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RESEARCH ARTICLE

The impact of COVID-19-induced lockdowns during spring 2020 on nitrogen dioxide levels over major American counties

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COVID-19 has quickly spread throughout the world, infecting and killing millions of people. In an effort to contain the spread of the virus, many governments implemented stringent lockdown measures. These lockdown restrictions, coupled with social distancing, severely curtailed transportation and industrial activities, which are the primary drivers of nitrogen oxides emissions. This study investigates whether lockdown orders in the United States have impacted tropospheric nitrogen dioxide (NO_2) levels by evaluating 12 major counties with a total population of 38 million. For each county, Sentinel-5P satellite data were obtained and analyzed to determine NO_2 column concentrations during the pre-lockdown, peak lockdown, and loosening lockdown periods in 2020. Then, NO_2 levels were compared during these three periods to the same time frame in 2019. Our results show that the lockdowns in the 12 major U.S. counties analyzed led to a significant decline in NO_2 levels, with an average reduction of 28.7% (±14.6%) and 17.6% (±10.9%) during peak lockdown and loosening lockdown periods, respectively.

Keywords: Nitrogen dioxide, Air quality, America, COVID-19, Transport, Counties

1. Introduction

In late December 2019, a novel coronavirus (COVID-19) emerged in Wuhan and began spreading rapidly around the world (Isaifan, 2020). The virus's rapid spread led the Chinese government to mandate stringent lockdowns in various major cities, impacting a large swath of China's citizens (Fanelli and Piazza, 2020). As COVID-19 spread to other nations in Asia, Europe, and the United States of America, similar lockdowns were enacted to curb the virus's rapid spread (Kontis et al., 2020).

These large-scale lockdowns severely restricted anthropogenic activity responsible for air pollution, such as the operation of individual vehicles, energy consumption, and industrial activity (Menut et al., 2020). Previous studies found that the lockdowns were responsible for an estimated 48%–60% decline in on-road traffic in China and Italy (Gualtieri et al., 2020; Y Wang et al., 2020). Similarly, the lockdowns in the United States were responsible for a 41% decline in on-road traffic during April 2020, compared to the levels during the previous 3 years (U.S. Department of Transportation, 2020). In some countries, industrial production and energy consumption declined by 30% following lockdown measures (Liu et al., 2020).

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Recently conducted studies found significant decreases in nitrogen dioxide (NO_2) levels in China, India, and Western Europe during the COVID-19 lockdowns (Liu et al., 2020; Vadrevu et al., 2020; Venter et al., 2020). The significant decline in major nitrogen oxides ($NO_x = NO + NO_2$) emitting activity during lockdowns, such as driving, public transportation, and operation of power plants, has been cited as the primary reason for this reduction in NO_2 levels (Wang and Su, 2020). Specifically, in Northern China, a 53% reduction in NO_2 levels during the lockdown period was observed (Shi and Brasseur, 2020). In India, there was an estimated 40%–70% reduction in NO_2 levels, with a 40%–50% decline observed in Delhi and Mumbai (Sarfraz et al., 2020; Singh et al., 2020). In major Western European cities, there was roughly a 27% decline in NO_2 levels during the lockdown period (Bauwens et al., 2020).

The significant decrease in NO_2 in these countries is a positive side effect of an otherwise devastating crisis. NO_2 is a toxic air pollutant, and exposure to high levels of NO_2 is associated with aggravated respiratory diseases, inflamed airways, hypertension, heart disease, chronic pulmonary disease, asthma, reduced lung function, and diabetes (Samoli et al., 2006; Achakulwisut et al., 2019). It has been reported that the exposure to high levels of NO_2 is responsible for 79,000 premature deaths per year in Europe and far more premature deaths globally. It is no surprise, therefore, that the dramatic decrease in NO_2 levels, along with the decrease of other air pollutants such as particulate matter during the COVID-19 induced lockdowns, saved around 11,000 lives in Europe and

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26,000–39,000 lives in China (Rupani et al., 2020; M Wang et al., 2020).

In the United States, according to Johns Hopkins's Coronavirus Resource Center, there were 710 confirmed cases of COVID-19 on March 10. Starting as of March 11, COVID-19 and the subsequent social distancing and lockdown measures began to escalate rapidly in America. On March 16, San Francisco County became the first U.S. county to impose a lockdown type order on its citizens, mandating that they stay at home, barring essential trips. On March 19, California issued a statewide lockdown order. On March 23, a series of American states, including Massachusetts, Michigan, and Washington, followed suit, issuing statewide lockdown orders. Throughout March and April, more states began to impose lockdown orders, as America's confirmed number of COVID-19 cases continued to rise exponentially.

On April 20, partial reopening went into effect in South Carolina, the first state to begin some form of reopening. By May 1, many American states had loosened lockdown restrictions, and Americans began to engage in some of the daily activities they partook in before lockdown. However, most Americans were still under some social distancing orders, and it was not until May 20 that every American state had introduced some form of reopening (Wu et al., 2020).

Given that many major regions of the United States enacted stringent lockdowns that curbed human activity as discussed earlier, and resulted in a 41% decrease in traffic levels in April 2020, it was interesting to explore whether similar declines in air pollution, as seen in China, India, and Western Europe, would be observed in major American cities during the COVID-19 lockdowns (U.S. Department of Transportation, 2020). In this study, in an attempt to determine whether a significant decline in NO_2 pollution occurred during America's COVID-19 lockdowns, tropospheric NO_2 column densities were analyzed in 12 major American counties during the peak lockdown and loosening lockdown periods in 2020, and compared to NO_2 levels prior to lockdown in 2020 and to the corresponding periods in 2019.

2. Material and methods

2.1. Data source

The data used in our analysis are obtained from the TROPOspheric Monitoring Instrument (TROPOMI) on the European Space Agency's Sentinel-5P satellite, launched in 2017 (Van Geffen et al., 2019). For our analysis of the change in NO_2 levels over the United States due to the COVID-19 lockdowns, the Sentinel-5P offline NO_2 product by Google Earth Engine was used. Specifically, the tropospheric NO_2 column density band was used, which measures the density of NO_2 molecules from ground level through the troposphere (S5P Mission Performance Centre Nitrogen Dioxide [L2-NO_2] Readme document number, 2020). All data used in the study are filtered according to the data provider's guidelines such that it only includes pixels with a qa_value greater than 0.75. This removes low-quality pixels impacted by cloud cover, snow or ice, and errors or problematic retrievals (S5P Mission Performance Centre Nitrogen Dioxide [L2-NO_2] Readme document number, 2020). TROPOMI tropospheric NO_2 column data are estimated to have a systemic bias of $-14\% \pm 12\%$ in urban areas (Tack et al., 2021). The statistical uncertainty is 8.63 $\mu mol/m^2$ for all pixels, around 30% lower than that of the Ozone Monitoring Instrument (Van Geffen et al., 2020).

2.2. Time periods over which NO_2 change was analyzed

To determine whether NO_2 levels have declined in the United States due to COVID-19 lockdowns, 12 major American counties were investigated. A pre-lockdown period spanning February 1 to February 29, 2020 (February 1 to February 28 in 2019) was designated. During this period, no social distancing was occurring, and COVID-19 had not yet impacted daily life in the United States. Then, in each county, peak lockdown was designated as the period from when the official city lockdown order was announced to when the first steps to loosen lockdown restrictions began. The 30-day period after restrictions began loosening was deemed the loosening lockdown period, when residents of the county were still under social distancing or lockdown measures, but the measures were less restrictive than during peak lockdown. The peak and loosening lockdown periods are unique to each city and determined by analyzing government ordinances (more information on this provided in the supplementary information). Generally, peak lockdown periods spanned late March through April, while loosening lockdown periods typically fell during the month of May as shown in **Table 1**.

2.3. Calculation of the change in NO_2

The average tropospheric NO_2 column concentrations were calculated in each county over each of the three time periods in 2020 and the corresponding time frames in 2019. To do so, the weighted average value was found (which accounts for pixels that are not entirely within the bounds of the selected county) of all pixels within the county boundary on each day. The calculations excluded measurements for days where no data existed for the specific county because it was filtered out due to high levels of cloud coverage, snow or ice cover, or other algorithmic errors. For certain counties, particularly counties that are smaller in terms of area, a significant number of days had no data because they were filtered out. County boundaries were determined using shapefiles provided by the National Weather Service. Then, using the daily average levels of NO_2 for each county, the average level of NO_2 present over each county for the three time periods in 2020 and the corresponding time frames in 2019 was calculated. Using these values, the percentage shift in NO_2 values using four intervals of comparison: 2020 pre-lockdown to 2020 peak lockdown, 2020 pre-lockdown to 2020 loosening lockdown, 2019 peak lockdown to 2020 peak lockdown, and 2019 loosening lockdown to 2020 loosening lockdown, was then determined.

2.4. Meteorological data

The National Oceanic and Atmospheric Administration's local climatological data were used to evaluate meteorological conditions in the analyzed counties (National Centers for Environmental Information, National Ocean and

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Table 1. Summary of peak lockdown and loosening lockdown time frames for each county. DOI: https://doi.org/10.1525/elementa.2021.00002.t1

County	Peak Lockdown	Loosening Lockdown
New York City	March 22 to June 7	June 8 to July 7
Los Angeles County (Los Angeles)	March 20 to May 7	May 8 to June 6
Cook County (Chicago)	March 23 to April 30	May 1 to May 30
Harris County (Houston)	March 24 to April 30	May 1 to May 30
Santa Clara County (Santa Clara)	March 17 to May 3	May 4 to June 2
Wayne County (Detroit)	March 24 to April 23	April 24 to May 23
Philadelphia County (Philadelphia)	March 23 to April 30	May 1 to May 30
Allegheny County (Pittsburgh)	March 23 to April 30	May 1 to May 30
Fulton County (Atlanta)	March 24 to April 23	April 24 to May 23
San Francisco County (San Francisco)	March 17 to May 3	May 4 to June 2
Denver County (Denver)	March 24 to May 8	May 9 to June 7
Washington, DC	April 1 to May 17	May 18 to June 16

Atmospheric Information, 2021). Specifically, hourly temperature, wind speed, wind direction, and relative humidity data from stations situated in each of the 12 counties were analyzed. The average level of these four meteorological variables in each county during the 2019 and 2020 peak and loosening lockdown periods was calculated. Then, the mean value across all 12 counties for each meteorological variable during these four periods was found, enabling us to determine the percentage shift in temperature, wind speed, wind direction, and relative humidity from 2019 peak and loosening lockdown to the 2020 peak and loosening lockdown, as well as in comparison to a 2015–2018 baseline. These results are summarized in the supplementary information section.

3. Results and discussion

3.1. 2020 pre-lockdown compared to 2020 peak lockdown and loosening lockdown

The COVID-19 lockdowns in the United States had far-reaching impacts throughout the country. In the United States, like in Europe and Asia, lockdown measures severely reduced transportation and industry, the two primary emitters of NO_x.

NO_2 shifts in the 12 analyzed counties were calculated using four measures. The first two intervals compare NO_2 levels during the 2020 pre-lockdown period in each county to NO_2 levels during the 2020 peak and loosening lockdown periods, respectively. All counties observed a significant decline in NO_2 levels from the 2020 pre-lockdown period to the 2020 peak lockdown period, with a mean decline of 49.3% (**Table 2**). From the 2020 pre-lockdown period to the 2020 loosening lockdown period, the decline in NO_2 is even more drastic at 54.2% (**Table 2**). Comparing NO_2 levels between the 2020 pre-lockdown period to the 2020 peak and loosening lockdown periods, however, does not account for the seasonal shift in NO_2. NO_2 concentrations are typically higher during winter despite NO_x emissions usually peaking during the summer (Goldberg et al., 2020; Shah et al., 2020). Due to the increased sunlight, the reaction rate of NO_x with OH occurs more rapidly in the summer, resulting in the transformation of NO_x to other species that have shorter lifetime than NO_x itself. In urban regions, this results in 1.5–3 times higher NO_2 levels in the winter compared to the summer (Goldberg et al., 2020). This is important to consider when analyzing our results. Similarly, the seasonal weakening of the surface inversion layer is also a factor that potentially impacts our results. In winter, surface inversions are more frequent and longer lasting due to colder temperatures (Baumbach and Vogt, 2003; Czarnecka and Nidzgorska-Lencewicz, 2017; L Wang et al., 2020). This inversion layer prevents the vertical transport of pollutants, and therefore, pollutants are more concentrated near the surface (Shmool et al., 2014). The dramatic decline in NO_2 levels in 2020 from the pre-lockdown period to the peak lockdown period and loosening lockdown period is, therefore, only partially the result of decreased NO_x emissions due to lockdowns, as seasonal variability also plays a significant role. The pre-lockdown period occurred during a colder period than the peak lockdown and loosening lockdown periods. This likely explains why the decrease in NO_2 levels from pre-lockdown to loosening lockdown is greater than the decrease from pre-lockdown to peak lockdown; loosening lockdown occurred during a warmer period than peak lockdown, and so while restrictions were not as strict, and NO_x emissions were likely higher, increased sunlight and higher temperatures likely resulted in shorter NO_2 atmospheric lifetime, fewer and weaker surface inversions, and therefore lower observed NO_2 levels.

3.2. Comparison of the 2020 peak lockdown time window with 2019

The third interval of comparison, which best reflects the impact of COVID-19 lockdowns on air pollution, compares

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Table 2. Summary of county-level data comparing 2020 pre-lockdown NO_2 levels to 2020 peak and loosening lockdown NO_2 levels and comparing 2020 peak and loosening lockdown NO_2 levels to NO_2 levels during the corresponding periods in 2019. DOI: https://doi.org/10.1525/elementa.2021.00002.t2

County Name (Largest City)	Δ in 2020 Between Pre-Lockdown and Peak Lockdown Period (%)	Δ in 2020 Between Pre-lockdown and Loosening Lock-down Period (%)	Δ Between 2019 and 2020 (Peak Lockdown Period; %)	Δ Between 2019 and 2020 (Loosen-ing Lockdown Period; %)
Allegheny County (Pittsburgh)	−48.6	−45.0	−46.0	−20.7
New York City	−50.1	−55.1	−41.2	−18.0
Wayne County (Detroit)	−48.9	−51.1	−38.9	−16.5
Fulton County (Atlanta)	−31.4	−46.5	−34.3	−25.9
Philadelphia County (Philadelphia)	−57.8	−64.9	−30.9	−30.7
San Francisco County (San Francisco)	−69.2	−73.6	−29.3	−11.9
Cook County (Chicago)	−44.2	−43.1	−28.9	−17.3
Washington D.C.	−54.9	−60.4	−28.5	−14.3
Santa Clara County (Santa Clara)	−53.2	−54.6	−27.9	−24.1
Los Angeles County (Los Angeles)	−58.2	−61.6	−26.6	−20.0
Denver County (Denver)	−40.1	−51.6	−25.0	−24.4
Harris County (Houston)	−35.2	−42.8	12.7	12.8
Mean	−49.3	−54.2	−28.7	−17.6

NO_2 levels during the 2020 peak lockdown period in each county to the corresponding period in 2019 as shown in **Figure 1**. Using this interval, it was found that 11 of the 12 counties experienced lower NO_2 levels during the 2020 peak lockdown period compared to 2019, ranging from Allegheny County's 46.0% decline to Denver County's 25.0% decline (**Table 2**). Harris County, however, saw 12.7% higher NO_2 levels (**Table 2**). The mean decline across all counties was 28.7% (**Table 2**). For context, Wuhan, the epicenter of China's COVID-19 outbreak and a city placed on stringent lockdown for over a month, observed an average of 53% decline in NO_2 during lockdown (Lian et al., 2020). This significant decline in NO_2 levels in the major U.S. counties analyzed during peak lockdown was expected. As discussed above, lockdowns severely halted transportation and industrial activity, both of which are primary drivers of NO_x emissions; therefore, it's unsurprising that NO_2 levels declined significantly. This 2019–2020 decline, however, might have a contribution from the long-term trend in atmospheric NO that has been observed throughout the United States (Goldberg et al., 2020). Simon et al. (2015) have also reported that from 2002 to 2011, nationwide anthropogenic NOx emissions declined from 46.2 to 28 million tons per year.

3.3. Comparison of the 2020 loosening lockdown time window with 2019

The fourth interval of comparison compares NO_2 levels during the 2020 loosening lockdown period in each county to the corresponding period in 2019. This interval allows us to determine whether even during the loosening lockdown phase, NO_2 levels were lower than during the same time frame in 2019. Likewise, it also enables us to compare the severity of the reduction in NO_2 levels between the peak lockdown period and the loosening lockdown period. Using this interval, 11 of the 12 counties observed lower NO_2 levels during the 2020 loosening lockdown period compared to 2019, ranging from Philadelphia County's 30.7% decline to San Francisco County's 11.9% decline (**Table 2**). The mean decline across all counties was 17.6% (**Table 2**). Harris County, however, saw 12.8% higher NO_2 levels (**Table 2**). The 28.7% mean decrease in NO_2 levels during the analyzed counties' peak lockdown periods is significantly larger than the 17.6% decline during the loosening lockdown period. This is largely expected given that as restrictions are loosened, human activity such as driving resumes, likely causing NO_x emissions to rise.

3.4. Meteorology

Meteorological factors must be considered when analyzing the decline in NO_2 levels during the 2020 peak lockdown and loosening lockdown periods. Year to year meteorological variations can result in around a 15% difference in monthly NO_2 levels (Goldberg et al., 2020). In cities with relatively flat topography such as New York City, Chicago, Washington, DC, and Atlanta, increasing wind speeds from essentially stagnant to greater than 8 m/s results in 30%–60% lower NO_2 levels (Goldberg et al., 2020). Likewise, in cities such as Los Angeles, which feature heterogenous topography, increasing wind speeds from nearly stagnant to greater than 8 m/s results in 70%–85% lower NO_2 levels (Goldberg et al., 2020). Wind, particularly high-speed wind, disperses pollution away

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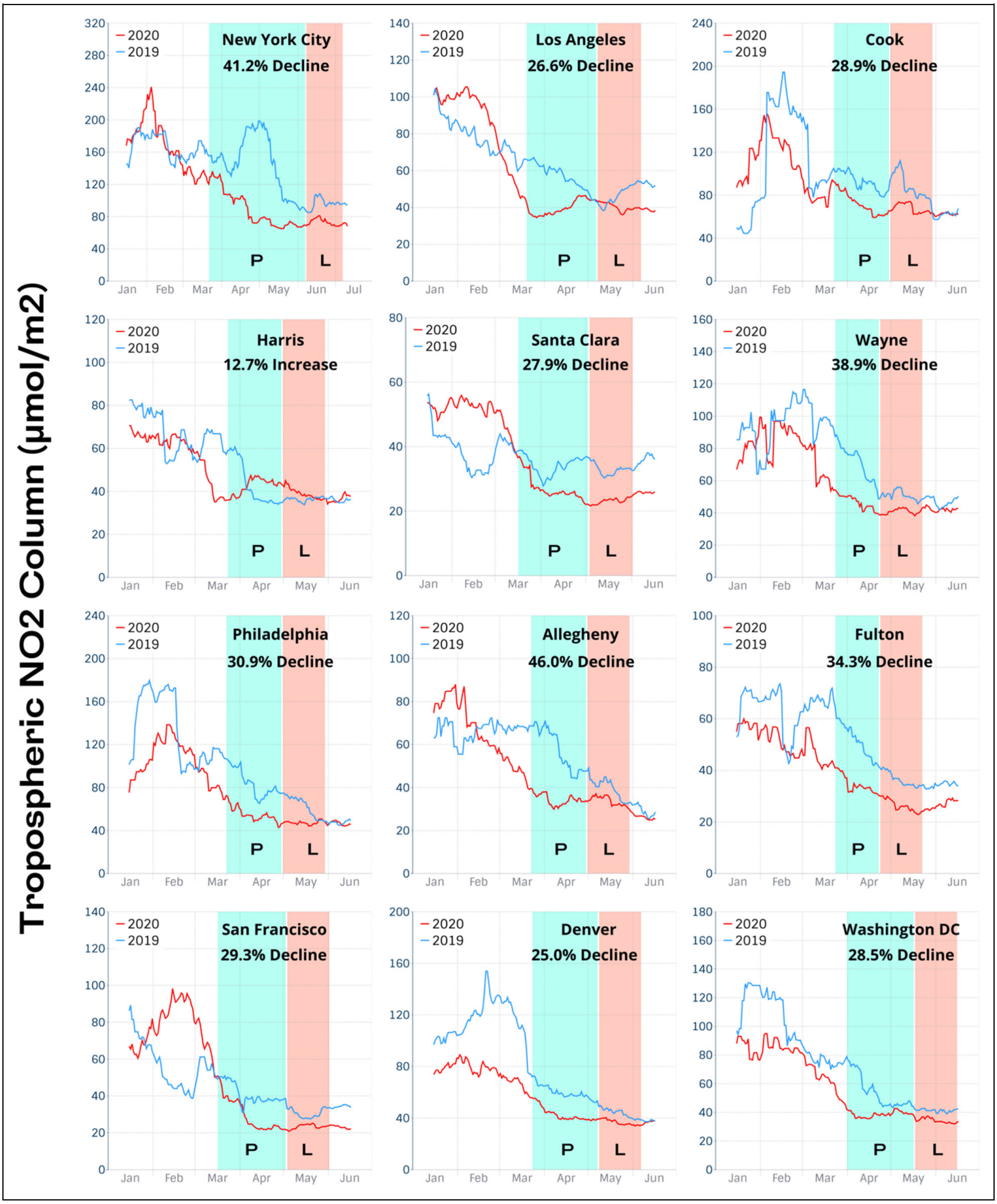

Figure 1. Time series graphs of 28-day rolling average tropospheric NO_2 column concentrations in 2020 and 2019 in the 12 analyzed counties. Each graph illustrates county name and percent decline in NO_2 during 2020 peak lockdown period compared to 2019. The light blue shaded region labeled with the letter "P" represents peak lockdown period. The light pink-shaded region labeled with the letter "L" represents loosening lockdown period. DOI: https://doi.org/10.1525/elementa.2021.00002.f1

from city centers resulting in lower levels of NO_2. Wind direction also plays a significant role in determining urban air pollution levels. While the effects of wind direction are nonlinear, largely dependent on the location of other major cities, northwest winds tend to result in the cleanest air (Goldberg et al., 2020). The impact of other meteorological factors, such as temperature and relative humidity, on NO_2 levels are less clear (Harkey et al., 2015). Of the four metrological variables studied, wind speed has the most significant impact on NO_2 (Roberts-Semple et al.,

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2012). To evaluate the degree to which meteorology potentially influenced the observed reduction in NO_2 concentrations in 2020, temperature, wind speed, wind direction, and relative humidity will be analyzed and investigated further in our future work.

4. Conclusion

Although the spread of COVID-19 has negatively affected global health and economic well-being, it has positively impacted the air quality around the world. This work has investigated the impact of lockdown on NO_2 levels in 12 major cities in the United States. NO_2 is a toxic air pollutant responsible for 79,000 annual deaths in Europe alone, and many more around the world. The overall decline in NO_2 during the peak lockdown periods in the analyzed counties and the substantial decline during the loosening lockdown period is a positive impact amid this devastating pandemic. During peak lockdown, it was found that 11 of the 12 counties experienced lower NO_2 levels during 2020 compared to 2019, ranging from Allegheny County's 46.0% decline to Denver County's 25.0% decline. The decline in NO_2 during the U.S. COVID-19 lockdowns likely saved lives and caused other positive health impacts associated with reduced NO_x emissions, such as fewer asthma attacks and lung diseases. Moreover, the decline in NO_2 directly impacts ozone levels and in turn would have further health and environmental impacts. However, the relation between NO_2 and O_3 during COVID-19 lockdown is complex. Several studies have reported that higher O_3 levels were observed during lockdown when NO_2 levels decreased (Steinbrecht et al., 2020; Tang et al., 2020). For example, Sicard et al. (2020) recently reported that the daily mean O_3 concentrations increased at urban stations by 24% in Nice, 14% in Rome, 27% in Turin, 2.4% in Valencia, and 36% in Wuhan during the lockdown in 2020, compared to the same period in 2017–2019. On the other hand, others have reported on lower O_3 monthly anomalies during 2020 lockdown periods (Miyazaki et al., 2020; Cristofanelli et al., 2021).

The outcomes of this study show that it is therefore crucial that American policymakers and environmental leaders learn from this experience. The reduction in human activity, as seen during the COVID-19 lockdowns, has significantly reduced NO_2 concentrations.

Data accessibility statement

Tropospheric NO_2 data were obtained from Google Earth Engine at https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S5P_OFFL_L3_NO2. Shapefile data used to designate county boundaries were obtained from the National Weather Service at https://www.weather.gov/gis/Counties. Meteorological data were obtained from NOAA's local climatological data at https://www.ncdc.noaa.gov/cdo-web/datatools/lcd.

Supplemental files

The supplemental files for this article can be found as follows:

Figure S1. Location and geographic boundaries of San Francisco County, Santa Clara County, and Los Angeles County.

Figure S2. Location and geographic boundaries of New York City, Philadelphia County, Allegheny County, and Washington, DC.

Figure S3. Location and geographic boundaries of Denver County, Cook County, Wayne Count, Harris County, and Fulton County.

Figure S4. Visualized NO_2 levels in each county over analyzed time periods.

Table S1. Supplementary NO_2 data used in calculations.

Table S2. Raw meteorological data for temperature, wind speed, wind direction, and relative humidity during 2019 and 2020.

Table S3. Raw meteorological data and percentage shift for temperature, wind speed, wind direction, and relative humidity during 2015–2018 baseline, 2019, and 2020.

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Competing interests

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Author contributions

Contributed to conception and design: JP, RI.

Contributed to acquisition of data: JP.

Contributed to analysis and interpretation of data: JP.

Drafted and/or revised the article: JP, RI.

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References

Achakulwisut, P, Brauer, M, Hystad, P, Anenberg, SC. 2019. Global, national, and urban burdens of paediatric asthma incidence attributable to ambient NO_2 pollution: estimates from global datasets. *The Lancet Planetary Health* 1–13. DOI: http://dx.doi.org/10.1016/S2542-5196(19)30046-4.

Baumbach, G, Vogt, U. 2003. Influence of inversion layers on the distribution of air pollutants in urban areas. *Water, Air, Soil Pollution Focus* **3**(5): 67–78. DOI: http://dx.doi.org/10.1023/A:1026098305581.

Bauwens, M, Compernolle, S, Stavrakou, T, Müller, J-F, van Gent, J, Eskes, H, Levelt, PF, van der A, R, Veefkind, JP, Vlietinck, J, Yu, H, Zehner, C. 2020. Impact of coronavirus outbreak on NO_2 pollution assessed using TROPOMI and OMI observations. *Geophysical Research Letters* **47**(11). DOI: http://dx.doi.org/10.1029/2020GL087978.

Cristofanelli, P, Putero, D, Serva, F, Arduini, J, Sprenger, M, Maione, M, Bonasoni, P, Calzolari, F, Busetto, M, Trisolino, P. 2021. Negative ozone

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anomalies at a high mountain site in northern Italy during 2020: a possible role of COVID-19 lockdowns? Virtual Global Monitoring Annual Conference. Available at: https://gml.noaa.gov/annualconference/abs.php?refnum=29-210423-A.

Czarnecka, M, Nidzgorska-Lencewicz, J. 2017. The impact of thermal inversion on the variability of PM10 concentration in winter seasons in Tricity. *Environment Protection Engineering* **44**(2): 157–172. DOI: http://dx.doi.org/10.5277/epe170213.

Fanelli, D, Piazza, F. 2020. Analysis and forecast of COVID-19 spreading in China, Italy and France. *Chaos, Solitons & Fractals* **134**: 109761. DOI: http://dx.doi.org/10.1016/j.chaos.2020.109761.

Goldberg, DL, Anenberg, SC, Griffin, D, McLinden, CA, Lu, Z, Streets, DG. 2020. Disentangling the impact of the COVID-19 lockdowns on urban NO2 from natural variability. *Geophysical Research Letters* **47**: 1–11. DOI: http://dx.doi.org/10.1029/2020GL089269.

Gualtieri, G, Brilli, L, Carotenuto, F, Vagnoli, C, Zaldei, A, Gioli, B. 2020. Quantifying road traffic impact on air quality in urban areas: A Covid19-induced lockdown analysis in Italy. *Environmental Pollution* **267**: 115682. Elsevier Ltd. DOI: http://dx.doi.org/10.1016/j.envpol.2020.115682.

Harkey, M, Holloway, T, Oberman, J, Scotty, E. 2015. An evaluation of CMAQ NO_2 using observed chemistry-meteorology correlations. *Journal of Geophysical Research* **120**(22): 11775–11797. DOI: http://dx.doi.org/10.1002/2015JD023316.

Isaifan, RJ. 2020. The dramatic impact of coronavirus outbreak on air quality: Has it saved as much as it has killed so far? *Global Journal of Environmental Science and Management* **6**: 275–288. DOI: http://dx.doi.org/10.22034/gjesm.2020.03.01.

Kontis, V, Bennett, JE, Rashid, T, Parks, RM, Pearson-Stuttard, J, Guillot, M, Asaria, P, Zhou, B, Battaglini, M, Corsetti, G, McKee, M. 2020. Magnitude, demographics and dynamics of the effect of the first wave of the COVID-19 pandemic on all-cause mortality in 21 industrialized countries. *Nature Medicine* **26**: 1919–1928. DOI: http://dx.doi.org/10.1038/s41591-020-1112-0.

Lian, X, Huang, J, Huang, R, Liu, C, Wang, L, Zhang, T. 2020. Impact of city lockdown on the air quality of COVID-19-hit of Wuhan city. *Science of the Total Environment* **742**: 140556. DOI: http://dx.doi.org/10.1016/j.scitotenv.2020.140556.

Liu, F, Page, A, Strode, SA, Yoshida, Y, Choi, S, Zheng, B, Lamsal, LN, Li, C, Krotkov, NA, Eskes, H, van der A, R, Veefkind, P, Levelt, PF, Hauser, OP, Joiner, J. 2020. Abrupt decline in tropospheric nitrogen dioxide over China after the outbreak of COVID-19. *Science Advances* **6**(28): eabc2992. DOI: http://dx.doi.org/10.1126/sciadv.abc2992.

Liu, Z, Deng, Z, Ciais, P, Lei, R, Davis, SJ, Feng, S, Zheng, B, Cui, D, Dou, X, He, P, Zhu, B. 2020. *COVID-19 causes record decline in global CO2 emissions*. arXiv. Available at https://arxiv.org/abs/2004.13614.

Menut, L, Bessagnet, B, Siour, G, Mailler, S, Pennel, R, Cholakian, A. 2020. Impact of lockdown measures to combat Covid-19 on air quality over western Europe. *Science of the Total Environment* **741**: 140426. DOI: http://dx.doi.org/10.1016/j.scitotenv.2020.140426.

Miyazaki, K, Bowman, K, Sekiya, T, Takigawa, M, Neu, J, Sudo, K, Osterman, G, Eskes, H. 2020. Global tropospheric ozone responses to reduced NO_x emissions linked to the COVID-19 world-wide lockdowns. *The Earth and Space Science Open Archive*. DOI: http://dx.doi.org/10.1002/essoar.10504795.1.

National Centers for Environmental Information, National Ocean and Atmospheric Information. 2021. Available at https://www.ncdc.noaa.gov/cdo-web/datatools/lcd. Accessed 18 April 2021.

Roberts-Semple, D, Song, F, Gao, Y. 2012. Seasonal characteristics of ambient nitrogen oxides and ground-level ozone in metropolitan northeastern New Jersey. *Atmospheric Pollution Research* **3**(2): 247–257. DOI: http://dx.doi.org/10.5094/APR.2012.027.

Rupani, PF, Nilashi, M, Abumalloh, RA, Asadi, S, Samad, S, Wang, S. 2020. Coronavirus pandemic (COVID-19) and its natural environmental impacts. *International Journal of Environmental Science and Technology* **17**: 4655–4666. DOI: http://dx.doi.org/10.1007/s13762-020-02910-x.

S5P Mission Performance Centre Nitrogen Dioxide [L_2-NO_2] Readme document number." 2020. Available at https://sentinel.esa.int/documents/247904/3541451/Sentinel-5P-Nitrogen-Dioxide-Level-2-Product-Readme-File. Accessed 13 April 2021.

Samoli, E, Aga, E, Touloumi, G, Nisiotis, K, Forsberg, B, Lefranc, A, Pekkanen, J, Wojtyniak, B, Schindler, C, Niclu, E, Brunstein, R. 2006. Short-term effects of nitrogen dioxide on mortality: An analysis within the APHEA project. *European Respiratory Journal* **17**: 1129–1138. DOI: http://dx.doi.org/10.1183/09031936.06.00143905.

Shah, VJ, Jacob, D, Li, K, Silvern, R, Zhai, S, Liu, M, Lin, J, Zhang, Q. 2020. Effect of changing NO_x lifetime on the seasonality and long-term trends of satellite-observed tropospheric NO_2 columns over China. *Atmospheric Chemistry and Physics* **20**: 1483–1495. DOI: http://dx.doi.org/10.5194/acp-20-1483-2020.

Shehzad, K, Sarfraz, M, Ghulam, S, Meran Shah, SG. 2020. The impact of COVID-19 as a necessary evil on air pollution in India during the lockdown. *Environmental Pollution* **266**: 115080. DOI: http://dx.doi.org/10.1016/j.envpol.2020.115080.

Shi, X, Brasseur, GP. 2020. The response in air quality to the reduction of Chinese economic activities during the COVID-19 Outbreak. *Geophysical Research Letters* **47**(11). DOI: http://dx.doi.org/10.1029/2020GL088070.

Shmool, JLC, Michanowicz, DR, Cambal, L, Tunno, B, Howell, J, Gillooly, S, Roper, C, Tripathy, S, Chubb, LG, Eisl, HM, Gorczynski, JE. 2014. Saturation sampling for spatial variation in multiple air

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pollutants across an inversion-prone metropolitan area of complex terrain. *Environmental Health A Global Access Science Source* **13**(28): 1–16. DOI: http://dx.doi.org/10.1186/1476-069X-13-28.

Sicard, P, De Marco, A, Agathokleous, E, Feng, Z, Xu, X, Paoletti, E, Rodriguez, JJD, Calatayud, V. 2020. Amplified ozone pollution in cities during the COVID-19 lockdown. Amplified ozone pollution in cities during the COVID-19 lockdown. *Science of the Total Environment* **735**: 139542. DOI: http://dx.doi.org/10.1016/j.scitotenv.2020.139542.

Simon, H, Reff, A, Wells, B, Xing, J, Frank, N. 2015. Ozone trends across the United States over a period of decreasing NO_x and VOC emissions. *Environmental Science & Technology* **49**: 186–195. DOI: http://dx.doi.org/10.1021/es504514z.

Singh, V, Singh, S, Biswal, A, Kesarkar, AP, Mor, S, Ravindra, K. 2020. Diurnal and temporal changes in air pollution during COVID-19 strict lockdown over different regions of India. *Environmental Pollution* **266**(3): 115368. DOI: http://dx.doi.org/10.1016/j.envpol.2020.115368.

Steinbrecht, W, Kubistin, D, Plass-Dulmer, C, Davies, J, Tarasick, DW, von der Gathen, P, Deckelmann, H, Jepsen, N, Kivi, R, Lyall, N, Palm, M, Notholt, J, Kois, B, Oelsner, P, Allaart, M, Piters, A, Gill, M, Van Malderen, R, Delcloo, AW, Sussmann, R, Mahieu, E, Servais, C, Romanens, G, Stübi, R, Ancellet, G, Godin-Beekmann, S, Yamanouchi, S, Strong, K, Johnson, B, Cullis, P, Petropavlovskikh, I, Hannigan, JW, Hernandez, J-L, Rodriguez, AD, Nakano, T, Chouza, F, Leblanc, T, Torres, C, Garcia, O, Röhling, AN, Schneider, M, Blumenstock, T, Tully, M, Paton-Walsh, C, Jones, N, Querel, R, Strahan, S, Stauffer, RM, Thompson, AM, Inness, A, Engelen, R, Chang, K-L, Cooper, OR. 2021. COVID-19 crisis reduces free tropospheric ozone across the Northern Hemisphere. *Geophysical Research Letters* **48**: e2020GL091987. DOI: http://dx.doi.org/10.1029/2020GL091987.

Tack, F, Merlaud, A, Iordache, MD, Pinardi, G, Dimitropoulou, E, Eskes, H, Bomans, B, Veefkind, P, Van Roozendael, M. 2021. Assessment of the TROPOMI tropospheric NO_2product based on airborne APEX observations. *Atmospheric Measurement Techniques* **14**: 615–646. DOI: http://dx.doi.org/10.5194/amt-14-615-2021.

Tang, R, Huang, X, Zhou, D, Wang, H, Xu, J, Ding, A. 2020. Global air quality change during the COVID-19 pandemic: Regionally different ozone pollution responses COVID-19. *Atmospheric and Oceanic Science Letters*. DOI: http://dx.doi.org/10.1016/j.aosl.2020.100015.

U.S. Department of Transportation. 2020. Seasonally adjusted transportation data. Bureau of Transport Statistics. Available at https://www.transtats.bts.gov/osea/seasonaladjustment/?PageVar=VMT. Accessed 29 November 2020.

Vadrevu, KP, Eaturu, A, Biswas, S, Lasko, K, Sahu, S, Garg, JK, Justice, C. 2020. Spatial and temporal variations of air pollution over 41 cities of India during the COVID-19 lockdown period. *Science Report* **10**: 16574. DOI: http://dx.doi.org/10.1038/s41598-020-72271-5.

Van Geffen, J, Folkert Boersma, K, Eskes, H, Sneep, M, Ter Linden, M, Zara, M, Pepijn Veefkind, J. 2020. S5P TROPOMI NO2 slant column retrieval: Method, stability, uncertainties and comparisons with OMI. *Atmospheric Measurement Techniques* **13**(3): 1315–1335. DOI: http://dx.doi.org/10.5194/amt-13-1315-2020.

Venter, ZS, Aunan, K, Chowdhury, S, Lelieveld, J. 2020. COVID-19 lockdowns cause global air pollution declines. *Proceedings of the National Academy of Sciences of the United States of America* **117**(32): 18984–18990. DOI: http://dx.doi.org/10.1073/pnas.2006853117.

Wang, L, Wang, J, Tan, X, Fang, C. 2020. Analysis of NO_x pollution characteristics in the atmospheric environment in Changchun city. *Atmosphere (Basel)* **11**(1): 30. DOI: http://dx.doi.org/10.3390/ATMOS11010030.

Wang, M, Liu, F, Zheng, M. 2020. Air quality improvement from COVID-19 lockdown: Evidence from China. *Air Quality, Atmosphere and Health* **14**: 591–604. DOI: http://dx.doi.org/10.1007/s11869-020-00963-y.

Wang, Q, Su, M. 2020. A preliminary assessment of the impact of COVID-19 on environment: A case study of China. *Science of the Total Environment* **728**: 138915. DOI: http://dx.doi.org/10.1016/j.scitotenv.2020.138915.

Wang, Y, Wen, Y, Wang, Y, Zhang, S, Zhang, KM, Zheng, H, Xing, J, Wu, Y, Hao, J. 2020. Four-month changes in air quality during and after the COVID-19 lockdown in six megacities in China. *Environmental Science & Technology Letters* **7**: 808. DOI: http://dx.doi.org/10.1021/acs.estlett.0c00605.

Wu, J, Muccari, R, Sundberg, A, DeJesus-Banos, B, O'Boyle, K. 2020 Jun 11. Reopening America: All 50 states have begun to reopen. See what that means for your state. NBC News. Available at https://www.nbcnews.com/news/us-news/reopening-america-see-what-states-across-u-s-are-starting-n1195676. Accessed 24 December 2020.

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