Unexpected Impact of COVID-19 Lockdown on the Air Quality in the Metro Atlanta, USA Using Ground-based and Satellite Observations

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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 TROPospheric Monitoring Instrument (TROPOMI). Ground ozone and PM_{2.5} 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 air quality over 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 NO₂ reductions, as collocated TROPOMI observations revealed ~23% and ~21% reductions of tropospheric NO₂ columns over NR and UA stations, respectively. Several factors may explain this disagreement: First, tropospheric NO₂ columns and ground NO₂ 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 NO₂ due to uncertainties from air mass factors. Fourth, the uncertainties of chemiluminescence NO₂ measurements used by ground stations. Consequently, studies using space-borne tropospheric NO₂ column and ground NO₂ measurements should take these factors into account.

Keywords: COVID-19, Air quality, TROPOMI, NO₂

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.

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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-Solís *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 NO_2 concentrations over populous areas in the world (Lamsal *et al.*, 2013, 2008). It is not surprising that ambient 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 NO_2 . The production of ozone depends on volatile organic compounds (VOCs) and NO_x with the presence of sunlight. When VOCs are high and NO_x is low, it is the “ NO_x ” controlled situation. In this situation, more NO_x means more ozone. When VOCs are low and NO_x is high, it is the “VOCs” limited situation. More 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 $\text{PM}_{2.5}$ 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 $\text{PM}_{2.5}$ 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 meteorological 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 $\text{PM}_{2.5}$ 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 metropolises 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.*, 2015, 2017). 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.

The state of Georgia declared a Public Health State of Emergency in response to COVID-19 on March 14, 2020 (The State of Georgia, 2020a), a shelter-in-place order on March 23, 2020 in order to slow the spread of COVID-19, lifted the order on April 30, 2020 (The State of Georgia, 2020b). The 2020 COVID-19 lockdown period and its analogous period of 2019 are defined March 14–April 30, 2020 and March 14–April 30, 2019, respectively, in this study.

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 NO₂ 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 NO₂ has been measured by U.S. Environmental Protection Agency (U.S. EPA)-designated NO₂ 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–NO₂–NO_x) Analyzer for NO₂ monitoring with 0–0.05 to 100 ppm range and ± 0.40 ppb precision (Georgia Department of Natural Resources, 2020). These regulatory NO₂ chemiluminescence measurements are known to contain some uncertainties due to their sensitivity to other nitrogen species (Dunlea *et al.*, 2007). The magnitude

Fig. 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 measurements sites, respectively. The airplane symbol represents the Atlanta International Airport. The shadow area shows the downtown and midtown areas of Atlanta.

of the total interference is variable, and depends not only on the relative fraction of actual NO_2 to total reactive nitrogen compounds (NO_y), 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 $\text{PM}_{2.5}$ and ozone measurements are obtained from South DeKalb and United Avenue stations, both urban UA stations. The hourly data at South DeKalb station are from a Teledyne T640 PM Mass Monitor which is an optical aerosol spectrometer for measurement with $0.1\text{--}10000\text{ }\mu\text{g m}^{-3}$ measurement range and $0.5\text{ }\mu\text{g m}^{-3}$ (1-h average) (Georgia Department of Natural Resources, 2019). The United Avenue station uses a tapered element oscillating microbalance (TEOM) which collects particles on a filter with a measurement range of $0\text{--}5\text{ g m}^{-3}$, and $1.5\text{ }\mu\text{g m}^{-3}$ 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 (2 m) wind speed, 2 m wind direction, 2 m temperature and 2 m 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 $0.5^\circ \times 0.625^\circ$. 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 $7\text{ km} \times 3.5\text{ km}$ at nadir, and the resolution has been improved to $5.5\text{ km} \times 3.5\text{ km}$ 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 $0.01^\circ \times 0.01^\circ$ grid and using a physical oversampling method to the regridded level 3 tropospheric NO₂ 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 2 m wind are similar in 2019 ($1.12 \pm 0.53 \text{ m s}^{-1}$) and 2020 ($1.09 \pm 0.50 \text{ m s}^{-1}$) with wind direction changing from southwesterly ($233^\circ \pm 91^\circ$) in 2019 to westerly ($273^\circ \pm 83^\circ$) in 2020. 850 hPa and 500 hPa winds have also increased 16% from 8.53 m s^{-1} ($\pm 4.61 \text{ m s}^{-1}$) in 2019 to 9.92 m s^{-1} ($\pm 4.29 \text{ m s}^{-1}$) in 2020, and 44% from 17.89 m s^{-1} ($\pm 7.53 \text{ m s}^{-1}$) in 2019 to 25.72 m s^{-1} ($\pm 7.04 \text{ m s}^{-1}$) in 2020, respectively. The wind direction at 850 hPa has changed from $247^\circ (\pm 74^\circ)$ in 2019 to $264^\circ (\pm 41^\circ)$ in 2020, while the wind direction at 500 hPa has changed slightly from $266^\circ (\pm 32^\circ)$ in 2019 to $270^\circ (\pm 19^\circ)$ 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 2 m 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 NO₂ 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 NO₂ columns observed by TROPOMI than ground NO₂ 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, the precipitation in 2020 is 28% higher than 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

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.

	2 m WS (m s^{-1})	2 m WD ($^\circ$)	850 hPa WS (m s^{-1})	850 hPa WD ($^\circ$)	500 hPa WS (m s^{-1})	500 hPa WD ($^\circ$)	Temp. ($^\circ\text{C}$)	PBL Top (hPa)	Rh (%)	Cloud Cover	Prep. (mm)
2020	1.09 ± 0.50	273 ± 83	9.92 ± 4.29	264 ± 41	25.72 ± 7.04	270 ± 19	15.60 ± 3.17	902 ± 29	81 ± 9	0.56 ± 0.38	172
2019	1.12 ± 0.53	233 ± 91	8.53 ± 4.61	247 ± 74	17.89 ± 7.53	266 ± 32	14.49 ± 4.55	901 ± 24	78 ± 8	0.53 ± 0.40	134

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 Figs. 2(b) and 2(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).

Fig. 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.

4.3 NO₂

Tropospheric NO₂ columns from TROPOMI in 2020 COVID-19 lockdown and the analogous period in 2019 are shown in Figs. 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 associated 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.* (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 NO₂ 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 NO₂ 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 NO₂ in 2020 COVID-19 lockdown and the analogous period of 2019. Although daily mean NO₂ has decreased in 2020, hourly mean NO₂ in 2020 are not consistently lower than 2019 as shown in Fig. 4(a). 2020 NR NO₂ during 19:00 and 8:00 is up to ~25% lower than 2019 NR NO₂ at the same hours, while 2020 NR NO₂ during 11:00 and 18:00 is up to 35% higher than 2019. On the other hand, UA NO₂ in 2020 is ~10% higher than 2019 during 22:00 to 1:00, while 2020 UA NO₂ become up to 30% lower than 2019 from 3:00 to 10:00. UA NO₂ from 11:00 to 20:00 in 2020 is slightly less than 2019.

Fig. 3. Tropospheric NO₂ column densities over the Atlanta area observed by TROPOMI during the 2020 COVID-19 lockdown (March 14–April 30, 2020) in panel (a) and the 2019 analogous period (March 14–April 30, 2019) in panel (b). MT and DT represents the midtown and downtown areas of Atlanta. Panel (c) plots the differences of tropospheric NO₂ columns over the Atlanta area in 2020 COVID-19 lockdown and 2019 analogous period (2020 minus 2019).

Table 2. Mean and standard deviation of NO₂ (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.

	NO ₂ (ppb)		Ozone (ppb)	PM _{2.5} ($\mu\text{m m}^{-3}$)
	NR	UA		
2020	13.37 $\pm$ 4.24	7.57 $\pm$ 3.02	28.40 $\pm$ 8.94	9.98 $\pm$ 1.58
2019	14.99 $\pm$ 5.67	8.25 $\pm$ 3.23	33.67 $\pm$ 9.78	10.44 $\pm$ 1.78

Fig. 4. Hourly mean NO₂ 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 NO₂ 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 NO₂ to 2019 NO₂ 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 NO₂ columns measured by TROPOMI collocated with NR and UA ground stations, respectively.

Collocated TROPOMI observations have indicated more significant reductions of tropospheric NO₂. These collocated tropospheric NO₂ columns are mean values of tropospheric NO₂ columns of 3×3 grids centered at each station. TROPOMI observations have shown tropospheric NO₂ 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 NO₂ 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 NO₂ columns measured by TROPOMI and NO₂ measured by ground stations are not the same, although tropospheric NO₂ columns and ground NO₂ 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 NO₂ and tropospheric NO₂ columns. Second, meteorological conditions may have different impacts on TROPOMI and ground measurements as discussed in Section 4.1. 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). Ground NO₂ measurements in 4:00–8:00 show ~18–30% reductions of NO₂ in both NR and UA stations as shown in Fig. 4(b). These NO₂ reduction measured by ground stations agree well with TROPOMI

observations. Consequently, studies using satellite and ground NO_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_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_x emissions have developed a more NO_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_x emission of COVID-19 lockdowns and increased HCHO emission of high temperature.

4.5 $\text{PM}_{2.5}$

Mean $\text{PM}_{2.5}$ during 2020 COVID-19 lockdowns is $9.98 \mu\text{g m}^{-3}$ ($\pm 1.58 \mu\text{g m}^{-3}$), with 5% less than $10.44 \mu\text{g m}^{-3}$ ($\pm 1.78 \mu\text{g m}^{-3}$) in the analogous period in 2019 as listed in Table 2. Hourly mean $\text{PM}_{2.5}$ concentrations during 2020 COVID-19 lockdown are slightly lower than the analogous period in 2019 at most time as shown in Fig. 6. $\text{PM}_{2.5}$ in 2020 is up to ~17% lower than 2019 most time but up to ~8% higher during 13:00–16:00. The $\text{PM}_{2.5}$ chemistry is more complicated than ozone.

Fig. 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.

Fig. 6. Same as Fig. 5 but for Particulate Matter 2.5 (PM_{2.5}) concentrations measured by two urban ambient stations, South DeKalb and United Avenue.

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 NO₂, 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 NO₂ in 2020 has reduced 10.8% and 8.2% by NR and UA stations, respectively. The reductions of ground NO₂ indicate strong temporal variation in NR and UA stations. Tropospheric NO₂ 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 NO₂ columns have decreased ~23% and ~21% over NR and UA stations, respectively, while collocated ground NO₂ 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 NO₂ changes between ground and satellite observations. First, tropospheric NO₂ 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 NO_x emission may cause different percentage changes in tropospheric NO_2 columns and ground NO_2 concentrations. 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 (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). Consequently, studies using satellite and ground NO_2 measurements should take these factors into account.

Ground ozone and $\text{PM}_{2.5}$ 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 NO_x -controlled for ozone photochemistry due to the local NO_x 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 NO_x -controlled scenario for ozone photochemistry.

$\text{PM}_{2.5}$ in the 2020 COVID-19 period has decreased ~5% relevance to the analogous period of 2019. Hourly $\text{PM}_{2.5}$ 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 $\text{PM}_{2.5}$, but further studies are needed to understand the non-linear chemistry of $\text{PM}_{2.5}$.

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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