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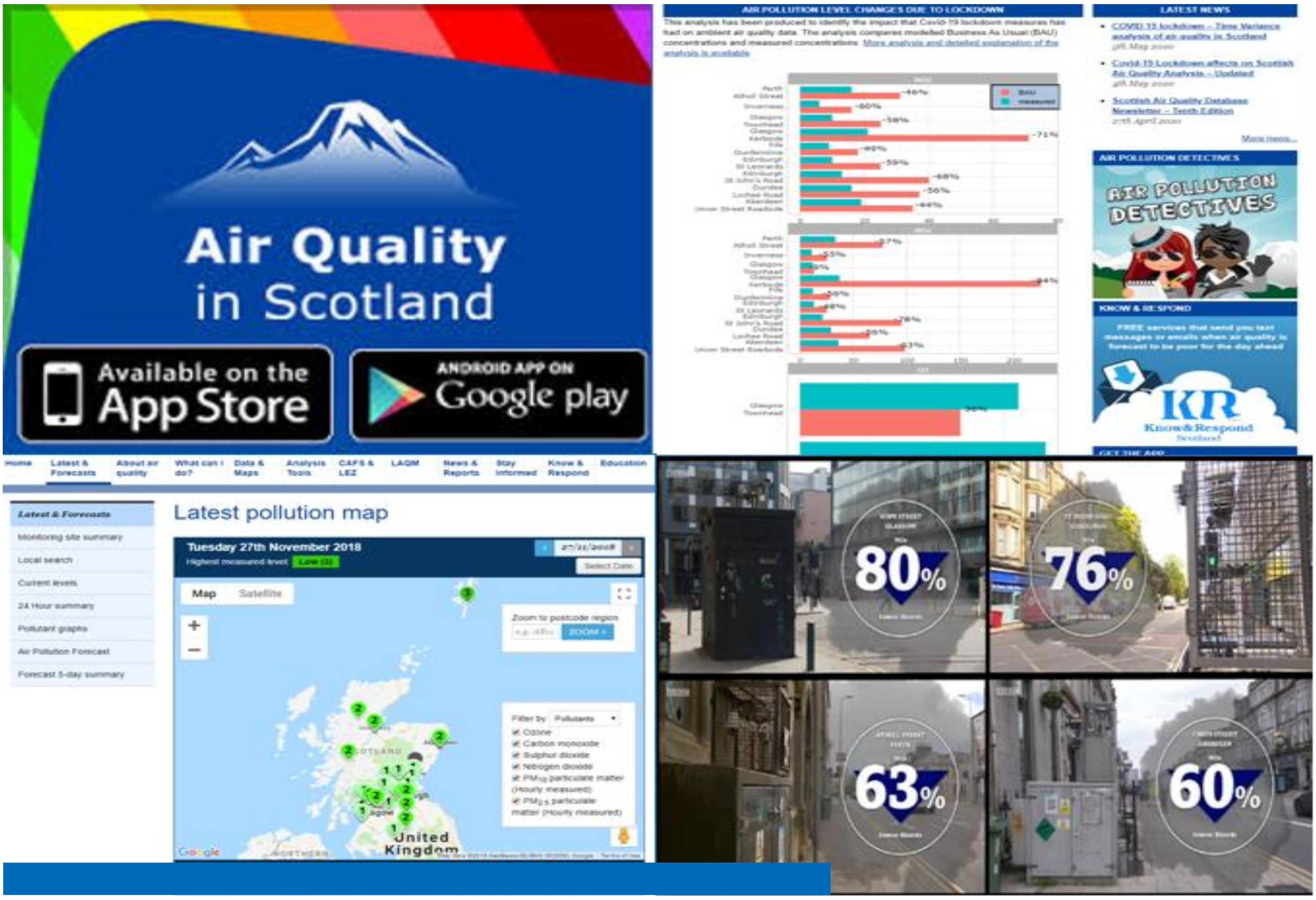

Impact of Lockdown Measures on Scottish Air Quality in 2020

Report for Scottish Government

Technical Report for the Scottish Government

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Executive summary

Ricardo Energy & Environment (Ricardo) have carried out analysis on behalf of the Scottish Government to assess the air quality during the Covid-19 pandemic. Air quality data presented within this report are sourced from the Scottish Air Quality Database (http://www.scottishairquality.scot).

To assess the impact of the lockdown measures on air quality across Scotland, statistical models have been developed to account for meteorological variations. The models are then used to predict a business as usual (BAU) scenario, i.e. an estimate of the pollutant concentrations if the lockdowns had not taken place.

During the first national lockdown, from 23rd March to 28th May, NOx and NO_2 concentrations at urban traffic monitoring stations were estimated to have decreased, on average, by 58% and 52%, respectively, when compared with BAU.

A comparison of the diurnal variation in NOx concentrations at two urban traffic sites, before and during the lockdown, shows that the largest decreases were observed during the daytime, in particular during the rush hour periods.

Traffic data analysis by Transport Scotland shows a sharp decrease in the number of cars on the roads during the lockdown period.

The annual mean measured NO_2 concentrations were compared to those predicted by the model. For the majority of sites, the annual mean was lower than predicted.

Ozone measured at urban background sites during the first lockdown period increased by an estimated 11.5%, when compared to BAU. Averaged over the whole year, however, measured O_3 concentrations were very similar to predicted.

Assessing changes in PM_{10} and $PM_{2.5}$ as a result of lockdown is more challenging than for NOx, as a large contribution of PM arises from regional and background sources. To investigate changes on a local scale, the urban increment in PM (i.e. the PM concentrations above those measured at a background site) were investigated. The analysis shows the estimated decrease in urban $PM_{2.5}$ averaged across all sites was 0.6 μgm^{-3}. It should be noted however, that in absolute terms this change is very small and highly uncertain.

Analysis of data for the first four months of 2021 shows that NO_2 concentrations at urban traffic sites were lower than those predicted by the BAU model. The data for 2021, however, are currently provisional pending full QA/QC, and subject to change.

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1 Introduction

1.1 Background

On March 23rd, 2020, a "stay at home" requirement was implemented by the UK Government in response to the Covid-19 pandemic. The lockdown continued until 29th May, at which point Scotland entered various phases of lockdown easing.

The initial lockdown and subsequent measures put in place, resulted in a large reduction in the volume of traffic on the road network in Scotland.

With a reduction in traffic, we may expect to see a change in the air quality. However, it is important to think about the best way to quantify any changes and also take into account any effects due to weather conditions, as the weather can have a large impact on pollutant levels observed.

This report focusses on changes in nitrogen oxides (NO, NO_2), ozone (O_3), and particulate matter (PM_{10} and $PM_{2.5}$), which are monitored as part of the Scottish Air Quality Database (http://www.scottishairquality.scot), during 2020. We use proven modelling techniques to take into account variations in weather conditions on ambient pollutant concentrations.

1.2 Statistical Models

An issue when assessing changes in pollutant concentrations as a result of an intervention or mitigation measure, is determining how much is due to changes in emissions and how much is the result of variations in meteorology. One way of addressing this problem is to develop statistical models to determine what the pollutant concentrations would be if no changes were implemented, based on pollutant and weather data from previous years, i.e. the counterfactual or "business-as-usual" (BAU) scenario.

There are different approaches in developing a statistical mode. Here we use the deweather (https://github.com/davidcarslaw/deweather) R package. This statistical approach uses Boosted Regression Trees to model the ambient pollutants [1]. A model is built based on hourly concentration data from the Scottish Air Quality Database and local meteorological data from the WRF regional scale model run by Ricardo. The model is trained over the period January 2018 to February 2020. Once a suitable model is built, this is then used to predict what the concentrations would be from March 1st 2020 onwards under a BAU scenario. The BAU pollutant concentrations can then be compared to the measured data to assess changes as a result of lockdown.

Figure 1: Example inputs for statistical modelling.

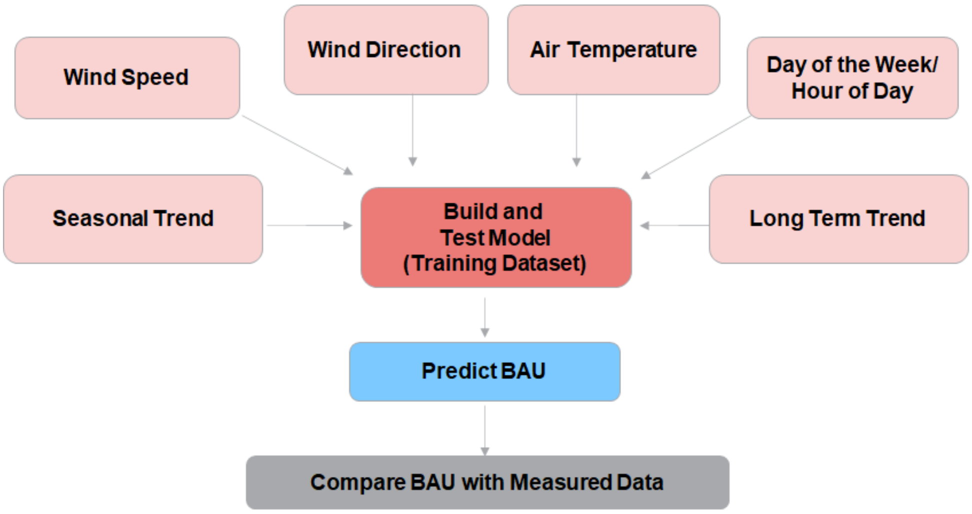
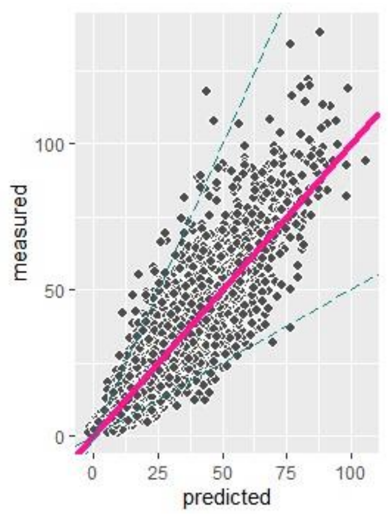


Figure 2 shows an example of the results for a model based on hourly NO_2 concentrations and meteorological variables from Glasgow High Street between January 2018 to December 2019. The data is randomly split into a training data set (80% of data) and a testing dataset (20%). The test data is only used for assessing the model, and not used in the model development.

The figure on the left shows a scatter plot of the predicted and measured (test data) NO_2 concentrations. The values in the tables show summary statistics of the model performance against the training and test data. The FAC2 value (0.92) is the fraction of modelled values within a factor of two of the measured values with 1.0 being ideal. The correlation coefficient value of 0.86, also indicates that the model does a good job of predicting the NO_2 concentrations for the test data.

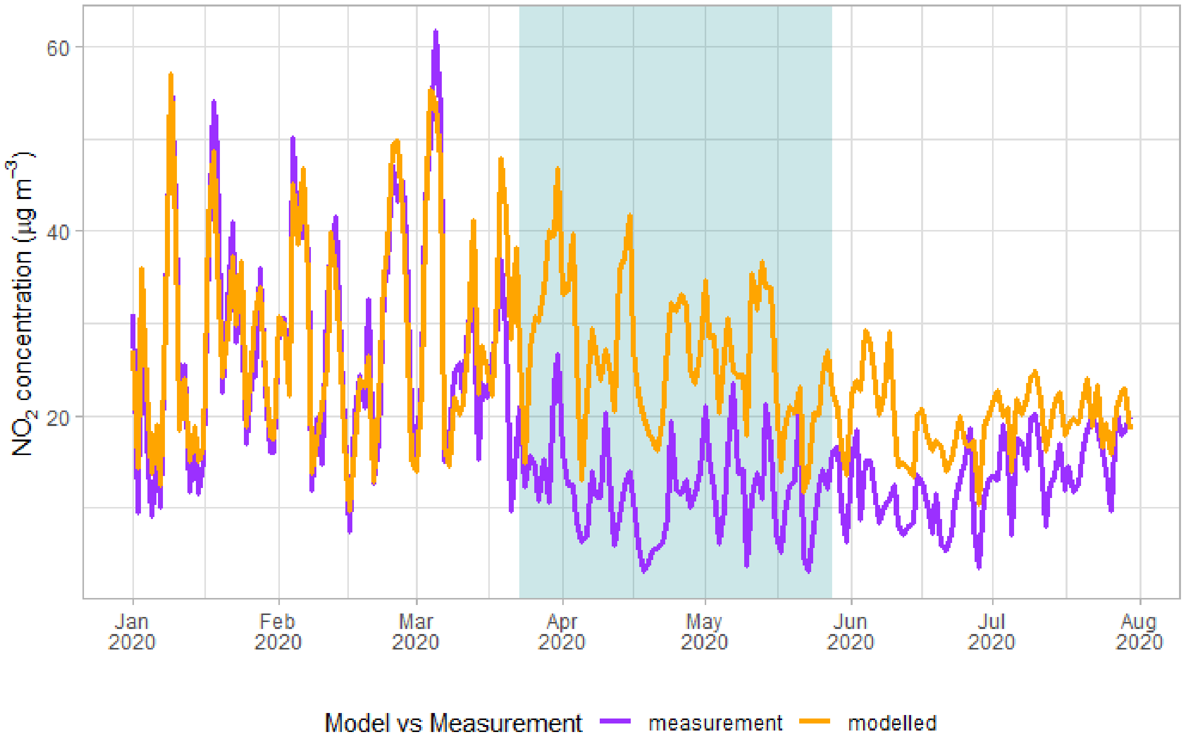
Figure 2: Example model results for NO_2 for Glasgow High Street for the period January 2018 to December 2019.



statistic	value
Test data	NA
n	3428.00
FAC2	0.92
MB	-0.05
MGE	7.50
NMB	0.00
NMGE	0.25
RMSE	10.37
r	0.86
COE	0.52
IOA	0.76

Figure 3 shows an example of measured and modelled (BAU) NO2 concentrations at the Glasgow High Street monitoring station for the period 1st January to 1st August 2020. From January up until the lockdown started on 23rd March, the modelled and measured NO_2 concentrations are very similar, showing that the model is able to predict the measured concentrations before lockdown. Around 23rd March, the two lines deviate – with measured NO_2 concentrations consistently lower than BAU concentrations, which may be the result of a reduction in NOx emissions due to reduced traffic activity in the area. As the initial lockdown ended and restrictions were eased, the two lines start to come together again.

Figure 3: Daily averaged measured (purple) and modelled BAU (purple) NO2 concentrations at the Glasgow High Street monitoring site from 1st January to 1st August 2020. The shaded region represents the period of the national lockdown between 23rd March and 28th May 2020.



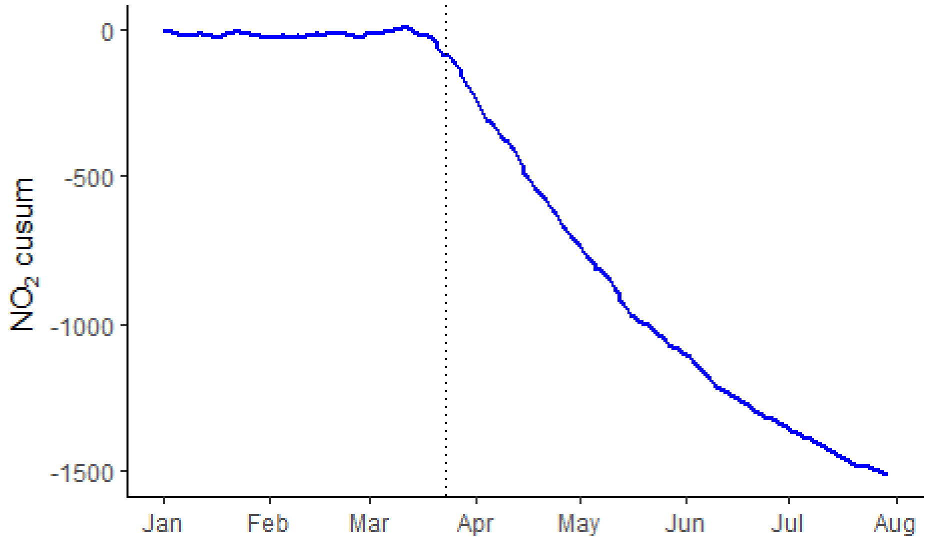
1.3 Cusum analysis

In the example above for Glasgow High Street, the difference between measured and BAU NO_2 concentrations during lockdown is clear. However, this is not always the case, as some deviations may be small. In this report we use cumulative sum (cusum) analysis to determine how measured concentrations deviate from BAU concentrations. The cusum analysis can be useful when identifying small changes.

Figure 4 shows the NO2 cusum analysis for Glasgow High Street between 1st January and 1st August 2020. Here the cusum value is the sum of the differences between measured and BAU no2 concentrations. So, on Jan 1st the cusum is the difference in measured and BAU NO_2 on that day, for Jan 2nd the cusum is the difference in measured and BAU NO_2 on Jan 2nd **plus** the difference on Jan1st, and so on.

In January and February, the average cusum is around zero, as the modelled and measured NO_2 levels are very similar. Around the time of the lockdown is when the differences become more apparent, and we see a negative cusum.

Figure 4: Daily NO_2 cusum for Glasgow High Street 1st January to 1st August 2020. The dashed vertical line represents the start of the first national lockdown on 23rd March 2020.



2 Meteorology

As discussed in the introduction, comparing pollutant levels before and after lockdown is challenging due to variations in weather conditions.

February 2020 was particularly windy with the arrival of Storm Ciara and Storm Dennis to the UK. In addition, April 2020 was the sunniest April in Scotland since 1929, with 151% of average sunshine and 31% average rainfall[1].

Figure 5 Wind roses for Edinburgh Airport. Data source: NOAA Integrated Surface Database (ISD)(2016) https://www.ncdc.noaa.gov/isd.

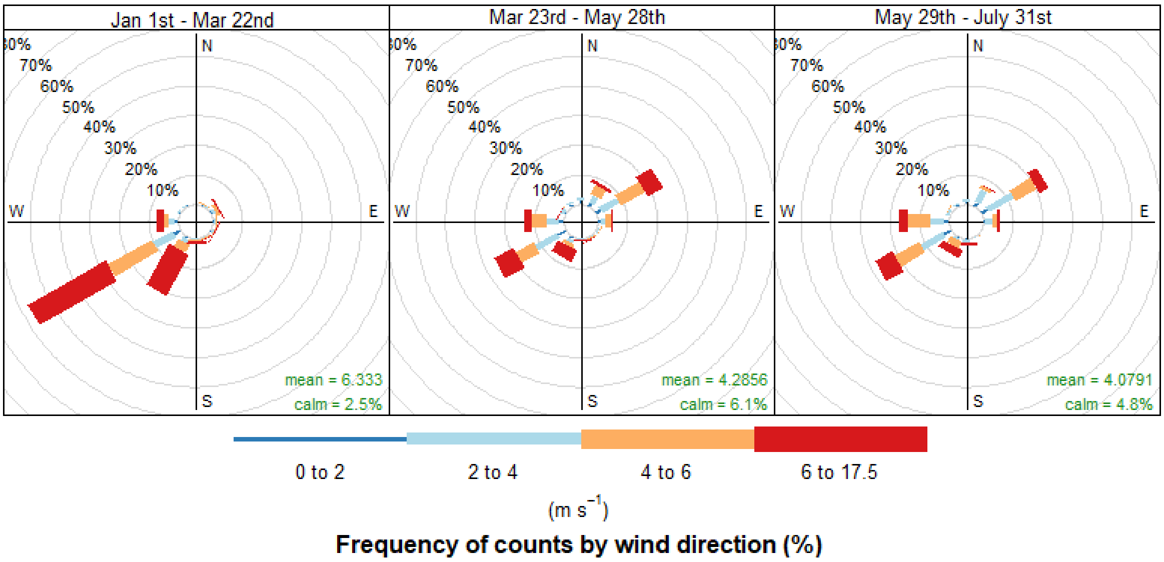


Figure 5 shows wind roses for three periods in 2020 at Edinburgh Airport. Between January and March 22nd. The predominant wind direction was from the south west and the mean wind speed was

[1] https://www.metoffice.gov.uk/research/climate/maps-and-data/summaries/index

6.3 ms^{-1}. During the lockdown period the average wind speed dropped to 4.3 ms^{-1} and the wind direction was more variable, with winds from a north easterly direction also observed. Similar conditions were observed in June and July. The differences in meteorology observed before and during lockdown will have an impact on the pollutant levels observed. The air mass origin will also have an impact on pollutant levels, particular for particulate matter. This is explored further in section 3.5.1.

3 Changes in Pollutant Concentrations

There are 99 automatic monitoring sites within the Scottish Air Quality Database. For this report we focused on those sites which had an annual data capture rate > 75% for the target pollutant for each year from 2018 to 2020, to ensure there was enough valid data to perform the modelling analysis. All data from 2018 to 2020 is fully ratified.

Table 1 provides a summary of the number of sites under each site type, for NOx, O_3, PM_{10} and $PM_{2.5}$. A full list of the sites included in the analysis is provided in A1.

Table 1 Number of sites within the database with data to perform the modelling and analysis (75% DC and data back to Jan 2018)

Site type	NOx	O3	PM_{10}	$PM_{2.5}$
Rural Background	4	6	-	-
Suburban Background	2	2	-	-
Urban Background	6	2	5	4
Urban Industrial	3	-	2	1
Urban Traffic	36	-	32	21
Total	**51**	**10**	**39**	**26**

3.1 NOx Analysis

Nitrogen oxides (NOx) refer to the sum of nitrogen oxide (NO) and nitrogen dioxide (NO_2). In the UK the primarily source of NOx is transport (i.e., vehicle exhaust emissions), followed by industrial processes and energy generation.

Figure 6 shows the daily averaged NOx concentrations for 15 sites across Scotland. The dark grey shading represents the national lockdown period between 23rd March and 29th May. The lighter grey shadings represent the periods of Phase 1 and Phase 2 easing of restrictions, ending on 10th July. Although there appears to be a decrease in NOx at some sites in March and April, it is difficult to tell from the time series alone whether concentrations changed at a result of lockdown.

The cusum analysis of measured minus business as usual NOx concentrations, as shown in Figure 7, provides a better indication of how NOx concentrations changed during the lockdown period. The cusum indicates that many sites show a decrease in NOx concentrations around the start of the lockdown, however the timings do vary.

Figure 6 Time series of daily averaged NOx in 2020 for a range of monitoring sites across Scotland. The shaded grey region represents the period between 23rd March (when the national lockdown began) and 10th July (start of Phase 3 lockdown easing).

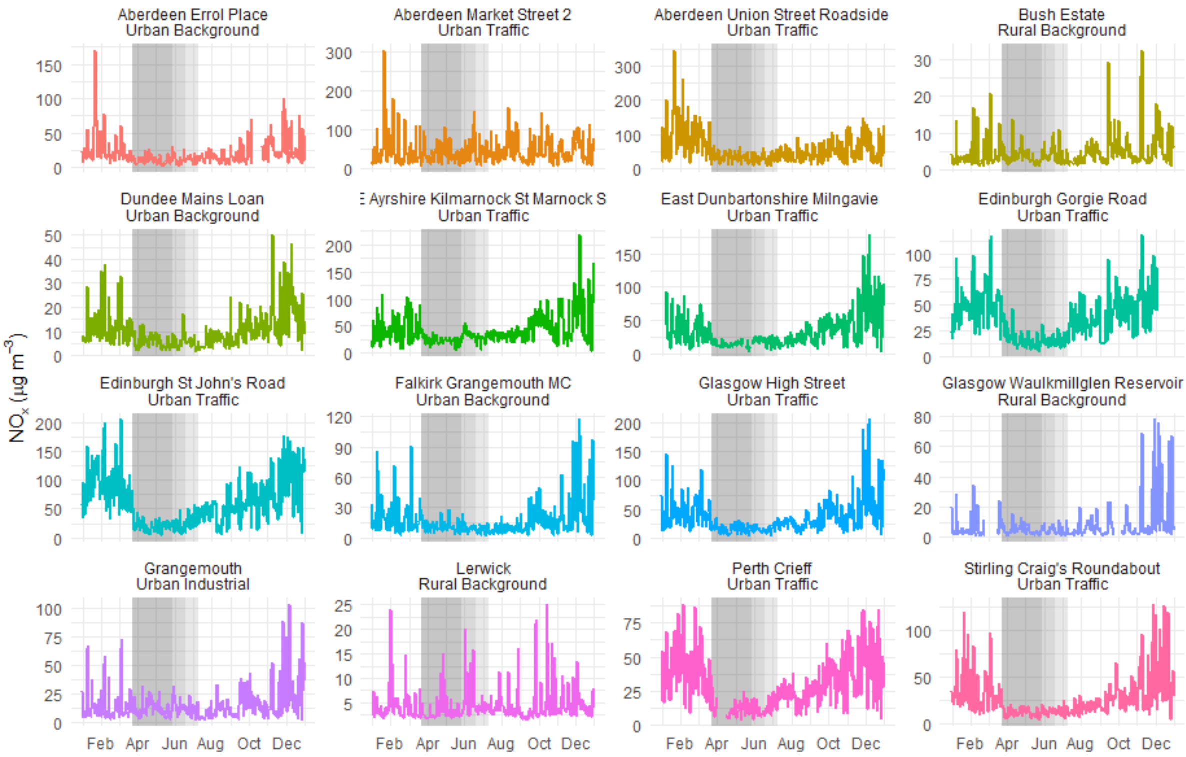


Figure 7 Daily NOx cusum analysis of measured minus BAU for sites in Scotland from 1st January to 29th May. The dashed line represents the start of the lockdown on 23rd March. Highlighted lines represent monitoring sites which displayed the largest decrease.

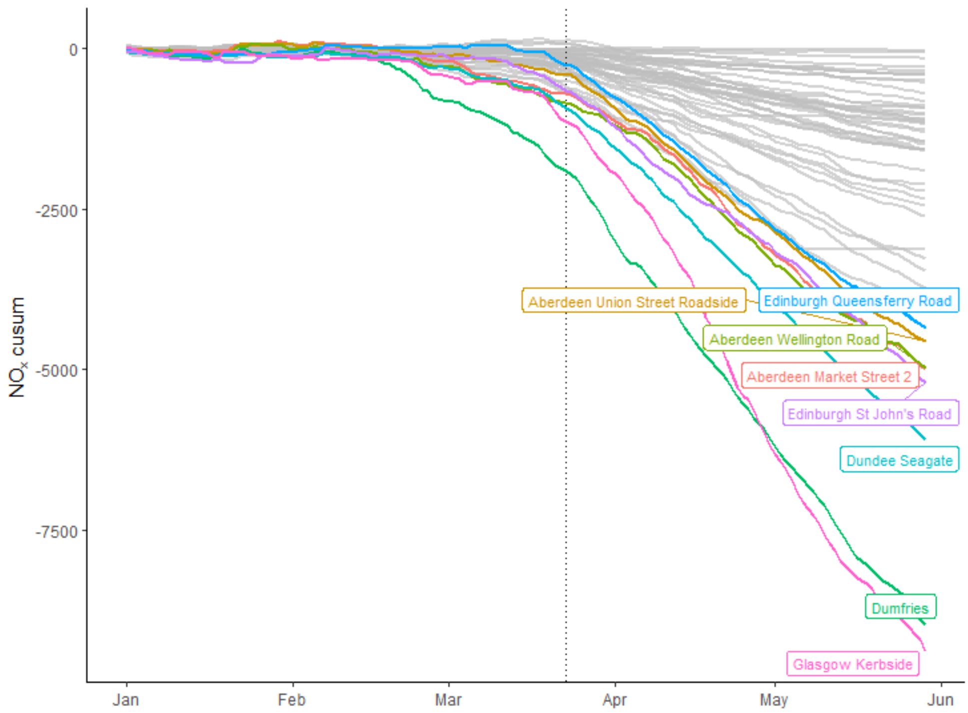


Figure 8 shows a bar chart of measured and modelled BAU annual NOx concentrations for 2020, for each site. For the majority of the sites analysed the measured annual NOx concentration is lower than BAU. The exceptions are Glasgow Great Western Road and Inverness where the measured and BAU NOx concentrations, in both cases, are around the same.

Figure 8 Measured and business as usual annual NOx concentrations by site.

3.2 Nitrogen Dioxide Analysis

NO_2 is a respiratory irritant, and at very high levels can increase susceptibility to respiratory infections, such as influenza. NO_2 is formed from combustion processes, for example road vehicles and power plants and can be emitted directly from the source (primary NO_2) or from the oxidation of NO (also emitted during fuel combustion), in the atmosphere to form secondary NO_2.

In the UK, the national air quality objectives for NO_2 for the protection of human health, are:

- NO_2 1-hr limit value of >200 µg m^{-3} not to be exceeded more than 18 times per year
- NO_2 Annual mean limit value of >40 µg m^{-3}

Figure 9 and Figure 10 show the daily averaged concentrations and cusum analysis for NO_2. As for NOx, the cusum analysis indicates a decrease in NO_2 concentrations when compared to BAU, around the time lockdown started. However, the sites that show the greatest decrease in NO_2 (highlighted lines in Figure 10) are not necessarily the same sites with the greatest decrease in NOx, due to the non-linear relationship between NOx and NO_2. Further information on this relationship is given in section 3.4.

Figure 9 Time series of daily averaged NO_2 in 2020 for a range of monitoring sites across Scotland. The shaded grey region represents the period between 23rd March (when the national lockdown began) and 10th July (start of Phase 3 lockdown easing).

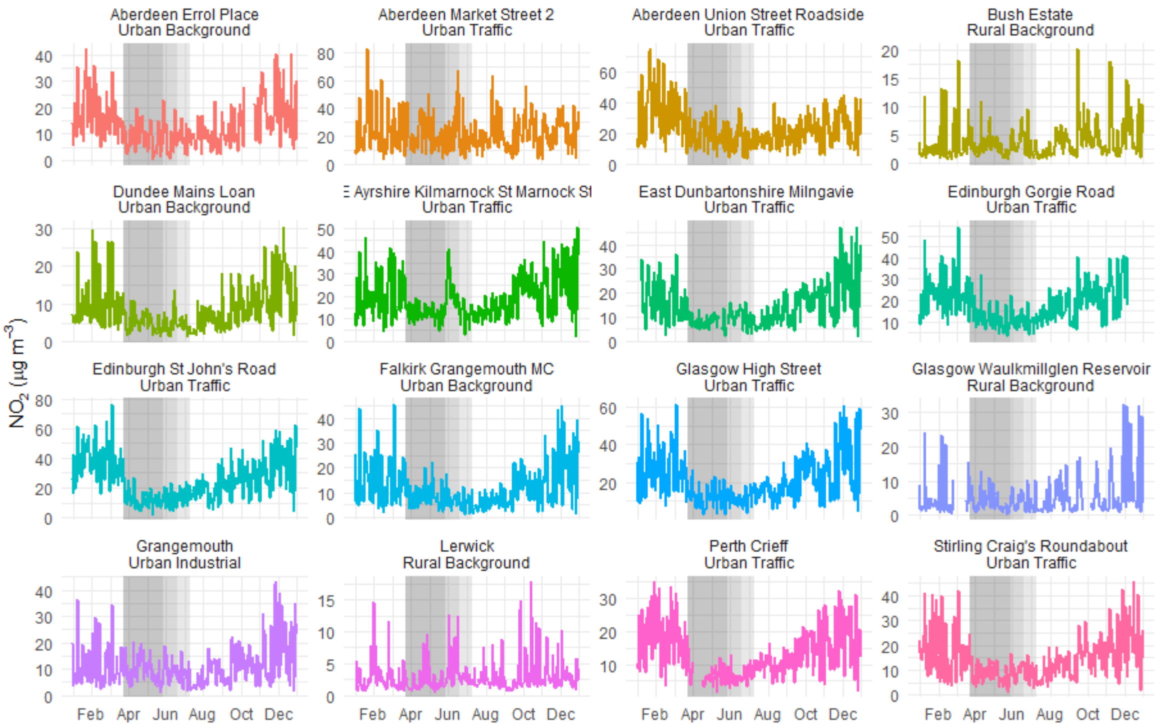
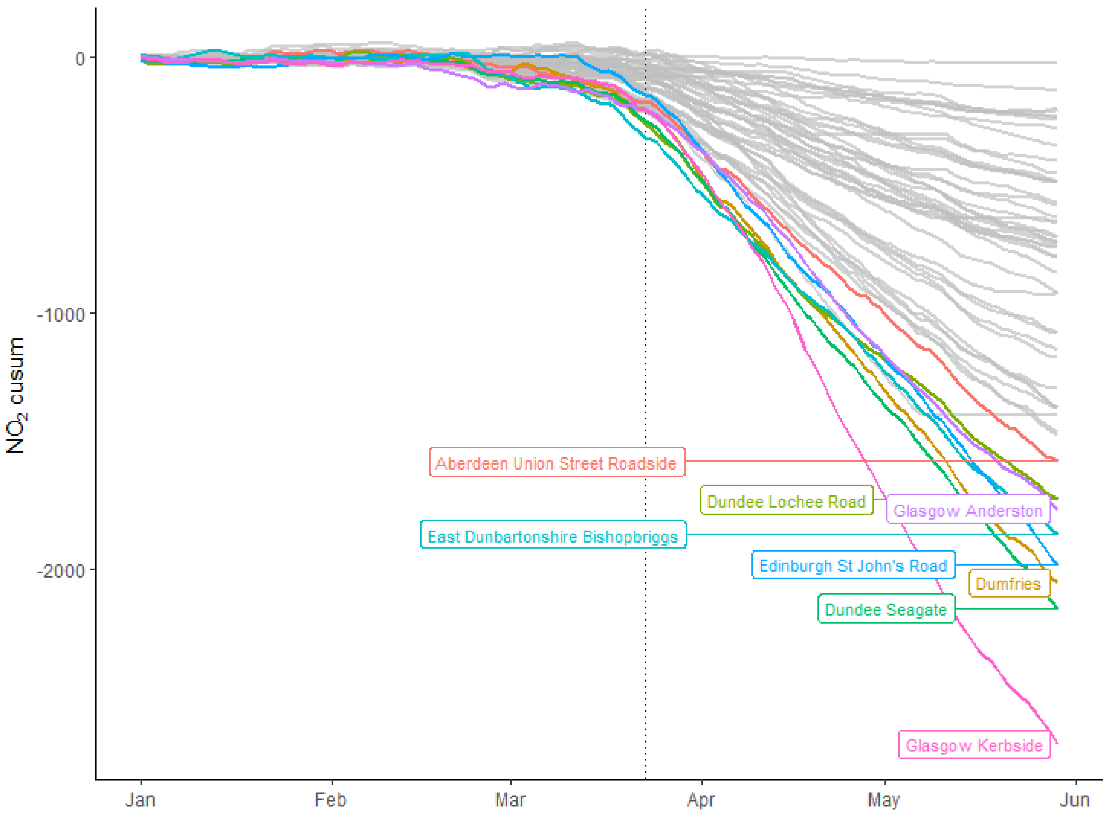
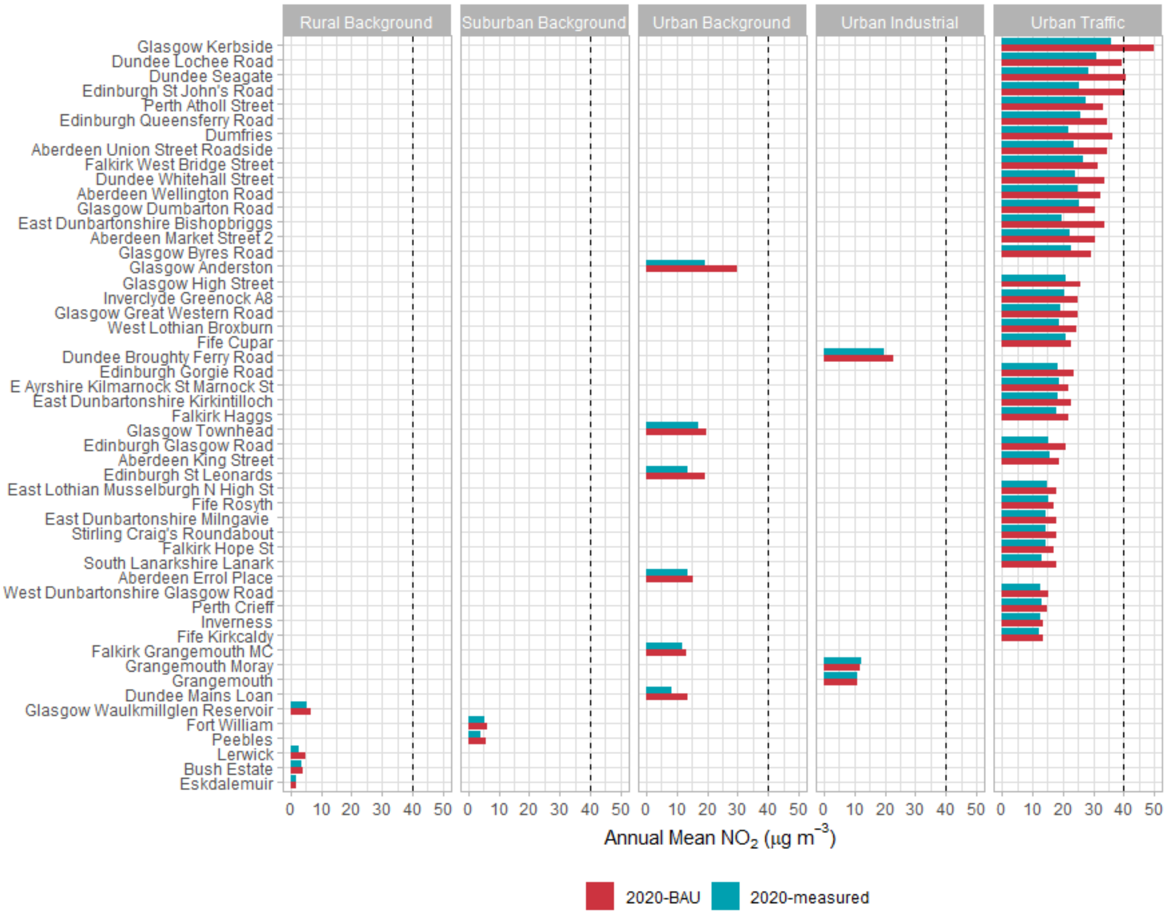


Figure 10 Daily NO_2 cusum analysis of measured minus BAU for sites in Scotland from 1st January to 29th May. The dashed line represents the start of the lockdown on 23rd March. Highlighted lines represent monitoring sites which displayed the largest decrease.



The annual mean measured and modelled BAU NO_2 concentrations for 2020, for each site, are shown in Figure 11. For most of the sites the annual mean measured NO_2 is lower than predicted by the model. Glasgow Kerbside, Dumfries, and Edinburgh St John's Road observe the greatest decrease in NO_2, when compared to BAU with the measured annual average NO_2 between 14 and 15 µgm^{-3} lower than predicted. At Glasgow Kerbside, the BAU NO_2 annual mean concentration exceeded the UK NO_2 annual mean limit of 40 µg m^{-3}, however the measured NO_2 concentration was actually much lower, at 36 µg m^{-3}, therefore no exceedance was observed at this site.

Figure 11 Measured and business as usual annual NO_2 concentrations by site. The dashed line represents the UK NO_2 annual mean limit of 40 µg m^{-3}.



3.3 NOx and NO_2 summary

Overall, the average NOx and NO_2 concentrations across Scotland monitoring sites were lower in 2020 when compared to BAU, by 19.4% and 20.5%, respectively (Table 2). If we focus specifically on the lockdown period between 23rd March and 29th May, the difference between measured and modelled concentrations were even greater, with reductions of 52.2% for NOx and 48.8% for NO_2, when compared to BAU. The greatest decrease in NOx and NO_2 during lockdown, on average, were at Urban Traffic sites.

Table 2 Estimated percentage change in NOx and NO_2 concentrations between measured and business as usual for 2020, and for the lockdown period (23 March to 29 May)

	Lockdown period		2020	
Site type	NOx(%)	NO_2(%)	NO_x(%)	NO_2 (%)
Rural Background	-34.4	-35.9	-17.3	-18.3
Suburban Background	-30.4	-49.2	-19.9	-25.2
Urban Background	-49.9	-50.9	-16.7	-23.5
Urban Industrial	-25.5	-21.8	-3.72	-3.9
Urban Traffic	-58.3	-52.2	-21.3	-21.3
All sites	**-52.5**	**-48.8**	**-19.4**	**-20.5**

3.4 Ozone Analysis

High up in the atmosphere ozone (O_3) protects us from harmful UV radiation, however closer to the ground ozone is a pollutant, which may cause irritation to eyes and breathing difficulties when present in high concentrations. High ambient ozone levels can also result in damage to vegetation.

Ambient O_3 is classified as a secondary pollutant as it is not directly emitted from sources in large quantities but formed via reactions with other pollutants, primarily volatile organic compounds (VOCs) and NOx, in the presence of sunlight. These reactions can take hours or even days to form ozone, therefore, ozone measured in one location may have been the result of emissions of VOCs and NOx hundreds or thousands of miles downwind.

One of the ways ozone is removed from the atmosphere is via reaction with nitrogen oxide (NO). NOx emissions as a result of combustion processes are primarily in the form of NO. Once emitted, NO can react rapidly with O_3 to form NO_2.

Close to roadsides where NO levels are high, O_3 levels are often very low as most of the ozone has reacted with NO shortly after the NO is emitted. Therefore, we typically observe higher O_3 concentrations in rural areas, rather than urban areas.

During the lockdown, with a reduction in traffic and decrease in NOx emissions, ozone concentrations may be expected to increase, as there is less NO available to remove it. The time series of daily averaged O_3 (Figure 12) does appear to show an increase in O_3 concentrations around the time of the lockdown, at some sites in Scotland. However, high O_3 concentrations are typically observed in the spring and summer in the UK, as temperatures are warmer (higher temperatures can accelerate ozone production), and more sunlight compared to winter.

Figure 12 Time series of daily averaged O_3 in 2020 monitoring sites across Scotland. The shaded grey region represents the period between 23rd March (when the national lockdown began) and 10th July (start of Phase 3 lockdown easing).

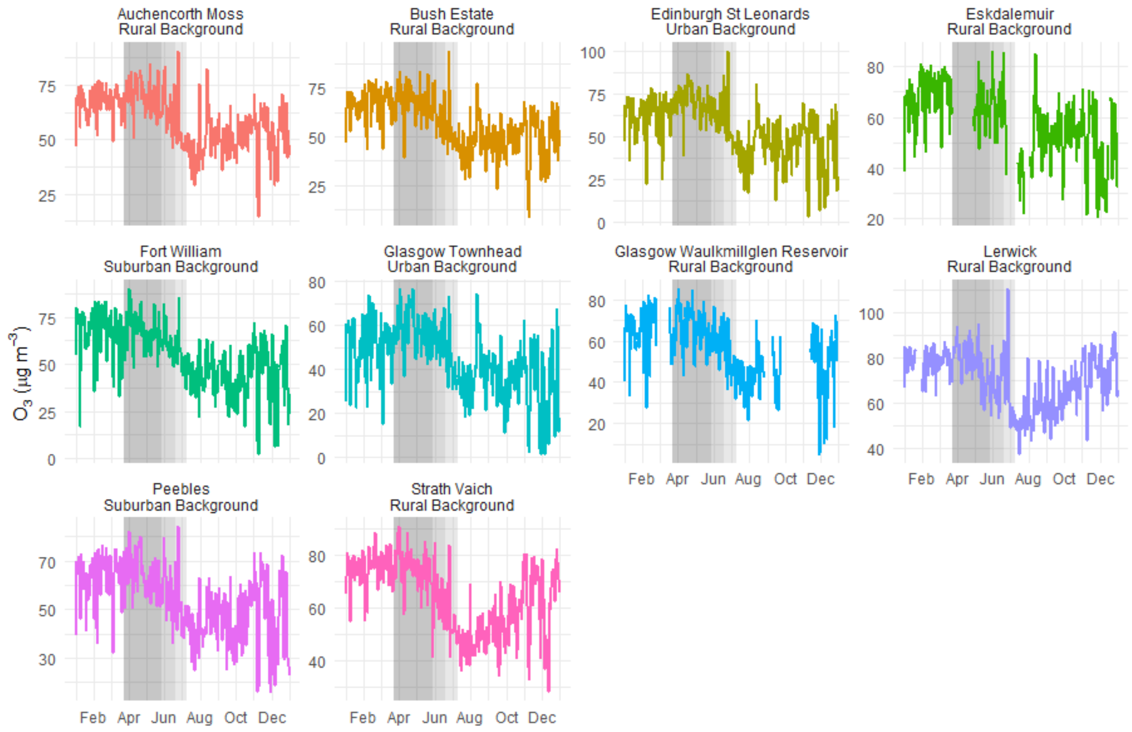
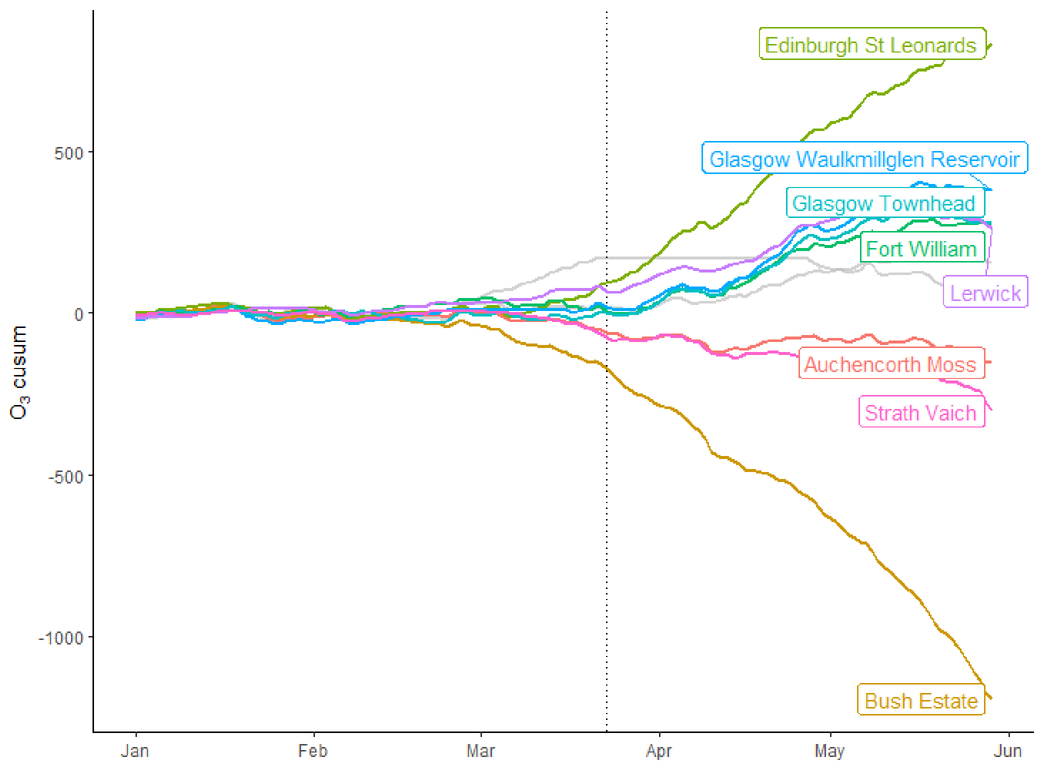


Figure 13 Daily O_3 cusum analysis of measured minus BAU for sites in Scotland from 1st January to 29th May. The dashed line represents the start of the lockdown on 23rd March. Highlighted lines represent monitoring sites which displayed the largest change.



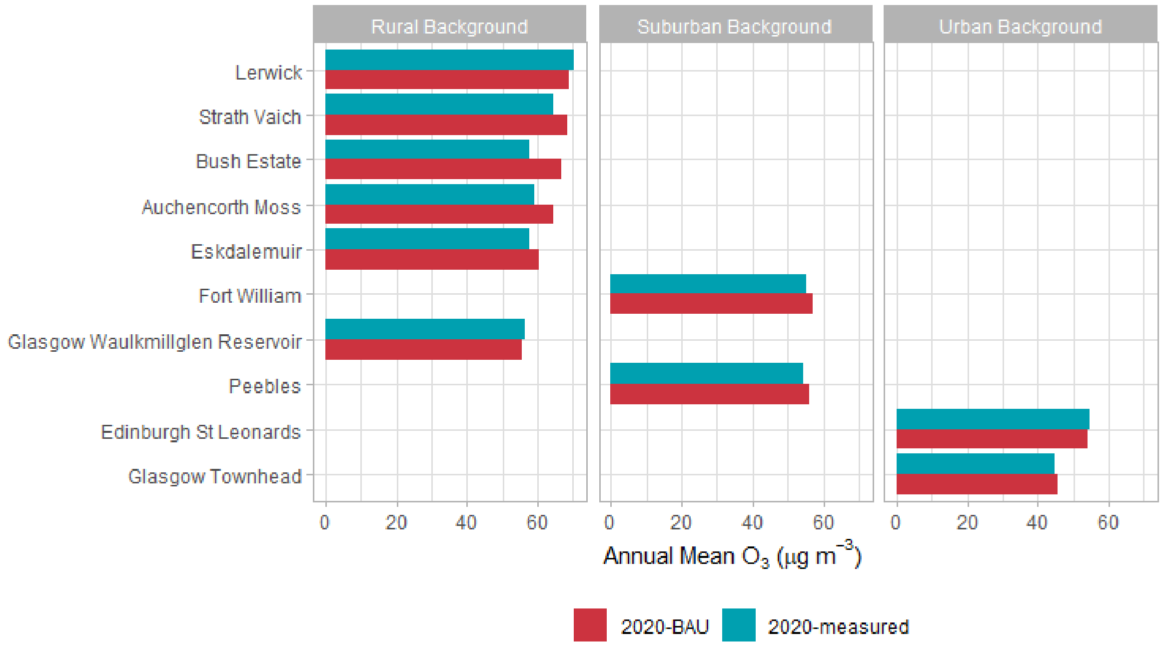
The cusum analysis of measured minus BAU O_3, shown in Figure 13 indicates that the change in O_3 concentrations around the time of the lockdown varied greatly between sites. Rural background sites typically show a decrease in measured O_3 concentrations and suburban/urban background sites an increase (Table 3).

Table 3 Percentage change in O_3 concentrations between measured and business as usual for 2020, and for the lockdown period (23 March to 29 May).

Site type	Lockdown period O_3(%)	2020 O_3 (%)
Rural Background	-4.70	-4.84
Suburban Background	3.57	-3.24
Urban Background	11.5	-1.11
All sites	**0.20**	**-3.78**

When looking at the whole of 2020, on average, measured O_3 concentrations are lower than BAU, however, the estimated percentage differences are very small.

Figure 14 Measured and business as usual annual O_3 concentrations by site in 2020. The numbers show the percentage change in measured O_3 concentration, relative to BAU.



3.5 Particulate Matter

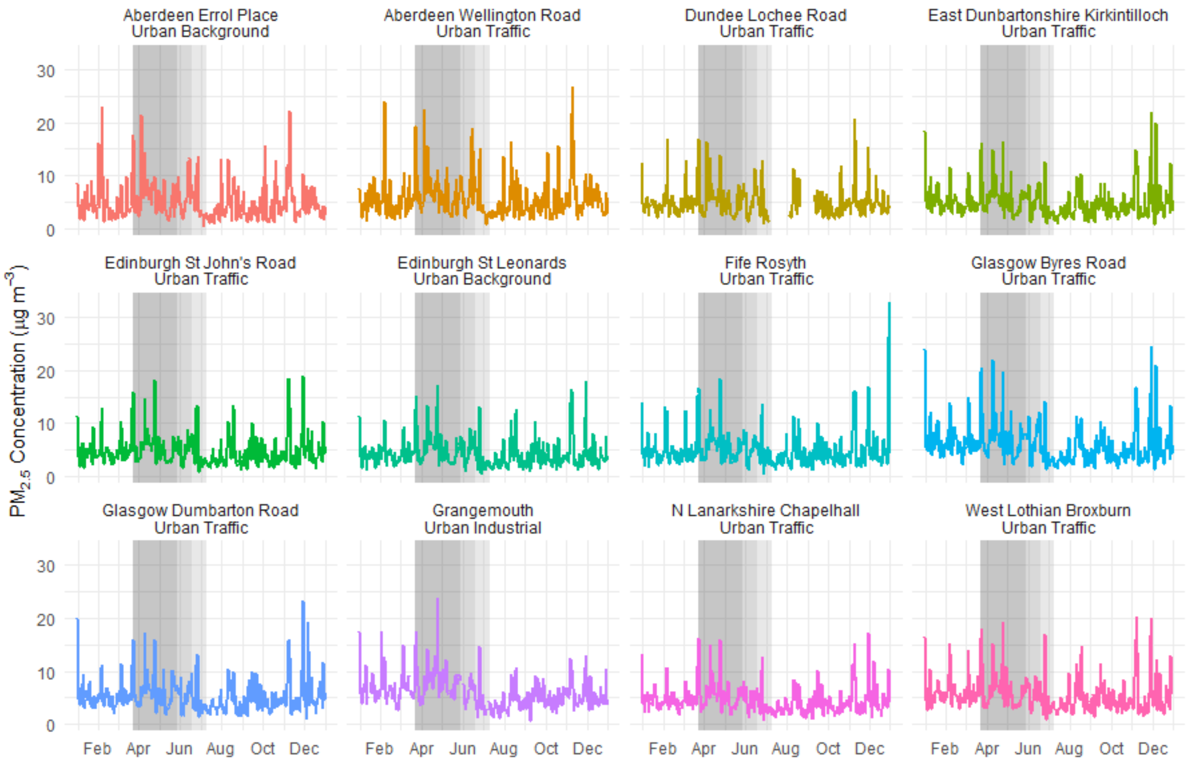
PM can be come from natural sources (e.g. soil, sea salt, pollen), emitted directly from anthropogenic sources (vehicle exhausts, industrial combustion processes, domestic heating), and also formed via reactions between sulphur dioxide, NOx and other chemical species (known as secondary PM).

Secondary PM can be transported long distances, so PM in one location may be strongly influenced by the regional and continental transport of pollutants. As a result, it is much more challenging to assess changes in particulate matter as a result of lockdown, compared to NOx.

Figure 15 shows the daily mean $PM_{2.5}$ concentrations at various sites across Scotland. Unlike NOx, which indicated a decrease in concentrations during lockdown, the $PM_{2.5}$ actually seems to increase during this period. A springtime peak in $PM_{2.5}$. is not uncommon, however, as agricultural activity over

Europe increases during this period, resulting in an increase in ammonium nitrate from fertilisers, which can contribute to secondary $PM_{2.5}$.

Figure 15 Time series of daily averaged $PM_{2.5}$ in 2020 monitoring sites across Scotland. The shaded grey region represents the period between 23rd March (when the national lockdown began) and 10th July (start of Phase 3 lockdown easing).



3.5.1 Cluster analysis

To investigate the influence of transported pollutants to PM2.5 in Scotland, 96-hour back trajectories, centred on Bush Estate in Edinburgh (55.86222, -3.206111), were run and plotted using the Openair R package. The trajectories, shown in Figure 16, are clustered together and provide the estimated location of an air mass and the percentage of time the airmasses were from the specific cluster.

By combining the arrival of the air mass from different clusters with the measured $PM_{2.5}$ concentrations, we can investigate changes in concentrations with different air mass origins. An example is shown in Figure 17, where daily averaged $PM_{2.5}$ concentrations at Edinburgh St John's Road are coloured according to the origin of the air mass. The figure shows that just after lockdown began in March and again in late April, air masses from cluster 6 (originating from Europe) coincided with high $PM_{2.5}$ concentrations. Clusters 2, 3 and 4, which originated from the Atlantic and therefore expected to be less polluted, were often associated with lower $PM_{2.5}$ concentrations at Edinburgh St John's Road.

Figure 16 Cluster analysis of air mass origins for 2020 from 01 January to 22 March and 23 March to 01 July. The numbers show the percent of time the air was from each cluster.

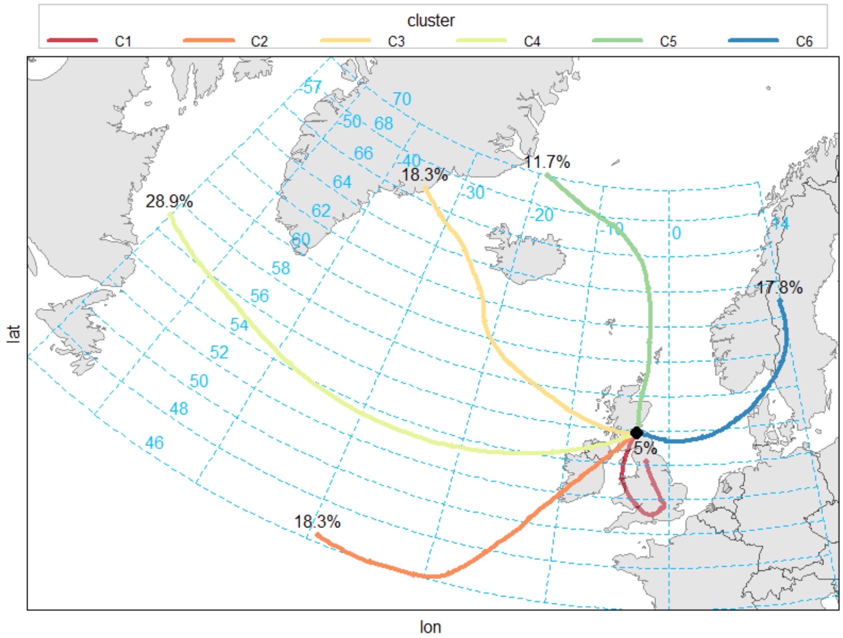
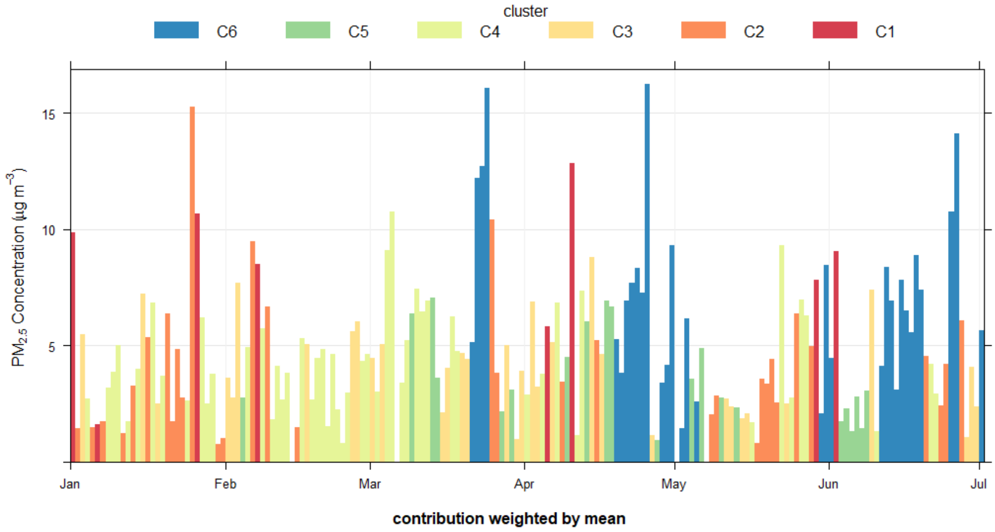


Figure 17 Daily mean $PM_{2.5}$ concentration measured at Edinburgh St John's Road coloured by the air mass cluster shown in Figure 16.



3.5.2 Increment in PM

Investigating changes in PM as a result of lockdown requires careful consideration as any local change may be masked by long range transported pollutants.

Instead, we can consider the *urban increment in PM*, i.e. the PM level above the background. Subtracting the PM concentration measured at a rural background location (which is more representative of a wider area) from the PM measured at each site, should provide more information on changes in concentrations at a local level.

In the analysis presented here, concentrations measured at the Auchencorth Moss rural monitoring site were used to calculate the increment in $PM_{2.5}$ and PM_{10}.

Figure 18 Cusum analysis of daily averaged measured minus BAU increment in $PM_{2.5}$ for sites in Scotland from 1st January to 29th May. The dashed line represents the start of the lockdown on 23rd March. Highlighted lines represent monitoring sites which displayed the largest decrease.

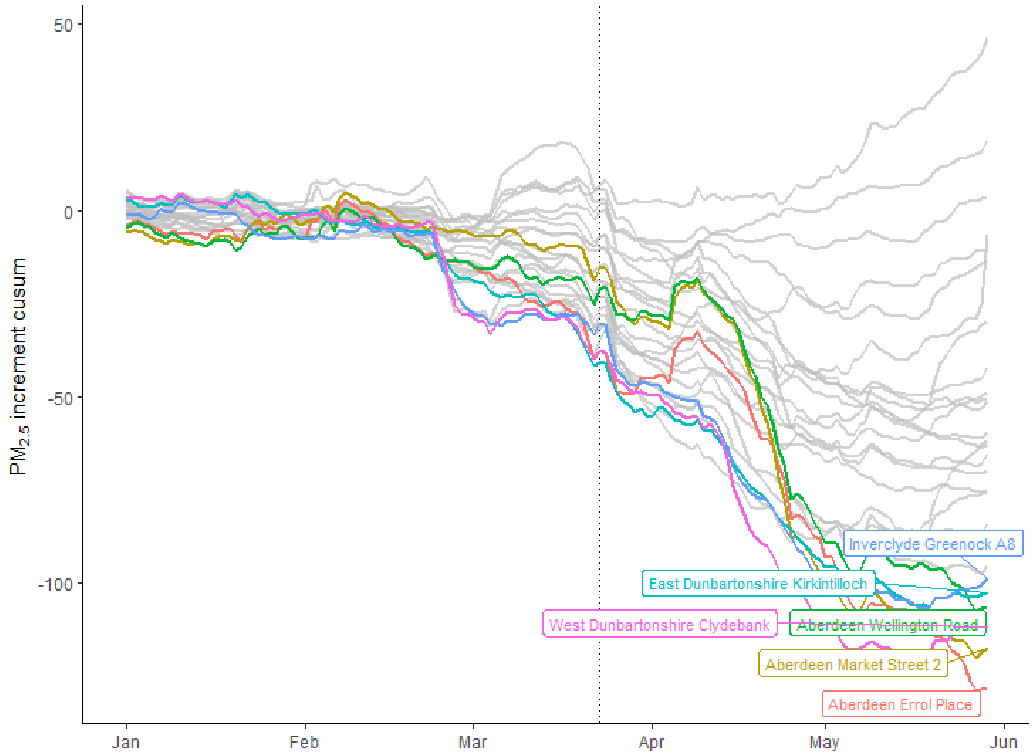
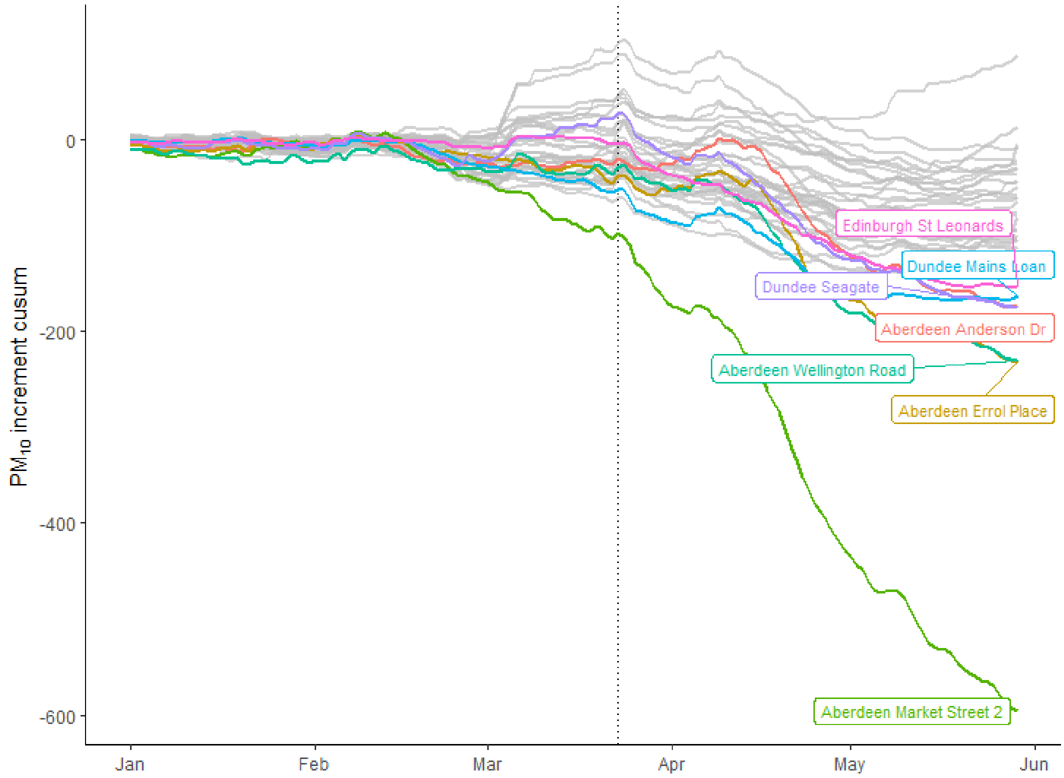


Figure 19 Cusum analysis of daily averaged measured minus BAU increment in PM_{10} for sites in Scotland from 1st January to 29th May. The dashed line represents the start of the lockdown on 23rd March. Highlighted lines represent monitoring sites which displayed the largest decrease.



The cusum analysis for the $PM_{2.5}$ and PM_{10} increments above background concentrations are shown in Figure 18 and Figure 19, respectively. Compared to NOx and O_3, it is less clear if changes in PM occurred around lockdown, and there is a large variation between sites. However, there does appear to be some evidence of a decrease in $PM_{2.5}$ and PM_{10} (above background levels) at some sites.

Across all sites, the change in absolute PM when compared to BAU is very small over the lockdown period, with an average decrease of 1.5 μgm^{-3} in PM_{10} and 0.59 μgm^{-3} in $PM_{2.5}$. These values are also more uncertain than for NOx and O_3, as the choice of the background site used for calculating the PM increment can have a large impact on the estimated PM increment.

Table 4 Change in $PM_{2.5}$ and PM_{10} increment above background concentrations with respect to business as usual, for the lockdown period (23 March to 29 May)

Site type	Lockdown period	
	PM_{10} (μgm^{-3})	$PM_{2.5}$ (μgm^{-3})
Urban Background	-1.8	-0.92
Urban Industrial	-1.3	-0.26
Urban Traffic	-1.5	-0.54
All sites	**-1.5**	**-0.59**

4 Changes in Traffic Flow during 2020

The main source of NOx emissions in Scotland is the transport sector (Table 5), accounting for 47.7% of total NOx emissions in 2018. Transport sources also contributed 15.3% of PM_{10} emissions and 20.1% of $PM_{2.5}$ emissions in Scotland in 2018.

Table 5 Air pollutant emission estimates for Scotland (kt) in 2018. Emissions are based on the 2018 data from the Air Pollutant Inventory Report for England, Scotland, Wales and Northern Ireland (Ricardo Energy & Environment 2020) [2] using data from the National Atmospheric Emission Inventory (NAEI) (BEIS, 2020) [3].

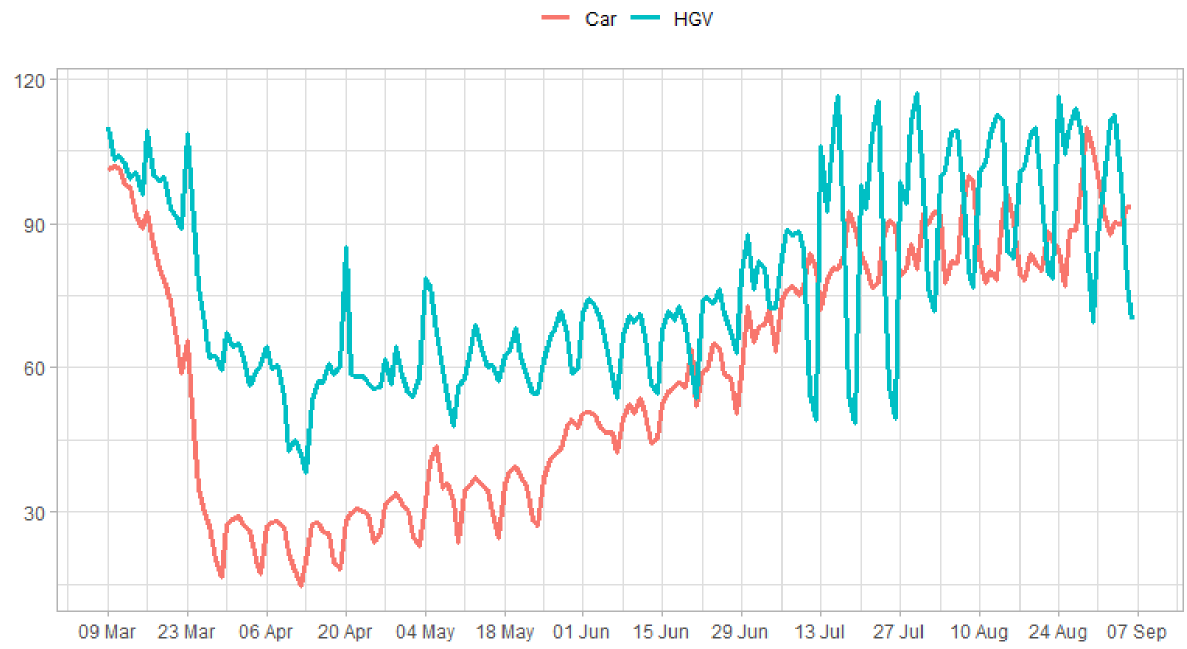
Sector	NOx	PM_{10}	$PM_{2.5}$
Energy Industries	10.9	0.24	0.2
Industrial Combustion	12.2	1.17	1.14
Transport Sources	**40.9**	**2.32**	**1.69**
Residential, Commercial & Public Sector Combustion	16.9	3.8	3.72
Industrial Processes	0.005	4.18	0.77
Solvent Processes		0.1	0.03
Agriculture	0.04	2.65	0.38
Waste	0.01	0.16	0.15
Other	5.02	0.53	0.34
Total	**85.9**	**15.2**	8.42

Transport Scotland have published a report on transport trends for the first 6 months of the pandemic [4]. Figure 20 shows the national daily trend in Car and HGV vehicles for the period 9th March to 6th September 2020. The values given are based on the equivalent day in 2019, i.e., a value of 100 indicates the same level of traffic for the transport mode, on the same day in 2019.

As expected, there was a sharp decrease in the number of cars on the roads around the time social distancing was advised on 16th March and reaching a minimum towards the end of March.

The report by Transport Scotland states *"Car traffic levels dropped to around 25 per cent of 2019 levels, but had recovered to 91 per cent of 2019 levels by the end of the six month period. Car traffic on tourist routes fell to a lower minimum level, but recovered more than on non-tourist routes once tourism reopened"* [4]

Figure 20: Trend in daily car and Heavy Goods Vehicles (HGVs) (equivalent day in 2019 = 100). Source: Transport Scotland. Contains public sector information licensed under the Open Government Licence v3.0[2].



NOx concentrations in areas with high traffic volumes typically show a pattern associated with traffic emissions, i.e. high levels during morning and evening rush hour periods. With the large reduction in traffic numbers in March and April we may expect to see a change in this diurnal pattern. Figure 21 and Figure 22 show diurnal profiles of NOx adjusted for variations in local meteorology (windspeed, wind direction and air temperature) at two urban traffic monitoring sites - Glasgow Roadside and Edinburgh St Johns Road, before and after lockdown. In both cases the profile before lockdown (green line) is as expected – with peaks in NOx in the morning and evening. During lockdown (pink line), the diurnal profile is much lower overall, and the evening peak has all but disappeared. The observed change in the diurnal profile provides some indication that the reduction in NOx is consistent with a reduction in traffic emissions.

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[2] http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/

Figure 21 Meteorologically adjusted NOx for the periods before and after lockdown for Glasgow Roadside for Weekdays, Saturday, and Sunday. The green lines represent the average diurnal profile for the period before lockdown, the pink lines the average diurnal profile during lockdown, and the blue shaded regions are the difference between these.

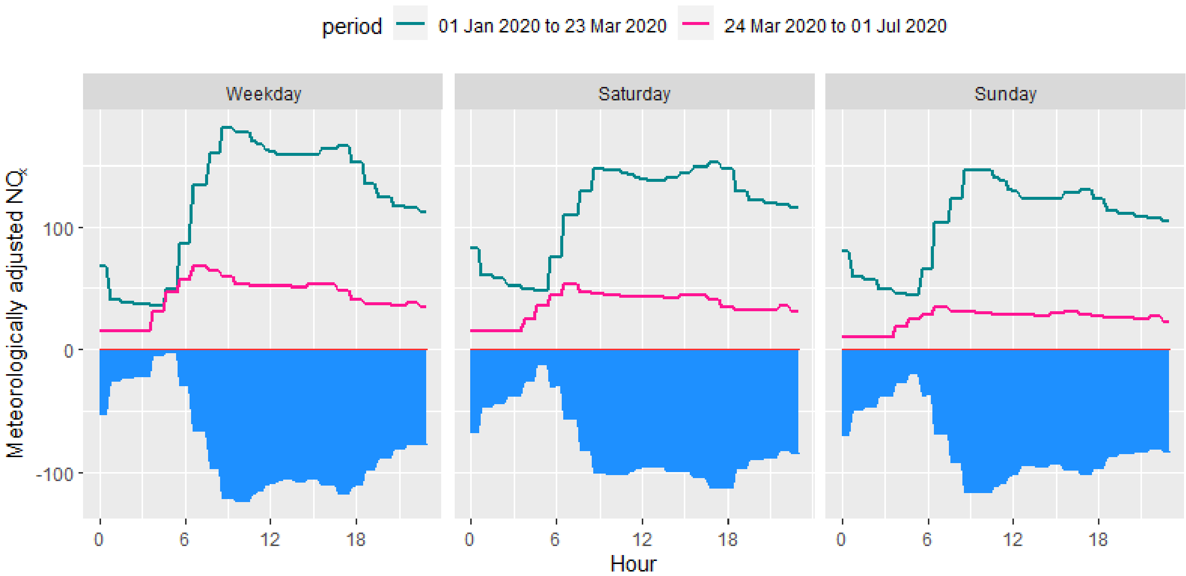
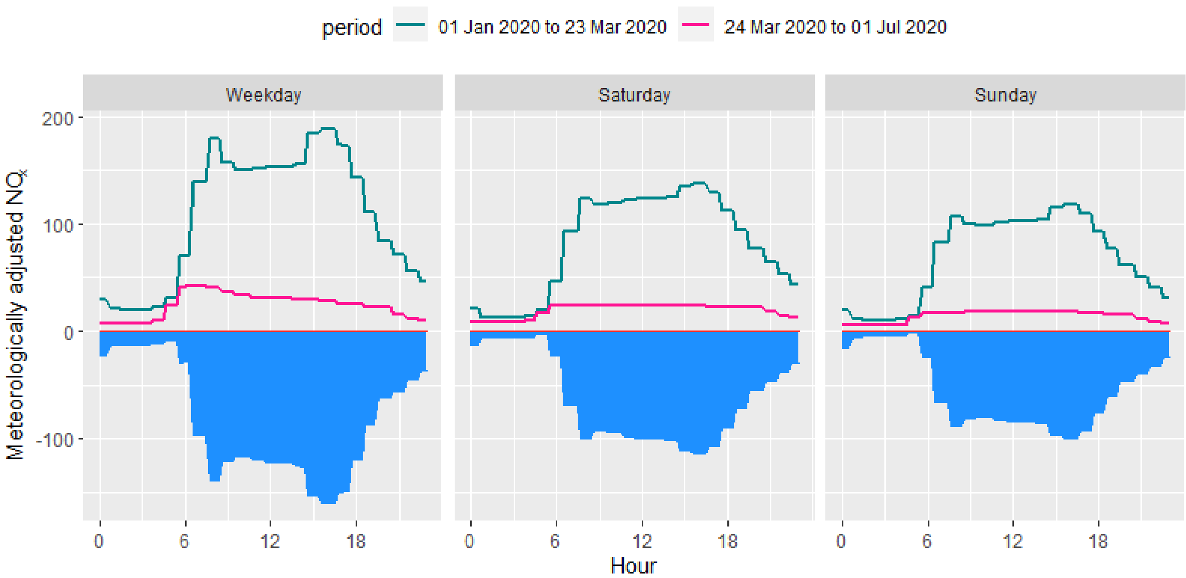


Figure 22 Same as Figure 21, for Edinburgh St John's Road.



5 Preliminary Analysis for 2021

The analysis for 2020 has been extended into 2021 to assess changes in NO_2 concentrations as lockdown restrictions begin to ease. Please note, the analysis presented in this section contains preliminary NO_2 data, which has yet undergone full QA/QC processes, therefore is subject to change.

Figure 23 shows the mean monthly difference in measured and BAU NO_2 concentrations for each of the 36 urban traffic sites analysed, from January 2020 to April 2021. A similar pattern is observed across most of the sites, with measured NO_2 concentrations sharply decreasing with respect to BAU after the first lockdown began in March 2020. This was followed by a steady return towards predicted levels in late summer/early autumn. However, for many sites, the measured NO_2 concentrations still remained below BAU concentrations during those months. Over winter, measured NO_2 concentrations decreased once again, when compared to the modelled concentrations. From January to April 2021, NO_2 measured concentrations at the traffic sites, on average, remained lower than predicted.

Figure 23 Monthly mean difference in measured and modelled "business as usual" (BAU) concentrations for urban traffic sites. Red bars represent measurements greater than modelled concentrations and blue bars represent measurements lower than modelled concentrations. Note the different scales on the y-axis for each site.

6 Conclusions

This report investigates the change in ambient pollutant concentrations (NOx, NO_2, O_3, PM_{10}, and $PM_{2.5}$) in Scotland as a result of the Covid-19 pandemic. The report covers the period between Jan 1st and December 31st, 2020, with a particular focus on the first UK lockdown period between 23rd March and 29th May 2020.

- During the first UK national lockdown in 2020, NOx and NO_2 concentrations in Scotland were estimated to decrease, on average, by 52.2% and 48.8%, respectively, when compared with BAU. The largest decrease was observed at urban traffic monitoring sites.

- Overall, for 2020, NOx and NO_2 concentrations were lower than predicted by the model and none of the sites analysed here exceeded the UK NO_2 annual mean limit of 40 µg m^{-3}.
- Ozone measured at urban background sites increased by an estimated 11.5%, during the first lockdown period when compared to BAU, whereas at rural sites O_3 concentrations were lower than predicted, on average. Urban background sites would typically have higher NOx levels than rural sites, therefore the reduction in NOx, would result in less NO available to remove O_3.
- PM_{10} and $PM_{2.5}$ concentrations are dominated by sources on a regional scale; therefore, it is challenging to separate any local changes as a result of lockdown. To address this issue the urban increments in PM (PM above background levels) were investigated. The results show that during the lockdown period the estimated change in the urban increment in PM concentrations was very small, with an absolute change of 1.5 μgm^{-3} in PM_{10} and 0.59 μgm^{-3} in $PM_{2.5}$, when compared to BAU. As these changes are very small, and dependent on the choice of the background site, the PM analysis has much greater uncertainty, compared to NOx and O_3.
- The analysis of the diurnal variation in NOx concentrations at two urban traffic monitoring sites, before and during the first lockdown, showed that NOx concentrations decreased during the day and the pattern was consistent with a reduction in road traffic.
- A comparison of measured and BAU NO_2 concentrations at urban traffic sites was carried out for each month from January 2020 to April 2021. The analysis shows the greatest reduction in measured NO_2 concentrations occurred in Spring 2020 and Winter 2020/2021.

7 References

[1] D. C. Carslaw and P. J. Taylor, “Analysis of air pollution data at a mixed source location using boosted regression trees,” *Atmospheric Environment,* vol. 43, p. 3563–3570, 2009.

[2] Ricardo Energy & Environment, “Air Pollutant Inventories for England, Scotland, Wales, and Northern Ireland: 1990-2017,” Harwell, Didcot: Ricardo Energy & Environment., 2019.

[3] NAEI, “National Atmospheric Emissions Inventory,” 2019. [Online]. Available: http://www.naei.org.uk.

[4] Transport Scotland, “COVID-19: Scotland’s transport and travel trends during the first six months of the pandemic,” 2020.

Appendices

A1: Automatic Monitoring Sites Included in the Analysis

A1 Automatic Monitoring Sites included in the analysis

A1.1 Nitrogen Oxides

Site	Site Type	Site	Site Type
Aberdeen Errol Place	Urban Background	Falkirk West Bridge Street	Urban Traffic
Aberdeen King Street	Urban Traffic	Fife Cupar	Urban Traffic
Aberdeen Market Street 2	Urban Traffic	Fife Kirkcaldy	Urban Traffic
Aberdeen Union Street Roadside	Urban Traffic	Fife Rosyth	Urban Traffic
Aberdeen Wellington Road	Urban Traffic	Fort William	Suburban Background
Bush Estate	Rural Background	Glasgow Anderston	Urban Background
Dumfries	Urban Traffic	Glasgow Byres Road	Urban Traffic
Dundee Broughty Ferry Road	Urban Industrial	Glasgow Dumbarton Road	Urban Traffic
Dundee Lochee Road	Urban Traffic	Glasgow Great Western Road	Urban Traffic
Dundee Mains Loan	Urban Background	Glasgow High Street	Urban Traffic
Dundee Seagate	Urban Traffic	Glasgow Kerbside	Urban Traffic
Dundee Whitehall Street	Urban Traffic	Glasgow Townhead	Urban Background
E Ayrshire Kilmarnock St Marnock St	Urban Traffic	Glasgow Waulkmillglen Reservoir	Rural Background
East Dunbartonshire Bishopbriggs	Urban Traffic	Grangemouth	Urban Industrial
East Dunbartonshire Kirkintilloch	Urban Traffic	Grangemouth Moray	Urban Industrial
East Dunbartonshire Milngavie	Urban Traffic	Inverclyde Greenock A8	Urban Traffic
East Lothian Musselburgh N High St	Urban Traffic	Inverness	Urban Traffic
Edinburgh Glasgow Road	Urban Traffic	Lerwick	Rural Background
Edinburgh Gorgie Road	Urban Traffic	Peebles	Suburban Background
Edinburgh Queensferry Road	Urban Traffic	Perth Atholl Street	Urban Traffic
Edinburgh St John's Road	Urban Traffic	Perth Crieff	Urban Traffic
Edinburgh St Leonards	Urban Background	South Lanarkshire Lanark	Urban Traffic
Eskdalemuir	Rural Background	Stirling Craig's Roundabout	Urban Traffic
Falkirk Grangemouth MC	Urban Background	West Dunbartonshire Glasgow Road	Urban Traffic
Falkirk Haggs	Urban Traffic	West Lothian Broxburn	Urban Traffic
Falkirk Hope St	Urban Traffic		

A1.2 Ozone

Site	Site Type
Auchencorth Moss	Rural Background
Bush Estate	Rural Background
Edinburgh St Leonards	Urban Background
Eskdalemuir	Rural Background
Fort William	Suburban Background
Glasgow Townhead	Urban Background
Glasgow Waulkmillglen Reservoir	Rural Background
Lerwick	Rural Background
Peebles	Suburban Background
Strath Vaich	Rural Background

A1.3 Particulate Matter

Site	Site Type	PM_{10}	$PM_{2.5}$
Aberdeen Anderson Dr	Urban Traffic	✓	
Aberdeen Errol Place	Urban Background	✓	✓
Aberdeen Market Street 2	Urban Traffic	✓	✓
Aberdeen Wellington Road	Urban Traffic	✓	✓
Dundee Broughty Ferry Road	Urban Industrial	✓	
Dundee Lochee Road	Urban Traffic	✓	✓
Dundee Mains Loan	Urban Background	✓	✓
Dundee Meadowside	Urban Traffic	✓	
Dundee Seagate	Urban Traffic	✓	
Dundee Whitehall Street	Urban Traffic	✓	
East Dunbartonshire Bearsden	Urban Traffic	✓	
East Dunbartonshire Bishopbriggs	Urban Traffic	✓	
East Dunbartonshire Kirkintilloch	Urban Traffic	✓	✓
East Dunbartonshire Milngavie	Urban Traffic	✓	
East Lothian Musselburgh N High St	Urban Traffic	✓	
Edinburgh Salamander St	Urban Traffic	✓	
Edinburgh St John's Road	Urban Traffic	✓	✓
Edinburgh St Leonards	Urban Background	✓	✓
Fife Cupar	Urban Traffic	✓	✓
Fife Dunfermline	Urban Traffic	✓	✓
Fife Kirkcaldy	Urban Traffic	✓	✓
Fife Rosyth	Urban Traffic	✓	✓
Glasgow Byres Road	Urban Traffic	✓	✓
Glasgow Dumbarton Road	Urban Traffic	✓	✓
Glasgow High Street	Urban Traffic	✓	✓
Glasgow Townhead	Urban Background	✓	✓
Grangemouth	Urban Industrial	✓	✓
Inverclyde Greenock A8	Urban Traffic	✓	✓
N Lanarkshire Chapelhall	Urban Traffic	✓	✓
Paisley Gordon Street	Urban Traffic	✓	
Perth Atholl Street	Urban Traffic	✓	✓
Perth Crieff	Urban Traffic	✓	✓
Perth Muirton	Urban Background	✓	
South Lanarkshire East Kilbride	Urban Traffic	✓	✓
South Lanarkshire Lanark	Urban Traffic	✓	✓
South Lanarkshire Rutherglen	Urban Traffic	✓	✓
Stirling Craig's Roundabout	Urban Traffic	✓	
West Dunbartonshire Clydebank	Urban Traffic	✓	✓
West Lothian Broxburn	Urban Traffic	✓	✓

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