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Air pollution in Ontario, Canada during the COVID-19 State of Emergency

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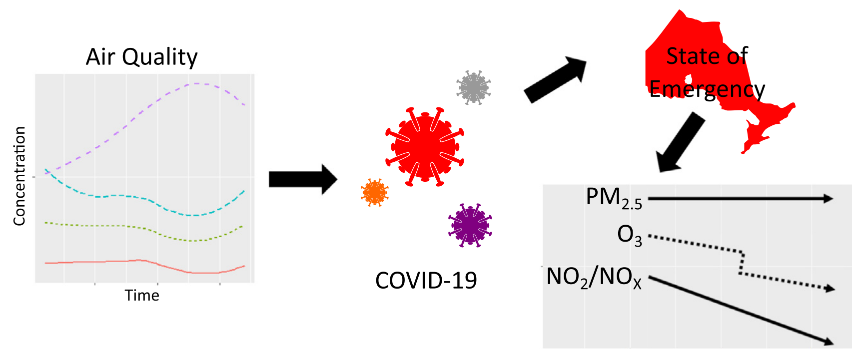
HIGHLIGHTS

- Air pollution response to a region-wide state of emergency was assessed.
- Fine particulate matter concentrations did not change.
- Moderate evidence of ozone concentration reductions
- Strong evidence for reductions of nitrogen dioxide and nitrogen oxides
- Pollutants with transportation dominated source profiles responded the most.

GRAPHICAL ABSTRACT



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ABSTRACT

In March of 2020, the province of Ontario declared a State of Emergency (SOE) to reduce the spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which causes the coronavirus disease (COVID-19). This disruption to the economy provided an opportunity to measure change in air pollution when the population spends more time at home with fewer trips. Hourly air pollution observations were obtained for fine particulate matter, nitrogen dioxide, nitrogen oxides and ozone from the Ontario air monitoring network for 2020 and the previous five years. The analysis is focused on a five-week period during the SOE with a previous five-week period used as a control. Fine particulate matter did not show any significant reductions during the SOE. Ozone concentrations at 12 of the 32 monitors were lower than any of the previous five-years; however, four locations were above average. Average ozone concentrations were 1 ppb lower during the SOE, but this ranged at individual monitors from 1.5 ppb above to 4.2 ppb below long-term conditions. Nitrogen dioxide and nitrogen oxides demonstrated a reduction across Ontario, and both pollutants displayed their lowest concentrations for 22 of 29 monitors. Individual monitors ranged from 1 ppb (nitrogen dioxide) and 5 ppb (nitrogen oxides) above average to 4.5 (nitrogen dioxide) and 7.1 ppb (nitrogen oxides) below average. Overall, both nitrogen dioxide and nitrogen oxides demonstrated a reduction across Ontario in response to the COVID-19 SOE, ozone concentrations suggested a possible reduction, and fine particulate matter has not varied from historic concentrations.

1. Introduction

On March 17, 2020, a province-wide State of Emergency (SOE) was announced by the Premier of Ontario, Canada. The objective of this order was to "flatten the curve", which is to say, reduce the load on the medical system by slowing the spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) that causes the coronavirus disease (COVID-19). The major government responses began on March 12th when there was an announcement that all publicly funded elementary and secondary schools would remain closed for an additional two weeks following their mid-winter break (Monday, March 16, 2020 – Friday, March 20, 2020). The March 17 SOE implemented a limit on public events to 50 or fewer people, the closing of restaurants

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and bars (excluding take-out and delivery), and the closure of theatres, private schools, libraries, and daycares. On March 23, it was announced that all non-essential businesses must close by March 25th. Public gatherings were limited to five people on March 27th. Across the province on March 30th, all outdoor recreational facilities were closed (e.g. beaches and playgrounds). Generally, the entire economy was affected in Ontario by the SOE.

Dutheil et al. (2020) propose that COVID-19 related quarantines in China have reduced nitrogen dioxide emissions by up to 30%, and carbon dioxide emissions were reduced by 25% in China and 6% globally. They suggest the possibility that the reduced air pollution concentrations may have a net reduction in the total number of deaths, in that, the reduction in air pollution related deaths will be larger than the number of COVID-19 related deaths. Wang et al. (2020) identified that during the COVID-19 outbreak severe fine particulate matter air pollution events were not completely avoided in the North China Plain, where pollution precursors were reduced two-times more than concentrations. They identified that during their study period (January 1st to February 12, 2020) that meteorological conditions were favorable for major air pollution events. Conticini et al. (2020) propose that the high concentrations of air pollution in Northern Italy are a co-factor for the high rate of lethality due to SARS-CoV-2. They suggest that individuals who live in areas of high air pollution will have an increased risk of chronic respiratory conditions, which can increase infection rates. Frontera et al. (2020) hypothesize that high air pollution concentrations can act to increase the suspension time of viral particles, and increase non-direct disease spread.

The situation in Ontario has presented the opportunity to examine potential changes in air quality due to a massive reduction in commuting, travel and general economic output as many businesses are closed, except for those in essential services. In this paper, we examine if air pollution across Ontario has responded significantly to changes in population level behaviours caused by a province-wide SOE to limit the spread of SARS-CoV-2. We define a significant change as an average concentration for a period of five-weeks during the SOE that is lower than the average concentration during that same period in any of the previous five years. We believe that changes that are within the five-year variation are not outside of the normal range and should not be attributed to the SOE. Additionally, we utilize a five-week period five weeks prior to the SOE to determine if concentrations were already lower than previous five-year observations, as this would suggest another possible effect.

2. Methodology

2.1. Data acquisition

The April 17, 2020 Google COVID-19 Community Mobility Report for Canada was obtained (Google, 2020). These reports present aggregated median values on how busy in recent weeks (an aggregation of the number of trips and length of trips) retail and recreation, grocery and pharmacy, parks, transit stations, workplaces and residential locations are relative to a five-week period (January 3 to Feb 6, 2020). The purpose of this review was to determine if the expected changes in mobility were being observed during the SOE, which we anticipated would include more time spent in residential locations, and less on all other activities.

Air pollution data were obtained from the Ontario Ministry of the Environment, Conservation and Parks' air pollution data portal on April 27, 2020 (Ontario Ministry of the Environment Conservation and Parks, 2010). Data from all operational monitoring stations were obtained beginning on January 1st, 2015 until the day of retrieval. We retained air monitor data, by pollutant, only when observations were available for the entire time-period, for example, if an air pollution monitor was installed after January 1st, 2015, we did not include it in our analysis. We then assessed the percent of missing data for each monitor per year, to ensure a suitable amount of data were available. Stations that excluded one or more months of data (defined as all missing data) were removed. Air pollution observations were reported as hourly averages and we obtained concentration data for particulate matter 2.5 μm or smaller in aerodynamic diameter ($PM_{2.5}$), nitrogen dioxide (NO_2), nitrogen oxides (NO_X) and ground-level ozone (O_3). In Table S1, 2016 population counts are provided for the city of each monitoring station.

2.2. Statistical analysis

To compare year to year variations at the weekly level. We used the US Centre for Disease epidemiological week (week) throughout our analysis, which begins on a Sunday and the first epidemiological week ends on the first Saturday in January that is at least four days into the month. Our analysis focused on weeks 1 to 17; the first reported case of COVID-19 was on January 15, 2020 in Canada (week 3) (Public Health Agency of Canada, 2020). The 17th week was the last complete week available when these data were analyzed. It is important to note that Ontario public schools have a mid-winter break (Elementary and Secondary Schools), which occurred in the 11th epidemiological week in all years except for 2020, when it occurred in week 12. In 2018, there were over 2 million students that would have observed the mid-winter break (Queen's Printer for Ontario, 2020). Ontario colleges and universities typically have a winter break that aligns with the Ontario Family Day Holiday, which is the third Monday in February (but the timing/observance of this break is school dependent). Family Day occurred during week 7 in 2015 and 2016, and in week 8 during all subsequent years. These two holidays may introduce variation in pollution, due to changes in commute behaviour, when comparing air pollution observations by week across years as they are not consistent in their annual timing.

Long-term trends (year-to-year) in air quality for the period of interest were assessed visually for all of Ontario and for each air monitor. We analyzed the mean concentration for each pollutant during the study period (weeks 1 to 17) by year. This was completed to identify any long-term trends in air quality that could be responsible for reductions in 2020 observations. For example, are any pollutants generally decreasing across Ontario or at a specific monitoring location. The presence of long-term air pollution trends, either positive or negative, would make it difficult to attribute causality to the SOE in Ontario.

Seasonal trends (week-to-week) in air quality across Ontario and at individual monitors were assessed using local polynomial regressions fit to the weekly mean values by year. We used the ggplot2 package (Wickham, 2016) in R: A language and environment for statistical computing (R Core Team, 2020) for visualization and local polynomial regression fitting. The objective was to determine if air pollutants varied throughout the period of interest. For example, does O_3 increase from winter to spring. These trends are important because if they occur, it does not allow for a simple comparison of previous weeks in 2020 with observations during the SOE in 2020. This analysis excluded the 2020 observations.

We calculated the Ontario mean concentration by pollutant for weeks 8–12 and 13–17, where weeks 13–17 are the complete five weeks during the Ontario State of Emergency (SOE weeks) and 8–12 are a five-week period prior to the SOE (pre-SOE). These calculations were completed individually for 2020 observations and for 2015–2019 observations. The objective of this comparison was to determine if in 2020 the concentrations in the prior period were lower than historical averages, which would indicate a potential effect other than the SOE.

Our definition of a significant change in air quality was specified as the mean concentration during the SOE being lower than the minimum value for that same period in any of the previous five years. For each year, we calculated the mean concentration by pollutant and station for the SOE and pre-SOE periods. We compared the 2020 mean SOE concentration with the mean from the previous five years. After, we examined if the 2020 mean values were lower than the minimum value of the previous five years. We also identified if the pre-SOE period demonstrated these reduced concentrations, as that may indicate another factor is responsible for the effect.

3. Results

Within Ontario, the Google Mobility Report indicated that people were responding as expected to the SOE. Time spent in residential locations increased relative to the baseline (+28%), while all other locations were reduced. Retail and recreation (−56%), grocery & pharmacy (−23%), parks (−33%), transit stations (−69%) and workplace (−62%). The reduction in activities indicates that overall transportation movements should have declined.

Air pollution observations (hourly averages) were retrieved for the 38 active monitoring stations. After excluding monitors that were installed after January 1st, 2015 or missing more than one-month of data, we retained 32 monitors for $PM_{2.5}$ and O_3, and 29 for NO_2 and NO_X. Data were filtered to only include weeks 1 through 17 for each of the six years (2015–2020). Observation data were missing 1.23% of the time, which ranged from 0.92% in 2018 to 1.54% in 2016. The percent missing varied less by pollutant from $PM_{2.5}$ (1.15% missing) to NO_2 (1.32% missing). Within a single month the average number of missing observations were 7.5, with a maximum of 239 and a minimum of 0 missing values. In Table 1, we present province-wide descriptive statistics of the air pollution concentrations. In Table S2, mean concentrations are provided by monitor and pollutant.

The long-term mean pollutant concentrations across Ontario for weeks 1 to 17 by year (2015 to 2019) are presented in Fig. 1. These same data are presented separated by monitoring station in Fig. S1. Across Ontario, no pollutants demonstrated long-term trends. Individual monitors also did not demonstrate long-term trends. The seasonal temporal trends, represented as the mean concentration by week, for Ontario are presented in Fig. 2 and presented by station in Fig. S2, which included air pollution observations between 2015 and 2019. Across Ontario, O_3 demonstrates an increasing trend at monitoring locations with a peak at the transition between the pre-SOE and SOE periods, $PM_{2.5}$ is flat, and NO_2/NO_X both demonstrate decreasing trends starting in the pre-SOE and continuing through the SOE period.

During the SOE in 2020 mean air pollution concentrations across Ontario air monitors were lower than previous years during that period (weeks 13–17) for NO_2, NO_X and O_3; however, $PM_{2.5}$ demonstrated average conditions. During the 2020 SOE period the average concentrations were 5.6 μg/m^3 ($PM_{2.5}$), 5 ppb (NO_2), 7 ppb (NO_X) and 33 ppb (O_3). When compared to the mean values for the previous five years, these were reductions of 2 ppb (NO_2), 2 ppb (NO_X) and 1 ppb (O_3); $PM_{2.5}$ did not show a reduction. During the 2020 pre-SOE period (weeks 8–12) $PM_{2.5}$ was 1 μg/m^3 lower, NO_2 was 2 ppb lower, and NOx was 2 ppb lower compared to the 2015–2019 means, while O_3 was displaying average conditions.

Changes in mean air quality during the SOE for 2020 relative to the 2015–2019 mean values are presented in Table 2. We have indicated on this table when the 2020 mean value is also lower than the mean values of all individual previous years, which we consider as our significant reductions. Table S3 presents the same analysis for the pre-SOE period. $PM_{2.5}$ demonstrates significantly below average concentrations at four monitors, which range from 0.4 μg/m^3 to 1.2 μg/m^3 reductions. One monitor was significantly lower for $PM_{2.5}$ in the pre-SOE period, which was the Sault Ste. Marie monitor that was not significantly lower in the SOE period. Many monitors demonstrated above average conditions for $PM_{2.5}$ during the SOE period. NO_2 concentrations during the SOE were at or below average conditions for all except one monitor (Toronto Downtown). Twenty-two of the NO_2 monitors were showing their lowest concentrations during this period; however, six of those monitors were also at their lowest concentrations during the pre-SOE period but with a smaller reduction. NO_X concentrations were

Table 1
Descriptive statistics of Ontario air pollution observations for weeks 1–17 in 2015–2020.

Pollutant	5th Percentile	Median	Mean	95th Percentile	Max
Fine Particulate Matter (μg/m^3)	1	5	7	18	76
Nitrogen Dioxide (ppb)	1	6	9	27	78
Nitrogen Oxides (ppb)	1	7	11	35	387
Ozone (ppb)	9	31	30	45	94

All minimum values were zero.

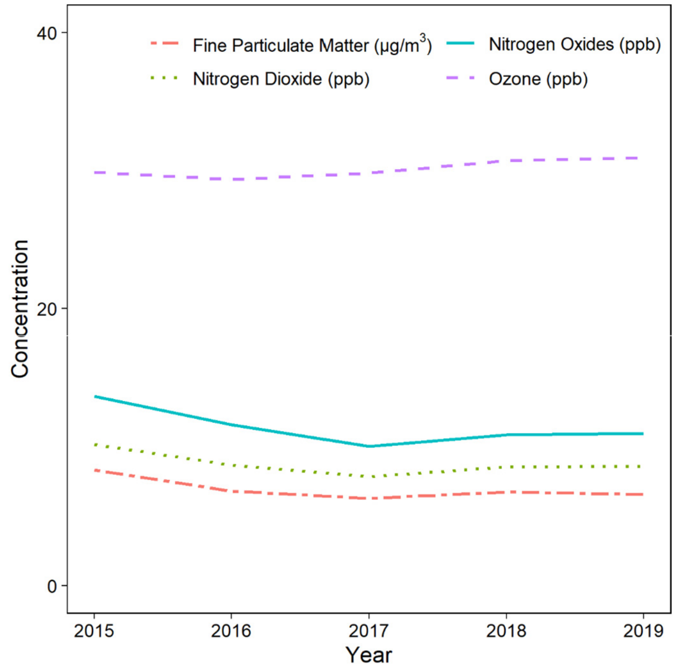

Fig. 1. Long-term temporal trends of mean air pollution for weeks 1–17 across Ontario.

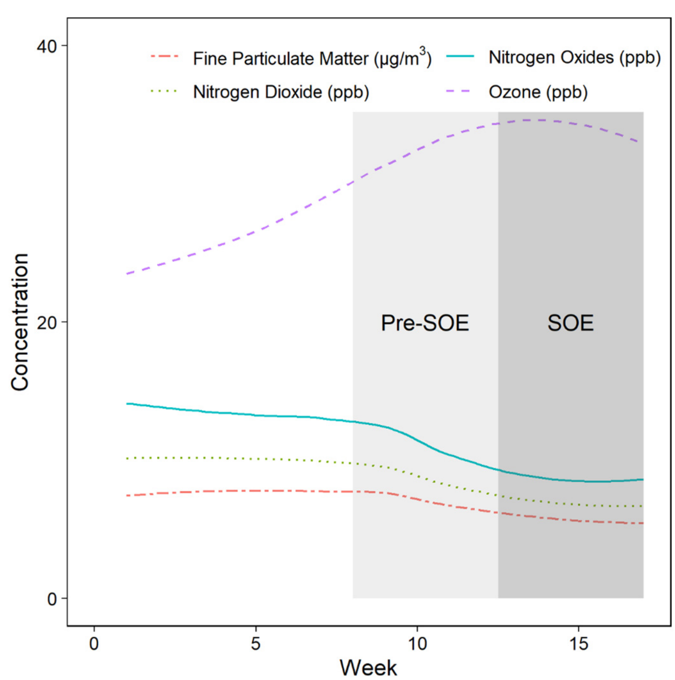

Fig. 2. Weekly mean trends for years 2015–2019 across Ontario.

Table 2
Change in mean air quality during the SOE. If mean air quality is the lowest during 2020 since any year between 2015 and 2019, the reduction to the previous minimum annual value is presented in brackets.

Station name	$PM_{2.5}$ (μg/m^3)		NO_2 (ppb)		NO_X (ppb)		O_3 (ppb)	
	SOE	Reduction	SOE	Reduction	SOE	Reduction	SOE	Reduction
Cornwall	−0.2		0.4		0.4		2.2	(0.8)[a]
Ottawa Downtown	−0.4		1.2	(0.6)[a]	1.6	(1.2)[a]	1	
Kingston	0.5	(0.2)[a]	0.7		0.7	(0.1)	0.8	
Belleville	−0.3		0.9	(0.3)[a]	1	(0.1)[a]	1	
Petawawa [R]	−0.2		NA		NA		0.8	
Peterborough	0.1		0.7	(0.5)[a]	0.6	(0.3)[a]	3.3	(1.8)[a]
Dorset	−0.3		NA		NA		2.7	(0.7)[a]
Toronto East	0.3		4.5	(2.4)	6.5	(4)	−1.3	
Toronto Downtown	0.1		−1		−4.9		3.5	(2.5)[a]
North Bay	0.3		1.3	(0.3)[a]	1.6	(0.3)[a]	0.6	
Newmarket	0.1		1.8	(1.1)[a]	2.8	(1.7)	2.2	(1.4)[a]
Toronto West	0.2		4.2	(1.8)	7.1	(3.1)	−1.5	
Mississauga	0.3		2.1	(0.9)[a]	3	(0.6)[a]	1	
Oakville	1.2	(0.3)[a]	2.3	(1)	3.1	(1.4)	1.2	
Barrie	−1.2		1.3	(0.3)[a]	2.5	(0.7)[a]	1.7	(0.6)[a]
Burlington	1	(0.1)[a]	2	(0.4)[a]	2.3		−0.5	
Hamilton Downtown	0.7		4	(3.1)	5.9	(4.4)	0.5	
Hamilton West	0.7		3.1	(0.4)	4.4	(0.2)	−0.6	
Parry Sound	0.4		0.4	(0.1)[a]	0.6	(0.2)[a]	0.8	
Guelph	0		1.7	(0.9)[a]	2.1	(1.1)[a]	2.5	(0.7)
Brantford	0.6		0.9		1.5	(0.1)[a]	1.5	(0.6)[a]
Kitchener	0.2		1.5	(0.3)[a]	1.9	(0.4)[a]	2.9	(2)[a]
Sudbury	0.2		0		0.3		0.6	
Port Stanley [R]	0.2		0.5	(0.3)[a]	0.5	(0.3)[a]	3.7	(1.7)
London	0.4	(0.2)[a]	1.6	(1.3)[a]	1.7	(1.3)[a]	1	
Tiverton [R]	−0.5		NA		NA		3.3	(1.9)
Grand Bend [R]	0.7		0.6	(0.1)[a]	0.5		1.2	
Chatham	0.1		1.1		1.4		1.7	
Windsor Downtown	0.5		2.1	(1)	2.9	(1.4)	1.8	
Windsor West	−1.8		1.4	(0.3)[a]	2	(0.4)	4.2	(1)
Sault Ste. Marie	−0.1		0.5		0.6		2.2	
Thunder Bay	0		2.1	(1)[a]	3.7	(1.7)[a]	2.5	

[R] indicates monitor is in a rural location. Negative values indicate mean concentrations above the five-year mean.
[a] Not significantly lower during the pre-SOE period.

like NO_2, with one monitor demonstrating above average conditions and 22 monitors showing significantly lower SOE concentrations (9 of those were significantly lower during the pre-SOE period). Twelve O_3 monitors were significantly lower during the SOE, but four of those were also significantly lower during the pre-SOE period. Four O_3 monitors were higher than average during the SOE. Overall, four $PM_{2.5}$ monitors, 16 NO_2 monitors, 13 NO_X monitors and 8 O_3 monitors are demonstrating their lowest concentrations since 2015, which were not significantly lower during the pre-SOE period.

4. Discussion

Our analysis was conducted using ground-level air pollution observations, which differs from other COVID-19 related air pollution studies that have applied modelling approaches (Wang et al., 2020) or atmospheric column estimates from remote sensing systems (Dutheil et al., 2020). This provides a benefit as the concentration data we examine are measured at or near breathing height; however, it limits the spatial density of our analysis. We must assume that the site selection of monitors is representative of local conditions (city scale). The monitors we analyzed are used for assessing the state of Ontario's air quality (Ontario Ministry of the Environment and Climate Change, 2016), which suggests they should be suitable for regional conditions.

We did not observe significant changes in $PM_{2.5}$ concentrations. This is not unexpected in this region because of the source profile. Dabek-zlotorzynska et al. (2019) characterized the sources of $PM_{2.5}$ air pollution at two monitoring locations within Toronto (largest city by population in Canada), one adjacent to a major highway (365,000–411,600 vehicles daily) and another at an urban road street canyon (15,000–26,000 vehicles daily). In those transportation dominated environments, they found that transportation related $PM_{2.5}$ was only responsible for 27.2% (major highway) and 14.9% (street canyon) of the observed concentrations. These transportation related portions are what we would have expected to be affected by the SOE, and likely decrease further from the source. The most recent Air Quality in Ontario report estimates 56% of Ontario's $PM_{2.5}$ emissions are residential sources (Ontario Ministry of the Environment and Climate Change, 2016). Given the 28% increase in time at home during the SOE, residential emissions are likely to increase and offset any vehicle emission reductions, for example, increased outdoor cooking using barbeques.

Nitrogen dioxide and NO_X both demonstrated many monitors at their lowest concentrations during the SOE period, compared to the previous five years. Wang et al. (2018) using the same monitoring locations as Dabek-zlotorzynska et al. (2019) identified that local contributions from vehicle emissions were much greater for NO_X, where 69% (urban street canyon) and 75% (major highway) of NO_X pollution was attributable to local transportation sources. Ontario emissions from the transportation sector for NO_X are estimated at 69% of total emissions. It is worthwhile to note that during the SOE period for all six years in Ontario that NO_2 composed 7 ppb of the 9 ppb NO_X average. Given, the consistent reductions in NO_2 and NO_X, and transportation as a major source across the region, it is reasonable to expect at least a portion of the observed reductions to be attributable to the SOE and subsequent changes in economic and commuting behaviours.

The Toronto Downtown monitor's NO_X concentrations are not responding similarly to the two other monitors in Toronto, which is a station located in the downtown core. Observations during the pre-SOE period were also higher than average, which suggests other local factors are affecting concentrations at this monitor. The Toronto Downtown monitor is a roadside site located 10 m above the ground, which is much lower than the surrounding buildings. There may be a change in local sources, such as increased traffic or construction activities that could be responsible for this increase. This suggest this station may not have the required temporal stationarity to be suitable for our analysis approach.

The evidence for the change in O_3 attributable to the SOE is less clear compared to NO_2 and NO_X. As O_3 is not directly emitted but is produced in the presence of NO_X, volatile organic compounds (VOCs) and solar radiation, there is an interplay beyond emissions only. The dependence on meteorology is similar to the findings from Wang et al. (2020) where $PM_{2.5}$ concentrations were not reduced as much as the emissions during COVID-19 responses. In Ontario, it is estimated that the transportation sector emits 28% of VOCs, which should be reduced by the SOE. As well, industrial processing (15% of Ontario emissions) and general solvent use (26% of Ontario emissions) (Ontario Ministry of the Environment and Climate Change, 2016), may have possibly seen a reduction. The pre-SOE period for O_3 is inconsistent, some stations have demonstrated their lowest concentrations in the previous five years, which makes it more challenging to identify if meteorology or changes in emission sources in this current year are responsible for observed variations. The evidence of many monitors at their lowest concentrations within the last six years, and most being below average, suggests the effects from the SOE are reducing O_3 concentrations. The evidence is not as clear as NO_2 and NO_X, but there is a reasonable mechanism, which is the reduction of precursor pollutants. If the SOE continues through the summer, it will be useful to revisit this portion of the analysis as urban areas reach their annual peak concentrations.

Our results suggest for this region a simple comparison of pre-SOE conditions with SOE conditions may not be an appropriate approach for assessing change in air pollution due to COVID-19 restrictions. Seasonality of O_3 is affected by meteorology, emissions of precursors and location (Vingarzan and Taylor, 2003). Areas consisting primarily of background O_3 typically undergo peak O_3 concentrations in Spring (Vingarzan, 2004), while areas with anthropogenic emissions of primary pollutants observe summer-time maximums (Vingarzan and Taylor, 2003). This effect is suggested in our analysis where O_3 concentrations were trending upwards as Ontario moves from winter to spring. In contrast, we observed decreasing trends in NO_2/NO_X over this same period. Our approach has attempted to overcome the issue of seasonality by comparing to historic concentrations; however, we are susceptible to monitoring stations where air quality is not temporally stationary during this period. Our analysis indicated general year-to-year temporal stability, but some potential outliers exist, such as the Toronto Downtown monitor that showed above average conditions of NO_X for both the pre-SOE and SOE periods.

5. Conclusions

The air pollutants investigated did not respond equally across Ontario during the SOE. Pollutants with source profiles that are dominated by transportation emissions showed clear reductions, which included both NO_2 and NO_X. The evidence for a reduction in O_3 is weaker, but there is some suggestion due to the reductions of precursor transportation related pollutants. No reductions occurred for $PM_{2.5}$ that could be attributed to the COVID-19 SOE in Ontario.

Future research will need to explore if the changes in air pollution translate into reductions in health effects for the Ontario population. Additionally, as the mobility analysis research grows it will be valuable to compare local and regional changes in air quality with refined estimates of goods movements and personal mobility. When the province transitions out of the SOE it will be important to examine if changes in air quality are lasting or were only temporary. Policy implications are challenging to identify at this current stage until further research can determine connections between specific behavioural and economic shifts and air quality; however, this period is likely to serve as an example of where and how air pollution can respond due to changes in mobility and economic output. This example can be drawn upon to support scenario planning for the continued electrification of vehicles, public transportation planning and goods movement policies.

CRediT authorship contribution statement

Matthew D. Adams: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.140516.

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