Unexpected impact of COVID-19 lockdown on the air quality in the Metro Atlanta, USA using ground-based and satellite observations

Guanyu Huang1*, Reyla Ponder2,3, Amber Bond1, Hailey Brim1*, Akua Temeng4, Aaron R. Naeger5, Lei Zhu6

1Environmental and Health Sciences Program, Spelman College. 350 Spelman LN SW, Atlanta GA, USA, 30314.
2Department of Mathematics, Spelman College. 350 Spelman LN SW, Atlanta GA, USA, 30314.
3College of Civil and Environmental Engineering, Georgia Institute of Technology. 790 Atlantic Drive, Atlanta, GA, 30332.
4Department of Chemistry and Biochemistry, Spelman College. 350 Spelman LN SW, Atlanta GA, USA, 30314.
5Earth System Science Center, University of Alabama in Huntsville. 320 Sparkman Dr NW, Huntsville, AL, 35805.
6School of Environmental Science and Engineering, Southern University of Science and Technology. 1088 Xueyuan Avenue, Nanshan District, Shenzhen, China, 518055.
*now at Columbia Climate School, Columbia University. 601 W 125th St, New York, NY, USA, 10027.

*Corresponding author: Guanyu Huang. Tel: +1-404-270-5903
Email: ghuang@spelman.edu

Abstract

We studied the impact of COVID-19 (coronavirus disease 2019) lockdown on the air quality over the Atlanta area using satellite and ground-based observations, meteorological reanalysis data and traffic information. Unlike other cities, we found the air quality has improved slightly over the Atlanta area during the 2020 COVID-19 lockdown period (March 14 – April 30, 2020), compared to the analogous period of 2019 (March 14-April 30, 2019). Ground NO₂ concentrations have decreased slightly 10.8% and 8.2% over the near-road (NR) and urban ambient (UA) stations, respectively. Tropospheric NO₂ columns have reduced 13%-49% over the Atlanta area from space-borne observations of TROPspheric Monitoring Instrument (TROPOMI). Ground ozone and PM₂.₅ have decreased 15.7% and 5%, respectively. This slight air quality improvement is primarily caused by the reduced human activities, as COVID-19 lockdowns have reduced ~50% human activities, measured by traffic volume. Higher wind speed and precipitations also make the meteorological conditions favorable to this slight air quality improvement. We have not found a significant improvement in Atlanta amid the lockdown when human activities have reduced ~50%. Further studies are needed to understand the impacts of reduced human activities on atmospheric
chemistry. We also found TROPOMI and ground measurements have disagreements on NO$_2$ reductions, as collocated TROPOMI observations revealed ~23% and ~21% reductions of tropospheric NO$_2$ columns over NR and UA stations, respectively. Several factors may explain this disagreement: First, tropospheric NO$_2$ columns and ground NO$_2$ concentrations are not necessarily the same, although they are highly correlated in the afternoon; Second, meteorological conditions may have different impacts on TROPOMI and ground measurements. Third, TROPOMI may underestimate tropospheric NO$_2$ due to uncertainties from air mass factors. Fourth, the uncertainties of chemiluminescence NO$_2$ measurements used by ground stations. Consequently, studies using space-borne tropospheric NO$_2$ column and ground NO$_2$ measurements should take these factors into account.

**Keyword:** COVID-19, Air Quality, TROPOMI, NO$_2$.  

1 Introduction

As the outbreak of COVID-19 (coronavirus disease 2019) and its pandemic spread worldwide, many countries have implemented measures to slow down and prevent the spread of COVID-19. These COVID-19 lockdowns have caused significant reductions in human activities and traffic worldwide. As human activities have reduced, air quality has improved significantly worldwide (Bauwens et al., 2020; Goldberg et al., 2020; Huang and Sun, 2020; Jin et al., 2020; Koo et al., 2020; Liu et al., 2020; Morales-Solis et al., 2021; Naeger and Murphy, 2020; Oo et al., 2021; Represa et al., 2021). However, some studies found air quality has not improved as we expected or even worsened in some cities due to the complicated atmospheric chemistry, meteorological conditions, and emissions, even anthropogenic emissions from human activities and traffic have reduced significantly (Bekbulat et al., 2021; Chen et al., 2020; Le et al., 2020; Schiermeier, 2020; Shi and Brasseur, 2020).

The variation of ground air pollutants is controlled by complicated and non-linear physical and chemical processes (Kroll et al., 2020; Seinfeld and Pandis, 2016). Nitrogen oxides ($\text{NO}_x = \text{NO} + \text{NO}_2$) emitted into the atmosphere from anthropogenic sources are a major driver of ambient $\text{NO}_2$ concentrations over populous areas in the world (Lamsal et al., 2013, 2008). It is not surprising that ambient $\text{NO}_2$ has reduced significantly in many areas due to the reduced human activities by COVID-19 lockdowns (Huang and Sun, 2020; Liu et al., 2020; Naeger and Murphy, 2020). The chemistry of ozone and aerosols (e.g., Particulate Matter 2.5($\text{PM}_{2.5}$)) are more complicated than $\text{NO}_2$. The production of ozone depends on volatile organic compounds (VOCs) and $\text{NO}_x$ with the presence of sunlight. When VOCs are high and $\text{NO}_x$ is low, it is the “$\text{NO}_x$” controlled situation. In this situation, more $\text{NO}_x$ means more ozone. When VOCs are low and $\text{NO}_x$ is high, it is the “VOCs” limited situation. More $\text{NO}_x$ does not produce more ozone or even decrease ozone (Kroll et al., 2020). The chemistry of $\text{PM}_{2.5}$ is even more complicated. $\text{PM}_{2.5}$ can be emitted directly from combustion and produced through gas-phase chemical reactions to form products of low enough volatility to condense into the particle phase. In addition, secondary organic aerosols (SOAs) makes it even more complicated (Kroll et al., 2020; Seinfeld and Pandis, 2016). As a result, ozone and
PM$_{2.5}$ have had more diverse responses during the COVID-19 lockdowns (Bekbulat et al., 2021; Chen et al., 2020). Many studies have shown ozone increased, whereas PM$_{2.5}$ decreased slightly, as the increase of government stringency (Gkatzelis et al., 2021). However, cities with slightly better or even worse air quality during COVID-19 lockdowns may need further analysis due to their unexpected responses to reduced human activities. COVID-19 lockdowns provide us a special scenario to understand the mechanisms that controlling air quality under reduced human activities (Kroll et al., 2020). In addition, analysis on meteorology is essential to interpretate the relationship between COVID-19 lockdowns and air quality (Goldberg et al., 2020). Unfortunately, many previous studies had not taken metrological conditions into account (Gkatzelis et al., 2021).

Atlanta is the largest and most populous metropolitan area in the southeastern United States. People’s activities heavily depend on private vehicles, as traffic information is a good indicator of human activities. Geographically, Atlanta is an isolated non-attainment area and its major source of air pollutants are from local emissions (Diem, 2009). As one of the most diverse major cities in the U.S., Atlanta has been suffering air quality disparities and environmental justice for a long time (Park and Kwan, 2020; Servadio et al., 2019). These environmental justice issues have worsened worldwide during the COVID-19 pandemic (Kerr et al., 2021). Consequently, it is essential to analyze the impact of COVID-19 lockdown on the air quality in the Atlanta area for the local air quality management and environmental justice. Unfortunately, no previous studies have done such analysis in the Atlanta area.

This study aims to assess the impact of COVID-19 lockdown on the air quality in the Atlanta metropolitan using measurements of NO$_2$, ozone and PM$_{2.5}$ from multiple ground stations and space-based tropospheric NO$_2$ observations in conjunction with meteorological and traffic information.

2 Study Area, Data and Materials.

2.1 Study areas and COVID-19 control measures in Atlanta
The Atlanta metropolitan area in the state of Georgia is one of the major metropolitans in the United States that experience high concentrations of air pollution due to a range of factors, including urbanization and anthropogenic emissions (Diem, 2009; Henneman et al., 2017, 2015). Most population of Atlanta concentrates in the area inside of Interstate Loop Highway (I-285) including the City of Atlanta, other cities, and unincorporated areas. In this study, we focus on the highly urbanized and populous area inside of Interstate Highway 285 (I-285) loop as shown in Fig. 1.


2.2 Ground-based air quality measurements

We obtain our hourly measurements from ground stations operated and maintained by Georgia Environmental Protection Division, with monitor locations indicated in Fig. 1 (Georgia Department of Natural Resources, 2020). Hourly NO$_2$ measurements are obtained from the South DeKalb, an urban ambient (UA) station, and NR-285, a near-road (NR) background station (Georgia Department of Natural Resources, 2020). Ground NO$_2$ has been measured by U.S. Environmental Protection Agency (U.S. EPA)-designated NO$_2$ chemiluminescence automated Federal Reference Method (FRM) (Georgia Department of Natural Resources, 2020). The South DeKalb and NR-285 stations both use Thermo Scientific Model 42i (NO-NO$_2$-NO$_x$) Analyzer for NO$_2$ monitoring with 0-0.05 to 100 ppm range and ± 0.40 ppb precision (Georgia Department of Natural Resources, 2020). These regulatory NO$_2$ chemiluminescence measurements are known to contain some uncertainties due to their sensitivity to other nitrogen species (Dunlea et al., 2007). The magnitude of the total interference is variable, and depends not only on the relative fraction of actual NO$_2$ to total reactive nitrogen compounds (NO$_x$), but also on the characteristics of individual monitors.
(Lamsal et al., 2015). Consequently, ground NO$_2$ measurements may overestimate NO$_2$ concentrations, with minimum biases in the morning and maximum biases in the early afternoon, close to the overpass time of TROPOMI (Dunlea et al., 2007; Lamsal et al., 2015).

Hourly PM$_{2.5}$ and ozone measurements are obtained from South DeKalb and United Avenue stations, both urban UA stations. The hourly data at South DeKalb station is from a Teledyne T640 PM Mass Monitor which an optical aerosol spectrometer for measurement with 0.1-10000 µg/m$^3$ measurement range and 0.5 µg/m$^3$ (1-h average) (Georgia Department of Natural Resources, 2019). The United Avenue station uses a tapered element oscillating microbalance (TEOM) which collected particles on a filter with a measurement range of 0-5 g/m$^3$, and 1.5 µg/m$^3$ precision (1-hour average) (Georgia Department of Natural Resources, 2020). The hourly ozone measurements of both stations are obtained from Model 49i Ozone Analyzer manufactured by Thermo Fisher that is based on continuous ultraviolet photometric method. The measurement range is from 0.05 ppb to 200 ppm with 1.0 ppb precision (Georgia Department of Natural Resources, 2020).

2.3 Meteorological data

We use meteorological data from MERRA-2 (Modern-Era Retrospective analysis for Research and Applications, Version 2) (Gelaro et al., 2017). These meteorological data include 2-meter (2m) wind speed, 2m wind direction, 2m temperature and 2m relative humidity (RH), 850 hPa and 500 hPa wind speed and wind direction, planetary boundary layer (PBL) top pressure and cloud cover. MERRA-2 is an atmospheric reanalysis model produced by NASA Global Modeling and Assimilation Office (GMAO) with a spatial resolution of 0.5°×0.625°. Due to the spatial resolution of our meteorological data, microscale and fine mesoscale features will not be accounted for, but these effects should be minor in this study. In addition, we obtain precipitation measurements from the weather station located in Atlanta Hartsfield Jackson International Airport as shown in Fig. 1.

2.4 TROPOMI NO$_2$ observations
TROPOMI is the single payload aboard the Sentinel 5 Precursor (S5P) satellite that has a sun-synchronous orbit with a local overpass time of approximately 13:30 with a near-daily global coverage since April 2018 (Veefkind et al., 2012). The TROPOMI NO$_2$ retrieval algorithm is developed by the Royal Netherlands Meteorological Institute and based on the NO$_2$ DOMINO algorithm with significant improvements including the improved retrieval of slant column density and spectral fitting (Boersma et al., 2018; Lorente et al., 2017; Van Geffen et al., 2015). TROPOMI retrieves tropospheric NO$_2$ with a pixel size of 7 km × 3.5 km at nadir, and the resolution has been improved to 5.5 km × 3.5 km with a change in the S5P operation scenario since August 6, 2019 (orbit 9388) (Eskes and Eichmann, 2019). We only use TROPOMI offline observations with cloud coverage less than 0.3, and quality assurance greater than 0.75 (Eskes and Eichmann, 2019).

2.5 Traffic data

We use traffic count data as the indicator of human activities in this study, as private vehicles are the major commuting tool in the Atlanta area (Atlanta Regional Commission, 2020). The traffic count data are collected from the Georgia Department of Transportation (GDOT) using the (GDOT)’s Traffic Analysis and Data Application (TADA) (https://gdottrafficdata.drakewell.com/publicmultinodemap.asp). GDOT collects traffic information through Continuous Count Stations (CCSs) installed on all types of public roads in Georgia. Each CCS is designed to provide volume counts continuously (24 hours per day, 7 days per week, 365 days per year) except during maintenance periods. We select three CCSs on major highways in the downtown and midtown areas of Atlanta to capture the traffic variation during the COVID-19 lockdown as shown in Fig. 1.

3 Methodology

3.1 Conversion of TROPOMI level 2 data to level 3
We produce level 3 data in the 2020 COVID-19 lockdown period (March 14 – April 30, 2020) and its analogous period of 2019 (March 14- April 30, 2019) by averaging level 2 data to a common, regular 0.01°×0.01° grid and using a physical oversampling method to the regridded level 3 tropospheric NO$_2$ data. The physical oversampling method by Sun et al. (2018) temporally and spatially averages the level 2 satellite observations to level 3 grids. Two-dimensional super Gaussian functions are used to represent the spatial response functions of satellite sensors. In comparison with conventional approaches that only consider the pixel corners, this method gives considerable advantages of visualizing the distribution and local gradients of trace gases and for scenarios with short temporal windows (Huang and Sun, 2020; Sun et al., 2018).

4 Results and Discussion

4.1 Meteorological Analysis

We compare meteorological parameters over the Atlanta area during the 2020 COVID-19 lockdown period and its analogous period in 2019 as listed in Table 1. The 2m wind are similar in 2019 (1.12 ± 0.53 m s$^{-1}$) and 2020 (1.09 ± 0.50 m s$^{-1}$) with wind direction changing from southwesterly (233° ± 91°) in 2019 to westerly (273° ± 83°) in 2020. 850 hPa and 500 hPa winds have also increased 16% from 8.53 m s$^{-1}$ (± 4.61 m s$^{-1}$) in 2019 to 9.92 m s$^{-1}$ (± 4.29 m s$^{-1}$) in 2020, and 44% from 17.89 m s$^{-1}$ ((± 7.53 m s$^{-1}$) in 2019 to 25.72 m s$^{-1}$ (± 7.04 m s$^{-1}$) in 2020, respectively. The wind direction at 850 hPa has changed from 247° (± 74°) in 2019 to 264° (± 41°) in 2020, while the wind direction at 500 hPa has changed slightly from 266°(± 32°) in 2019 to 270°(± 19°) in 2020.

The wind speed enhancement and wind direction change in 2020 may have strong and different impacts on the air pollution at ground level. 2-m wind direction has changed from 233° in 2019 to 273° in 2020, while the wind speed is similar. The dominant west wind in 2020 may transport air pollutants from downtown and midtown areas to the west of Atlanta, where all ground stations are, to increase ground stations' measurements. The impact of wind direction change may have a larger
impact on the NR station. The dominant southwest wind at 2m height in 2019 blows air pollutants away from the NR-285 station located in the south of I-285, while the dominant west wind in 2020 increases the concentrations at NR-285 station (Richmond-Bryant et al., 2017; Venkatram et al., 2013). As a result, the wind direction change may reduce the NO\textsubscript{2} difference between 2020 and 2019 measured by both ground stations.

The higher wind speed at 850 hPa in 2020 may improve air quality through rapid transport and dispersion of air pollutants from local emission sources, even 2-m wind speed are similar in 2019 and 2020 (Goldberg et al., 2020; Naeger and Murphy, 2020). The larger enhancement of wind speed at 500 hPa in 2020 may cause more reductions in tropospheric NO\textsubscript{2} columns observed by TROPOMI than ground NO\textsubscript{2} measurements.

Temperature in 2020 COVID-19 lockdown period is slightly higher than the analogous period of 2019, while relative humidity, atmospheric boundary layer heights and cloud cover are similar in 2019 and 2020. On the other hand, precipitation in 2020 is 28% higher than precipitation in 2019. The considerably larger precipitation in 2020 is expected to washout air pollutants to improve the air quality in 2020 (Goldberg et al., 2020). In sum, meteorological conditions have contributed to improved air quality in the Atlanta area in the 2020 COVID-19 lockdown period. The meteorological conditions have different impacts on concentrations of air pollutants measured by ground stations and satellites.

4.2 Traffic Volume

Traffic volume has reduced 48.7% in 2020 relative to 2019 in the downtown and midtown areas of Atlanta due to the COVID-19 lockdown. Fig. 2 (a) shows the mean hourly traffic volume from February 1 to April 30 in both 2019 and 2020. We have applied a 7-day moving average to smooth out the weekend’s effect on traffic volume. The traffic volume does not have a strong variation in 2019 and the traffic volume before the lockdown in 2020 is similar to 2019. The traffic volume has
decreased dramatically as the declaration of public health emergency on March 14, 2020, and reached the minimum on April 7, 2020, approximately 60% less than in the same period of 2019.

The daily variation of hourly traffic volume in the COVID-19 lockdown of 2020 and its analogous period of 2019 are shown in Fig. 2 (b) and (c). Atlanta has long peak traffic hours from 6:00-19:00 daily in 2019. These hourly traffic features in the 2020 COVID-19 lockdown are similar to 2019 with significant reductions. The traffic volume in 2020 has reduced 40%-50% during peak hours (6:00-19:00), and 50%-63% during off-peak hours (20:00 – 5:00).

4.3 NO₂

Tropospheric NO₂ columns from TROPOMI in 2020 COVID-19 lockdown and the analogous period in 2019 are shown in Fig. 3(a) and 3(b). Tropospheric NO₂ columns have remained high (> 0.1 Dobson Unit (DU)) over the entire Atlanta area in 2019, with tropospheric NO₂ hotspots along major highways, over the downtown and midtown of Atlanta (~0.15 DU), and Atlanta International Airport (>0.15 DU) as shown in Fig. 3(a). These tropospheric NO₂ hotspots in downtown and midtown areas are associated with human activities and ground traffic; the hotspot near Atlanta International Airport is associate with air traffic (Rissman et al., 2013).

During the COVID-19 lockdown, tropospheric NO₂ columns have reduced 28.1% (0.03DU) over the entire Atlanta metropolitan area as shown in Fig.3(c). However, some tropospheric NO₂ hotspots with fewer intensities still exist in 2020 in junctions of major highways located in the northwest, northeast and southwest corners of I-285 likely due to the remaining traffic. Goldberg et al., (Goldberg et al., 2020) has shown a 35.2% reduction of tropospheric NO₂ columns over the Atlanta area in 2020 lockdown period, compared to the analogous period of 2019. Our results are comparable with this study.

Mean ground NO₂ measurements in 2020 COVID-19 lockdown and the analogous period of 2019 are listed in Table 2. Ground NO₂ measurements have also decreased in 2020 COVID-19
lockdown period. NR NO$_2$ has decreased from 14.99 ppb (± 5.67 ppb) in 2019 to 13.37 ppb (± 4.42 ppb) in 2020 with 10.8% reduction. UA NO$_2$ has decreased from 8.25 ppb (± 3.23 ppb) in 2019 to 7.57 ppb (± 3.02 ppb) in 2020 with 8.2% reduction.

Fig. 4 plots the hourly variation of NO$_2$ in 2020 COVID-19 lockdown and the analogous period of 2019. Although daily mean NO$_2$ has decreased in 2020, hourly mean NO$_2$ in 2020 are not consistently lower than 2019 as shown in Fig. 4(a). 2020 NR NO$_2$ during 19:00 and 8:00 is up to ~25% lower than 2019 NR NO$_2$ at the same hours, while 2020 NR NO$_2$ during 11:00 and 18:00 is up to 35% higher than 2019. On the other hand, UA NO$_2$ in 2020 is ~10% higher than 2019 during 22:00 to 1:00, while 2020 UA NO$_2$ become up to 30% lower than 2019 from 3:00 to 10:00. UA NO$_2$ from 11:00 to 20:00 in 2020 is slightly less than 2019.

Collocated TROPOMI observations have indicated more significant reductions of tropospheric NO$_2$. These collocated tropospheric NO$_2$ columns are mean values of tropospheric NO$_2$ columns of 3×3 grids centered at each station. TROPOMI observations have shown tropospheric NO$_2$ over NR and UA stations have decreased ~23% and 21% at the overpass time of TROPOMI (~13:30 local time), respectively. These reductions of tropospheric NO$_2$ columns observed by TROPOMI are higher than the reductions observed by ground stations. There are several factors may cause this disagreement between TROPOMI and ground observations. First, the tropospheric NO$_2$ columns measured by TROPOMI and NO$_2$ measured by ground stations are not the same, although tropospheric NO$_2$ columns and ground NO$_2$ may have high correlations (Cersosimo et al., 2020; Demetillo et al., 2020). The reductions in traffic and human activities may cause different percentage reductions for ground NO$_2$ and tropospheric NO$_2$ columns. Second, meteorological conditions may have different impacts on TROPOMI and ground measurements as discussed in Section 4.1. Third, TROPOMI may underestimate tropospheric NO$_2$ due to uncertainties from air mass factors (Griffin et al., 2019). Forth, the uncertainties of chemiluminescence NO$_2$ measurement

may also contribute to this disagreement as these uncertainties reach maximum in the early afternoon and minimum in the morning (Dunlea et al., 2007; Lamsal et al., 2015). Ground NO\textsubscript{2} measurements in 4:00 – 8:00 show ~18-30% reductions of NO\textsubscript{2} in both NR and UA stations as shown in Fig. 4(b). These NO\textsubscript{2} reduction measured by ground stations agree well with TROPOMI observations. Consequently, studies using satellite and ground NO\textsubscript{2} measurements should take these factors into account.

4.4 Ozone

Mean ground ozone mixing ratio during COVID-19 lockdowns in 2020 and its analogue periods of 2019 are listed in Table 2. Mean ground ozone during 2020 COVID-19 lockdowns has decreased 15.7% from 33.67 ppb (± 9.78 ppb) to 28.40 ppb (± 8.94 ppb) in the analogous period in 2019.

Ground ozone during 2020 COVID-19 lockdowns has reduced consistently relevant to the analogous period in 2019 as shown in Fig. 5. Ground ozone has decreased 15-20% during daytime, and 20-30% during nighttime. Ground ozone has indicated the smallest reductions as 5-10% during morning and evening transition time. The Atlanta area is a NO\textsubscript{x}-controlled scenario for ozone production (Jin et al., 2020; McDonald et al., 2018; Wolff et al., 2013). The combination of slightly increased Formaldehyde (HCHO) (Sun et al., 2021) and reduced NO\textsubscript{x} emissions have developed a more NO\textsubscript{x}-controlled scenario for ozone production in the Atlanta area. As a result, this significant ozone reduction in the Atlanta area is primarily caused by the reduced NO\textsubscript{x} emission of COVID-19 lockdowns and increased HCHO emission of high temperature.

4.5 PM\textsubscript{2.5}

Mean PM\textsubscript{2.5} during 2020 COVID-19 lockdowns is 9.98 µg/m\textsuperscript{3} (± 1.58µg/m\textsuperscript{3}), with 5% less than 10.44 µg/m\textsuperscript{3} (± 1.78µg/m\textsuperscript{3}) in the analogous period in 2019 as listed in Table 2. Hourly mean PM\textsubscript{2.5} concentrations during 2020 COVID-19 lockdown are slightly lower than the analogous period in
2019 at most time as shown in Fig. 6. PM$_{2.5}$ in 2020 is up to ~17% lower than 2019 most time but up to ~8% higher during 13:00 - 16:00. The PM$_{2.5}$ chemistry is more complicated than ozone. Some PM$_{2.5}$ is primarily emitted directly from vehicles, which may be associated with the reduced traffic volumes due to the COVID-19 lockdowns. On the other hand, PM$_{2.5}$ is also produced through complex reactions of gases (Kroll et al., 2020). In sum, the reduced traffic may cause the reduction of PM$_{2.5}$, but more studies are needed to understand the non-linear chemistry behind the reductions.

5 Conclusions

We have utilized satellite and ground measurements, and reanalysis data in conjunction with traffic information to understand how NO$_2$, a major air pollutant, responds to the decreased human activities in the Atlanta metropolitan area during the 2020 COVID-19 lockdown (March 14- April 30, 2020). Human activities, measured by traffic volume, in 2020 COVID-19 lockdown period has decreased 48.7% relevance to the analogous period of 2019. Furthermore, the human activities in 2020 have reduced 40%-50% during peak hours (6:00-19:00), and 50%-63% during off-peak hours (20:00 – 5:00).

Air quality in the Atlanta area during COVID-19 lockdown period has improved slightly, although human activities in 2020 are only approximately half of 2019. Ground NO$_2$ in 2020 has reduced 10.8% and 8.2% by NR and UA stations, respectively. The reductions of ground NO$_2$ indicate strong temporal variation in NR and UA stations. Tropospheric NO$_2$ columns are observed 28.1% reductions by TROPOMI over the Atlanta area in 2020 COVID-19 lockdown period, compared to the analogous period of 2019. TROPOMI observations have indicated that tropospheric NO$_2$ columns have decreased ~23% and ~21% over NR and UA stations, respectively, while collocated ground NO$_2$ has increased ~20% by the NR station and decreased ~10% by the UA station on the overpass time of TROPOMI. Some factors may cause the disagreement on NO$_2$ changes between ground and satellite observations. First, tropospheric NO$_2$ columns measured by
TROPOMI and ground NO2 concentrations measured ground stations are not necessarily the same, although they are highly correlated in the afternoon (Cersosimo et al., 2020; Demetillo et al., 2020). The decreased ground NOx emission may cause different percentage changes in tropospheric NO2 columns and ground NO2 concentrations. Second, meteorological conditions may have different impacts on TROPOMI and ground measurements. Third, TROPOMI may underestimate tropospheric NO2 due to uncertainties from air mass factors (Griffin et al., 2019). Forth, the uncertainties of chemiluminescence NO2 measurement may also contribute to this disagreement as these uncertainties reach maximum in the early afternoon and minimum in the morning (Dunlea et al., 2007; Lamsal et al., 2015). Consequently, studies using satellite and ground NO2 measurements should take these factors into account.

Ground ozone and PM2.5 both have decreased over the Atlanta area during the 2020 COVID-19 lockdowns. Ground ozone in 2020 has decreased 15.7% relevance to 2019. The Atlanta area is NOx-controlled for ozone photochemistry due to the local NOx emission control (Jin et al., 2020; McDonald et al., 2018; Wolff et al., 2013). In 2020, the slightly increased HCHO concentrations over the southeast U.S. due to the warmer temperature made the Atlanta area a more NOx-controlled scenario for ozone photochemistry.

PM2.5 in the 2020 COVID-19 period has decreased ~5% relevance to the analogous period of 2019. Hourly PM2.5 concentrations in 2020 are slightly lower than 2019 in most time, but up to ~8% higher during 13:00-16:00. The reduced traffic may cause the slight decrease of ground PM2.5, but further studies are needed to understand the non-linear chemistry of PM2.5.

Meteorological conditions have also contributed to the improvement of air quality over the Atlanta area in 2020 COVID-19 period. Higher wind speed and precipitations in 2020 are favorable for better air quality (Goldberg et al., 2020).
We conclude that air quality has improved slightly in the Atlanta area during 2020 COVID-19 lockdown (March 14 – April 20, 2020) compared to the same period in 2019, although human activities has reduced ~50%. This slight improvement is primarily caused by reduced human activities induced by COVID-19 lockdowns. Meteorological conditions have also contributed to this improvement of air quality. Due to the complex chemistry, further studies are needed to quantitatively understand the impacts of reduced vehicle emissions on atmospheric chemistry as consequences of the COVID-19 pandemic.

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Figure 1 Map of the Atlanta metropolitan area. The purple lines represent major highways, including interstate highways (e.g. I-75, I-85, I-285 and I-675) and Georgia 400 highway (marked as GA-400). Orange and blue dots represent traffic volume measurement sites and air quality measurement sites, respectively. The airplane symbol represents the Atlanta International Airport. The shadow area shows the downtown and midtown areas of Atlanta.
Figure 2. Hourly traffic volume in the Atlanta area. Panel (a) plots time series of hourly traffic volume in 2019 (marked in light blue) and 2020 (marked in light orange), and 7-day moving average hourly traffic volume in 2019 by solid blue lines and 2020 by solid orange lines. Panel (b) plots hourly mean traffic volume during COVID-19 lockdown in 2020 marked by solid orange lines and the analogous period in 2019 marked by solid blue lines, respectively. Panel (c) plots ratios of hourly traffic of 2020 COVID-19 lockdown to the 2019 analogous period.
Figure 3. Tropospheric NO$_2$ column densities over the Atlanta area observed by TROPOMI during the 2020 COVID-19 lockdown (March 14 to April 30, 2020) in panel (a) and the 2019 analogous period (March 14 to April 30, 2019) in panel (b). MT and DT represents the midtown and downtown areas of Atlanta. Panel (c) plots the differences of tropospheric NO$_2$ columns over the Atlanta area in 2020 COVID-19 lockdown and 2019 analogous period (2020 minus 2019).
Figure 4 Hourly mean NO\textsubscript{2} measured by a near-road (NR, NR-285) station and urban ambient (UA, South Dekalb) station during 2020 COVID-19 lockdown period (March 14 – April 30, 2020) and the analogous period of 2019 (March 14 – April 30, 2019) in the Atlanta area. Panel (a) shows hourly mean NO\textsubscript{2} in 2019 (marked by blue) and 2020 (marked by orange) measured by near-road (NR, marked by triangles) and background (UA, marked by rounds), respectively. Panel (b) plots ratios of hourly 2020 NO\textsubscript{2} to 2019 NO\textsubscript{2} measured by NR and UA ground stations marked by blue triangles and rounds, respectively. The red triangle and round represent ratios of 2020 to 2019 tropospheric NO\textsubscript{2} columns measured by TROPOMI collocated with NR and UA ground stations, respectively.
Figure 5 Hourly mean ozone mixing ratio measured by urban ambient (UA) stations, South DeKalb and United Avenue during 2020 COVID-19 lockdown period (March 14 – April 30, 2020) and the analogous period of 2019 (March 14 – April 30, 2019). Panel (a) shows hourly mean ozone concentrations in 2019 (marked by blue) and 2020 (marked by orange), respectively. Panel (b) plots ratios of hourly 2020 ozone to 2019 ozone.
Figure 6 Same as Figure 5 but for Particulate Matter 2.5 (PM2.5) concentrations measured by two urban ambient stations, South DeKalb and United Avenue.
Table 1 Mean meteorological fields with standard deviations over the Atlanta area during the COVID-19 lockdown period in 2020 and the analogous period in 2019.

<table>
<thead>
<tr>
<th></th>
<th>2m WS (m/s)</th>
<th>2m WD (°)</th>
<th>850 hPa WS(m/s)</th>
<th>850 hPa WD(°)</th>
<th>500 hPa WS(m/s)</th>
<th>500 hPa WD(°)</th>
<th>Temp. (°C)</th>
<th>PBL Top (hPa)</th>
<th>Rh (%)</th>
<th>Cloud Cover (mm)</th>
<th>Prep. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>1.09 ± 0.50</td>
<td>273 ± 83</td>
<td>9.92 ± 4.29</td>
<td>264 ± 41</td>
<td>25.72 ± 7.04</td>
<td>270 ± 19</td>
<td>15.60 ± 3.17</td>
<td>902 ± 29</td>
<td>81 ± 9</td>
<td>0.56 ± 0.38</td>
<td>172</td>
</tr>
<tr>
<td>2019</td>
<td>1.12 ± 0.53</td>
<td>233 ± 91</td>
<td>8.53 ± 4.61</td>
<td>247 ± 74</td>
<td>17.89 ± 7.53</td>
<td>266 ± 32</td>
<td>14.49 ± 4.55</td>
<td>901 ± 24</td>
<td>78 ± 8</td>
<td>0.53 ± 0.40</td>
<td>134</td>
</tr>
</tbody>
</table>
Table 2 Mean and standard deviation of NO$_2$ (near-road (NR) and background(UA)), ozone and PM$_{2.5}$ concentrations during the COVID-19 lockdown period 2020 and the analogous period of 2019.

<table>
<thead>
<tr>
<th></th>
<th>NO$_2$ (ppb)</th>
<th>Ozone (ppb)</th>
<th>PM2.5 ($\mu$m/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NR</td>
<td>UA</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>13.37 ± 4.24</td>
<td>7.57 ± 3.02</td>
<td>28.40 ± 8.94</td>
</tr>
<tr>
<td>2019</td>
<td>14.99 ± 5.67</td>
<td>8.25 ± 3.23</td>
<td>33.67 ± 9.78</td>
</tr>
</tbody>
</table>