processes

MDPI

Article

The Impact of Coronavirus Disease of 2019 (COVID-19) Lockdown Restrictions on the Criteria Pollutants

Puneet Verma [1,*], Sohil Sisodiya [2,*], Sachin Kumar Banait [3], Subhankar Chowdhury [3], Gaurav Dwivedi [3] and Ali Zare [4]

1 School of Earth and Atmospheric Sciences, Queensland University of Technology, Brisbane City, QLD 4000, Australia
2 Department of Civil Engineering, University Departments, Rajasthan Technical University, Kota 324010, Rajasthan, India
3 Energy Centre, Maulana Azad National Institute of Technology, Bhopal 462003, India
4 School of Engineering, Waurn Ponds Campus, Building KE 75 Pigdons Road, Deakin University, Waurn Ponds, Victoria, VIC 3216, Australia
* Correspondence: puneet.verma@connect.qut.edu.au (P.V.); sohilsisodiya@gmail.com (S.S.)

Abstract: Air pollution is accountable for various long-term and short-term respiratory diseases and even deaths. Air pollution is normally associated with a decreasing life expectancy. Governments have been implementing strategies to improve air quality. However, natural events have always played an important role in the concentration of air pollutants. In Australia, the lockdown period followed the Black Summer of 2019–2020 and coincided with the season of prescribed burns. This paper investigates the changes in the concentration of criteria pollutants such as particulate matter, nitrogen dioxide, ozone, and sulphur dioxide. The air quality data for the lockdown period in 2020 was compared with the pre-lockdown period in 2020 and with corresponding periods of previous years from 2016 to 2019. The results were also compared with the post-lockdown scenario of 2020 and 2021 to understand how the concentration levels changed due to behavioural changes and a lack of background events. The results revealed that the COVID-19 restrictions had some impact on the concentration of pollutants; however, the location of monitoring stations played an important role.

Keywords: air quality; PM_{10}; $PM_{2.5}$; NO_2; COVID

Citation: Verma, P.; Sisodiya, S.; Banait, S.K.; Chowdhury, S.; Dwivedi, G.; Zare, A. The Impact of Coronavirus Disease of 2019 (COVID-19) Lockdown Restrictions on the Criteria Pollutants. *Processes* **2023**, *11*, 296. https://doi.org/10.3390/pr11010296

Academic Editors: Daniele Sofia, Paolo Trucillo and Avelino Núñez-Delgado

Received: 14 November 2022
Revised: 11 January 2023
Accepted: 12 January 2023
Published: 16 January 2023

1. Introduction

According to the World Health Organization's (WHO's) report, seven million deaths occur every year because of exposure to air pollution [1]. Air pollution is a cause of one in every eight deaths globally [2]. Unfortunately, worldwide nine out of ten people are exposed to a high level of air pollutants [1]. The severity of the effects of air pollution on human health is immense and there is an immediate need to curb this problem, and effective management of ambient air pollution can lead to a substantial reduction of pollutant concentrations [3]. However, the unprecedented outbreak of coronavirus disease of 2019 (COVID-19) has made a remarkable breakthrough in unresolved air pollution management [4].

The WHO declared COVID-19 a global pandemic on 12 March 2020 [5–7]. All affected countries enforced lockdowns and preventive measures to stop the virus's spread [8,9]. However, the situation was a little different in Australia. From 23 March 2020, the Queensland Department of Health announced that some businesses would be required to close or limit their operation [10]. On 5 June 2020, the Premier announced that the Queensland Tourism and Accommodation Industry COVID-19 Safe Plan had been approved, with the plan applying to thousands of tourism and accommodation businesses. This made Queensland's situation unique as there were some COVID-19-related restrictions, but no complete lockdown was enforced.

Pyrogenic events such as bushfires are a major environmental issue as they constitute up to 40% of carbon emissions every year [11] and worsen air quality around the world [12]. In general, the air quality levels in Brisbane and the rest of Queensland remain below the national air quality standards but particulate matter emissions have been an important air quality issue due to pyrogenic events such as bushfires, dust storms, and prescribed burning [13]. Due to restrictions on anthropogenic activities, the air quality around the world reportedly improved. Nitrogen dioxide (NO_2) concentrations in the lockdown periods of Wuhan, Delhi, New York, and Rome decreased by 65%, 69%, 56%, and 57%, respectively; $PM_{2.5}$ (levels of particles less than 2.5 µm) decreased by 49%, 69%, 53%, and 68%, respectively [14]. Similarly, a reduction of 24% in PM_{10} (particles less than 10 µm) concentrations was reported in Taiwan [4].

However, not all cities experienced declines in air pollution [15]. The impact of COVID-19 restrictions on air quality levels was not uniform across Australia. Some media publications reported from satellite imagery that NO_2 concentration levels decreased in Sydney but not in Perth and Melbourne [16]. As noted in the above paragraph, in most studies investigating changes in air quality, significant improvement was observed. However, in Australia, the lockdown period followed the Black Summer of 2019–2020 and coincided with the season of prescribed burns [17]. This paper investigates the changes in the concentration of criteria pollutants such as $PM_{2.5}$, PM_{10}, nitrogen dioxide, ozone, and sulphur dioxide during the lockdown period of 2020 compared to the pre-lockdown period of 2020, the preceding years from 2016 to 2019, and 2021.

2. Materials and Methods

2.1. Study Area

This study focuses on Brisbane City, which is situated in the Queensland state of Australia. Brisbane has coordinates of 27°28′2.39″S 153°01′24.00″E, and is the third largest city on the southeastern coast of Queensland. The city is surrounded by hills in the northwest [18]. Brisbane has the second-largest area in Australia, at 15,842 km^2. Brisbane's total population is 2,568,927 as of the 2021 Australian Census [19].

The air quality monitoring data were retrieved from the Queensland government's website (https://www.qld.gov.au, last accessed on 15 December 2022). The Queensland government's Department of Environment and Science maintains a range of air quality stations across the state. The locations of the monitoring stations used in this study are presented in Figure 1.

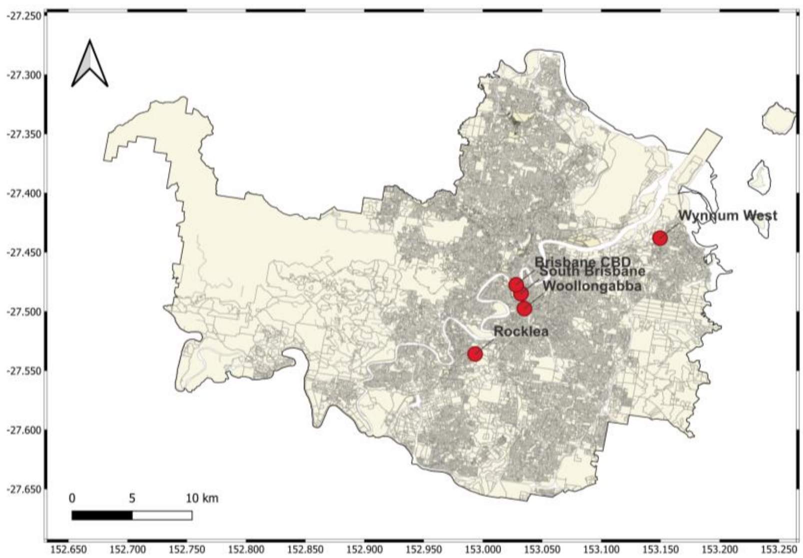

Figure 1. Study area boundary and location of monitoring stations.

We chose Rocklea monitoring station to collect most of the data on various air quality parameters such as PM_{10}, $PM_{2.5}$, NO_2, and ozone. The SO_2 monitoring data was collected from Springwood monitoring station. Meteorological parameters such as wind speed, wind direction, relative humidity, and ambient temperature were also collected from Rocklea monitoring station. Located approximately 500 metres southeast of the railway line in the grounds of the Oxley Common, the Rocklea monitoring station is surrounded by open parkland with light industry and residential uses surrounding the site. The site is well-placed to represent the background air quality for Brisbane and often used to establish the background concentrations in the air quality dispersion modelling assessments for different industrial emission sources in Brisbane. To investigate the impact of restricted emissions and behavioural changes, we analysed the $PM_{2.5}$, PM_{10}, and NO_2 data from other monitoring stations such as Brisbane Central Business Districts (Brisbane CBD), Woolloongabba, and South Brisbane.

2.2. Analysis Methodology

The raw data with hourly averages was downloaded and cleaned for any error values due to instrument malfunction such as -9999 and -1111. The error values were replaced with empty data cells. The plots were generated using the OpenAir package in the R programming environment. To analyse the impact of COVID-19 restrictions, the pollutant concentration data were segregated into periods: pre-lockdown (1 January 2020 to 19 March 2020), lockdown period (20 March 2020 to 5 June 2020), and post-lockdown period (6 June 2020 to 31 December 2020). The different periods were again compared with the same periods for each of the last four years (2016 to 2019) and for the year 2021. The comparison of pollutant concentrations for one year does not give a very clear idea of the variation in the emissions of the pollutants as the variations in the pollutants are very much dependent on the meteorological parameters [20], hence the meteorology of the other years was also compared.

3. Results and Discussion

3.1. Analysis of Meteorological Parameters

The changes in the meteorological parameters are presented in Figures 2 and 3. The wind speed and wind direction are presented in the form on wind-rose plots for different monitoring periods of 2020 in Figure 2. In general, the prevalent winds were from the northeast and southwest quadrants. There was a lower frequency of winds from the northeast quarter, which could be due to seasonal variation during the lockdown period and early parts of the post-lockdown period.

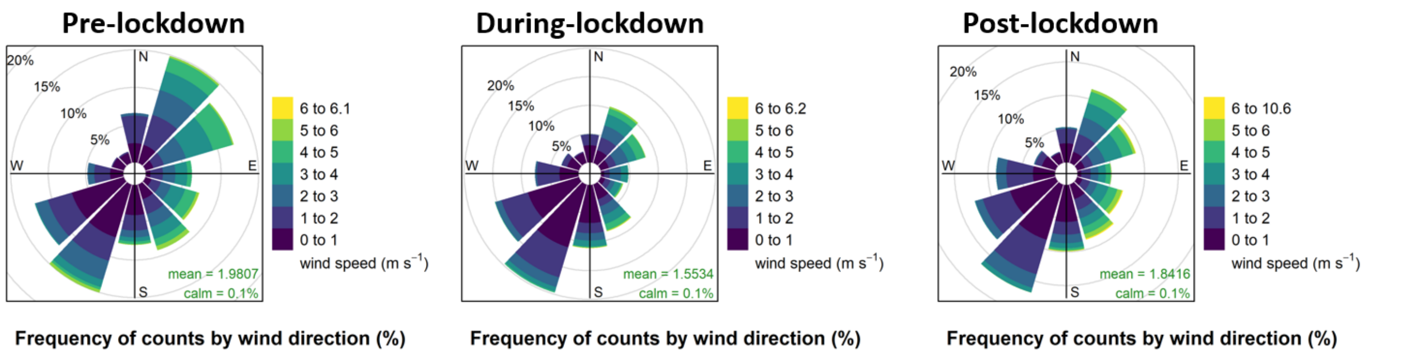

Figure 2. Wind-rose plots for different monitoring periods of the year 2020.

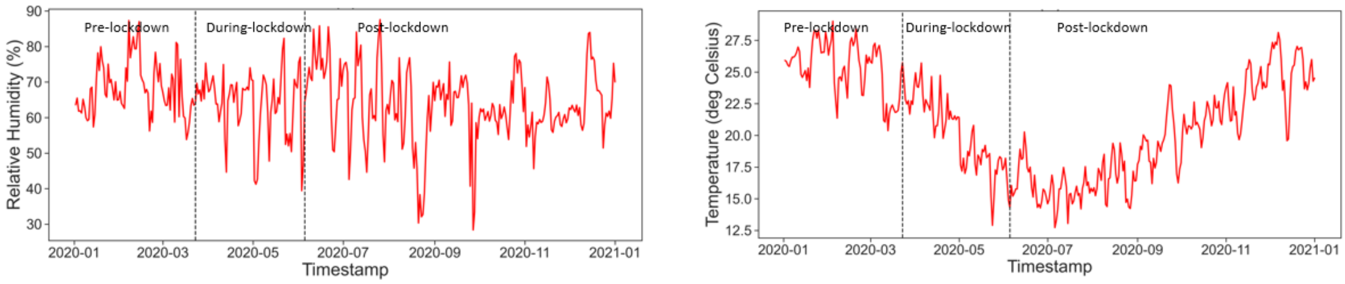

Figure 3. The variation in daily average relative humidity and temperature for different monitoring periods of the year 2020.

Figure 3 illustrates the daily average variation in ambient temperature and relative humidity. During the pre-lockdown period, temperatures were higher compared to during lockdown and the post-lockdown period, such that the highest temperature in the post-lockdown period was 0.1 °C lower than the lowest temperature in the pre-lockdown period. The average temperature of the study periods was found to follow a monotonically decreasing trend, having the highest average of 25.4 °C during the pre-lockdown period. The summer weather for Brisbane starts from December and winter starts from June [21].

A similar trend was observed for wind speed. With an average wind speed of 1.5 m/s, in the during-lockdown period, more frequent winds were from the south and southwest. According to the Bureau of Meteorology, Australia, Brisbane falls under the category of 'light winds' because the maximum daily average wind speed was 4 m/s, even though Brisbane comes under a tropical cyclone risk area [22]. Nonetheless, hourly wind speeds of up to 6.3 m/s were observed in Brisbane during the pre-lockdown and during-lockdown periods, which were mostly southerly winds. For the sudden increment of wind speed, we can consider Brisbane's topography, as well as the pressure-gradient force, the vertical exchange of horizontal momentum in the boundary layer, and the Coriolis force as some of the factors affecting it [23]. In terms of wind speed, the post-lockdown period was relatively calm, and slow and calm wind speeds are due to northerly winds. The statistical comparison of the different meteorological parameters for the during-lockdown period for the years 2016 to 2021 are shown in Table S1. There were no substantial differences in the meteorological variables among years during the lockdown period.

3.2. Analysis of Pollutants for 2020 Events

This section explains the differences in the 24 h average concentrations for the different pollutants in 2020. Table S2 in the Supplementary Materials summarises the changes in different statistical parameters for 24 h concentrations of all pollutants for 2020.

3.2.1. Particulate Matter

The time-series 24 h average PM_{10} and $PM_{2.5}$ concentrations are presented in Figure 4. The average 24 h PM_{10} concentration at Rocklea dropped by 15.8% during the lockdown period compared to the pre-lockdown concentration. Similarly, the 24 h PM_{10} concentration dropped by 8.2%, 3.1%, and 3.1% in Brisbane-CBD, South-Brisbane, and Woolloongabba, respectively. The average 24 h PM_{10} concentration witnessed a reduction of 8.3% during the lockdown period. The maximum 24 h concentration in the pre-lockdown period was 48 $\mu g/m^3$ recorded on 20 February 2020. However, this concentration was the only peak recorded in contrast to the general trend. This could be due to some regional event that resulted in the elevated concentration. Similarly, the during-lockdown period also recorded two minor peaks of 32 and 23 $\mu g/m^3$. The overall air quality levels did not change significantly on removing the peaks due to background events such as dust storms. The average 24 h PM_{10} concentration dropped by 7.5% during the lockdown period compared to the pre-lockdown period on removing the peaks due to background events. Hence, the reduction in the PM_{10} concentration could be due to the restricted transportation traffic and industrial emissions. Similar observations were made in other metropolitan cities around the world [24,25]. In addition to anthropogenic activities, the role of meteorology cannot be ignored. For example, there was a higher frequency of winds from the northeastern quadrant in 2020 during the lockdown period, as shown in Figure S1 (Supplementary Materials). Similarly, there were some notable differences in the frequency of the counts by wind direction for other years, as shown in Figures S2 and S3.

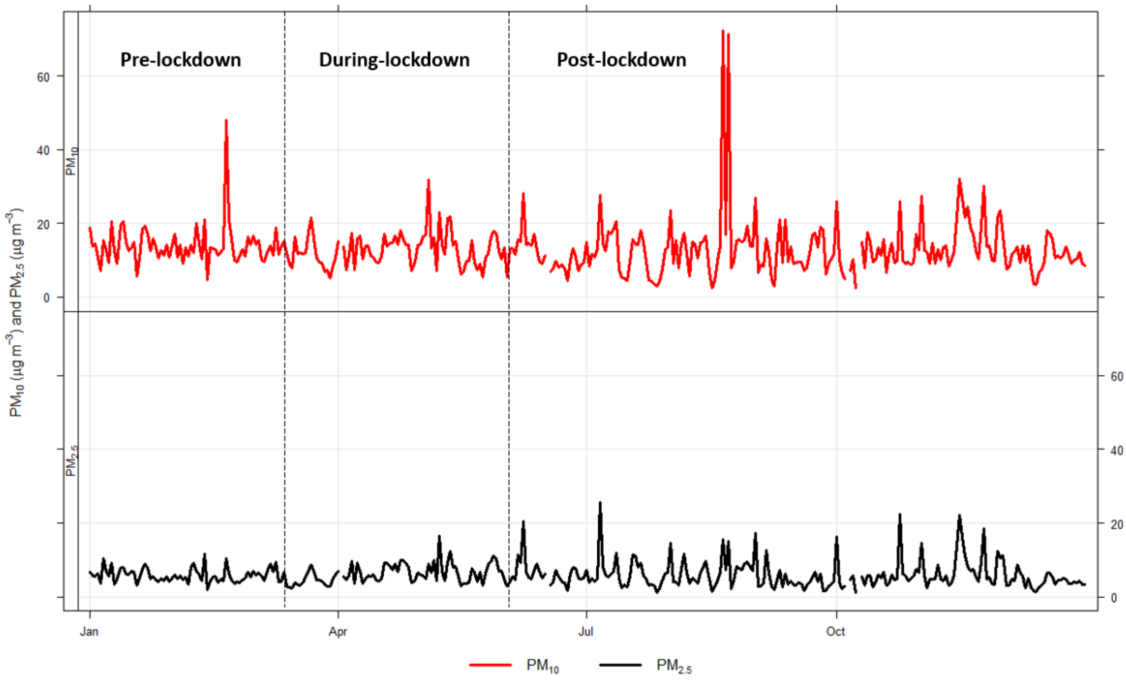

Figure 4. The variation in 24 h PM_{10} and $PM_{2.5}$ concentrations at Rocklea monitoring station for different periods.

In comparison to the pre-lockdown period, the during-lockdown period witnessed an increase of 10% of the average 24 h $PM_{2.5}$ concentration. The 24 h concentration during the post-lockdown period dropped marginally by 0.6% compared to during the lockdown period. The post-lockdown period also observed some peaks such as one of 25.6 $\mu g/m^3$ on 7 June 2020, which could have resulted from pyrogenic emissions or other regional events. Corresponding peaks were also observed in the PM_{10} plot. Hence, lockdown had little to no effect on the $PM_{2.5}$ concentration in the Rocklea area. This could be due to several reasons such as regional events, and the fact that vehicle movement was not as prominent as in the rest of Brisbane due to its proximity to light industry. The lockdown restrictions imposed in Brisbane were not like the curfew-like conditions in the rest of the world. Essential industries were allowed to operate as usual. Further, some peaks were noticed in the $PM_{2.5}$ concentration levels during the lockdown period, which could be due to a regional event and pyrogenic emission episodes [26–28].

Therefore, comparison of different periods at other monitoring stations gives a good indication of the impact of restrictions on $PM_{2.5}$ and PM_{10} concentration levels, as shown in Figure 5. The 24 h $PM_{2.5}$ concentration levels dropped by 13.5%, 12.3%, and 5.4% in Brisbane-CBD, South-Brisbane, and Woolloongabba, respectively. In general, Rocklea monitoring station recorded the lowest 24 h PM_{10} concentration and the highest $PM_{2.5}$ concentration compared to the other monitoring stations. However, for the post-lockdown period, Rocklea monitoring station recorded the lowest 24 h $PM_{2.5}$ concentration compared to the other stations.

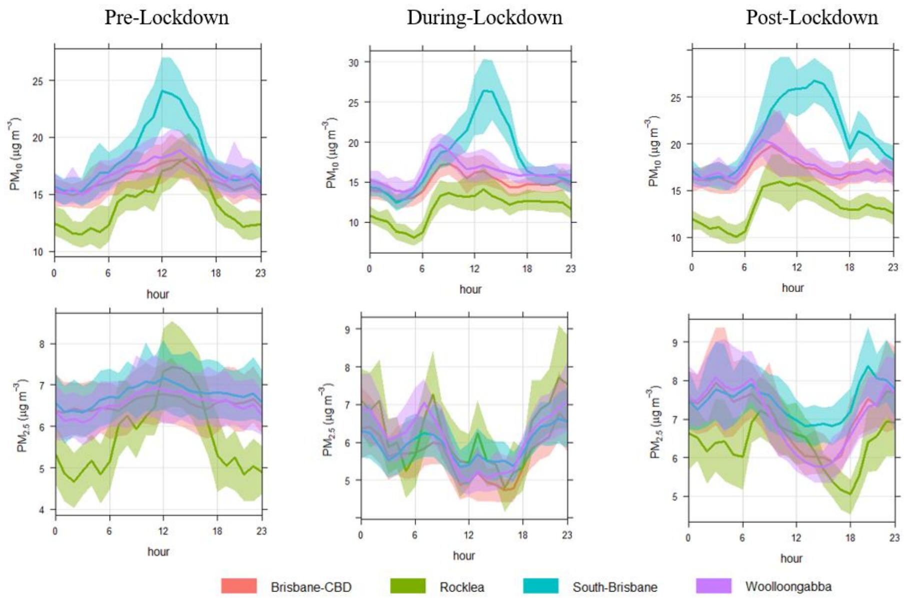

Figure 5. Hourly diurnal profile of PM_{10} and $PM_{2.5}$ concentrations at different monitoring stations during various periods.

3.2.2. Nitrogen Dioxide

Anthropogenic emissions from sources such as the combustion of fossil fuels (coal, gas, and oil), especially fuel used in vehicles and industrial activities, are mainly responsible for increasing level of nitric oxides (90 to 95%) and nitrogen dioxides (5 to 10%) [29–34]. In the atmosphere, hydroperoxyl radicals (HO_2) and organic peroxy radicals (RO_2) react with nitric oxide (NO) to convert it to NO_2; thus, increases in NO emissions lead to increases in NO_2 concentrations [35]. In Brisbane, the lockdown conditions were not similar to the rest of world. They did not restrict local transportation to ensure social distancing, but for maintaining social distancing during travel people were using personal vehicles. Exhaust emissions from personal vehicles could be a major source of nitrogen oxide (NO) that is converted to nitrogen dioxide by atmospheric chemistry. Also, during the post-lockdown period there were 10%, 12%, and 24% increases in the use of private vehicles in January 2021, July 2021, and January 2022, respectively, which could be responsible for the increased levels of NO_2 during the post-lockdown period compared to pre-lockdown conditions [36].

The 24 h average NO_2 concentration level and diurnal trends at Rocklea monitoring station are presented in Figure 6. As observed, the 24 h average concentration shows an increasing trend during the lockdown period. The 24 h average NO_2 concentration increased by 39% during the lockdown period compared to the pre-lockdown period. To further investigate the impact of restrictions, we analysed the changes in NO and NOx concentration levels at Rocklea monitoring station. The diurnal trends of NO, NO_2, and NOx are presented in Supplementary Materials Figure S4. The NO levels increased by 32% during lockdown compared to pre-lockdown levels. The NO levels were relatively similar during the post-lockdown period, i.e., they increased marginally by 0.3% compared to during the lockdown period. This means vehicular movement was higher during lockdown and the post-lockdown period. This is well-supported by public surveys in Australia [36]. Figure 7 shows a comparison of diurnal patterns of NO_2 concentration levels at different monitoring stations. There is a clear similarity in the diurnal profile of NO_2 in the during- and post-lockdown periods. The NO_2 concentration levels at South Brisbane and Woolloongabba monitoring stations were substantially higher than at Rocklea monitoring station. This could be due to the placement of the monitoring stations, as they are close to a major highway. A similar trend was observed in the $PM_{2.5}$ and PM_{10} emissions, as discussed in Section 3.2.1.

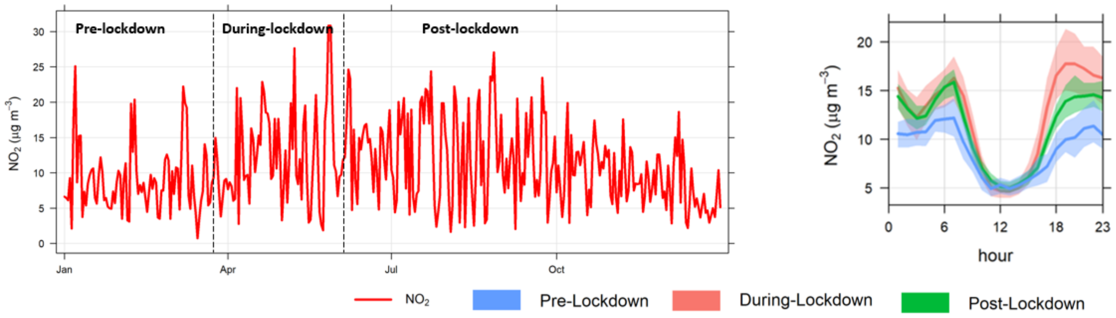

Figure 6. The variation in 24 h concentrations and hourly diurnal profile of NO_2 at Rocklea monitoring station for different periods.

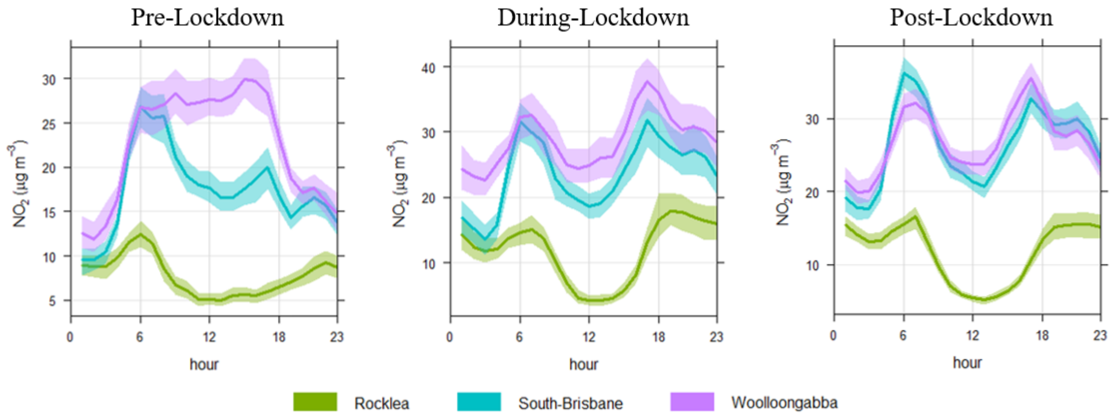

Figure 7. Hourly diurnal profile of NO_2 concentrations at different monitoring stations during various periods.

However, the post-lockdown period observed a decreasing trend as the average 24 h concentration dropped by 10% compared to the during-lockdown period. The NO_2 to NO_x ratio increased by 2% during the lockdown period compared to the pre-lockdown period. On the other hand, the NO_2 to NO_x ratio decreased by 6% during the post-lockdown period. The lower share of NO_2 levels for different periods in NO_x could be related to NO_2 changes due to seasonal variation and the increments in NO concentration levels could be related to more vehicles on the roads [36]. A similar pattern was also observed in Sydney by Duc et al. [37]. The authors mentioned that the variation in NO_2 concentration could be due to the photochemical reaction change involving nitrogen oxides, carbon monoxide, volatile organic compounds, and ozone from Australian summer months (December to February) to Australian autumn months (March to May) and winter months (June to August), which results in the reduction of ambient temperature. As the solar insolation decreased during Australian winters, there was a reduction in photochemical activities, and ozone was rapidly consumed by nitrogen monoxide (NO) and nitrogen dioxide produced [38].

The increasing trend of NO_2 levels is also evident in the diurnal pattern which gives the finer details of the average change in the NO_2 concentration levels at each hour of the day. This type of analysis has been used by several authors to assess the impact of different ambient conditions on the pollutant concentration. The NO_2 concentration levels were typically higher in the morning and then dropped during the mid-day before peaking in the evening at around 18:00 h. This increment in the NO_2 concentration levels was more dominant during the lockdown period.

3.2.3. Ozone

The presence of nitrogen oxides (NO_x), volatile organic compounds (VOCs), and solar irradiation are the cause of the formation of the secondary pollutant ozone [33]. The composition of photochemically aged air advected into a region (urban or rural) and mixed with local emissions has long been recognised as a key control on the production rates of ozone and other photochemical species. For O_3 production, nitrogen dioxide serves as a precursor [24]. The oxidation of NO by O_3, and combustion processes such as industrial boilers, vehicles, and ships are responsible for the direct emission of NO_2, even if there was a restriction related to the pandemic on public transit [25,38,39]. The 24 h average ozone concentration levels and the hourly diurnal profile are presented in Figure 8.

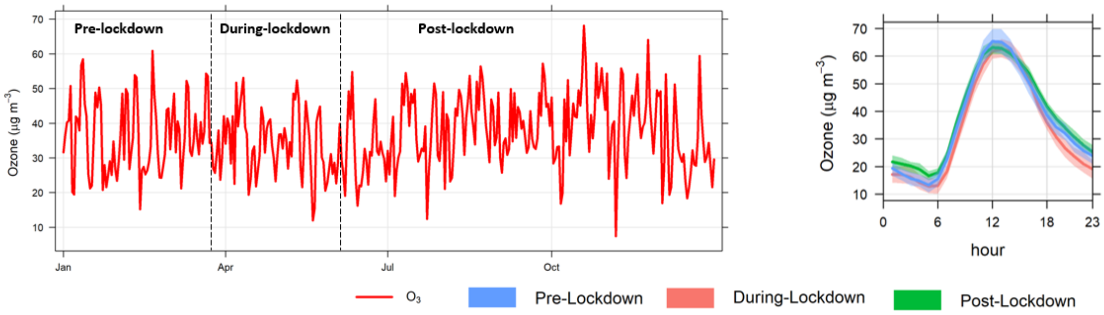

Figure 8. The variation in 24 h concentrations and hourly diurnal profile of ozone at Rocklea monitoring station for different periods.

As observed in Figure 8, the maximum daily concentration in the pre-lockdown period was 60.8 $\mu g/m^3$ in addition to some of the other peaks. In contrast, the maximum daily concentration during lockdown and post-lockdown was observed to be 53.1 and 68.1 $\mu g/m^3$. The average 24 h concentration dropped by 7.2% during the lockdown period compared to the pre-lockdown period and then increased by 12.4% during the post-lockdown period. On the other hand, the reduction in the median 24 h ozone levels was relatively lower (4.4%).

Similar trends were observed in the diurnal profile (right side of Figure 8). Peak ozone was observed during 10:00 to 16:00 h with the minimum concentration in the morning during 06:00 to 08:00 h. This agrees with the local diurnal temperature profiles and the typical NOx titration from local motor-vehicle-related emissions in the morning. The decreasing trend of ozone levels during the lockdown period could also be attributed to the seasonal variation as higher ozone levels occur in the warmer months (October to March) and peak ozone is usually recorded in January. In addition, the ambient emission concentrations also change seasonally as the solid-fuel heating and temperature-dependent emissions change due to weather changes [40]. Some evidence comes from a similar study conducted on ten major world cities from February to April. Sydney and Perth were included in this study and a comparison was made of February to April 2020 and 2019. The authors observed a reduction in NO_2, CO, and PM in February, March, and April but an increase in O_3 in February and April [37,41]. It is not an unexpected observation that median O_3 levels increased during the lockdown period. Mostly in volatile organic compounds (VOC), a limited regime of ozone formation occurs and, because of reduced levels of NO_x, the photochemistry reaction rate tends to increase and ozone levels also increase [42].

3.2.4. Sulphur Dioxide

The variation in the 24 h average concentration and the hourly diurnal profile are presented in the Figure 9. The pre-lockdown period witnessed a series of high 24 h SO_2 concentration levels during 19 January to 24 January 2020 when the concentration ranged between 10 and 37 $\mu g/m^3$. Similarly, several peaks were observed during lockdown and post-lockdown, such as a 24 h average concentration of 18 $\mu g/m^3$ on 30 April and 22 $\mu g/m^3$ on 31 October 2020. The average 24 h concentration during the lockdown period decreased by 18% whereas a negligible increment of 0.5% was observed during the post-lockdown period. As observed in the diurnal profile of the SO_2 concentration levels (Figure 6, right hand side plot), the SO_2 concentration levels peaked between 16:00 and 19:00 h, which could be due to vehicular movement. It could be inferred that SO_2 levels dropped during the lockdown period due to less traffic activity. The registered peak could be due to the regional wildfire events [43].

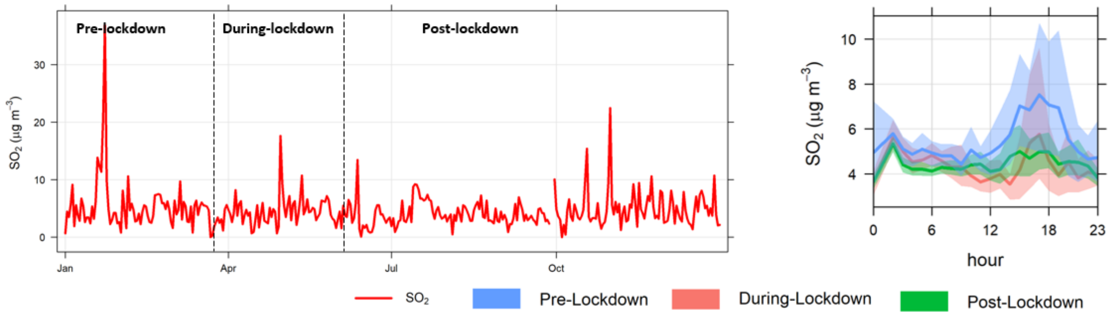

Figure 9. The variation in 24 h concentrations and hourly diurnal profile of SO_2 at Rocklea monitoring station for different periods.

3.3. Annual Trend Analysis of the Pollutants for 2016 to 2019 and 2021

The comparison of pollutant concentrations for one year does not give a very clear idea of the variation in the emissions of the pollutants as they are very much dependent on meteorological parameters [20]. As discussed above in Section 3.2, the changes in the criteria pollutants' concentration, especially NO_2 and O_3, were dependent on the seasonal variation between pre-lockdown and lockdown periods. Thus, comparison of the same period of different years gives more confidence to investigate if lockdown restrictions really affected the changes in the pollutants' concentrations. The comparison of the 24 h average concentration for different pollutants is presented in Figures S5 to S9 in the Supplementary Materials.

Figure 10 presents the comparison of PM_{10}, $PM_{2.5}$, and PM Ratio ($PM_{2.5}/PM_{10}$) for different periods from 2016 to 2021. The extreme high concentrations (24 h level of greater than 150 µg/m^3 for PM_{10} and greater than 50 µg/m^3 for $PM_{2.5}$) were excluded for better representation of these plots. As observed, the median values for 24 h PM_{10} concentrations during the pre-lockdown period remained similar for 2018 and 2019 but varied for other years. The post-lockdown period for all years observed greater variability in the median 24 h PM_{10} concentration levels. The year 2019 recorded the highest median value of 18.4 µg/m^3 whereas other years ranged between 10.4 to 15 µg/m^3. The higher median 24 h PM_{10} concentration for 2019 could be attributed to the wildfires during the summer of 2019–2020. This is the reason that PM_{10} levels were higher during the overlapping pre-lockdown period in 2020.

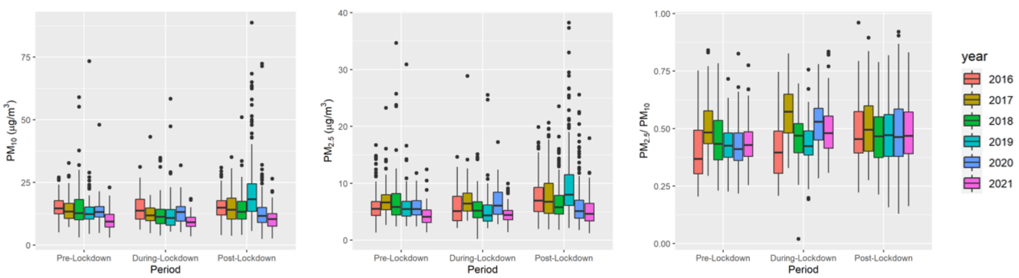

Figure 10. Comparison of PM_{10}, $PM_{2.5}$, and PM Ratio for different periods from 2016 to 2021.

In contrast to PM_{10} observations, the $PM_{2.5}$ trends were higher. The literature research has shown that $PM_{2.5}$ particles represent a main pollutant emitted from wildfire smoke constituting approximately 90% of the total particle mass [44–47]. A higher 24 h average on certain days in 2020 was observed (as shown in Figure S6). The PM ratio (ratio of $PM_{2.5}$

to PM_{10}) was higher during the lockdown period in 2020 compared to other years. This shows that during the lockdown period in 2020 $PM_{2.5}$ was impacted by background events of which the impact of the COVID-19 lockdown restrictions dominated. However, this was not the case for rest of Australia. The greater metropolitan region in New South Wales state observed a 12% reduction in $PM_{2.5}$ during the lockdown period in 2020 compared to 2019 [37].

As observed in Figure 11, the median of the 24 h NO_2 concentration levels during the lockdown period of 2020 was 14% higher than the average of the corresponding median values for 2016 to 2019. This was mainly due to the high-than-average NO_2 concentration during 2017 and 2018. Duc et al. [37] attributed the higher NO_2 concentrations during similar periods of 2017 and 2018 to higher temperatures. However, this was not the case in Brisbane as the median and mean temperature were not significantly different for all years except for the pre- and during-lockdown periods of 2021, as shown in Figure 12.

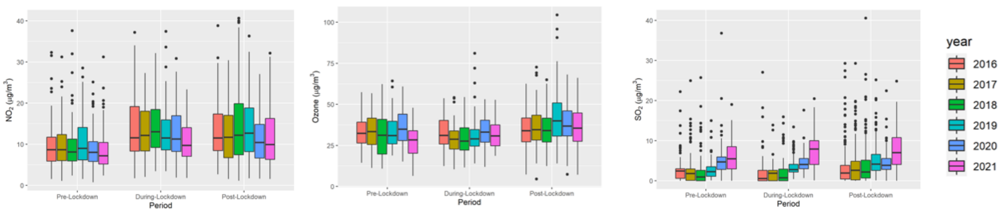

Figure 11. Comparison of NO_2, ozone, and SO_2 for different periods from 2016 to 2021.

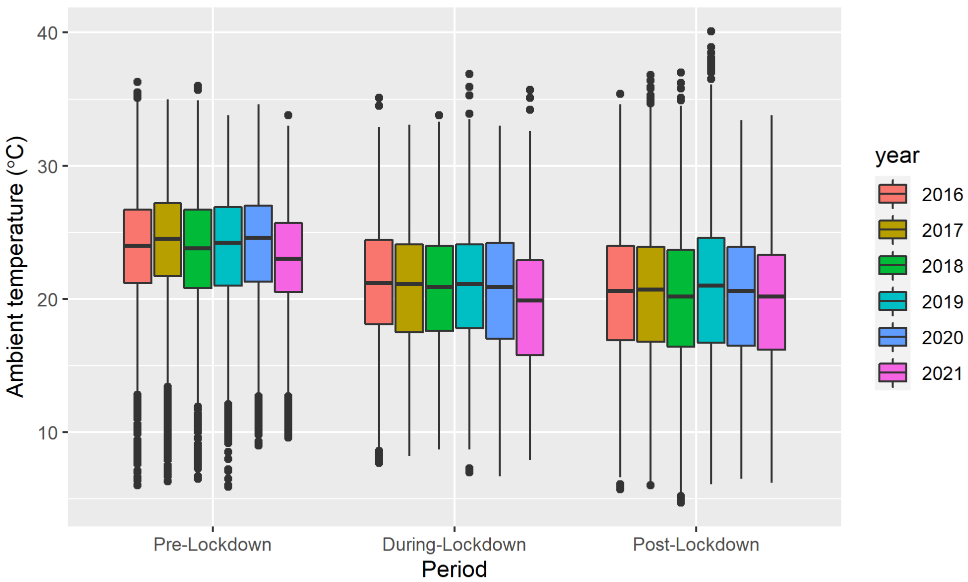

Figure 12. Comparison of ambient temperature for different periods from 2016 to 2021.

On the other hand, the ozone concentrations were higher in the pre-lockdown and lockdown periods of 2020 compared to the similar periods in the preceding years. However, the post-lockdown period in 2020 and 2021 recorded lower median ozone concentration levels compared to 2016 to 2019 levels. This inconsistency in the trend of ozone levels between 2019 and 2020 at different sites could be due to different meteorological conditions, as well as the photochemistry mechanism. The ozone levels were particularly higher in the pre-lockdown period of 2020 and post-lockdown period of 2019 which overlapped with the pyrogenic events and heatwave episodes of 2019–2020 in southeast Australia [48,49]. In contrast to the other pollutants, SO_2 concentration levels were highest in 2021.

4. Conclusions

Pyrogenic emissions such as bushfires, prescribed burns, and agricultural burning along with the COVID-19-related restrictions and post-lockdown behavioural changes have resulted in episodes of substantial changes (positive or negative) in air quality parameters. The various criteria pollutants for different periods in 2020 were analysed and their comparison with the corresponding periods in 2016 to 2019 and 2021 was conducted. The following conclusions can be drawn from this study:

1. The air quality levels during the lockdown period improved; however, some pollutant concentrations were largely impacted by background events.
2. Meteorology also played an important role in the changes in pollutant concentration across different periods. However, across the different years, meteorological conditions were only marginal different. For example, there was a higher frequency of winds from the northeastern quadrant in 2020 during the lockdown period.
3. The average 24 h PM_{10} concentration dropped by 3.1% to 15.8% during the lockdown period compared to the pre-lockdown concentration levels at different monitoring stations.
4. The lockdown period had no impact on the $PM_{2.5}$ concentration levels at Rocklea monitoring station. In comparison to the pre-lockdown period, the during-lockdown period witnessed an increase of 10% in the average 24 h $PM_{2.5}$ concentration. The 24 h concentration during the post-lockdown period dropped marginally by 0.6% compared to during the lockdown period. The $PM_{2.5}$ could be largely impacted by background events such as dust storms and bushfires. The 24 h $PM_{2.5}$ concentration levels dropped by 13.5%, 12.3%, and 5.4% in Brisbane-CBD, South-Brisbane, and Woolloongabba, respectively.
5. The 24 h average NO_2 concentration increased by 39% during the lockdown period compared to the pre-lockdown period. The median of the 24 h NO_2 concentration levels during the lockdown period of 2020 was 14% higher than the average of the corresponding median values for 2016 to 2019. This was mainly due to the higher-than-average NO_2 concentration during 2017 and 2018.
6. The average 24 h SO_2 concentration during the lockdown period decreased by 18%, whereas a negligible increment of 0.5% was observed during the post-lockdown period. The diurnal profile of the SO_2 concentration levels showed an incremental trend in the evening which could be due to vehicular movement.

The implication from COVID-19-related restrictions showed that the improvements in the concentration of criteria pollutants was small but measurable. Natural activities such as bushfires impacted the concentration substantially and contributed to elevated background levels. Hence, due to the location of monitoring stations and contextual natural events, the transition from combustion vehicles to electric or hybrid vehicles may not be enough for reducing pollutant concentrations in the future and biogenic sources such as dust and bushfires also play a critical role in air quality management in urban areas.

Supplementary Materials: https://www.mdpi.com/article/10.3390/pr11010296/s1, Figure S1: Windrose plots for pre-lockdown period for different years, Figure S2: Windrose plots for during-lockdown period for different years, Figure S3: Windrose plots for post-lockdown period for different years, Figure S4: Diurnal trends of NO, NO2 and NOx concentration levels at Rocklea monitoring station for year 2020, Figure S5: Calendar plot for Average 24-h PM10 concentration, Figure S6: Calendar plot for Average 24-h PM2.5 concentration, Figure S7: Calendar plot for Average 24-h NO2 concentration, Figure S8: Calendar plot for Average 24-h Ozone concentration, Figure S9: Calendar plot for Average 24-h SO2 concentration; Table S1. Data Attributes for Meteorological Parameters, Table S2. Statistical Data Attributes for pollutant parameters.

Author Contributions: Conceptualization, S.C., P.V. and A.Z.; Data curation, S.S., S.K.B. and P.V.; Formal analysis, S.C., S.S., S.K.B. and A.Z.; Methodology, S.C.; Project administration, G.D. and P.V.; Resources, G.D.; Software, S.C.; Supervision, G.D. and P.V.; Writing—original draft, S.C.; Writing—review & editing, G.D., A.Z. and P.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data for this study can be accessed from the Queensland Government website (https://www.data.qld.gov.au, last accessed on 15 December 2022).

Acknowledgments: The authors duly acknowledge the Queensland Government Department of Environment and Science for maintaining the air quality monitoring stations and Don Neale providing all of the datasets used in this study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tiwari, A.; Williams, I. *Air Pollution: Measurement, Modelling and Mitigation, Fourth Edition*, 4th ed.; CRC Press: Boca Raton, FL, USA, 2018; Volume 13, 33487-2742; ISBN 978-1138503663.
2. Whitacre, P. Air Pollution Accounts for 1 in 8 Deaths Worldwide, According to New WHO Estimates. *WHO News Release*, 25 March 2014.
3. GBD MAPS Working Group. Burden of Disease Attributable to Major Air Pollution Sources in India—Health Effects Institute. 2018. Available online: https://www.healtheffects.org/publication/gbd-air-pollution-india (accessed on 1 May 2021).
4. Wong, Y.J.; Shiu, H.-Y.; Chang, J.H.-H.; Ooi, M.C.G.; Li, H.-H.; Homma, R.; Shimizu, Y.; Chiueh, P.-T.; Maneechot, L.; Nik Sulaiman, N.M. Spatiotemporal Impact of COVID-19 on Taiwan Air Quality in the Absence of a Lockdown: Influence of Urban Public Transportation Use and Meteorological Conditions. *J. Clean. Prod.* **2022**, *365*, 132893. [CrossRef] [PubMed]
5. Gautam, A.S.; Dilwaliya, N.K.; Srivastava, A.; Kumar, S.; Bauddh, K.; Siingh, D.; Shah, M.A.; Singh, K.; Gautam, S. Temporary Reduction in Air Pollution Due to Anthropogenic Activity Switch-off during COVID-19 Lockdown in Northern Parts of India. *Environ. Dev. Sustain.* **2021**, *23*, 8774–8797. [CrossRef] [PubMed]
6. Jain, S.; Sharma, T. Social and Travel Lockdown Impact Considering Coronavirus Disease (COVID-19) on Air Quality in Megacities of India: Present Benefits, Future Challenges and Way Forward. *Aerosol Air Qual. Res.* **2020**, *20*, 1222–1236. [CrossRef]
7. Hu, M.; Chen, Z.; Cui, H.; Wang, T.; Zhang, C.; Yun, K. Air Pollution and Critical Air Pollutant Assessment during and after COVID-19 Lockdowns: Evidence from Pandemic Hotspots in China, the Republic of Korea, Japan, and India. *Atmos. Pollut. Res.* **2021**, *12*, 316–329. [CrossRef] [PubMed]
8. Mor, S.; Kumar, S.; Singh, T.; Dogra, S.; Pandey, V.; Ravindra, K. Impact of COVID-19 Lockdown on Air Quality in Chandigarh, India: Understanding the Emission Sources during Controlled Anthropogenic Activities. *Chemosphere* **2021**, *263*, 127978. [CrossRef]
9. Gouda, K.C.; Singh, P.; Benke, M.; Kumari, R.; Agnihotri, G.; Hungund, K.M. Assessment of Air Pollution Status during COVID-19 Lockdown (March–May 2020) over Bangalore City in India. *Environ. Monit. Assess.* **2021**, *193*, 395. [CrossRef]
10. Queensland Government Business Closures and Restrictions. Available online: https://statements.qld.gov.au/statements/89582 (accessed on 15 October 2022).
11. Van Der Werf, G.R.; Randerson, J.T.; Collatz, G.J.; Giglio, L.; Kasibhatla, P.S.; Arellano, A.F.; Olsen, S.C.; Kasischke, E.S. Continental-Scale Partitioning of Fire Emissions During the 1997 to 2001 El Niño/La Niña Period. *Science* **2004**, *303*, 73–76. [CrossRef]
12. Castagna, J.; Senatore, A.; Bencardino, M.; D'Amore, F.; Sprovieri, F.; Pirrone, N.; Mendicino, G. Multiscale Assessment of the Impact on Air Quality of an Intense Wildfire Season in Southern Italy. *Sci. Total Environ.* **2021**, *761*, 143271. [CrossRef]
13. Queensland Government State of the Environment Report. Key Messages. 2021. Available online: https://www.stateoftheenvironment.des.qld.gov.au/pollution/air-quality (accessed on 6 May 2022).
14. Deng, M.; Lai, G.; Li, Q.; Li, W.; Pan, Y.; Li, K. Impact Analysis of COVID-19 Pandemic Control Measures on Nighttime Light and Air Quality in Cities. *Remote Sens. Appl.* **2022**, *27*, 100806. [CrossRef]
15. Rodríguez-Urrego, D.; Rodríguez-Urrego, L. Air Quality during the COVID-19: PM2.5 Analysis in the 50 Most Polluted Capital Cities in the World. *Environ. Pollut.* **2020**, *266*, 115042. [CrossRef]
16. Sánchez-García, E.; Leon, J. These 5 Images Show How Air Pollution Changed over Australia's Major Cities before and after Lockdown. 2020. Available online: https://theconversation.com/these-5-images-show-how-air-pollution-changed-over-australias-major-cities-before-and-after-lockdown-136723 (accessed on 6 December 2022).
17. Brisbane City Council. Planned Burns. 2023. Available online: https://www.brisbane.qld.gov.au/community-and-safety/community-safety/disasters-and-emergencies/types-of-disasters/busfires/plannedburns#:~{}:text=Most%20planned%20burns%20in%20Brisbane,day%20for%20each%20planned%20burn (accessed on 6 December 2022).
18. Latitude. GPS Coordinates of Brisbane, Australia. Available online: https://latitude.to/articles-by-country/au/australia/452/brisbane (accessed on 30 May 2021).

19. Australian Bureau of Statistics Regional Population. Statistics about the Population for Australia's Capital Cities and Regions. Available online: https://www.abs.gov.au/statistics/people/population/regional-population/latest-release (accessed on 15 October 2022).
20. Elminir, H.K. Dependence of Urban Air Pollutants on Meteorology. *Sci. Total Environ.* **2005**, *350*, 225–237. [CrossRef]
21. Tourism Australia. Weather in Australia. Available online: https://www.australia.com/en-in/facts-and-planning/weather-in-australia.html (accessed on 9 May 2021).
22. Marine Knowledge Centre Waves. Reference Material. Available online: http://www.bom.gov.au/marine/knowledge-centre/reference/wind.shtml (accessed on 9 May 2021).
23. Wu, J.; Zha, J.; Zhao, D.; Yang, Q. Changes in Terrestrial Near-Surface Wind Speed and Their Possible Causes: An Overview. *Clim. Dyn.* **2018**, *51*, 2039–2078. [CrossRef]
24. Xu, K.; Cui, K.; Young, L.-H.; Hsieh, Y.-K.; Wang, Y.-F.; Zhang, J.; Wan, S. Impact of the COVID-19 Event on Air Quality in Central China. *Aerosol Air Qual. Res.* **2020**, *20*, 915–929. [CrossRef]
25. Collivignarelli, M.C.; Abbà, A.; Bertanza, G.; Pedrazzani, R.; Ricciardi, P.; Carnevale Miino, M. Lockdown for CoViD-2019 in Milan: What Are the Effects on Air Quality? *Sci. Total Environ.* **2020**, *732*, 139280. [CrossRef]
26. Van Oldenborgh, G.J.; Krikken, F.; Lewis, S.; Leach, N.J.; Lehner, F.; Saunders, K.R.; Van Weele, M.; Haustein, K.; Li, S.; Wallom, D.; et al. Attribution of the Australian Bushfire Risk to Anthropogenic Climate Change. *Nat. Hazards Earth Syst. Sci.* **2021**, *21*, 941–960. [CrossRef]
27. Rahman, R.; Zafarullah, H. Impact of Climate Change on Human Health: Adaptation Challenges in Queensland, Australia. *Clim. Res.* **2020**, *80*, 59–72. [CrossRef]
28. Qi, F.; Zhou, Y.; Feng, S. Strengthening Destinations' Resilience from Bushfires—A Study of Eastern Australia. *J. Manag. Sustain.* **2021**, *11*, 43. [CrossRef]
29. Shah, V.; Jacob, D.J.; Li, K.; Silvern, R.F.; Zhai, S.; Liu, M.; Lin, J.; Zhang, Q. Effect of Changing NOx Lifetime on the Seasonality and Long-Term Trends of Satellite-Observed Tropospheric NO2 Columns over China. *Atmos. Chem. Phys.* **2020**, *20*, 1483–1495. [CrossRef]
30. Queensland Government. Nitrogen Oxides. 2013. Available online: https://www.qld.gov.au/environment/management/monitoring/air/air-pollution/pollutants/nitrogen-oxides (accessed on 29 December 2022).
31. United States Environmental Protection Agency. Basic Information about NO2. 2022. Available online: https://www.epa.gov/no2-pollution/basic-information-about-no2#What%20is%20NO2 (accessed on 29 December 2022).
32. Jarvis, D.J.; Adamkiewicz, G.; Heroux, M.-E.; Rapp, R.; Kelly, F.J. Nitrogen dioxide. 2010. Available online: https://www.ncbi.nlm.nih.gov/books/NBK138707/ (accessed on 29 December 2022).
33. Davis, M.L.; Cornwell, D.A. *Introduction to Environmental Engineering*; McGraw-Hill: New York, NY, USA, 2008.
34. Goldberg, D.L.; Anenberg, S.C.; Griffin, D.; McLinden, C.A.; Lu, Z.; Streets, D.G. Disentangling the Impact of the COVID-19 Lockdowns on Urban NO2 From Natural Variability. *Geophys. Res. Lett.* **2020**, *47*, e2020GL089269. [CrossRef]
35. Stockwell, W.R.; Lawson, C.V.; Saunders, E.; Goliff, W.S. A Review of Tropospheric Atmospheric Chemistry and Gas-Phase Chemical Mechanisms for Air Quality Modeling. *Atmosphere* **2012**, *3*, 1–32. [CrossRef]
36. Transurban. Urban Mobility Trends from COVID-19. 2022. Available online: https://www.transurban.com/content/dam/transurban-pdfs/03/Mobility-Trends-Report-1H22.pdf (accessed on 29 December 2022).
37. Duc, H.; Salter, D.; Azzi, M.; Jiang, N.; Warren, L.; Watt, S.; Riley, M.; White, S.; Trieu, T.; Tzu-Chi Chang, L.; et al. The Effect of Lockdown Period during the COVID-19 Pandemic on Air Quality in Sydney Region, Australia. *Int. J. Environ. Res. Public Health* **2021**, *18*, 3528. [CrossRef] [PubMed]
38. Zhang, C.; Stevenson, D. Characteristic Changes of Ozone and Its Precursors in London during COVID-19 Lockdown and the Ozone Surge Reason Analysis. *Atmos. Environ.* **2022**, *273*, 118980. [CrossRef] [PubMed]
39. Pour-Biazar, A.; McNider, R.T.; Roselle, S.J.; Suggs, R.; Jedlovec, G.; Byun, D.W.; Kim, S.; Lin, C.J.; Ho, T.C.; Haines, S.; et al. Correcting Photolysis Rates on the Basis of Satellite Observed Clouds. *J. Geophys. Res. Atmos.* **2007**, *112*, 1–17. [CrossRef]
40. Riley, M.L.; Watt, S.; Jiang, N. Tropospheric Ozone Measurements at a Rural Town in New South Wales, Australia. *Atmos. Environ.* **2022**, *281*, 119143. [CrossRef]
41. Habibi, H.; Awal, R.; Fares, A.; Ghahremannejad, M. COVID-19 and the Improvement of the Global Air Quality: The Bright Side of a Pandemic. *Atmosphere* **2020**, *11*, 1279. [CrossRef]
42. Wang, Y.; Wen, Y.; Wang, Y.; Zhang, S.; Zhang, K.M.; Zheng, H.; Xing, J.; Wu, Y.; Hao, J. Four-Month Changes in Air Quality during and after the COVID-19 Lockdown in Six Megacities in China. *Environ. Sci. Technol. Lett.* **2020**, *7*, 802–808. [CrossRef]
43. Ditto, J.C.; He, M.; Hass-Mitchell, T.N.; Moussa, S.G.; Hayden, K.; Li, S.-M.; Liggio, J.; Leithead, A.; Lee, P.; Wheeler, M.J.; et al. Atmospheric Evolution of Emissions from a Boreal Forest Fire: The Formation of Highly Functionalized Oxygen-, Nitrogen-, and Sulfur-Containing Organic Compounds. *Atmos. Chem. Phys.* **2021**, *21*, 255–267. [CrossRef]
44. Mahato, S.; Pal, S.; Ghosh, K.G. Effect of Lockdown amid COVID-19 Pandemic on Air Quality of the Megacity Delhi, India. *Sci. Total Environ.* **2020**, *730*, 139086. [CrossRef]
45. Vicente, A.; Alves, C.; Monteiro, C.; Nunes, T.; Mirante, F.; Evtyugina, M.; Cerqueira, M.; Pio, C. Measurement of Trace Gases and Organic Compounds in the Smoke Plume from a Wildfire in Penedono (Central Portugal). *Atmos. Environ.* **2011**, *45*, 5172–5182. [CrossRef]

46. Vicente, A.; Alves, C.; Monteiro, C.; Nunes, T.; Mirante, F.; Cerqueira, M.; Calvo, A.; Pio, C. Organic Speciation of Aerosols from Wildfires in Central Portugal during Summer 2009. *Atmos. Environ.* **2012**, *57*, 186–196. [CrossRef]
47. Vicente, A.; Alves, C.; Calvo, A.I.; Fernandes, A.P.; Nunes, T.; Monteiro, C.; Almeida, S.M.; Pio, C. Emission Factors and Detailed Chemical Composition of Smoke Particles from the 2010 Wildfire Season. *Atmos. Environ.* **2013**, *71*, 295–303. [CrossRef]
48. Bureau of Meteorology. Special Climate Statement 73—Extreme Heat and Fire Weather in December 2019 and January 2020. 2020. Available online: http://www.bom.gov.au/climate/current/statements/scs73.pdf (accessed on 5 December 2022).
49. Bureau of Meteorology. Annual Climate Statement 2020. 2020. Available online: http://www.bom.gov.au/climate/current/annual/aus/2020/ (accessed on 5 December 2022).