**Air Pollution Exceedance Events in Melbourne and Sydney, Australia, between 2000 and 2024**

Simon William Mkasimongwa a, Stephen J. Livesley b, Robert G. Ryan a, Robyn Schofield a

a School of Geography Earth and Atmospheric Science, University of Melbourne, Melbourne, VIC, Australia.

b School of Agriculture, Food and Ecosystem Sciences, Burnley Campus, University of Melbourne, 500 Yarra Boulevard, Richmond, VIC 3121, Australia.

**Abstract**

Many Australian cities with good air quality still face significant challenges from air pollution events. Using air quality exceedance analysis, this study evaluates publicly available data in Melbourne and Sydney, focusing on compliance with World Health Organization (WHO) guidelines, national and state standards, the frequency and types of air pollution exceedance events, and data coverage for city-scale evaluation. Melbourne’s air quality generally complies with national and state standards more often than Sydney’s; however, both cities consistently fail to meet WHO air quality guidelines. Since 2000, Sydney recorded single-pollutant events on 15% of measured days and multi-pollutant events on 85% of measured days. In Melbourne, single-pollutant events were recorded on 43% of measured days, and multi-pollutant events on 7%. In Sydney, NO2 exceeded WHO guidelines on 96% of measured days, PM2.5 on 79%, PM10 on 64%, and O3 on 6%. In Melbourne, NO2 exceeded on 47% of measured days, PM2.5 on 4%, PM10 on 6%, and O3 on 1%. Evaluating long-term, city-scale air quality is challenging due to significant variations in spatial and temporal data coverage especially in Melbourne. Many monitoring stations have limited temporal coverage and do not consistently measure all key pollutants, meaning the true extent of air pollution may not be fully captured. Since 2017, Melbourne has had only five active monitoring stations, compared to over 20 in Sydney. Further research is needed to better understand the health and environmental impacts of multi-pollutant events and to expand and improve the monitoring network to enhance data coverage.

**Keywords:** Data coverage, Exceedance events, single exceedance, multipollutant exceedances, urban air pollution.

1. **Introduction**

Approximately 99% of the global population lives in areas with poor air quality, particularly in densely populated regions (WHO, 2022). The health impacts of air pollution are severe, leading to high estimates of premature deaths despite relatively stable global pollution levels (HEI, 2024). Air pollution is the second leading global risk factor for premature death, causing approximately 8.1 million deaths globally, with outdoor air pollution alone accounting for 58% of overall premature death (HEI, 2024). Additionally, exposure to air pollution is estimated to shorten the average human’s lifespan by 1.8 years (Max Roser, 2021; HEI, 2022).

Recent studies have reported an increase of ambient air pollution events per year in densely populated urban areas, with some particulate matter (PM10 and PM2.5) levels reaching hazardous level as high as 350µg/m³ (Haque et al., 2021; Grant & Runkle, 2022; Lai et al., 2023). An air pollution event occurs when a pollutant exceeds threshold levels. However, research on their spatial and temporal distribution is limited due to poor air quality monitoring network coverage in many regions. Air pollution events can be classified into two categories: single pollutant events, where only one pollutant exceeds threshold levels, and multi-pollutant events, where multiple pollutants exceed threshold levels (Song and Stettler, 2022).

Air quality studies rarely consider the assessment of multi pollutant events. People living in areas with poor air quality are typically exposed to a complex mixture of air pollutants, yet it remains unclear how these pollutants interact (Zhu et al., 2022). Emerging evidence suggests that simultaneous exposure to multiple pollutants may have more severe health impacts than exposure to individual pollutants. For example, combined exposure to PM2.5 and O3 has been linked to worsened respiratory issues and higher mortality rates (Zhu et al., 2022). As awareness of the risks associated with multi-pollutant air pollution grows, it becomes crucial to integrate the analysis and management of both single- and multi-pollutant exceedances (Song and Stettler, 2022).

The evaluation of air pollution events depends on the standards or guidelines applied, which are determined by national, state or local authority policy priorities. Air quality standards are legally binding regulations set by authorities to limit pollutant concentrations, while air quality guidelines, such as those provided by the World Health Organization (WHO), are non-binding recommendations. These guidelines provide health-based benchmarks to guide policymakers in setting national standards aimed at minimizing health risks. Each country selects which air pollutants to monitor and establishes corresponding thresholds for acceptable levels. WHO guidelines are often more stringent than national standards, prioritizing health on a global scale (WHO, 2022).

In Australia, the responsibility for measuring and monitoring air quality, is delegated to the state and territory-based Environmental Protection Authorities (EPA). In Victoria, the Environment Protection Authority (EPA-VIC) operates under the Environment Protection Act 2017 (VIC) (EPA-VIC, 2018). In New South Wales, the EPA-NSW functions under the Protection of the Environment Operations Act 1997 (NSW), granting the authority to regulate and monitor both air and water quality (Emmerson & Keywood, 2021).

Air pollution is further regulated under the National Environment Protection Measure for Ambient Air Quality (Air NEPM), which sets standards for six criteria air pollutants: carbon monoxide (CO), nitrogen dioxide (NO2), sulfur dioxide (SO2), ozone (O3), lead, and particulate matter (PM10 and PM2.5) (NEPM, 2021). Our study focuses on NO2, particulate matter (PM10 and PM2.5), and O3 because they are common in urban areas, are strongly linked to health issues, and are monitored more widely than the other criteria pollutants. EPA-NSW and EPA-VIC assess NO2 on a one-hour average basis, O3 on an 8-hour average, and PM10 and PM2.5 over a 24-hour period. In contrast, WHO guidelines assess NO2 on a daily average basis, O3 on an 8-hour and seasonal average, and PM10 and PM2.5 as daily averages (Table 1).

Table 1. International air quality guidelines from WHO and National air quality standards from NEPM, Environment Protection Authority in New South Wales (EPA-NSW), and Environment Protection Authority in Victoria (EPA-VIC).

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | PM2.5  µg/m3 | |  | PM10  µg/m3 | |  | NO2  ppb | | |  | O3  ppb | |
|  | 24 hours | 1 year |  | 24 hours | 1 year |  | 24 hours | 1 hour | 1 year |  | 8-hour average | Per-Season |
| WHO | 15 | 5 |  | 45 | 15 |  | 13 | - | 5 |  | 50 | 30 |
| NEPM | 25 | 8 |  | 50 | 25 |  | - | 80 | 15 |  | 65 | - |
| EPA-VIC | 25 | 8 |  | 50 | 20 |  | - | 80 | 15 |  | 60 | - |
| EPA-NSW | 25 | 8 |  | 50 | 25 |  | - | 80 | 15 |  | 65 | - |

Melbourne and Sydney, Australia's largest cities, together account for approximately 40% of the country's total population. These cities have experienced significant growth and development in recent years, leading to increased population density and human activity (Searle, 2020). Although, most Australian cities generally reported with good air quality that complies with national standards, air pollution events still occur (Emmerson & Keywood, 2021). With ongoing urban expansion, the risk of air pollution events impacting more people increases. Therefore, a long-term evaluation of air pollution events is essential to assess the adequacy of the current monitoring network, track changes in air quality over time, and understand the distribution of pollution events across expanding urban areas.

This study is the first to evaluate the spatiotemporal distribution of air pollution events in Melbourne and Sydney over a multi-decadal period. The objectives of this study are to answer the following research questions:

1. How has the air quality in Melbourne and Sydney changed over the 24 years from 2000 to 2024 in relation to WHO guidelines, national, and state standards?
2. How many air pollution events, comprising single or multiple pollutants, occurred between 2000 and 2024, and what are their spatiotemporal distributions?
3. Does the EPA air quality monitoring network in Melbourne and Sydney provide sufficient data coverage for city-scale air quality evaluation?

We used pollutant concentrations as the primary metric for this study, guided by the National Environment Protection Measures (NEPM), Environment Protection Authority in New South Wales (EPA-NSW) and Victoria (EPA-VIC) air quality standards, and World Health Organization (WHO) air quality guidelines. By incorporating both national and state-based standards alongside WHO guidelines, we aimed to ensure a comprehensive evaluation of air quality. This approach balances locally enforced regulations with globally recognized health benchmarks.

1. **Methods**
   1. **Data**

Air quality data for both Melbourne and Sydney since 2000 were sourced from publicly available platforms (EPA-VIC Historical Data and Resources, 2023), while the data for Sydney was retrieved from the EPA-NSW data platform (EPA-NSW Data download facility, 2023). In Melbourne, data were collected from 24 air quality monitoring stations, whereby in Sydney, data were collected from 23 monitoring stations. However, since 2017 only 5 stations remaining active in Melbourne while in Sydney all stations are still active (Figure 1).

A screenshot of a satellite image

Description automatically generated

Figure 1. Air quality monitoring stations in Melbourne (A) and Sydney (B). The white dotes with black dotes represent all active stations, and the white dotes with “X” mark shows all non-active stations.

* 1. **Instruments**

EPA-NSW and EPA-VIC use similar air quality monitoring instruments (Table 2). Nitrogen dioxide (NO2) is monitored using gas phase chemiluminescence, and O3 with the non-dispersive ultraviolet method. PM2.5 is measured using beta attenuation monitors and a gravimetric reference method with a low-volume sampler. PM10 is monitored using a tapered element oscillating microbalance analyzer, which requires adjustments for temperature variations to ensure data accuracy that help reflect real environmental conditions under changing atmospheric conditions (EPA-NSW, 2021; EPA-VIC 2022). The setting of all air quality monitoring stations in Australia follows National Association of Testing Authorities (NATA) guidelines to ensure accurate, representative data (Table 2) (EPA-VIC, 2020; EPA-NSW, 2021; Emmerson & Keywood, 2021).

Table 2. Air quality monitoring instruments used by EPA-NSW and EPA-VIC

|  |  |  |
| --- | --- | --- |
| Monitoring Guidelines | Pollutant | Instrumentation |
| 1.5-10m above ground | NO2 | Gas phase chemiluminescence |
| Minimum distance to support structure | O3 | Non-dispersive ultraviolet photometry |
| Clear sky angle of 120° | PM10 | Tapered element oscillating microbalance |
| Unrestricted airflow >270° | PM2.5 | Beta attenuation monitors and Gravimetric method |
| At least 20m from trees |  |  |
| At least 50m from roads |  |  |

* 1. **Quality assurance and quality control**

Air quality monitoring also requires strict data quality control and quality analysis to ensure reliability and accuracy (Table 2). All measurements must follow standardized procedures, with laboratories accredited by National Association of Testing Authorities to perform sampling and analysis. Quality assurance includes proficiency testing, validation of methods, and adherence to guidelines for handling samples and maintaining equipment. Proper documentation and calibration of instruments are essential, as well as regular checks to ensure data integrity throughout the monitoring process. Data that does not meet the requirements of these standards is considered invalid. Such data cannot be used for assessing compliance or determining ambient air quality, as it may not accurately reflect the environmental conditions (Standards Australia, 2016).

* 1. **Data analysis**

The analysis had two parts. First, all air quality monitoring stations were averaged to represent the city's air quality. Each monitoring station was evaluated individually to understand pollution at specific location. Long-term changes in NO2, PM2.5, PM10, and O3 concentrations in Melbourne and Sydney were evaluated by calculating daily, weekly, monthly, and annual means along with their standard deviations. A linear regression on the annual mean concentrations was performed to identify long-term trends, with significance assessed using a t-test. To evaluate air quality compliance with the international, national, and state air quality standards we used the hourly and annual mean concentrations of NO2, PM2.5, and PM10 along with the 8-hourly average O3 concentration. An air pollution event was recorded if the concentration of a pollutant exceeded its threshold in the appropriate sample period, following the standards listed in Table 1. A multi-pollutant event was recorded if more than one pollutant exceeded its threshold at a time.

1. **Results**
   1. **Air quality changes in Melbourne and Sydney from 2000 to 2024 in relation to WHO guidelines, and national, and state standards**

The evaluation of long-term air quality trends in Melbourne is limited by poor data coverage. Many air quality stations in Melbourne have only short-term data, ranging from a few months to a few years, and most do not monitor all criteria pollutants (NO2, PM2.5, PM10, and O3). Instead, many stations only monitor one or two pollutants, with only a few, such as Alphington, Footscray, Altona North, Dandenong, and Mooroolbark, providing data for all the criteria pollutants. Since 2000, air quality has been monitored at 24 different stations at different times in Melbourne. Since 2017, only 5 remain active. In contrast, Sydney’s stations generally offer better data coverage, monitoring all the criteria pollutants, with over 20 stations remaining active since 2017.

In Sydney, NO2 concentrations are decreasing at a significant rate of -0.25 ppb per year, while in Melbourne, NO2 is decreasing at a significant rate of -0.13 ppb per year. For PM2.5, both cities show non-significant trends, with a rate of -0.04 µg/m³ per year in Sydney and -0.03 µg/m³ per year in Melbourne. PM10 levels in Sydney show a non-significant decreasing rate of -0.26 µg/m³ per year, while Melbourne records a rate of -0.05 µg/m³ per year. O3 levels in Sydney show a slight, non-significant increasing rate of +0.04 ppb per year, whereas Melbourne shows a significant increasing rate of +0.18 ppb per year (Table 3).

In Melbourne, NO2, PM2.5, and PM10 concentrations generally complied with national air quality standards, except in 2014 and 2020, when PM2.5, exceeded the standard (Figure 2). In contrast, Sydney's concentrations of NO2, PM2.5, and PM10 did not meet national air quality standards (Figure 3). Although Melbourne's air quality largely complies with national standards, both cities fail to meet the WHO air quality guidelines.

Table 3. Summary statistics for NO2, PM2.5, PM10, and O3 in Sydney and Melbourne. The table includes the mean, maximum, and minimum concentrations, standard deviation, slope (trend rate), p-values, and statistical significance at the 95% confidence level.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| City | Pollutant | Mean | Max | Min | Standard Deviation | Slope | Significant |
| Sydney | NO2 (ppb) | 17 | 46 | 2 | 5.85 | -0.25 | Yes |
|  | PM2.5 (µg/m3) | 18 | 479 | 3 | 13.44 | -0.04 | No |
|  | PM10 (µg/m3) | 38 | 783 | 7 | 25.72 | -0.26 | No |
|  | O3 (ppb) | 16 | 44 | 2 | 5.56 | +0.04 | No |
| Melbourne | NO2 (ppb) | 10 | 33 | 1 | 4.78 | -0.13 | Yes |
|  | PM2.5 (µg/m3) | 7 | 122 | 1 | 4.02 | -0.03 | No |
|  | PM10 (µg/m3) | 16 | 214 | 3 | 8.01 | -0.05 | No |
|  | O3 (ppb) | 16 | 68 | 1 | 6.13 | +0.18 | Yes |

* 1. **Air quality temporal patterns in Melbourne**

A summary of air quality temporal patterns in Melbourne is presented in Figure 2. NO2 concentrations peak in cooler months (April to August), with the highest levels in July, and are lowest during the warmer months (November to March). PM2.5 levels are high from April to June and from December to January, with lower levels from August to October. PM10 concentrations are high from November to May and low from June to August. O3 levels are highest from August to March. NO2 concentrations are higher on weekdays and lower on weekends. PM2.5 does not show a clear weekly pattern, while PM10 concentrations are slightly higher on weekdays, particularly Wednesdays, and lower on weekends. O3 levels are slightly higher on weekends. Diurnally, NO2 and PM2.5 peak during morning and evening rush hours, while O3 levels are highest between noon and 21:00. PM10 does not show a clear diurnal pattern (Figure 2).

A group of blue and black graphs

Description automatically generated

Figure 2. Temporal analysis for Melbourne using the 24 years of available data. Annual means and standard deviations are displayed (top row), monthly (second row), day of week (third row), and hourly (bottom row). Air pollutants analysed are: NO2 (left column), PM2.5 (second column), PM10 (third column) and ozone (right column). The blue dashed lines denote the NEPM annual standard and the black dashed line the annual, and daily WHO guideline values (refer to Table 1). The red dashed line shows the EPA-NSW annual standard and purple dashed line shows the EPA-VIC annual standard values (refer to Table 1).

* 1. **Air quality temporal patterns in Sydney**

In Sydney, NO2 concentrations also peak in cooler months (April to October) and are lowest between December and January. PM2.5 levels are high between May and August and low during warmer months (December to March). PM10 concentrations are high from November to May and low from June to July. O3 levels peak from August to April and are low between May and July. NO2 concentrations are higher on weekdays and lower on weekends. PM2.5 shows no clear weekly trend, while PM10 concentrations are slightly higher on weekdays. O3 concentrations are higher on weekends. Diurnally, NO2, PM2.5, and PM10 peak during morning and evening rush hours, while O3 concentrations are highest around noon and lower during the night and morning rush hours (Figure 3).

A screenshot of a graph

Description automatically generated

Figure 3. Temporal analysis for Sydney using the 24 years of available data. Annual means and standard deviations are displayed (top row), monthly (second row), day of week (third row), and hourly (bottom row). Air pollutants analysed are: NO2 (left column), PM2.5 (second column), PM10 (third column) and ozone (right column). The blue dashed lines denote the NEPM annual standard and the black dashed line the annual and daily WHO guideline values (refer to Table 1). The red dashed line shows the EPA-NSW annual standard and purple dashed line shows the EPA-VIC annual standard values (refer to Table 1).

* 1. **Air pollution exceedance events in Melbourne and Sydney**

Since 2000, Melbourne has recorded a total of 4,148 NO2 exceedance events, with the highest seasonal average in winter (62) and the lowest in summer (21). In comparison, Sydney reported more than double exceedance events compared to Melbourne, with 8,483 NO2 exceedance events, showing relatively consistent seasonal averages throughout the year (ranging from 81 to 91). For PM2.5, Sydney recorded 6,968 exceedance events, compared to Melbourne’s 380 events. Seasonal averages in Sydney remained relatively high across all seasons, while Melbourne’s exceedance events were notably low, averaging just 1 per month. PM10 exceedance events showed a similar disparity: Sydney recorded 5,661 events, with consistent seasonal averages, while Melbourne recorded only 569, concentrated mostly in autumn and summer. For O3, Melbourne’s 80 recorded exceedances were lower than Sydney’s 529, with both cities experiencing O3 events during summer. Overall, single-pollutant exceedances were most common in Melbourne with a total of 3,100 events, while Sydney recorded a higher prevalence of multi-pollutant exceedances, with 7,380 events (Table 4).

Table 4. Air pollution exceedance events in Melbourne and Sydney. The evaluation of air pollution exceedance for NO2, PM2.5, and PM10 was based on daily average, whereby for O3 was based on 8-hour average. And the frequency of air pollution exceedance event on weekly, monthly and seasonal basis ((S)Summer, (A) Autumn, (W) Winter, (S) Spring).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | Total days | Exceedance days (%) | Exceedance Week | Exceedance Month | Exceedance Season | | | |
| S | A | W | Sp |
| Sydney | NO2 | 8766 | 8483 (97) | 7 | 29 | 81 | 91 | 92 | 90 |
|  | PM2.5 | 8766 | 6968 (79) | 6 | 24 | 68 | 73 | 79 | 69 |
|  | PM10 | 8766 | 5661 (65) | 5 | 20 | 59 | 58 | 57 | 60 |
|  | O3 | 26205 | 529 (6) | 0 | 2 | 15 | 1 | 0 | 6 |
| Single events |  |  | 1284 (15) | 1 | 4 | 16 | 14 | 9 | 14 |
| Multi-pollutant |  |  | 7412 (85) | 6 | 25 | 72 | 78 | 83 | 76 |
|  |  |  |  |  |  |  |  |  |  |
| Melbourne | NO2 | 8722 | 4148 (47) | 3 | 14 | 22 | 52 | 62 | 37 |
|  | PM2.5 | 4951 | 380 (4) | 0 | 1 | 3 | 6 | 7 | 1 |
|  | PM10 | 8739 | 569 (6) | 0 | 2 | 9 | 8 | 2 | 5 |
|  | O3 | 26157 | 80 (1) | 0 | 1 | 7 | 1 | 0 | 0 |
| Single events |  |  | 3100 (43) | 3 | 13 | 21 | 45 | 55 | 37 |
| Multi-pollutant |  |  | 591 (7) | 0 | 2 | 6 | 10 | 8 | 3 |

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | |  |  |  | | | |
|  |  |  |  |
|  |  |  | |  |  |  |  |  |  |  |
|  |  |  | |  |  |  |  |  |  |  |
|  |  |  | |  |  |  |  |  |  |  |
|  |  |  | |  |  |  |  |  |  |  |
|  |  |  | |  |  |  |  |  |  |  |
|  |  |  | |  |  |  |  |  |  |  |
|  |  |  | |  |  |  |  |  |  |  |
|  |  |  | |  |  |  |  |  |  |  |
|  |  |  | |  |  |  |  |  |  |  |
|  |  |  | |  |  |  |  |  |  |  |
|  |  |  | |  |  |  |  |  |  |  |
|  |  |  | |  |  |  |  |  |  |  |

* 1. **Spatiotemporal distribution of air pollution exceedance events and the EPA-VIC air quality data coverage in Melbourne**

The highest frequency of NO2 events in Melbourne were seen for monitoring stations located withing 7 km radius from Central Business District (CBD). However, the evaluation of long-term trends in NO2 events in these stations is limited due to extremely limited monitoring durations. For example, the RMIT station recorded the highest frequency of NO2 events between 2000 and 2005, but no data has been available from this station since 2006. This limitation in data coverage is also common to other pollutants, such as PM2.5, PM10 and O3. Although new stations were introduced in 2022 and 2023, only one station (Melbourne CBD) was located in the CBD and this station monitors only NO2 and PM2.5.

Alphington and Footscray are the only two stations that monitor all key pollutants: NO2, PM2.5, PM10, and O3. Most air quality stations typically monitor only one or two of these key pollutants. Since 2007, there has been no station within a 6 km radius of Melbourne's CBD providing O3 data. The nearest station providing O3 data is in Footscray, approximately 7 km from the CBD. The only available O3 data within the CBD was recorded at the RMIT station, located 0.4 km from the CBD, which provided O3 data for only three years (2003-2006), and the Moonee Ponds station, 4 km from the CBD, which recorded a few months of O3 data in 2002 (Figure 4). Overall, Figure 4 highlights strongly the lack of long-term or consistent monitoring of air pollution in Melbourne.

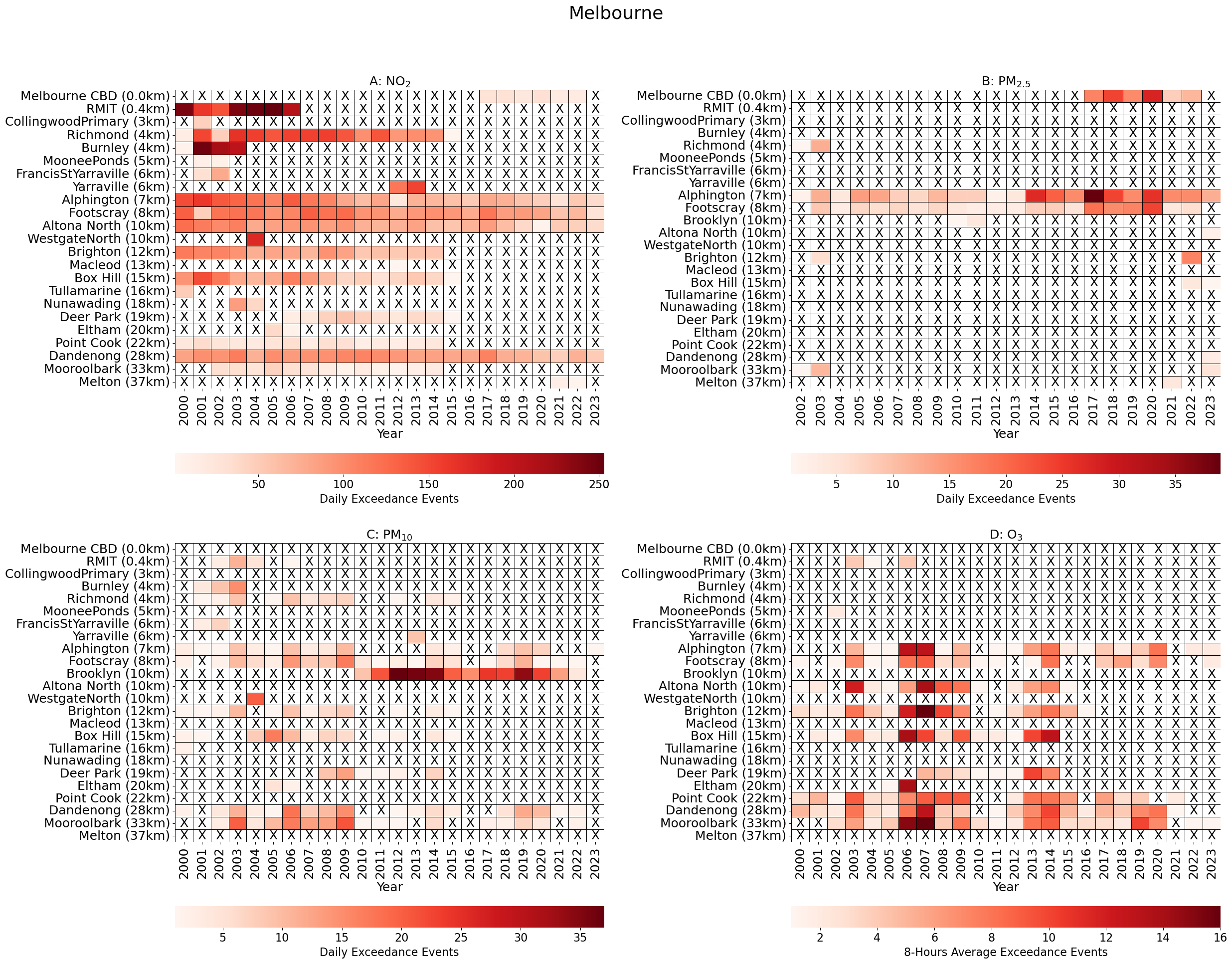


Figure 4. Spatiotemporal distribution of air quality exceedance events in Melbourne for (A) NO2, (B) PM2.5, (C) PM10, and (D) O3. The numbers in brackets after the name of each air quality monitoring station indicate the total number of events for all 24 years. “X” indicates no data at all in that year.

* 1. **Spatiotemporal distribution of air pollution exceedance events and the EPA-NSW air quality data coverage in Melbourne and Sydney**

In contrast, most air quality monitoring stations in Sydney have significantly better temporal data coverage compared to those in Melbourne. Nearly all stations monitor the key pollutants. Since 2015, the EPA in New South Wales has expanded its network by adding new air quality stations in various locations, resulting in a current total of 23 active monitoring stations. The data shows a high frequency of NO2 events in Sydney for all monitoring stations. However, there is a slight decrease in NO2 events at stations within a 10 km radius of Sydney’s CBD, while newly established stations farther from the CBD have shown an increase in NO2 events. PM2.5, PM10, and O3 events vary from year to year; for instance, a high frequency of O3 events was recorded in 2018, while PM2.5 and PM10 events peaked during the 2019-2020 period (Figure 5).

A screenshot of a graph

Description automatically generated

Figure 5. Spatiotemporal distribution of air quality exceedance events in Sydney for (A) NO2, (B) PM2.5, (C) PM10, and (D) O3. The numbers in brackets after the name of each air quality monitoring station indicate the total number of events for all 24 years. “X” indicates no data at all in that year.

1. **Discussion**

Air quality data coverage make it difficult for the evaluation of long-term, city-scale air quality, particularly in Melbourne. Long-term evaluations are significantly limited by poor data coverage. Most monitoring stations in Melbourne operate only for short periods and do not consistently monitor key pollutants, such as NO2, PM2.5, PM10, and O3 (Figure 4). Sydney has a well-established and extensive air quality monitoring network, with most stations providing good data coverage. Unlike Melbourne, Sydney's stations measure both weather and air quality at the same locations, and most stations monitor all major pollutants, including PM10, PM2.5, NO2, and O3 (EPA-NSW, 2018; 2020; 2021; 2022).

The EPA-NSW and EPA-VIC use similar air quality monitoring equipment and follow the same national guidelines for monitoring pollutants (Tables 1 and 2). However, each city has a different air-quality monitoring system. The EPA-VIC uses screening procedures to assess whether continuous monitoring of certain pollutants is necessary. If pollutant concentrations consistently remain below regulatory standards, EPA-VIC may reduce, eliminate, or relocate monitoring to other areas (EPA-VIC, 2022). For instance, the RMIT station was permanently closed in 2006, followed by discontinuation of O3 monitoring at Moorooduc in May 2006 (EPA-VIC, 2007). In March 2011, O3 monitoring ceased at Point Henry Station (EPA-VIC, 2012), and Richmond Station closed in 2016. Additionally, O3 monitoring at Brighton, Dandenong, Melton, Mooroolbark, and Point Cook was conducted only during the summer months, when O3 levels are typically higher (EPA-VIC, 2017). In early 2021, the Footscray monitoring station, which had previously monitored all key pollutants, was relocated to Melbourne CBD, which only monitors NO2 and PM2.5 (EPA-VIC, 2022)

However, this approach carries several risks. The frequent relocation of stations compromises their ability to track long-term trends, resulting in poor data coverage. Additionally, Inconsistent monitoring in Melbourne makes it difficult to understand the real changes in air quality. Without comprehensive data coverage, the extent of air pollution is unclear, which could lead to underestimation of pollution levels. Poor monitoring coverage may miss high-pollution areas or critical high-pollution events, resulting in trends that inaccurately indicate compliance. Without consistent long-term monitoring, it is difficult to determine whether the observed improvements in air quality are genuine or simply a result of insufficient data. For instance, Figure 3 shows a decreasing trend in NO2 concentrations that comply with national standards in Melbourne; however, this trend may be misleading because of the reduction in the number of stations, particularly those with high pollution levels.

Despite the limitations in data coverage for both cities, the available data highlight a pressing issue that demands further research owing to its serious public health implications. The data revealed that residents in both Melbourne and Sydney are frequently exposed to air pollution exceedance events, particularly multi-pollutant exceedance events. This means that people are simultaneously exposed to a dangerous mix of harmful pollutants, each exceeding the health threshold and reaching hazardous concentration levels at the same time (Table 4).

The frequency of these events varies seasonally, and influenced by both natural events and human activities. O3 events increase during spring and summer in both cities and are driven by elevated temperatures and sunlight, which promote photochemical reactions (Utembe et al., 2018; Duc et al., 2022). In Sydney, O3 events are frequently high at sites such as Rozelle and Liverpool, which are significantly influenced by traffic emissions and industrial activities (EPA-NSW, 2021). Similarly, in Melbourne, O3 events increased on hot summer days, particularly in suburban areas such as Alphington and Dandenong, owing to a combination of vehicle emissions and high temperatures (Emmerson & Keywood, 2021; EPA-VIC, 2022).

PM2.5 and PM10 events increased in warmer months and in winter in both cities. In Sydney, bushfires significantly affected air quality between November and January, with PM10 events recorded in areas such as Richmond and Prospect (EPA-NSW, 2020; EPA-NSW, 2021). Similarly, in Melbourne, PM2.5, and PM10 events increased during May and July owing to the use of wood heaters and bushfires, with exceedances noted in areas such as Footscray and Alphington. High PM10 events in Melbourne are frequently recorded in the industrial area of Brooklyn, particularly during late winter and spring. These elevated levels are driven by dust storms and heavy industrial activities in the area (EPA-VIC, 2018; EPA-VIC, 2020; EPA-VIC, 2022).

NO2 exceedances are frequently recorded near highways and industrial areas in both Sydney and Melbourne (Kendrick et al., 2015; Ryan et al., 2018; Cowie et al., 2019; Haddad & Vizakos, 2020). In Sydney, this is particularly notable in Chullora and Rozelle, and in Melbourne, in Altona North, where heavy traffic during rush hours and industrial activities drive increased NO2 levels (EPA-NSW, 2021; EPA-VIC, 2022). These concentrations are further exacerbated by temperature inversions, which are more frequent in winter, trapping pollutants close to the ground, and worsening air quality (Kendrick et al., 2015; Ryan et al., 2018).

The increasing occurrence of multi-pollutant air pollution events poses a significant challenge to public health and environmental safety; however, there are still considerable gaps in understanding their full impact (Billionnet et al., 2012). Current research has primarily focused on single-pollutant exposure, leaving multi-pollutant events underexplored, particularly concerning their long-term effects on health. Studies have revealed that air pollution consists of complex mixtures of contaminants, and exposure to these mixtures may have additive or synergistic effects, making it difficult to predict their combined impact on human health (Billionnet et al., 2012; Tong et al., 2018; Guo et al., 2022)​.

Recent studies have indicated that multi-pollutant events can have severe health implications (Tan et al., 2021; Zhu et al., 2022). For instance, there is an increased risk of developing cardiovascular diseases, respiratory problems, and even renal damage, especially in vulnerable populations, such as children and the elderly​. These events expose individuals to dangerous levels of pollutants, often exceeding health thresholds, amplifying the harmful effects compared to single-pollutant exposure (Zhu et al., 2022; Guo et al., 2022).

Given these findings, there is an urgent need to focus on mitigating multi-pollutant events and enhancing air quality monitoring systems to prevent long-term health impacts​. Expanding the monitoring network to include more continuous air quality monitoring stations is essential for providing continuous data that can be used to support effective air quality management strategies. A comprehensive and reliable monitoring network is crucial in guiding mitigation efforts and sustainable urban planning, ultimately ensuring that cities are developed with a focus on improving air quality and public health.

1. **Conclusion**

In this study, we aimed to evaluate the long-term air quality in Melbourne and Sydney from 2000 to 2024, focusing on compliance with international, national, and state standards, the frequency and types of air pollution exceedance events, and the air quality monitoring data coverage for city-scale evaluations.

The findings show that while Melbourne's air quality generally complies with national standards more frequently than Sydney's, neither city meets the WHO air quality guidelines. Despite Melbourne appearing to have better air quality, it suffers from poor data coverage compared to Sydney. Most air quality stations in Melbourne operate for short periods, and many do not monitor all key pollutants. Since 2017, Melbourne has had only five active air quality monitoring stations, whereas Sydney has over 20 active stations. This disparity limits the ability to accurately evaluate long-term trends and makes fair comparisons between the two cities difficult.

The data reveal that air quality in both cities varies according to season, day of the week, and time of day. In Melbourne, NO2 concentrations peak during the cooler months, from April to August, while in Sydney, NO2 levels are highest between April and October. Both cities show similar seasonal trends for particulate matter and O3, with PM2.5 levels rising during colder months due to increased heating and the trapping of pollutants caused by temperature inversions. Ozone levels, driven by photochemical reactions, are higher in the warmer months in both cities.

In both Melbourne and Sydney, NO2 concentrations are higher on weekdays and lower on weekends. PM2.5 does not show a clear weekly pattern, while PM10 levels are slightly higher on weekdays, particularly Wednesdays, and lower on weekends. Ozone levels are somewhat higher on weekends. Diurnally, in Melbourne, NO2 and PM2.5 peak during morning and evening rush hours, while ozone levels are highest between noon and 9 PM. In Sydney, NO2, PM2.5, and PM10 also peak during rush hours, with ozone levels highest around midday and lowest during the night and morning rush hours.

Although available data suggest Melbourne has better air quality with low frequency of air pollution exceedance events than Sydney, the limited data coverage makes it difficult to fairly compare the two cities. Some stations in Melbourne, such as RMIT in the CBD, recorded higher exceedance events but were only active for a few years, means that in many air quality stations in Melbourne the true extent of air pollution may not be fully captured. Therefore, while current data indicate better air quality in Melbourne, the actual levels could be similar to, worse than, or equal to those in Sydney.Exposure to multiple pollutants poses significant health risks, as the combined impact of different pollutants can be more harmful than single-pollutant exposures. The scale of these multi-pollutant exceedances in Sydney highlights the need for stronger policy interventions to reduce pollution sources and protect public health.

Additionally, our findings suggested the urgent need to improve the air quality monitoring network, especially in Melbourne. Expanding the number of active monitoring stations and ensuring continuous long-term monitoring of all key pollutants are essential for accurately understanding air quality trends and developing effective mitigation strategies. Comprehensive data coverage is vital to accurately assess pollution levels, protect public health, and meet both national and international air quality standards.

**Funding**

This research is supported by an Australian Government Research Training Program (RTP) Scholarship (SWM). SL and RS have received funds from Australian Research Council Linkage Project [LP190100089].

**Authorship contribution statement.**

Simon William Mkasimongwa: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. Robyn Schofield: Supervision, Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Conceptualization. Stephen Livesley: Supervision, Writing – review & editing, Methodology, Investigation, Formal analysis. Robert G. Ryan: Writing – review & editing, Validation, Methodology.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

**Data and Codes availability**

This study used publicly available data from the EPA-NSW and EPA-VIC platforms. To ensure reproducibility, all analysis codes will be published alongside the manuscript.

**References**

Billionnet, C., Sherrill, D., & Annesi-Maesano, I. (2012). Estimating the health effects of exposure to multi-pollutant mixture. Annals of Epidemiology, 22(2), 126-141. <https://doi.org/10.1016/j.annepidem.2011.11.004>

Cowie, C. T., Garden, F., Jegasothy, E., Knibbs, L. D., Hanigan, I., Morley, D., Hansell, A., Hoek, G., & Marks, G. B. (2019). Comparison of model estimates from an intra-city land use regression model with a national satellite-LUR and a regional Bayesian maximum entropy model, in estimating NO2 for a birth cohort in Sydney, Australia. Environmental Research, 174, 24-34. <https://doi.org/10.1016/j.envres.2019.03.068>

Duc, H. N., Rahman, M. M., Trieu, T., Azzi, M., Riley, M., Koh, T., Liu, S., Bandara, K., Krishnan, V., Yang, Y., Silver, J., Kirley, M., White, S., Capnerhurst, J., & Kirkwood, J. (2022). Study of planetary boundary layer, air pollution, air quality models and aerosol transport using ceilometers in New South Wales (NSW), Australia. Atmosphere, 13(2), 176. <https://doi.org/10.3390/atmos13020176>

Emmerson KM & Keywood MD. (2021). Australia state of the environment 2021: air quality, independent report to the Australian Government Minister for the Environment, Commonwealth of Australia, Canberra. Australia state of the environment 2021. <https://soe.dcceew.gov.au/>

Environment Protection Authority New South Wales (EPA-NSW), N. (2021, July 14). Regional-air-quality. NSW Environment Protection Authority. <https://www.epa.nsw.gov.au/your-environment/air/regional-air-quality>

Environment Protection Authority New South Wales (EPA-NSW). (2018). New South Wales annual compliance report 2017. NSW Environment and Heritage. <https://www.environment.nsw.gov.au/research-and-publications/publications-search/new-south-wales-annual-compliance-report-2017>

Environment Protection Authority New South Wales (EPA-NSW). (2020). New South Wales annual compliance report 2018. NSW Environment and Heritage. <https://www.environment.nsw.gov.au/research-and-publications/publications-search/new-south-wales-annual-compliance-report-2018>

Environment Protection Authority New South Wales (EPA-NSW). (2022). New South Wales annual compliance report 2021. NSW Environment and Heritage. <https://www.environment.nsw.gov.au/research-and-publications/publications-search/new-south-wales-annual-compliance-report-2021>

Environment Protection Authority Victoria (EPA-VIC). (2007). 1137: Air monitoring report 2006 – Compliance with the national environment protection (Ambient air) measure. Environment Protection Authority Victoria. <https://www.epa.vic.gov.au/about-epa/publications/1137>

Environment Protection Authority Victoria (EPA-VIC). (2012). 1483: Air monitoring report 2011 - Compliance with the national environment protection (Ambient air quality) measure. <https://www.epa.vic.gov.au/about-epa/publications/1483>

Environment Protection Authority Victoria (EPA-VIC). (2017). 1663: Air monitoring report 2016 – Compliance with the national environment protection (Ambient air quality) measure. <https://www.epa.vic.gov.au/about-epa/publications/1663>

Environment Protection Authority Victoria (EPA-VIC). (2018). 1709: Air pollution in Victoria – a summary of the state of knowledge. Environment Protection Authority Victoria. <https://www.epa.vic.gov.au/about-epa/publications/1709>

Environment Protection Authority Victoria (EPA-VIC). (2020). Air pollution sources in inner west Melbourne. <https://www.epa.vic.gov.au/about-epa/publications/2060-air-pollution-inner-west-melbourne>

Environment Protection Authority Victoria (EPA-VIC). (2020). Air quality issues near the Brooklyn industrial precinct. <https://www.epa.vic.gov.au/for-community/current-projects-issues/preventing-pollution-brooklyn>

Environment Protection Authority Victoria (EPA-VIC). (2022). Air monitoring report 2021: Compliance with the ambient air quality national environment protection measure. Environment Protection Authority Victoria. <https://www.epa.vic.gov.au/about-epa/publications/2052-nepm-compliance-air-monitoring-report>

EPA-NSW Data download facility. (2023, December 19). Data download facility. Air Quality NSW. <https://www.airquality.nsw.gov.au/air-quality-data-services/data-download-facility>

EPA-VIC Historical Data and Resources. (2023). EPA air watch all sites air quality hourly averages - Yearly - Victorian government data directory. <https://discover.data.vic.gov.au/dataset/epa-air-watch-all-sites-air-quality-hourly-averages-yearly/historical>

Grant, E., & Runkle, J. D. (2022). Long-term health effects of wildfire exposure: A scoping review. The Journal of Climate Change and Health, 6, 100110. <https://doi.org/10.1016/j.joclim.2021.100110>

Guo, C., Chang, L., Wei, X., Lin, C., Zeng, Y., Yu, Z., Tam, T., Lau, A. K., Huang, B., & Lao, X. Q. (2022). Multi-pollutant air pollution and renal health in Asian children and adolescents: An 18-year longitudinal study. Environmental Research, 214, 114144. <https://doi.org/10.1016/j.envres.2022.114144>

Haddad, K., & Vizakos, N. (2020). Air quality pollutants and their relationship with meteorological variables in four suburbs of greater Sydney, Australia. Air Quality, Atmosphere & Health, 14(1), 55-67. <https://doi.org/10.1007/s11869-020-00913-8>

Haque, M. K., Azad, M. A., Hossain, M. Y., Ahmed, T., Uddin, M., & Hossain, M. M. (2021). Wildfire in Australia during 2019-2020, its impact on health, biodiversity and environment with some proposals for risk management: A review. Journal of Environmental Protection, 12(06), 391-414. <https://doi.org/10.4236/jep.2021.126024>

Health Effects Institute (HEI). (2022). How does air pollution affect life expectancy around the world. State of Global Air. <https://www.stateofglobalair.org/resources/report/how-does-air-pollution-affect-life-expectancy-around-world>

Health Effects Institute (HEI). (2024). State of Global Air 2024. Special Report. Boston, MA:Health Effects Institute. State of Global Air. <https://www.stateofglobalair.org/resources/report/state-global-air-report-2024>

Kendrick, C. M., Koonce, P., & George, L. A. (2015). Diurnal and seasonal variations of NO, NO 2 and PM 2.5 mass as a function of traffic volumes alongside an urban arterial. Atmospheric Environment, 122, 133-141. <https://doi.org/10.1016/j.atmosenv.2015.09.019>

Lai, H., Dai, Y., Mkasimongwa, S. W., Hsiao, M., & Lai, L. (2023). The impact of atmospheric synoptic weather condition and long-range transportation of air mass on extreme PM10 concentration events. Atmosphere, 14(2), 406. <https://doi.org/10.3390/atmos14020406>

Martins, L. D., Wikuats, C. F., Capucim, M. N., De Almeida, D. S., Da Costa, S. C., Albuquerque, T., Barreto Carvalho, V. S., De Freitas, E. D., De Fátima Andrade, M., & Martins, J. A. (2017). Extreme value analysis of air pollution data and their comparison between two large urban regions of South America. Weather and Climate Extremes, 18, 44-54. <https://doi.org/10.1016/j.wace.2017.10.004>

Max Roser. (2021). How many people die from air pollution? Our World in Data. <https://ourworldindata.org/data-review-air-pollution-deaths>

National Environment Protection (Ambient Air Quality) Measure (NEMP). (2021). Federal Register of legislation. Air quality standards for Ambient Air Quality (Air NEPM), (National Environment Protection Measure). Federal Register of Legislation.. <https://www.legislation.gov.au/F2007B01142/2016-02-03/text>

Ryan, R. G., Rhodes, S., Tully, M., Wilson, S., Jones, N., Frieß, U., & Schofield, R. (2018). Daytime HONO, NO&lt;sub&gt;2&lt;/sub&gt; and aerosol distributions from MAX-DOAS observations in Melbourne. Atmospheric Chemistry and Physics, 18(19), 13969-13985. <https://doi.org/10.5194/acp-18-13969-2018>

Searle, G. H. (2020). Population growth and development: An outcome of Sydney's metropolitan governance. Australian Planner, 56(2), 65-72. <https://doi.org/10.1080/07293682.2020.1739095>

Song, J., & Stettler, M. E. (2022). A novel multi-pollutant space-time learning network for air pollution inference. Science of The Total Environment, 811, 152254. <https://doi.org/10.1016/j.scitotenv.2021.152254>

Standards Australia. (2022). Methods for sampling and analysis of ambient air Guide to siting air monitoring equipment. <https://www.intertekinform.com/en-au/standards/as-nzs-3580-1-1-2016-100904_saig_as_as_212008/>

Tan, X., Han, L., Zhang, X., Zhou, W., Li, W., & Qian, Y. (2021). A review of current air quality indexes and improvements under the multi-contaminant air pollution exposure. Journal of Environmental Management, 279, 111681. <https://doi.org/10.1016/j.jenvman.2020.111681>

Tong, Y., Luo, K., Li, R., Pei, L., Li, A., Yang, M., & Xu, Q. (2018). Association between multi-pollutant mixtures pollution and daily cardiovascular mortality: An exploration of exposure-response relationship. Atmospheric Environment, 186, 136-143. <https://doi.org/10.1016/j.atmosenv.2018.05.034>

Utembe, S. R., Rayner, P. J., Silver, J. D., Guérette, E., Fisher, J. A., Emmerson, K. M., Cope, M., Paton-Walsh, C., Griffiths, A. D., Duc, H., Monk, K., & Scorgie, Y. (2018). Hot summers: Effect of extreme temperatures on ozone in Sydney, Australia. Atmosphere, 9(12), 466. <https://doi.org/10.3390/atmos9120466>

World Health Organization (WHO). (2021, September 22). WHO global air quality guidelines: Particulate matter (‎PM2.5 and PM10)‎, ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. <https://www.who.int/publications/i/item/9789240034228>

World Health Organization (WHO). (2022, December 19). Ambient (outdoor) air pollution. <https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health>

Zhu, J., Chen, L., & Liao, H. (2022). Multi-pollutant air pollution and associated health risks in China from 2014 to 2020. Atmospheric Environment, 268, 118829. <https://doi.org/10.1016/j.atmosenv.2021.118829>