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Impact of the COVID-19 Pandemic on Air Quality in Metropolitan New Jersey

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Abstract Improved air quality has been the silver lining of the pandemic since early 2020. The air quality in northern New Jersey (NJ) was continuously measured during the COVID-19 pandemic and through the three stages of recovery, i.e., the Stay-at-home stage, Reopening stage 1, and Reopening stage 2. A significant change in air quality was observed during the Stay-at-home stage (March 16 to May 16, 2020) as most people stayed home and industrial activity decreased 60%. Compared to 2019, carbon dioxide (CO_2) decreased 17%, carbon monoxide (CO) decreased 7%, and nitrogen oxides (NO_x) decreased 51% during the Stay-at-home stage in 2020. However, the ground-level ozone (O_3) increased in 2020 because of the reduced NO_x emission and the possibly increased levels of volatile organic compounds (VOCs) due to warmer weather. With the step-by-step reopening process, the difference in local CO_2 levels between 2019 and 2020 was reduced, and the NO_x concentration returned to its 2019 level. The CO_2 concentrations were positively correlated with CO, and the NO_x concentrations were negatively correlated with O_3. Under the COVID-19 pandemic in 2020, NJ consumed 14% less natural gas and 21% less gasoline; therefore, the CO_2, CO, and NO_x emissions and concentration levels were reduced besides the effects of meteorology parameters on air quality in metropolitan New Jersey. Our findings support that replacing fossil fuels with electric or renewable energy in the transportation systems and industry could be beneficial for the concentration reduction of certain greenhouse gases.

Keywords COVID-19 · Air quality · Carbon dioxide · Carbon monoxide · Nitrogen oxides · Ground-level ozone

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1 Introduction

2019 novel coronavirus disease (COVID-19) is an ongoing disease caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The World Health Organization declared the outbreak a public health emergency of international concern on January 30, 2020 (World Health Organization, 2020b), and a pandemic on March 11 (World Health Organization, 2020a). Millions of cases of COVID-19 have been reported in more than 200 countries and territories, resulting in more than 3 million

deaths (CSSE, 2021). New Jersey, a densely populated state of 9 million people, was in the epicenter of the pandemic's first wave in the USA in early 2020. New Jersey is the state that had the second most cases in the USA before July 2020. On March 16, Executive Order No. 104 (Stay-at-home order) was issued in New Jersey to implement aggressive social distancing measures to mitigate the further spread of COVID-19 (State of New Jersey, 2020a). From March 16 to May 16, schools and universities were closed, as were many businesses such as casinos, fitness centers, movie theaters, and performing arts centers. In this first wave, New Jersey had reached the highest number of single-day deaths (412) on April 13 and the highest number of single-day new cases (4391) on April 16 (New Jersey COVID-19 Information Hub, 2020). New Jersey started reopening state parks, forests, and golf courses on May 2. From May 17 to June 15, New Jersey fully entered the Reopening stage 1, which allowed the reopening of low-risk activities and establishments such as non-essential construction, outdoor recreation, public and private beaches, boardwalks, and lakes (State of New Jersey, 2020b). New Jersey entered "Reopening stage 2" of its recovery from the pandemic on Monday, June 15. Moderate-risk activities and establishments, including outdoor dining, organized sports, childcare centers, non-essential retail stores, swimming pools, and other indoor facilities at limited capacity, gradually reopened (State of New Jersey, 2020b).

The COVID-19 pandemic has had and continued to have massive impacts on the economy and environment (Saadat et al., 2020). However, for air quality, the decreases of air pollutants concentrations were widely reported. Compared to the spring of 2019, the carbon monoxide levels in New York have dropped almost 50% and carbon dioxide by 10% due to the Stay-at-home order (Morrison, 2020), and decreases in $PM_{2.5}$ (36%) and NO_2 (51%) concentrations were also observed after the shutdown (Zangari et al., 2020). Around Pittsburgh, PA, the CO and NO_2 concentrations around the high-traffic sites were reduced up to 50% after COVID-related closures (Tanzer-Gruener et al., 2020). Nitrogen dioxide (NO_2) emission decreased in various European countries, such as Spain, the UK, and northern Italy, as shown by satellite remote sensing (Ficetola & Rubolini, 2020; Menut et al., 2020).

The air quality changes during the COVID-19 pandemic could be a reference for regional air quality control. In 2007, the state of New Jersey set a goal to reduce greenhouse gas emissions to 80% below 2006 levels by 2050 in Executive Order #54 (State of New Jersey, 2007). Globally, the CO_2 level in 2006 was about 380 ppm. The CO_2 level in 2020 reached 420 ppm. Many climatologists agree that the global atmospheric concentration of CO_2 increased roughly 2 ppm per year over the period 2006–2015 (Lindsey, 2020). The Intergovernmental Panel on Climate Change (IPCC) indicates that an emission scenario that would lead to a CO_2 equivalent concentration equal to or lower than 450 ppm would likely maintain warming to below a 2 °C increase relative to pre-industrial levels (IPCC, 2014). With the Regional Greenhouse Gas Initiative (RGGI), New Jersey's goal is to achieve 100% clean energy by 2050 by shifting to clean and renewable energy sources and reducing greenhouse gas emissions (RGGI, 2020). Greenhouse gas emissions (CO_2) during the pandemic were reduced, with about 60% of transportation and business activities turned off. This reduction provides an opportunity to understand the effects of massively reducing fossil fuel consumption on local greenhouse gas emissions. This highlights the effects clean and renewable energy would have on air quality.

The air quality in metropolitan New Jersey is a concern because of the high population density, multiple super-highways, three main US airports, power plants, trash incinerators, and industry. Northern New Jersey has the city of Newark, which is the largest city in the state with over 278,000 residents including 52% African American and 33% Hispanic/mixed, and where 28% of residents live below the poverty line (EPA, 2015). The city of Newark is well known for its poor air quality as it is surrounded by Port Newark, Newark International Airport, several energy generating stations, busy highways, and one of the largest incinerators on the east coast (Ironbound community corporation, 2020). Under the COVID-19 scenario and reduced economic activities, we can better understand the contributions of air pollutants from the local emission sources.

This study is centered in the metropolitan area of northern New Jersey, and the goal was to evaluate atmospheric concentrations of CO_2, CO, NO_x, and O_3 during the pre-pandemic stage, Stay-at-home stage, and stages of recovery and compare these with levels

in 2019. Our findings provide a reference of gas-phase air pollutant reductions that are possible if we change the transportation system to electric and use renewable energy to power our industry.

2 Methods and Materials

2.1 Study Area

Air quality was continuously monitored at the Meadowlands Environmental Research Institute (MERI) located at 2 Dekorte Park Plaza, Lyndhurst, NJ (40° 47′ 08.26″ N 74° 06′ 11.94″ W), and about 8 miles north of Newark, NJ (Fig. 1). This site has been used to support urban air quality studies in the past (Song et al., 2011; Xia & Gao, 2011). The parameters measured were CO_2, CO, NO_x, and ground-level ozone. The prevailing winds are from the southwest in the summer and from the northwest in the winter.

2.2 Study Period

The timeline of events for the COVID-19 pandemic is listed in Table 1. We studied the air quality data at the study site from March 2019 to July 2020. The first confirmed case of COVID-19 in the USA was reported on January 20, 2020 (Holshue et al., 2020), and the first reported death occurred on February 29, 2020 (Centers for Disease Control and Prevention, 2020). We considered the period from January 1 to March 15, 2020, to be the pre-pandemic stage. We separated the pandemic period (March 16 to July 30) into three stages: (1) The Stay-at-home stage, from March 16 to May 16. On March 16th, a Stay-at-home order was issued by the Governor of New Jersey (State of New Jersey, 2020a). After the order, traffic and business activity significantly decreased. (2) Reopening stage 1, from May 17 to June 14. On May 17, with fewer new cases and enhanced testing capacity, New Jersey moved forward to Reopening stage 1 (New Jersey COVID-19 Information Hub, 2020). Restrictions were relaxed on low-risk activities, and traffic slowly started to increase. (3) Reopening stage 2, from June 15 to July 30. On June 15, NJ moved to the second stage of reopening with additional activities permitted and proportionally increased traffic (New Jersey COVID-19 Information Hub, 2020). During Reopening stage 2, gas-phase pollutants were continuously monitored, but there was a data gap due

Fig. 1 Map of the study site

Table 1 Timeline of the COVID-19 pandemic in 2020

Timeline	Events	Stage	Reference
Jan 20, 2020	First confirmed case reported in the USA	Pre-pandemic	(Holshue et al., 2020)
Jan 30, 2020	WHO declares global health emergency		(World Health Organization, 2020b)
Feb 29, 2020	First reported death from COVID-19 in the USA		(Centers for Disease Control and Prevention, 2020)
March 16, 2020	NJ Stay-at-home order issued	Stay-at-home	(State of New Jersey, 2020a)
April 14, 2020	Peak hospital census		(New Jersey COVID-19 Information Hub, 2020)
May 17, 2020	Fully move to first stage of re-open	Reopening stage 1	(State of New Jersey, 2020b)
June 15, 2020	Move to second stage of re-open	Reopening stage 2	(State of New Jersey, 2020b)

to power outages and instrument malfunctions from July 6, 2020, to July 21, 2020. Table 2 shows the primary data availability within the study period.

2.3 Sampling and Analysis Method

Air samples were filtered with Whatman 5-μm pore size 47-mm-diameter Teflon filters to remove large particulate matter and then pumped into the gas analyzers from inlets through separate plastic tubes (Roberts-Semple et al., 2012). The gas analyzers were operated at room temperature. A data acquisition system (Envidas) (DR DAS LTD, USA) was used for gas analyzer calibration and data management. Every 5 min, the air sample was measured, and the results were added to the database.

Ozone was measured by a Thermo Scientific gas analyzer 49i, which uses UV Photometric technology to analyze the amount of ozone in the air from ppb levels up to 200 ppm. Carbon dioxide was analyzed by a Thermo

Scientific gas analyzer 410i. The CO level in the air was monitored by a Thermo Scientific gas analyzer 48i-TLE and by CO absorption of infrared radiation at a wavelength of 4.6 microns. The Model 48i-TLE uses an exact calibration curve to accurately linearize the instrument output over a wide range of concentrations. NO_x was analyzed by a Thermo Scientific gas analyzer 42i and by chemiluminescence (Roberts-Semple et al., 2012).

The meteorology data, including temperature, wind speed, wind direction, relative humidity (RH), solar radiation (SR), precipitation, and atmospheric pressure, was collected by the MERI weather station (Campbell Scientific), which is part of the New Jersey Weather Network, and it is co-located with the gas analyzers. The network used for data sharing is Mesonet.

2.4 Statistical Analysis

Parametric and non-parametric tests were used to determine differences between each month in 2019 and 2020 from March to June. Specifically, we used the analysis of variance (ANOVA) and the Wilcoxon non-parametric tests. Linear regression analysis was used to explore the relationship between the gas-phase air pollutants. The significance level for all tests was set to $p < 0.05$, and the corresponding confidence level was higher than 95%.

Table 2 Data collected at MERI and used in this study

| Parameters	Major valid data period
CO_2	March 2019 to July 2020
CO	March 2019 to April 2020
O_3	March 2019 to July 2020
NO_x	March 2019 to Dec. 2019, April 2020 to July 2020
Temperature	March 2019 to July 2020
Wind speed	March 2019 to July 2020
Wind direction	March 2019 to July 2020
Relative humidity	March 2019 to July 2020
Atmospheric pressure	March 2019 to July 2020

3 Results and Discussion

### 3.1 Air Quality Variation due to Activity Change

Based on the availability of our data, Fig. 2 illustrates the boxplots of CO_2, CO, NO_x, and O_3 concentration

at the study site during the pre-pandemic, Stay-at-home stage, Reopening stage 1, and Reopening stage 2. The data shown that the CO_2 level at the study site gradually decreased starting in March 2020. Our measuring station was close to a heavily trafficked highway, and therefore, the CO_2 level at this location was higher than the global CO_2 level. This reduction of CO_2 level could be caused by seasonal temperature variation, as solar radiation and photosynthesis level increased in the spring, resulting in the decrease of the CO_2 level (Gratani & Varone, 2005). However, the COVID-19 effects may dominate the CO_2 concentration reduction. Because of the "Stay-at-home" order, business activities and traffics decreased, which reduced fossil fuels consumption and CO_2 emissions. Based on the New Jersey natural gas consumption data, New Jersey consumed a total of 1.86×10^4 m³

natural gas in 2020, the lowest consumption amount since 2013 and 14% less than that consumed in 2019 (EIA, 2021b). For gasoline, the main product of fossil fuels and the primary US transportation fuel, New Jersey consumed 92,761 thousand barrels in 2019 and 73,693 thousand barrels in 2020, ~21% reduction of gasoline consumption in 2020 (EIA, 2021a). Figure 3A compares the CO_2 concentration levels in 2019 and 2020 at different temperatures. Results shown that with the same air temperature, the mean CO_2 level in 2020 was lower than that in 2019, suggesting the influence of COVID-19 effects on CO_2 concentration. In addition, as shown in Fig. 2, the CO_2 concentration had the smallest variation during the Stay-at-home stage compared to other stages, probably caused by the reduced anthropogenic emission.
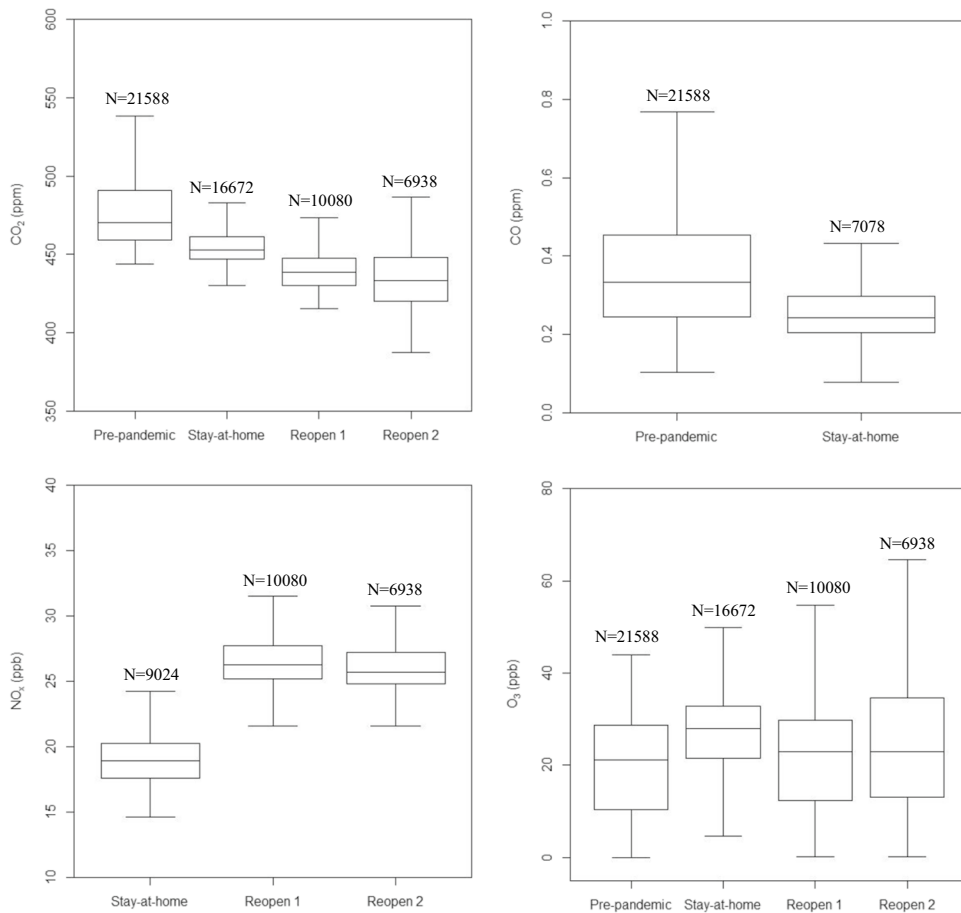
Fig. 2 The boxplots of CO_2, CO, NO_x, and O3 concentrations during the pre-pandemic period, Stay-at-home stage, and the Reopening stages. The numbers of the data points are listed above the boxes
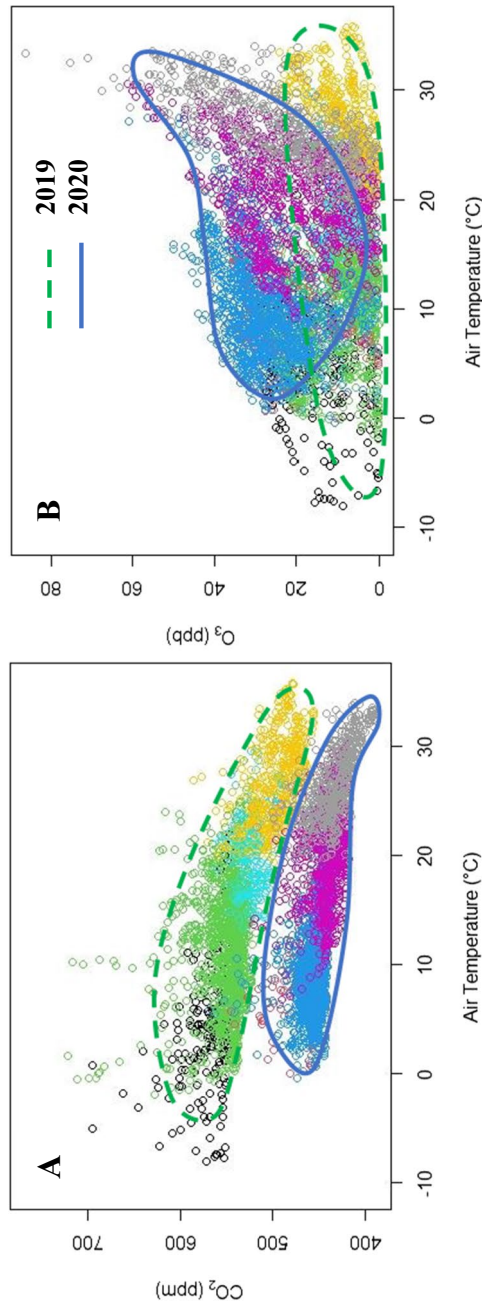
Fig. 3 **A** Effects of air temperature on the concentrations of CO_2; **B** effects of air temperature on the concentrations of O_3. Green dash line indicates the cluster of 2019 data points; blue solid line indicates the cluster of 2020 data points. Black circles are the data points for 2019 March 1 to March 15 (pre-pandemic period); orange circles are the data points for 2020 March 1 to March 15 (pre-pandemic period); green circles are the data points for 2019 March 16 to May 16 (Stay-at-home stage); blue circles are the data points for 2020 March 16 to May 16 (Stay-at-home stage); light blue circles are the data points for 2019 May 17 to June 14 (Reopening stage 1); purple circles are the data points for 2020 May 17 to June 14 (Reopening stage 1); yellow circles are the data points for 2019 June 15 to July 30 (Reopening stage 2); gray circles are the data points for 2020 June 15 to July 30 (Reopening stage 2)

Table 3 compares the CO_2 concentration levels in 2019 and 2020 at different stages. The mean, median, standard deviation, the *p*-value of ANOVA, and the *p*-value of Wilcoxon of each stage's CO_2 concentration are listed in Table 3. During the Stay-at-home stage, the CO_2 mean concentration of 2020 decreased 17%. During the Reopening stage 1 and stage 2, the CO_2 mean level of 2020 decreased 15% and 12%, respectively, as traffic and business activities were gradually restored during the reopening process. The CO_2 reductions during all three stages in 2020 were significant ($p < 0.01$) and comparable to the reduction observed in New York, which is about 10% compared to the spring of 2019 (Morrison, 2020). The decrease of local CO_2 levels in the atmosphere during the COVID-19 pandemic could be caused by the reduction of CO_2 emissions from the nearby highways, airports, power plants, trash incinerators, and industry. For New Jersey, petroleum products are the primary energy source (53.4%), and the prime supplier sales of regular gasoline decreased from 8664 thousand gallons per day in February 2020 to 4005 thousand

Table 3 Summary of the statistical analyses for the concentrations of CO_2, CO, NO_x, and O_3 in three stages from March to July in 2019 and 2020*

	Stay-at-home stage		Reopening stage 1		Reopening stage 2	
CO_2 (ppm)	2019	2020	2019	2020	2019	2020
N	18,144	16,672	3122	10,080	5649	6938
Mean	550	455	521	441	497	434
Median	543	452	521	438	494	432
SD	24	15	17	16	23	22
Difference	−17%		−15%		−12%	
ANOVA	<0.01		<0.01		<0.01	
Wilcoxon	<0.01		<0.01		<0.01	
CO (ppm)	2019	2020	2019	2020	2019	2020
N	18,035	7075	3038	0	5576	0
Mean	0.28	0.26	0.27	-	0.31	-
Median	0.25	0.24	0.24	-	0.3	-
SD	0.14	0.09	0.14	-	0.13	-
Difference	−7%					
ANOVA	<0.01		-		-	
Wilcoxon	<0.01		-		-	
NO_x (ppb)	2019	2020	2019	2020	2019	2020
N	18,144	8880	3122	10,080	5649	6938
Mean	39.47	19.34	25.73	26.16	20.65	26.3
Median	36.38	17.34	22.24	24.18	18.37	25.57
SD	9.28	7.13	10.31	8	6.76	6.81
Difference	−51%		2%		27%	
ANOVA	<0.01		<0.01		0.89	
Wilcoxon	<0.01		<0.01		<0.01	
O_3 (ppb)	2019	2020	2019	2020	2019	2020
N	17,867	16,579	3059	10,021	5498	6920
Mean	10.89	27.17	7.95	21.57	7.92	25.24
Median	8.58	28.39	7.94	22.16	6.31	23.67
SD	8.43	9.23	4.21	12.43	**6.01**	15.33
Difference	149%		171%		219%	
ANOVA	<0.01		<0.01		<0.01	
Wilcoxon	<0.01		<0.01		<0.01	

*Three stages: Stay-at-home stage (Mar 16 to May 16); Reopening stage 1 (May 17 to Jun 14); Reopening stage 2 (Jun 15 to Jul 30)

gallons per day in April 2020 (EIA, 2022). By early April, the daily global CO_2 emissions had decreased 17% compared to the mean level in April of 2019 (Le Quéré et al., 2020). At the peak of the COVID-19 outbreak, the CO_2 emissions in each country decreased by 26% on average (Le Quéré et al., 2020). However, this reduction is not enough to limit global warming to less than 1.5 °C set by the 2015 Paris Agreement (Evans, 2020). Globally, the atmospheric temperature is still increasing, and the CO_2 concentration observed from National Oceanic and Atmospheric Administration (NOAA) Mauna Loa station reached 417.2 parts per million (ppm) in May 2020 (NOAA, 2020). To reach the 1.5 °C global temperature increase limit, global CO_2 emissions must decrease about 7.6% every year, which is about 2800 $MtCO_2$ in 2020 (Evans, 2020). As reported by Carbon Brief (a UK-based climate science website), the coronavirus caused the largest ever annual decrease in CO_2 emissions, about 2000 million tons of CO_2 (MtCO2), equivalent to about 5% of 2019's global emissions, which is still lower than the goal of 7.6% emission decrease (Evans, 2020).

In this study, we also observed CO reduction from the pre-pandemic stage to the Stay-at-home stage (Fig. 2). Carbon monoxide is produced by the incomplete combustion of gasoline, wood, propane, charcoal, or other fuels, and it is one of the six "criteria" air pollutants based on national ambient air quality standards (NAAQS) (EPA, 2015). The largest anthropogenic source of ambient CO in the USA is vehicle emissions, including cars, trucks, and other machinery with internal combustion engines (EPA, 2020). Therefore, ambient CO levels are closely correlated with transportation and industrial activities. Figure 2 shows that the CO concentration during the Stay-at-home stage was lower compared to other stages. Starting in March 2020, the CO concentration at the study site gradually decreased with the CO_2 concentration decrease, consistent with the COVID-19 timeline. Comparing CO 2020 and 2019 data (Table 3), CO mean value of the Stay-at-home stage was 7% less than the 2019 CO mean value during the same period. The mean CO value during the pre-pandemic period was 3% less than the 2019 value, which might be due to the warmer winter weather, as 2019 had the third mildest winter in New Jersey since 1895 (Robinson, 2020). The difference of CO levels between 2019 and 2020 for the Stay-at-home stage was higher

than that in the pre-pandemic period, and this difference was significant ($p < 0.01$) based on ANOVA and Wilcoxon analyses. The CO data for Reopening stage 1 and Reopening stage 2 was not available because of instrument malfunctions, but there was a positive correlation between CO and CO_2 as shown in Fig. 4, and we can extrapolate from CO_2 concentration to CO concentration. There could be a lower CO concentration during the Reopening stage 1 and Reopening stage 2 as well in 2020.

Nitrogen oxides (NO_x) levels decreased during the Stay-at-home stage and increased accordingly during the Reopening stage 1 and Reopening stage 2 (Fig. 2). The monthly average NO_x level of the study sites in 2019 April, May, and June was 38 ± 9 ppb, 37 ± 11 ppb, and 22 ± 7 ppb, respectively. In 2020, the monthly average in April, May, and June was 18 ± 6 ppb, 22 ± 9 ppb, and 26 ± 7 ppb, respectively. Therefore, compared to the 2019 level, the NO_x concentration in 2020 decreased 51% during the Stay-at-home stage and increased 2% and 27%, respectively, during the Reopening stages 1 and 2 (Table 3). From the statistical aspect, the concentrations of NO_x were not normally distributed, but based on Wilcoxon analysis (Table 3), the differences between 2019 and 2020 were significant. NO_x is formed by the reaction of oxygen and nitrogen during combustion at high temperatures. Combustion of all kinds of fuel, such as diesel, gas, oil, or organic matter, can generate NO_x (EPA, 1999). During the COVID-19 pandemic, the NO_x concentration decreased worldwide (Table 4). NO_x emissions in North New Jersey are mainly from transportation systems and power plants. New Jersey's busy highways, Port Newark, International airport, power plants, and industrial activities are all sources of NO_x. Because of the Stay-at-home order, New Jersey had much less transportation and almost no traffic congestion, which could have significantly reduced the emission of NO_x during the Stay-at-home stage. The monthly gasoline sales of 2020 in NJ (EIA, 2021a) are shown in Fig. S1 in Supplementary Information (SI), and we can find that the gasoline sale dropped about 54% from February 2020 to April 2020. In the Reopening stages (from May to July), the gasoline sale was back to about 85% of the February level, and the gasoline sale in July was 1.87 times that in April. Therefore, the NO_x concentration increased accordingly, and the NO_x concentration during the Reopening stages was higher than that in
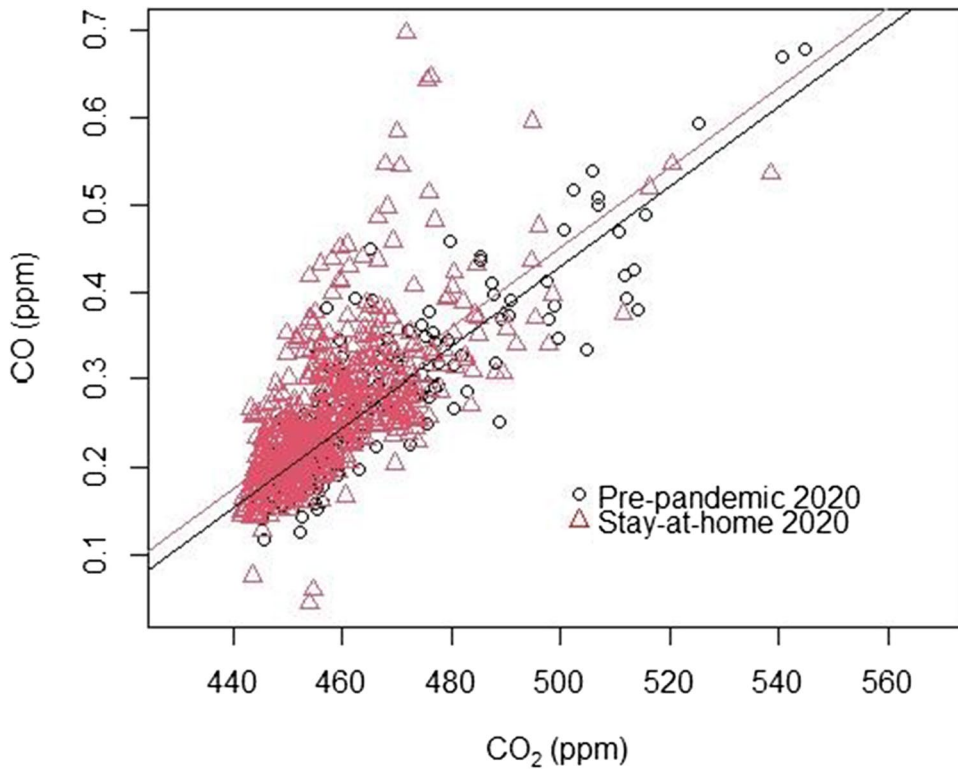
Fig. 4 Regression analysis between CO_2 (ppm) and CO (ppm) during the pre-pandemic period and Stay-at-home stage. For the pre-pandemic period in 2020, $[CO] = 0.0046 \times [CO_2] - 1.868$, $R^2 = 0.79$, $p < 0.01$; for Stay-at-home stage in 2020, $[CO] = 0.0046 \times [CO_2] - 1.835$, $R^2 = 0.45$, $p < 0.01$

Table 4 Comparison of the concentrations of selected gas-phase air pollutants (NO_x, O_3, CO) around the world

Area	NO_x decrease	O_3 increase	CO decrease
China	60% (Zhang et al., 2020); 25% (Wang & Su, 2020); ~40% (Bauwens et al., 2020); 36–53% (Wang et al., 2020)	Flat (Wang & Su, 2020); 36% (Sicard et al., 2020); 47% (Zhao et al., 2020)	6.2% (Wang & Su, 2020)
Europe	24–56% (Bauwens et al., 2020; Ficetola & Rubolini, 2020; Menut et al., 2020; Sicard et al., 2020)	17–27% (Sicard et al., 2020)	-
South Korea	24–43% (Bauwens et al., 2020)	-	-
Iran	Flat (Bauwens et al., 2020)	-	-
Sao Paulo, Brazil	Up to 77.3%	-	Up to 64.8%
India	60–78%	-	-
USA	24–48% (Bauwens et al., 2020); 50% (Tanzer-Gruener et al., 2020)	From 0.031 to 0.053 ppm (Adhikari & Yin, 2020)	Up to 50% (Tanzer-Gruener et al., 2020) (Morrison, 2020)
North New Jersey (this case)	Up to 51%	Doubled	7%

the Stay-at-home stage. However, the mean NO_x concentration in 2020 June (26 ± 7 ppb) was higher than the mean NO_x in 2019 June (22 ± 7 ppb), because 2019 June had 15 rainy days and 2020 June had only 10 rainy days. Rain can effectively remove NO_x and lower the NO_x level in the atmosphere (Irwin & Williams, 1988).
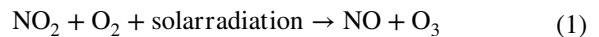
The ozone concentration and the variation of the ozone concentration increased at the study site from January 2020 to July 2020, along with the temperature increase over time. However, based on the boxplot in Fig. 2, the median ozone concentration during the Stay-at-home stage was higher than all other three stages, probably due to the reduced industrial activities during the COVID-19 pandemic. Ground-level ozone is a "secondary" air pollutant formed by NO_x reacting with volatile organic compounds (VOCs) under sunlight and in stagnant air. Therefore, ground-level ozone concentration usually varies inversely with NO_x and VOCs and regularly increases with solar radiation and temperature (Sillman et al., 1990). Ozone concentration is proportionally related to VOCs, NO_x, and solar radiation (Song et al., 2011).

3.2 Correlation Between the Gases

The ambient CO_2 concentration changed with CO concentration. At the end of January 2020 and the beginning of February 2020, when the lowest temperature prevailed, CO_2 had a higher concentration than other warmer periods, and CO shown a similar trend of concentration variation. With lower temperatures, the consumption of fossil fuel increases during the wintertime, which could lead to a relatively higher level of CO_2 and CO emissions and ambient concentrations (Elbayoumi et al., 2014). From March 2020, the CO_2 and CO concentrations at the study site gradually decreased with increased air temperature. Figure 4 explores the correlation between the concentrations of CO_2 and CO by linear regression analysis. CO_2 was positively correlated with CO concentration with an adjusted R squared (the coefficient of determination) of 0.79 for the pre-pandemic period and 0.45 for the Stay-at-home period. The correlation between CO_2 and CO changed slightly from the pre-pandemic period to the Stay-at-home stage. For these two periods, the slopes of the correlation between CO_2 and CO were almost the same, and the intercept shifted higher for the Stay-at-home stage, which

means that with the same CO level in the ambient air, the CO_2 concentration level decreased.

Furthermore, with lower NO_x levels in the spring of 2020, we observed higher ozone concentrations in the spring of 2020 than in the spring of 2019 (Table 3). This phenomenon was also observed in other areas of the world, including China (Zhao et al., 2020), Europe (Sicard et al., 2020), and the USA (Semple & Moore, 2020). Because of the lowered traffic activities during the COVID-19 pandemic, less NO was generated by the transportation system. NO can degrade ozone, so that lower NO levels could lead to higher ozone concentrations. In addition, NO_2-based ozone formation occurs under warm and sunny conditions. Because of global climate change, New Jersey had warmer winter temperatures than the previous year, so more biogenic VOCs could be generated by decomposition processes and enter the atmosphere in the spring of 2020 (Forbes et al., 2014). These VOCs could quickly react with NO to generate NO_2. Consequently, the NO concentration further decreased, and NO_2 was formed, which resulted in even higher ozone concentrations. These processes are shown in Eq. 1 through Eq. 3.

$$NO_2 + O_2 + solar\,radiation \rightarrow NO + O_3 \tag{1}$$

Reversely,

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{2}$$

$$VOCs + NO \rightarrow NO_2 \tag{3}$$

Another leading cause of the low ozone level in 2019 was the large variation in temperature in May and June 2019. Especially in May, the daily high temperature at the study site shifted from 10 to 25 °C almost every other day. This large temperature variation was caused by climate change and could decrease the amount of VOCs entering the atmosphere and thus significantly reduced the ground-level ozone concentration. The average ground-level ozone concentration in May and June 2020 was more than twice that in 2019. During the Stay-at-home stage, the ozone concentration increased 149%, and based on Wilcoxon analysis, the difference in ozone concentration between 2019 and 2020 was significant. Similarly, Zoran et al. (2020) also reported positive correlations of ground-level ozone and negative correlations of NO_2 with increased COVID-19 infections

in Milan, Italy. However, the mean ozone concentration value at the study site ranged from 21 to 27 ppb, which was much less than 70 ppb, the National Ambient Air Quality Standards (NAAQS) for ozone, daily maximum 8-h average concentration. Therefore, the ozone level was still safe for the public and the local ecosystem.

Figure 5 investigates the correlation between the concentrations of NO_x and O_3 during the Stay-at-home stage and the Reopening stages by linear regression analysis. The data points clearly clustered together for the 2020 Stay-at-home stage or the Reopening stages. For the Stay-at-home stage, the average ozone concentration was higher with lower NO_x concentrations. For the Reopening stage, the average ozone concentration became lower with a higher average NO_x concentration. Many other parameters could also affect the ozone concentration, including air temperature, solar radiation, and VOCs. Moreover, with the traffic patterns and business activities changed by the COVID-19 pandemic, the variation of NO_x concentrations increased during the pandemic. Based on

the statistical analysis of the data points collected in this study, NO_x and O_3 concentrations were negatively correlated ($p < 0.01$); however, only about 6% of NO_x concentration variation could be explained by O_3 variation (R^2 is about 0.06). Nevertheless, the changing trends of the concentration levels of these two parameters could still imply the inherent correlation between them.

3.3 Effects of Meteorological Parameters

The effects of meteorological parameters on the concentration levels of carbon dioxide, carbon monoxide, nitrogen oxides, and ground-level ozone were also explored to differentiate the effects coming from COVID-19. The relationships between meteorology parameters (i.e., air temperature, relative humidity, solar radiation, wind speed, and precipitation) and gas-phase air pollutants (i.e., CO_2, CO, NO_x, and O_3) were investigated using regression models (Fig. S2 to Fig. S15). Figure 3 shows the effects of air temperature on CO_2 and O_3 concentration. With increased air
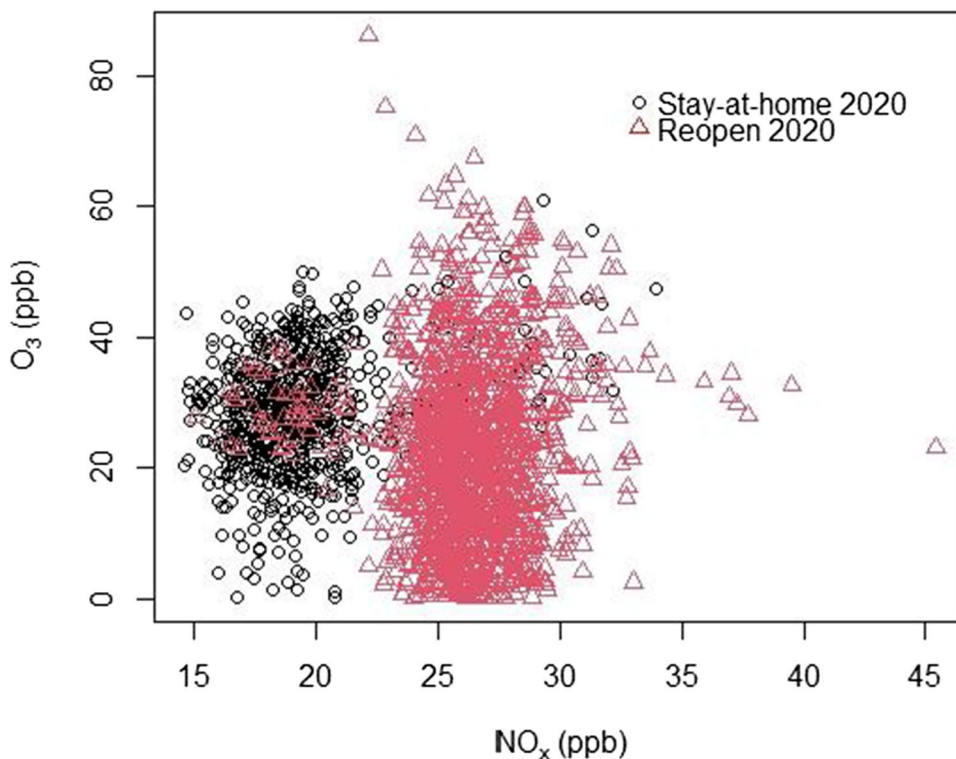
Fig. 5 Regression analysis between NO_x (ppb) and O_3 (ppb) during the 2020 Stay-at-home stage and the Reopening stages

temperature, the CO_2 concentration decreased, and the O_3 concentration increased. The seasonal pattern of CO_2 change with temperature change in 2020 was similar to that in 2019. However, at the same air temperature, CO_2 concentration in 2020 was less than that in 2019, implying that parameters besides air temperature affected the CO_2 level in 2020. The positive correlation between O_3 and temperature was reported previously by Roberts-Semple et al. (2012) at the same location as well. The ozone concentration maintained a relatively low level in 2019, and with the air temperature increase, the ozone concentration increased slightly. However, in 2020, the ozone concentration increased more with the same air temperature increase. No significant effect of air temperature on CO and NO_x was observed (Fig. S2 and S3). Fig. S4 in SI compares the correlation between ground-level ozone and relative humidity or solar radiation in 2019 and 2020, and the results from this study are consistent with previous studies (Li et al., 2021; Roberts-Semple et al., 2012). With increased relative humidity, ozone concentration decreased; with increased solar radiation levels, ozone concentration increased. The correlation between ground-level ozone and relative humidity or solar radiation in 2019 was similar to that in 2020. However, ozone levels were higher in 2020, and with a single unit of relative humidity increase, ozone concentration in 2020 increased more than that in 2019. With a higher wind speed, the concentrations of CO_2, CO, and NO_x were lower (Fig. S5 to S7). At the same wind speed, the 2020 NO_x levels during the Stay-at-home stage were lower than that in 2019 (Fig. S7). However, the O_3 concentration was higher at a higher wind speed (Fig. S8), which is similar to the data reported by Roberts-Semple et al. (2012) and Ainslie and Steyn (2007). Our study site was located downwind of busy highways, and the prevailing southwestern winds could bring in the high concentrations of pollutants from that direction (Roberts-Semple et al., 2012). High precipitation rates resulted in relatively low concentrations of CO_2, CO, NO_x, and O_3 (Fig. S9 to Fig. S12), indicating the washout effect of precipitation (Jiménez-Guerrero et al., 2012). At the same precipitation level, the CO_2 and NO_x in the 2020 Stay-at-home stage had lower concentrations than that in 2019, and O_3 in the 2020 Stay-at-home stage had higher concentrations than that in 2019. In addition, CO_2, CO, and NO_x slightly decreased when the solar radiation increased (Fig. S13 to Fig. S15), which could be caused by the seasonal effects (Elbayoumi et al., 2014; Järvi et al., 2012; Roberts-Semple et al., 2012). At the same level of solar radiation, the lower levels of CO_2 and NO_x were also observed in the 2020 Stay-at-home stage, which proved that the emissions and concentration levels of CO_2 and NO_x were reduced during the COVID-19 pandemic besides the effects of meteorology parameters in metropolitan New Jersey.

4 Conclusion

Under the current COVID-19 pandemic, humanity's lives and activities have significantly changed. However, our air quality and traffic conditions have improved. In metropolitan New Jersey, compared to 2019, CO_2, CO, and NO_x decreased a significant amount during the Stay-at-home stage in 2020. However, the ground-level ozone increased during the Stay-at-home stage, which could be caused by the reduced NO_x emissions and the possible increased VOC levels affected by warm weather. CO_2 was positively correlated with CO, and NO_x was negatively correlated with the ozone level. By exploring the effects of meteorology parameters on CO_2, CO, NO_x, and O_3 concentrations in 2019 and 2020, we found different patterns of relationships between air temperature and CO_2 or O_3, O_3 and relative humidity, or solar radiation in those 2 years, which could be caused by the human activity changes during the COVID-19 pandemic. These findings provide a reference for other areas to assess the impacts of the COVID-19 pandemic on the environment at the air quality aspect. The reduction of traffic and human activities during the pandemic is still not enough to limit global warming to less than 1.5 °C. Replacing fossil fuels with electric or renewable energy in the transportation systems and industry could be beneficial for reducing greenhouse gas emissions and slowing down global warming.

Data Availability The full data set of this study can be downloaded from the MERI environmental monitoring database: https://vdvcloud.com/vdv.php/historical/292.

Declarations

Competing Interests The authors declare no competing interests.

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