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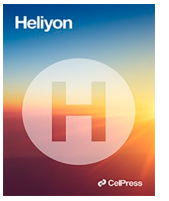

Research article

Mortality burden attributable to exceptional $PM_{2.5}$ air pollution events in Australian cities: A health impact assessment

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A R T I C L E I N F O

Keywords:
Particulate matter less than 2.5 μm ($PM_{2.5}$)
Daily mortality
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A B S T R A C T

Background: People living in Australian cities face increased mortality risks from exposure to extreme air pollution events due to bushfires and dust storms. However, the burden of mortality attributable to exceptional $PM_{2.5}$ levels has not been well characterised. We assessed the burden of mortality due to $PM_{2.5}$ pollution events in Australian capital cities between 2001 and 2020.

Methods: For this health impact assessment, we obtained data on daily counts of deaths for all non-accidental causes and ages from the Australian National Vital Statistics Register. Daily concentrations of $PM_{2.5}$ were estimated at a 5 km grid cell, using a Random Forest statistical model of data from air pollution monitoring sites combined with a range of satellite and land use-related data. We calculated the exceptional $PM_{2.5}$ levels for each extreme pollution exposure day using the deviation from a seasonal and trend loess decomposition model. The burden of mortality was examined using a relative risk concentration-response function suggested in the literature.

Findings: Over the 20-year study period, we estimated 1454 (95 % CI 987, 1920) deaths in the major Australian cities attributable to exceptional $PM_{2.5}$ exposure levels. The mortality burden due to $PM_{2.5}$ exposure on extreme pollution days was considerable. Variations were observed across Australia. Despite relatively low daily $PM_{2.5}$ levels compared to global averages, all Australian cities have extreme pollution exposure days, with $PM_{2.5}$ concentrations exceeding the World Health Organisation Air Quality Guideline standard for 24-h exposure. Our analysis results indicate that nearly one-third of deaths from extreme air pollution exposure can be prevented with a 5 % reduction in $PM_{2.5}$ levels on days with exceptional pollution.

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Interpretation: Exposure to exceptional $PM_{2.5}$ events was associated with an increased mortality burden in Australia's cities. Policies and coordinated action are needed to manage the health risks of extreme air pollution events due to bushfires and dust storms under climate change.

1. Introduction

Building sustainable cities and communities by achieving clean and safe air is one of our most pressing global challenges [1]. Air pollution levels have risen dramatically due to human activities in the past centuries, and the drive for clean air action and effective policy implementation has been far from ideal, in part reflecting the persistent reliance on fossil fuel combustion for energy and transport [2]. The minimal effort in most countries, including Australia, to act on recommendations to promote safe air strategies contrasts with the widely recognised urgency that air pollution presents one of our time's most challenging populational health risks [3]. In the 2019 Global Burden of Diseases Study, exposure to air pollution climbed the ranking of risk factors associated with global deaths compared to the leading risks in 1990 [4]. Exposure to ambient particulate matter features in the top ten leading risks of death for all age groups, except adolescents and young people, with vulnerable populations, including children, older adults, and individuals with pre-existing health conditions at heightened risk.

Exceptional air pollution events, such as bushfires and dust storms, represent additional acute and chronic health hazards [5,6], and Australia is at high risk of extreme air pollution due to flammable and friable landscapes and a history of extended droughts. Epidemiological studies have explored how exposure to air pollution affects population health, particularly concerning the fine particulate matter (PM) with a diameter of less than 10 and 2.5 μm (PM_{10} and $PM_{2.5}$) [7–9]. PM is produced by fossil fuel combustion for transport, industry, agriculture and construction, and by bushfires, volcanic eruptions and dust-related events such as storms and windblown dust [10]. Short-term exposure to $PM_{2.5}$ has been linked to various adverse health effects leading to increased all cause and

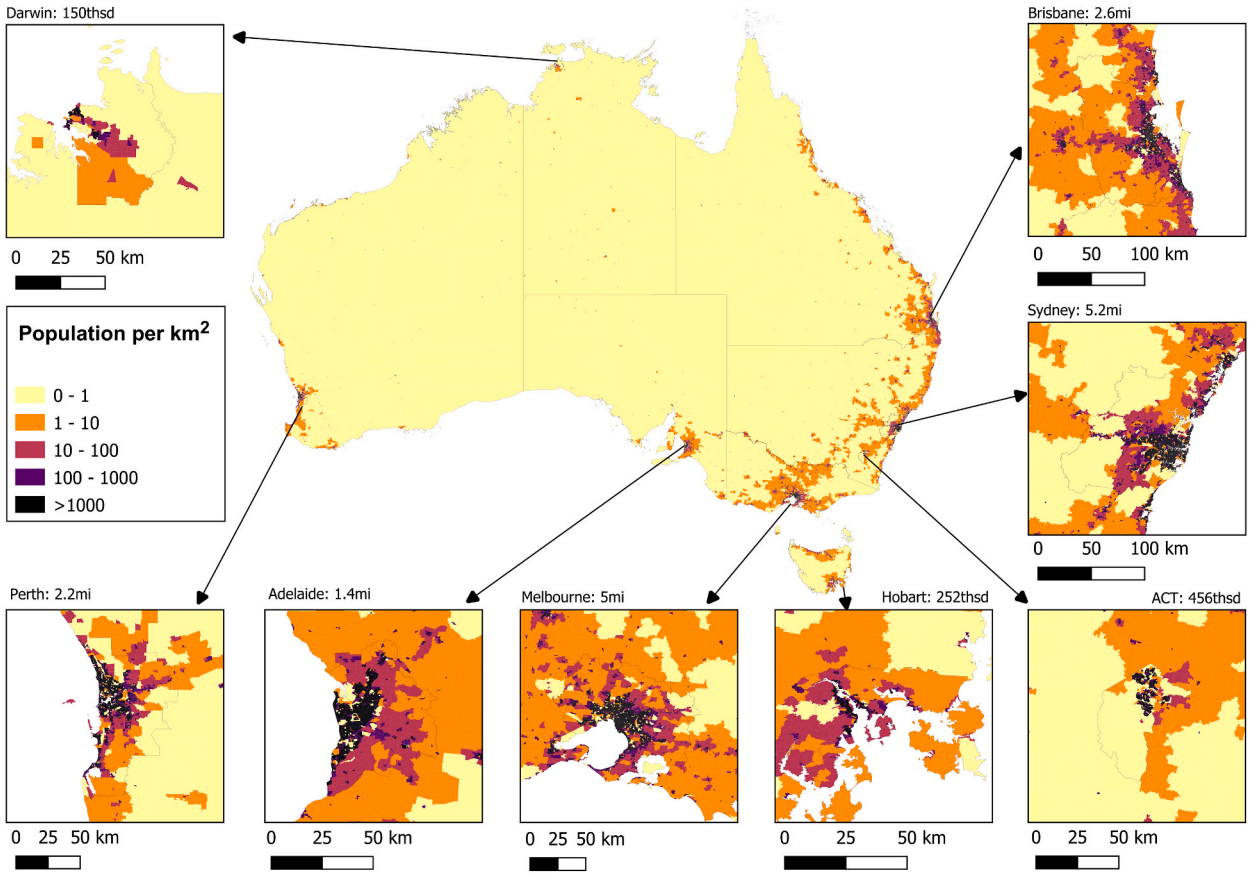


Fig. 1. Australian Bureau of Statistics Great Capital City areas included in the analysis with population density.
Fig. 1 Alt text: Map of Australia featuring zoomed-in maps of the eight Greater Capital City Areas: Darwin, Perth, Adelaide, Melbourne, Hobart, ACT, Sydney, and Brisbane. Each city map includes the city name and estimated population, ranging from Darwin with 150,000 to Sydney with 5.2 million. A colour-coded legend indicates population density per square kilometre, with shades ranging from light to dark representing 0 to over 1000 densities. Coastal areas generally show higher population densities. All maps include scale bars for size reference.

cause-specific mortality [11]. Studies have shown that exposure to $PM_{2.5}$ increases hospital admissions for all respiratory causes, chronic respiratory conditions, including asthma exacerbation, chronic obstructive pulmonary disease (COPD), lung infections, and cardiovascular disease outcomes, such as heart attacks and strokes [12,13]. Continued exposure can also exacerbate pre-existing conditions leading to severe outcomes like lung cancer and premature death [14,15].

Previous studies cover multiple areas and cities worldwide, focusing on long-term and short-term exposures to $PM_{2.5}$ [16–20]. In countries with intense bushfire seasons like Australia, understanding the impacts of exposure to exceptional levels of air pollution during extreme events is a public health priority. The country experiences fire regimes mostly during summer in the southern hemisphere despite low-moderate annual average $PM_{2.5}$ levels compared to other countries [21]. Australia's landscapes are also prone to dust-related events, particularly in windy, dry climates with higher temperatures [22].

Australia presents a unique case study due to its specific geographical conditions and climate. While the continent is extensive and ecologically diverse, its urban centres are primarily concentrated in coastal cities. It is also an influential country in the Western Pacific Region, and its policies might encourage other countries to promote change within their regulatory frameworks. The country has been recognising the pressures posed by climate change, and national regulatory frameworks are suggesting reductions in the desired levels of the 24-h standard for $PM_{2.5}$ from 25 $\mu g/m^3$ to 20 $\mu g/m^3$ in 2025 [23]. This new standard is important, yet less ambitious than the new WHO Air Quality Guidelines, which sets a target of 15 $\mu g/m^3$ for daily $PM_{2.5}$ and offers a significant policy commitment to act for climate change mitigation [24].

Despite recognising the importance of reducing short-term levels of $PM_{2.5}$ to achieve safer air across the country, little is known about the implications of current extreme event exposure levels on human health outcomes, such as attributable deaths in population centres. The health impacts of short-term exposures have been assessed in particular cities and for specific bushfire seasons [25–27], but no nationwide assessments have been published to date.

The mortality burden of exceptional air pollution events across Australia has been quantified in this study, focusing on concentrations above the expected levels due to recurring patterns of particulate air pollution influenced by seasonality. Sensitivities to an alternative scenario, achievable through air pollution reduction and mitigation measures, were also explored. The findings of this study are intended to provide valuable evidence to inform policy decisions aimed at mitigating climate change and adapting to future shifts in extreme weather conditions and exceptional air pollution events.

2. Methods

2.1. Study region

Our health impact assessment studied eight Australian Greater Capital City Statistical Areas (GCCSAs), namely Sydney, Melbourne, Brisbane, Adelaide, Perth, Hobart, Darwin, and Australian Capital Territory, representing the most populous and densely populated areas in the country with approximately 15.5 million residents in 2016 (Fig. 1).

2.2. Mortality data

Data on daily counts of deaths for all non-accidental causes and ages were obtained from eight GCCSAs from 2001 to 2019 from the Australian Institute of Health and Welfare (AIHW) National Mortality Database and used to estimate non-COVID deaths in 2020 [28]. Daily mortality data were averaged by day every three years in non-overlapping tranches to estimate a day-of-the-year average mortality number time series. The average was then applied to each of the three years in the tranch, enabling a simulated daily death count that smooths out annual stochastic variation in daily deaths. Daily mortality rates can fluctuate due to various factors, including rare events or short-term local phenomena [18]. To address these variations, we averaged daily deaths over three years to produce a smoothed representation of seasonal mortality trends. This methodology efficiently broke down the data into distinct three-year periods, starting from 2001 to 2003 and following in successive triennial batches. We computed the average mortality for every day of the year and GCCSAs within each period. If available, deaths from 2020 would have potentially biased our results due to COVID-related events, thus the previous three-year average period was inserted for this year to enable estimation of the scenario in 2020 based on previous trends.

2.3. Air pollution exposure

Exposure data were provided from the Centre for Safe Air data platform CARDAT's BushfireSmoke modelling project (version 1.3) [29]. Daily concentrations of $PM_{2.5}$ were estimated at the 5 km grid cell level for the Australian Continent from 2001 to 2020 using $PM_{2.5}$ data from air pollution monitoring sites, combined with satellite, weather and land use data using a Random Forest statistical model (using the randomForest R library) [30]. The Random Forest was chosen because it offers robust integration of diverse data types, including ground monitoring data, satellite observations, and meteorological inputs. It has been previously used in a spatio-temporal machine learning method to reconstruct levels of pollution across Great Britain with significant advantages from previous models by integrating multiple data sources [31]. This integration is crucial for capturing the complex nature of air pollution distribution. The predictive performance of the Random Forest model was $R^2 = 0.67$ with a root mean squared error (RMSE) of 4.7 $\mu g/m^3$, and this result is consistent with performance metrics reported in the literature [31].

The Seasonal Trend Decomposition using the LOESS (STL) method was employed to estimate the season and trend components of the $PM_{2.5}$ time series [32]. This algorithm distils the time series into its three core elements: trend (tendency of the data over time),

seasonal (recurring patterns of pollution), and remainder (part of the data that the seasonal and trend components cannot explain). The day-to-day fluctuations are due to exceptional events and would not be expected if all else were equal. When the remainder is positive, this indicates that the level of $PM_{2.5}$ is higher than expected by the seasonal and trend decomposition model.

We defined the amount of $PM_{2.5}$ concentration for a counterfactual scenario as the sum of the seasonal and trend components, which are usually expected based on normal conditions (i.e., without exceptional events such as bushfires or dust storms). Then, we compared the daily estimated air pollution with a counterfactual scenario. Subsequently, we define daily exceptional $PM_{2.5}$ during air pollution event days as the positive residuals (i.e. the difference or Δ) between the $PM_{2.5}$ model-based estimate of the predicted value on that day and the counterfactual concentration (for details and definitions of exceptional days see Fig. S3). Indicative values of the Australian National Environment Protection (Ambient Air Quality) Measure (NEPM) were used to contextualise the concentration estimated in our model with the current 24-h standard for $PM_{2.5}$ (25 μg/m^3) and future desirable levels to be implemented as the national goal in 2025 (20 μg/m^3). For global comparison, indicative target values from the WHO Air Quality Guideline for 24 h (15 μg/m^3) were also included.

2.4. Population data

We retrieved population data from the Australian Bureau of Statistics (ABS) at the Statistical Area Level 1 (SA1s) geographic boundary system from the 2016 Census [33]. Then, we aggregated these smaller statistical areas and summed the total population of the eight GCCSAs used in the analysis, which are geographical areas built from the Statistical Areas Level 4 (SA4s).

2.5. Statistical analyses of attributable death from exceptional $PM_{2.5}$ exposure

Our analysis was conducted in three steps. First, descriptive statistics were calculated, including summary statistics on estimated daily $PM_{2.5}$ concentrations (μg/m^3) and a summary of the number of days per air quality level in the selected study areas (number of days exceeding 25 μg/m^3 and 20 μg/m^3, corresponding to NEPM current and new standard respectively, and WHO AQG standard of 15 μg/m^3 day average). Second, we adopted the a concentration-response function relating daily mean $PM_{2.5}$ exposure with all-cause mortality in all age groups from a recently published systematic review and meta-analysis [18]. Due to the limited number of studies in Australian cities of short-term $PM_{2.5}$ air pollution exposure and mortality, we used the relative risk (RR) function of 1.0065 (95 % CI 1.0044, 1.0086) per 10-μg/m^3 increment. Finally, we used this RR to estimate the attributable fraction (AF) of deaths associated with short-term $PM_{2.5}$ exposure for each GCCSA, using an equation suggested in the literature [34,35] for estimation of the burden of disease due to risk factors:

$$AF = \frac{RR - 1}{RR} \times N$$

where: AF represents the attributable fraction in the population; RR the relative risk, calculated for exceptional event days as the exponential of the product of beta and the daily delta (and set this to RR = 1 on non-exceptional days): $RR = \exp(\beta \times \Delta_{daily})$ where $\beta = \log\left(RR_{per\ 10\ \frac{\mu g}{m^3}\ increment}\right) \Big/ 10$; N is the smoothed number of all-cause deaths for all ages in each GCCSA on that day.

The results were then summed, across all days per year and GCCSA, to give the total annual premature mortality in attributable numbers (AN) from exceptional $PM_{2.5}$ events. To increase comparison between study areas and other studies and cities, we also estimated attributable death rates per 100,000 individuals per GCCSA and year (Table 4). The analysis used R (version 4.2.2[36] and the package 'targets' was used to organise the workflow and control for objects' dependencies (Fig. S1).

2.6. Sensitivities to change in $PM_{2.5}$ levels

We explored sensitivities by changing the exposure to simulate a hypothetical scenario. In this scenario, the top 5 % of the highest

Table 1
Estimated daily $PM_{2.5}$ in eight Greater Capital City areas from 2001 to 2020.

City	Min	25th percentile	Median	Mean	75th percentile	95th percentile	Max	Days >25 μg/m^3*	Days >20 μg/m^3**	Days >15 μg/m^3***
Sydney	0.49	5.47	6.91	7.77	9.10	12.71	166.14	58	88	181
Melbourne	3.11	4.97	5.96	6.88	7.73	11.78	127.25	34	54	134
Brisbane	1.97	4.88	5.93	6.54	7.42	10.45	111.05	23	38	88
Adelaide	3.37	5.63	6.35	6.67	7.34	9.54	35.54	5	9	31
Perth	0.45	6.31	7.30	7.77	8.74	11.64	43.50	7	26	84
Hobart	0.75	2.29	3.15	4.17	4.99	10.27	52.25	11	14	22
Darwin	2.00	4.30	8.02	9.66	14.02	20.68	43.48	75	490	1578
Canberra	0.71	4.56	6.04	7.66	8.17	13.18	574.96	84	97	199

*Number of days exceeding the NEPM day average standard for $PM_{2.5}$ concentration level.

**Number of days exceeding the new NEPM day average standard to be implemented on January 1st, 2025, for $PM_{2.5}$ concentration level.
***Number of days exceeding the WHO AQG day average target for $PM_{2.5}$ concentration level.

Table 2
Number of daily deaths in study cities from 2001 to 2020 and population in 2016.

City	Population (2016)	Deaths	Min	25th percentile	Median	Mean	75th percentile	95th percentile	Max
Sydney	4,823,897	618,067	1	76.33	84.00	84.67	92.67	104.67	136
Melbourne	4,485,226	557,186	0	69.67	76.00	76.33	82.33	93.67	119
Brisbane	2,270,956	278,566	0	33.67	38.00	38.16	42.00	50.00	71
Adelaide	1,295,674	216,568	0	26.67	29.40	29.67	32.67	37.67	57
Perth	1,943,630	230,698	0	27.67	31.33	31.60	35.00	41.33	61
Hobart	222,362	41,271	0	4.33	5.66	5.65	6.67	9.00	16
Darwin	136,878	11,261	0	1.00	1.33	1.54	2.00	3.28	10
Canberra	396,883	39,012	0	4.00	5.00	5.34	6.33	8.67	15

predicted $PM_{2.5}$ air pollution days were set to their counterfactual concentration levels (the background expected concentration if exceptional events did not occur – e.g. if the expected concentration in a specific day was 10 $\mu g/m^3$, and the actual concentration was above the 95th percentile – 200 $\mu g/m^3$, for example – we estimated the attributable deaths using the 10 $\mu g/m^3$ and not the actual 200 $\mu g/m^3$) (Fig. 3, and Tables S3 and S4). We aimed to explore the potential public health benefits in the eventual reduction in attributable deaths to induce a scenario where policy mitigated the impacts of extreme pollution days or avoided them through coordinated action (e.g. evacuation orders informed by air quality forecasting systems, health protection interventions such as indoor air filters, exposure reduction policies). This enables us to estimate the number of preventable deaths under this hypothetical scenario, shedding light on the potential health benefits of substantial reductions in exceptional air pollution events. In addition to this hypothetical scenario, we also estimated the number of all deaths attributable to exposure to all concentrations of $PM_{2.5}$. This estimation involved a second hypothetical scenario. We estimated deaths attributable to all $PM_{2.5}$ concentrations, and the delta (variation) was set as the difference between predicted $PM_{2.5}$ and minimum concentration observed in the time series (as a minimum of zero would be unrealistic). For a detailed explanation, see Supplementary Material (Fig. S3 and the following details).

3. Results

3.1. Exposure assessment

The minimum daily average $PM_{2.5}$ estimated concentration varied from 0.45 to 3.37 $\mu g/m^3$ (Perth and Adelaide), and maximum concentrations from 35.54 to 574.96 $\mu g/m^3$ (Adelaide and Canberra). Table 1 shows estimated daily average minimum, median, mean, and maximum concentrations and includes 25th, 75th and 95th percentiles for all GCCSAs in the study.

Minimum, median, and mean daily average concentrations varied little between study areas. In Darwin, estimates showed elevated concentrations at the 75th and 95th percentiles, indicating a considerable number of days with higher $PM_{2.5}$ concentrations than other cities. Most cities recorded their daily averages (from the 25th to the 75th percentile) within a relatively narrow band, suggesting consistent $PM_{2.5}$ levels in the studied period. The highest peak was in Canberra, with a maximum of 574.96 $\mu g/m^3$ estimated on Jan 1, 2020 (Fig. 2).

3.2. Mortality burden due to exceptional events

Table 2 shows descriptive statistics of deaths in the study period and areas (also see Fig. S2). As expected, higher estimates of deaths were observed in more populous GCCSAs like Sydney and Melbourne, and mean deaths across the study areas ranged from 1.54 to 84.67 (Darwin and Sydney). In the GCCSAs Adelaide, Brisbane, and Melbourne, there is a pattern of a higher number of daily average deaths coinciding with the southern hemisphere winter season, and this pattern is even more prominent in Sydney closer to the 200th day of the year.

Table 3 presents the average mortality burden in each Australian GCCSA per day and the sum of all combined GCCSAs and years. When considering combined study areas, we estimate that the yearly mortality burden attributable to exceptional daily $PM_{2.5}$ ranged from 47 to 142 deaths (2008 and 2019, respectively), totalling 1454 deaths (95 % CI 987, 1920). Taken separately, Sydney presents the highest number for a single year (72 in 2019), and estimates for 2002, 2003, 2005, 2010, 2013 and 2016 in Darwin are the lowest, with no attributable mortality due to exceptional daily average $PM_{2.5}$ exposure. Tables S5 and S6 present detailed information on the total number of deaths attributable to exposure to $PM_{2.5}$, including non-exceptional days, totalling 6953 deaths (95 % CI 4716, 9182).

In a scaled version with estimated rates per 100,000 individuals per study area, we estimate that the high mortality burden in Sydney in 2019 compared to other years reflects a high scaled rate (1.49, 95 % CI 1.01, 1.97) (Table 4). However, considering the population dimension, 2020 in Canberra stands out with 3.39 attributable deaths (95 % CI 2.36, 4.38) per 100,000 inhabitants.

3.3. Sensitivity analysis

When setting the 5th percentile of days with the highest air pollution concentrations to their counterfactual levels, with a threshold calculated at a specific level for each city, the mortality burden is reduced consistently across the years, as shown in Table S3 and Fig. 3 (for Relative Risk, see Table S2). In this hypothetical scenario, the mortality burden ranged from 42 to 60 deaths (2008 and 2013, respectively), considering the combined study areas, which could have resulted in 1028 deaths (95 % CI 697, 1358). For a scaled rate

Table 3
Premature mortality numbers associated with exceptional daily $PM_{2.5}$ exposure by GCCSA and year.

	City, n (95 % CI)								
Year	Sydney	Melbourne	Brisbane	Adelaide	Perth	Hobart	Darwin	Canberra	All GCCSAs
2001	32 (22, 42)	17 (12, 23)	5 (3, 7)	3 (2, 4)	5 (4, 7)	2 (1, 2)	0 (0, 1)	1 (1, 2)	66 (45, 87)
2002	48 (33, 64)	13 (9, 17)	8 (5, 11)	3 (2, 4)	6 (4, 7)	1 (1, 1)	0 (0, 0)	1 (1, 2)	81 (55, 106)
2003	27 (18, 35)	49 (34, 65)	5 (3, 7)	5 (3, 6)	5 (3, 6)	1 (1, 2)	0 (0, 0)	5 (3, 7)	97 (66, 128)
2004	22 (15, 29)	11 (7, 14)	7 (5, 9)	4 (3, 5)	6 (4, 7)	1 (1, 2)	1 (0, 1)	1 (1, 2)	52 (35, 69)
2005	21 (14, 28)	15 (10, 20)	5 (3, 7)	4 (3, 5)	5 (4, 7)	1 (1, 1)	0 (0, 0)	1 (1, 1)	53 (36, 70)
2006	20 (13, 26)	30 (21, 40)	5 (4, 7)	6 (4, 8)	6 (4, 8)	2 (1, 2)	0 (0, 1)	2 (1, 2)	71 (48, 94)
2007	18 (12, 24)	19 (13, 25)	5 (4, 7)	4 (3, 5)	4 (3, 6)	1 (1, 2)	0 (0, 1)	1 (1, 2)	53 (36, 70)
2008	15 (10, 19)	16 (11, 21)	5 (3, 6)	3 (2, 4)	5 (3, 7)	2 (1, 2)	1 (0, 1)	1 (1, 1)	47 (32, 62)
2009	31 (21, 41)	27 (18, 35)	20 (13, 26)	5 (3, 7)	7 (5, 9)	1 (1, 1)	1 (1, 1)	1 (1, 2)	92 (63, 122)
2010	15 (10, 20)	16 (11, 21)	5 (3, 6)	3 (2, 5)	8 (5, 10)	2 (1, 2)	0 (0, 0)	1 (1, 2)	50 (34, 67)
2011	21 (14, 27)	16 (11, 21)	9 (6, 12)	5 (3, 7)	5 (3, 7)	1 (1, 2)	1 (0, 1)	1 (1, 2)	59 (40, 78)
2012	18 (12, 24)	14 (9, 18)	8 (5, 11)	4 (3, 6)	8 (6, 11)	1 (1, 2)	1 (1, 1)	1 (1, 1)	55 (38, 73)
2013	30 (21, 40)	19 (13, 26)	8 (5, 10)	4 (3, 6)	6 (4, 8)	1 (1, 2)	0 (0, 0)	1 (1, 2)	71 (48, 94)
2014	19 (13, 25)	23 (15, 30)	8 (6, 11)	5 (3, 6)	6 (4, 8)	2 (1, 3)	1 (0, 1)	1 (1, 2)	65 (44, 86)
2015	21 (14, 28)	19 (13, 25)	6 (4, 8)	4 (3, 6)	12 (8, 15)	1 (1, 2)	1 (0, 1)	2 (1, 2)	65 (44, 86)
2016	25 (17, 32)	17 (12, 23)	8 (6, 11)	4 (3, 5)	7 (5, 9)	1 (1, 2)	0 (0, 0)	2 (1, 2)	64 (44, 85)
2017	23 (15, 30)	25 (17, 33)	9 (6, 12)	6 (4, 7)	10 (7, 13)	2 (1, 2)	0 (0, 1)	2 (1, 2)	76 (51, 100)
2018	26 (17, 34)	22 (15, 30)	11 (8, 15)	4 (3, 6)	8 (5, 10)	1 (1, 2)	1 (0, 1)	2 (1, 2)	75 (51, 99)
2019	72 (49, 95)	25 (17, 33)	26 (18, 35)	4 (3, 6)	9 (6, 12)	3 (2, 3)	1 (0, 1)	3 (2, 5)	142 (97, 188)
2020	39 (26, 51)	45 (31, 59)	7 (5, 10)	6 (4, 8)	6 (4, 8)	2 (1, 3)	0 (0, 0)	13 (9, 17)	118 (81, 156)
All years	541 (367, 715)	438 (297, 578)	171 (116, 226)	88 (60, 116)	132 (90, 175)	29 (20, 39)	9 (6, 12)	45 (31, 59)	1454 (987, 1920)

Table 4
Premature mortality attributable rates per 100,000 individuals associated with exceptional $PM_{2.5}$ by GCCSA and year.

	City, Mortality rate (95 % CI)							
Year	Sydney	Melbourne	Brisbane	Adelaide	Perth	Hobart	Darwin	Canberra
2001	0.66 (0.45, 0.87)	0.39 (0.26, 0.51)	0.22 (0.15, 0.29)	0.25 (0.17, 0.33)	0.27 (0.19, 0.36)	0.68 (0.46, 0.89)	0.29 (0.2, 0.39)	0.29 (0.19, 0.38)
2002	1 (0.68, 1.32)	0.29 (0.2, 0.39)	0.35 (0.24, 0.47)	0.23 (0.16, 0.31)	0.29 (0.19, 0.38)	0.34 (0.23, 0.45)	0.25 (0.17, 0.33)	0.38 (0.25, 0.5)
2003	0.55 (0.37, 0.73)	1.1 (0.75, 1.45)	0.22 (0.15, 0.29)	0.36 (0.24, 0.48)	0.25 (0.17, 0.33)	0.63 (0.43, 0.84)	0.14 (0.1, 0.19)	1.27 (0.87, 1.67)
2004	0.45 (0.31, 0.6)	0.23 (0.16, 0.31)	0.31 (0.21, 0.41)	0.32 (0.22, 0.42)	0.29 (0.2, 0.39)	0.53 (0.36, 0.7)	0.42 (0.28, 0.55)	0.34 (0.23, 0.44)
2005	0.44 (0.3, 0.58)	0.34 (0.23, 0.45)	0.22 (0.15, 0.29)	0.31 (0.21, 0.4)	0.27 (0.18, 0.36)	0.49 (0.33, 0.65)	0.19 (0.13, 0.25)	0.28 (0.19, 0.37)
2006	0.41 (0.28, 0.54)	0.68 (0.46, 0.9)	0.23 (0.16, 0.31)	0.47 (0.32, 0.62)	0.3 (0.2, 0.39)	0.76 (0.51, 1)	0.35 (0.24, 0.47)	0.44 (0.3, 0.58)
2007	0.37 (0.25, 0.49)	0.41 (0.28, 0.55)	0.24 (0.16, 0.31)	0.31 (0.21, 0.41)	0.22 (0.15, 0.29)	0.6 (0.4, 0.79)	0.34 (0.23, 0.44)	0.33 (0.23, 0.44)
2008	0.3 (0.2, 0.4)	0.36 (0.24, 0.47)	0.2 (0.14, 0.27)	0.25 (0.17, 0.34)	0.26 (0.18, 0.35)	0.71 (0.48, 0.94)	0.38 (0.26, 0.5)	0.26 (0.17, 0.34)
2009	0.64 (0.44, 0.85)	0.59 (0.4, 0.79)	0.86 (0.58, 1.13)	0.39 (0.26, 0.51)	0.35 (0.24, 0.46)	0.48 (0.33, 0.64)	0.58 (0.39, 0.76)	0.34 (0.23, 0.45)
2010	0.32 (0.22, 0.42)	0.35 (0.24, 0.46)	0.22 (0.15, 0.29)	0.27 (0.18, 0.35)	0.4 (0.27, 0.53)	0.79 (0.54, 1.05)	0.14 (0.09, 0.18)	0.31 (0.21, 0.4)
2011	0.43 (0.29, 0.57)	0.35 (0.24, 0.47)	0.41 (0.28, 0.54)	0.39 (0.26, 0.51)	0.26 (0.17, 0.34)	0.51 (0.35, 0.68)	0.41 (0.28, 0.54)	0.33 (0.22, 0.44)
2012	0.37 (0.25, 0.49)	0.31 (0.21, 0.41)	0.35 (0.24, 0.46)	0.33 (0.23, 0.44)	0.42 (0.28, 0.55)	0.52 (0.35, 0.68)	0.57 (0.39, 0.76)	0.27 (0.18, 0.36)
2013	0.63 (0.43, 0.83)	0.43 (0.29, 0.57)	0.35 (0.23, 0.46)	0.34 (0.23, 0.45)	0.29 (0.2, 0.39)	0.67 (0.45, 0.88)	0.17 (0.11, 0.22)	0.35 (0.24, 0.46)
2014	0.4 (0.27, 0.53)	0.51 (0.34, 0.67)	0.37 (0.25, 0.49)	0.38 (0.25, 0.5)	0.32 (0.22, 0.42)	0.86 (0.58, 1.13)	0.47 (0.32, 0.62)	0.34 (0.23, 0.45)
2015	0.43 (0.29, 0.57)	0.41 (0.28, 0.55)	0.26 (0.18, 0.35)	0.34 (0.23, 0.45)	0.6 (0.41, 0.8)	0.65 (0.44, 0.87)	0.38 (0.26, 0.51)	0.39 (0.26, 0.51)
2016	0.51 (0.35, 0.67)	0.38 (0.26, 0.5)	0.36 (0.24, 0.48)	0.32 (0.22, 0.42)	0.35 (0.24, 0.46)	0.6 (0.4, 0.79)	0.25 (0.17, 0.32)	0.42 (0.28, 0.55)
2017	0.47 (0.32, 0.62)	0.55 (0.38, 0.73)	0.4 (0.27, 0.53)	0.43 (0.29, 0.56)	0.51 (0.35, 0.68)	0.69 (0.47, 0.91)	0.3 (0.2, 0.4)	0.41 (0.28, 0.54)
2018	0.53 (0.36, 0.7)	0.5 (0.34, 0.66)	0.49 (0.33, 0.65)	0.35 (0.23, 0.46)	0.4 (0.27, 0.53)	0.62 (0.42, 0.81)	0.44 (0.3, 0.59)	0.43 (0.29, 0.57)
2019	1.49 (1.01, 1.97)	0.55 (0.37, 0.73)	1.15 (0.78, 1.52)	0.33 (0.22, 0.43)	0.45 (0.3, 0.59)	1.18 (0.8, 1.56)	0.44 (0.3, 0.58)	0.87 (0.59, 1.15)
2020	0.81 (0.55, 1.06)	1 (0.68, 1.32)	0.32 (0.22, 0.42)	0.45 (0.3, 0.59)	0.3 (0.2, 0.39)	0.9 (0.61, 1.18)	0.21 (0.14, 0.27)	3.39 (2.36, 4.38)

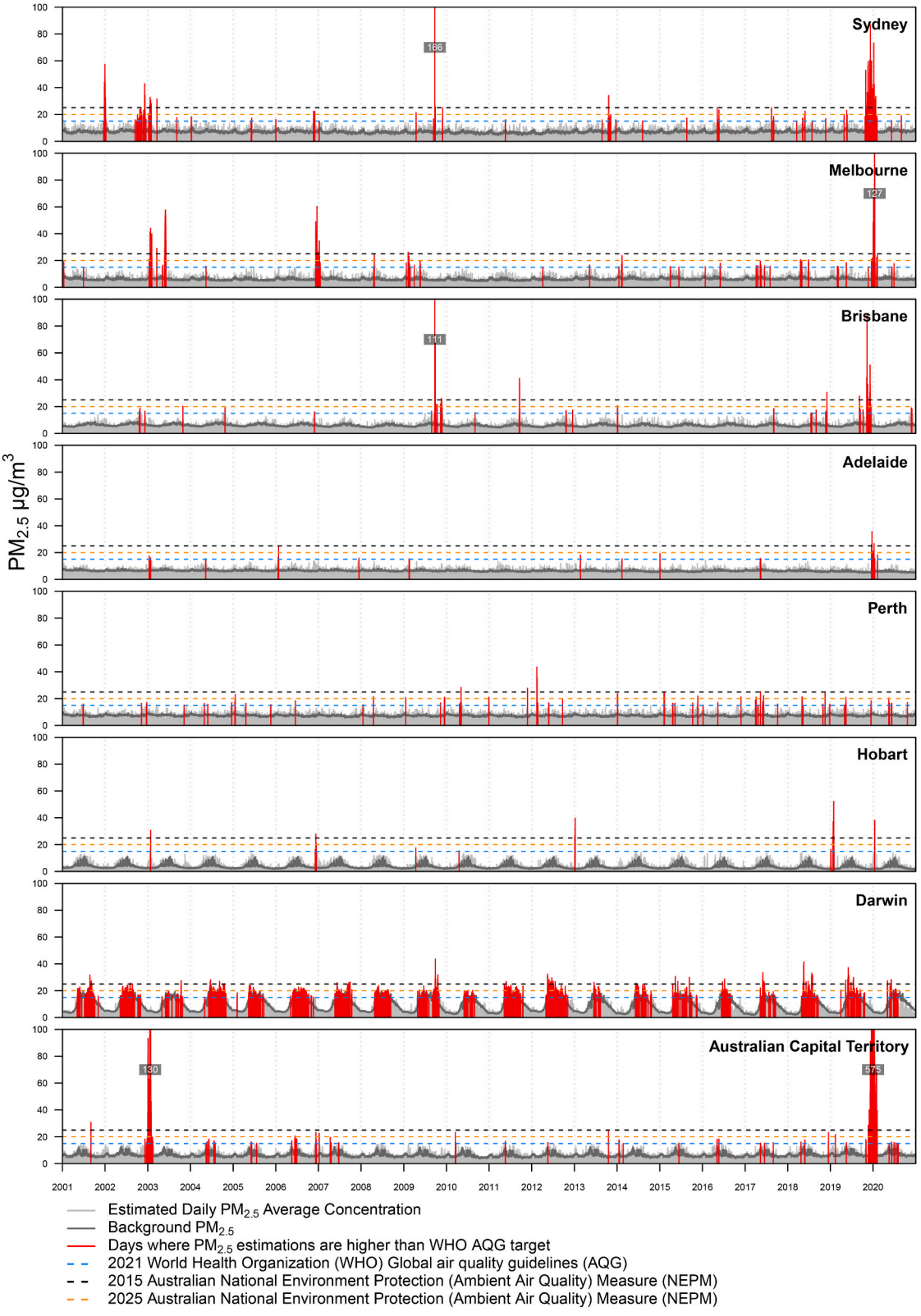
per 100,000 inhabitants, see Table S4.

4. Discussion

Our study revealed that 1454 (95 % CI 987, 1920) premature deaths from 2001 to 2020 in the most populous Australian urban areas were attributable to exposure to exceptional air pollution events, representing 20 % of all deaths attributable to $PM_{2.5}$ exposure. Our primary objective was to quantify the mortality burden attributable to exceptional events, with $PM_{2.5}$ as the indicator pollutant. The health impact varied across the studied regions. The attributable mortalities were assessed across the study areas during a relatively long study period of 20 years. Comparison of results across different cities was possible because all city-specific impacts were analysed using the same strategy and methods, with a standardised STL decomposition method and AF estimation.

While a growing body of evidence from various cities and countries demonstrates the health burden of long-term $PM_{2.5}$ exposure [12,15,36], few studies enumerate the additional deaths attributable to exceptional events of $PM_{2.5}$ [8,37]. In Australia, for example, various studies have estimated the mortality burden of chronic $PM_{2.5}$ exposures in specific cities and regional areas [19,38], and others have explored the health impacts of $PM_{2.5}$ at particular times of the year [25,26,39]. They have estimated a total number of 1386 deaths in the entire country during bushfire season from 2000 to 2020 [25].

Despite the relatively low average daily $PM_{2.5}$ levels observed in Australia, compared to other cities in the world [40,41], levels of fine particulate matter during exceptional events are increasing in Australian cities [42]. The Australian Government State of the Environment, a comprehensive assessment of health in various environmental aspects, reported that in 2019, no cities met the National Environment Protection Measures (NEPM) standard for $PM_{2.5}$. The current 24-h NEPM standard for $PM_{2.5}$ is 25 $\mu g/m^3$ (to be reduced to 20 $\mu g/m^3$ in 2025), and for a city to achieve the proposed standards, levels every day of the year should be below this threshold [42]. Despite the importance of regulatory frameworks, they are insufficient in this context, as cities can present days above the threshold and remain technically compliant if exceedances on air quality monitoring stations are classified as exceptional events where elevated



(caption on next page)

Fig. 2. Estimated $PM_{2.5}$ in study cities in 2001–2020.
Fig. 2 Alt text: Composite line graph featuring eight plots, each corresponding to one of Australia's Greater Capital City Areas, arranged from Sydney at the top to ACT at the bottom. Each plot shows estimated $PM_{2.5}$ air pollution levels from 2001 to 2020. The Y-axis measures $PM_{2.5}$ concentration in $\mu g/m^3$, and the X-axis represents years. The legend includes lines in a light colour for $PM_{2.5}$ levels, blue for background $PM_{2.5}$, red for days exceeding the 2023 National Environment Protection (Ambient Air Quality) Measure (NEPM), a dotted black line for the NEPM 2023 standard, and a dotted green line for the NEPM 2025 standard. Peaks in $PM_{2.5}$ levels are generally observed during summer months, except in Darwin, where peaks are spread throughout the year. Values of the highest peaks exceeding 100 $\mu g/m^3$ (Sydney, Melbourne, Brisbane and ACT) are displayed on grey boxes inside the plot.

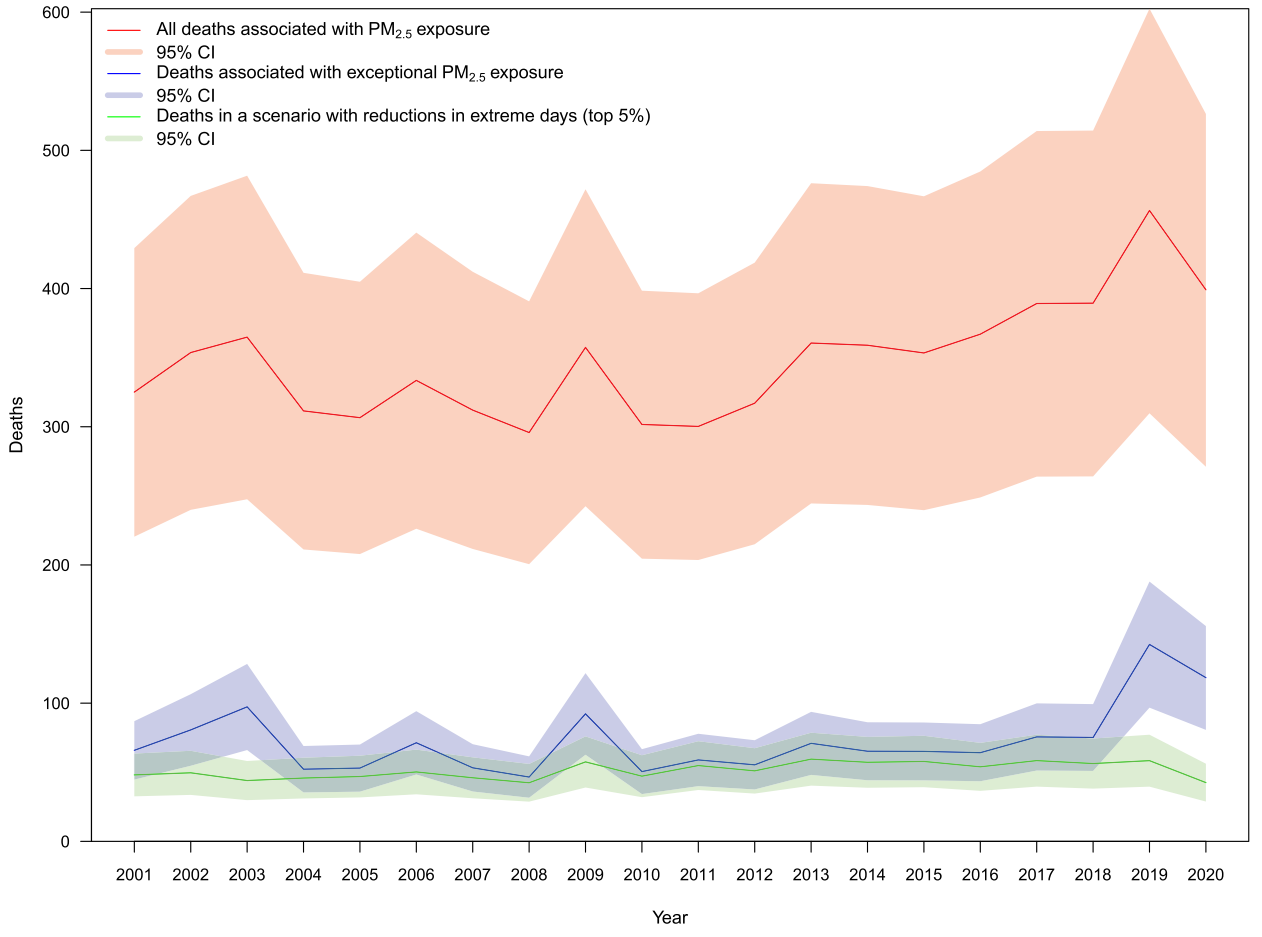


Fig. 3. Premature deaths associated with $PM_{2.5}$ exposure for all GCCSA areas used in this study, including sensitivity analysis.
Fig. 3 Alt text: Line graph plotting the estimated number of premature deaths associated with $PM_{2.5}$ exposure from 2001 to 2020. The Y-axis ranges from 0 to over 600 deaths, while the X-axis represents years. A red line indicates the estimated number of premature deaths associated with $PM_{2.5}$ exposure, with a lighter red shaded area representing the 95 % confidence interval. A blue line represents the deaths associated with exceptional $PM_{2.5}$ exposure, with a lighter blue shaded area representing the 95 % confidence interval. A green line represents the Sensitivity Analysis at the 95th percentile, with a lighter green shaded area for its 95 % confidence interval.

levels relate directly to bushfires, authorised hazard reduction burning or continental windblown dust [43].

In our study, we observed that Adelaide, Perth, and Hobart were close to achieving the current NEPM measures with only five, seven and eleven days exceeding the threshold, respectively. In comparison, Sydney and Canberra surpassed the proposed concentration measure by 58 and 84 days, respectively, reflecting air pollution peaks from bushfires and dust events [44,45]. Using retrospective data, we also estimated how many days would have exceeded the new NEPM standard, which will guide government agencies in their policies and coordinated actions from 2025. Urgent targeted intervention is needed nationwide, particularly in cities like Darwin, where air pollution is likely to breach NEPM standards frequently. According to a national report, during 2017, all days above the $PM_{2.5}$ threshold in Darwin that were also classified as exceptional events were related to hazard reduction burns or natural fire activities [43]. In the Northern Territory capital, air quality management action was recently implemented with the installation of an air quality station to monitor industrial and shipping-related pollution. A comprehensive health impact assessment will provide crucial

insights into local public health needs, demonstrating opportunities for further research.

Given the inherent complexities in managing air quality in a vast country with diverse ecosystems and distinctive regional characteristics, a national NEPM standard will likely present acute challenges to States and Territory Environment Protection Authorities, especially with the onset of climate change-induced extreme weather events, bushfires and dust storms. The Australian continent presents different air pollution levels in its regions, territories, and states, which are highly influenced by fire regimes, seasonality, economic activities, energy generation, and urbanisation. As the human capacity to manage bushfires is imperfect and likely to become more complex as climate change alters fire regimes [46], local authorities may not have the necessary resources to achieve the profound societal changes needed to improve air quality. However, they have a crucial role in regulating wood heaters, reducing emissions from road transport, and enhancing the control of industrial sources of air pollution.

Actions to mitigate the extreme air pollution events brought about by bushfires and dust storms include broad-reaching land use changes and natural resource management plans. For example, it is possible that many forests could be protected from fires if dead wood and leaves could be removed at sufficient scales to reduce the fuel load. It is also possible for public health actions to reduce the burden of mortality by using public health warnings and training populations about smoke avoidance behaviours. Crucial regulations should be accompanied by robust fund allocation and a series of options on which local authorities can rely.

Despite regional differences, this study provides novel information for public health planning at national and regional levels. We modelled a scenario in which the populations were not exposed to the smokiest 5 % of exceptional $PM_{2.5}$ days, which are likely related to extreme pollution from severe bushfires and dust storms. Almost one-third of attributable deaths could have been avoided with reductions in the most extreme days, as shown in our analysis exploring sensitivities to changes in the $PM_{2.5}$ levels.

This study is subject to several limitations. First, we only estimated the mortality burden associated with short-term exposure to $PM_{2.5}$, which does not capture the full impacts of $PM_{2.5}$ pollution on public health and health services. One important impact could be assessed via a costing study comparing investments that can be made to prevent air pollution and the cost of losses experienced, improving policy outreach and engagement. Second, due to a lack of an Australian-derived RR exposure-response function, we applied the RR from an up-to-date systematic review and meta-analysis [18]. Third, the application of an exposure-response function derived from international studies introduces potential inaccuracies in our findings due to differences in environmental, demographic, and health characteristics between the study populations and the Australian context. The function used may not fully capture the specificities of Australian cities, possibly leading to overestimations or underestimations in the mortality burden. This limitation highlights the need for localised studies to develop region-specific exposure-response functions that accurately reflect the health impacts of $PM_{2.5}$ in Australian populations. Finally, the database version used in this analysis does not incorporate the flags on specific bushfire days, and $PM_{2.5}$ levels may be linked to other air pollution sources. The ongoing improvement of the database may lead to further work in which pollution events can be distinguished and the source identified by increasing accuracy.

Despite such limitations, our study has several strengths. We used high-resolution daily air pollution models informed by satellite imaging, landscape and monitor data. Second, we used temporally disaggregated daily mortality data provided by AIHW, the custodian of a consolidated National Mortality Database. Finally, this is the first multicity Australian study estimating the mortality burden attributable to short-term $PM_{2.5}$ over a relatively long period, presenting implications for policymakers in the context of more stringent air quality regulations. Our study can inform decision-making for air quality control and management and future studies that estimate the burden of mortality attributable to air pollutants across the Australian Continent and elsewhere. Furthermore, our findings underscore the urgent need for proactive policy mitigating climate change impacts on human health, emphasising the critical role of coordinated action in health protection interventions and exposure reduction policies to extreme events such as bushfires and dust storms.

This study underscores the significant mortality burden from short-term $PM_{2.5}$ exposure in Australian urban areas, mainly due to exceptional pollution events. It highlights the necessity for enhanced air quality regulations and public health strategies that are tailored to local environmental conditions. Future efforts should concentrate on developing region-specific exposure-response functions and implementing comprehensive measures to mitigate the impact of air pollution on public health.

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Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Contributors

LH, GM and IH conceived and designed the study. LH and IH developed the statistical methods, took the lead in drafting the manuscript and interpreting the results, and verified the underlying data. CY prepared the exposure $PM_{2.5}$ data with IH support. Other authors contributed to interpreting the results and the submitted version of the manuscript. All authors had full access to all data and final responsibility to submit this paper for publication.

Data availability statement

The R codes are available in the Git Hub repository: https://github.com/cardat/ResPrj_bushfire_pm25_v1_3_abs_2016_gcc_aihw_mortality_2001-2019. The data associated with our study has not been deposited into a publicly available repository. Still, they can be requested, except mortality data, to its custodians in the Centre for Safe Air data platform "CARDAT" http://cardat.github.io/. Cause of Death Unit Record File data are provided to the AIHW by the Registries of Births, Deaths and Marriages and the National Coronial Information System (managed by the Victorian Department of Justice) and include cause of death coded by the Australian Bureau of Statistics (ABS). The data maintained by the AIHW in the National Mortality Database can be requested at http://datarequest.aihw.gov.au.

CRediT authorship contribution statement

Lucas Hertzog: Writing - review & editing, Writing - original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Geoffrey G. Morgan:** Writing - review & editing, Supervision, Methodology, Conceptualization. **Cassandra Yuen:** Writing - review & editing, Formal analysis, Data curation. **Karthik Gopi:** Writing - review & editing, Data curation. **Gavin F. Pereira:** Writing - review & editing, Methodology. **Fay H. Johnston:** Writing - review & editing. **Martin Cope:** Writing - review & editing. **Timothy B. Chaston:** Writing - review & editing. **Aditya Vyas:** Writing - review & editing. **Sotiris Vardoulakis:** Writing - review & editing, Funding acquisition. **Ivan C. Hanigan:** Writing - review & editing, Writing - original draft, Visualization, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e24532.

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