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

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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 ($\Delta$CO) 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 $\Delta$CO 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 CO mole fractions are compared with simulated CO mole fractions by WRF-STILT to assess the relationship between atmospheric measurements and urban emissions from Toronto.

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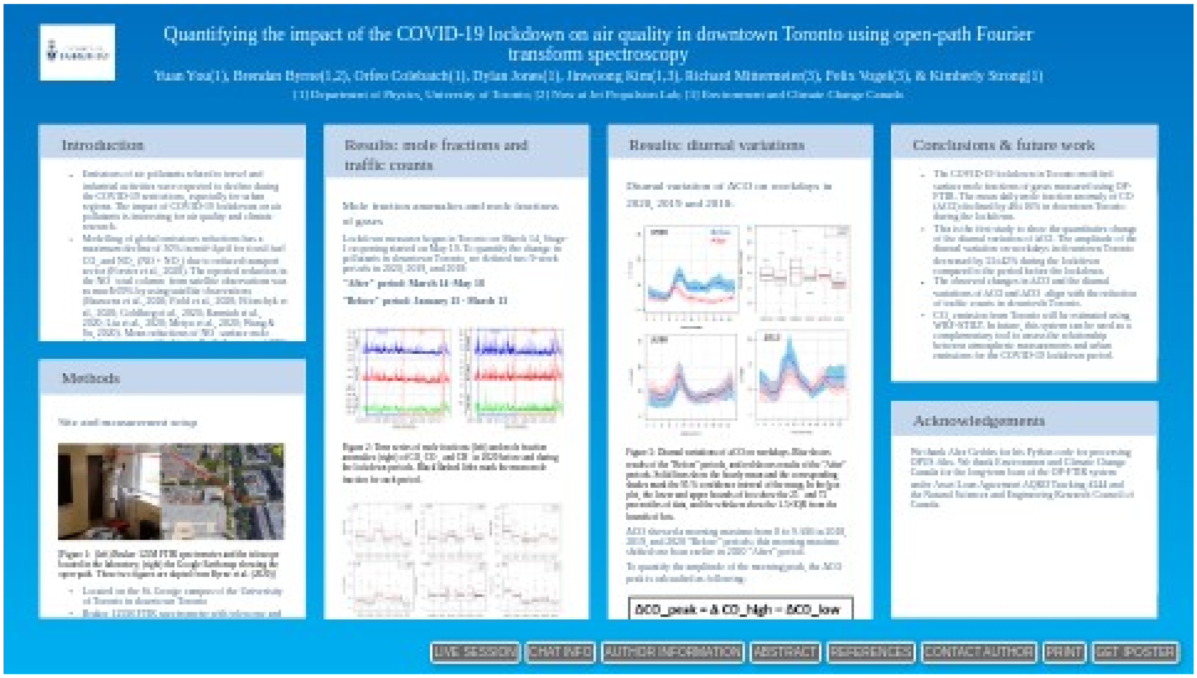


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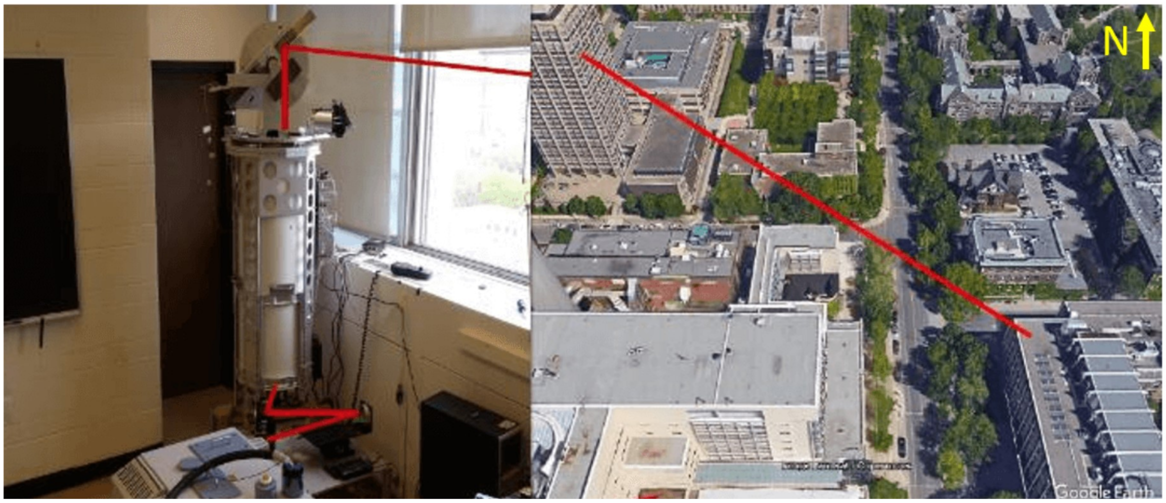
PRESENTED AT:

# 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 $CO_2$ and $NO_x$ (NO + $NO_2$) due to reduced transport sector (Forster et al., 2020). The reported reduction in the $NO_2$ 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 $NO_2$ 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, $CH_4$, $CO_2$ and $N_2O$ 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 $NO_2$ vertical column density and surface concentrations of $NO_2$ 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, $CO_2$ or $CH_4$ 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, $CO_2$, and $CH_4$ 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 dapted from Byrne et al. (2020)]

- Located on the St. George campus of the Univerisity 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 $CO_2$, CO, $CH_4$ and $N_2O$ 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, $CO_2$ and $CH_4$ 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, $N_2O$ | $H_2O$ | 2141-2234.97 |
| $CH_4$ | $H_2O$ | 2900-3027 |
| $H_2O$, 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 a., 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**

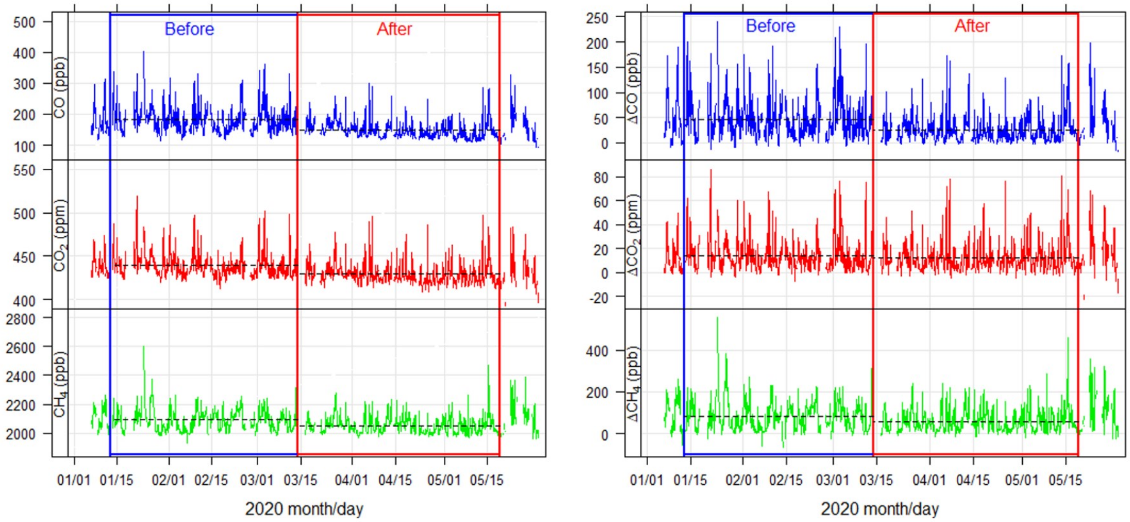



Figure 2: Time series of mole fractions (left) and mole fraction anomalies (right) of CO, $CO_2$, and $CH_4$ in 2020 before and during the lockdown periods. Black dashed lines mark the mean mole fraction for each period.

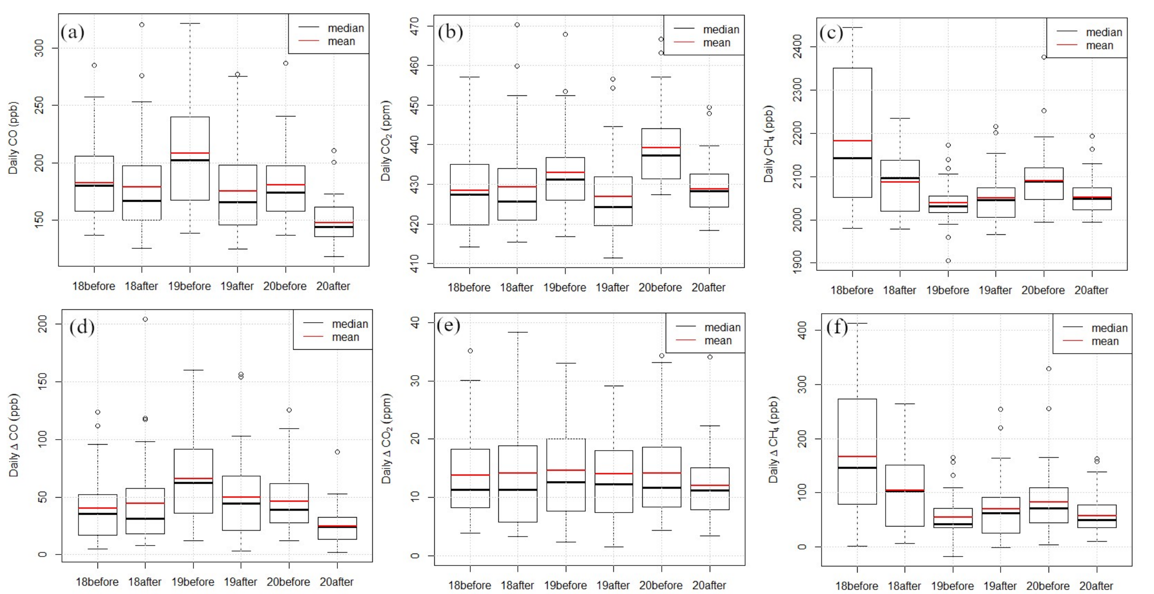



Figure 3: Daily averages of mole fractions (a-c) and mole fraction anomalies (d-f) of CO, $CO_2$ and $CH_4$. Black lines label the median, red lines label the mean. The upper and lower bounds of boxes are 25th and 75th percentiles, and whiskers are 1.5×interquartile range (IQR) from the bounds of box.

Table 1: Means of daily mole fraction anomalies and mole fractions of CO, $CO_2$ and $CH_4$ 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% |
| $\Delta CO_2$ (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% |
| $\Delta CH_4$ (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 $\Delta CO_2$ for the six periods considered. This result is expected given the long atmospheric lifetime of $CO_2$ and other significant local sources beside traffic.
- Mean daily $\Delta CH_4$ during the lockdown in 2020 declined by 25 ppb (30±21%) compared to the "Before" period in 2020. The variability in $CH_4$ 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.

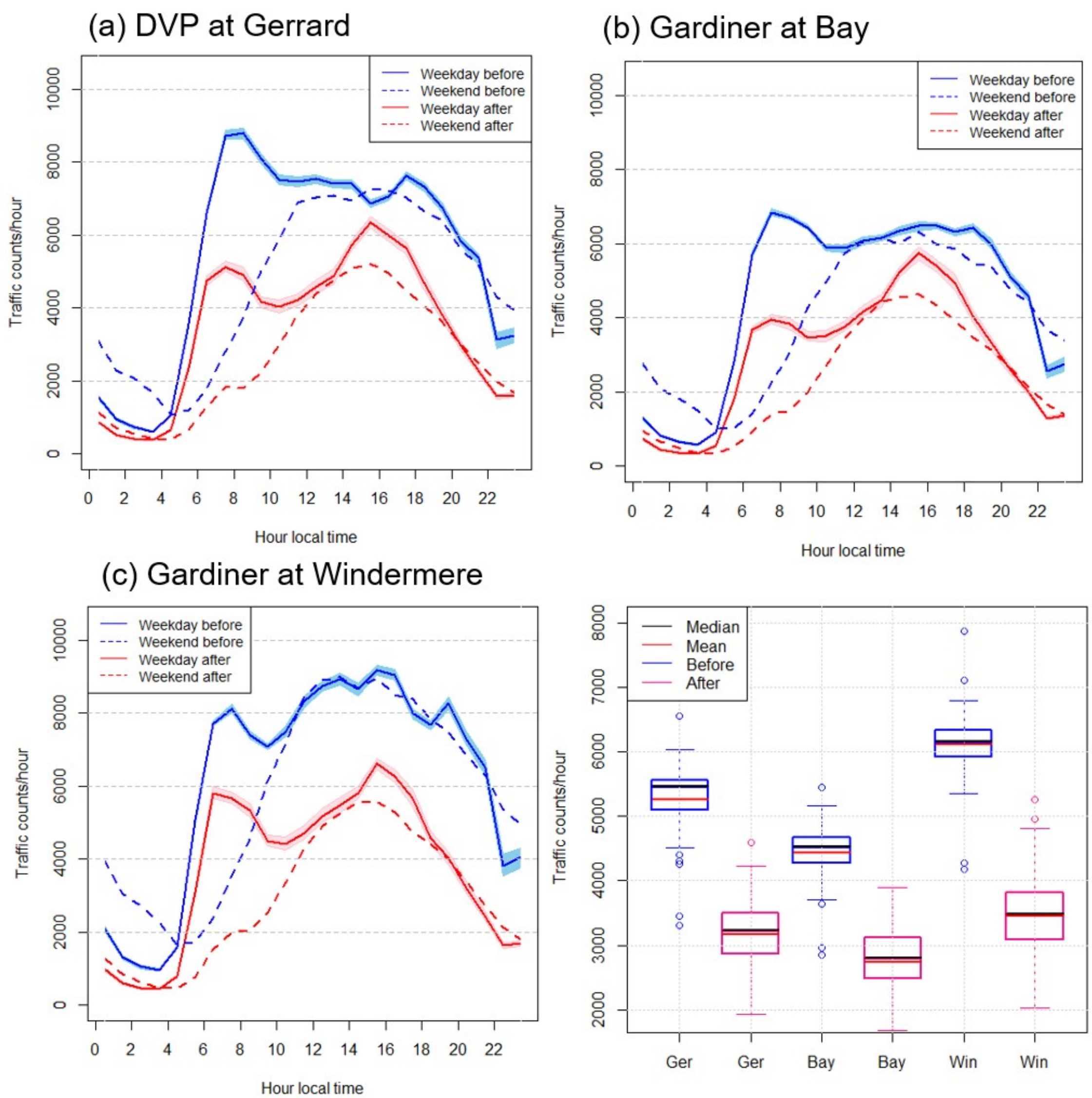



Figure 4: Diurnal variations of traffic counts in 2020 along the Don Valley Parkway or the Gardiner Expressway in downtown Toronto crossing (a) Gerrard Street, (b) Bay Street, and (c) Windermere Avenue. Solid lines show the hourly mean; the corresponding shades mark the 95 % confidence interval of the 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 25$^{th}$ and 75$^{th}$ percentiles of data, and the whiskers show the 1.5× IQR from the bounds of box.

| | Before | | After | | After compared to Before | |
|---|---|---|---|---|---|---|
| DVP or Gardiner crossing | 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:

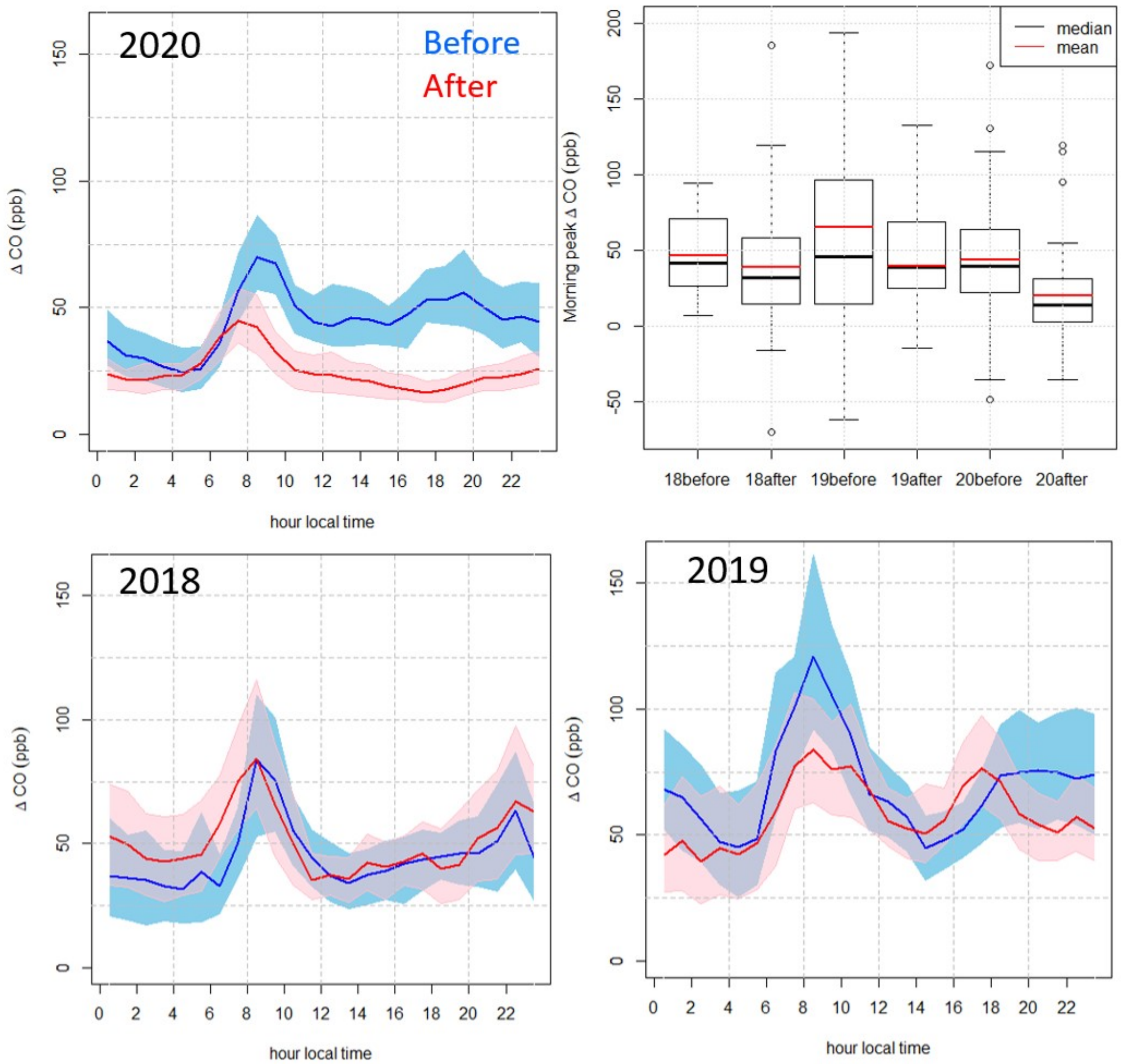



Figure 5: Diurnal variations of ΔCO on weekdays. Blue shows results of the "Before" periods, and red shows results of the "After" periods. Solid lines show the hourly mean and the corresponding shades mark the 95 % confidence interval of the mean. In the box plot, the lower and upper bounds of box show the 25$^{th}$ and 75$^{th}$ 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 calcualted as following:

**ΔCO_peak = Δ CO_high – ΔCO_low**
ΔCO_high = average from 8 to 9 am
ΔCO_low = average from 3 to 6 am

Except for 2020 after lockdown
ΔCO_high = average from 7 to 8 am
ΔCO_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 $\Delta CO_2$:

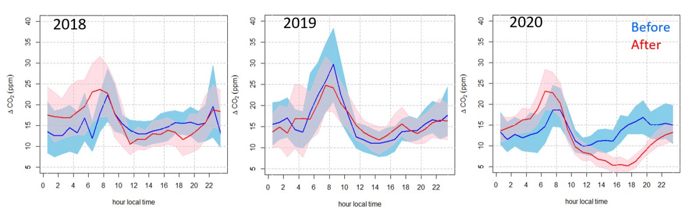



Figure 6: Diurnal variations of $\Delta CO_2$ on weekdays. Blue shows results of the "Before" periods, and red shows results of the "After" periods. Solid lines show the hourly mean and the corresponding shades mark the 95 % confidence interval of the mean.

- In 2020, $\Delta CO_2$ 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±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±42% during the lockdown compared to the period before the lockdown.
- The observed changes in ΔCO and the diurnal variations of ΔCO and $\Delta CO_2$ 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.

# ACKNOWLEDGEMENTS

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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, $CO_2$, and $CH_4$ 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 ($\Delta$CO) for the period from March 14 to May 18, 2020 declined by 46 ± 16% compared to the period before lockdown from January 13 to March 13, 2020. The mean daily $\Delta$CO during the lockdown also declined relative to the same period in previous years: by 50 ± 20% relative to 2019 and by 44 ± 25% relative to 2018. Changes in the diurnal variations of CO, $CO_2$ and $CH_4$ during the lockdown are also investigated and compared to 2019 and 2018. Both CO and $CO_2$ 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/$CO_2$ 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 $CO_2$ mole fractions are compared with simulated $CO_2$ mole fractions by WRF-STILT to assess the relationship between atmospheric measurements and urban emissions from Toronto.

# REFERENCES


Adams, M. (2020). Air pollution in Ontario, Canada during the COVID-19 state of emergency.Science of the Total Environment,742.doi: 10.1016/j.scitotenv342.2020.140516

Ammoura, L., Xueref-Remy, I., Vogel, F., Gros, V., Baudic, A., Bonsang, B., . . . Chevallier, F.(2016). Exploiting stagnant conditions to derive robust emission ratio estimates for $CO_2$, CO and volatile organic compounds in Paris. Atmospheric Chemistry and Physics,16(24), 15653-15664.doi:34110.5194/acp-16-15653-2016

Anil, I., & Alagha, O. (2020). The impact of COVID-19 lockdown on the air quality of Eastern Province, Saudi Arabia.Air Quality, Atmosphere and Health. doi:34410.1007/s11869-020-00918-3

Baldasano, J. M.(2020).COVID-19 lockdown effects on air quality by $NO_2$ in the cities of Barcelona and Madrid (Spain).Science of The Total Environment,347741, 140353. doi: https://doi.org/10.1016/j.scitotenv.2020.140353

Bauwens, M., Compernolle, S., Stavrakou, T., Möller, J.-F., van Gent, J., Eskes, H., . . Zehner, C. (2020). Impact of coronavirus outbreak on $NO_2$ pollution as-354sessed using TROPOMI and OMI observations.Geophysical Research Letters,35547(11), e2020GL087978. doi: 10.1029/2020GL087978

Bedi, J. S., Dhaka, P., Vijay, D., Aulakh, R. S., & Gill, J. P. S. (2020). Assessment of air quality changes in the four metropolitan cities of India during COVID-19 pandemic lockdown.Aerosol and Air Quality Research,20(10), 2062–2070.359doi: 10.4209/aaqr.2020.05.0209

Broomandi, P., Karaca, F., Nikfal, A., Jahanbakhshi, A., Tamjidi, M., & Kim, J. R.(2020). Impact of COVID-19 event on the air quality in Iran.Aerosol and Air Quality Research,20(8), 1793–1804. doi: 10.4209/aaqr.2020.05.0205

Byrne, B., Strong, K., Colebatch, O., You, Y., Wunch, D., Ars, S., . . . Griffith,364D. W. T.(2020).Monitoring urban greenhouse gases using open-path Fourier transform spectroscopy.Atmosphere-Ocean,58(1), 25-45. doi:36610.1080/07055900.2019.1698407

Dantas, G., Siciliano, B., Fran ̧ca, B., da Silva, C., & Arbilla, G.(2020).The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil.Science of the Total Environment,729.doi:37010.1016/j.scitotenv.2020.139085

Fan, C., Li, Y., Guang, J., Li, Z., Elnashar, A., Allam, M., & de Leeuw, G.(2020).372The impact of the control measures during the COVID-19 outbreak on air pollution in China.Remote Sensing,12(10). doi: 10.3390/rs12101613

Field, R. D., Hickman, J. E., Geogdzhayev, I. V., Tsigaridis, K., & Bauer, S. E.(2020). Changes in satellite retrievals of atmospheric composition over eastern China during the 2020 COVID-19 lockdowns. Atmospheric Chemistry and Physics Discussions, 2020, 1–31. doi: 10.5194/acp-2020-567

Filonchyk, M., Hurynovich, V., Yan, H., Gusev, A., & Shpilevskaya, N.(2020). Impact assessment of COVID-19 on variations of $SO_2$, $NO_2$, CO and AOD over east China. Aerosol and Air Quality Research,20(7), 1530-1540. doi:38110.4209/aaqr.2020.05.0226

Forster, P., Forster, H., Evans, M., Gidden, M., Jones, C., Keller, C., . . . Turnock, S.(2020). Current and future global climate impacts resulting from COVID-19. Nature Climate Change,10(10), 913-919. doi: 10.1038/s41558-020-0883-0

Goldberg, D. L., Anenberg, S.C., Griffin, D., McLinden, C. A., Lu, Z., & Streets, D.G.(2020).Disentangling the impact of the COVID-19 lockdowns on urban $NO_2$ from natural variability. Geophysical Research Letters,47(17),391e2020GL089269. doi: 10.1029/2020GL089269

Gordon, I., Rothman, L., Hill, C., Kochanov, R., Tan, Y., Bernath, P., . . . Zak, E.(2017).The HITRAN2016 molecular spectroscopic database.Journal of Quantitative Spectroscopy and Radiative Transfer,203, 3 - 69.doi:https://doi.org/10.1016 /j.jqsrt.2017.06.038

Griffin, D., McLinden, C. A., Racine J., Moran, M. D., Fioletov, V., Pavlovic, R., and Eskes, H. (2020). Assessing the impact of Corona-virus-19 on nitrogen dioxide levels over southern Ontario, Canada. Submitted to Geophysical Research Letters, https://www.essoar.org/pdfjs/10.1002/essoar.10503538.2 (https://www.essoar.org/pdfjs/10.1002/essoar.10503538.2)

Griffith, D. W. T. (1996).Synthetic calibration and quantitative analysis of gas-phase FT-IR spectra.Applied Spectroscopy,50(1), 59-70. doi: 10.1366/4040003702963906627

Griffith, D. W. T., Pohler, D., Schmitt, S., Hammer, S., Vardag, S. N., and Platt, U.(2018). Long open-path measurements of greenhouse gases in air using near-infrared Fourier transform spectroscopy. Atmospheric Measurement Techniques,11(3), 1549–1563. doi:10.5194/amt-11-1549-2018

Grutter, M., Flores, E., Basaldud, R., and Ruiz-Suarez, L. G.(2003). Open-path FTIR spectroscopic studies of the trace gases over Mexico City.Atmospheric Oceanic Optics,16(3).

Kanniah, K. D., Kamarul Zaman, N. A. F., Kaskaoutis, D. G., & Latif, M. T. (2020). COVID-19's impact on the atmospheric environment in the South- east Asia region. Science of The Total Environment,736, 139658.doi: 10.1016/j.scitotenv.2020.139658

Kerimray, A., Baimatova, N., Ibragimova, O. P., Bukenov, B., Kenessov, B., Plotitsyn, P., & Karaca, F.(2020). Assessing air quality changes in large cities during COVID-19 lockdowns: The impacts of traffic-free urban conditions in Almaty, Kazakhstan. Science of The Total Environment,730, 139179.doi: 10.1016/j.scitotenv.2020.139179

Li, L., Li, Q., Huang, L., Wang, Q., Zhu, A., Xu, J., . . . Chan, A.(2020). Air quality changes during the COVID-19 lockdown over the Yangtze River Delta Region: An insight into the impact of human activity pattern changes on air pollution variation. Science of the Total Environment,732.doi:43010.1016/j.scitotenv.2020.139282

Lian, X., Huang, J., Huang, R., Liu, C., Wang, L., & Zhang, T.(2020). Impact of city lockdown on the air quality of COVID-19-hit of Wuhan city. Science of The Total Environment,742, 140556. doi: 10.1016/j.scitotenv434.2020.140556

Liu, Q., Harris, J. T., Chiu, L. S., Sun, D., Houser, P. R., Yu, M., . . . Yang, C.(2021).Spatiotemporal impacts of COVID-19 on air pollution in California, USA.Science of The Total Environment,750, 141592.doi:10.1016/j.scitotenv.2020.141592

Metya, A., Dagupta, P., Halder, S., Chakraborty, S., & Tiwari, Y. (2020). COVID-19 lockdowns improve air quality in the South-East Asian regions, as seen by the remote sensing satellites. Aerosol and Air Quality Research,20(8),4421772-1782. doi: 10.4209/aaqr.2020.05.0240

Mor, S., Kumar, S., Singh, T., Dogra, S., Pandey, V., & Ravindra, K.(2021). Impact of COVID-19 lockdown on air quality in Chandigarh, India: Understanding the emission sources during controlled anthropogenic activities. Chemosphere,263. doi: 10.1016/j.chemosphere.2020.127978

Nakada, L. Y. K., & Urban, R. C. (2020). COVID-19 pandemic: Impacts on the air quality during the partial lockdown in Sao Paulo state, Brazil. Science of The Total Environment,730, 139087. doi: 10.1016/j.scitotenv.2020450.139087

Patel, H., Talbot, N., Salmond, J., Dirks, K., Xie, S., & Davy, P.(2020).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. Science of The Total Environment,746, 141129. doi:10.1016/455j.scitotenv.2020.141129

Ropkins, K., & Tate, J.(2021).Early observations on the impact of the COVID-19 lockdown on air quality trends across the UK. Science of the Total Environment,754. doi: 10.1016/j.scitotenv.2020.142374

Sargent, M., Barrera, Y., Nehrkorn, T., Hutyra, L. R., Gately, C. K., Jones, T., . . .Wofsy, S. C.(2018). Anthropogenic and biogenic $CO_2$ fluxes in the Boston urban region. Proceedings of the National Academy of Sciences,115(29), 4687491–7496. doi: 10.1073/pnas.1803715115

Shakoor, A., Chen, X., Farooq, T., Shahzad, U., Ashraf, F., Rehman, A., . . . Yan, W.(2020). Fluctuations in environmental pollutants and air quality during the lockdown in the USA and China: two sides of COVID-19 pandemic. Air Quality, Atmosphere and Health. doi: 10.1007/s11869-020-00888-6

Shi, X., and Brasseur, G. P.(2020). The response in air quality to the reduction of Chinese economic activities during the COVID-19 outbreak. Geophysical Research Letters,47(11), e2020GL088070. doi: 10.1029/2020GL088070

Singh, V., Singh, S., Biswal, A., Kesarkar, A., Mor, S., & Ravindra, K.(2020). Diurnal and temporal changes in air pollution during COVID-19 strict lockdown over different regions of India. Environmental Pollution, 266. doi:47910.1016/j.envpol.2020.115368

Wang, Q., and Su, M.(2020).A preliminary assessment of the impact of COVID-19 on environment – a case study of China.Science of The Total Environment,489728, 138915. doi: 10.1016/j.scitotenv.2020.138915

Wiacek, A., Li, L., Tobin, K., and Mitchell, M.(2018). Characterization of trace gas emissions at an intermediate port. Atmospheric Chemistry and Physics,49418(19), 13787–13812. doi: 10.5194/acp-18-13787-2018

Wyche, K., Nichols, M., Parfitt, H., Beckett, P., Gregg, D., Smallbone, K., & Monks, P.(2021). Changes in ambient air quality and atmospheric composition and reactivity in the South East of the UK as a result of the COVID-19 lockdown.Science of The Total Environment,755, 142526.doi:499https://doi.org/10.1016/j.scitotenv.2020.142526

Xiang, J., Austin, E., Gould, T., Larson, T., Shirai, J., Liu, Y., . . . Seto, E. (2020). Impacts of the COVID-19 responses on traffic-related air pollution in a North-western US city. Science of The Total Environment,747, 141325. doi:10.1016/j.scitotenv.2020.141325

You, Y., Staebler, R. M., Moussa, S. G., Su, Y., Munoz, T., Stroud, C., . . . Moran, M. D.(2017). Long-path measurements of pollutants and micrometeorology over Highway 401 in Toronto. Atmospheric Chemistry and Physics,17(22),50714119–14143. doi: 10.5194/acp-17-14119-2017

Yuan, Q., Qi, B., Hu, D., Wang, J., Zhang, J., Yang, H., . . . Li, W.(2021). Spatiotemporal variations and reduction of air pollutants during the COVID-19 pandemic in a megacity of Yangtze River Delta in China.Science of The Total Environment,751, 141820.doi:10.1016/512j.scitotenv.2020.141820

Zalakeviciute, R., Vasquez, R., Bayas, D., Buenano, A., Mejia, D., Zegarra, R., . . . Lamb, B. (2020). Drastic improvements in air quality in Ecuador during the COVID-19 outbreak. Aerosol and Air Quality Research,20(8), 1783–1792. doi:51610.4209/aaqr.2020.05.0254

Zangari, S., Hill, D. T., Charette, A. T., & Mirowsky, J. E.(2020). Air quality changes in New York City during the COVID-19 pandemic.Science of The Total Environment,742, 140496.doi: 10.1016/520j.scitotenv.2020.140496