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

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
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 CO₂ level in 2006 was about 380 ppm. The CO₂ level in 2020 reached 420 ppm. Many climatologists agree that the global atmospheric concentration of CO₂ increased roughly 2 ppm per year over the period 2006–2015 (Lindsay, 2020). The Intergovernmental Panel on Climate Change (IPCC) indicates that an emission scenario that would lead to a CO₂ 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 (CO₂) 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 CO₂, CO, NOₓ, and O₃ 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 \( \text{CO}_2 \), \( \text{CO} \), \( \text{NO}_x \), 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](image-url)
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. NOx 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%.

### 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 $1.86 \times 10^4$ m$^3$ 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.

![Boxplots of CO$_2$, CO, NO$_x$, and O$_3$ concentrations](image-url)

**Fig. 2** The boxplots of CO$_2$, CO, NO$_x$, and O$_3$ 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 CO₂; B effects of air temperature on the concentrations of O₃. 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 CO₂ 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 CO₂ concentration are listed in Table 3. During the Stay-at-home stage, the CO₂ mean concentration of 2020 decreased 17%. During the Reopening stage 1 and stage 2, the CO₂ mean level of 2020 decreased 15% and 12%, respectively, as traffic and business activities were gradually restored during the reopening process. The CO₂ 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 CO₂ levels in the atmosphere during the COVID-19 pandemic could be caused by the reduction of CO₂ 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 gallons per day in March 2020.

Table 3 Summary of the statistical analyses for the concentrations of CO₂, CO, NOₓ, and O₃ in three stages from March to July in 2019 and 2020*  

|          | Stay-at-home stage | Reopening stage 1 | Reopening stage 2 |
|----------|-------------------|-------------------|-------------------|
|          | 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   |         |         |         |         |         |
| **NOₓ (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  |         |         |         |
| **O₃ (ppb)** | 2019    | 2020    | 2019    | 2020    | 2019    | 2020    |
| **N**    | 17,867  | 16,579  | 3059    | 10,021  | 5498    | 6920    |
| **Mean** | 10.89   | 7.95    | 7.94    | 22.16   | 7.92    | 25.24   |
| **Median** | 8.58    | 9.23    | 4.21    | 12.43   | 6.31    | 23.67   |
| **SD**   | 10.89   | 7.95    | 7.94    | 22.16   | 7.92    | 25.24   |
| **Difference** | 149%   | 171%    | 219%    |         |         |         |
| **ANOVA** | < 0.01  | < 0.01  | < 0.01  |         |         |         |
| **Wilcoxon** | < 0.01   | < 0.01  | < 0.01  |         |         |         |

*Table 3: Summary of the statistical analyses for the concentrations of CO₂, CO, NOₓ, and O₃ in three stages from March to July in 2019 and 2020.

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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions must decrease about 7.6% every year, which is about 2800 MtCO₂ in 2020 (Evans, 2020). As reported by Carbon Brief (a UK-based climate science website), the coronavirus caused the largest ever annual decrease in CO₂ emissions, about 2000 million tons of CO₂ (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 CO₂ 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 CO₂ as shown in Fig. 4, and we can extrapolate from CO₂ 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 (NOₓ) 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 NOₓ level of the study sites in 2019 April, May, and June was 38 ± 9 ppb, 22 ± 7 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 NOₓ 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 NOₓ were not normally distributed, but based on Wilcoxon analysis (Table 3), the differences between 2019 and 2020 were significant. NOₓ 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 NOₓ (EPA, 1999). During the COVID-19 pandemic, the NOₓ concentration decreased worldwide (Table 4). NOₓ 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 NOₓ. 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 NOₓ 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 NOₓ concentration increased accordingly, and the NOₓ concentration during the Reopening stages was higher than that in
Fig. 4 Regression analysis between CO₂ (ppm) and CO (ppm) during the pre-pandemic period and Stay-at-home stage. For the pre-pandemic period in 2020, $[\text{CO}] = 0.0046 \times [\text{CO}_2] - 1.868$, $R^2 = 0.79$, $p < 0.01$; for Stay-at-home stage in 2020, $[\text{CO}] = 0.0046 \times [\text{CO}_2] - 1.835$, $R^2 = 0.45$, $p < 0.01$

Table 4 Comparison of the concentrations of selected gas-phase air pollutants (NOₓ, O₃, CO) around the world

| Area                | NOₓ decrease | O₃ 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\textsubscript{x} concentration in 2020 June (26±7 ppb) was higher than the mean NO\textsubscript{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\textsubscript{x} and lower the NO\textsubscript{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 box-plot 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\textsubscript{x} reacting with volatile organic compounds (VOCs) under sunlight and in stagnant air. Therefore, ground-level ozone concentration usually varies inversely with NO\textsubscript{x} and VOCs and regularly increases with solar radiation and temperature (Sillman et al., 1990). Ozone concentration is proportionally related to VOCs, NO\textsubscript{x}, and solar radiation (Song et al., 2011).

3.2 Correlation Between the Gases

The ambient CO\textsubscript{2} concentration changed with CO concentration. At the end of January 2020 and the beginning of February 2020, when the lowest temperature prevailed, CO\textsubscript{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\textsubscript{2} and CO emissions and ambient concentrations (Elbayoumi et al., 2014). From March 2020, the CO\textsubscript{2} and CO concentrations at the study site gradually decreased with increased air temperature. Figure 4 explores the correlation between the concentrations of CO\textsubscript{2} and CO by linear regression analysis. CO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{2} concentration level decreased.

Furthermore, with lower NO\textsubscript{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\textsubscript{x}-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\textsubscript{2}. Consequently, the NO concentration further decreased, and NO\textsubscript{2} was formed, which resulted in even higher ozone concentrations. These processes are shown in Eq. 1 through Eq. 3.

\[
\text{NO}_2 + \text{O}_2 + \text{solarradiation} \rightarrow \text{NO} + \text{O}_3
\] (1)

Reversely,

\[
\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2
\] (2)

\[
\text{VOCs} + \text{NO} \rightarrow \text{NO}_2
\] (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\textsubscript{x} 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\textsubscript{x} and O\textsubscript{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\textsubscript{x} concentrations. For the Reopening stage, the average ozone concentration became lower with a higher average NO\textsubscript{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\textsubscript{x} concentrations increased during the pandemic. Based on the statistical analysis of the data points collected in this study, NO\textsubscript{x} and O\textsubscript{3} concentrations were negatively correlated ($p<0.01$); however, only about 6% of NO\textsubscript{x} concentration variation could be explained by O\textsubscript{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\textsubscript{2}, CO, NO\textsubscript{x}, and O\textsubscript{3}) were investigated using regression models (Fig. S2 to Fig. S15). Figure 3 shows the effects of air temperature on CO\textsubscript{2} and O\textsubscript{3} concentration. With increased air
temperature, the CO₂ concentration decreased, and the O₃ concentration increased. The seasonal pattern of CO₂ change with temperature change in 2020 was similar to that in 2019. However, at the same air temperature, CO₂ concentration in 2020 was less than that in 2019, implying that parameters besides air temperature affected the CO₂ level in 2020. The positive correlation between O₃ 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 CO₂ change with temperature change in 2020 was similar to that in 2019. At the same air temperature, CO₂ concentration in 2020 was less than that in 2019, implying that parameters besides air temperature affected the CO₂ level in 2020. The positive correlation between O₃ 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 NOₓ 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 CO₂, CO, and NOₓ were lower (Fig. S5 to S7). At the same wind speed, the 2020 NOₓ levels during the Stay-at-home stage were lower than that in 2019 (Fig. S7). However, the O₃ 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 CO₂, CO, NOₓ, and O₃ (Fig. S9 to Fig. S12), indicating the washout effect of precipitation (Jiménez-Guerrero et al., 2012). At the same precipitation level, the CO₂ and NOₓ in the 2020 Stay-at-home stage had lower concentrations than that in 2019, and O₃ in the 2020 Stay-at-home stage had higher concentrations than that in 2019. In addition, CO₂, CO, and NOₓ 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 CO₂ and NOₓ were also observed in the 2020 Stay-at-home stage, which proved that the emissions and concentration levels of CO₂ and NOₓ 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, CO₂, CO, and NOₓ decreased a significant amount during the 2020 Stay-at-home stage. However, the ground-level ozone increased during the Stay-at-home stage, which could be caused by the reduced NOₓ emissions and the possible increased VOC levels affected by warm weather. CO₂ was positively correlated with CO, and NOₓ was negatively correlated with the ozone level. By exploring the effects of meteorology parameters on CO₂, CO, NOₓ, and O₃ concentrations in 2019 and 2020, we found different patterns of relationships between air temperature and CO₂ or O₃, O₂ 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.

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

Declarations

Competing Interests The authors declare no competing interests.

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