The effect of lockdown period during Covid-19 pandemic on air quality in Sydney region, Australia.

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Abstract

In early 2020 from April to early June, the metropolitan area of Sydney as well as the rest of New South Wales (NSW, Australia) experienced a period of lockdown to prevent the spread of Covid-19 virus in the community. The effect of reducing anthropogenic activities including transportation had an impact on the urban environment in term of air quality which is shown to have improved for a number of pollutants, such as nitrogen dioxides (NO_2) and carbon monoxide (CO), based on monitoring data on ground and from satellite. Besides primary pollutants CO and NO_x emitted from mobile sources, $PM_{2.5}$ (primary and secondary) and secondary ozone (O_3) during the lockdown period will also be analysed using both air quality data and modelling method. The results show that NO_2, CO and $PM_{2.5}$ levels decreased during the lockdown, but O_3 instead increased. The change in the concentration levels however are small considering the large reduction in traffic volume of ~30%.

By estimate the decrease in traffic volume in Sydney region, the corresponding decrease in emission input to the WRF-CMAQ (Weather Research and Forecasting - Community Multiscale Air Quality Modeling System) air quality model is then used to estimate the effect of lockdown on the air quality especially CO, NO_2, O_3 and $PM_{2.5}$ in the Greater Metropolitan Region (GMR) of Sydney. COVID-19 lockdown period is an ideal case to study the effect of motor vehicle and mobile source contribution to air pollutants such as those listed above in the GMR.

Keywords: Covid-19 lockdown, air quality, Greater Metropolitan Region of Sydney, WRF-CMAQ

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1. Introduction

The COVID-19 pandemic in 2020 has caused death and economic misery in all countries of the world. The disease was named as COVID-19 (Coranavirus diseases 2019) by WHO and is caused by a type of coranavirus strain called Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2). Although it is not as deadly in term of death statistics as the 1918 H1N1 flu pandemic but it is unprecedented in the rapid transmission of viral agents from human to human. Started in the city of Wuhan, China in late December, in a few months nearly all corner of the world was affected by the pandemic due to the highly contagious nature of the virus and the rapid transmission was also helped by the extensive global connectivity in our age as compared to previous times. Similar to H1N1 virus of avian origin, the SARS-CoV-2 virus was thought to have its origin in bat. In the first wave of the pandemic in early February to June 2020, many cities in the world were in the state of lockdown and many business activities were shut down in the effort to minimize the social contact and to contain the virus transmission.

Australia closed the border on 20 of March 2020 to all non-citizens and a week later most states in the country were in the state of lockdown. The state of NSW and the city of Sydney in particular was lockdown for most of April and May with less restriction in June. Lockdown started on 16 March then a hard lockdown on 1 April 2020 and ease of lockdown from 15 May till 16 June when further easing with private homes could have up to 20 guests [1].

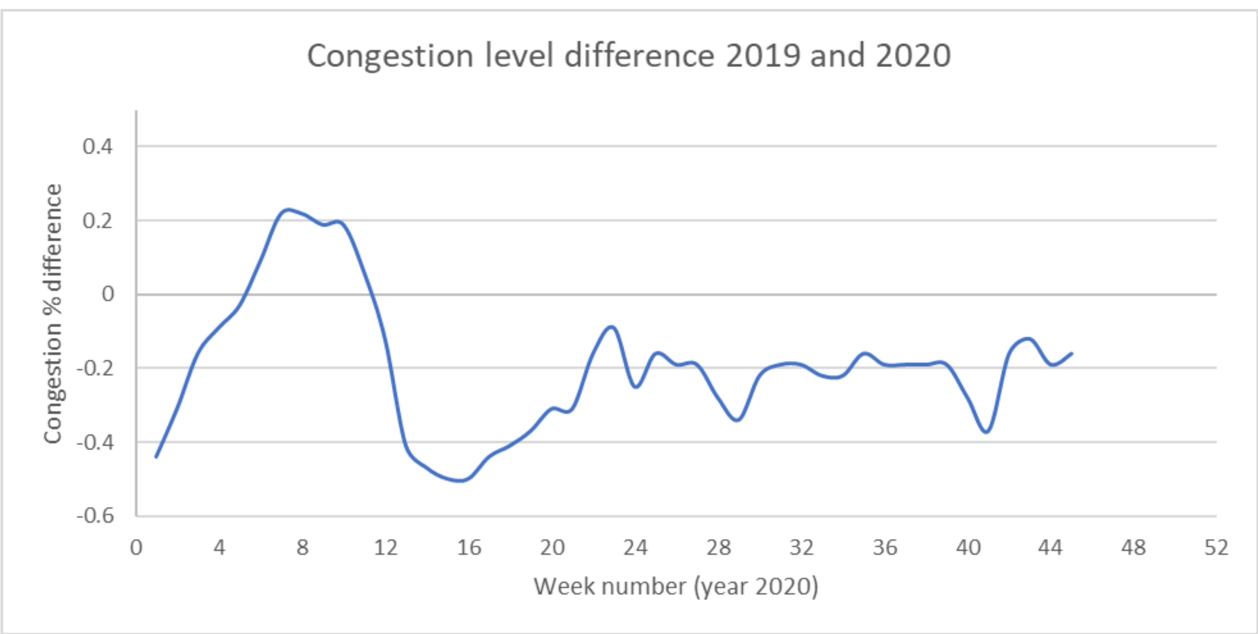
One of the consequences of the lockdown is the effect on environment such as air quality in the urban area where anthropogenic activities were curtailed. As for the impact of air quality on health during the pandemic, Zoran et al. 2020 [2] have found that exposure to increasing levels of PM air pollution in the COVID-19 pre-lockdown (January–February 2020) as well as during lockdown period in Milan (Italy) might make the inhabitants more susceptible to viral infection. From their study, however, the mechanism of this environment effect on the transmission of coronavirus COVID-19 is not clear whether the increase in new cases is due to viral attachment to aerosols through airborne diffusion or some other mechanism. Chakrabarty et al. 2020 [3] in their study of $PM_{2.5}$ exposure and spread of COVID-19 in the United States also reported that long-term exposure to air pollution makes the population more susceptible to the disease and exposure to $PM_{2.5}$ associates with COVID-19 basic reproduction ratio (R_0) i.e. increase the spread of the disease. Chen et al. 2020b [4] have estimated the public health benefits due to reduction in NO_2 and $PM_{2.5}$ during the COVID-19 lock down: 8911 avoided NO_2-related deaths and 3214 avoided $PM_{2.5}$-related deaths from cardiovascular diseases, COPD (Chronic Obstructive Pulmonary Disease) and other diseases. Thus, lowering the ambient level of $PM_{2.5}$ not only reduces the health burden in the exposed population but also lessening the spread of the COVID-19 viral transmission. Smith et al. 2020 [5] has found, in their modelling of microdroplets exhaled directly from host of covid-19 viral load, the probability of infection is not high, and this mode of transmission is not efficient. However, they do not consider the cases where existing $PM_{2.5}$ particles in the air can affect the transmission of covid-19 virus.

Rodríguez-Urregoa et al. 2020 [6] has reported, in their study of the effect of lockdown on $PM_{2.5}$ pollutant concentration in 50 most polluted cities in the world, that $PM_{2.5}$ levels were reduced in most of the cities compared to the levels before the lockdown. There are some cities that the $PM_{2.5}$ levels increase during the lockdown but overall, the average reduction is 12% of $PM_{2.5}$ concentration before lockdown for these 50 cities. Chauhana and Singh, 2020 [7], also report $PM_{2.5}$ reduction in major cities around the world with the most pronounced reduction in Delhi and Mumbai in India. Similarly, Habibi et al. 2020 [8] using the same method using daily data of major cities around the world from the World Air Quality Index (WAQI) project for the January 2019–April 2020 period, has reported that NO_2, CO, $PM_{2.5}$ levels reduced while O_3 (Ozone) increased for most of the world major cities between February, March and April 2020 as compared to the levels of corresponding period in 2019. Ming et al. 2020 [9] using air quality data in many cities across China and travel data from Baidu web site to study the air quality effect from the lockdown in China during the Lunar New Year and COVID-19 pandemic period. They reported a reduction of about 7 µg/m^3 of $PM_{2.5}$ during the pandemic lockdown across China. Chen et al. 2020a [10] in their study on impact of lockdown from 23 January to 2 February on air quality and $PM_{2.5}$ composition in Shanghai reported the reduction in the concentrations of $PM_{2.5}$, SO_2, NO_x, and CO but increase level of O_3 in Shanghai as compared to those in the pre-lockdown period from 8 to 23 January. Similar results were obtained in the Chu et al. 2020 [11] study of other Chinese cities.

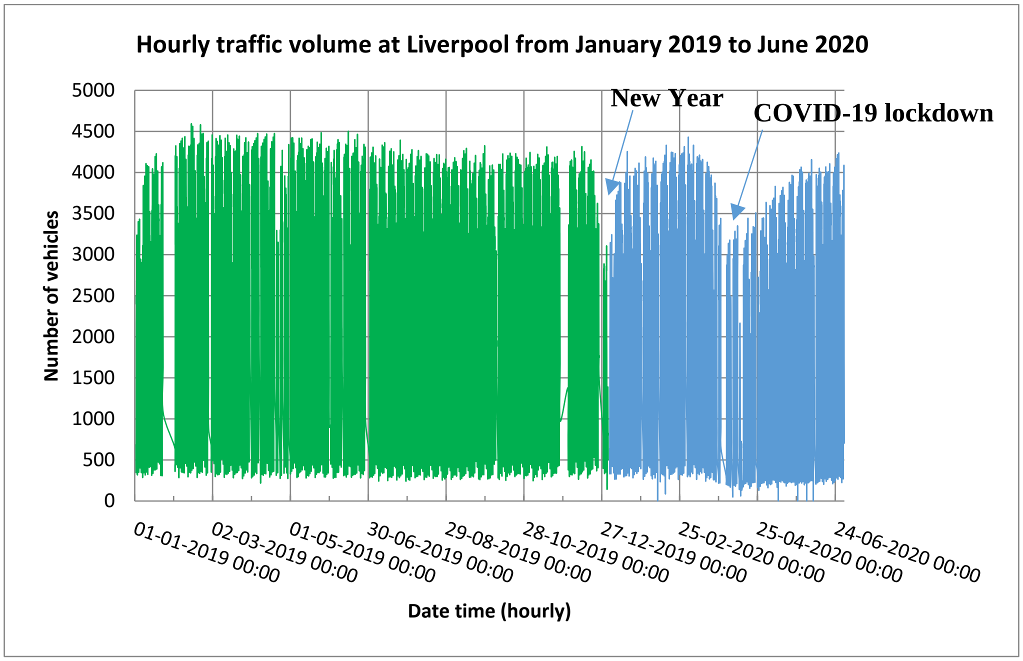
Zangari et al. 2020 [12] analysed the trend in air quality from January to May 2020 before and after the lockdown in New York City. They reported the improvement in $PM_{2.5}$ by 36% and NO_2 by 51% concentrations shortly after the shutdown took place; however, when improvement trend in these pollutant concentrations were compared to those measured during the same period in 2015–2019, no significant difference between the years was found. For this reason, it is important also to consider the trend of air quality in the period before and after the lockdown in 2020 and compare with those in the previous years to determine whether the improvement trend in 2020 is in fact due to the lockdown and not due to meteorological or seasonally emission variation.

The main reason for the reduction during the lockdown period is the reduced anthropogenic activities which cause emission of air pollutants and hence degrade air quality in the environment. The transportation sector, which is still much reliant on combustion type technology, is the main contributor to the emission of pollutants. Kaskaoutis et al. 2021 [13] have shown the reduction in Black Carbon (BC) concentration from fossil fuel combustion due to lockdown period in Athens, Greece and hence reduction in spectral scattering and absorption of aerosols.

Significant reduction in traffic volume and hence congestion on Sydney road since the lockdown began in late March 2020 is shown in Figure 1a. The congestion since then until the end of 2020 is less than that in corresponding period in 2019. This is expected as less traffic volume means less congestion in the metropolitan area. Figure 1b shows the hourly traffic volume from January 2019 to June 2020 on Liverpool Road near Chullora monitoring station. Significant drop in traffic volume in April and May can be seen. Hourly traffic volume decreased from about 4000 vehicles to below 3000 in the first week of April, which was similar to the level in the first week of the New Year holiday period.



(a)



(b)

Figure 1 - Congestion level difference 2019 and 2020 (percentage greater than standard weekly congestion level in 2019) (a) (source: Tomtom traffic flow https://www.tomtom.com/en_gb/traffic-index/sydney-traffic/) and number of vehicles per hour on Liverpool Road as counted at a traffic site from January 2019 to June 2020 (source: NSW Road and Maritime Services, RMS).

As less emission from motor vehicle, it is expected that the ambient levels of emitted species such as NO_x, CO as well as for particulate matter such as PM_{10}, $PM_{2.5}$ will reduce during the lockdown period.

In this study, we focus on the effect of lockdown on air quality in the Greater Metropolitan Region (GMR) of Sydney from April to June 2020, specifically on criteria pollutants CO, NO_2, $PM_{2.5}$ and O_3. This study is different from the previous studies [6] [7] [8], in that not only we compare the air quality during the lockdown 2020 with one in the corresponding period of 2019 but also in previous years of 2016, 2017 and 2018 to control for the effect of meteorological variability. And the detailed analysis on different sites in addition to the overall regional average are conducted together with air quality modelling using WRF-CMAQ (Weather Research Forecast – Community Multiscale Air Quality) model to understand the sensitivities of the air pollutants to change in emission and meteorological conditions.

2. Data and methodology

It is expected that the lockdown will improve air quality due to substantial reduction in mobile source emission. Traffic data from the NSW Road and Maritime Services (RMS) at many traffic counters located in the Greater Metropolitan Region of Sydney are used to estimate the reduction in the amount traffic during the lockdown period as compared with traffic before the lockdown. The estimated amount of reduction will also be used to perform a simulation study using the air quality model WRF-CMAQ to estimate the change in air quality.

With air quality monitoring data available from DPIE air quality network in NSW, one of the methods used in this study is to compare the pollutant concentrations during the lockdown period 2020 with those of the corresponding period in 2019, 2018. Note that the assumption made implicitly here is

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that the meteorological conditions are essential similar (autumn period April to June) and the emission (inventory) does not change much (except mobile source reduction in 2020 lockdown otherwise all other sources are same). These two assumptions are not quite right, especially the meteorological component and hence the dispersion of emitted pollutants, and we expect there is some variation at some sites. However, analysis based on the above assumption can give us some indication of comparative pollutant concentration and insights of air quality during the COVID-19 lockdown 2020. This method of comparing the 'control' group and 'treatment' group was used by [6] [8] [9] [11]. But as Zangari et al. 2020 [12] pointed out recently the improvement trend in air quality before and after the lockdown could also be due to other factors. For this reason, we will also analyse the trend of air pollutants before and after the lock down in 2020 and compare with those during the same period in 2015-2019 to determine whether the seasonally variation in meteorology and emission can influence the results.

In addition to the data-driven method, air quality simulation during the lockdown period using WRF-CMAQ is also conducted to take into account the meteorological and emission variation. Motor vehicle emission as input to the model is reduced by a quantified emission amount based on traffic volume data to predict the air quality variables under the lockdown as compared with no emission reduction scenario.

In addition to observed data from DPIE air quality monitoring stations in the GMR of Sydney (Figure 3 (a)), data from satellite observation and from MERRA-2 global assimilation model before and during the lockdown period in NSW are also used to analyse the effect of lockdown on air quality in the GMR in particular and in NSW in general. The Ozone Monitoring Instrument (OMI) onboard Aura mission satellite measures criteria pollutants such as O_3, NO_2, SO_2, and aerosols. There are a number of retrieval products from OMI [14]. The OMI-NASA retrieval product is used in this study to obtain NO_2 tropospheric column.

The main pollutants, CO, NO_2, $PM_{2.5}$ (Particulate Matter less than 2.5 µm in diameter) and O_3 (Ozone) are considered in this study. The anthropogenic emission sources that were affected by the lockdown are mostly on-road mobile sources such as motor vehicles, and to a lesser extend the aircraft emission and shipping emission. It is expected that the primary pollutants from these combustion sources, carbon monoxides (CO), nitrogen oxides (NOx), $PM_{2.5}$, PM_{10} and Volatile Organic Compounds (VOC) such as toluene, benzene, xylenes will be decreased. But for ozone, a secondary pollutant, the effect can be complex and the level can increase or decrease depending on the location due to interaction of meteorology driving the dispersion of primary pollutants NOx, VOCs and the photochemical reactions forming the ozone levels across the domain. Statistical analysis such as box plot, regression method, diurnal analysis is useful to assess the effect of lock down on air pollutant levels at different sites in the GMR.

The COVID-19 lockdown period is an ideal case study of the source contribution of mobile sources on the ambient concentration of ozone and $PM_{2.5}$ in the GMR. Air quality modelling tool such as WRF-CMAQ is used to simulate the ozone and $PM_{2.5}$ levels in the GMR using emission data with and without the mobile source emission. In the previous studies [15] [16], the effect of motor vehicle emission is mostly pronounced in the south west Sydney where maximum level of ozone is influenced by emission of motor vehicle more than anywhere in the GMR. The prediction from the previous studies can be tested and evaluated from the observation of ozone during the lockdown period in 2020.

The WRF-CMAQ modeling system developed by the US-EPA is a well-known air quality model used frequently around the world in many air quality studies. This study uses WRF-CMAQ model (version 5.3.1) based on CB6 (Carbon Bond 6 version 3 with aerosol treatment of Secondary Organic Aerosol, cb6r3_ae7_aq). The GMR emission inventory data provided by the New South Wales Environment Protection Authority (EPA) is used as anthropogenic emission input and the U.S NCEP

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(National Centers for Environmental Prediction) Global Reanalysis data as the meteorological driver. Other emissions to the WRF-CMAQ include the global emission database EDGAR for emission outside the GMR, the biogenic emission based on MEGAN biogenic model, the marine aerosol (sea salt) and soil dust emission as provided inline in the CMAQ model. To simulate the effect of COVID-19 lockdown, the motor vehicle emission is reduced by 30% on average as observed from the traffic count pattern at a number of traffic counter sites in the GMR.

The simulation domain configuration for WRF-CMAQ run is a 3-nested domain with the outer domain (d01) covers much of Eastern Australia at the resolution of 12km x 12km. The inner domain (d02) is at 4km x 4km resolution and cover most of NSW while the innermost domain (d03) is at 1km x 1km resolution and covers the Greater Metropolitan Region (GMR) of Sydney. Figure 3 (b) shows the 3-nested domain used for the WRF-CMAQ study simulation.

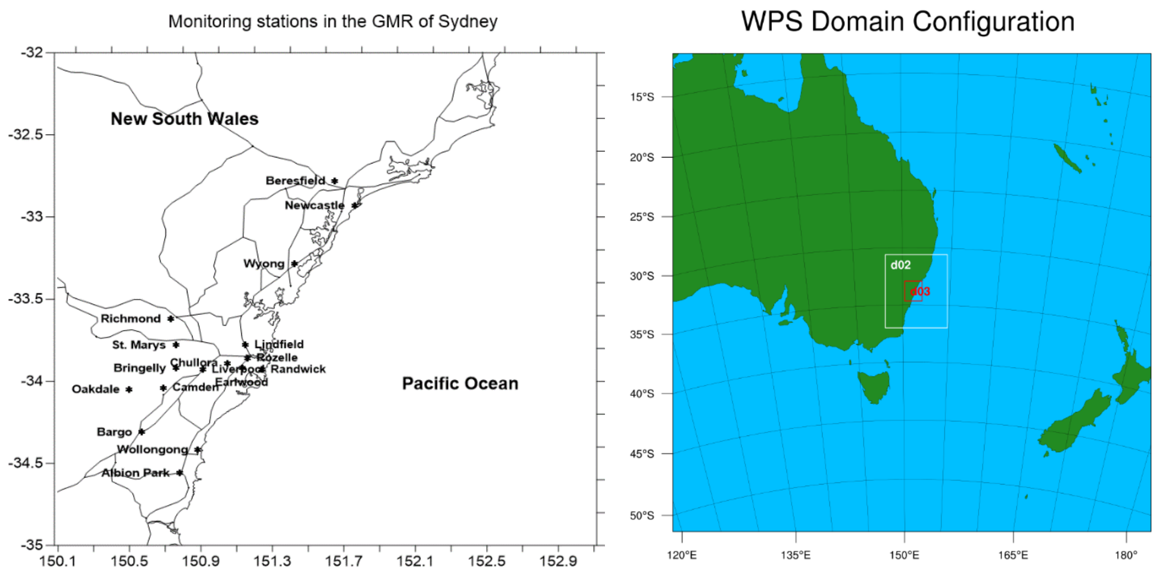
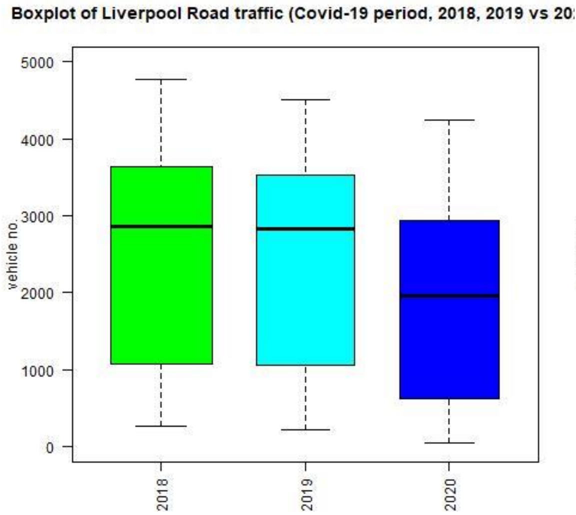


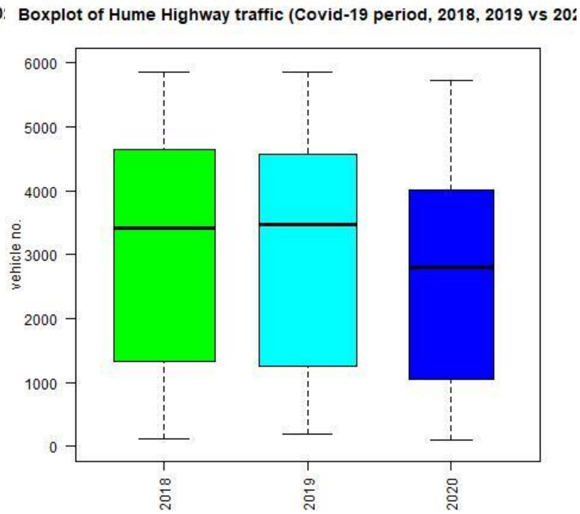
Figure 3 – (a) DPIE air quality monitoring stations and major roads (b) the 3-nested domain consisting of the outer domain (d01), inner domain (d02) and innermost domain (d03). The d02 domain covers most of NSW while the d03 domain overs the Greater Metropolitan Region (GMR) of Sydney.

3. Results

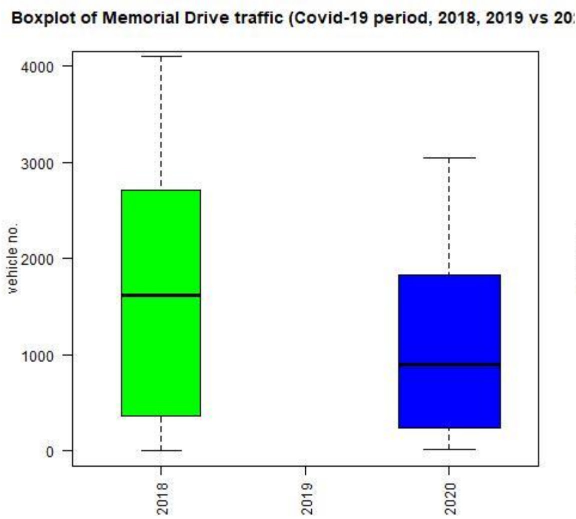
The hourly traffic volume during the period from April to June 2020 at traffic sites is reduced significantly in 2020 as compared to those in 2018 and 2019 as shown in Figure 2. The distribution of hourly traffic in 2019 and 2018 is nearly identical for sites shown in Figure 2 while the distribution in 2020 is different and has lower median and maximum value than those in 2018 and 2019. Table 1 shows the location of some of the traffic counter sites used in the study. The sites are located on the main arterial roads and highways in the GMR of Sydney.


Boxplot of Liverpool Road traffic (Covid-19 period, 2018, 2019 vs 20
vehicle no.
5000
4000
3000
2000
1000
0
2018
2019
2020

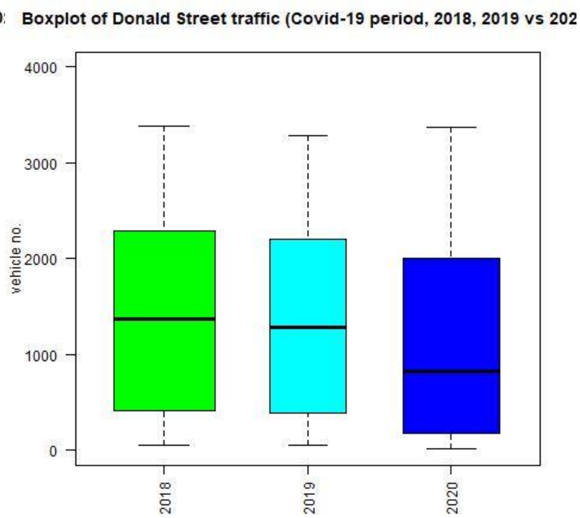
(a)


Boxplot of Hume Highway traffic (Covid-19 period, 2018, 2019 vs 20
vehicle no.
6000
5000
4000
3000
2000
1000
0
2018
2019
2020

(b)


Boxplot of Memorial Drive traffic (Covid-19 period, 2018, 2019 vs 20
vehicle no.
4000
3000
2000
1000
0
2018
2019
2020

(c)


Boxplot of Donald Street traffic (Covid-19 period, 2018, 2019 vs 202
vehicle no.
4000
3000
2000
1000
0
2018
2019
2020

(d)

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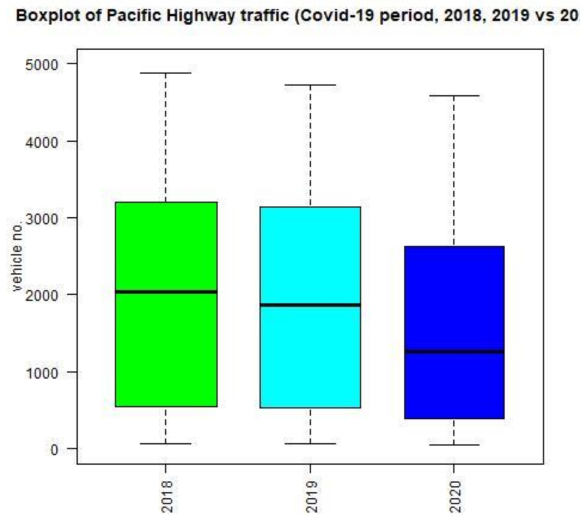

(e)

Figure 2 – Boxplot of traffic volume per hour in 2018, 2019 and 2020 during the period April to June at Liverpool Road (a), Hume Highway (b) in Sydney, Memorial Drive in Wollongong (c) and Donald Street (d), Pacific Highway (e) in Newcastle.

Traffic counting site	Location (lat, lon) in degrees	Nearest monitoring site	2019 (median, mean) hourly traffic volume	2020 (median, mean) hourly traffic volume	Percentage decrease
Liverpool Road	(-33.887,151.073)	Chullora	(2830, 2421)	(1968, 1902)	30%
Hume Highway	(-33.905,151.041)	Chullora	(3476,3052)	(2801,2667)	19%
Memorial Drive	(-34.384,150.900)	Wollongong	(1613,1669)*	(896,1076)	44%
Donald Street	(-32.918,151.740)	Newcastle	(1284,1355)	(822,1113)	36%
Pacific Highway	(-32.818,151.692)	Beresfield	(1874,1907)	(1266,1555)	32%

Table 1 – Traffic counting site and comparison of 2019 and 2020 median hourly traffic volume (*) data for 2019 is not available, data for 2018 is used instead.

The spatial extent of the effect on air quality can be seen from OMI satellite measurement of column tropospheric NO_2. Figure 2 shows the NO_2 column tropospheric average value for April 2020 (a) April 2020 (b) and the difference of NO_2 tropospheric column value in April 2019 and April 2020 (c). Figure 2(d) (e) and (f) are similarly shown for May 2019 and May 2020. The most distinct reduction in NO_2 is in May 2020.

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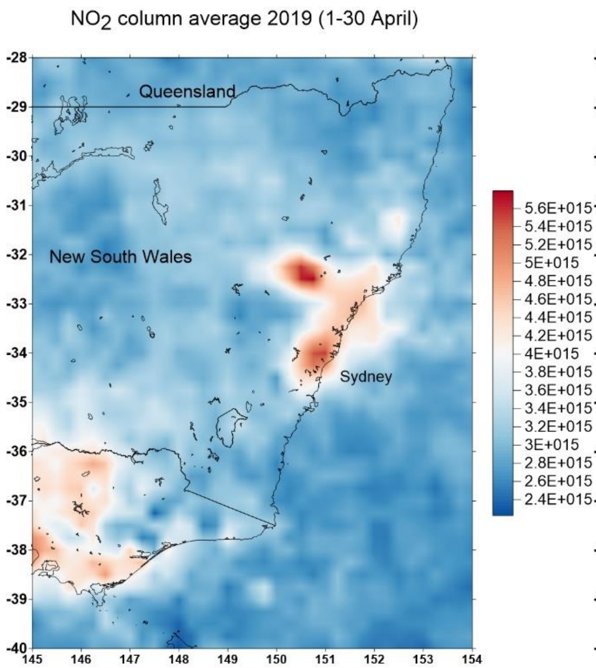
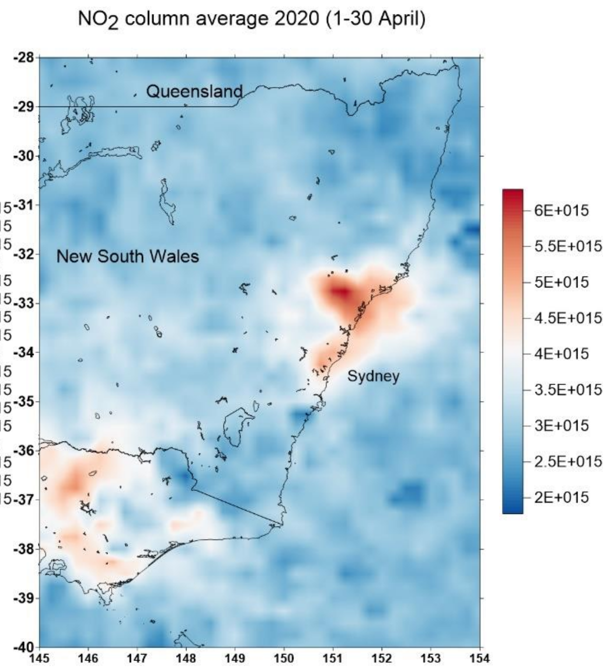
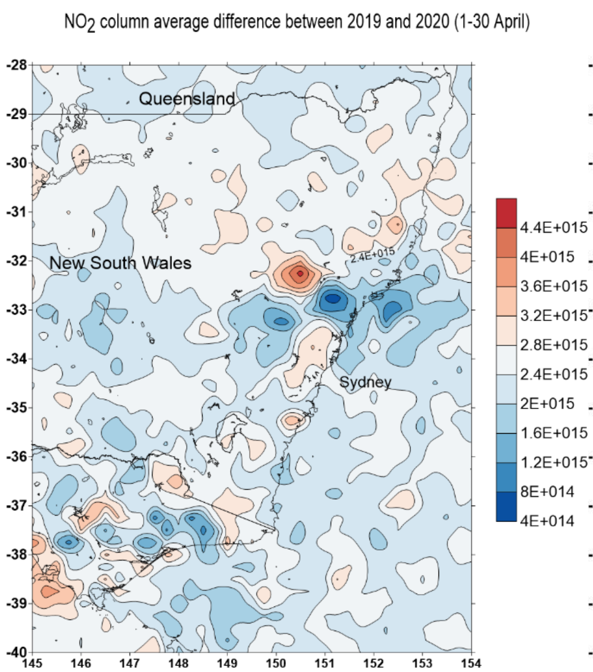


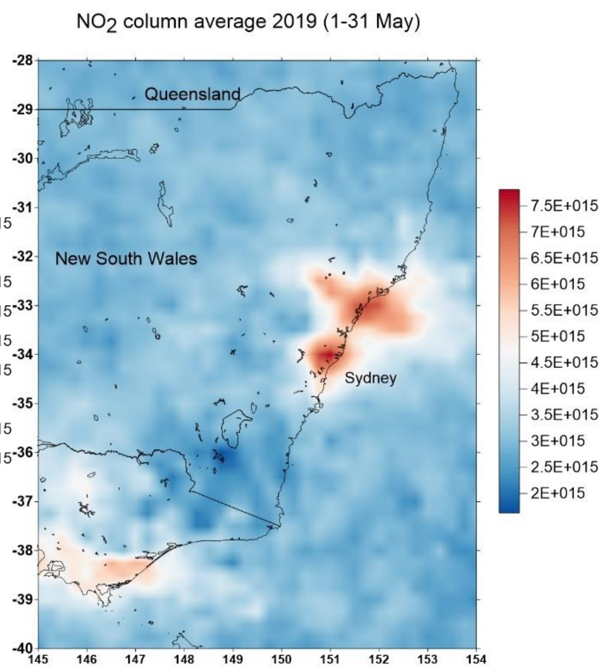
(a)



(b)



(c)



(d)

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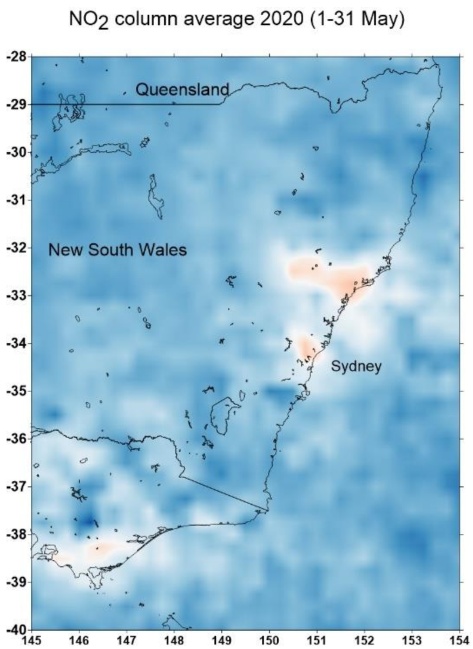
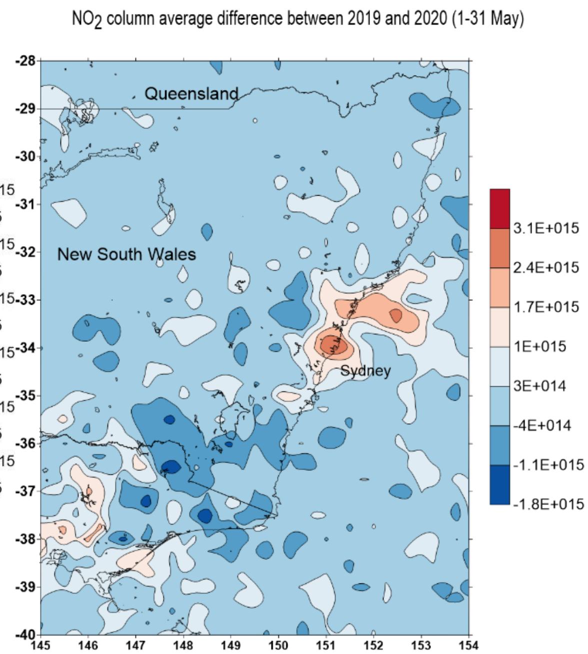


(e)



(f)

Figure 2 - Time averaged map of NO_2 tropospheric column (30% cloud screened) daily 0.25 deg. [OMI OMNO2d v003] 1/cm2 in April 2019 (a), April 2020 (b) and the difference in April 2019 and 2010. Similarly (d), (e) and (f) are for May 2019 and May 2020. The unit is in molecules/cm^2 (Data source: NASA Giovanni online https://giovanni.gsfc.nasa.gov/).

CO observation from MOPITT and AIRS instrument on satellites are of coarse resolution 1 degree (as compared to OMI NO2 instrument at 0.25deg resolution) are of limited values. But the MERRA-2 global model provides better spatial resolution at 0.5° x 0.625° of surface CO concentration. Figure 3 shows the predicted monthly CO surface concentrations in May 2019 and May 2020. The surface CO concentration is reduced in the GMR. The largest reduction is in metropolitan Melbourne in Victoria.

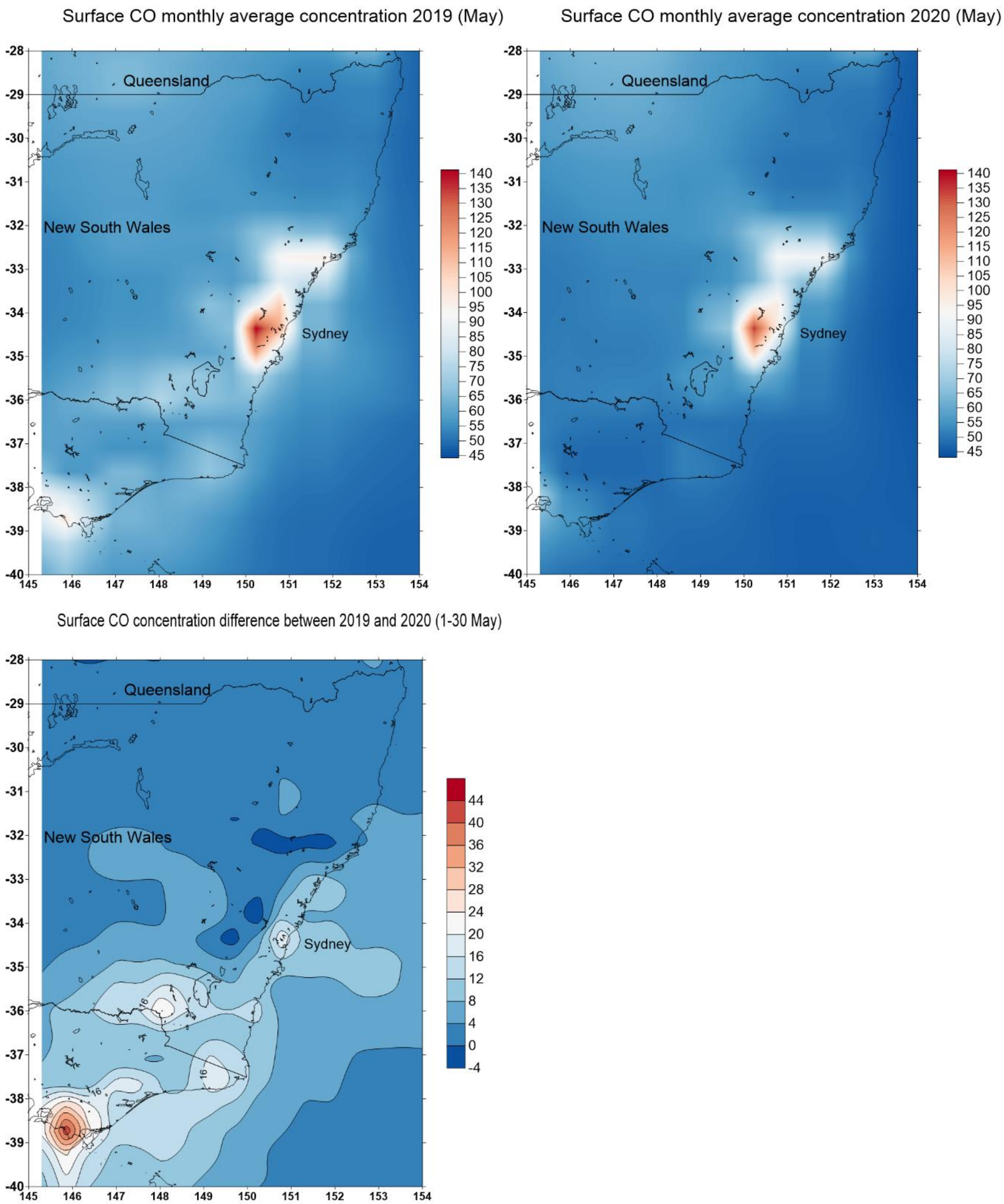


Figure 3 - Monthly averaged map of CO surface concentration (ENSEMBLE) monthly 0.5 x 0.625 deg. [MERRA-2 Model M2TMNXCHM v5.12.4]. The unit is ppbv (parts per billion volume) (Data source: NASA Giovanni online https://giovanni.gsfc.nasa.gov/).

3.1 Analysis of air quality monitoring data over the whole GMR

Data from each monitoring site in the GMR are aggregated together to provide an overall status of the air quality over the whole region

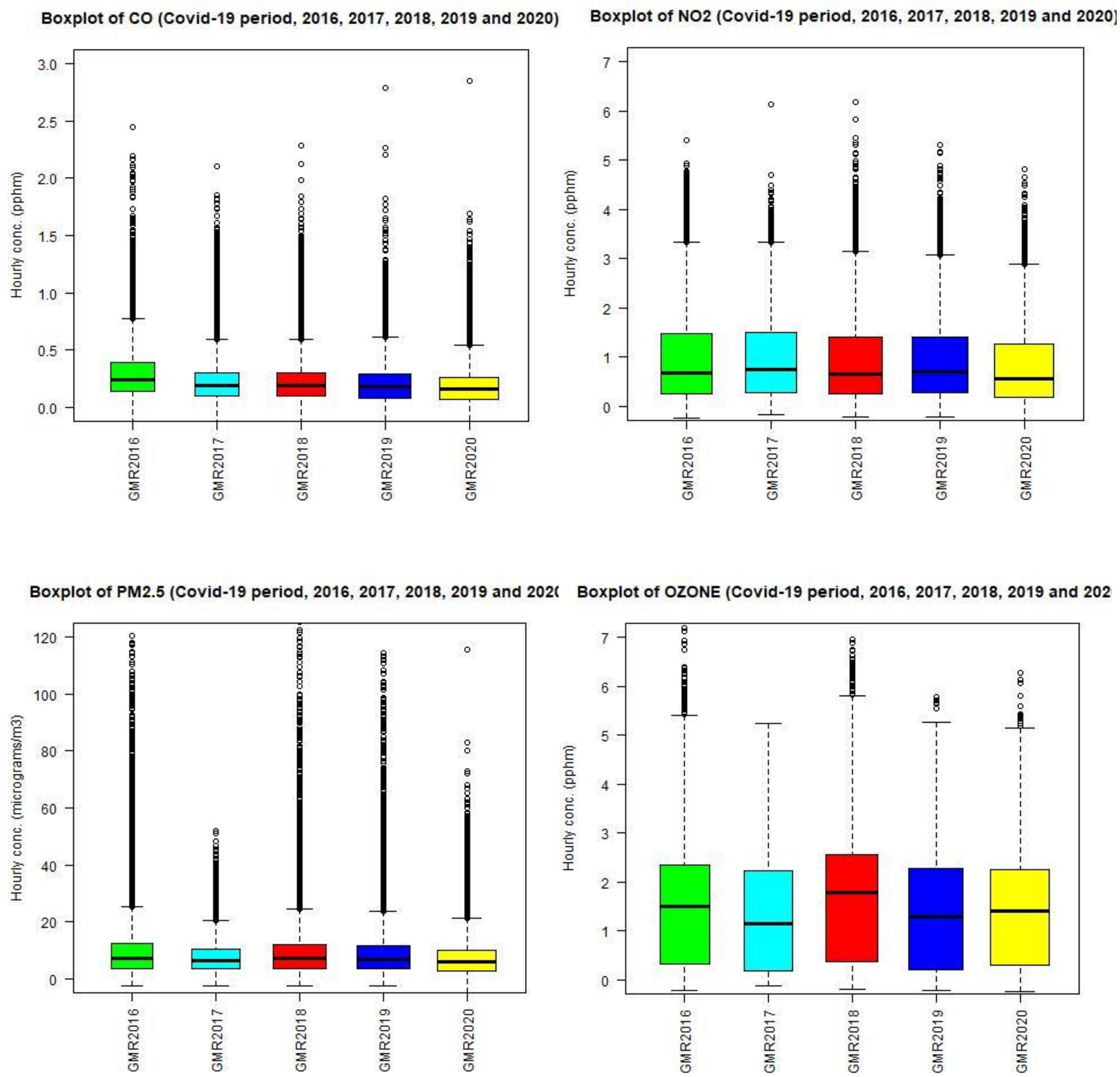


Figure 4 – Boxplot of NO_2, CO, $PM_{2.5}$ and O_3 for April to June in 2017, 2028, 2019 and 2020 over all the sites in the GMR.

From the boxplot of NO_2, CO, $PM_{2.5}$ and O_3 for April to June period in 2016, 2017, 2028, 2019 and 2020 over all the sites in the GMR as shown in Figure 4, the median values of NO_2, CO and $PM_{2.5}$ in 2020 are lower than those in 2017, 2018 and 2019. Table 1 summarises the change in median, mean and maximum value of hourly data in April to June for each of those years

		NO_2	CO	$PM_{2.5}$	O_3
2016	Mean	0.947	0.294	10.07	1.47
	Median	0.685	0.242	7.12	1.49
	Max	5.41	2.446	320.74	8.45
2017	Mean	0.944	0.234	7.437	1.27
	Median	0.736	0.191	6.503	1.15
	Max	6.128	2.107	51.97	5.24

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2018	Mean	0.909	0.231	9.389	1.64
	Median	0.657	0.187	7.135	1.78
	Max	6.185	2.283	335.40	7.44
2019	Mean	0.912	0.211	8.790	1.34
	Median	0.694	0.181	6.694	1.29
	Max	5.301	2.785	295.25	5.77
2020	Mean	0.792	0.193	7.10	1.38
	Median	0.570	0.162	5.87	1.42
	Max	4.821	14.397	115.72	6.27
Welch t-test (2020 vs 2019)		t=20.615 p-value < 2.2e-16 Different (null hypothesis rejected)	t=8.36 p-value < 2.2e-16 Different (null hypothesis rejected)	t=25.121 p-value < 2.2e-16 Different (null hypothesis rejected)	t=-4.93 p-value=8.19e-07 Different (null hypothesis rejected)

Table 1 – Summary statistics of NO_2, CO, $PM_{2.5}$ and O_3 for the period April to June in 2027, 2018, 2019 and 2020.

The change in NO_2 median value in 2020 lockdown as compared to the average mean value of previous years (2017, 2018 and 2019) is -18%. The figures for CO and $PM_{2.5}$ are -13% and -13% while for O_3 is +1.5%. If comparison is made between 2020 and 2019, the figures for NO_2, CO, $PM_{2.5}$ and O_3 are -18%, -10%, -12% and +10% respectively.

For ozone, 2018 is a particular warm year in the period of April to June compared to other years with the mean, median and maximum ozone concentrations higher than those of 2017, 2019 and 2020. For this reason, if compared to 2018, the ozone level during the lockdown period in 2020 is still less than that in 2018 while for other years (2019, 2017) the level in 2020 lockdown is higher.

3.2 Analysis of air quality monitoring data from monitoring sites

The air quality monitoring station data at each site in the Sydney region provide valuable evidence for the understanding of the effect of lockdown on some air pollutants such as NO_2 , CO, O_3 and $PM_{2.5}$ in some sub-regions of the GMR. The time series of NO_2 and CO at a number of sites (Camden and Liverpool in south west Sydney) for 2009 and 2020 in April to June are shown in Figure 4. Summary statistics from the pollutant time series allows us to compare the levels between the tow considered periods.

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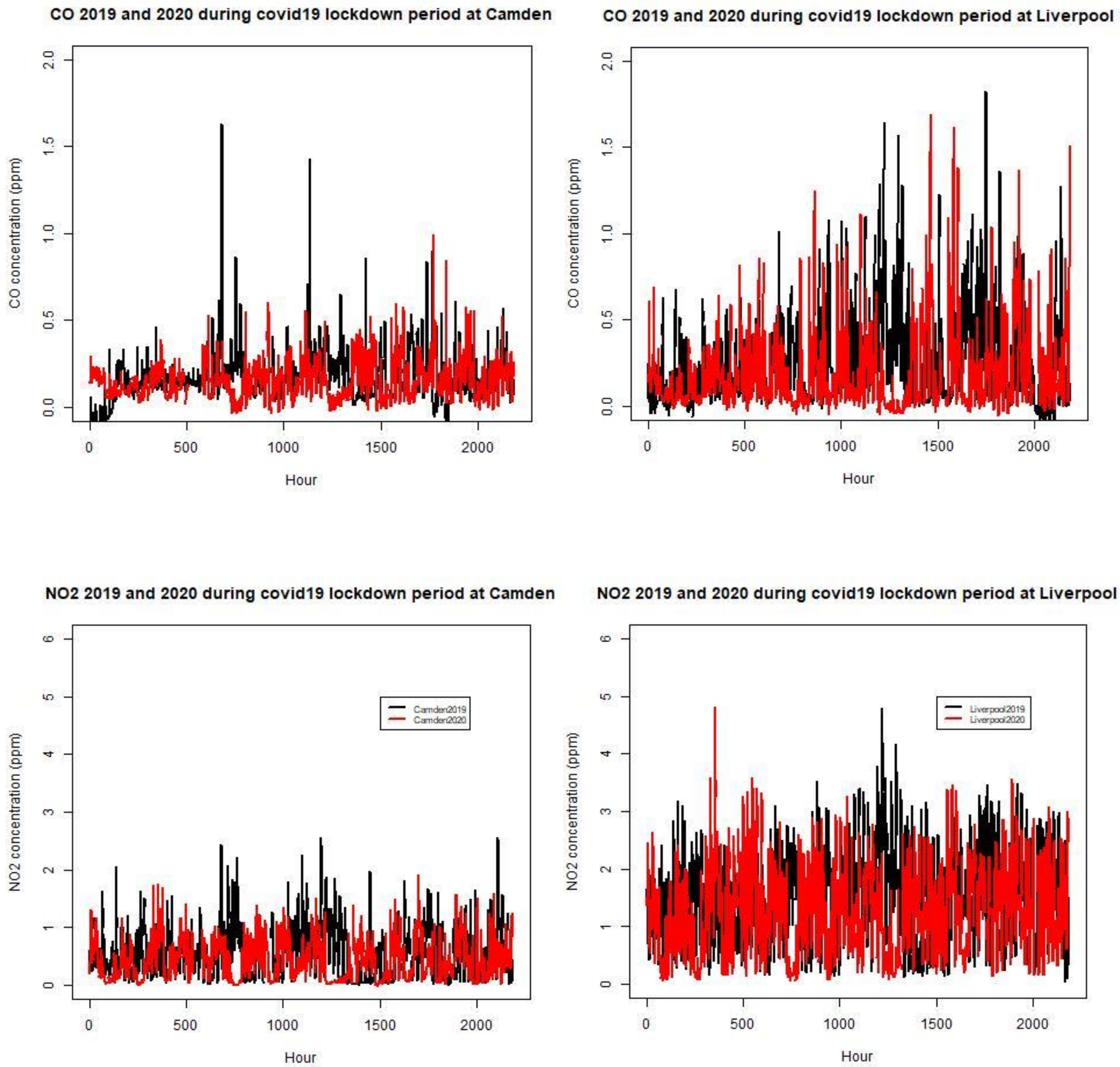

Figure 4 – Time series of CO and NO_2 at Camden and Liverpool for 2019 and 2020 during the April to June period (red as 2010 series, black 2019 series)

A summary of the time series can be represented by using the box plots. Figure 5 shows the box plots of NO_2 and CO at different sites in the GMR for 2019 and 2020 for the period from April to June. It is clear that there is a decrease of NO_2 and CO in median values at all the sites in the GMR.

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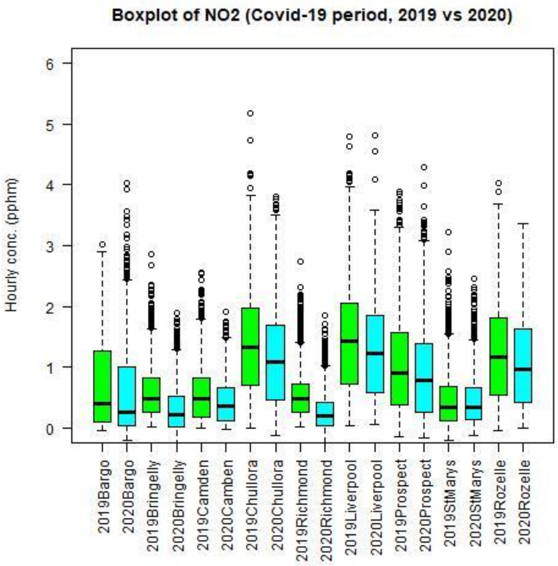
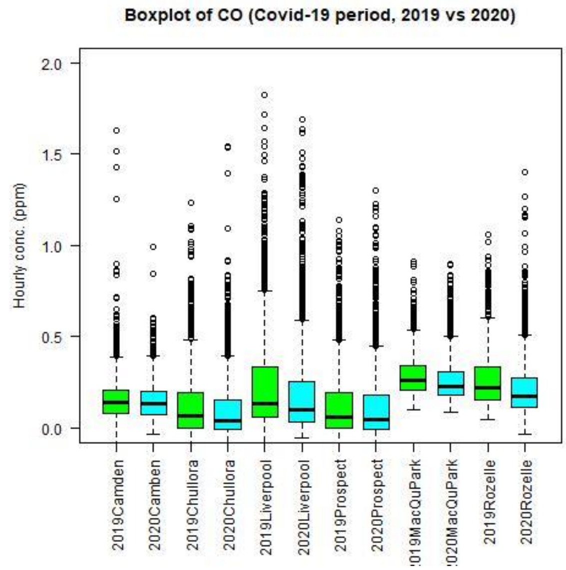
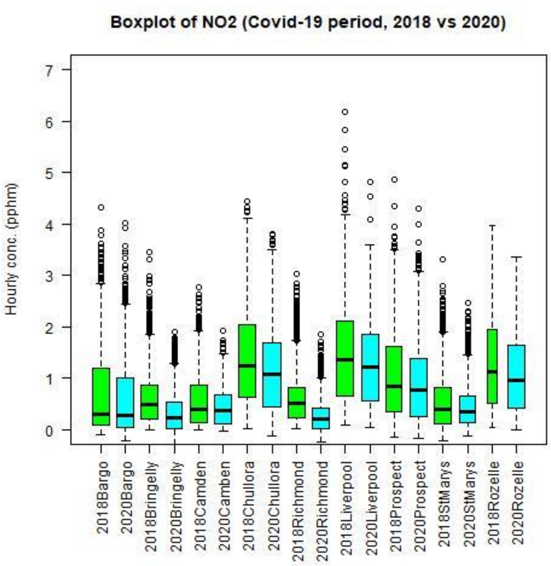


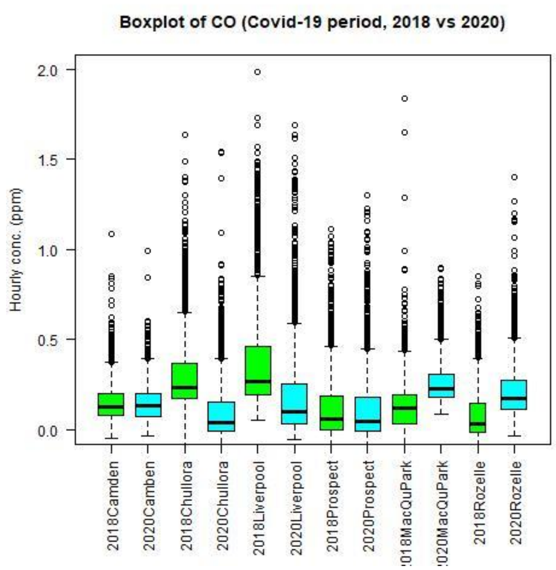
(a)



(b)



(c)



(d)

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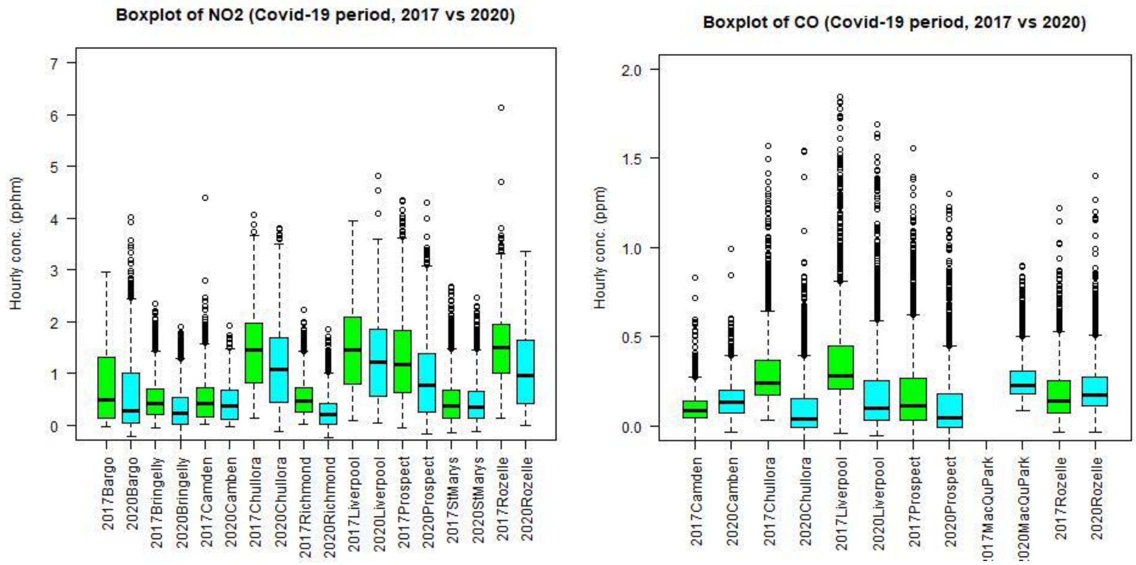

(e) (f)

Figure 5 – Boxplot of NO_2 and CO at different sites in the GMR in 2019 and 2020 side by side for the period from April to June (a) and (b). Boxplot of NO_2 and CO in 2018 and 2020 side by side (c) (d). And in 2017 and 2020 side by side (e) (f)

A more detail analysis using average diurnal patterns of these pollutants for the lockdown period (April to June) also shows a decrease of the concentration of NO2 and CO during daytime as shown in Figure 6. The CO diurnal (average of all the hourly data for COVID-19 lockdown period at each hour of the day) for 24-hour at a number of sites shows a typical pattern with 2 peaks, one in early morning and one in early evening. For all the sites considered, the 2020 Covid-19 lock down period as compared to 2019 of the same periods shows a drop of CO for all the hours except from midnight to early morning before 7am at some sites (Camden and Prospect). At this time, traffic emission is insignificant. But for NO_2, a decrease in concentration level at all sites for all hours.

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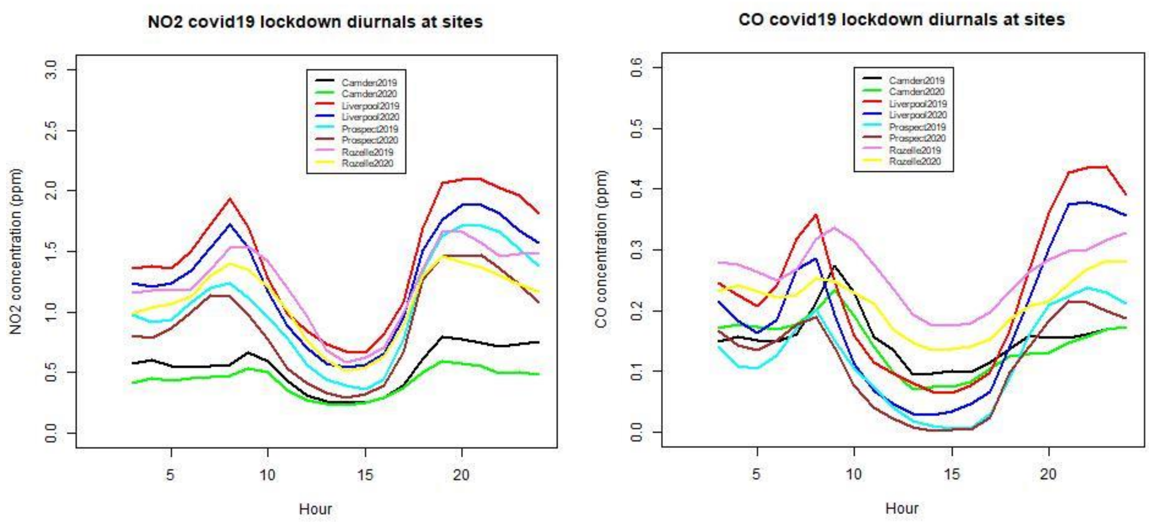
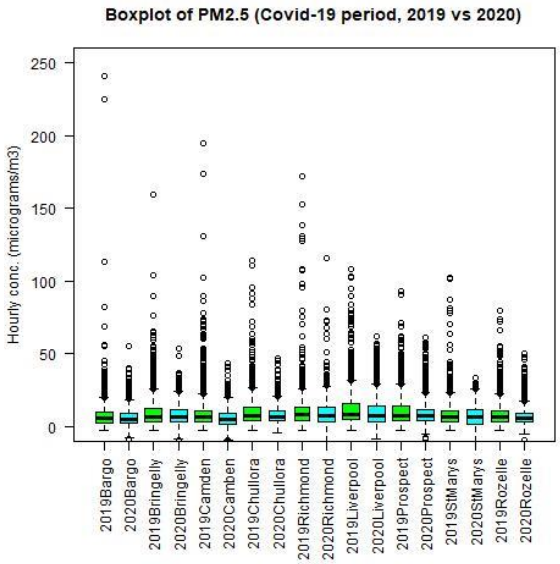


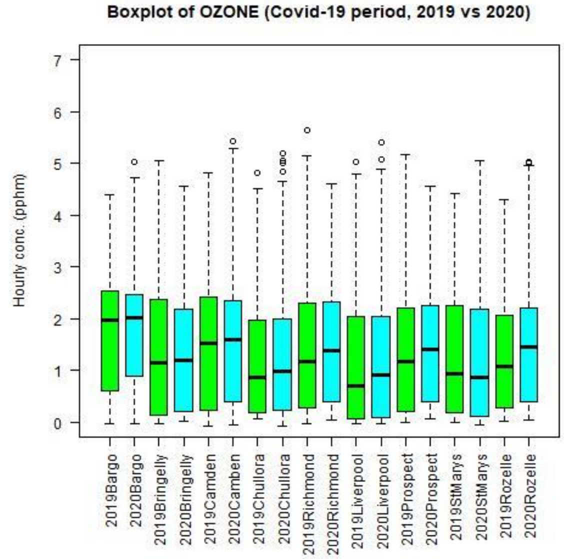
Figure 6 – Diurnal patterns of NO_2 and CO for 2019 and 2020 from April to June at different sites in the GMR

For $PM_{2.5}$, the median and maximum level at nearly all sites (except at Richmond in north west Sydney) decreases during the lockdown period as compared to the 2019 and 2018 levels of the corresponding period. The difference in meteorological conditions or emission in 2019 (or 2017, 2018) and 2020 can influence the results of comparison but the general trend is that the levels of $PM_{2.5}$ decrease during the lockdown in 2020 as compared with those if lockdown did not occur.

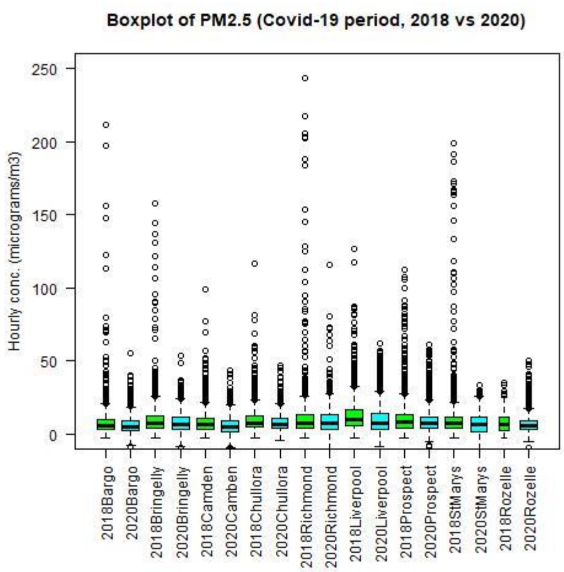
However, the effect of lockdown on ozone concentration is different from those on CO, NO_2 and $PM_{2.5}$ levels. The box plots of ozone levels at different sites in 2019 and 2020 are shown in Figure 7. The ozone median level at most sites (except St Marys) in fact increases during the lockdown period as compared to the levels in 2019 (Figure 7b) but the maximum level decreases at some sites (Bringelly, Richmond, Prospect) and increases at other sites (Bargo, Camden, Liverpool, Chullora, St Marys, Rozelle). This inconsistency in trend of ozone levels between 2019 and 2020 at different sites could be due to different meteorological conditions as well as the photochemistry mechanism in April to June period for these two years. For this reason, the comparison of ozone during lockdown period in 2020 with those in 2017 and 2018 data is also performed. The results for 2018 are more consistent. Both median and maximum ozone levels in 2020 (Figure 7d) decrease at nearly all sites as compared to those levels in 2018 for the corresponding period of April to June. However as compared with 2017 corresponding period, the ozone levels in 2020 are higher than those in 2017. It is noted that the daily maximum temperature in 2018 for April to June is on average higher than those in 2017, 2019 and 2020. As ozone level is highly correlated with temperature which is acting as a proxy for photolysis rate, it is expected that average ozone levels in 2018 over the GMR are higher than those of 2017, 2019 and 2020.


Boxplot of PM2.5 (Covid-19 period, 2019 vs 2020)
Hourly conc. (micrograms/m3)
0
50
100
150
200
250
2019Bargo
2020Bargo
2019Bringelly
2020Bringelly
2019Camden
2020Camben
2019Chullora
2020Chullora
2019Richmond
2020Richmond
2019Liverpool
2020Liverpool
2019Prospect
2020Prospect
2019StMarys
2020StMarys
2019Rozelle
2020Rozelle

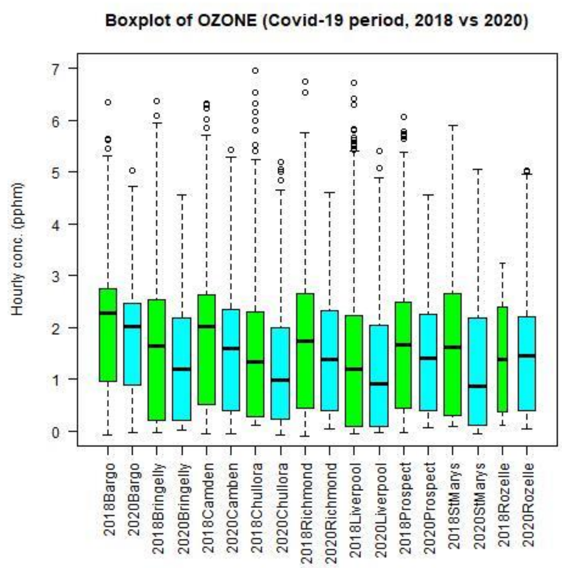
(a)


Boxplot of OZONE (Covid-19 period, 2019 vs 2020)
Hourly conc. (pphm)
0
1
2
3
4
5
6
7
2019Bargo
2020Bargo
2019Bringelly
2020Bringelly
2019Camden
2020Camben
2019Chullora
2020Chullora
2019Richmond
2020Richmond
2019Liverpool
2020Liverpool
2019Prospect
2020Prospect
2019StMarys
2020StMarys
2019Rozelle
2020Rozelle

(b)


Boxplot of PM2.5 (Covid-19 period, 2018 vs 2020)
Hourly conc. (micrograms/m3)
0
50
100
150
200
250
2018Bargo
2020Bargo
2018Bringelly
2020Bringelly
2018Camden
2020Camben
2018Chullora
2020Chullora
2018Richmond
2020Richmond
2018Liverpool
2020Liverpool
2018Prospect
2020Prospect
2018StMarys
2020StMarys
2018Rozelle
2020Rozelle

(c)


Boxplot of OZONE (Covid-19 period, 2018 vs 2020)
Hourly conc. (pphm)
0
1
2
3
4
5
6
7
2018Bargo
2020Bargo
2018Bringelly
2020Bringelly
2018Camden
2020Camben
2018Chullora
2020Chullora
2018Richmond
2020Richmond
2018Liverpool
2020Liverpool
2018Prospect
2020Prospect
2018StMarys
2020StMarys
2018Rozelle
2020Rozelle

(d)

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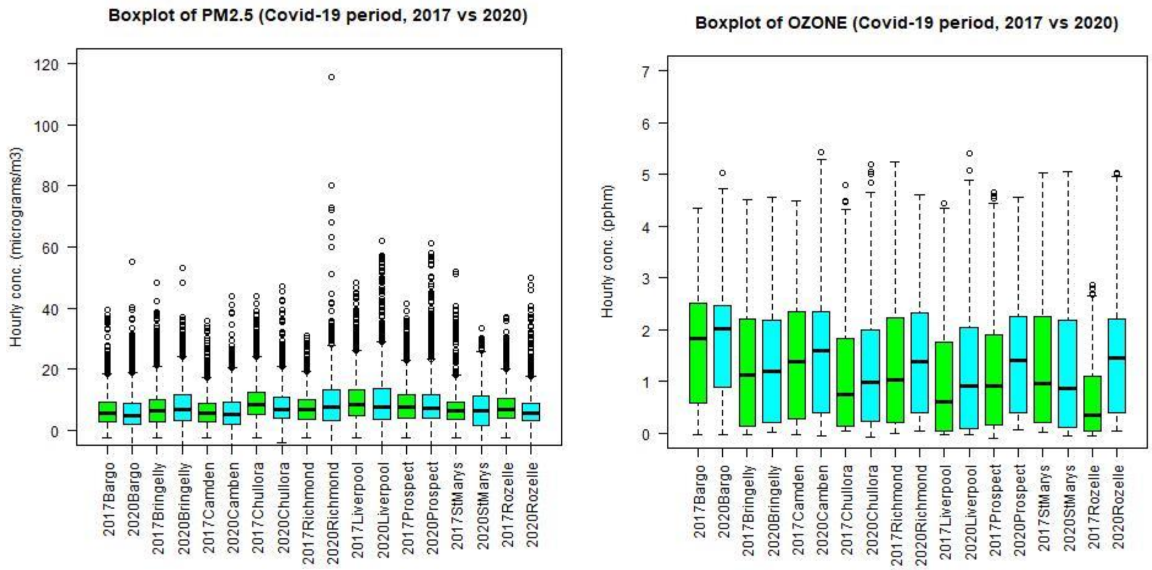
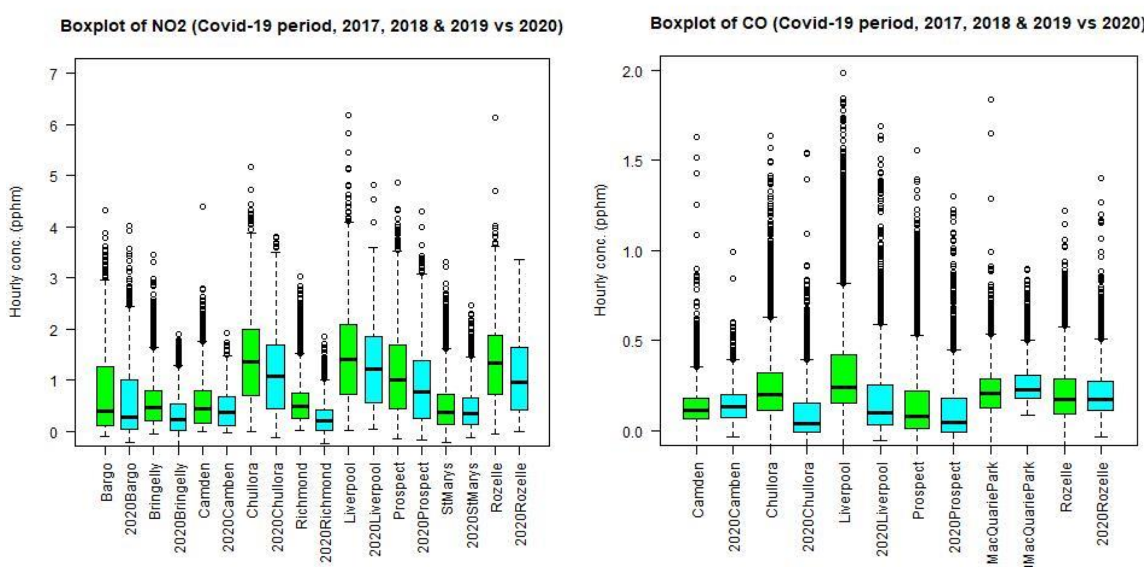


(e) (f)

Figure 7 - Boxplot of $PM_{2.5}$ and Ozone at different sites in the GMR in 2019 and 2020 side by side for the period from April to June (a) and (b). Boxplot of $PM_{2.5}$ and Ozone in 2018 and 2020 side by side (c) (d). And in 2017 and 2020 side by side (e) (f).

If we combine the previous years (2017, 2018 and 2019) of hourly values of CO, NO_2, $PM_{2.5}$ and O_3 and compare with the 2020 values, we can reduce the effect of interannual meteorological variability and emission uncertainty when comparison is made against the pooled values of 3 years. Figure 8 shows the boxplots of CO, NO_2, $PM_{2.5}$ and O_3 of the pooled values of 2017, 2018 and 2019 as compared with those of 2020. The results are similar to previous ones with NO2 median and maximum levels decrease at all sites and CO levels decrease at most sites. For $PM_{2.5}$, the median levels decrease at most sites and for O_3 the median levels mostly increase but the changes for these two pollutants are small.



(a) (b)

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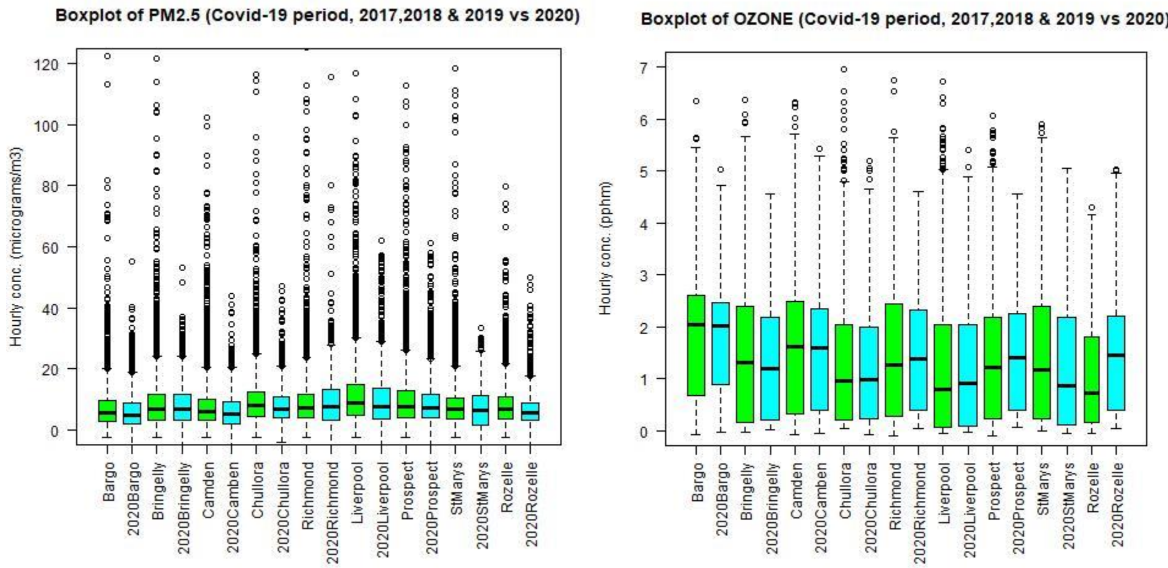


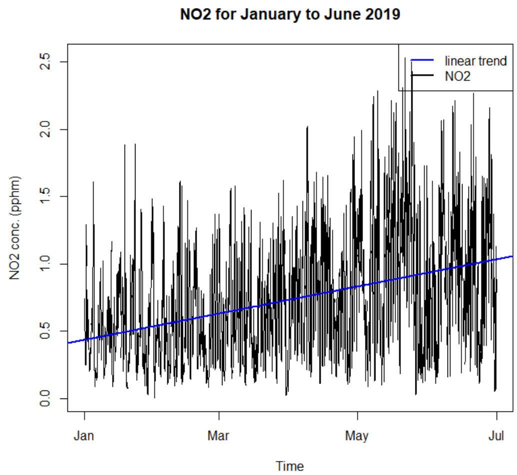
(c) (d)

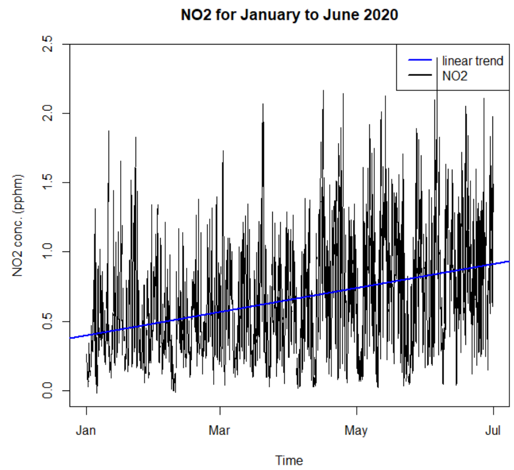
Figure 8 - Boxplot of NO_2 (a), CO (b), $PM_{2.5}$ (c) and O_3 (d) at different sites in the GMR based on pooled 2017, 2018 and 2019 data and those based on 2020 side by side for the period from April to June.

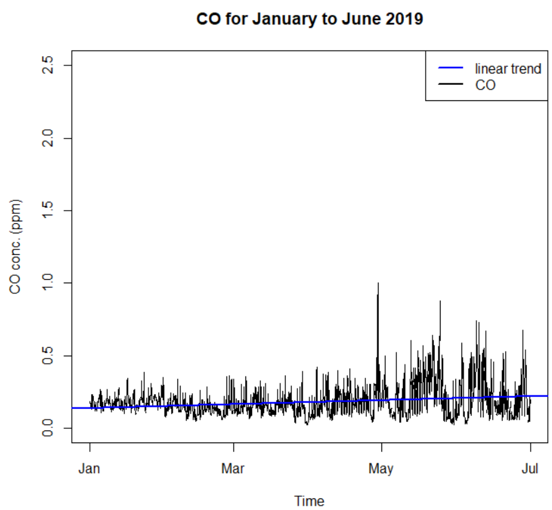
Putting all site measurements together for the whole GMR of Sydney for each year from 2016 to 2020, the results, as shown in Figure A.1 in the Appendix, show that for all pollutants (NO_2, CO, $PM_{2.5}$ and O_3), even though the COVID-19 lockdown period of 2020 in the GMR caused less CO, NO_2 and $PM_{2.5}$ and increase in O_3 as compared to 2019 but if other years are taken into consideration, the change is not noticeable or significant when looking at the over interannual trend.

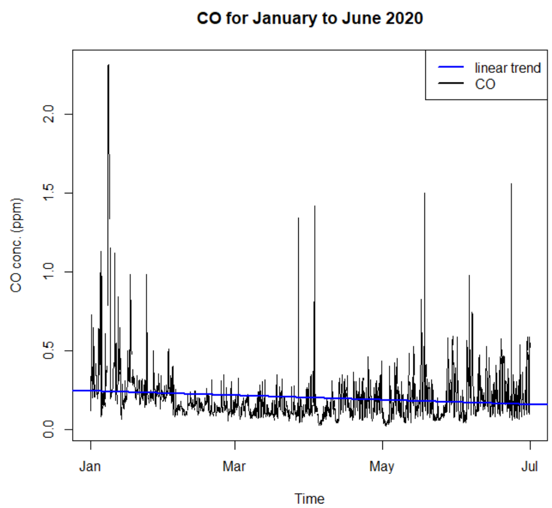
3.3 Trend analysis

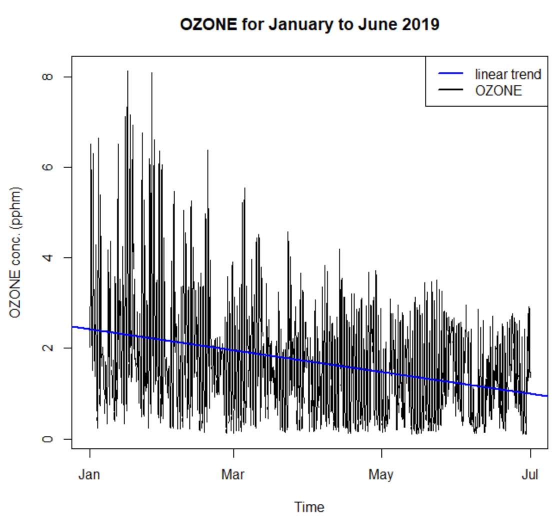
Trend of air quality in 2020 before and after the lockdown period as compared with trends in previous years during the same period has been used by [12]. We analyse the trends of average hour concentration of all Sydney monitoring sites for NO_2, CO, $PM_{2.5}$ and O_3 from January to June period in 2020 which covers the time before and after the lockdown period and the trends of these pollutants in 2019. It can be seen that the trends for NO_2 in 2019 and 2020 are both increasing, but NO_2 level in April and May 2020 is lower than that in 2019. There is no indication that the lockdown period in April and May caused a downward trend in NO_2. The increasing trend is mainly due to photochemical reaction change involving NO_x, CO, O_3 and Volatile Organic Compound (VOC) from austral summer (January-February) to autumn (March to May) and winter (June to August) when temperature is decreasing. In January and early February 2020 before the lockdown period in April and May, the summer 2019-2020 wildfires caused $PM_{2.5}$ and CO levels to be elevated in the Sydney region. The downward trend of these pollutants therefore is due to the decrease in emission from natural source. As for decreasing trend in O3, it is due to the seasonally change in meteorology when temperature drops in cooler weather of autumn and early winter. In addition, emission also changes seasonally such as solid fuel heating and temperature-dependent tail-piped and evaporative emission. Solely using the trend to detect the impact of lockdown on air quality is not reliable.

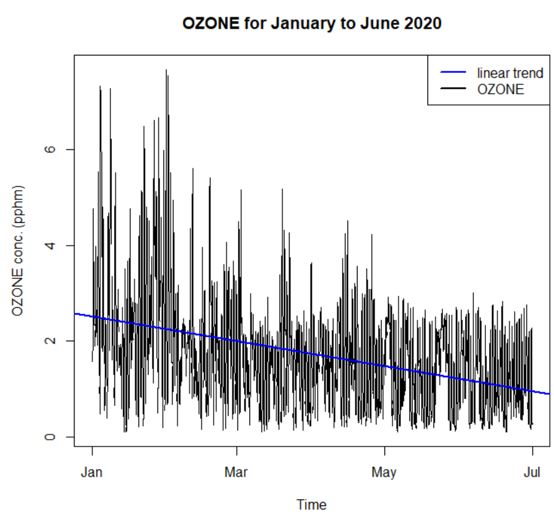

NO2 for January to June 2019
linear trend
NO2
NO2 conc. (pphm)
Time
Jan
Mar
May
Jul


NO2 for January to June 2020
linear trend
NO2
NO2 conc. (pphm)
Time
Jan
Mar
May
Jul


CO for January to June 2019
linear trend
CO
CO conc. (ppm)
Time
Jan
Mar
May
Jul


CO for January to June 2020
linear trend
CO
CO conc. (ppm)
Time
Jan
Mar
May
Jul


OZONE for January to June 2019
linear trend
OZONE
OZONE conc. (pphm)
Time
Jan
Mar
May
Jul


OZONE for January to June 2020
linear trend
OZONE
OZONE conc. (pphm)
Time
Jan
Mar
May
Jul

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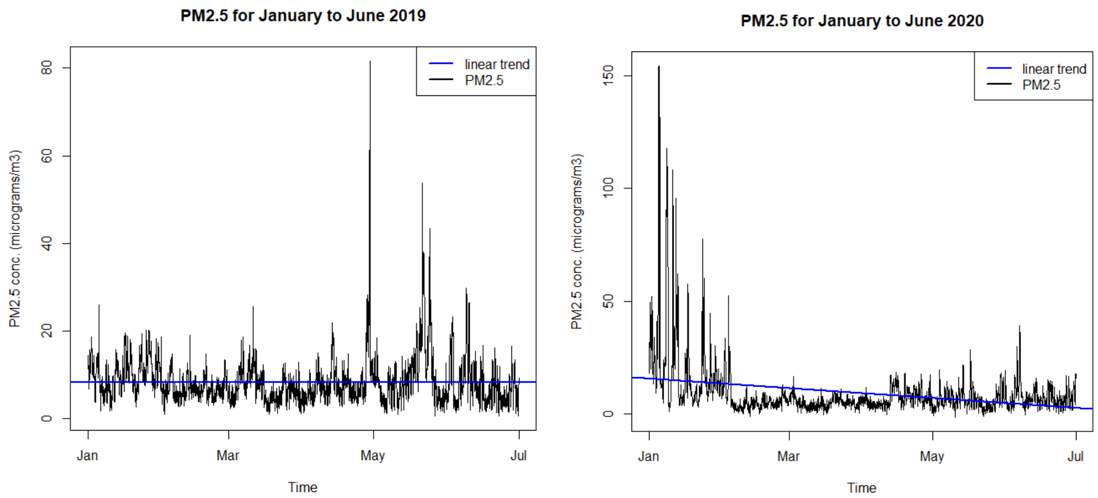
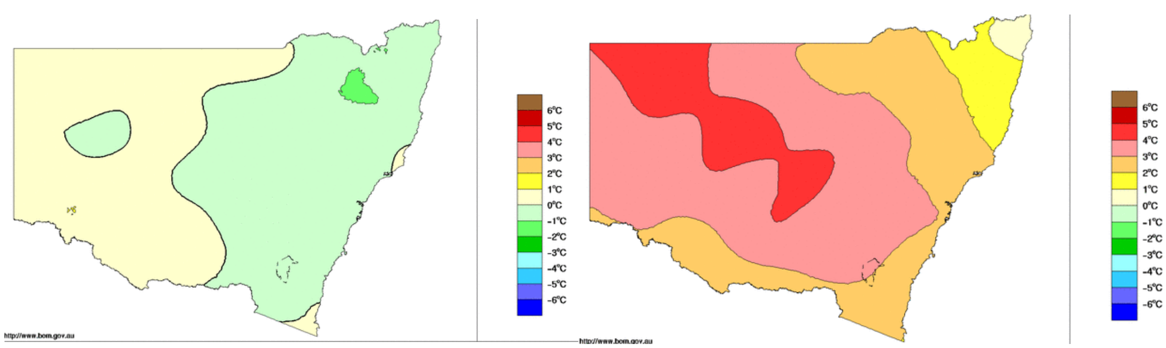


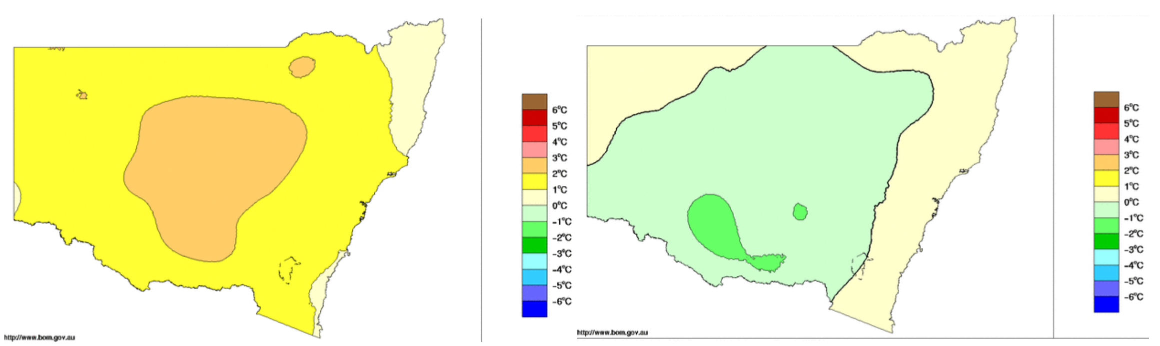
Figure 9 – Average hourly concentration of all monitoring sites of NO_2, CO, O_3 and $PM_{2.5}$ from January to June period in 2019 and 2020 and linear trend using GLM (Generalized Linear Model).

3.4 Meteorological analysis

It is important to control change in meteorology in the "control and treatment" method when compare the air quality in the lockdown period in 2020 with those in the previous years of the same corresponding period. The assumption is that on average the meteorological conditions over the period from April to June is similar in 2020 and to those in previous years. However, as mentioned before 2018 is a particular hot year compared to others, the ozone level on average in 2018 is higher than those of other years. Figure 10 shows the anomaly of mean temperature across NSW in different year as compared to the average over the standard reference period of 1961–1990.



(a) (b)



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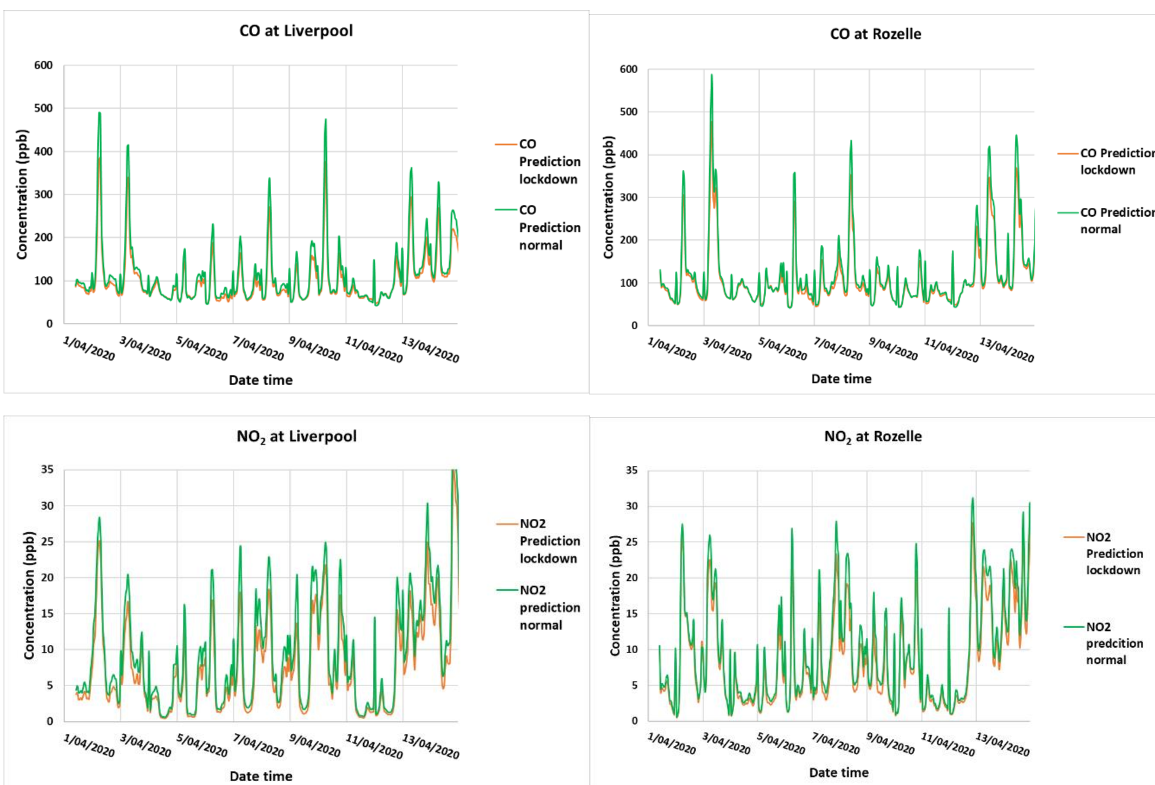
(c) (d)

Figure 10 – Mean temperature anomaly in NSW for April: (a) 2017, (b) 2018, (c) 2019 and (d) 2020.

From Figure 10, the year of 2020 is a cooler year in April as compared to the same month in 2019 and 2018 but is about the same as in April 2017. Note that 2018 is a hot year in April. For May, the patterns are also similar to those in April with May 2020 is cooler than May in previous years. But for June, the mean temperature anomaly in 2020 is similar to those in June of previous years. The hotter year 2018 in April and May explains why the median ozone level in 2018 is higher than the corresponding level in 2020 of the COVID-19 lockdown (Figure 7d) while the levels in 2017 and 2019 are lower than the COVID-19 2020 level (Figure 7b and Figure 7f). In other word, the meteorological effect in 2028 causing higher ozone in 2018 as compared with that in 2020 is stronger than the effect of reduced emission in 2020 causing higher ozone in 2020 as compared with 2018 due to the COVID-19 lockdown. This shows the importance of controlling the effect of meteorology in different years when the effect of reduced emission on air quality such as during the lockdown in 2020 is being investigated.

3.5 Air quality modelling of emission change during the lockdown period

The simulation results from WRF-CMAQ 5.3.1 are obtained for the 3 domains d01, d02 and d03. As we focus in the Sydney metropolitan area, the inner most d03 domain (1km by 1km) are used to extract the time series of CO, NO_2, O_3 and $PM_{2.5}$ at each of the grid point nearest to the location of the monitoring sites from the results of simulation (1 to 14 April 2020). Simulation is based on emission before lockdown (normal emission) and reduced emission during lockdown. Figure 11 shows the time series of these pollutants from 1 to 14 April 2020 at Liverpool in the south west of Sydney and Rozelle in the Sydney centre as predicted from the WRF-CMAQ model for the above two scenarios.



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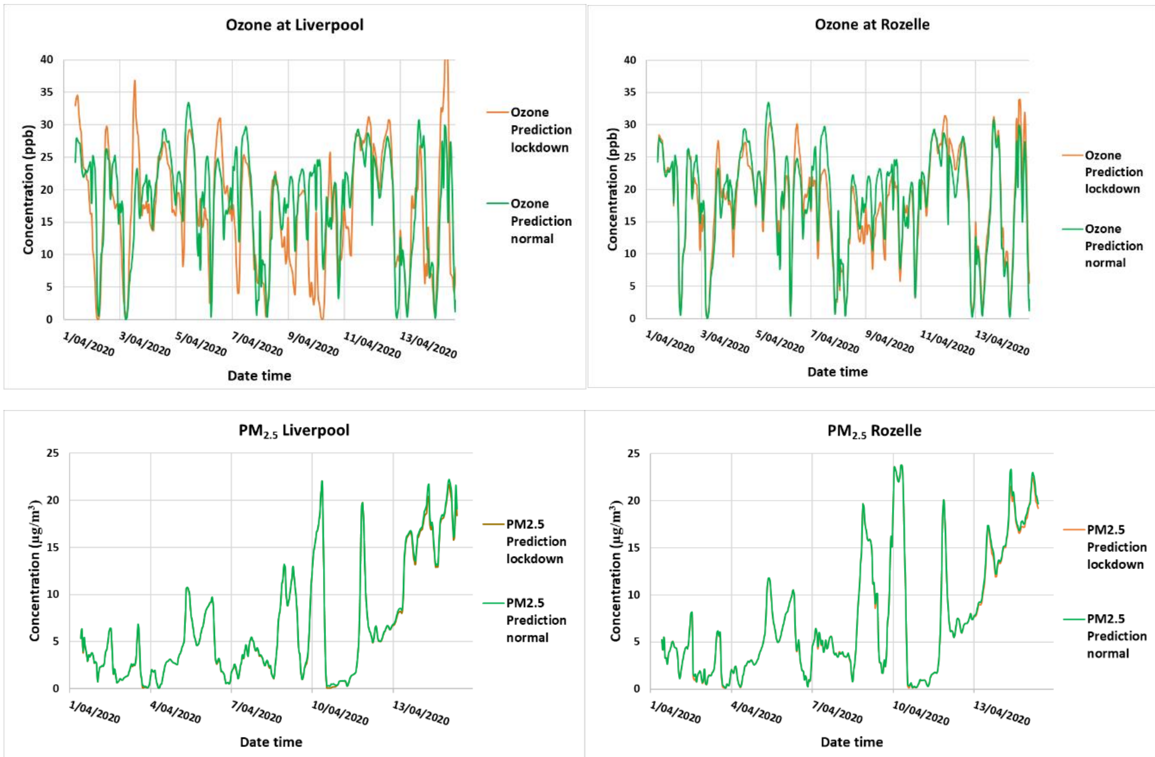

Figure 11 – CO, NO_2, O_3 and $PM_{2.5}$ prediction from 1 to 14 April 2020 at Liverpool and Rozelle during lockdown with 30% less traffic emission and with normal traffic emission.

Figure A.2 of the Appendix shows the results for other sites, Wollongong in the Illawarra south of Sydney and Richmond in the north west of Sydney where the influence of traffic is much less than the sites of Liverpool and Rozelle. The results however are similar. For CO, NO_2 the decrease of the pollutant concentration during the lockdown period when the traffic emission is about 30% less than normal traffic emission is predicted for all the sites in the GMR. The increase is rather not significant. For O_3, the daily peak values in 2020 most often increase during the period of simulation even though the increase is small. Figure A.3 in the Appendix shows that the prediction of CO, NO_2 and O_3 from simulation using WRF-CMAQ for the lockdown period from 1 to 14 April 2020 corresponds well with observation. For $PM_{2.5}$, however, the soil dust component of $PM_{2.5}$ from the dust emission module in CMAQ is overestimated. Removing this soil component improves the total $PM_{2.5}$ predicted concentration as compared to observation. Comparison of predicted $PM_{2.5}$ during lockdown period and normal period shows that there is virtual no change in predicted $PM_{2.5}$ concentration with decrease of $PM_{2.5}$ (mainly Elemental Carbon, Organic Carbon, Organic Matter components) during lockdown is too small to be detected.

4. Discussion

Of the four pollutants CO, NO_2, $PM_{2.5}$ and O_3, when comparison is made between the levels of those pollutants in 2020 and those of the previous years (2017, 2018 and 2019) only O_3 did not show a decrease in concentration consistently. Using monitoring data, the effect of the lockdown could be masked by different meteorological conditions and emission in 2017, 2018, 2019 and 2020. Our results are consistent with the results from other studies in cities around the world such as [10] in Shanghai, [8] in 10 major world cities including Sydney and Perth in Australia, [11] in Chinese cities. Rodríguez-Urregoa et al. 2020 [6] compared the $PM_{2.5}$ time series of a typical week during lockdown with that of 1 week before the lockdown for 50 most polluted cities in the world. They reported most of the cities such as Dhaka, Delhi, Ulanbator, Colombo, Tashkent, Kuwait City, Tehran, Beijing have

$PM_{2.5}$ level significantly reduced from 40% highest (Delhi) to 8% (Beijing). But other cities such as Kathmandu, Hanoi, Jakarta, Singapore and Tokyo had an increase trend of $PM_{2.5}$ concentration by 11%. Their method of comparison using one-week $PM_{2.5}$ time series data entering the lockdown and a typical week time series before the lockdown is rather short and does not take into account of meteorological and other variabilities and therefore cannot explain the reason for the change in $PM_{2.5}$ level as due to emission reduction or due to meteorological effect.

Habibi et al. 2020 [8] conducted a similar study using the 10 world major cities air quality data from WAQI for February to April period. Sydney and Perth from Australia were included. The comparison was made between February to April 2020 and 2019. Sydney was reported to have reduction in NO_2, CO and $PM_{2.5}$ in February, March and April but increase in O_3 in February, April. Their results correspond to ours using March to June period. Sydney has the lowest reduction of NO_2 emission among the 10 cities but highest reduction of $PM_{2.5}$ (-34.5%) in March to April. To account for change in meteorology, temperature and wind speed for the months of February, March and April in 2019 and 2020 were also considered. There are little changes in monthly temperature median values of these parameters for Sydney. Our results of reduction in NO_2, CO and $PM_{2.5}$ levels and increase O_3 level during the April to June 2020 lockdown period correspond to their results which are based on data from February to April. However, our results show the change is relatively small. Using air quality data in Sydney from April 2019 and April 2020, Brimblecombe and Lai 2020 compared the NO_2, $PM_{2.5}$ and O_3 levels and reported that the decreases during the lockdown period of 2020 is small and not significant. Their results correspond to those in our study.

The decreased level of $PM_{2.5}$ during the lockdown period can be due to both the decrease of primary $PM_{2.5}$ and the reduction of secondary inorganic aerosols from less nitrate formation. Chen et al. 2020a in their study of impact of lockdown on chemical composition of $PM_{2.5}$ in Shanghai showed that reduction in $PM_{2.5}$ is attributed to the decreasing concentrations of primary aerosols and nitrate and decreasing level of NO_x led to increasing O_3 and decreasing nitrate. They also found that as the proportion of nitrate in $PM_{2.5}$ decreased the proportion of sulphate and oxygenated organic aerosols (OOA) increased and hence inhibited the decrease of $PM_{2.5}$ level further.

The increase in the median O_3 level during the lockdown 2020 period is not unexpected as ozone formation in the GMR is mostly in VOC-limited (or light-limited) regime and hence a reduction in NO_x (or NO_2) will increase the rate of photochemistry reaction and hence the ozone level. Wang, Wen et al. 2020 [17], using machine learning method, also reported increasing levels of O_3 during the 4-months lockdown period in 6 mega-cities in China. Chen et al. 2020a [10] also reported that O_3 level increased in Shanghai during the lockdown period as the results of the decreasing NO_x level. The results from our study highlights the need to reduce the VOC emission as well to improve the ozone level in the GMR as reduction of NO_x is not necessary to improve the ozone. The previous source apportionment study to ozone level in the Sydney Metropolitan Region [15] indicated that motor vehicle emission has the largest influence on maximum ozone level in the south west and west of Sydney and reduction of motor vehicle emission will improve maximum ozone level in the GMR. Figure 8 shows that the maximum ozone level is improved during the 2020 lockdown period for sites in the south west of Sydney (Liverpool, Camden, Bargo, Bringelly and StMarys) even though the median level increases at most sites.

To control the effect of meteorology, air quality model such as WRF-CMAQ is used. In this way, the effect of lockdown due to change in emission on air quality can be simulated. The results from the simulation for the first two weeks of the lockdown period in April confirmed the results using statistical analysis of air quality monitoring data. The CO, NO_2 and $PM_{2.5}$ concentrations decreased while O_3 increased during the lockdown. However, the changes in those concentration are not significant. Similarly, the simulation study using WRF-CMAQ air quality model for 2017, 2018, 2019 and 2020 April to June period with global meteorological data from these years with the same

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emission data input can allow us to find out the influence of meteorological conditions on ozone level separately. It is noted that the soil dust emission in WRF-CMAQ 5.3.1 is overestimated. This overestimation was also observed by [18]. Removing this wind-blown dust (WBD) component improve the $PM_{2.5}$ prediction as compared with observation.

In our simulation using air quality model for the COVID-19 lockdown period of April to June 2020 in Sydney, there is uncertainty in quantifying the changes in emission. The effect of lockdown had an impact not only on the motor vehicle emission, shipping and aircraft emission but also can potentially increase the domestic sector emission and lead to a decrease of emission in the commercial sector. The overall domestic and commercial emission therefore can offset some of the transport sector emission reduction due to this trade off. This study does not consider those change in emission in other sectors.

Using the trend method, Zangari et al. 2020 [12] found that no significant difference in trend of $PM_{2.5}$ and NO_2 in the period before and after the lockdown with those of the previous years during the same period. This result of no improvement in air quality from the COVID-19 lockdown is in contrast with those reported by other authors analyzing data in other countries such as India and China. They speculated that major improvements in air quality due to the lockdown were only found in places that had higher levels of air pollutants before COVID-19 pandemic, compared to locations with relatively clean air to begin with such as in New York City in U.S. We suggest that the improvement trend based on the air quality data from January to May (from boreal winter to autumn) in 2020 and in previous years in their work is due to the improvement in the emission (such as less solid fuel heater emission) and hence masked the small improvement in 2020 due to COVID-19 lockdown. Comparison of trend before and after the COVID-19 lockdown period in 2020 with those in previous years is not a reliable method as the change due to seasonal change in meteorology and emission is larger than the change in emission due to lockdown. The results of our trend analysis show that trends in NO_2, CO, $PM_{2.5}$ and O_3 before and after lockdown can be due to seasonal change in meteorology and emission in addition to complex photochemical reaction between primary pollutants NO_2, CO and $PM_{2.5}$ and secondary pollutants (O_3 and secondary organic or inorganic aerosols components of $PM_{2.5}$).

Our study shows that the trend method cannot be used to detect the effect of short lockdown period (a few months) due to change in emission by using interannual comparison of trend unless intra-annual effect or seasonal meteorological change is taken into account. On the other hand, by estimating the change in emission from quantifying the change in traffic activities during and before the lockdown, the control of meteorology is achieved by using air quality model to predict the change in air quality due to lockdown effect.

Wang, Chen et al. 2020 [19] used WRF-CMAQ model to predict the effect of COVID-19 lockdown in China on $PM_{2.5}$ pollution and showed that even though the levels in many cities are reduced due to large emissions reduction in transportation and slight reduction in industrial but that alone would not help avoid severe air pollution, especially when meteorology is unfavorable. Other methods to predict the effect of different lockdown scenarios on air quality have also been used, such as the data-driven Artificial Neuron Network (ANN) used recently by [20] as applied to lockdown in Brazil, South America.

5. Conclusion

The reduction of emission mainly from the transport sector during the COVID-19 lockdown period in Sydney and NSW in April to June has resulted in an improvement of air quality in the GMR in term of reduction of the pollutants of NO_2, CO and $PM_{2.5}$. But this also caused an increase in the secondary pollutant O_3 median and average levels. The simulation using air quality model on the effect of emission change on air quality also confirmed the above results derived from statistical analysis of air quality monitoring data. Even though the change in air quality during the lockdown period is small but it is detectable.

The lesson from the COVID-19 lockdown showed that improvement in air quality due to reduction of transport emission is small but measurable and it highlights the importance of not only transition from the current dominant combustion-technology vehicle fleet to electric or non-combustion technology but also the effort in emission reduction from other sources (shipping, aircraft, locomotive, power stations,…) including biogenic sources such as dust to make significant impact on air quality improvement in the urban areas.

Author Contributions: Conceptualisation, H.D., M.A., M.R and N.J.; methodology, H.D., D.S., S.W. (Sean Watt), S.W. (Stephen White), L.W.; data procurement: D.S., T.T., X.B.; formal analysis, H.D., D.S., S.W. (Sean Watt), and L.T.-C.C.; investigation, H.D., N.J., L.W., S.W. (Sean Watt) and S.W. (Stephen White); writing—original draft preparation, H.D.; validation: S.W. (Sean Watt) and S.W. (Stephen White); visualisation, H.D., T.T., H.N.; resources: X.B., D.F., H.N; supervision, H.D., M.A., N.J and M.R.; and project administration, H..D., M.A, M.R., and N.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgement: The MERRA-2 data used in this study/project were provided by the Global Modeling and Assimilation Office (GMAO) at NASA Goddard Space Flight Center Analyses and visualisations, where they are indicated in the paper, were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC. Traffic data are obtained from the NSW Road and Maritime Services (RMS) and Tomtom traffic site (https://www.tomtom.com), and meteorological data from the Australian Bureau of Meteorology (BOM).

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Appendix

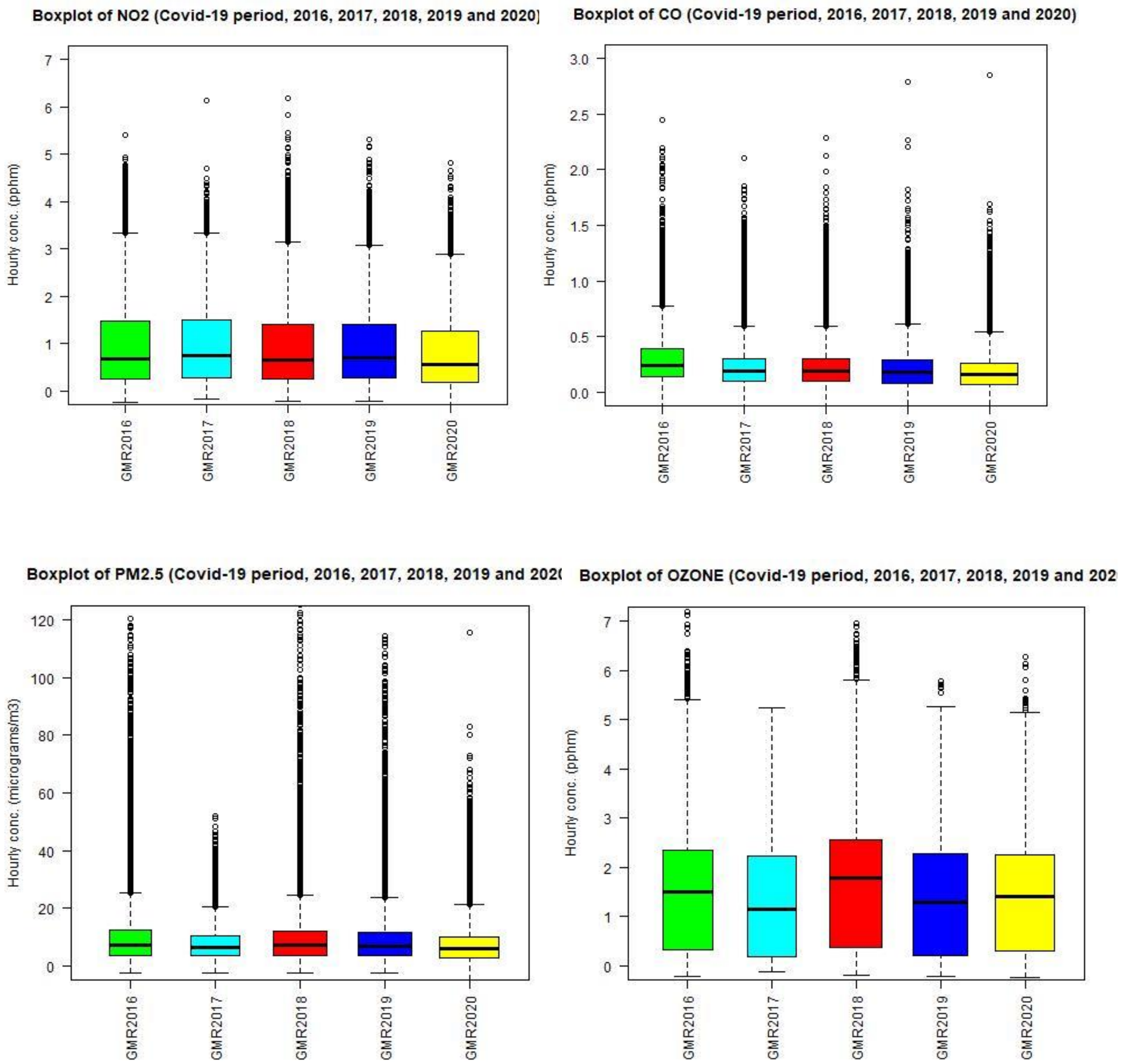
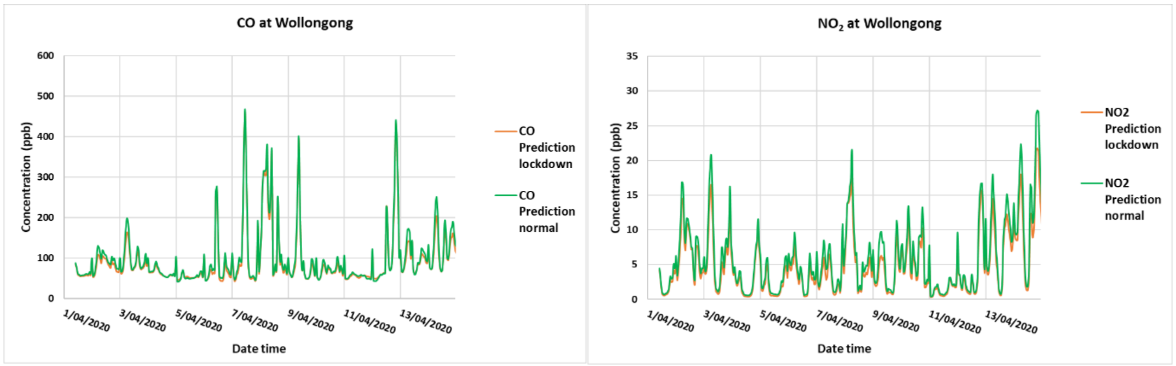


Figure A.1 -



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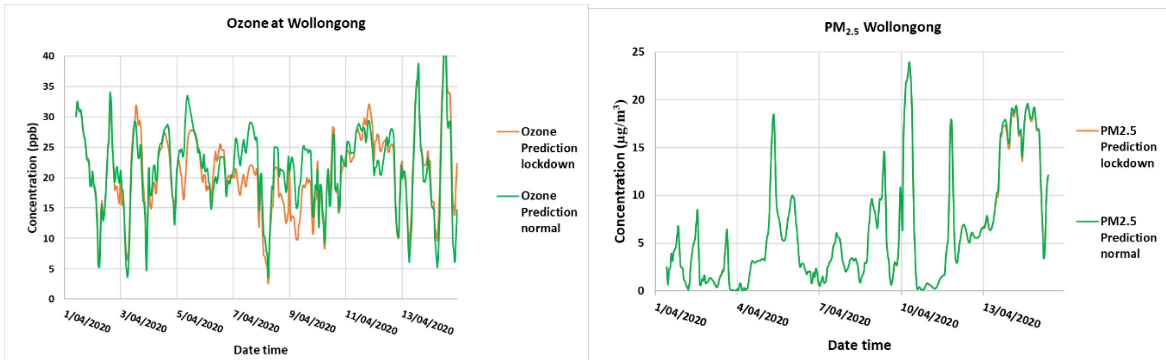

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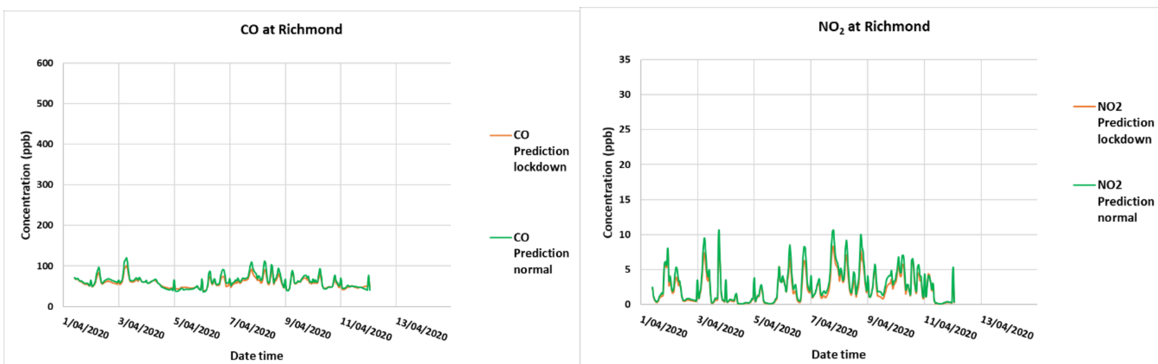

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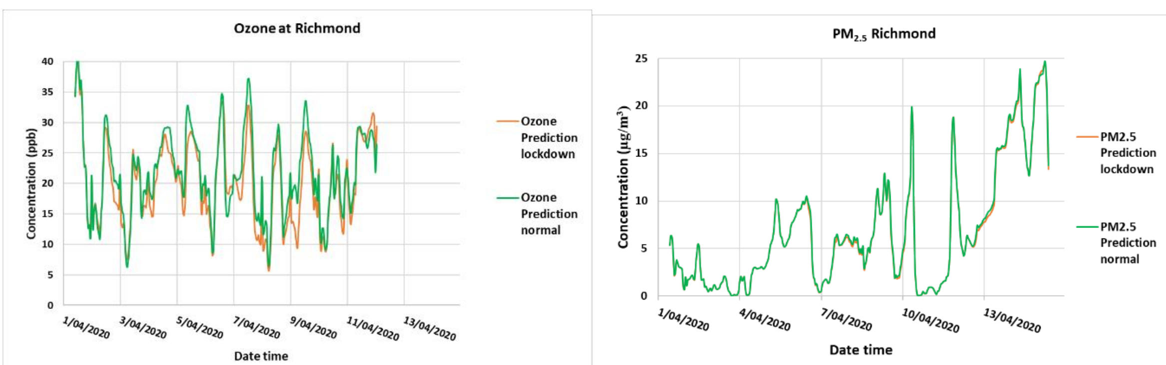

(g) (h)

Figure A.2 - CO, NO_2, O_3 and $PM_{2.5}$ prediction from 1 to 14 April 2020 at Wollongong and Richmond during lockdown with 30% less traffic emission and with normal traffic emission

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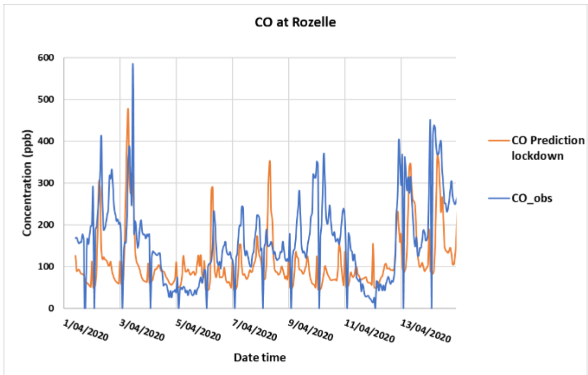

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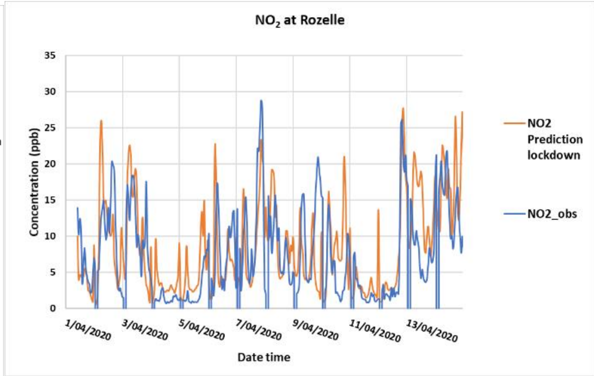

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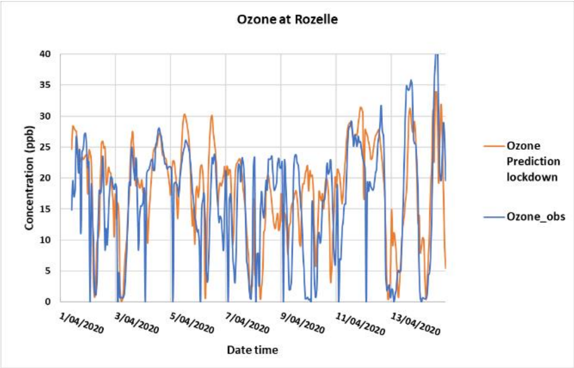

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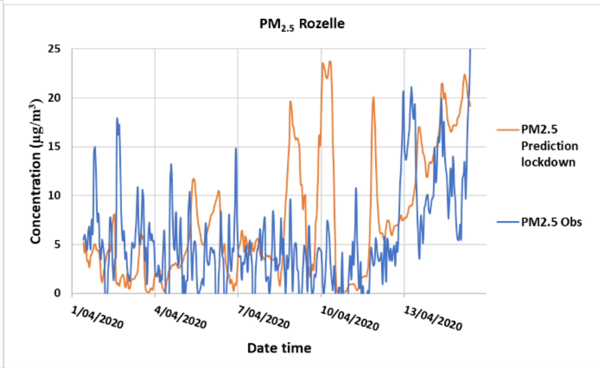

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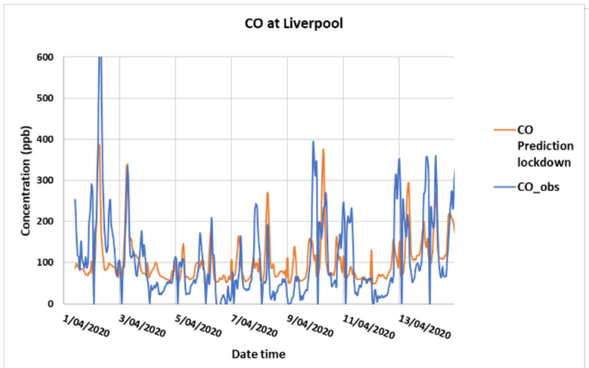

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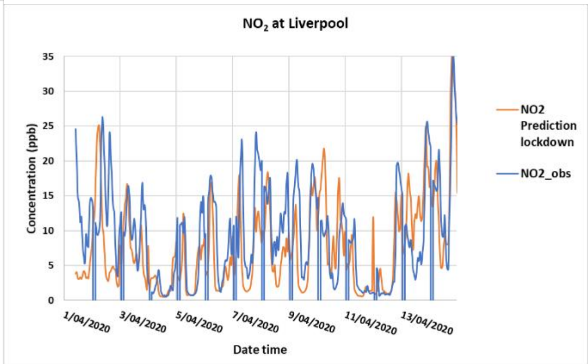

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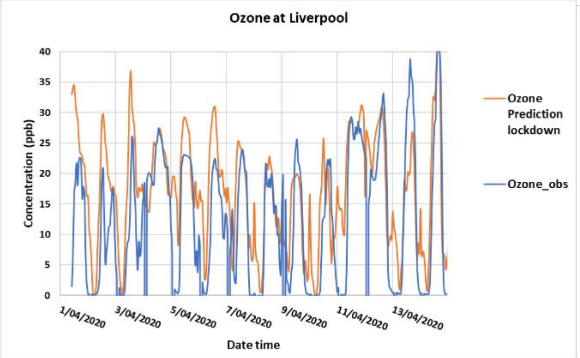

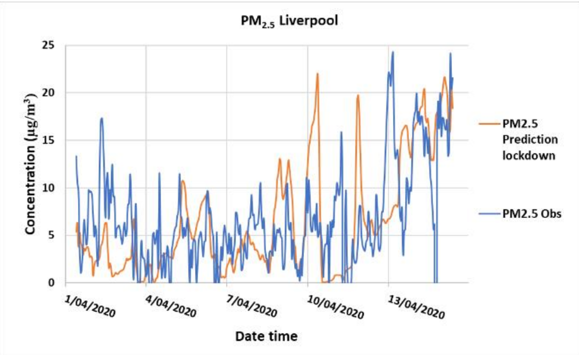

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(g) (h)

Figure A.3 - CO, NO_2, O_3 and $PM_{2.5}$ prediction from 1 to 14 April 2020 at (a, b, c and d) Rozelle and (e, f, g and h) Liverpool during lockdown as compared with observation. The predicted $PM_{2.5}$ consists of the following subcomponents: PM25_EC (elemental carbon), PM25_OC (organic carbon), PM25_OM (organic matter), PM25_CL (chlorine), PM25_MG (manganese), PM25_NO3 (nitrate) and PM25_NH4 (ammonium) as defined in the CMAQ model.