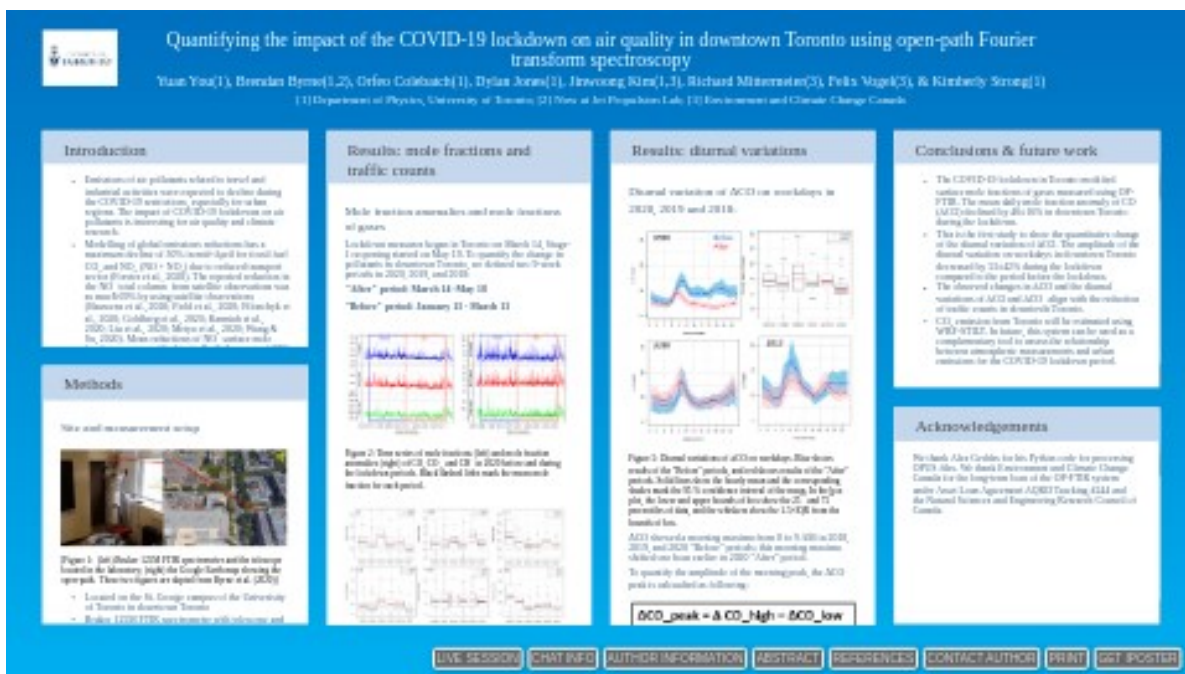


Quantifying the impact of the COVID-19 lockdown on air quality in downtown Toronto using open-path Fourier transform spectroscopy



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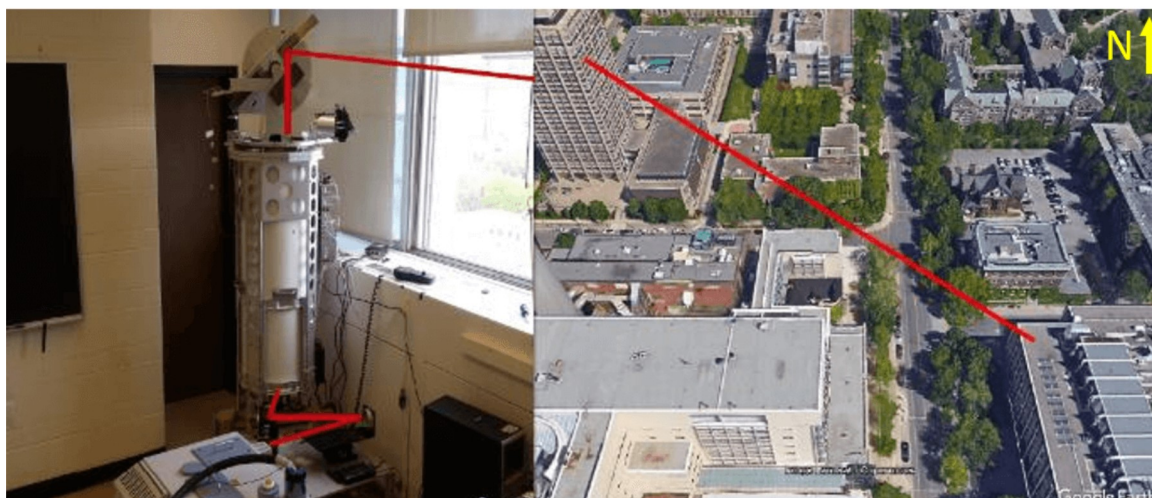


INTRODUCTION

- Emissions of air pollutants related to travel and industrial activities were expected to decline during the COVID-19 restrictions, especially for urban regions. The impact of COVID-19 lockdowns on air pollutants is interesting for air quality and climate research.
- Modelling of global emissions reductions has a maximum decline of 30% in mid-April for fossil fuel CO₂ and NO_x (NO + NO₂) due to reduced transport sector (Forster et al., 2020). The reported reduction in the NO₂ total column from satellite observations was as much 69% by using satellite observations (Bauwens et al., 2020; Field et al., 2020; Filonchyk et al., 2020; Goldberg et al., 2020; Kanniah et al., 2020; Liu et al., 2020; Metya et al., 2020; Wang & Su, 2020). Mean reductions of NO₂ surface mole fraction were quantified typically in the range of 30% to 83% by using data from ground monitoring stations (Anil & Alagha, 2020; Baldasano et al., 2020; Bedi et al., 2020; Broomandi, et al., 2020; Dantas, et al., 2020; Kerimray et al., 2020; Li et al., 2020; Mor et al., 2021; Nakada, et al., 2020; Patel et al., 2020; Ropkins & Tate, 2021; Shakoor et al., 2020; Shi & Brasseur, 2020; Singh et al., 2020; Wyche et al., 2021; Xiang et al., 2020; Yuan et al., 2021; Zalakeviciute et al., 2020; Zangari et al., 2020).
- In addition to NO_x, CO is a major air pollutant in urban regions emitted by vehicular fossil fuel combustion. Studies using satellite observations in the mid-troposphere show small or insignificant reduction of CO during the COVID-19 lockdown (Fan et al., 2020; Field et al., 2020; Filonchyk et al., 2020; Metya et al., 2020). The decline of surface CO mole fraction in urban regions was reported in range from 5% to 67% by using ground-based surface mole fraction measurements (Anil & Alagha, 2020; Bedi et al., 2020; Broomandi, et al., 2020; Dantas, et al., 2020; Kanniah et al., 2020; Kerimray et al., 2020; Li et al., 2020; Lian et al., 2020; Liu et al., 2020; Mor et al., 2021; Nakada, et al., 2020; Shakoor et al., 2020; Shi & Brasseur, 2020; Singh et al., 2020; Wyche et al., 2021; Xiang et al., 2020; Yuan et al., 2021).
- Open-path Fourier transform infrared spectroscopy (OP-FTIR) is a non-intrusive technique which can simultaneously measure multiple atmospheric trace gases in the boundary layer almost continuously. Because of this advantage, OP-FTIR has been used to monitor CO, CH₄, CO₂ and N₂O from traffic vehicular emissions and other urban sources (Griffith et al., 2018; Grutter et al., 2003; Wiacek et al., 2018; You et al., 2017).
- Toronto is the fourth largest city in North America, and over 6 million people live in Toronto region. While reductions in NO₂ vertical column density and surface concentrations of NO₂ in this region have been reported (Adams. 2020; Goldberg et al., 2020; Griffin et al., 2020), there are no published results on changes of CO, CO₂ or CH₄ in Toronto during the COVID-19 period. Therefore, the goal of this study is to quantify the mole fraction change of primary gaseous pollutants CO, CO₂, and CH₄ in downtown Toronto during the COVID-19 lockdown.

METHODS

Site and measurement setup



[Figure 1: (left) Bruker 125M FTIR spectrometer and the telescope located in the laboratory; (right) the Google Earth map showing the open-path. These two figures are adapted from Byrne et al. (2020)]

- Located on the St. George campus of the University of Toronto in downtown Toronto
- Bruker 125M FTIR spectrometer with telescope and retroreflector, two-way path length is about 320m
- Two co-located weather stations
- On going measurements since November 2017 with initial focus on CO₂, CO, CH₄ and N₂O in downtown Toronto

Retrievals

- Measurements over spectral range 1900-6000 cm⁻¹, with 0.4 cm⁻¹ resolution, coadded 40 scans over 5 min
- Ambient emission and stray light which enters the instrument are subtracted from the measured spectra
- Transmission spectra are calculated before retrieval analysis
- Trace gas mole fractions are retrieved with the MALT non-linear least squares fitting algorithm (Griffith., 1996)
- Retrieved gases and spectral windows are listed below
- Spectral line data are taken from HITRAN2016 (Gordon et al., 2017)
- The input temperature is the linear interpolation of the temperature measured near the two ends of the path
- Dry mole fractions were calculated
- Dry mole fractions of CO, CO₂ and CH₄ were calibrated with measurements from the two co-located cavity ring-down spectroscopy instruments (Byrne et al., 2020)

| Species fitted | Interfering species co-fitted | Spectral region (cm ⁻¹) |
|--|-------------------------------|-------------------------------------|
| CO ₂ , CO, N ₂ O | H ₂ O | 2141-2234.97 |
| CH ₄ | H ₂ O | 2900-3027 |
| H ₂ O, HDO | CH ₄ | 2713-2952 |

Calculating pollutants anomalies

- The 5th percentile of mole fraction of a pollutant over a 5-day running window centered at each measurement time is

taken as the background mole fraction (Ammoura et al., 2016). The mole fraction (mf) anomaly of a gas (Δ gas) from each measurement is calculated as:

$$\Delta gas = mf(gas, measured) - mf(gas, background)$$

RESULTS: MOLE FRACTIONS AND TRAFFIC COUNTS

Mole fraction anomalies and mole fractions of gases

Lockdown measures began in Toronto on March 14, Stage-1 reopening started on May 19. To quantify the change in pollutants in downtown Toronto, we defined two 9-week periods in 2020, 2019, and 2018:

"After" period: March 14 -May 18

"Before" period: January 13 - March 13

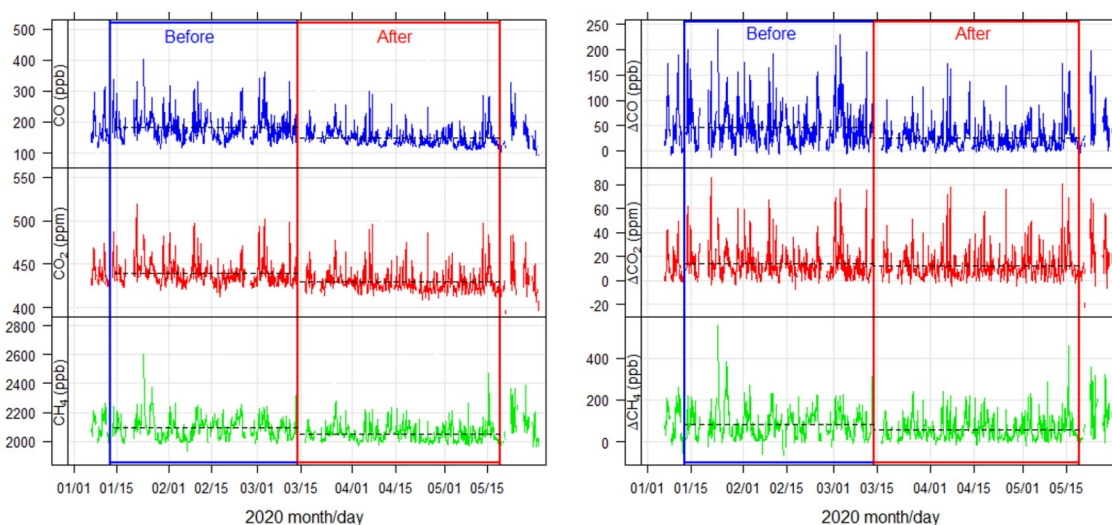


Figure 2: Time series of mole fractions (left) and mole fraction anomalies (right) of CO, CO₂, and CH₄ in 2020 before and during the lockdown periods. Black dashed lines mark the mean mole fraction for each period.

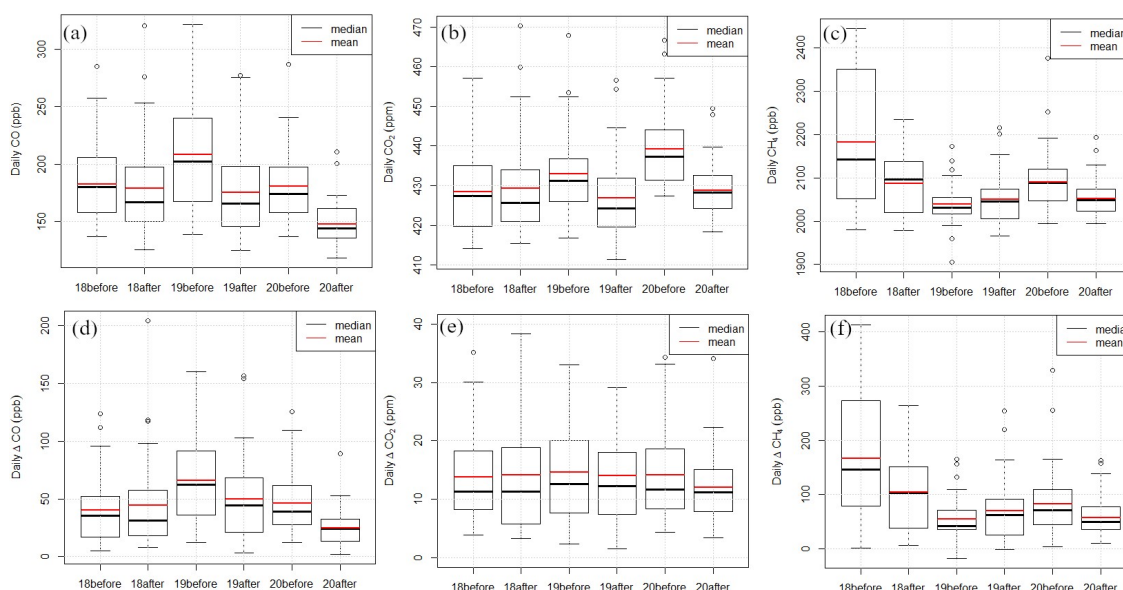


Figure 3: Daily averages of mole fractions (a-c) and mole fraction anomalies (d-f) of CO, CO₂ and CH₄. Black lines label the median, red lines label the mean. The upper and lower bounds of boxes are 25th and 75th percentiles, and whiskers are 1.5×interquartile range (IQR) from the bounds of box.

Table 1: Means of daily mole fraction anomalies and mole fractions of CO, CO₂ and CH₄ for the “before” and “after” periods in three years. Difference is the mean of the “before” period minus the mean of the “after” period. “Not significant” means the p-value of the t-test is greater than 0.05. “NA” means not applicable, since the difference is not significant. The differences and relative decreases are with 95% confidence interval.

| | 2018 | | | | 2019 | | | | 2020 | | | |
|------------------------|--------|-------|--------------------|-------------------|--------|-------|-------------------|-------------------|--------|-------|-------------------|-------------------|
| | before | after | Difference | Relative decrease | before | after | Difference | Relative decrease | before | after | Difference | Relative decrease |
| ΔCO (ppb) | 40.2 | 44.4 | Not significant | NA | 65.9 | 49.8 | 16.1 (1.5, 30.6) | 24 ± 23% | 46.0 | 24.9 | 21.1 (13.8, 28.4) | 46 ± 16% |
| CO (ppb) | 182 | 179 | Not significant | NA | 208 | 176 | 32.5 (15.4, 49.7) | 16 ± 8% | 181 | 148 | 32.6 (23.8, 41.5) | 18 ± 5% |
| ΔCO ₂ (ppm) | 13.8 | 14.1 | Not significant | NA | 14.6 | 14.1 | Not significant | NA | 14.2 | 12 | Not significant | NA |
| CO ₂ (ppm) | 429 | 429 | Not significant | NA | 433 | 427 | 6.1 (2.1, 10.3) | 1.4 ± 0.9% | 439 | 429 | 10.5 (7.5, 13.3) | 2.4 ± 0.7% |
| ΔCH ₄ (ppb) | 166.5 | 104.4 | 62.1 (21.7, 102.4) | 37 ± 24% | 54.9 | 69.9 | Not significant | NA | 82.3 | 57.6 | 24.7 (7.7, 41.6) | 30 ± 21% |
| CH ₄ (ppb) | 2182 | 2088 | 94.4 (44.3, 144.5) | 4.3 ± 2.2% | 2039 | 2050 | Not significant | NA | 2091 | 2051 | 39.3 (19.9, 58.6) | 1.9 ± 0.9% |

- The mean daily ΔCO for the “After” period (during the lockdown) declined by 46±16% compared to the mean of the “Before” period in 2020, while the CO mole fraction declined by 18±5%. In 2019 the mean daily ΔCO showed a smaller decline (by 24±23%) compared to the “Before” period; while in 2018 the mean daily ΔCO and CO mole fraction were statistically the same during the “Before” and the “After” periods.
- There is no significant difference in mean daily ΔCO₂ for the six periods considered. This result is expected given the long atmospheric lifetime of CO₂ and other significant local sources beside traffic.
- Mean daily ΔCH₄ during the lockdown in 2020 declined by 25 ppb (30±21%) compared to the “Before” period in 2020. The variability in CH₄ between periods and years is likely be influenced by the steam plant on the southwest near the site (Byrne et al., 2020).

Traffic counts in 2020

The Don Valley Parkway (DVP) and the Gardiner Expressway are two major expressways in Toronto. Here, hourly traffic counts along one of the expressways crossing three major roads in downtown are analyzed to quantify the change in traffic volume during the lockdown.

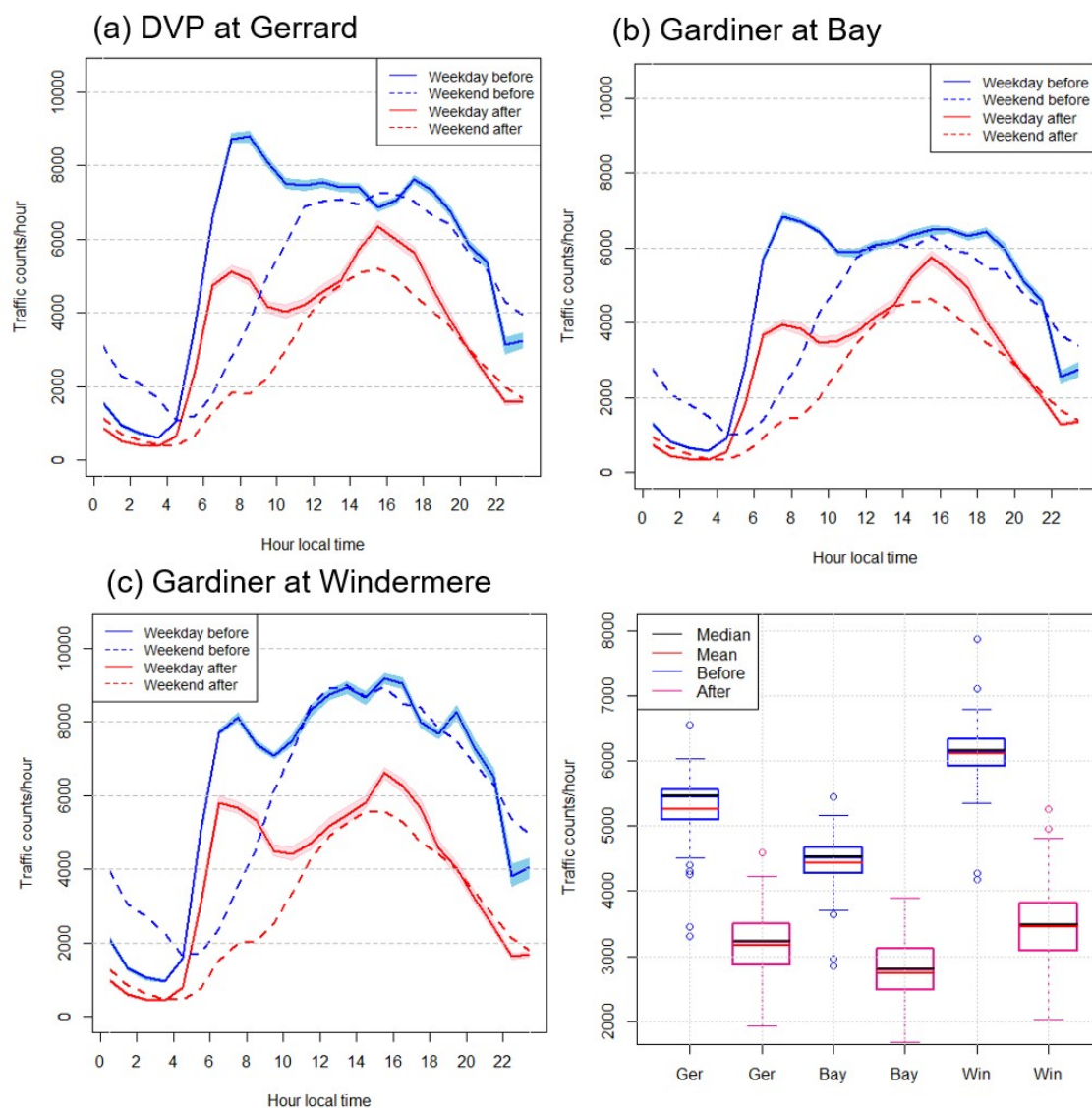


Figure 4: Diurnal variations of traffic counts in 2020 along the Don Valley Parkway or the Gardiner Expressway in downtown Toronto crossing (a) Gerrard Street, (b) Bay Street, and (c) Windermere Avenue. Solid lines show the hourly mean; the corresponding shades mark the 95 % confidence interval of the mean. (d) Mean daily traffic counts per hour of the "Before" and the "After" periods comparison at intersections of the Gerrard Street ("Ger"), the Bay Street, and the Windermere Avenue ("Win"). The lower and upper bounds of box show the 25th and 75th percentiles of data, and the whiskers show the 1.5× IQR from the bounds of box.

| DVP or Gardiner crossing | Before | | After | | After compared to Before | |
|--------------------------------|----------|-------------|----------|-------------|--------------------------|----------------------|
| | wday 7am | weekend max | wday 7am | weekend max | weekday _7am drop(%) | weekend_max drop (%) |
| Bay | 6853 | 6317.7 | 3959.9 | 4643.5 | 42 | 27 |
| Gerrard | 8732.1 | 7265.1 | 5134.2 | 5202.5 | 41 | 28 |
| Windermere | 8128.5 | 8990.1 | 5670.3 | 5601 | 30 | 38 |

- There is a reduction of 30% to 42% in traffic counts from 7 to 8 AM on weekdays during the lockdown compared to the "Before" period
- On weekends, maxima in the traffic counts occur in the afternoon and these also declined by 27% to 38%, crossing the three roads

- The observed decline of ΔCO aligns with the reduction of traffic counts

RESULTS: DIURNAL VARIATIONS

Diurnal variation of ΔCO on weekdays in 2020, 2019 and 2018:

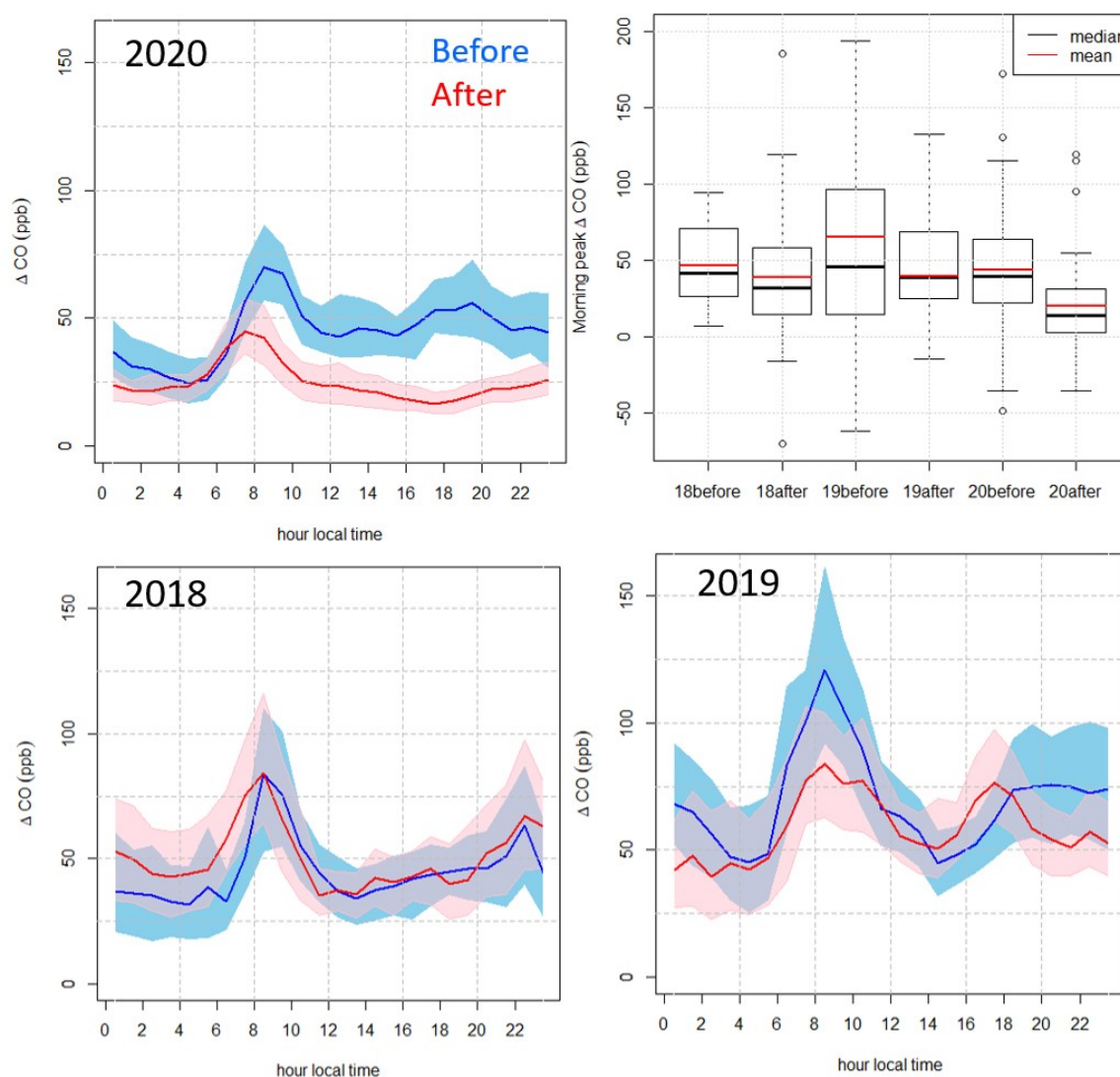


Figure 5: Diurnal variations of ΔCO on weekdays. Blue shows results of the "Before" periods, and red shows results of the "After" periods. Solid lines show the hourly mean and the corresponding shades mark the 95 % confidence interval of the mean. In the box plot, the lower and upper bounds of box show the 25th and 75th percentiles of data, and the whiskers show the 1.5×IQR from the bounds of box.

ΔCO showed a morning maxima from 8 to 9 AM in 2018, 2019, and 2020 "Before" periods; this morning maxima shifted one hour earlier in 2020 "After" period.

To quantify the amplitude of the morning peak, the ΔCO peak is calculated as following:

$$\Delta\text{CO}_{\text{peak}} = \Delta\text{CO}_{\text{high}} - \Delta\text{CO}_{\text{low}}$$

$\Delta\text{CO}_{\text{high}}$ = average from 8 to 9 am

$\Delta\text{CO}_{\text{low}}$ = average from 3 to 6 am

Except for 2020 after lockdown

$\Delta\text{CO}_{\text{high}}$ = average from 7 to 8 am

$\Delta\text{CO}_{\text{low}}$ = average from 3 to 6 am

Statistics of changes of mean ΔCO peak between the "Before" and the "After" periods :

| | 2018 | 2019 | 2020 |
|--------------------------------------|------|------|-------------------------|
| Peak(Before) – Peak (After) (ppb) | 7.5 | 25.3 | 23.3± 18.1 (53±42%) |
| t-test p value | 0.53 | 0.18 | 0.013 |
| 95% confidence | not | not | significant |

Only in 2020 is the change in the ΔCO peak between the "Before" and the "After" periods significant. This is consistent with the reduction in local traffic during the lockdown.

Diurnal variation of ΔCO_2 :

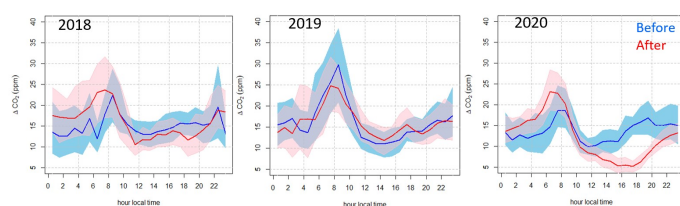


Figure 6: Diurnal variations of ΔCO_2 on weekdays. Blue shows results of the "Before" periods, and red shows results of the "After" periods. Solid lines show the hourly mean and the corresponding shades mark the 95 % confidence interval of the mean.

- In 2020, ΔCO_2 in the early afternoon is the lowest amongst these six periods examined and is different than that in the early afternoon during the "Before" period.
- Biogenic uptake of CO_2 (Sargent et al., 2018) can be observed in the afternoon during the lockdown, due to less anthropogenic CO_2 emissions compared to previous years.

CONCLUSIONS & FUTURE WORK

- The COVID-19 lockdown in Toronto modified surface mole fractions of gases measured using OP-FTIR. The mean daily mole fraction anomaly of CO (ΔCO) declined by $46\pm 16\%$ in downtown Toronto during the lockdown.
- This is the first study to show the quantitative change of the diurnal variation of ΔCO . The amplitude of the diurnal variation on weekdays in downtown Toronto decreased by $53\pm 42\%$ during the lockdown compared to the period before the lockdown.
- The observed changes in ΔCO and the diurnal variations of ΔCO and ΔCO_2 align with the reduction of traffic counts in downtown Toronto.
- CO_2 emission from Toronto will be estimated using WRF-STILT. In future, this system can be used as a complementary tool to assess the relationship between atmospheric measurements and urban emissions for the COVID-19 lockdown period.

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AUTHOR INFORMATION

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ABSTRACT

During the global COVID-19 pandemic, anthropogenic emissions of air pollutants and greenhouse gases, especially traffic emissions in urban areas, have declined significantly. Long-term measurements of trace gas concentrations in urban areas can be used to quantify the impact of emission reductions on local air quality. Open-path Fourier transform infrared (OP-FTIR) spectroscopy is a non-intrusive technique that can be used to simultaneously measure multiple atmospheric trace gases in the boundary layer. This study investigates the reduction of surface CO, CO₂, and CH₄ mole fractions during the lockdown in downtown Toronto, Canada, which is the fourth largest city in North America. The mean daily CO mole fraction anomaly (ΔCO) for the period from March 14 to May 18, 2020 declined by $46 \pm 16\%$ compared to the period before lockdown from January 13 to March 13, 2020. The mean daily ΔCO during the lockdown also declined relative to the same period in previous years: by $50 \pm 20\%$ relative to 2019 and by $44 \pm 25\%$ relative to 2018. Changes in the diurnal variations of CO, CO₂ and CH₄ during the lockdown are also investigated and compared to 2019 and 2018. Both CO and CO₂ show early morning maxima on weekdays corresponding to rush hour. The change of the amplitude of the diurnal variation in CO during the lockdown is significant, compared to the period before lockdown. The differences in the diurnal variation in CO during the same two periods in 2019 and 2018 are not significant. Ratios of CO/CO₂ anomalies show seasonal variations, which are also likely due to seasonal changes of emissions from local sources. These results show that the COVID-19 lockdown in Toronto modified surface mole fractions, diurnal variations, and ratios of air pollutants monitored by OP-FTIR. In addition, measured CO₂ mole fractions are compared with simulated CO₂ mole fractions by WRF-STILT to assess the relationship between atmospheric measurements and urban emissions from Toronto.

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