Implications for air quality management of changes in air quality during lockdown in Auckland (New Zealand) in response to the 2020 SARS-CoV-2 epidemic

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HIGHLIGHTS

- The COVID-induced 'natural experiment' significantly impacted air quality.
- The Isolated city of Auckland generates its own pollutants, with little to no long-range transport.
- Significant reductions in NO_2 & BC were observed while O_3 concentrations increased.
- Observed non-linear responses to changes in emissions.

GRAPHICAL ABSTRACT
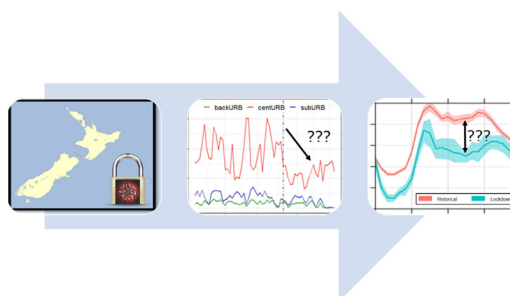
ARTICLE INFO

ABSTRACT

The current changes in vehicle movement due to 'lockdown' conditions (imposed in cities worldwide in response to the COVID-19 epidemic) provide opportunities to quantify the local impact of 'controlled interventions' on air quality and establish baseline pollution concentrations in cities. Here, we present a case study from Auckland, New Zealand, an isolated Southern Hemisphere city, which is largely unaffected by long-range pollution transport or industrial sources of air pollution. In this city, traffic flows reduced by 60–80% as a result of a government-led initiative to contain the virus by limiting all transport to only essential services. In this paper, ambient pollutant concentrations of NO_2, O_3, BC, $PM_{2.5}$, and PM_{10} are compared between the lockdown period and comparable periods in the historical air pollution record, while taking into account changes in the local meteorology. We show that this 'natural experiment' in source emission reductions had significant but non-linear impacts on air quality. While emission inventories and receptor modelling approaches confirm the dominance of traffic sources for NO_x (86%), and BC (72%) across the city, observations suggest a consequent reduction in NO_2 of only 34–57% and a reduction in BC of 55–75%. The observed reductions in $PM_{2.5}$ (still likely to be dominated by traffic emissions), and PM_{10} (dominated by sea salt, traffic emissions to a lesser extent, and affected by seasonality) were found to be significantly less (8–17% for $PM_{2.5}$ and 7–20% for PM_{10}). The impact of this unplanned controlled intervention shows the importance of establishing accurate, local-scale emission inventories, and the potential of the local atmospheric chemistry and meteorology in limiting their accuracy.

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1. Introduction

Globally, it has been estimated that air pollution kills 7 million people per annum (World Health Organization, 2018). In many cities, especially in European and in North American countries, urban air pollution is dominated by road traffic emissions (Squires et al., 2019; Rajé et al., 2018; Comert et al., 2020). To address this, a wide range of interventions are being considered which aim to improve air quality, reduce congestion, and address public health concerns associated with exposure to such emissions (Burns et al., 2020). However, the social and economic consequences resulting from attempts to reduce and mitigate traffic emissions (such as changing access and reducing speeds in central urban areas) often present a significant obstacle in terms of the acquisition of an evidence base which quantifies the causal link between the proposed change and the resulting improvements in air quality. The design of effective interventions aimed at reducing traffic-related emissions has been further hindered by uncertainties in model estimates of the impact of such interventions (Albert Van Aardenne, 2002; Zhao et al., 2015) due to limitations associated with emissions inventories, the complex dispersion patterns associated with urban environments and their non-linear and non-stationary causal links to meteorological and environmental conditions. The evaluation of local case studies testing traffic management interventions often show that, although local improvements in air quality can be achieved, the re-routing of traffic means that urban background and regional air pollution levels can remain high, or may even increase (Titos et al., 2015; Ellison et al., 2013). Highly localised traffic calming and tactical urbanisation strategies provide some opportunities to observe resultant changes in air quality, but can prove limited in their scaled-up modelling potential, given the limited scope of their implementation.

Internationally, social restrictions, imposed to limit the spread of COVID-19, have resulted in rapid and significant changes in the emission patterns of air pollutants across many major cities, with traffic flows severely reduced and industries closed or operating at significantly reduced rates as service provisions are limited to essential categories only (Dantas et al., 2020; Tobías et al., 2020). These changes are equivalent to large-scale "controlled interventions" and thus provide an unprecedented opportunity to study the impact of citywide emission reductions on air quality in cities worldwide. Preliminary analyses suggest reductions in concentrations in the order of 20–50% for pollutants such as black carbon (BC) and nitrogen dioxide (NO_2). Smaller reductions have been observed for concentrations of particulate matter of less than ten and 2.5 μm in equivalent diameter (PM_{10} and $PM_{2.5}$) respectively, with local increases noted in ozone (O_3) consistently reported (Dantas et al., 2020; Tobías et al., 2020; Muhammad et al., 2020; Sicard et al., 2020). The results suggest that larger reductions are observed for pollutants primarily associated with road transport, such as BC and NO_2, while the dependence of O_3 on NO_x emissions, which explains the apparent anomaly, points to the importance of atmospheric chemistry in determining non-linear patterns in the relationship between emission patterns and ambient pollutant concentrations (Dantas et al., 2020; Tobías et al., 2020). Other analyses of this unique period show the importance of local meteorological conditions in determining the correlation between reduced emissions associated with COVID-19 and related improvements in air quality (Wang et al., 2020).

The changes observed can also be used to provide insights into our understanding of the relative importance of different emissions sources, the accuracy of emissions inventories and the performance and reliability of air quality models under different emissions scenarios. Emissions inventories are essential for enhancing our understanding of the ways in which sources of air pollution contribute to the mix of pollutants in the atmosphere, and ultimately their impact on people and the environment, providing pertinent information relevant to both science and policy development (Kelly and Fussell, 2015; World Health Organization, 2018). They are used to monitor trends over long periods, check compliance with international standards and guidelines, as well as provide data used as input into complex mathematical models used to enhance understanding of the chemical and physical processes occurring in the ambient air (Albert Van Aardenne, 2002). However, they are based on a number of assumptions, developed as regional averages, and especially for vehicle emissions, there are few opportunities to evaluate their performance based on quantifiable changes in fleet composition or size.

This study presents the findings of an exploratory study investigating the changes in air quality observed in Auckland, New Zealand which resulted from changes in emissions patterns associated with COVID-19 restrictions during the one-month period of New Zealand's Level 4 COVID-19 lockdown. The purpose of this work is firstly to assess the extent of the reductions observed in air pollution levels across the city as a result of the lockdown, but also to gain an understanding of the impact of this unintentional large-scale intervention on air quality. It is also to improve our understanding of the relationship between known emission sources and ambient pollutant concentrations and to determine whether the importance of other emissions sources may have been overlooked. Since this city is unique in that it is largely dominated by traffic emissions, the results of this paper provide insight into the local and regional impact of traffic-reduction interventions on air quality in the absence of confounding factors. This is of relevance to decisionmakers as they evaluate the risks and benefits of traffic management interventions currently under consideration for Auckland (Talbot and Lehn, 2018) as well as in other cities, both in New Zealand and internationally.

2. Methodology

2.1. Site description

Auckland is located in the North Island of New Zealand (36.8485° S, 174.7633° E) between two large bodies of water (the Pacific Ocean to the east and the Tasman Sea to the west). The Isthmus city, with a population of approximately 1.6 million people (Statistics New Zealand, 2020), experiences a mild subtropical climate with humid summers and mild winters (Chappell, 2013). An Auckland-wide emissions inventory has indicated a wide range of air pollution sources across the city, with road transport being the major contributor. This analysis suggests that for road transport emissions annually across the city, PM_{10} contributes 3820 t yr^{-1}, $PM_{2.5}$ contributes 2719 t yr^{-1} and NO_x contributes 20,520 t yr^{-1}, thus transport accounts for 57% of the PM_{10}, 41% of the $PM_{2.5}$ and 86% of the NO_x produced (Xie et al., 2019). As a comparison, long-term elemental analysis and receptor modelling of particulate matter suggest that motor vehicles account for 43% of the $PM_{2.5}$ and 29% of the PM_{10} (see Fig. S1.1) (Davy et al., 2017). Importantly, the compositional analysis approach identifies oceanic sources (sea salt and secondary sulphate) as significant contributors to both $PM_{2.5}$ and PM_{10} in Auckland, sources not accounted for by the emissions inventory approach. Emissions inventory estimates suggest that domestic heating using wood burners contributes 35% to PM_{10}, 49% to $PM_{2.5}$ and 1.3% to NO_x (Xie et al., 2019). It is important to note that Auckland's aging road traffic fleet emits 92–97% of the total NO_x in the form of NO (Harrison and Shi, 1996), although in newer vehicles, this percentage may be higher (Carslaw et al., 2007). The minimal levels of secondary NO_2 formation observed (Gimson, 2005; Salmond et al., 2013) are explained by the very low annual mean ozone concentrations (19 ppb) observed across the city (Weissert et al., 2017).

Studies in Auckland have also identified variability in the relative contribution of sources depending on the location of monitoring stations in relation to the land use of the surrounding area (whether a major road, an industrial area, or residential, etc.). For example, a study focussing on air pollution levels in the city centre suggests that diesel vehicles contribute disproportionately to NO_2, BC and $PM_{2.5}$ concentrations (Talbot and Lehn, 2018). However, despite their dominance

in terms of a source, traffic emissions citywide have reduced in recent times due to technological advances in engine efficiency within the vehicle fleet, as well as through the use of cleaner fuels, leading to significant improvements in the quality of the air, except in the city centre where NO_2 and $PM_{2.5}$ concentrations have increased significantly (Talbot and Crimmins, 2020). The authors attribute this change to the increased flows of buses, recent large-scale construction and development work underway, as well as ever-taller constructed buildings increasing the urban valley depth, potentially reducing pollutant dispersion in the area.

While emission inventories and source apportionment studies carried out in the Auckland Region have noted road transport as a major source of pollution, domestic heating is also a significant contributor; however, unlike traffic and industry, transport is highly variable in terms of source strength across seasons with peaks occurring during the cooler seasons (Xie et al., 2019; Davy et al., 2017). The lockdown period being investigated took place during the Southern Hemisphere's autumn, a time of year when temperatures drop and the weather can become more changeable (Chappell, 2013), and when home heating sources can be expected to be emerging.

2.2. New Zealand lockdown

The World Health Organization declared the Coronavirus a global pandemic on March 11th 2020, shortly after New Zealand announced its first confirmed case on the 28th of February. The New Zealand government set an ambitious target of eliminating the virus through the introduction of nation-wide extended 'lockdown' measures. Restrictions started with a closing of New Zealand's borders on March 19th to all except New Zealand permanent residents and citizens. A four-level alert system was introduced on March 21st. Introduction of 'Level 3' on Tuesday the 25th March, restricted travel to local movements only. On midnight on the 27th of March, Level 4, commonly referred to as 'lockdown,' was instigated, restricting travel to essential services and for the purpose of replenishing food supplies, and for seeking medical services and medicines. Social contact was reduced to household-sized 'bubbles', and the use of public transport reserved only for essential services (Radio New Zealand, 2020). The resultant lockdown was listed as one of the most restrictive and well-observed globally. It was finally relaxed from midnight of the 26th April.

2.3. Data

Data from three fixed-site air quality monitoring sites within the Auckland urban area (Fig. 1) are analysed here. Both the Queen Street and Customs Street sites (considered to be 'Central Urban' – centURB and referred to as one site) are located in a street canyon within the Central City area. The area is a major retail centre, with key transport hubs and high pedestrian volumes. Due to space constraints at the existing Queen Street site, BC is measured 200 m away from the main site. The Henderson site, located alongside a major arterial road within a light industrial mixed zone, is considered to be 'Suburban Roadside' (subURB). Patumahoe, a rural background site, is located in the outskirts of greater Auckland. It is considered to be 'Urban Background' (backURB). Due to operational limitations, backURB is the only site measuring O_3 in the Auckland region. Pollutants measured include PM_{10}, $PM_{2.5}$, BC, O_3, and NO_2. Details about the instruments used for data collection and details of the datasets are presented in Table 1. The lockdown period was considered to be from 27 March until 17 April 2020, with data from this period compared with 'business as usual' (BAU) historical data for a similar time of year (February to April) extending back to 2015 (where available), allowing for consideration of the impacts of the local meteorology on air pollution levels at the same time of year.

While BC concentrations, measured at both the Customs Street and Henderson sites, were obtained using on-line aethalometers, the air quality monitoring for all other sites and pollutants mentioned was measured using regulatory-compliant instruments and best practice techniques (Ministry for the Environment, 2009). Data were further supplemented with NO_2 concentrations and satellite measurements for further evidence of the temporal changes in the spatial patterns averaged over regional scales. Analysis is also supplemented by source apportionment information using methodologies described by Davy et al. (2017), demonstrating the likely impact of emission sources under business-as-usual (BAU) scenarios, providing further evidence of changes in the contributions of the various sources to the observed air pollution levels.

2.4. Meteorological data

Meteorological data were retrieved from the National Institute of Water and Atmospheric Research Cliflow database (National Institute of Water and Atmospheric Research, 2020). A summary of the meteorological conditions observed during the periods of interest are presented in Table 2. The temperature and relative humidity were slightly lower during the lockdown period (-2.7 °C (t = 10.1, P < 0.05), -4.6% (t = 7.9, P < 0.05), respectively) than during previous years at the same time of year, based on daily averages. Wind speeds were found to be similar to those observed in previous years (t = 1.1, P < 0.05). Historical wind data for this time of year show a predominance of northeast - southwest wind flows. However, during the lockdown period, winds were predominantly from the west-south-westerly direction (see Fig. 2). Rainfall was found to be historically low for this period compared with the same time of year in other years: 3.2 mm on average for the same period from 2015 to 2019 but 0.1 mm for the lockdown year.

2.5. Traffic data

Historical traffic data, including information on the fleet composition for the roads adjacent to both the Henderson and Queen Street sites were obtained for a selected week during 2018 (see Table 3). Traffic data during lockdown for light vehicles and heavy goods vehicles, recorded at State Highway 1, were obtained from the New Zealand Transport Agency.

Fig. 3 shows significantly reduced volumes of traffic along Auckland's major motorways when compared with the same period for the previous year, both with respect to light and heavy vehicles; light vehicle flows reduced from a daily average of (29,800 ± 2200) to just (6200 ± 1300) vehicles per day, or a reduction of about 79%. Heavy goods traffic reduced from an average of (3800 ± 160) to (1500 ± 390) vehicles per day, or an overall reduction of 60% on the previous year.

3. Results

Statistically significant changes in the 24-hour average air pollution concentrations were observed before and after lockdown at the central urban site (centURB) and the suburban roadside (subURB) site for all pollutants evaluated, based on t-tests (Fig. 4, Table 4). Statistically significant changes at the urban background (backURB) site were only observed for NO_2 and O_3, and not $PM_{2.5}$ nor PM_{10}.

3.1. Observed changes in NO_2 concentrations

The average daily NO_2 concentrations decreased by 34.1% at the centURB site, 56.9% at the subURB site and 35.6% at the backURB site. Although the largest proportional drop was observed at the subURB site, the greatest concentration decrease occurred at the centURB site, the site which consistently recorded the highest NO_2 means. The observed reduction in daily concentrations was therefore more significant at the centURB site compared with other sites, recording a concentration of 12.2 μg m^{-3}, double that of the subURB site (5.5 μg m^{-3}) and over ten
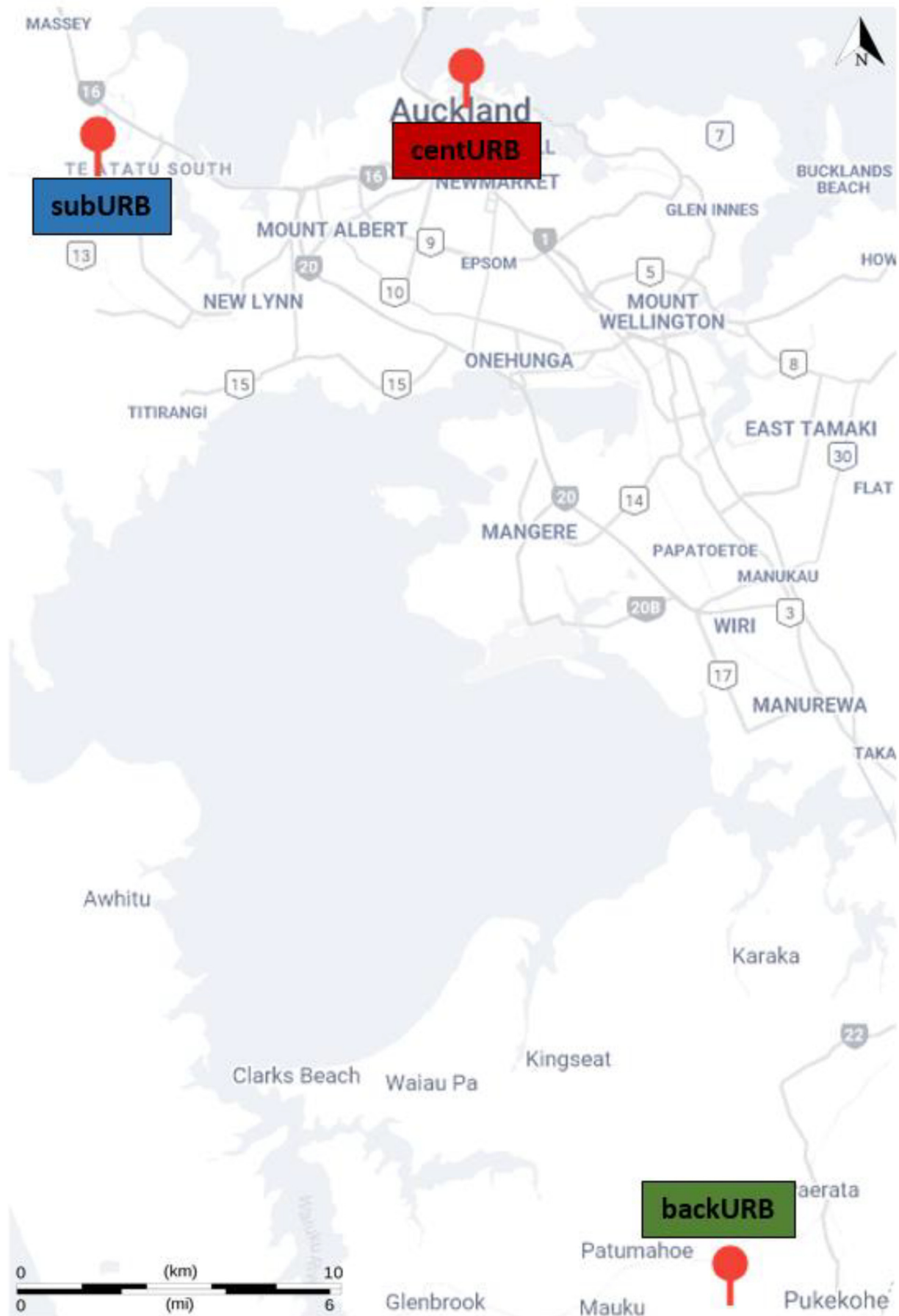
Fig. 1. Map of sampling locations for air quality data within the Auckland region. Auckland central (centURB), Henderson (subURB) and Patumahoe (backURB).

Table 1
Details of instruments located at centURB, subURB & backURB sites.

Site	Pollutant	Instrument	Federal reference/federal equivalent method	Date of first record	Percent data available since install	Manufacturer Info
centURB	BC	MetOne 1060	No	August 2019	99%	MetOne Instruments Inc., Oregon, USA
	NO_2	Teledyne 200E	Yes	Pre 2015	99%	Teledyne Air Pollution Instruments, California, USA
	$PM_{10}/PM_{2.5}$	Teledyne T640X	Yes	March 2017	99%	Teledyne Air Pollution Instruments, California, USA
subURB	BC	Magee AE33	No	December 2016	99%	Magee Scientific, California, USA
	NO_2	Teledyne 200E	Yes	Pre 2015	99%	Teledyne Air Pollution Instruments, California, USA
	PM_{10}	Thermo Scientific FH62C14 BAM	Yes	Pre 2015	99%	Thermo Scientific, Massachusetts, USA
backURB	NO_2	Teledyne 200E	Yes	Pre 2015	82%	Teledyne Air Pollution Instruments, California, USA
	O_3	Thermo 49i	Yes	Pre 2015	92%	Thermo Scientific, Massachusetts, USA
	PM_{10}	Thermo Scientific FH62C14 BAM	Yes	Pre 2015	94%	Thermo Scientific, Massachusetts, USA
	$PM_{2.5}$	Thermo 5014i BAM	Yes	Pre 2015	77%	Thermo Scientific, Massachusetts, USA

Table 2
Historical (February, March & April 2016–2020) and lockdown (26th March 2020–17th April 2020) min, max mean & standard deviations for meteorological conditions. Daily observations show.

	Daily historical				Daily lockdown				Daily variation			
	Min	Max	Mean	Std. Dev	Min	Max	Mean	Std. Dev	Mean	%	t-Test	P-value
Temperature (°C)	5.4	29.4	18.8	2.4	6.8	25.5	16.1	1.13	−2.7	−14.4	10.1	<0.05
Relative humidity (%)	29.8	97.3	72.8	14.0	33.3	88.8	68.2	13.2	−4.6	−6.3	7.9	<0.05
Wind speed (ms^{-1})	0.0	12.6	2.7	1.7	0.0	7.7	2.6	1.7	−0.1	−3.7	1.1	0.274
Rainfall (mm)			3.2				0.1		−3.1	−1.0	3.2	<0.05

times that of the backURB site (1.3 $\mu g\,m^{-3}$) (see Fig. 5). This large reduction in NO_2 concentrations has significant implications for population exposure, especially for New Zealand's most densely populated street.

Data from the Auckland Council emission inventory (Xie et al., 2019) suggest that 85.6% of NOx emissions are derived from vehicle emissions annually, with little seasonal or urban/regional variation (note that
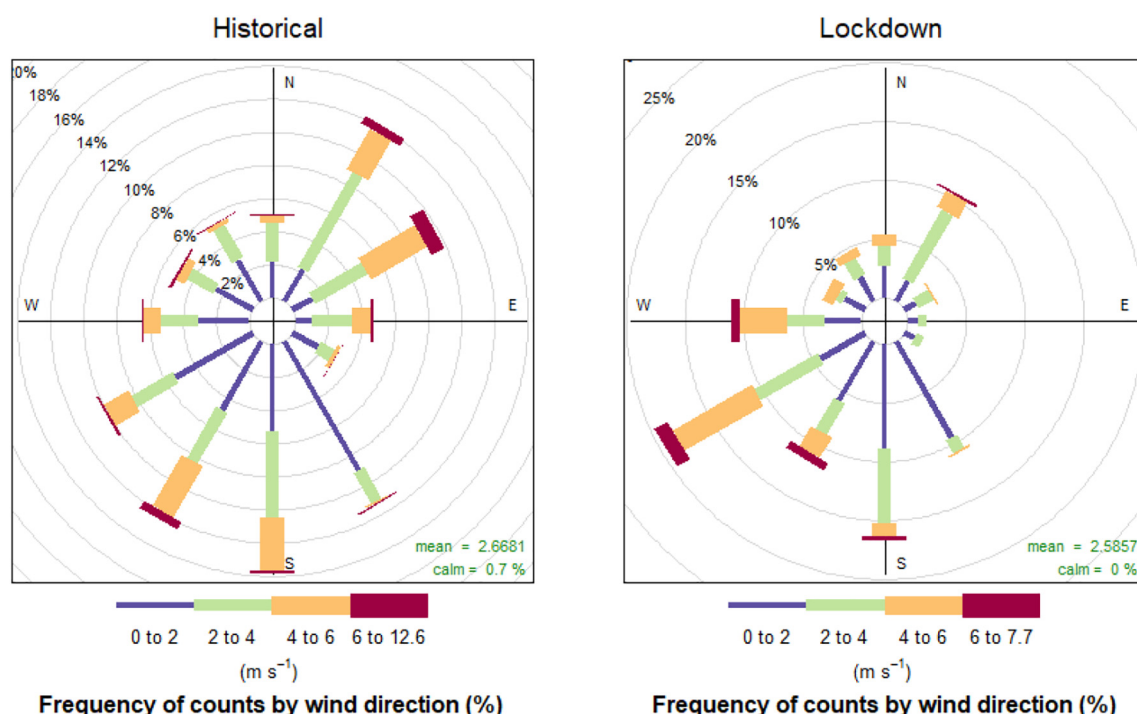

Fig. 2. Wind roses for the historical (February, March & April 2016–2020) and lockdown (26th March 2020–17th April 2020) periods. Hourly averaged data shown.

Table 3
Traffic data showing the number and composition of the fleet by vehicle type for Lincoln Rd (subURB) and Queen St (centURB).

Road name	Peak traffic per hour	% car	% commercial	% heavy goods	Peak hour	Average daily total (ADT)
Lincoln Road, Henderson (subURB)	2434	92	8	6	1500	30,638
Queen Street, Auckland (centURB)	580	93	7	7	1115	9292

emissions data for NO_2 specifically are not available). During lockdown, reductions in vehicle flow of approximately 80% for light vehicles and 60% for heavy goods vehicles were observed (Waka Kotahi NZ Transport Agency, 2020). There is less reduction in NO_2 concentrations than traffic flow, as might be expected. This could be explained by regional differences in changes in traffic flow (which are not identifiable in the traffic data currently available), or perhaps reflects the dominance of diesel emission sources (buses in particular) that remained in operation during lockdown, albeit at a reduced rate. It could be also due to a higher proportion of NO being oxidised into NO_2 at lower NO_x concentrations. Port emissions are another potentially significant contributor to the city's NO_x, with previous reports suggesting emissions from the port are non-negligible (Xie et al., 2019; Butler et al., 2020). In addition, it has been reported that heavy vehicle traffic to the Ports of Auckland increased during a selected period of lockdown compared to the weeks prior (Fig. S1.2) (Ministry of Transport, 2020). It has also been found that concentrations of NO_2 and diesel vehicle PM sources were correlated at the centURB site (Figs. S1.3, S1.4), suggesting that the lesser decrease in NO_2 observed during lockdown could be due to a source other than local diesel vehicle emissions, such as shipping emissions at the port (Fig. S1.5).

Differences in the meteorology between the lockdown period and the period prior could also be a contributing factor, impacting on the dispersion characteristics of the near-surface atmospheric environment. Comparisons between the hourly trends in NO_2 concentration show that, at all three sites, the concentrations observed during lockdown

Fig. 3. Change in traffic volume on Auckland's State Highway 1 before and after lockdown for light vehicles (left) and for heavy goods vehicles (right). Error bars represent the standard errors of the mean (Waka Kotahi NZ Transport Agency, 2020).

and at the same time of year in the years prior are broadly similar in terms of their temporal patterns, with two peaks coincident with expected traffic flow patterns (Fig. 6). However, the BAU morning peak is much larger than the evening peak, whereas under lockdown conditions, the magnitude of the two peaks are more similar, as the morning traffic congestion seems to have disappeared. Unfortunately, it is not possible to ascertain whether the increased reduction observed in the morning is a product of changed emissions patterns from traffic flow, reduced congestion, reduced idling time for delivery vehicles and buses, or due to changes in atmospheric chemistry that may have occurred at the time.

Changes in atmospheric NO_2 are also seen at regional scales from NASA satellite (Aura/OMI) measurements of the tropospheric column (see Fig. 7). From the first day of lockdown and towards the end of the lockdown period, concentrations were observed to have been 18% and 42% lower than the 2015–2019 the BAU baseline, respectively. This compares well with localised ground-based measurements (34–57% reductions in NO_2). Thus, for Auckland, despite the reduction in traffic emissions resulting from a reduction in vehicle numbers of 60–80%, reductions of only 34–57% in NO_2 concentrations were observed locally, and 18–42% regionally. The decoupling between traffic volume and NO_2 concentrations can be explained by meteorological impacts on dispersion and the large variability of emission factors for different vehicles, even within the light vehicle fleet. Contributions from other sources such as shipping and some industry may have been largely unaffected during the lockdown. However, it is also interesting to note that satellite data for February 2020 indicate that levels were 25% greater than the regional BAU baseline. This may reflect changes in actual recent emission patterns, outdating the 2016 emissions inventory. Nevertheless, this has important implications for future traffic-based policy interventions.

The changes in NO_2 concentrations estimated in Auckland are similar to those observed in both Barcelona, Spain and Rio de Janerio, Brazil. Although the changes in vehicle fleet characteristics in Spain associated with lockdown have yet to be quantified, the changes in Rio de Janerio have been found to be similar to those observed in Auckland, with reductions in private vehicles of 70–80% and public transport of approximately 50%. Mobility reports released by Google show a 72% reduction in people movements across grocery, pharmacy, retail, recreation, parks and transit stations and a 32% increase in people movements across residential areas within the Auckland region (Google, 2020). The results are also similar, at regional scales, to those observed by satellite in countries such as China, Italy, France, Spain, USA and Brazil where 20–30% reductions in NO_2 have been observed; this is attributed to a significant reduction (−90%) in mobility across countries worldwide (Muhammad et al., 2020; Dutheil et al., 2020).

3.2. BC

The largest and most marked reductions in observed air pollutant concentrations by species was for BC. At the centURB site, a 75% decrease in concentration was recorded, while a 55.7% decrease was observed at the subURB site. During lockdown, BC concentrations at the centURB site dropped to within 0.2 μg m^{-3} of the subURB site. Source apportionment and academic emission inventory studies show that most of the urban BC emanates from diesel vehicles, with transport emissions accounting for 62% of emissions annually, of which 56% is from diesel vehicles (Crimmins, 2017), with lesser contributions from
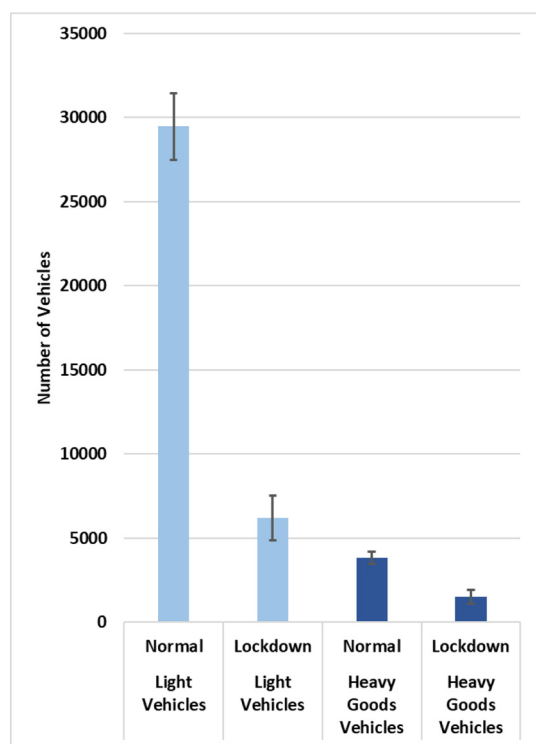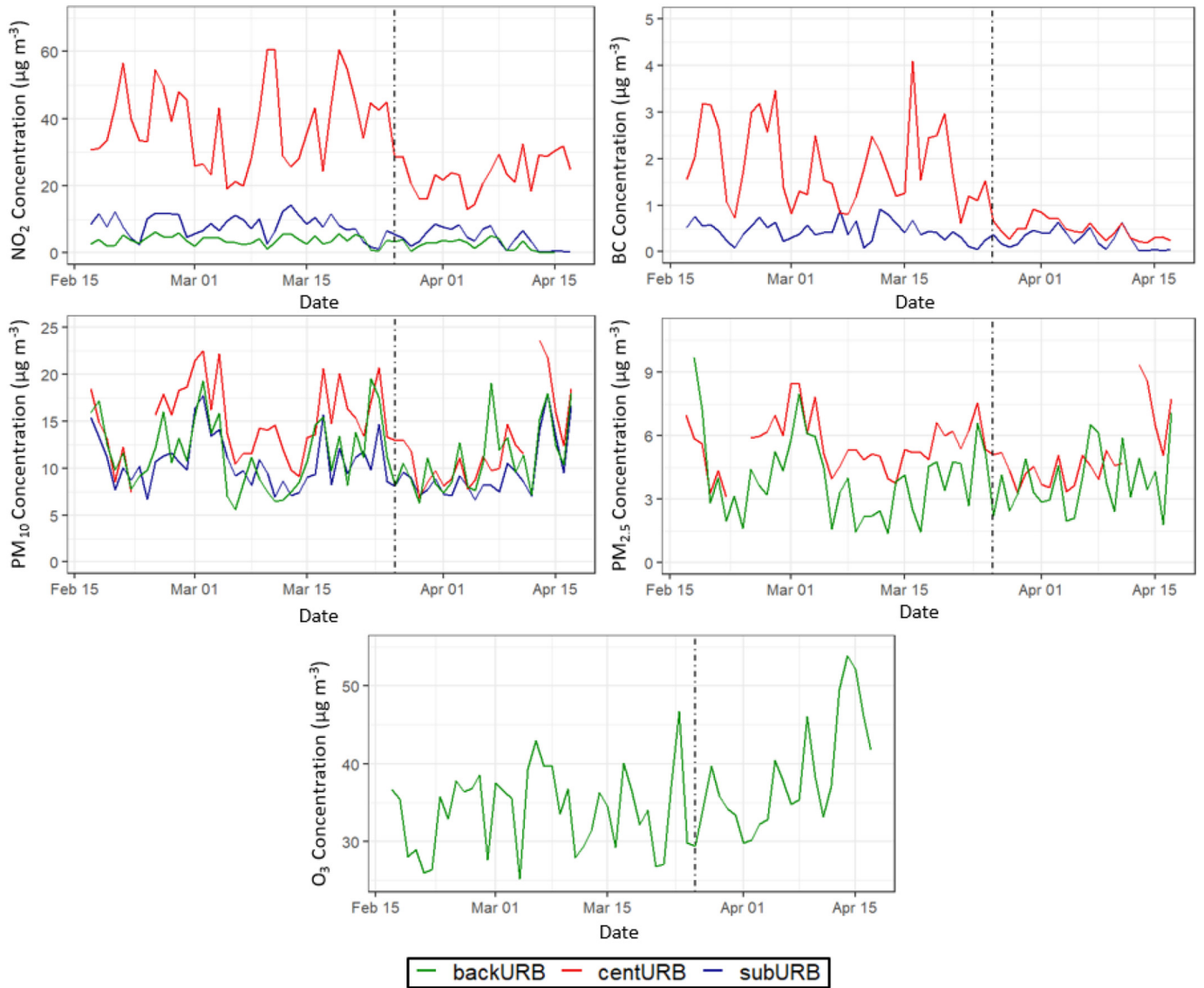
Fig. 4. Daily 24-hour average time-series concentrations for NO_2, O_3 $PM_{10,}$ $PM_{2.5}$ & BC at the subURB (blue), centURB (red) & backURB (green) sites between 17 February 2020–17 April 2020. The lockdown date is indicated by the black dashed line (27 March 2020).

Table 4
: Historical (February, March & April 2016–2020) and lockdown (26 March 2020–17 April 2020) daily mean (24-h) concentrations for NO_2, O_3 $PM_{10,}$ $PM_{2.5}$ & BC for the centURB, subURB and backURB sites.

| Site & pollutant | Concentration ($\mu g\ m^{-3}$) | | | | | | Variation | | | |
| | Historical | | | Lockdown | | | | | | |
	Mean	Std. dev.	Std. error	Mean	Std. dev.	Std. error	($\mu g\ m^{-3}$)	(%)	t-Test	P-value
centURB										
PM_{10}	15.3	1.7	0.3	12.2	4.5	1.0	−3.1	−20.1	3.0	<0.05
$PM_{2.5}$	6.1	4.2	0.1	5.1	1.7	0.4	−1.0	−17.0	2.7	<0.05
NO_2	35.7	12.8	0.6	23.5	5.7	1.2	−12.2	−34.1	9.1	<0.05
BC	1.9	0.9	0.1	0.5	0.2	0.0	−1.4	−75.4	11.1	<0.05
subURB										
PM_{10}	11.5	3.3	0.2	9.6	3.1	0.7	−1.9	−16.2	2.7	<0.05
NO_2	9.7	4.7	0.2	4.2	3.0	0.6	−5.5	−56.9	8.2	<0.05
BC	0.6	0.4	0.0	0.3	0.2	0.0	−0.3	−55.7	7.1	<0.05
backURB										
PM_{10}	12.2	4.7	0.2	11.4	2.7	0.8	−0.8	−6.6	1.0	0.3
$PM_{2.5}$	4.4	1.9	0.1	4.0	1.5	0.3	−0.4	−8.2	1.1	0.3
O_3	33.1	9.0	0.4	38.6	7.0	1.5	5.5	16.7	−3.6	<0.05
NO_2	3.6	2.0	0.1	2.3	1.6	0.3	−1.3	−35.6	3.7	<0.05
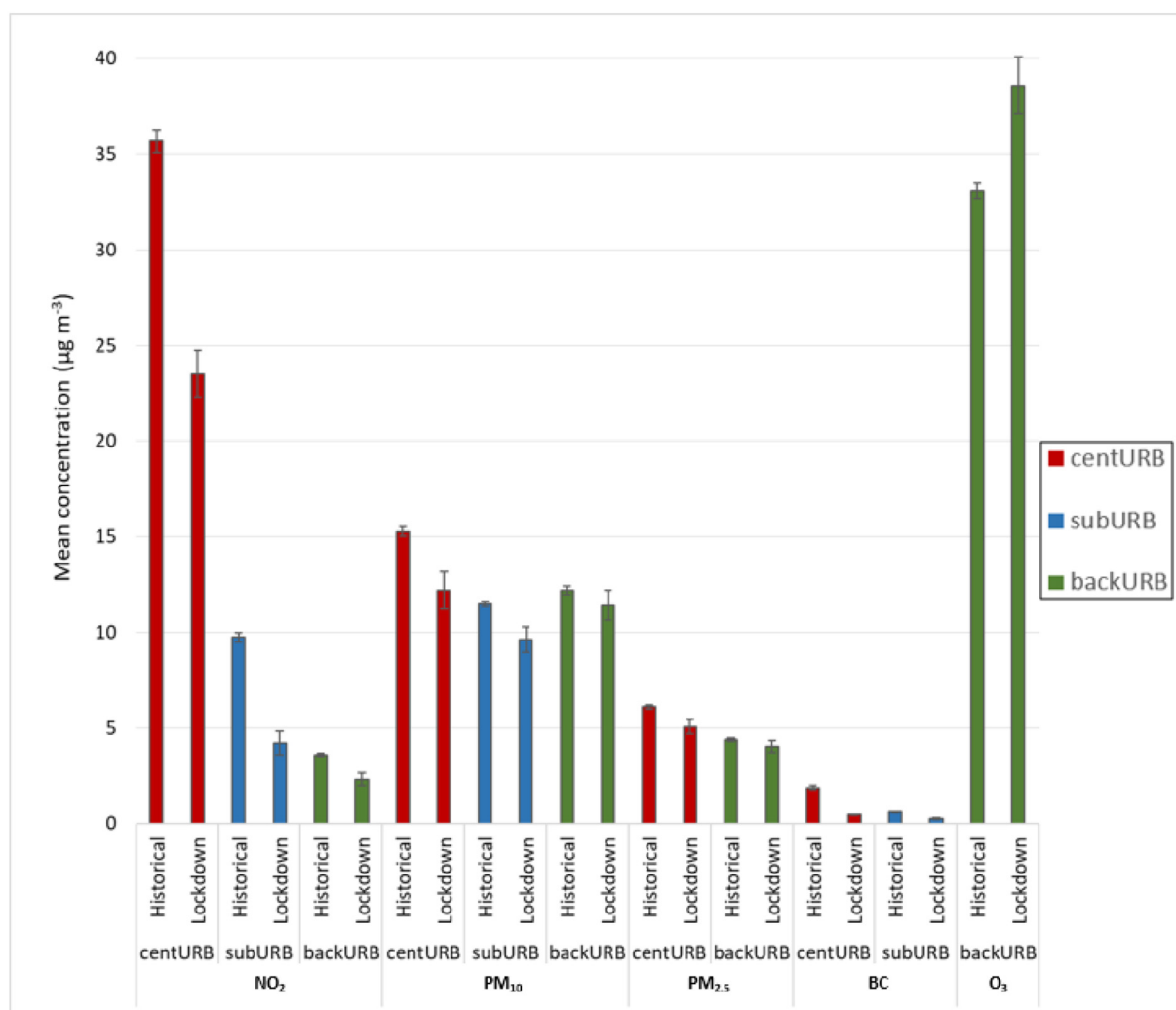
Fig. 5. Mean concentrations with standard errors for NO_2, BC, $PM_{2.5}$, PM_{10} & O_3 for historical (February, March & April 2016–2020) and lockdown (26th March 2020–17th April 2020) periods at the centURB, subURB and backURB sites. The error bars represent the standard error from the mean based on daily averages.

petrol-fuelled vehicles, industry and shipping (Davy et al., 2017). The large reduction recorded may be due to the lack of historical BC data at this site (the instrument was installed in August 2019). Reductions in NO_2 and BC concentrations at the subURB site were found to be similar (~55%), the site likely being strongly influenced by the close proximity of vehicle emissions. Day-of-the-week investigations (Fig. 8) show that NO_2 and BC follow the same weekly profile, with a drop off in concentrations on weekends, suggesting a high correlation with traffic flows, the primary source of these pollutants.

Analysis of the hourly variability (see Fig. 6) in BC at both the centURB and subURB sites shows that during the BAU periods for this time of the year, two marked peaks in BC concentrations are observed, the largest of which occurs in the morning, coincident with the morning rush hour. During this time, the observed morning peak reductions were 4.06 μg m^{-3} for the centURB site and 0.98 μg m^{-3} for the subURB site, suggesting that reduced vehicle emissions is at play. The second peak in the BAU scenario occurs at the centURB site in the mid to late afternoon, coincident with high traffic loads and congestion often seen at this time of the day. This peak is absent during the lockdown period. Tobías et al. (2020) reported a large reduction in BC at peak traffic sites, with a lesser reduction at urban background sites; reductions were similar to those of NO_2. At the subURB site, under BAU conditions, the second peak occurs later in the evening, and is more likely

associated with domestic heating emissions. This characteristic is more marked under lockdown conditions than in the BAU case. This may reflect changes in human behaviour as people are home more and moving less, requiring or desiring warmer houses.

Analysis of both the BAU and lockdown variabilities in NO_2 and BC concentrations by wind direction at the subURB site shows the localised nature of emission sources within 2 km to the NE of the site after lockdown (see Fig. 9 (left)). Prior to lockdown, sources to the SE were also dominant for both pollutants, but more noticeably for NO_2, suggesting a stronger influence of vehicle-related emissions from the main arterial road. For the centURB site (see Fig. 9 (right)), it is evident that historically, sources leading to high concentrations of NO_2 dominate from the west (perhaps the nearby State Highway 1) (Talbot and Lehn, 2018) which become significantly reduced under lockdown conditions. The same can be seen for BC from the south with no obvious identifiable 'hotspot' sources, and is perhaps associated with local idling vehicles or traffic congestion. It is interesting to note the differences between the sources of these two pollutants, which may reflect a longer-range transport of gaseous NO_2, or the formation of secondary NO_2, while particulate BC is characterised by more local sources. Under lockdown conditions, emission rates are significantly reduced, and concentrations more diffuse for both pollutants, and lacking in any obvious local point sources.
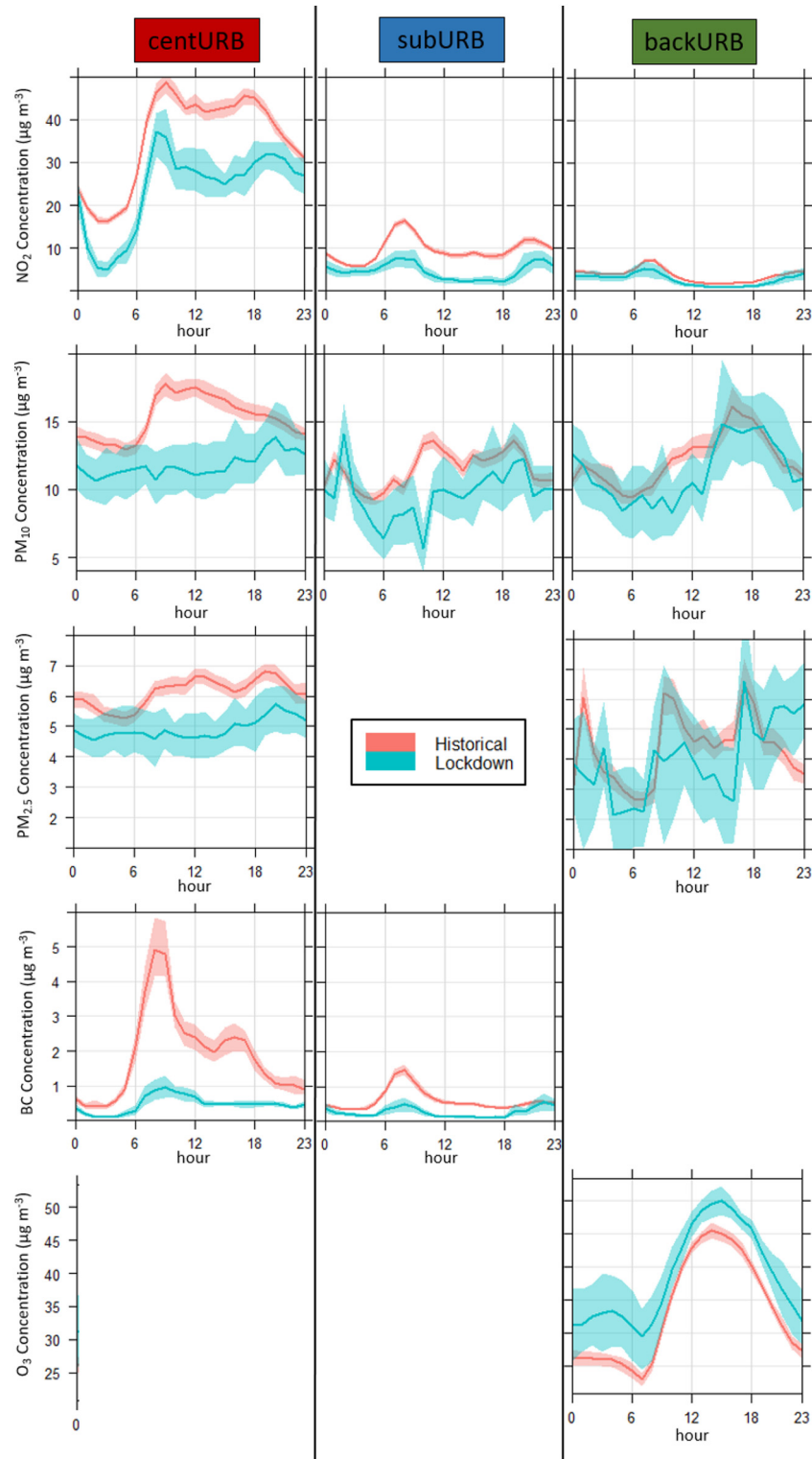
Fig. 6. Hour-of-day concentrations for NO$_2$, BC, PM$_{2.5}$, PM$_{10}$ & O$_3$ at the centURB, subURB and backURB sites for historical (February, March & April 2016–2020) and lockdown (26th March 2020–17th April 2020) periods. The red line indicates historical concentrations and the blue line indicates lockdown concentrations with 95% confidence (shaded area).

3.3. O$_3$

While all other pollutants recorded a marked reduction in concentrations during lockdown, O$_3$ recorded a statistically significant (t = −3.59, P < 0.05) increase in daily mean concentrations (5.52 µg m^{-3} (+16.7%)) at the backURB site in comparison with BAU. Hourly trend comparisons (see Fig. 6) in O$_3$ concentrations show that concentrations observed during the lockdown and historical periods at the backURB site share a similar trend in their temporal patters with minimum concentrations observed in the morning (0600–0800), peaking in the late afternoon (1500–1700) before gradually decreasing overnight. Daily mean concentrations are lower but in line with previous studies;
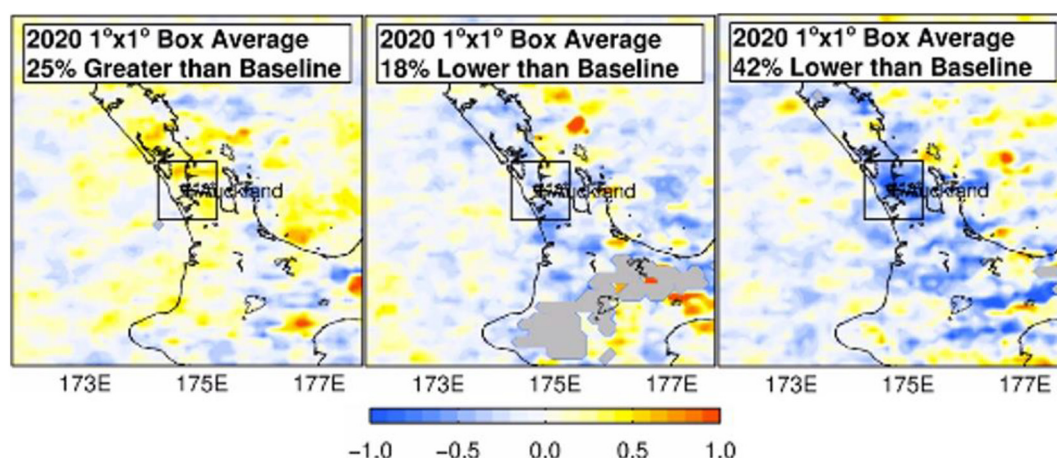
Fig. 7. Median NO$_2$ anomaly (x10^{15} molec. cm^{-2}) based on 2015–2019 running median for 17th February 2020 (left), 26th March 2020 (middle) & 17th April 2020 (right) (NASA, 2020).

~14 μg m^{-3} lower than previously recorded by Weissert et al. (2017) and ~ 9 μg m^{-3} lower than previously recorded by Adeeb & Shooter (2004). Hourly trend comparisons with historical studies demonstrate a similar temporal trend although ozone minima are observed later in the morning (0800–1000) and maxima later in the evening (1800–2000) (Adeeb and Shooter, 2004). It is important to note that NO/NO$_2$ peaks during this study are also recorded later in the day (0900–1100) which would contribute to the destruction of O$_3$ with freshly emitted NO (Adeeb and Shooter, 2004).

An increase in O$_3$ witnessed during the lockdown would be expected with the reduction in traffic contributing to precursor emissions (NO/NO$_2$) (Weissert et al., 2017). Increases in O$_3$ are in line with what has been witnessed in other countries with increases of up to 30–60% in ozone concentrations during the lockdown period, although to a lesser degree in Auckland (+16.7%) (Nakada and Urban, 2020; Tobías et al., 2020; Dantas et al., 2020). A lesser increase in O$_3$ can also be expected due to the already low background levels of O$_3$ observed in the southern hemisphere (Weissert et al., 2017).
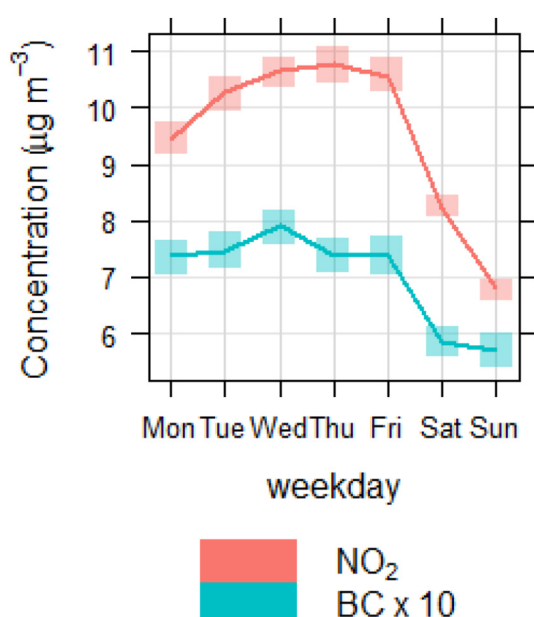
3.4. PM

PM$_{10}$ concentrations decreased by 20.1% at the centURB site, 16.2% at the subURB site and 6.6% at the backURB site during the lockdown period compared with BAU. PM$_{2.5}$ concentrations showed smaller reductions of 17% and 8.2% at the centURB and backURB sites, respectively. Source apportionment studies have revealed that the composition of Auckland's PM$_{10}$ is dominated by sea salt (43% or 6.9 μg m^{-3} as an annual average) all year, and PM$_{2.5}$ is strongly influenced by motor vehicle emissions (mainly diesel) in areas with high traffic volumes and in the presence of emissions from solid fuel fires (wood burning) for residential space heating during cool seasons (Davy et al., 2017; Xie et al., 2019). Strong weekday and seasonal patterns are also shown in emissions inventories, with domestic heating sources accounting for 64% of PM$_{10}$ emissions and transport only 31.5% on average winter weekdays. During the summer, although the total emissions are reduced, domestic emissions account for only 2.8% of the total, while transport emissions are responsible for 85.2%. It is likely that for PM$_{10}$, resuspended road dust (estimated to contribute 17% to PM$_{10}$ at the centURB site from receptor modelling (see Fig. S2.1) (Davy and Trompetter, 2019)) is a major component of the total mass explaining the traffic-related modes.

Analyses of the hourly concentrations (see Fig. 6) of PM$_{10}$ and PM$_{2.5}$ show a strong morning peak in the BAU scenario which is not observed during the lockdown period at either the centURB nor the suburban sites (data available for PM$_{10}$ only). These peaks are broadly consistent with changes in traffic-related patterns, but it is not clear why the pattern remains at the backURB site. Elevated nocturnal concentrations of PM$_{2.5}$ and PM$_{10}$, which are likely coincident with domestic heating, are observed at both the subURB site (data available for PM$_{10}$ only) and the backURB site during both the lockdown and BAU periods. However, there are no obvious increases in nocturnal concentrations during lockdown as is observed for BC. However, overall, PM$_{10}$ concentrations are more temporally variable during the lockdown period than prior, most likely reflecting the variability in background sea salt and natural sources of secondary sulphate present.

The prevalence of natural sources of particulate matter may help explain the lower decreases observed for both PM$_{2.5}$ and PM$_{10}$ during the lockdown period, especially given the comparatively low concentrations observed. Although statistically significant, the largest reductions in both PM$_{10}$ and PM$_{2.5}$ were only 3.1 μg m^{-3} and 1.0 μg m^{-3} respectively, observed at the centURB site.

Comparison of PM data with Black Carbon (BC) provides a more forensic subset analysis of particulate matter origin. Given that BC is predominantly from diesel emissions during the warmer months (in the absence of woodsmoke from domestic solid fuel appliance emissions), roadside measurements provide evidence of changes in traffic-related
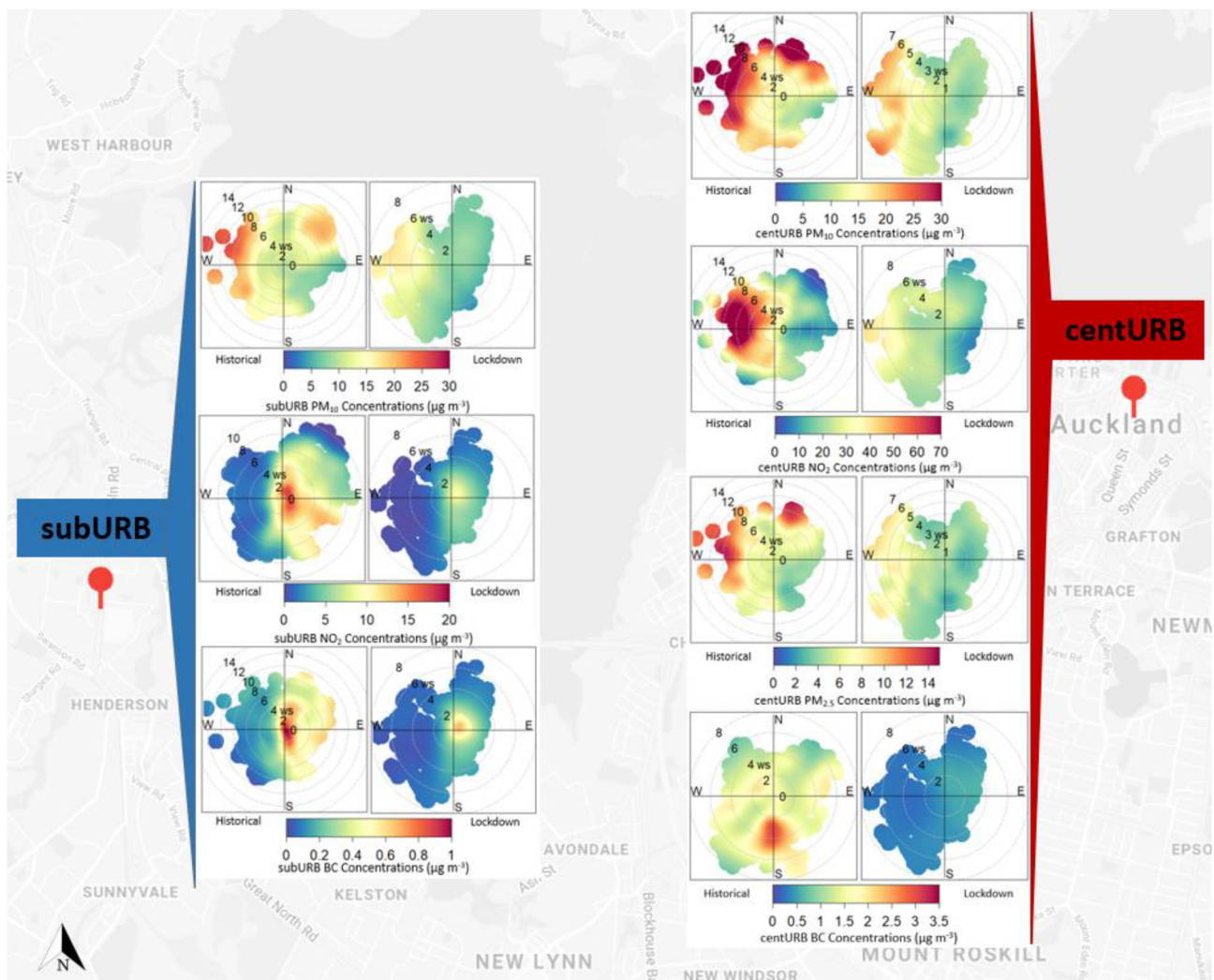

Fig. 8. Historical (2015–2020) day-of-week NO$_2$ & BC concentrations from the subURB site.

Fig. 9. Polar plots of PM_{10}, NO_2 & BC at the subURB site (left) and polar plots of PM_{10}, $PM_{2.5}$, NO_2 & BC at the centURB site (right) site during historical (February, March & April 2016–2020) and lockdown (26th March 2020–17th April 2020) periods.

emissions. For example, the reduction in $PM_{2.5}$ at the centURB site can largely be explained by the reduction in BC, while the reduction in PM_{10} includes the $PM_{2.5}$ increment by definition, plus the reduction in road dust from the reduced vehicle flow, and also the complete cessation of contributions from construction activities due to their shutdown. The level of reduction in BC and in both PM_{10} and $PM_{2.5}$ is evident from Fig. 6, specifically, the disappearance of the bi-modal distribution at the centURB site. The subURB site shows a smaller reduction in modality, likely due to its location next to major supermarkets, light industry, and a hospital, all which require frequent deliveries by on-road vehicles.

As a key component of Auckland city's air pollution, it is useful to attempt to quantify the proportional reduction that has been observed during the lockdown period. In the absence of exact vehicle emissions data for this period, an estimate of the motor vehicle tailpipe (primarily diesel) and road dust emissions can be calculated from Auckland's extensive receptor modelling programme (Davy and Trompetter, 2019) which assumes that non-vehicle particulate matter concentrations remain more or less stable during the lockdown period. Taking the diesel and road-dust component in isolation, it is then possible to find the closest PM_{10} measurement fit from the on-line instrumentation.

A receptor modelling study undertaken for daily $PM_{2.5}$ and $PM_{10-2.5}$ sample sets collected at the backURB site during 2010 did not reveal a motor vehicle signal, most likely due to the relative rural setting of the monitoring site and no significant traffic activity nearby (Davy et al.,

2012). Therefore, it is expected that particulate matter concentrations at the backURB site would be relatively unaffected by the drop-off in motor vehicle activity observed during lockdown. Instead the particulate matter sources at the backURB site reflect the natural background, plus local farming activities (soil disturbance, fertiliser application, biomass combustion during winter). Indeed, the marine aerosol (sea salt) contribution for 2010 at the backURB site was found to be well correlated with that at the centURB site, as presented in Fig. 10, illustrating the ubiquitous nature of this source across the regional airshed and the unique environment in which Auckland is located.

An overview of the modelling process is provided in Fig. 11. The average historical (2006–2019) weekday PM_{10} mass concentrations for the same time period (1 February to 17 April) are shown on the left-hand graph (note the weekday/weekend concentration difference that illustrates the motor vehicle influence from weekday commuters and commercial vehicle activity). The blue graph shows the 'background' (i.e. sea salt, secondary sulphate and shipping emissions) source contributions as a constant (contributions from the construction sector were assumed to be zero as such activities were effectively shut down over the lockdown period), the purple plot shows the measured PM_{10} concentrations during lockdown, and the right-hand plot shows the 'predicted' mass by adding the background contribution with the motor vehicle tailpipe and road dust contributions set at 40% (i.e. a reduction of 60% aligned with the observed reduction in HGV activity). The
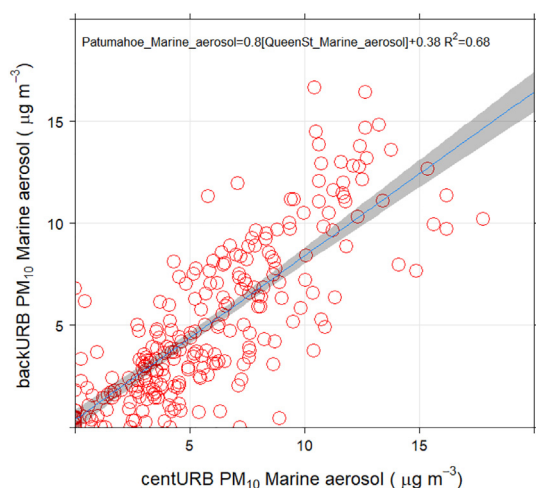
Fig. 10. Scatterplot demonstrating the correlation in PM_{10} marine aerosol contribution at the backURB and centURB sites in 2010.

average estimated PM_{10} concentration at the centURB site during lockdown by this method was $11.5 \pm 0.2\ \mu g\ m^{-3}$. This can be compared with the actual PM_{10} concentrations at the centURB site during lockdown, found to be $11.8 \pm 0.2\ \mu g\ m^{-3}$ (from Table 4). The Supplementary Material contains the receptor modelling source contributions for the centURB, subURB and backURB sites (see Figs. S1.1, S2.1–S2.5).

The exercise was repeated for the subURB site, as presented in Fig. 12. The average historical (2006–2019) weekday PM_{10} mass concentrations (1 Feb to 17 April) are shown on the left-hand graph. The blue graph shows the 'background' (i.e. sea salt and secondary sulphate) source contributions as a constant, the purple plot shows the measured PM_{10} concentrations during lockdown, and the right-hand plot shows the 'predicted' mass by adding background to the motor vehicle tailpipe and the road dust contributions set at 45% (i.e. a reduction of 55% aligned with the observed reduction in NO_2 and BC concentrations at the suburb site). Using this method, the average estimated PM_{10} concentration at the subURB site during lockdown was found to be $9.6 \pm 0.3\ \mu g\ m^{-3}$. This can be compared with the actual PM_{10} concentration ($9.7 \pm 0.2\ \mu g\ m^{-3}$) observed at the subURB site during lockdown (see Table 4).

4. Conclusions

The COVID pandemic led to an enforced lockdown period in New Zealand, severely curtailing social contact and all industry activity except those deemed essential services. During this period, there was a marked reduction in the recorded levels of NO_2, $PM_{2.5}$, PM_{10} and BC across Auckland but an increase in O_3. The largest reductions were from BC and NO_2, pollutants primarily associated with the combustion of fossil fuels by motor vehicles. The stark changes in air pollution concentrations observed during the lockdown period reveal that, once key emission sources (on-road combustion powered vehicles) were removed/reduced, air pollution across Auckland reduced substantially. Notwithstanding this, some interesting non-linear responses occurred that will require further investigation to better understand the sources of emissions and atmospheric chemistry. This paper highlights the lack of detail provided in previous emissions inventories, with some pollutants and sources potentially either underreported or misrepresented. The results of the BAU/lockdown comparison suggest that use of particulate matter source contributions from receptor modelling is a valid tool for examining 'what if' scenarios for interventions and policy evaluation to reduce the burden of urban particulate matter concentrations. However, the message to policy and regulatory bodies is clear: removing or severely limiting the key polluting source from the urban environment allows Aucklanders to breathe some of the world's cleanest air.

CRediT authorship contribution statement

Hamesh Patel: Conceptualization, Methodology, Software, Data curation, Visualization, Writing - review & editing, Formal analysis. **Nick Talbot:** Conceptualization, Methodology, Software, Data curation, Writing - review & editing, Formal analysis. **Jennifer Salmond:** Conceptualization, Writing - review & editing, Formal analysis. **Kim Dirks:** Conceptualization, Writing - review & editing, Formal analysis. **Shanju Xie:** Writing - review & editing. **Perry Davy:** Conceptualization, Software, Data curation, Writing - review & editing, Formal analysis.

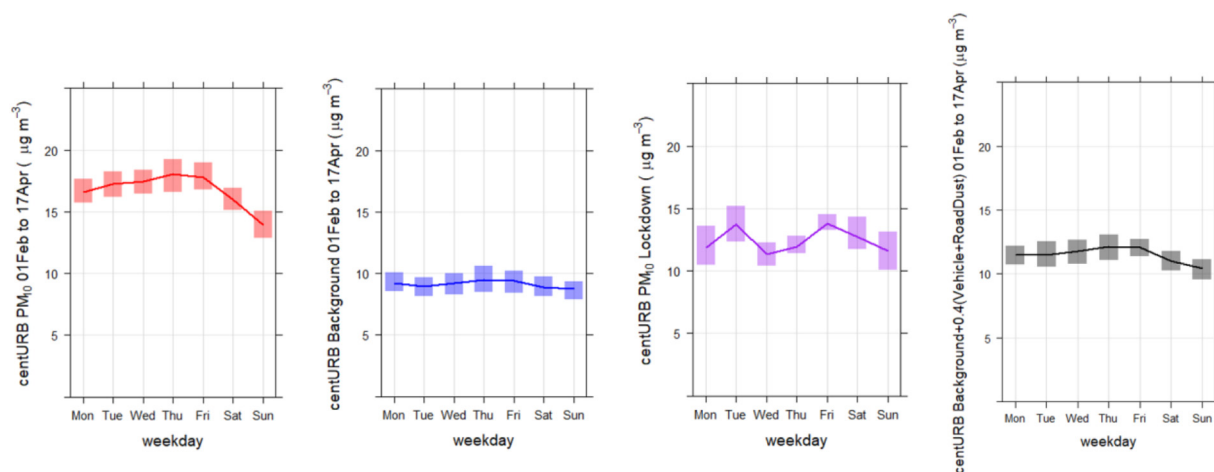## Declaration of competing interest

No known competing interests.

Fig. 11. Weekday PM_{10} at the centURB site; (a) Historical PM_{10} concentrations for the same time period, (b) Estimated background PM_{10} from receptor modelling, (c) PM_{10} concentrations during lockdown (d) estimated PM_{10} during lock down that includes background plus 40% of the diesel vehicle and road dust component. The dark lines indicate the mean concentrations with 95% confidence (shaded areas).
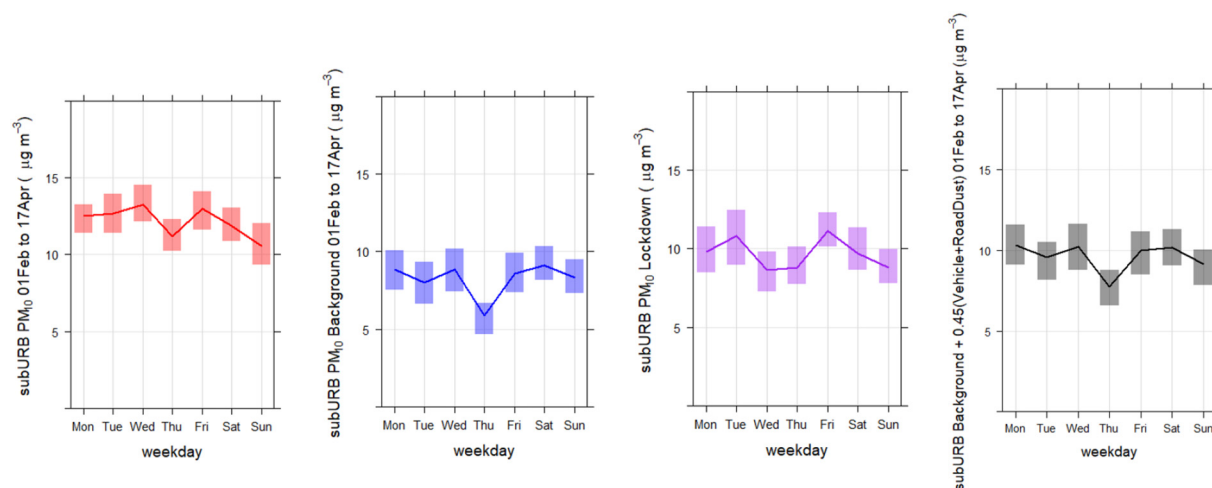
Fig. 12. Weekday PM_{10} at the suburb site; (a) Historical PM_{10} concentrations for Feb-April, (b) Estimated background PM_{10} from receptor modelling, (c) PM_{10} concentrations during lockdown (d) estimated PM_{10} during lock down that includes background plus 45% of the motor vehicle and road dust component. The dark lines indicate the mean concentrations with 95% confidence (shaded areas).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.141129.

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