abates trapped $PM_{2.5}$ indoors and increased indoor exposure to $PM_{2.5}$. Furthermore, for approximately 50% of households, indoor sources such as cooking activities, smoking and burning candles or incense contributed significantly to indoor $PM_{2.5}$.

Keywords: fine particulate matter, indoor air quality, infiltration, smoke, ventilation, biomass burning

Introduction

In their analyses of the trends in global fires from 1979 to 2013, Jolly et al. (2015) showed that there has been an increase of 18.7% in the global fire weather season length for this time period. This means that fires are becoming more widespread and frequent in some regions (Flannigan et al. 2009, Turetsky et al. 2011, Westerling et al. 2006). Johnston et al. (2012) identified that fire events are a significant source of air pollution and are likely to continue to grow in magnitude, resulting in increased health impacts.

Air pollution from bushfires and wood heaters has an impact on air quality and population health (Dennekamp and Abramson 2011, Johnston et al. 2011, Morgan et al. 2010). Currently, Australian homes are perceived to be a critical front line of defence against episodic severe outdoor air pollution resulting from bushfires and prescribed burns. With the increased risk and frequency of such biomass fires occurring in Australia (Jolly et al. 2015) it is important to investigate the extent to which sheltering in homes is an effective method for protecting population health.

Studies conducted internationally have demonstrated that much of the outdoor particulate matter generated through biomass burning is able to infiltrate indoors resulting in elevated indoor particulate matter concentrations (Barn et al. 2008, Chen et al. 2016, Henderson et al. 2005, Sharma and Balasubramanian 2017, Wheeler et al. 2014, Zhou et al. 2015). Factors that affect the influence of a smoke plume on indoor air include the air exchange rate (AER) (h^{-1}), the penetration factor (P) into the house (1=100% penetration) and the deposition rate (k) (h^{-1}). Air exchange occurs by infiltration through cracks, spaces and fixed ventilators in the building shell, as well as by natural ventilation through opening of windows and doors. Natural ventilation is commonly used in single- and double-storey residences in parts of Australia. Some houses may have some mechanical ventilation such as extraction fans in the kitchen, bathroom and toilet. Ventilation is therefore generally controlled within a residence by adjusting the state of external openings to the house. Research into housing characteristics and AER in 73 Australian naturally ventilated homes demonstrated that home age was the most important factor driving AERs (Metropolitan Fire and Emergency Services Board 2011). Older houses can have higher AERs, approximately 0.4 to 0.5 h^{-1}, while in newer houses these can be as low as ~0.15 h^{-1}. Overall, the AERs for houses built within the last 5 years were distinctly lower than those for houses constructed earlier. This is partially due to the removal of the requirement for fixed permanent ventilation (Building Code of Australia, 1990). It has also been demonstrated that opening doors and windows can result in initial

AERs in excess of 3 h^{-1} (Department of Environment and Heritage 2004, Dunne et al. 2006, He et al. 2005).

The infiltration factor (F_{inf}) is defined as the fraction of ambient particles that penetrate indoors and remain suspended under steady state conditions (Wilson et al. 2000). Kearney et al. (2014) reported that within and between-home variability in infiltration exists due to weather conditions, housing characteristics, particle size and particle composition making it challenging to apply infiltration data from one country to another.

This study adds to the evidence on outdoor and indoor exposures during smoke plume events for typical Australian houses. It determines if exposure to fine particulate matter ($PM_{2.5}$) during biomass burning smoke events can be minimised by remaining indoors and changing the home's AER through opening and closing doors and windows. This is the current guidance provided by Australian government agencies when such events occur (Victorian Government 2015).

Methods

Measurements

$PM_{2.5}$ monitoring was conducted between 2013 and 2015 in the Yarra Valley and Gippsland, two regions in South-Eastern Victoria, Australia that have a high likelihood of smoke impacts from prescribed burns or bushfires (Figure S1). The Yarra Valley is located approximately 70 km east of Melbourne. Due to the topography of the area, smoke tends to accumulate in the valley, dispersing slowly. The Gippsland area is located 206 km east of Melbourne close to the High Country of Victoria and is frequently impacted by smoke from either prescribed burns or bushfires in the surrounding forested areas. Ambient $PM_{2.5}$ measurements were conducted at a central location in each region. Additionally, week-long indoor and outdoor air measurements were conducted at 21 residences in 2014 and 2015 to assess the influence of smoke plumes on indoor air quality (Table S1). Due to the unpredictability of prescribed burns, residences impacted by smoke from either private burn-offs or emissions from domestic woodheaters were also included to assess infiltration of outdoor $PM_{2.5}$ indoors. Private burn-offs of grass, stubble, undergrowth and other vegetation are commonly conducted on private properties outside the fire danger period.

Measurements of outdoor $PM_{2.5}$ were made using a low-volume aerosol sampler, E-sampler-9800 (Met One Instruments, Inc., Oregon, USA) fitted with a $PM_{2.5}$ size-selective inlet. The sampler was operated at a height of ~ 2m to collect both continuous $PM_{2.5}$ measurements at a 5-minute interval by light-scattering and to also collect particle mass on pre-weighed 47mm Fluoropore membrane filters with a 1 μm pore size (Merck Millipore). The gravimetric mass measurements were used to correct the E-sampler's response. Inside each residence continuous $PM_{2.5}$ concentrations were logged at 5-min intervals in a central location using a DustTrak (DustTrak II, TSI, USA) fitted with a $PM_{2.5}$ impactor plate. The instrument's response was corrected against gravimetric $PM_{2.5}$ concentrations collected on a 37mm Fluoropore membrane filter over the 7-day period. Zero and flow checks for each instrument were done before and after deployment. The weekly filter samples were analysed for gravimetric mass using an ultra-microbalance (Model XP2U, Mettler Toledo, Australia) with a specialty filter pan in a temperature (20-23°C) and relative humidity (RH<30%) controlled environment. Only gravimetrically-corrected values are reported here. Filters collected for gravimetric mass concentrations were also used for analysis of levoglucosan using a Dionex ICS-3000 high performance anion exchange chromatograph with an electrochemical detector operated in the integrating (pulsed) amperometric mode (HPAEC-PAD) as described in Reisen et al. (2011) to confirm biomass burning sources. Outdoor meteorological data was obtained from a central weather station in the Yarra Valley and Gippsland.

A short questionnaire, administered to residents, provided information on housing characteristics, including age, building material, type of primary and secondary home heating, stove and air conditioning system (if present) and number of rooms, windows and external doors. In 2015, residents also completed a daily diary to identify potential indoor PM sources (e.g. cooking, cleaning, burning candles or incense, smoking and woodheater operation) and outdoor PM sources (e.g. garden waste burns, BBQ, smoking, mowing) and time periods when doors and windows were opened.

Air exchange rates (AER)

In this study no AER measurements were completed for the 21 residences. This is a limitation of the current study and for any future studies we recommend getting AERs for the corresponding measurement period. In the absence of AER in the current study, we used data from a previous study on indoor and outdoor pollutants in residences in Melbourne during winter and summer of 2003 (Galbally et al. 2011) that measured AERs in 15 residences using a carbon dioxide (CO_2) release method described in Dunne et al. (2006) (see Supplementary materials), with a similar housing stock to the ones in this study. The study assessed relationships between AER(CO_2), dwelling age, window openings, wind speed and indoor to outdoor temperature differences (Galbally et al. 2010a, b). In the absence of AER measurements, the established relationships that were developed in the Melbourne indoor air study were used to estimate AERs for the residences in this study (see supplementary materials). AERs were also estimated by measuring the decrease in indoor $PM_{2.5}$ concentrations following an indoor PM peak event. A plot of the natural log of indoor $PM_{2.5}$ concentrations versus time provides a straight line where the slope equals the total decay rate, a+k. The peaks were required to have a concentration of at least 50 μg m^{-3}, decay over at least 90 minutes and a regression with an R2>0.9 (Kearney et al. 2011, Wallace et al. 2013). The AER was estimated by assuming a deposition rate of 0.2 h^{-1} and 0.4 h^{-1} for $PM_{2.5}$ particles to fall within the range of reported values in the literature (0.17-0.56 h^{-1}). (Figure S2 and Table S2).

The infiltration factor (F_{inf}) is defined as the fraction of outdoor $PM_{2.5}$ that enters indoors and remains suspended (Allen et al. 2003, Long et al. 2001). In the absence of indoor sources estimates of F_{inf} during smoke plume events were calculated as the ratio of the hourly averaged indoor $PM_{2.5}$ concentration divided by the hourly averaged outdoor $PM_{2.5}$ concentration (MacNeill et al. 2014).

Results & Discussion

During the measurement period, only one significant biomass burning event was observed each year. Due to limited prescribed burning events we were only able to capture the effects of emissions on two homes in 2015. An additional five residences were impacted by smoke from either private burn-offs or emissions from domestic woodheaters. The housing characteristics of the relevant residences and biomass burning events are detailed in Table 1.

Table 1 here

Ambient $PM_{2.5}$ concentrations and composition during biomass burning events

A number of exceedances of the 24-h advisory for $PM_{2.5}$ National Environment Protection Measures (NEPM) standard of 25 µg m^{-3} (National Environmental Protection Council 2003) were observed due to biomass burning events (Table S3). These included planned burns in the Yarra Valley in 2013 and 2015, extensive bushfires in east Gippsland and an open-cut coal mine fire close to Traralgon in 2014 and a private burn-off close to the monitoring site in Warburton in 2015. Hourly $PM_{2.5}$ concentrations measured during periods of excessive haze in the Yarra Valley are shown in Figure 1. Peak hourly $PM_{2.5}$ concentrations during prescribed burns (Figure 1a and 1c) were similar to those observed during bushfires (Figure 1b). The smoke plume events from prescribed burns in 2013 and 2015 were short-lived, with $PM_{2.5}$ concentrations staying elevated for 9-13 hours. During the bushfire event in 2014 $PM_{2.5}$ concentrations stayed elevated for 25-54 hours. Generally impacts from prescribed burns are expected to be shorter in duration than large-scale bushfires (Table S4 and Haikerwal et al. (2015)).

During the 2013 prescribed burn smoke event, $PM_{2.5}$ concentrations were consistent across the Yarra Valley with both monitoring stations displaying similar $PM_{2.5}$ concentrations (Figure 1a). The smoke plume originated from a prescribed burn located approximately 40 km south-west of the monitoring site, resulting in uniform plume concentrations across the valley (Figure S3). This is consistent with what has been observed in other studies where monitoring sites were co-located in the same well-mixed airshed and valley (Ward et al. 2004). However in 2015, we observed significant spatial variability in $PM_{2.5}$ concentrations across the valley with higher concentrations measured at Warburton than at Yarra Junction, located approximately 10 km south-west of Warburton (Figure 1c). This is likely due to the prescribed burn being located approximately 10-20 km to the east of the monitoring stations (Figure S3) and the smoke plume draining into the valley. The closer proximity of Warburton to the prescribed burn resulted in high concentrations with a dilution of the smoke plume across the valley. This shows that the impact on downwind communities is strongly dependent on the distance to the burn area and the predominant wind directions.

Figure 1 here

When the $PM_{2.5}$ filter composition was analysed there were high median levoglucosan levels observed in 2015 suggesting influences by local woodheater emissions (Table S3). During the winter, the levoglucosan fraction averaged 21% at Yarra Junction and 13% at Warburton. These levels are consistent with previous observations in the Huon valley, TAS where fractions averaged 12-24% (Reisen et al. 2013). Furthermore a study on woodheater emissions found an average levoglucosan fraction of 25% from well oxygenated combustion of Eucalypt fuels in woodheaters (Meyer et al. 2008).

Indoor measurements at residences

Indoor $PM_{2.5}$ measurements were made in 21 residences and detailed results are shown in Table S5. Results were highly variable with hourly and daily $PM_{2.5}$ concentrations in the range of 0-774 µg m^{-3} and 0.03-80.9 µg m^{-3} respectively. Figure 2 shows that more than 90% of the 24-h $PM_{2.5}$ concentrations were below the 24-h advisory $PM_{2.5}$ NEPM standard of 25 µg m^{-3}. The remaining elevated indoor $PM_{2.5}$ concentrations were either due to indoor activities (e.g. cooking, frying, grilling, smoking, burning candle or incense) (shown in grey) or due to outdoor air pollution events (shown in blue). The contribution of any indoor sources to indoor $PM_{2.5}$ was identified from the diaries. In addition, we observed elevated indoor $PM_{2.5}$ concentrations but no concurrent outdoor $PM_{2.5}$ concentrations. Figure 2 also shows that hourly peak $PM_{2.5}$ concentrations can be very high and are mainly linked to indoor sources, consistent with peak values observed during cooking activities (He et al. 2004). The measured indoor $PM_{2.5}$ concentrations compare with other studies where indoor sources of $PM_{2.5}$ resulted in daily ranges of between 0.54 – 74 and 0.54 – 140 µg m^{-3} (Kearney et al. 2014), and 0.93 - 50 and 0.04 – 100 µg m^{-3} in winter and summer respectively (MacNeill et al. 2014). A Canadian study investigating the impact of air cleaners on indoor air quality demonstrated that when the air cleaners were not operational daily indoor $PM_{2.5}$ data ranged from <0.1 – 74.9 µg m^{-3} (Barn et al. 2008). Calculated daily indoor concentrations in homes in Brisbane ranged between 7.9-17.5 µg m^{-3} during non-activity periods and between 8.0-36.9 µg m^{-3} during activity periods (Morawska et al. 2003), while studies conducted in European cities measured indoor $PM_{2.5}$ concentrations ranging between 2-140 µg m^{-3} (Hanninen et al. 2004).

Figure 2 here

The median $PM_{2.5}$ indoor/outdoor (I/O) ratio ranged between 0.13 and 2.93 with an outlier of 33.2 observed at a residence where participants were smoking. The frequency distribution showed that approximately 50% of the 24-hour $PM_{2.5}$ I/O ratios were greater than 1, suggesting that about 50% of the households had significant indoor sources of $PM_{2.5}$ resulting in higher $PM_{2.5}$ exposure indoors than outdoors (Figure S4). This compares with results from a research study that included 121 measurements of 24-hour averaged $PM_{2.5}$ within residences in Melbourne from August 2003 to February 2005 where I/O ratios ranged from 0.29−26.3 (Abramson 2008) (Figure S4). It also compares with Wheeler et al. (2014) where I/O ratios had a median of 1.11 and a range of 0.17−117.8 on days when wood stoves were operational in homes.

The indoor $PM_{2.5}$ measurements showed that there are important contributions from indoor sources on indoor $PM_{2.5}$. Approximately 27% of indoor peaks exceeded an hourly $PM_{2.5}$ concentration of 100 μg m^{-3}, highlighting that indoor sources need to be considered when assessing population exposures.

Infiltration of outdoor $PM_{2.5}$ indoors

The outdoor and indoor $PM_{2.5}$ concentrations measured at 7 residences during smoke plume events are summarised in Table 2. Plots of hourly outdoor and indoor $PM_{2.5}$ concentrations are shown in Figure 3 for smoke plume events (e.g. homes 10, 11, 12 and 16) and Figures S5 and S6 for wood smoke events (e.g. homes 7, 8 and 21).

Figure 3 here

In a closed state, the increase in indoor $PM_{2.5}$ concentrations was delayed (e.g. H16), while an immediate increase in indoor $PM_{2.5}$ concentrations was observed for houses in an open state (e.g. H10 & H12).

Table 2 here

Prescribed burns. The time series plots of the 5-minute averaged indoor and outdoor $PM_{2.5}$ concentrations measured during a smoke plume event at two residences (H10 and H11) are shown in Figure 4. The two residences are located in Warburton (VIC) approximately 3km apart from each other. Outdoor $PM_{2.5}$ concentrations were comparable at the two residences, with measured maximum hourly $PM_{2.5}$ concentrations of 336 and 387 μg m^{-3} and 24-hour averaged $PM_{2.5}$ concentrations of 89.8 μg m^{-3} and 99.2 μg m^{-3} respectively. The plume event lasted approximately 9 hours and outdoor concentrations peaked at ~ 7am.

Figure 4 here

Indoor $PM_{2.5}$ concentrations differed between the 2 residences. During the event the $PM_{2.5}$ 24-hour averaged indoor concentration was 77.4 μg m^{-3} at residence H10 and 55.6 μg m^{-3} at residence H11. The difference in indoor $PM_{2.5}$ concentrations during the smoke plume event was attributed to differences in ventilation and housing characteristics.

Residence H10 had 1 window and 1 door open during the smoke plume that resulted in only a 12% reduction in the maximum hourly indoor $PM_{2.5}$ concentration compared to the equivalent outdoor values. The I/O ratio remained at approximately 0.8 until more windows and doors were opened at 9am. Opening 2 doors and 2 windows at 9am when the smoke plume had passed resulted in a rapid decrease in indoor $PM_{2.5}$ concentrations. By remaining indoors the total exposure to $PM_{2.5}$ during the smoke plume event was reduced by 14% from 2100 μg m^{-3} h to 1800 μg m^{-3} h. The majority of the indoor exposure (95%) occurred during the increase in outdoor $PM_{2.5}$ concentrations between 12am and 9am.

A delayed response in the elevation of indoor $PM_{2.5}$ concentrations was observed at residence H11. The residence had 2 windows open until midnight after which the residence remained in a closed-up state. This resulted in a 57% reduction in indoor $PM_{2.5}$ concentrations. At 8am there was a decrease in outdoor $PM_{2.5}$ concentrations, however, indoor $PM_{2.5}$ concentrations remained elevated as doors and windows remained closed; this shows that it takes time for indoor concentrations to decrease and re-equilibrate with outdoor air without active ventilation. During the smoke plume the I/O ratio was 0.3 until about 8am. A decrease in outdoor concentrations was observed around 8am that resulted in an increase in the I/O ratio from 0.3 to a maximum of 15 at 11am. Opening 2 windows at 11am resulted in a decrease in indoor $PM_{2.5}$ concentrations and a decrease in the I/O ratio from 15 to 2.6 at 3pm. By remaining indoors the total exposure to $PM_{2.5}$ during the smoke plume event was reduced by 45% from 2300 μg m^{-3} h to 1300 μg m^{-3} h. While 63% of the indoor exposure occurred during the increase in outdoor $PM_{2.5}$ concentrations between 12am and 9am, 37% of the indoor exposure to $PM_{2.5}$ occurred when ambient $PM_{2.5}$ had abated. This shows that leaving windows and doors closed after the smoke plume event can trap fine particles indoors and increase indoor exposure to $PM_{2.5}$.

Private burn-offs. Private burn-offs included garden waste burns or wood fire burns that residents conducted on their properties during times when fire bans were lifted. During the monitoring period, 5 residences noted in their activity diaries either garden waste burns on their own property or garden waste burns/wood fire burns on a neighbour's property, of which two were used to evaluate indoor infiltration (Table 1). During the private burn-offs, maximum hourly $PM_{2.5}$ concentrations of 56 μg m^{-3} were observed outdoors and the events lasted on average about 3 hours (Table 2). Maximum 5-minute $PM_{2.5}$ concentrations ranged from 137-190 μg m^{-3} while maximum indoor $PM_{2.5}$ concentrations ranged from 35 to 114 μg m^{-3}. A reduction of 39-49% in maximum hourly $PM_{2.5}$ concentrations was observed indoors. The smallest reduction in indoor $PM_{2.5}$ concentrations was observed at residence H12 which had 4 windows open during the event allowing increased infiltration of outdoor particles indoors.

Woodheater emissions. Woodheaters are commonly used in regional areas of Victoria and emissions from them have been shown to impact on outdoor $PM_{2.5}$ concentrations (http://www.epa.nsw.gov.au/woodsmoke/; (Meyer et al. 2011, Hibberd et al. 2013). Indoor and outdoor measurements conducted in late May 2014 at Maffra and in winter 2015 in the Yarra Valley highlighted elevated outdoor $PM_{2.5}$ concentrations most likely due to domestic woodheating. Levoglucosan levels made up 3-17% of the $PM_{2.5}$ mass, consistent with filter samples impacted by wood smoke. Maximum 5-minute outdoor $PM_{2.5}$ concentrations ranged from 41-390 μg m^{-3} while maximum indoor $PM_{2.5}$ concentrations ranged from 8 to 59 μg m^{-3}. A reduction of 38-76% in maximum hourly $PM_{2.5}$ concentrations was observed indoors (Table 2).

Infiltration factors. Infiltration factors (F_{inf}) were calculated using indoor/outdoor ratios during the smoke plume event and are shown in Table 2. F_{inf} varied from 0.17 to 0.83, indicating that for some houses a significant proportion of outdoor particles remained suspended indoors and the house provided little protection against outdoor $PM_{2.5}$. It should be noted that windows were often open during smoke plume events resulting in increased infiltration rates. The lowest F_{inf} of 0.17 was measured at H7, while the highest F_{inf} of 0.83 was measured at the oldest residence H10.

The impact on residential indoor air quality from the infiltration of ambient $PM_{2.5}$ concentrations has been evaluated in a number of studies. These have predominantly been conducted in North America where building characteristics and building codes are very different from Australia. The majority of the studies included traffic emissions as the primary source of ambient $PM_{2.5}$ (Allen et al. 2003, Hystad et al. 2009, Kearney et al. 2014, MacNeill et al. 2014, MacNeill et al. 2012). Infiltration rates ranged significantly in these different studies with measured F_{inf} in the range of 0.1-1.0 (Barn et al. 2008, Kearney et al. 2014, MacNeill et al. 2014, MacNeill et al. 2012), consistent with this study. The large variability was attributed to season, housing characteristics and dynamics, use of air conditioning and filtration systems (Allen et al. 2003, Urban et al. 2012, Barn et al. 2008, Hanninen et al. 2011, Kearney et al. 2014, Long et al. 2001, MacNeill et al. 2014, MacNeill et al. 2012, Wheeler et al. 2014). Overall, infiltration was highest in summer due to window opening frequency, while houses in a closed state in winter resulted in the lowest infiltration rates.

Implications of AER, ventilation status and smoke plume characteristics on indoor $PM_{2.5}$.

Due to the unpredictability of prescribed burns and the short duration of such events, capturing measurements of indoor and outdoor $PM_{2.5}$ during smoke events are challenging. The limited data set collected in this study showed that remaining indoors protects residents from peak outdoor $PM_{2.5}$ concentrations with highly variable degrees of protection. Reductions ranged between 12 - 76%. We identified some potential factors likely to result in reduced infiltration of outdoor $PM_{2.5}$. These include ventilation (e.g. having windows/doors open or closed) and age of building. The study also showed that it is critical to ventilate the house when the smoke plume abates to minimise trapping $PM_{2.5}$ indoors.
The data was used to further assess whether the age and ventilation status of a house (data that can be easily obtained via a questionnaire and diary) are sufficient to provide an estimate of the infiltration of outdoor $PM_{2.5}$ indoors and whether a simplified infiltration model can provide an indication of the level of protection that sheltering indoors may provide during a smoke plume event. The infiltration model was based on a mass-balance equation that took into account age and ventilation of a residence, if available, and assuming an 80% and 100% penetration efficiency of $PM_{2.5}$ particles through the building shell (see supplementary materials). This is based on the fact that particles in the accumulation mode penetrate buildings most effectively (Allen et al. 2003, Chen and Zhao 2011, Kopperud et al. 2004, Long et al. 2001, Nazaroff 2004, Thatcher et al. 2002, Thatcher and Layton 1995, Diapouli et al. 2013). In addition, it is generally assumed that a dwelling operates as a single compartment where complete mixing occurs. AER(CO_2) was varied as a function of the ventilation status of the house and wind speed based on relationships established for 15 residences in Melbourne (Galbally et al. 2010a, b). As a previous study conducted on houses in south-eastern Australia did not find a relationship between AER(CO_2) and indoor-outdoor temperature difference, this factor was not taken into account in this study when estimating

AER(CO_2) (see supplementary material for further details). We attributed the observed lack of relationship between AER and indoor-outdoor temperature on the different housing stock found in south-eastern Australia, which may result in smaller temperature differences and a larger wind effect.The deposition rate k was assumed to remain constant across the measurement period.

Figure 5 shows the measured and modelled $PM_{2.5}$ concentrations during the prescribed burn event in March 2015 with additional events shown in Figure S7.

Figure 5 here

For smoke plume events (due to prescribed burning or private burn-offs, e.g. H10, H11, H12, H16), the model performed reasonably well when the ventilation status was taken into account (Table S6). Differences in measured and modelled indoor $PM_{2.5}$ concentrations are attributed to uncertainties in the AER(CO_2)s and deposition rates as well as local effects of turbulent mixing of air and wind speed/direction in relation to window openings.

For residences impacted by outdoor domestic wood smoke (e.g. H7, H8, H21), indoor $PM_{2.5}$ concentrations are potentially more challenging to model due to possible contributions from both outdoor wood smoke and smoke escaping from the wood stove use indoors.

Results from the infiltration model showed that for residence H10, closing windows and doors during the smoke plume event decreased hourly indoor $PM_{2.5}$ concentrations by 29% compared to the measured 12% reduction when windows were open. It was one of the oldest houses, which have previously been demonstrated to have the highest AER(CO_2), and even in a closed-up state it provides a small reduction in indoor $PM_{2.5}$ concentrations. This suggests that for Australian homes, older homes are leaky and may provide the least protection during smoke plume event. For residence H12 the model showed that closing windows resulted in a 68% reduction in hourly $PM_{2.5}$ concentrations compared to the measured 38.5% when windows were open. Overall remaining indoors with doors and windows closed provided reduced exposure to peak $PM_{2.5}$ concentrations ranging from 29-76% with a median of 66.5%. The modelled results confirm that a tighter house, in terms of reduced ventilation, provides greater protection against particle infiltration, with a significant difference between a tight house (AER(CO_2) of 0.15 h^{-1}) and a leaky house (AER(CO_2) of 0.8h^{-1}). The infiltration factor drops from 0.72 for a leaky house to 0.35 for a tight house.

Opening windows when the outdoor smoke abates can further reduce indoor exposures to $PM_{2.5}$, but this is dependent upon the smoke plume characteristics. For a rapid drop in outdoor $PM_{2.5}$ concentrations, e.g. due to change in wind direction, opening windows can significantly reduce indoor $PM_{2.5}$ concentrations (see Figure S8). This can be assessed by the householder based on outdoor visibility.

The model performance confirmed that information on housing characteristics and the ventilation status of the house during a smoke plume event can provide an approximate assessment of how well protected a house will be during a biomass burning event.

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Supplementary materials

The supplementary materials contain additional information to support this manuscript. Further information is provided on measurement locations, calculations of AERs, ambient $PM_{2.5}$ measurements, indoor and outdoor $PM_{2.5}$ data collected at the 21 residences and infiltration model evaluation.

References

Abramson, M., 2008. "Personal communication, Monash University, Department of Epidemiology and Preventative Medicine. NHMRC Project Grant 236934. The relationship between airborne particle exposure, incident respiratory symptoms and decline in lung function."

Allen, R., T. Larson, L. Sheppard, L. Wallace, and L. J. S. Liu. 2003. "Use of real-time light scattering data to estimate the contribution of infiltrated and indoor-generated particles to indoor air." *Environmental Science & Technology* 37 (16):3484-3492.

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

Chen, A. L., Q. L. Cao, J. Zhou, B. Yang, V. W. C. Chang, and W. W. Nazaroff. 2016. "Indoor and outdoor particles in an air-conditioned building during and after the 2013 haze in Singapore." *Building and Environment* 99:73-81.

Chen, C., and B. Zhao. 2011. "Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor." *Atmos Environ* 45 (2):275-288.

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

Department of Environment and Heritage. 2004. Unflued gas appliances and air quality in Australian homes. Technical Report No. 9. Australia: Commonwealth of Australia, Department of Environment and Heritage.

Diapouli, E., A. Chaloulakou, and P. Koutrakis. 2013. "Estimating the concentration of indoor particles of outdoor origin: A review." *Journal of the Air & Waste Management Association* 63 (10):1113-1129.

Dunne, E., W. Kirstine, I.E. Galbally, J. Powell, P. Selleck, and S. Lawson. 2006. "A study of gaseous indoor air quality for a Melbourne home." *Clean Air and Environmental Quality* 40 (3):45-51.

Flannigan, M. D., M. A. Krawchuk, W. J. de Groot, B. M. Wotton, and L. M. Gowman. 2009. "Implications of changing climate for global wildland fire." *International Journal of Wildland Fire* 18 (5):483-507.

Galbally, I., M. Cheng, R. Gillett, M. Keywood, S. Lawson, S. Molloy, and J. Powell. 2010a. Indoor Air Project. Part 1: Main Report - Indoor Air in Typical Australian Dwellings CSIRO: Aspendale, Victoria. http://www.environment.gov.au/protection/publications/indoor-air-project.

Galbally, I., M. Cheng, R. Gillett, M. Keywood, S. Lawson, S. Molloy, and J. Powell. 2010b. The Indoor Air Project. Part 2: Appendices. CSIRO: Aspendale, Victoria. http://www.environment.gov.au/protection/publications/indoor-air-project.

Galbally, I., M.D. Keywood, J.C. Powell, S.L. Lawson, M. Cheng, E. Dunne, R. Gillett, S. Molloy, P. Selleck, J. Ward, and F. Reisen. 2011. "An overview of the CSIRO 2008-2009 indoor air quality study." *Air Quality and Climate Change* 45 (1):27-35.

Haikerwal, A., F. Reisen, M. R. Sim, M. J. Abramson, C. P. Meyer, F. H. Johnston, and M. Dennekamp. 2015. "Impact of smoke from prescribed burning: Is it a public health concern?" *Journal of the Air & Waste Management Association* 65 (5):592-598.

Hanninen, O., G. Hoek, S. Mallone, E. Chellini, K. Katsouyanni, C. Gariazzo, G. Cattani, A. Marconi, P. Molnar, T. Bellander, and M. Jantunen. 2011. "Seasonal patterns of outdoor PM infiltration into indoor environments: review and meta-analysis of available studies from different climatological zones in Europe." *Air Quality Atmosphere and Health* 4 (3-4):221-233.

Hanninen, O. O., E. Lebret, V. Ilacqua, K. Katsouyanni, F. Kunzli, R. J. Sram, and M. Jantunen. 2004. "Infiltration of ambient PM(2.5) and levels of indoor generated non-ETS PM(2.5) in residences of four European cities." *Atmos Environ* 38 (37):6411-6423.

He, C. R., L. D. Morawska, J. Hitchins, and D. Gilbert. 2004. "Contribution from indoor sources to particle number and mass concentrations in residential houses." *Atmos Environ* 38 (21):3405-3415.

He, C. R., L. Morawska, and D. Gilbert. 2005. "Particle deposition rates in residential houses." *Atmos Environ* 39 (21):3891-3899. doi: 10.1016/j.atmosenv.2005.03.016.

Henderson, D. E., J. B. Milford, and S. L. Miller. 2005. "Prescribed burns and wildfires in Colorado: Impacts of mitigation measures on indoor air particulate matter." *Journal of the Air & Waste Management Association* 55 (10):1516-1526.

Hibberd, M., P. Selleck, M.D. Keywood, D. Cohen, E. Stelcer, and A. Atanacio. 2013. Upper Hunter Valley Particle Characterization Study. In *Final Report to NSW Office of Environment and Heritage and NSW Department of Health*. CSIRO: Aspendale, Victoria.

Hystad, P. U., E. M. Setton, R. W. Allen, P. C. Keller, and M. Brauer. 2009. "Modeling residential fine particulate matter infiltration for exposure assessment." *Journal of Exposure Science and Environmental Epidemiology* 19 (6):570-579.

Johnston, F. H., S. B. Henderson, Y. Chen, J. T. Randerson, M. Marlier, R. S. DeFries, P. Kinney, Dmjs Bowman, and M. Brauer. 2012. "Estimated Global Mortality Attributable to Smoke from Landscape Fires." *Environmental Health Perspectives* 120 (5):695-701.

Johnston, F., I. Hanigan, S. Henderson, G. Morgan, and D. Bowman. 2011. "Extreme air pollution events from bushfires and dust storms and their association with mortality in Sydney, Australia 1994-2007." *Environmental Research* 111 (6):811-816.

Jolly, W. M., M. A. Cochrane, P. H. Freeborn, Z. A. Holden, T. J. Brown, G. J. Williamson, and Dmjs Bowman. 2015. "Climate-induced variations in global wildfire danger from 1979 to 2013." *Nature Communications* 6:7537.

Kearney, J., L. Wallace, M. MacNeill, M. E. Heroux, W. Kindzierski, and A. Wheeler. 2014. "Residential infiltration of fine and ultrafine particles in Edmonton." *Atmos Environ* 94:793-805.

Kearney, J., L. Wallace, M. MacNeill, X. Xu, K. VanRyswyk, H. You, R. Kulka, and A. J. Wheeler. 2011. "Residential indoor and outdoor ultrafine particles in Windsor, Ontario." *Atmos Environ* 45 (40):7583-7593.

Kopperud, R. J., A. R. Ferro, and L. M. Hildemann. 2004. "Outdoor versus indoor contributions to indoor particulate matter (PM) determined by mass balance methods." *Journal of the Air & Waste Management Association* 54 (9):1188-1196.

Long, C. M., H. H. Suh, P. J. Catalano, and P. Koutrakis. 2001. "Using time- and size-resolved particulate data to quantify indoor penetration and deposition behavior (vol 35, pg 2089, 2001)." *Environmental Science & Technology* 35 (22):4584-4584.

MacNeill, M., J. Kearney, L. Wallace, M. Gibson, M. E. Heroux, J. Kuchta, J. R. Guernsey, and A. J. Wheeler. 2014. "Quantifying the contribution of ambient and indoor-generated fine particles to indoor air in residential environments." *Indoor Air* 24 (4):362-375.

MacNeill, M., L. Wallace, J. Kearney, R. W. Allen, K. Van Ryswyk, S. Judek, X. Xu, and A. Wheeler. 2012. "Factors influencing variability in the infiltration of PM2.5 mass and its components." *Atmos Environ* 61:518-532.

Metropolitan Fire and Emergency Services Board. 2011. A best practice approach to shelter-in-place for Victoria. Victorian Emergency Management Grants Program (issuing body).

Meyer, C.P. (Mick), A. K. Luhar, R. W. Gillett, and M.D. Keywood. 2008. Measurement of real-world PM10 emission factors and emission profiles from wood-heaters by in situ source monitoring and atmospheric verification methods. In *Final Report of Clean Air Research Project 16 for the Australian Government Department of the Environment, Water, Heritage and the Arts.* CSIRO: Aspendale, Victoria.

Meyer, C.P. (Mick), F. Reisen, M.D. Keywood, and S. Crumeyrolle. 2011. Impacts of smoke from regeneration burning on air quality in the Huon Valley, Tasmania. CSIRO: Aspendale, Victoria.

Morawska, L., C. R. He, J. Hitchins, K. Mengersen, and D. Gilbert. 2003. "Characteristics of particle number and mass concentrations in residential houses in Brisbane, Australia." *Atmos Environ* 37 (30):4195-4203.

Morgan, G., V. Sheppeard, B. Khalaj, A. Ayyar, D. Lincoln, B. Jalaludin, J. Beard, S. Corbett, and T. Lumley. 2010. "Effects of Bushfire Smoke on Daily Mortality and Hospital Admissions in Sydney, Australia." *Epidemiology* 21 (1):47-55. doi: 10.1097/EDE.0b013e3181c15d5a.

National Environmental Protection Council. 2003. National Environment Protection (Ambient Air Quality) Measure (Amendment). Canberra, EPHC.

Nazaroff, W. W. 2004. "Indoor particle dynamics." *Indoor Air* 14:175-183.

Reisen, F., C. P. Meyer, and M. D. Keywood. 2013. "Impact of biomass burning sources on seasonal aerosol air quality." *Atmos Environ* 67:437-447.

Reisen, F., C. P. Meyer, L. McCaw, J. C. Powell, K. Tolhurst, M. D. Keywood, and J. L. Gras. 2011. "Impact of smoke from biomass burning on air quality in rural communities in southern Australia." *Atmos Environ* 45 (24):3944-3953.

Sharma, R., and R. Balasubramanian. 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.

Thatcher, T. L., A. C. K. Lai, R. Moreno-Jackson, R. G. Sextro, and W. W. Nazaroff. 2002. "Effects of room furnishings and air speed on particle deposition rates indoors." *Atmos Environ* 36 (11):1811-1819.

Thatcher, T. L., and D. W. Layton. 1995. "Deposition, Resuspension, and Penetration of Particles within a Residence." *Atmos Environ* 29 (13):1487-1497.

Turetsky, M. R., E. S. Kane, J. W. Harden, R. D. Ottmar, K. L. Manies, E. Hoy, and E. S. Kasischke. 2011. "Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands." *Nature Geoscience* 4 (1):27-31.

Urban, R. C., M. Lima-Souza, L. Caetano-Silva, M. E. C. Queiroz, R. F. P. Nogueira, A. G. Allen, A. A. Cardoso, G. Held, and M. L. A. M. Campos. 2012. "Use of levoglucosan, potassium, and water-soluble organic carbon to characterize the origins of biomass-burning aerosols." *Atmos Environ* 61:562-569.

Victorian Government. 2015. Community smoke, air quality and health standard. Air quality assessment, forecasting and health protection messaging for particulate matter. Melbourne, Australia: Victorian Government.

Wallace, L., W. Kindzierski, J. Kearney, M. MacNeill, M. E. Heroux, and A. J. Wheeler. 2013. "Fine and Ultrafine Particle Decay Rates in Multiple Homes." *Environmental Science & Technology* 47 (22):12929-12937.

Ward, T. J., R. F. Hamilton, and G. C. Smith. 2004. "The Missoula, Montana PM2.5 speciation study - seasonal average concentrations." *Atmos Environ* 38 (37):6371-6379.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. "Warming and earlier spring increase western US forest wildfire activity." *Science* 313 (5789):940-943.

Wheeler, A. J., M. D. Gibson, M. MacNeill, T. J. Ward, L. A. Wallace, J. Kuchta, M. Seaboyer, E. Dabek-Zlotorzynska, J. R. Guernsey, and D. M. Stieb. 2014. "Impacts of Air Cleaners on Indoor Air Quality in Residences Impacted by Wood Smoke." *Environmental Science & Technology* 48 (20):12157-12163.

Wilson, W. E., D. T. Mage, and L. D. Grant. 2000. "Estimating separately personal exposure to ambient and nonambient particulate matter for epidemiology and risk assessment: Why and how." *Journal of the Air & Waste Management Association* 50 (7):1167-1183.

Zhou, J., A. L. Chen, Q. L. Cao, B. Yang, V. W. C. Chang, and W. W. Nazaroff. 2015. "Particle exposure during the 2013 haze in Singapore: Importance of the built environment." *Building and Environment* 93:14-23.

Tables

Table 1 Characteristics of the houses monitored when biomass burning (BB) events were captured

Characteristic	H10	H11	H12	H16	H7/H8	H21
Location relative to smoke event	10-20km (see Figure 1c)	10-20km (see Figure 1c)	Garden waste burn (few m)	Neighbour's burn (few m)	Local wood smoke	
Number of rooms	9	9	NA[1]	7	NA	10
Age of house	~98 years	8 years	28 years	~30 years	NA	~23 years
Building material	Timber	Colourbond	Timber or weatherboard	Timber or weatherboard	NA	Double brick
Number of windows	8	16	4 (sampling area)	8	NA	14
Number of doors to outside	4	4	2	3	NA	4
Heating system					NA	
Primary	Electric	Enclosed WH	Electric	Electric		Enclosed WH
Secondary	Enclosed WH[2]			Enclosed WH		Electric
Wood heater	yes	yes	NA	Yes	NA	yes
Type of stove	Electric	Electric	Gas	Electric	NA	Gas/electric
Air conditioner	Yes[3]	Yes[3]	Yes[3]	Yes[3]	NA	Yes[3]

[1] NA – data not available

[2] WH – Woodheater

[3] Air conditioner present but not used

Table 2 Summary table on outdoor and indoor $PM_{2.5}$ measurements during smoke plume events

	Duration (hours)[1]	Total $PM_{2.5}$ (µg m^{-3} h)		Hourly max $PM_{2.5}$ (µg m^{-3})		Reduction in hourly max indoor $PM_{2.5}$ (%)	F_{inf}[9]	Ventilation status
		Outdoor	Indoor	Outdoor	Indoor			
Residence 10	11	2083	1792	335.8	295.6	12.0	0.83	Window/door open
Residence 11	15	2337	1282	386.5	167.3	56.7	0.39	Windows open
Residence 12	2	69.2	53.1	56.1	34.5	38.5	0.61	Windows/door open
Residence 16	6	157.5	110.9	56.0	28.8	48.5	0.49	Closed
Residence 7	11	99.3	63.9	17.1	7.9	53.8	0.32	Not available
Residence 7	14	194.8	83.7	38.5	9.3	75.9	0.17	Not available
Residence 8	10.5	183.3	106.4	25.1	15.5	38.4	0.58	Not available
Residence 8	10.5	236.9	87.0	48.7	16.9	65.4	0.32	Not available
Residence 21	4.5	159.5	94.8	118.5	38.5	67.5	0.26	4-6 windows open (1 hr)
Residence 21	14.5	355.1	203.9	70.4	21.3	69.7	0.24	1 window open (7 hrs)
Residence 21	8	136.4	50.0	41.1	10.0	75.7	0.18	1 window open (5 hrs)
Residence 21	5	97.9	34.6	35.0	9.6	72.7	0.19	1 window open (1 hr)

[1] This represents the time that a residence was impacted by smoke due to a smoke plume event or a wood smoke event

Figure Captions

Figure 1 Hourly ambient $PM_{2.5}$ concentrations during smoke plume events

Figure 2 Frequency distribution of the 24-h indoor $PM_{2.5}$ concentrations (left) and hourly indoor $PM_{2.5}$ concentrations (right) measured at the 21 residences. Outdoor sources are shown in blue and indoor sources are shown in grey.

Figure 3 Hourly outdoor and indoor $PM_{2.5}$ concentrations and ventilation conditions during smoke plume events

Figure 4 Time series plots of 5-minute $PM_{2.5}$ concentrations measured indoors and outdoors at residence H10 (top) and residence H11 (bottom) during a smoke plume event in 2015

Figure 5 Measured and modelled $PM_{2.5}$ concentrations during smoke plume events