Assessing the impact of Corona-virus-19 on nitrogen dioxide levels over southern Ontario, Canada

Debora Griffin[1,1], Chris McLinden[1,1], Jacinthe Racine[1,1], Michael Moran[1,1], Vitali Fioletov[1,1], Radenko Pavlovic[1,1], and Henk Eskes[2,2]

[1]Environment and Climate Change Canada
[2]Royal Netherlands Meteorological Institute (KNMI)

November 29, 2022

Abstract

A lockdown was implemented in Canada mid-March 2020 to limit the spread of COVID-19. In the wake of this, declines in nitrogen dioxide (NO2) were observed from the Tropospheric Monitoring Instrument (TROPOMI). A method is presented to quantify how much of this decrease is due to the lockdown itself as opposed to variability in meteorology and satellite sampling. The operational air quality forecast model, GEM-MACH, was used with TROPOMI to determine expected NO2 columns that represents what TROPOMI would have observed for a non-COVID scenario. Decreases in NO2 due to the lockdown were seen across southern Ontario, with an average 40% in Toronto and even larger declines in the city center. Natural and satellite sampling variability accounted for as much as 20-30%. A model run using a lockdown emissions scenario were found to be consistent with TROPOMI suggesting the prescribed declines in transportation and industry emissions are reasonable.

Assessing the impact of Corona-virus-19 on nitrogen dioxide levels over southern Ontario, Canada

Debora Griffin[1], Chris A. McLinden[1,2], Jacinthe Racine[3], Michael D. Moran[1], Vitali Fioletov[1], Radenko Pavlovic [3], Henk Eskes[4]

[1]Air Quality Research Division, Environment and Climate Change Canada, Toronto, Ontario, Canada
[2]Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, Saskatchewan, Canada
[3]Canadian Meteorological Centre Operations Division, Environment and Climate Change Canada, Dorval, Quebec, Canada
[4]Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands

Key Points:

- Satellite NO_2 observations show a rapid decline following the COVID-19 associated lockdown and decrease by roughly 40% in Toronto.
- Meteorology is important when estimating emission reductions over a short time period; in Toronto this accounts for about 20%.
- A lockdown emissions scenario with reductions in traffic, aviation, and industry emissions represents the TROPOMI NO_2 observations well.

Corresponding author: Chris McLinden, chris.mclinden@canada.ca

Abstract

A lockdown was implemented in Canada mid-March 2020 to limit the spread of COVID-19. In the wake of this, declines in nitrogen dioxide (NO_2) were observed from the Tropospheric Monitoring Instrument (TROPOMI). A method is presented to quantify how much of this decrease is due to the lockdown itself as opposed to variability in meteorology and satellite sampling. The operational air quality forecast model, GEM-MACH, was used with TROPOMI to determine expected NO_2 columns that represents what TROPOMI would have observed for a non-COVID scenario. Decreases in NO_2 due to the lockdown were seen across southern Ontario, with an average 40% in Toronto and even larger declines in the city center. Natural and satellite sampling variability accounted for as much as 20–30%. A model run using a lockdown emissions scenario were found to be consistent with TROPOMI suggesting the prescribed declines in transportation and industry emissions are reasonable.

Plain Language Summary

States of emergency were declared throughout much of the world in the wake of the outbreak of Coronavirus disease in 2019 (COVID-19), with many countries, including Canada, imposing a lockdown. Consequently, emission patterns shifted away from transportation towards residential, leading overall to a sharp decrease observed levels of nitrogen dioxide (NO_2), an air pollutant which negatively impacts human and environmental health as seen from space-based sensors. Using satellite observations of NO_2 and air quality models, and accounting for confounding factors, we estimated that NO_2 levels in the Toronto, Canada area dropped by 40 % during the lockdown and attribute this to reduced vehicle and aircraft traffic and reductions in industry.

1 Introduction

The outbreak of Coronavirus disease in late 2019 (COVID-19) reached Canada in early 2020, with the first Canadian COVID-related death reported in early March 2020. By mid-March provinces were beginning to limit the size of gatherings and initiating an overall lockdown of their populations. In Ontario, the lockdown was announced on March 16, 2020. This greatly disrupted traffic patterns, with traffic density observed to decrease by roughly 50% by early April. Travel restrictions also greatly curtailed air travel. These circumstances provided a unique and unprecedented natural experiment where emissions patterns were rapidly and drastically altered, especially in southern Ontario, home to the Greater Toronto Area (GTA), the most populous urban area in Canada. The GTA consists of the City of Toronto and four surrounding regional municipalities (see Supplement material Fig. S4) and includes many limited-access highways and expressways, rail lines, and Toronto Pearson International Airport, Canada's busiest airport. Its population in 2016 was over 6.4 million. Ultimately, the emissions changes in the GTA and the rest of southern Ontario associated with the pandemic will allow for testing and refining of emissions from different sectors, most notably those from vehicle traffic.

Nitrogen oxides ($NO_x = NO_2 + NO$) are primarily emitted during combustion processes and have adverse effects on human and environmental health: they are a key ingredient in smog, as precursors to both ozone and particulate matter, and can contribute to acid deposition. NO_x concentrations strongly correlate with local emission sources due to its short lifetime of a few hours (Valin et al., 2013; Beirle et al., 2011) and, because of the high and localized enhancements compared to background levels, NO_x is a good tracer of human activity near cities. For example, urban NO_x displays a strong weekly and diurnal cycle resulting from differences in traffic and manufacturing activity on weekends versus weekdays (Beirle et al., 2003; de Foy et al., 2016). Observed NO_2 is not merely a function of NO_x emissions; but is also a function of the local chemical environment and meteorology. For example, it is well known that NO_2 impacts its own chemical lifetime (Valin et al., 2013). Furthermore, meteorological parameters such as cloud cover, temperature, and wind speed and direction all have a strong effect on local NO_2 enhancements. Given this temporal and spatial variability in NO_2, precisely where and when observations are made is also very important. Taken together, one important challenge when interpreting changes in NO_2 lies in disentangling potential changes in emissions from natural and sampling variability.

Satellite observations can help to identify NO_x emissions and their variation globally. Declines of NO_2 emissions, following the lockdown, have previously been observed by satellite instruments in China, India, Europe and North America (Zhang et al., 2020; Bauwens et al., 2020; Shi & Brasseur, 2020). In this study, observations from the European Space Agency's Sentinel-5p Tropospheric Monitoring Instrument (TROPOMI), in conjunction forecasts from Environment and Climate Change Canada's (ECCC's) operation regional air quality forecast model GEM-MACH (Global Environmental Multi-scale – Modelling Air quality and CHemistry) (Moran et al., 2010; Pendlebury et al., 2018), are used to isolate the impact of the COVID associated lockdown on NO_2 levels in southern Ontario, Canada. With the combination of satellite observations and model output it is possible to determine the impact of meteorology and sampling variability on the observed NO_2 column changes. The air quality model is further used to determine how possible lockdown-associated emission reductions impact the NO_2 columns, and whether those match the observed changes.

2 Methodology

In the context of satellite remote sensing, one method, and the most straightforward, to assess the impact of the COVID lockdown on NO_2 is to directly compare the COVID period with a non-COVID period, perhaps using the same period from different years (Bauwens et al., 2020). However, in order to completely isolate the COVID signal, this method assumes that among the two periods being compared (i) baseline emissions do not differ, (ii) natural or seasonal variability in winds, sunlight, temperature, and other meteorological parameters are not important, (iii) differences in satellite sampling do not play any role, and (iv) any differences in the satellite retrieval algorithm are minimal. For many locations, including the Canadian domain studied here, differences in interannual NO_x emission changes should be small, but meteorological variability can be important, and given that, sampling variability is also likely to lead to differences in the two periods. In the case of TROPOMI, different retrieval algorithms were used for spring 2019 vs. spring 2020 (v1.2 until April 2019 and thereafter v1.3, differences include the treatment of "negative" cloud fractions and the lower limit of the tropospheric air mass factor (AMF) relaxed influencing the qa_value). While differences tend to be small, it is difficult at present to completely eliminate this as a possible source of difference.

With these confounding factors in mind, the method used here is one in which the ECCC's operational GEM-MACH air quality model forecasts are used to control for non-COVID factors such as sampling variability, meteorological variability, and other sources of variability. Furthermore, to limit potential differences in the retrieval algorithm between 2019 and 2020, the two periods considered are consecutive in 2020: a pre-COVID period and the COVID-lockdown period.

2.1 TROPOMI Observations

Observations of NO_2 from the European Space Agency Tropospheric Monitoring Instrument (TROPOMI, 2017-present; Veefkind et al. (2012)), an Earth-viewing spectrometer, are used here. TROPOMI has a resolution of 3.5×5.5 km^2 (since August 2019, before 3.5×7 km^2) at nadir and measures back-scattered UV/visible/solar-IR sunlight from which NO_2 vertical column density (VCD), or the vertically-integrated NO_2 number density, can be derived. Details on the retrieval algorithm can be found elsewhere (van Geffen et al., 2019), but in short: a spectral fit is performed matching laboratory-measured NO_2 absorption cross-sections and other relevant parameters to these observed spectra which provide a determination of the NO_2 slant column densities (SCDs), or the number density integrated along the path of the sunlight through the atmosphere. In a second step, the stratospheric component of the SCD is determined using a chemical data assimilated system and subtracted. Finally, the remaining tropospheric SCD was then converted to a VCD using an AMF which quantifies the sensitivity of the satellite to a particular scene which depends on factors such as shape of the NO_2 profile and surface reflectivity. In this work, an alternative air mass factor is used which better accounts for the presence of snow and uses higher resolution NO_2 profile shapes to improve the effective spatial resolution (McLinden et al., 2014; Griffin et al., 2019); see Supplement material for more information (Côté et al., 1998; Girard et al., 2014; Houyoux et al., 2000; Schaaf et al., 2002; Makar, Gong, Milbrandt, et al., 2015; Makar, Gong, Hogrefe, et al., 2015; Gong et al., 2015, 2018; Akingunola et al., 2018; Cooper et al., 2018). A radiative transfer model is used to calculate AMFs (Palmer et al., 2001) which depends on factors such as solar and viewing geometry, the presence of clouds, scene reflectivity and the vertical distribution of the NO_2 via VCD=SCD/AMF. Lastly, the TROPOMI data are filtered to use only the highest quality data (qa_value>0.75 and the cloud cover of the pixels is at most 30 %).

2.2 GEM-MACH Air Quality Forecast Model

The Canadian operational air quality forecast model, GEM-MACH (Moran et al., 2010; Pavlovic et al., 2016; Makar et al., 2017; Pendlebury et al., 2018), is used in this work. GEM-MACH consists of an on-line chemical transport module that is embedded within ECCC's Global Environmental Multi-scale (GEM), weather forecast model, and is applied over a domain that covers most of North America. It includes emissions, chemistry, dispersion, and removal process representations for 41 gaseous and eight particle chemical species, and provides hourly concentrations between the surface and 0.1 Pa (on 80 hybrid vertical levels) with a $10\times10\,\mathrm{km}^2$ grid cell. The standard operational model run inputs hourly emissions fields that are prepared using the Sparse Matrix Operator Kernel Emissions (SMOKE) (Coats, 1996) that account for seasonal, weekly and daily variations. The current version of the emissions files used by the operational model are based on a Canadian emissions inventory compiled for the 2013 base year and a 2017 projected U.S. inventory (Moran & Ménard, 2019). While using year-specific NO_x emissions is ideal, suitable emission inventories are not available in a timely manner. Alternative non-operational runs were also performed for a limited time period between March 15 and May 10, 2020 with updated Canadian base-year emissions and COVID-modified emissions for vehicle, aircraft, manufacturing, and residential sectors (see Sect. 3 for details)
.

GEM-MACH output is used in this study for two purposes. The first is to provide profile shapes which are used in the calculation of revised TROPOMI AMFs as discussed above in section 2.1. The second is to determine the time evolution of NO_2 on standard "business as usual" (BAU) input emissions that do not account for COVID impacts, which can then be contrasted with that observed by TROPOMI. In both cases, NO_2 profiles are obtained from operational forecasts, run at 10 km spatial resolution and launched every 12 hours (and every 24 hours for the special runs).

In this study, we integrate the model NO_2 profiles to obtain VCD values. The operational GEM-MACH model currently does not include NO_x sources in the free troposphere (such as lightning and aircraft at cruising altitude); as a consequence the model NO_x concentrations are near zero above the boundary layer. We obtain a more realistic free tropospheric column from a monthly GEOS-Chem run (averaged between 18-21 UTC, from 2 km to 12 km; $0.5\times0.67°$ resolution, version v8-03-01; http://www.geos-chem.org; Bey et al. (2001)), these partial columns are on the order of 10^{14} molec/cm^2. The model VCDs are then sampled (and filtered) in space and time at each TROPOMI pixel, and filtered like the TROPOMI observations.

2.3 Determination of Expected NO_2

In order to estimate the impact of the COVID measures on NO_2 levels, isolated from any other possible sources of variability, including seasonal, inter-annual, or shorter-term meteorological variability, and TROPOMI sampling variability, GEM-MACH output is used. GEM-MACH forecasts using standard emissions inventories for both the pre-lockdown and lockdown periods, are sampled at each TROPOMI pixel and overpass time.

Comparing pre-lockdown and lockdown TROPOMI observations together with pre-lockdown and lockdown GEM-MACH predictions will provide an estimate of the changes in NO_x emissions purely due to the lockdown, as this method accounts for effects of meteorology, seasonality, and sampling variability. The expected TROPOMI VCDs, $V_{T,e}$, under a BAU scenario, are determined from the TROPOMI VCDs before the lockdown and adjusted by the relative change seen in the model forecasts (GEM-MACH and free troposphere from GEOS-Chem) between the two time periods:

$$V_{T,e}(t_{covid}) = V_T(t_{pre}) \cdot \frac{V_{Model}(t_{covid})}{V_{Model}(t_{pre})}. \tag{1}$$

When averaging over time to produce spatially resolved maps, observations from February 15 to March 15, 2020 and March 16 to May 8, 2020 are used for the pre-lockdown and lockdown time periods, respectively. This end date is associated with some traffic rebound and increased emissions throughout May 2020 (see Sect. 3). When averaging spatially over an area to produce a time series, 15-day running means are used (the satellite data need to be averaged over multiple days in order to obtain enough data over this area, approximately 50 % of observations are filtered due to clouds). The expected columns for the 15-day running means are estimated as in Eq. 1, where $V_{T,e}(t_{covid})$ and $V_{Model}(t_{covid})$ are the 15-day means for a specific day.

3 Results

Figure 1 shows the TROPOMI and operational GEM-MACH NO_2 VCDs averaged over the pre-lockdown and lockdown periods. There is excellent agreement between TROPOMI, panel (a), and GEM-MACH, panel (d), across southern Ontario for the pre-lockdown period in terms of both spatial distribution and magnitudes which provides confidence that the NO_x emissions inventory and the model itself can accurately represent the complex physics and photochemistry of the real world.

When comparing TROPOMI observations between the pre-lockdown and lockdown periods, panel (a)–(c), there is a large decrease in VCDs over the GTA, the Windsor-Detroit urban area (which straddles the Canada-U.S. border), and virtually the entire domain. Decreases in the urban areas can reach or exceed 50%, and in parts of the GTA the decline can even exceed 60 %. However, there is also a decrease predicted by GEM-MACH, despite not accounting for COVID-related emissons reductions as shown in panels (d)–(f). This is due to a combination of a seasonal effect in which increased sunlight means a decrease in NO_x lifetime and less NO_x present as NO_2, but also expected seasonal changes in emissions (see Supplement material Fig. S2). This effect is on the order of 25 % over the GTA between the two time periods, and is especially large because it occurs during the change from cold season to warm season.

Even using several weeks of TROPOMI observations, meteorological and sampling variability can impact the average. Spring 2020 was colder than 2019 and particularly cloudy over southern Ontario, leading to fewer cloud-free overpasses on which to base

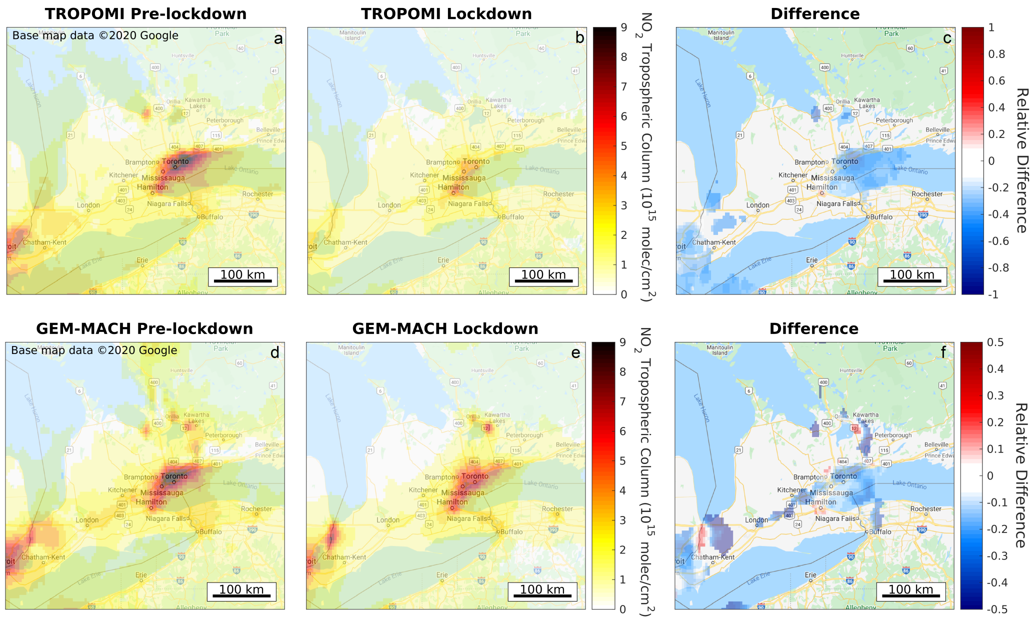

Figure 1. TROPOMI averaged VCDs over southern Ontario are shown for (a) a pre-lockdown (16 February – 15 March 2020; top) and (b) a lockdown (16 March – 8 May 2020) period. The relative differences are shown in panel (c) for areas that exceed 3 $\times$ 10^{15} molec/cm^2 in the pre-lockdown period. Panels (d), (e), (f) are the same but for the operational GEM-MACH model BAU NO_2 VCDs, sampled at the time and location of the TROPOMI pixels.

an average. The impact of the TROPOMI sampling pattern was investigated (see Supplement material Fig. S1). In general, approximately 50 % of TROPOMI data were removed due to cloud cover, so that the remaining cloud-free observations will be more representative of fair weather conditions. To determine the impact of the sampling variability, GEM-MACH averages were determined using all days over the entire domain, versus only those sampled as TROPOMI (qa>0.75). For the average NO_2 between March 16 and May 8, 2020, sampling variability can lead to differences as large as 10 % near cities.

As a test of the methodology to create expected TROPOMI columns for the COVID-19 period from the change in the model forecasts, the same procedure was applied to TROPOMI observations and operational GEM-MACH output from 2019. In this case, differences between expected and TROPOMI observations should be minimal. As can been seen in Figs. 2d and 2e, differences are small, suggesting the method is generally reliable. Averaged over the GTA, differences are 0–2%.

To help evaluate the difference between expected and observed TROPOMI NO_2 columns, as shown in Fig. 2, GEM-MACH was re-run using an alternative emissions scenario designed to represent COVID-19 emissions changes: (i) a 30 % reduction in industrial NO_x emissions, (ii) a 60 % reduction for traffic NO_x emissions, (iii) an 80 % reduction in aircraft NO_x emissions (landings and takeoffs), and (iv) a 20 % increase of residential fuel NO_x emissions due to people staying at home. Emissions of other air pollutants emitted by these source types (CO, VOC, NH_3, SO_2, $PM_{2.5}$, PM_{10}) were also changed by these same percentages. This scenario was determined using expert engineering judgement and, in the case of traffic emissions, is supported by observed changes in traffic counts. Over the entire GTA, average emissions went from 65 kt[NO_2]/yr pre-lockdown

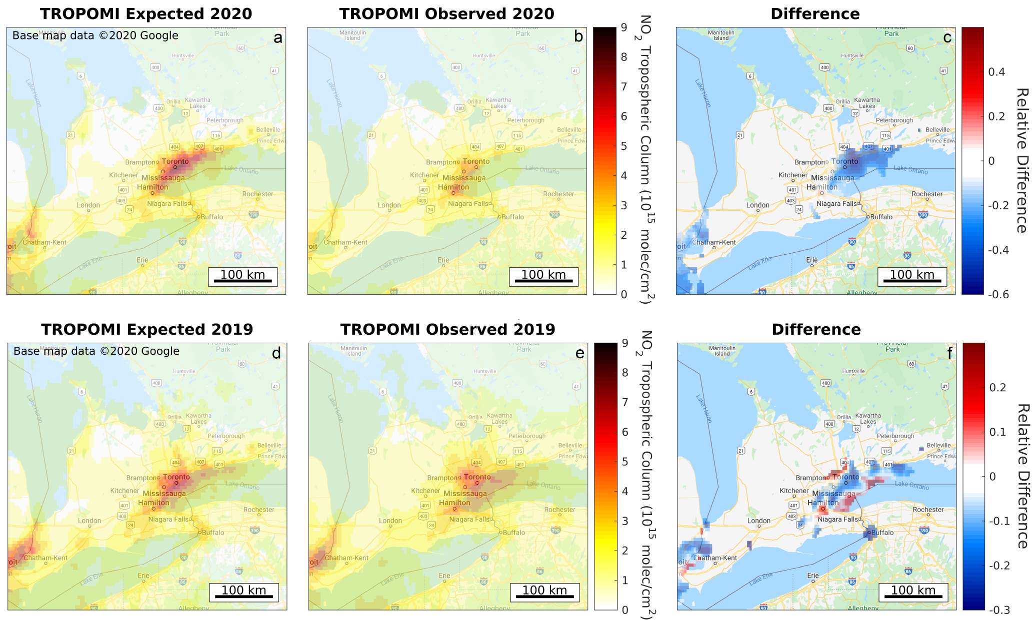

Figure 2. Expected and observed TROPOMI average VCD fields over southern Ontario for the lockdown period (16 March – 8 May 2020) are shown in panels (a) and (b), respectively. The same is shown in panels (d) and (e), but for 16 March – 8 May, 2019. Relative differences (for areas that exceed 3×10^{15} molec/cm^2) between the TROPOMI observations and the expected columns are shown in panel (c) and (f) for 2020 and 2019, respectively. Note that panel (b) is the same as Figure 1b.

to 40 kt[NO_2]/yr lockdown (around noon; see Figs. S3, S5 and S6). Note that only Canadian emissions were adjusted in this way due to the challenge of representing the complicated mixture of city-, county-, and state-level responses to COVID-19 in the U.S., but given the short atmospheric lifetime of NO_x this is unlikely to make a big difference to NO_2 levels except close to the international border. The results of this emissions scenario run are shown and compared to TROPOMI observations in Figs. 3 (for 1 April to May 8, 2020). Good agreement is evident over much of southern Ontario.

An alternative method of considering these various data sources is to average spatially and look at temporal changes. Figure 4 shows a time series of 15-day running average NO_2 over the Toronto and Mississauga area (part of the GTA with the highest emissions and population density, this area also includes Toronto Pearson Airport; see Supplement material Fig. S4). TROPOMI observations show a decline after the lockdown was announced (Fig. 4a), the expected columns agree well with the TROPOMI observations during the pre-lockdown period, but, differences emerge after the lockdown begins as emissions are reduced, but the model assumes BAU emissions. The alternate model run with reduced emissions (Fig. 4b) represents the decline observed by TROPOMI quite well and over the same time period, both the TROPOMI observations and the model predict a drop of roughly 40 % over the GTA core (using data from March 16 to May 8, 2020) as a result of the lockdown. When the 2019 and 2020 satellite data are compared directly, however, the drop is only about half as much (20 %), as the meteorology and sampling variability of the satellite were largely different in that area between 2019 and 2020. Note that the satellite data indicate that the peak of the emissions decline in Toronto and Mississauga occurred in mid-April. Throughout May 2020, the satellite measurements suggest that the NO_x emissions began to increase again gradually (Fig. 4a),

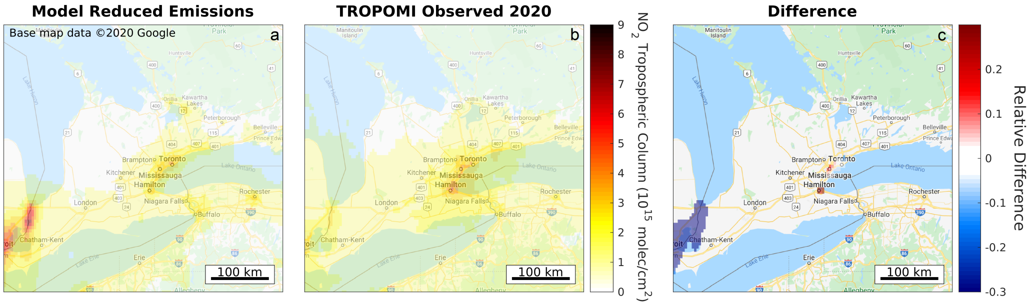

Figure 3. Model NO_2 VCDs from the reduced emissions scenario (a) and observed TROPOMI NO_2 VCDs (b) over southern Ontario averaged over the period 1 April – 8 May 2020. The relative differences are shown in panel (c) for areas that exceed 3×10^{15} molec/cm^2. Note that emissions have only been reduced in Canada; thus, large differences can be seen for the US cities near the border, especially Detroit.

though they are still lower than BAU emissions. Ontario entered Phase 1 of its re-opening on May 19, 2020, when certain restrictions were lifted.

4 Summary

We present a method to entangle the effects of meteorology and sampling variability on the observed NO_2 changes, from the lockdown-related changes in NO_x emissions. During the period from March 16 to May 8 2020, NO_2 columns in the center of the GTA decreased by nearly 60 % compared to the previous month. About 25 % of this decrease is associated with meteorological and seasonal changes independant of the COVID-19 pandemic. Even the TROPOMI sampling variability itself can impact the magnitude of the observed NO_2 columns over the course of one or two months averaging ($\sim$10 %). From the TROPOMI observations and GEM-MACH air quality model results, we estimate that due to the lockdown the NO_2 columns in Toronto and Mississauga declined by over 40 %. These changes vary spatially, and in certain locations columns declined by over 50 %. Reducing the NO_x input emissions of vehicle traffic, aircraft, and industry used by the GEM-MACH model resulted in a similar pattern as observed by TROPOMI, resulting in a drop of 36 % in NO_2 columns over the Mississauga and Toronto area. Although, spatial patterns over cities are somewhat visible, it is hard to disentangle the emission reductions by sector with our methodology. Nevertheless, emission changes of (i) a 30 % reduction in industry, (ii) a 60 % reduction for traffic, (iii) an 80 % reduction in aircraft landings and takeoffs, and (iv) a 20 % increase in residential fuel combustion, represent the TROPOMI NO_2 observations well, at least in southern Ontario. In the GTA, NO_x emissions of 40 kt[NO_2]/yr represent the observations well, this is a drop of over 37 % compared to a business as usual scenario. The drop in the input emissions is almost identical to the drop determined from the model NO_2 VCDs (36 %) over the same area which further indicates that the method presented works well.

This study highlights the importance of considering meteorological and sampling variability when estimating emission reductions. One needs to be cautious when simply comparing two months, since the effects of meteorological and sampling variability are not negligible when only a short series of data is averaged. As well, the emissions may vary strongly spatially, especially in cities. This can make it difficult to compare different studies unless the exact same areas are considered. The unique lockdown period associated with the 2020 COVID-19 pandemic can further be used to check and refine our existing emissions inventories for NO_x and other pollutants by looking at spatial and temporal distributions of available satellite and surface measurements for a number of different urban areas.

Acknowledgments

This work contains modified Copernicus Sentinel data. The Sentinel 5 Precursor TROPOMI Level 2 product is developed with funding from the Netherlands Space Office (NSO) and processed with funding from the European Space Agency (ESA). TROPOMI data can be downloaded from https://s5phub.copernicus.eu (last access: June 16, 2020). We would like to thank you MSC-REQA employees involved in emission adjustment and modelling: Rabab Mashayekhi, Mourad Sassi, Annie Duhamel and Jessica Miville.

References

Akingunola, A., Makar, P. A., Zhang, J., Darlington, A., Li, S.-M., Gordon, M., … Zheng, Q. (2018). A chemical transport model study of plume-rise and particle size distribution for the Athabasca oil sands. *Atmospheric Chemistry and Physics*, *18*(12), 8667–8688. Retrieved from `https://www.atmos-chem-phys.net/18/8667/2018/` doi: 10.5194/acp-18-8667-2018

Bauwens, M., Compernolle, S., Stavrakou, T., Müller, J.-F., van Gent, J., Eskes, H., … Zehner, C. (2020). Impact of coronavirus outbreak on NO2 pollution assessed using TROPOMI and OMI observations. *Geophysical Research Letters*, *n/a*(n/a), e2020GL087978. Retrieved from `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GL087978` (e2020GL087978 2020GL087978) doi: 10.1029/2020GL087978

Beirle, S., Boersma, K. F., Platt, U., Lawrence, M. G., & Wagner, T. (2011). Megacity emissions and lifetimes of nitrogen oxides probed from space. *Science*, *333*(6050), 1737–1739. Retrieved from `http://science.sciencemag.org/content/333/6050/1737` doi: 10.1126/science.1207824

Beirle, S., Platt, U., Wenig, M., & Wagner, T. (2003). Weekly cycle of NO_2 by GOME measurements: a signature of anthropogenic sources. *Atmospheric Chemistry and Physics*, *3*(6), 2225–2232. Retrieved from `https://www.atmos-chem-phys.net/3/2225/2003/` doi: 10.5194/acp-3-2225-2003

Bey, I., Jacob, D. J., Yantosca, R. M., Logan, J. A., Field, B. D., Fiore, A. M., … Schultz, M. G. (2001). Global modeling of tropospheric chemistry with assimilated meteorology: Model description and evaluation. *Journal of Geophysical Research: Atmospheres*, *106*(D19), 23073-23095. Retrieved from `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2001JD000807` doi: 10.1029/2001JD000807

Coats, C. J. (1996). High-performance algorithms in the sparse matrix operator kernel emissions (SMOKE) modeling system. Atlanta, GA, USA: American Meteorological Society. (Proceedings of the Ninth AMS Joint Conference on Applications of Air Pollution Meteorology with AWMA, 28 January–2 February 1996)

Cooper, M. J., Martin, R. V., Lyapustin, A. I., & McLinden, C. A. (2018). Assessing snow extent data sets over North America to inform and improve trace gas retrievals from solar backscatter. *Atmospheric Measurement Techniques*, *11*(5), 2983–2994. Retrieved from `https://www.atmos-meas-tech.net/11/2983/2018/` doi: 10.5194/amt-11-2983-2018

Côté, J., Gravel, S., Méthot, A., Patoine, A., Roch, M., & Staniforth, A. (1998). The Operational CMC–MRB Global Environmental Multiscale (GEM) Model. Part I: Design Considerations and Formulation. *Monthly Weather Review*, *126*(6), 1373-1395. Retrieved from `https://doi.org/10.1175/1520-0493(1998)126<1373:TOCMGE>2.0.CO;2` doi: 10.1175/1520-0493(1998)126⟨1373:TOCMGE⟩2.0.CO;2

de Foy, B., Lu, Z., & Streets, D. G. (2016). Satellite NO_2 retrievals suggest China has exceeded its NO_x reduction goals from the twelfth Five-Year Plan. *Scientific Reports*, *6*(35912). Retrieved from `http://dx.doi.org/10.1038/srep35912` doi: 10.1038/srep35912

Girard, C., Plante, A., Desgagné, M., McTaggart-Cowan, R., Côté, J., Charron, M., ... Zadra, A. (2014). Staggered Vertical Discretization of the Canadian Environmental Multiscale (GEM) Model Using a Coordinate of the Log-Hydrostatic-Pressure Type. *Monthly Weather Review*, *142*(3), 1183-1196. Retrieved from `https://doi.org/10.1175/MWR-D-13-00255.1` doi: 10.1175/MWR-D-13-00255.1

Gong, W., Beagley, S. R., Cousineau, S., Sassi, M., Munoz-Alpizar, R., Ménard, S., ... Holt, R. (2018). Assessing the impact of shipping emissions on air pollution in the Canadian Arctic and northern regions: current and future modelled scenarios. *Atmospheric Chemistry and Physics*, *18*(22), 16653–16687. Retrieved from `https://www.atmos-chem-phys.net/18/16653/2018/` doi: 10.5194/acp-18-16653-2018

Gong, W., Makar, P., Zhang, J., Milbrandt, J., Gravel, S., Hayden, K., ... Leaitch, W. (2015). Modelling aerosol–cloud–meteorology interaction: A case study with a fully coupled air quality model (GEM-MACH). *Atmospheric Environment*, *115*, 695 - 715. Retrieved from `http://www.sciencedirect.com/science/article/pii/S1352231015301333` doi: https://doi.org/10.1016/j.atmosenv.2015.05.062

Griffin, D., Zhao, X., McLinden, C. A., Boersma, F., Bourassa, A., Dammers, E., ... Wolde, M. (2019). High-Resolution Mapping of Nitrogen Dioxide With TROPOMI: First Results and Validation Over the Canadian Oil Sands. *Geophysical Research Letters*, *46*(2), 1049-1060. Retrieved from `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018GL081095` doi: 10.1029/2018GL081095

Houyoux, M. R., Vukovich, J. M., Coats Jr., C. J., Wheeler, N. J. M., & Kasibhatla, P. S. (2000). Emission inventory development and processing for the Seasonal Model for Regional Air Quality (SMRAQ) project. *Journal of Geophysical Research: Atmospheres*, *105*(D7), 9079-9090. Retrieved from `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/1999JD900975` doi: 10.1029/1999JD900975

Makar, P. A., Gong, W., Hogrefe, C., Zhang, Y., Curci, G., Žabkar, R., ... Galmarini, S. (2015). Feedbacks between air pollution and weather, part 2: Effects on chemistry. *Atmospheric Environment*, *115*, 499 – 526. Retrieved from `http://www.sciencedirect.com/science/article/pii/S1352231014008103` doi: https://doi.org/10.1016/j.atmosenv.2014.10.021

Makar, P. A., Gong, W., Milbrandt, J., Hogrefe, C., Zhang, Y., Curci, G., ... Galmarini, S. (2015, 08). Feedbacks between air pollution and weather, Part 1: Effects on weather. *Atmospheric Environment*, *115*.

Makar, P. A., Staebler, R. M., Akingunola, A., Zhang, J., McLinden, C., Kharol, S. K., ... Zheng, Q. (2017). The effects of forest canopy shading and turbulence on boundary layer ozone. *Nature Communications*, *8*. doi: 10.1038/ncomms15243

McLinden, C. A., Fioletov, V., Boersma, K. F., Kharol, S. K., Krotkov, N., Lamsal, L., ... Yang, K. (2014). Improved satellite retrievals of NO_2 and SO_2 over the Canadian oil sands and comparisons with surface measurements. *Atmospheric Chemistry and Physics*, *14*(7), 3637–3656. Retrieved from `https://www.atmos-chem-phys.net/14/3637/2014/` doi: 10.5194/acp-14-3637-2014

Moran, M. D., & Ménard, S. (2019). Regional Air Quality Deterministic Prediction System (RAQDPS): Update from version 020.2 to version 021. Montreal, CA: Canadian Centre for Meteorological and Environmental Prediction. (Technical note, p. 49 pp., http://collaboration.cmc.ec.gc.ca/cmc/cmoi/product_guide/docs/tech_notes/technote_raqdps-021_20190703_e.pdf [last access: 23 June 2020])

Moran, M. D., Ménard, S., Talbot, D., Huang, P., Makar, P. A., Gong, W., ... Sassi, M. (2010). *Particulate-matter forecasting with GEM-MACH15, a new Canadian air-quality forecast model, in: Air Pollution Modelling and Its Application XX.* Dordrecht, the Netherlands: Springer.

Palmer, P. I., Jacob, D. J., Chance, K., Martin, R. V., Spurr, R. J. D., Kurosu, T. P., ... Li, Q. (2001). Air mass factor formulation for spectroscopic measurements from satellites: Application to formaldehyde retrievals from the Global Ozone Monitoring Experiment. *Journal of Geophysical Research: Atmospheres*, *106*(D13), 14539-14550. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2000JD900772 doi: 10.1029/2000JD900772

Pavlovic, R., Chen, J., Anderson, K., Moran, M. D., Beaulieu, P.-A., Davignon, D., & Cousineau, S. (2016). The FireWork air quality forecast system with near-real-time biomass burning emissions: Recent developments and evaluation of performance for the 2015 North American wildfire season. *Journal of the Air & Waste Management Association*, *66*(9), 819-841. Retrieved from https://doi.org/10.1080/10962247.2016.1158214 (PMID: 26934496) doi: 10.1080/10962247.2016.1158214

Pendlebury, D., Gravel, S., Moran, M. D., & Lupu, A. (2018). Impact of chemical lateral boundary conditions in a regional air quality forecast model on surface ozone predictions during stratospheric intrusions. *Atmospheric Environment*, *174*, 148 - 170. Retrieved from http://www.sciencedirect.com/science/article/pii/S1352231017307185 doi: https://doi.org/10.1016/j.atmosenv.2017.10.052

Schaaf, C. B., Gao, F., Strahler, A. H., Lucht, W., Li, X., Tsang, T., ... Roy, D. (2002). First operational brdf, albedo nadir reflectance products from modis. *Remote Sensing of Environment*, *83*(1), 135 - 148. Retrieved from http://www.sciencedirect.com/science/article/pii/S0034425702000913 (The Moderate Resolution Imaging Spectroradiometer (MODIS): a new generation of Land Surface Monitoring) doi: https://doi.org/10.1016/S0034-4257(02)00091-3

Shi, X., & Brasseur, G. P. (2020). The Response in Air Quality to the Reduction of Chinese Economic Activities during the COVID-19 Outbreak. *Geophysical Research Letters*, *n/a*(n/a), e2020GL088070. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GL088070 (e2020GL088070 2020GL088070) doi: 10.1029/2020GL088070

Valin, L. C., Russell, A. R., & Cohen, R. C. (2013). Variations of OH radical in an urban plume inferred from NO_2 column measurements. *Geophysical Research Letters*, *40*(9), 1856–1860. Retrieved from http://dx.doi.org/10.1002/grl.50267 doi: 10.1002/grl.50267

van Geffen, J., Boersma, K. F., Eskes, H., Sneep, M., ter Linden, M., Zara, M., & Veefkind, J. P. (2019). S5P/TROPOMI NO_2 slant column retrieval: method, stability, uncertainties, and comparisons against OMI. *Atmospheric Measurement Techniques Discussions*, *2019*, 1–33. Retrieved from https://www.atmos-meas-tech-discuss.net/amt-2019-471/ doi: 10.5194/amt-2019-471

Veefkind, J., Aben, I., McMullan, K., Forster, H., de Vries, J., Otter, G., ... Levelt, P. (2012). TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. *Remote Sensing of Environment*, *120*, 70 - 83. Retrieved from http://www.sciencedirect.com/science/article/pii/S0034425712000661 (The Sentinel Missions - New Opportunities for Science) doi: https://doi.org/10.1016/j.rse.2011.09.027

Zhang, R., Zhang, Y., Lin, H., Feng, X., Fu, T.-M., & Wang, Y. (2020). NOx Emission Reduction and Recovery during COVID-19 in East China. *Atmosphere*, *11*(433).

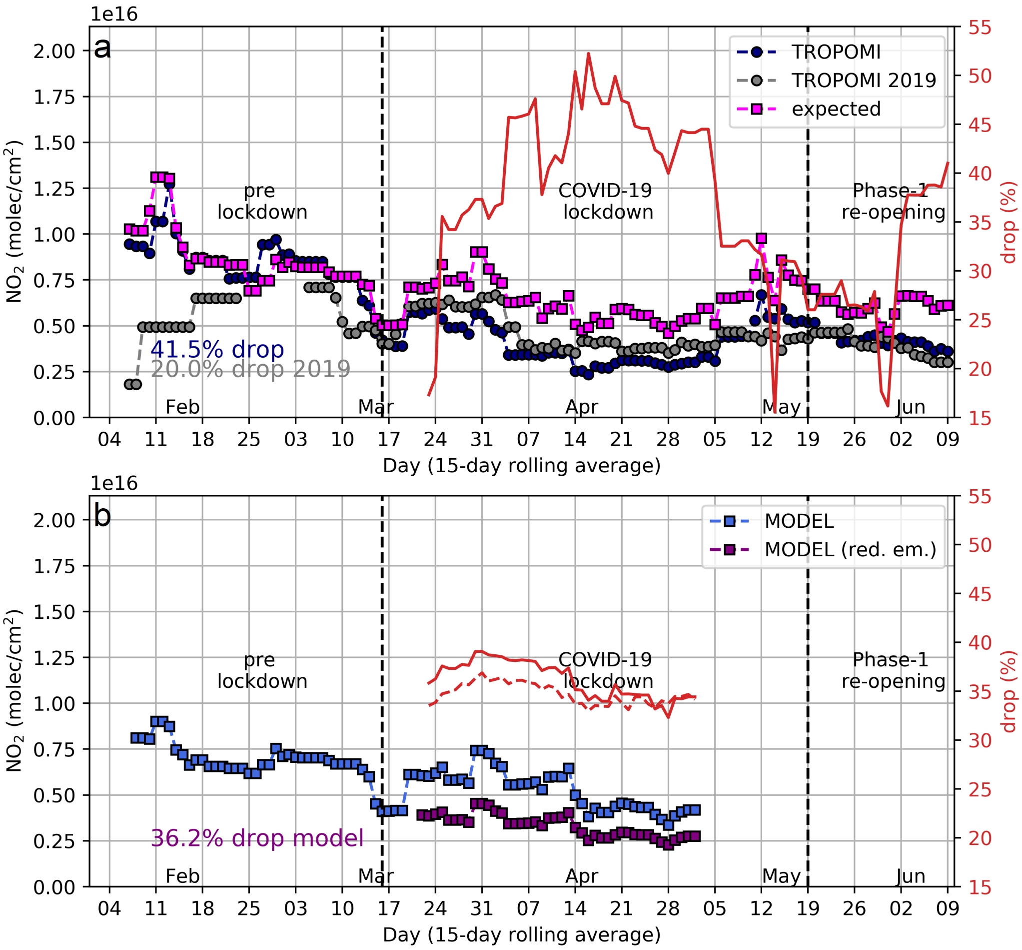

Figure 4. Timeseries of 15-day running mean of NO_2 VCDs over Toronto and Mississauga for 15 February to 9 June 2020, panel (a) shows the TROPOMI observations (navy), the expected columns (magenta). The timeseries of 2019 TROPOMI observations (grey) for the same period is shown as a reference. The red line indicates the percentage emission reductions based on the difference between the TROPOMI observations and expected columns. Panel (b) shows NO_2 columns from the model predictions sampled like TROPOMI assuming a BAU scenario with 2020 updated emissions (blue) and a 2020 COVID reduced emissions scenario (purple). The percentage decrease in model predicted VCDs (red line) is estimated from the difference between the two model runs, the red dashed line shows the drop for perfect sampling. Average emission reductions are highlighted using observations between March 16 to May 8, 2020.

Geophysical Research Letters

Supporting Information for

Assessing the impact of Corona-virus-19 on nitrogen dioxide levels over southern Ontario, Canada

Debora Griffin[1], Chris A. McLinden[1,2], Jacinthe Racine[3], Michael D. Moran[1], Vitali Fioletov[1], Radenko Pavlovic[3], Henk Eskes[4]

[1]Air Quality Research Division, Environment and Climate Change Canada, Toronto, Ontario, Canada

[2]Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, Canada

[3]Canadian Meteorological Centre Operations Division, Environment and Climate Change Canada, Dorval, Quebec, Canada

[4] Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands

Contents of this file

Introduction

Supplementary material for "Assessing the impact of Corona-virus-19 on nitrogen dioxide levels over Southern Ontario, Canada" by D. Griffin et al. This document contains further details about the methodology used in this study to determine the alternative air mass factors (AMFs). Figures that help with the interpretation of the results, but could not be included in the main manuscript (due to size limitations) are also included here.

Text S1.

Alternative Air Mass Factors

The information on the NO_2 profile shape is taken from ECCC's operational regional air quality forecast model; the Global Environmental Multiscale - Modelling Air-quality and Chemistry (GEM-MACH). The operational version of the model (Moran et al, 2010; Pavlovic et al., 2016; Pendlebury et al, 2018) has a 10x10km^2 grid cell size for a North American domain and considers 41 gas-phase chemical species a 2-size bin particulate matter (PM) size distribution, and 8 PM chemical species (sulphate, nitrate, ammonium, black carbon, primary organic matter, secondary organic matter, sea-salt, and crustal material). The meteorological component of GEM-MACH is within the physics module of the Global Environmental Multiscale (GEM) weather forecast model (Coté et al., 1998; Girard et al., 2014). Further details on GEM-MACH can be found in, e.g., Makar et al. (2015a,b), Gong et al. (2015, 2018), and Akingunola et al. (2018).

The operational forecast makes use of 2013 Canadian and 2017 projected U.S. emissions information (Zhang et al., 2018; Moran and Ménard, 2019). The emissions used in the model are processed using the Sparse Matrix Operator Kernel Emissions (SMOKE; Coats et al., 1996; Houyoux et al., 2000).

Here, we use the hourly model output for the closest hour of the measurements and the closest grid-box of the 10 km resolution version of GEM-MACH. The TM5-MP model used for the standard TROPOMI product has global coverage but with coarser horizontal spatial resolution (1°x1° , or about 111 x 80 km^2 at 44°N) and thus will be unable to capture fine-scale spatial gradients in the NO_2 profile distribution, due to very localized enhancements. This performance can be improved by using input from regional models. To generate an improved a priori NO_2 profiles, we use the NO_2 concentrations from 0-1.5 km from the GEM-MACH model for the closest hour of the TROPOMI overpass. Between 1.5-12 km we use the concentrations from a monthly GEOS-Chem model run at the approximate time of the TROPOMI overpass on a 0.5^{0}x0.67^0 resolution version v8-03-01 (http://www.geos-chem.org) (Bey et al., 2001; McLinden et al., 2014), as the GEM-MACH model currently does not include NOx sources in the free troposphere, such as lightning and aircraft emissions at cruising altitude.

MODIS provides white-sky albedo (WSA) and black-sky albedo (BSA), based on 16-day averages available every 8 days, at a resolution of 0.05^{0}x0.05^0 (collection 6.1 MCD43C3; Schaaf et al., 2002). From this, a monthly-mean albedo is computed considering only 100 % snow-free pixels. For surfaces with snow-cover, a climatology of the MODIS surface reflectance is used that only includes pixels with full snow-cover. To determine whether the TROPOMI pixel is snow covered, we use the daily IMS snow flag (http://www.natice.noaa.gov/ims/) on a on a 4x4 km^2 resolution. It has been shown that the IMS product is better suited than other snow-products in differentiating between snow and snow-free scenes (Cooper et al., 2018), including the NISE snow flag used for the standard TROPOMI product that has a tendency of missing thin snow layers (McLinden et al., 2014). The MODIS snow albedo shows that the value over snow and ice is not necessarily 0.6 as assumed for the original TROPOMI product. For many areas in North America this can be as high as 0.9, however, over the boreal forest the reflectance is relatively low (0.2-0.3) even with snow cover.

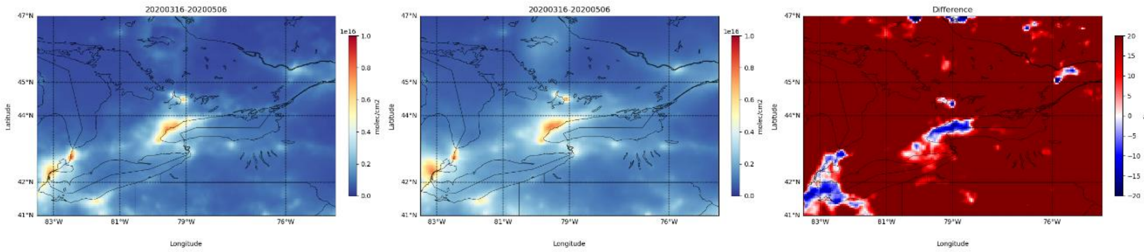

Figure S1. Impact of the sampling on the averaged TROPOMI columns. Model VCDs (a) filtered (like TROPOMI with qa>0.75) and (b) unfiltered (still sampled like TROPOMI) NO2 VCDs over southern Ontario averaged over the lockdown time period, 16 March - May 6 for 2020. Panel (c) shows the difference (in %) between panels (a) and (b).

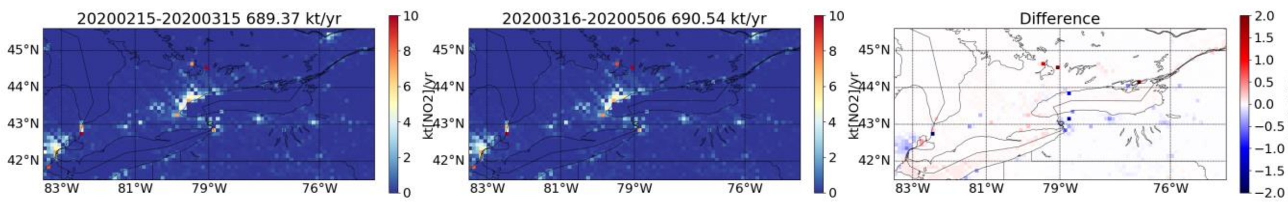

Figure S2.Shown are the operational forecast model's seasonal emission changes from the pre-lockdown versus lockdown period. Over the whole domain there is little change, however, in some area emissions decrease and in other increase slightly. The emissions shown here are the averaged emissions between 18-21 UTC.

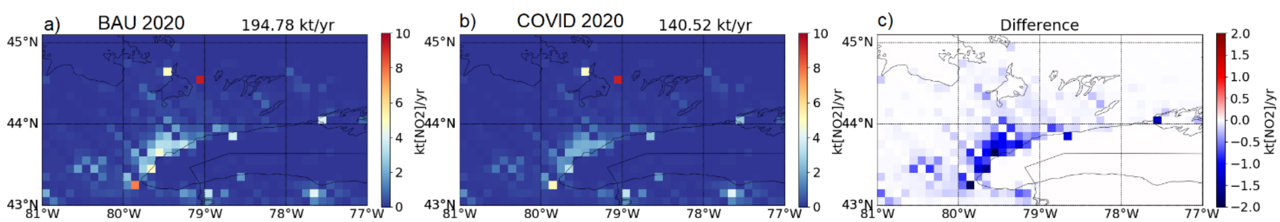

Figure S3. The model input NO_x emissions, binned to $0.1^0 x 0.1^0$, in the southern Ontario for (a) the 2020 business-as-usual emissions scenario and (b) the 2020 lockdown emissions scenario, assuming: (i) a 30% reduction in industry, (ii) a 60% reduction for traffic, (iii) 80% reduction in aircraft, and (iv) 20% increase of residential fuel combustion. The emissions shown here are the averaged emissions between 18-21 UTC.

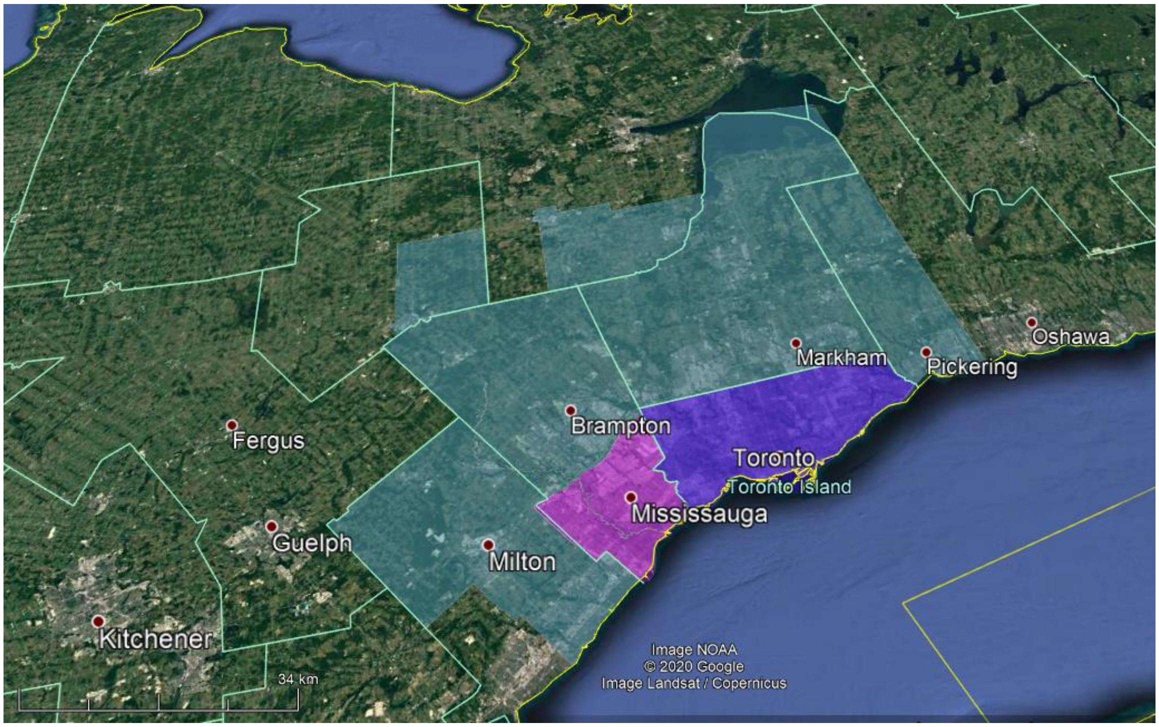

Figure S4. Boundaries of the Greater Toronto Area (GTA), shaded in grey. The Toronto and Mississauga city boundaries (used for the time series) are highlighted in violet and magenta, respectively.

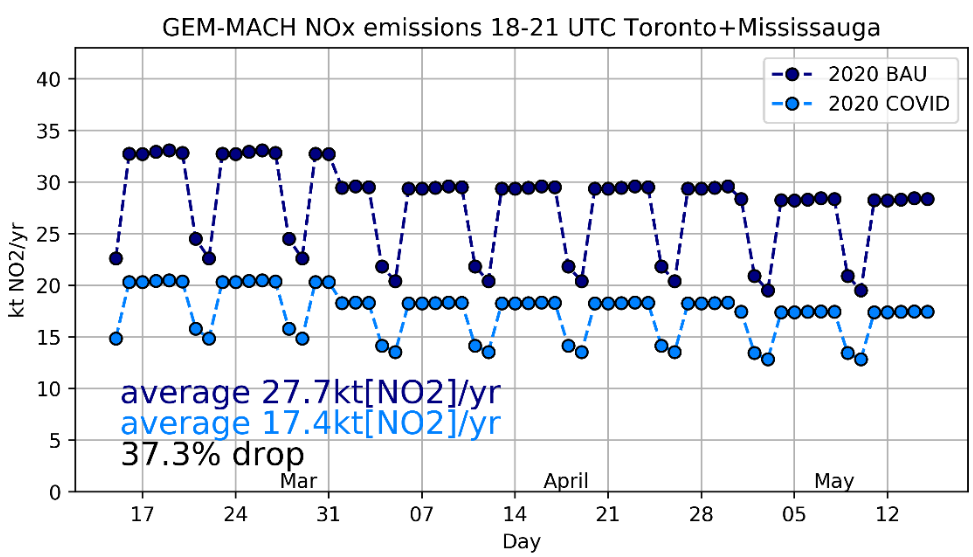

Figure S5. The model input NO_x emissions summed over the Toronto and Mississauga city boundaries, for the 2020 business-as-usual emissions scenario (navy) and the 2020 lockdown emissions scenario (blue), assuming: (i) a 30% reduction in industry, (ii) a 60% reduction for traffic, (iii) 80% reduction in aircraft, and (iv) 20% increase of residential fuel combustion. The emissions shown here are the averaged emissions between 18-21 UTC. Input emissions differ by day of week and by month.

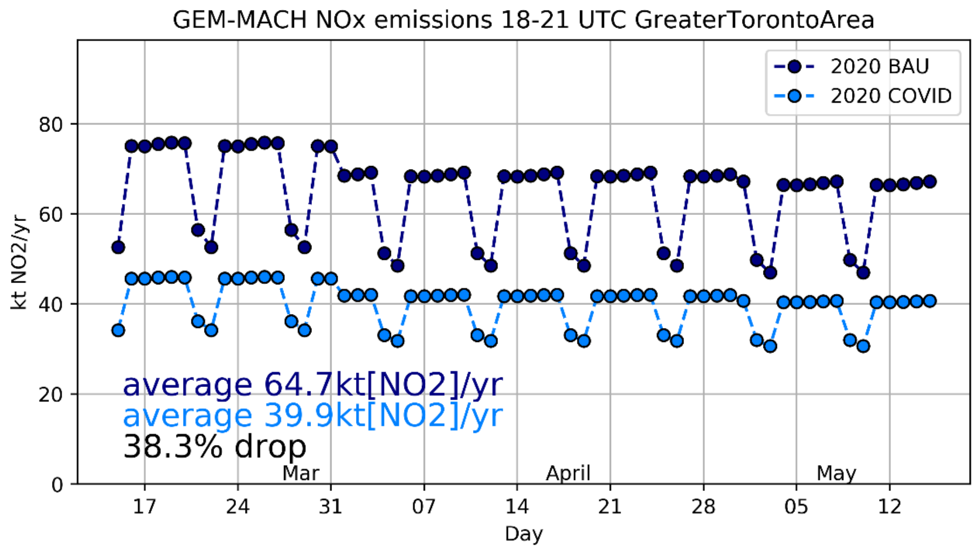

Figure S6. The model input NO_x emissions summed over the Greater Toronto Area (GTA, as shown in Figure S4), for the business as usual scenario (navy) and the lockdown scenario (blue), assuming: (i) a 30% reduction in industry, (ii) a 60% reduction for traffic, (iii) 80% reduction in aircraft, and (iv) 20% increase of residential fuel. The emissions shown here are the averaged emissions between 18-21 UTC. Input emissions differ by weekday and month.