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Short Communication

Nonuniform impacts of COVID-19 lockdown on air quality over the United States

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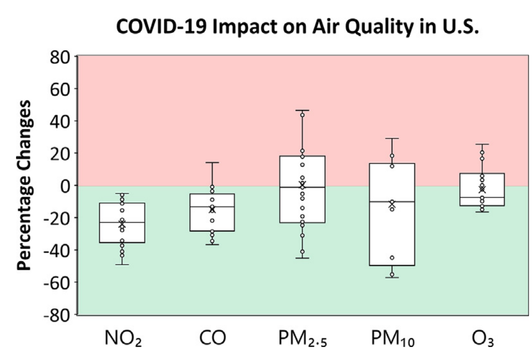
HIGHLIGHTS

- The lockdown issued due to COVID-19 had nonuniformly impacted air quality in the US.
- Consistent NO_2 and CO declines corroborate with low transportation/utility demands.
- Reductions in NO_2 ranged 5–49% and tended to increase with local population density.
- Significant PM reductions only occurred where NO_2 declined the most.
- The impact on O_3 was mixed, generally within ±20%.

GRAPHICAL ABSTRACT



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ABSTRACT

Most of the state governments in United States (U.S.) issued lockdown or business restrictions amid the COVID-19 pandemic in March 2020, which created a unique opportunity to evaluate the air quality response to reduced economic activities. Data acquired from 28 long-term air quality stations across the U.S. revealed widespread but nonuniform reductions of nitrogen dioxide (NO_2) and carbon monoxide (CO) during the first phase of lockdown (March 15–April 25, 2020) relative to a pre-lockdown reference period and historical baselines established in 2017–2019. The reductions, up to 49% for NO_2 and 37% for CO, are statistically significant at two thirds of the sites and tend to increase with local population density. Significant reductions of particulate matter ($PM_{2.5}$ and PM_{10}) only occurred in the Northeast and California/Nevada metropolises where NO_2 declined the most, while the changes in ozone (O_3) were mixed and relatively minor. These findings are consistent with lower transportation and utility demands that dominate NO_2 and CO emissions, especially in major urban areas, due to the lockdown. This study provides an insight into potential public health benefits with more aggressive air quality management, which should be factored into strategies to reopen the U.S. and global economy.

1. Introduction

The ongoing pandemic of coronavirus disease (COVID-19) has created challenges for governments around the world to balance public safety and economy. In the U.S., following the national emergency declared by President Trump on March 13, 2020, states and municipalities have issued various degrees of lockdown and/or stay-at-home policies suiting local

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specific conditions (Lin et al., 2020). Such policies impact air quality through, most notably, declined "non-essential" transportation and energy consumption (Le Quéré et al., 2020). Among the criteria air pollutants (CAPs), the U.S. Environmental Protection Agency (EPA)'s national emissions inventory attributes 74% of nitrogen oxides (NO_x, sum of nitrogen dioxide [NO_2] and nitric oxide [NO]) and 59% of carbon monoxide (CO) emissions to on- and off-road traffic and electric generation (U.S. EPA, 2016). Ambient levels of the two pollutants might be most affected by the lockdown, compared with primary $PM_{2.5}$ and PM_{10} (particulate matter with aerodynamic diameters below 2.5 and 10 μm, respectively) of which only 10% and 4% result from traffic and electric generation. Ozone (O_3) is formed in the atmosphere through photochemical reaction of NO_x and volatile organic compounds (VOCs). Reduced NO_x and VOCs emissions could either lower or lift O_3 concentrations depending on the local photochemical regime (Sillman and He, 2002).

The unprecedented situation of COVID-19 pandemic creates an opportunity to assess the contribution of transportation and commercial activities to local air quality and the potential outcome of more stringent emission regulations. Such assessments have been carried out for many large cities around the world (Kerimray et al., 2020; Nakada and Urban, 2020; Sharma et al., 2020; Tobías et al., 2020), but the evidence in the US is lacking. This paper analyzed data from long-term air quality monitoring stations across the U.S. and estimated reductions of CAPs during the first phase of extensive lockdown. Findings can inform future modeling studies that attempt to capture policy outcomes by simulating state-wise emission reductions. Such information is also important for the post-pandemic air quality management.

2. Methods

The EPA National Core (NCore) network tracks long-term trends of CAPs across the U.S. (Scheffe et al., 2009). Daily NCore data for January 1, 2020–April 30, 2020 were acquired from Airnowtech (https://www.airnowtech.org/) and cross-verified with those reported to the U.S. EPA AirData website (https://www.epa.gov/outdoor-air-quality-data). The six weeks or 42 days between March 15 and April 25, 2020 was designated as the first-phase lockdown period (P1), as many states began restricting businesses and schools in the week of March 15 but relaxed the restrictions somewhat coming into May 2020 (Lin et al., 2020; Raifman et al., 2020). A reference period deemed business as usual between January 25 and March 7, 2020 (P0) was also selected, and the relative concentration of a pollutant I, i.e., $[I]'$, is defined as the ratio of its mean values during P1 and P0, thus:

$$[I]' = \frac{\overline{[I]_{P1}}}{\overline{[I]_{P0}}} \quad (1)$$

It is anticipated that $[I]'_{2020}$ ($[I]'$ for year 2020) differs significantly from those of previous years without lockdown, if the lockdown did lower the concentrations of pollutant I. The percentage of change can then be estimated by:

$$\Delta I\% = \frac{[I]'_{2020} - [I]'_{\text{baseline}}}{[I]'_{\text{baseline}}} \times 100\% \quad (2)$$

where $[I]'_{\text{baseline}}$ was established from the corresponding P1/P0 periods in year 2017–2019 following Eq. (1). $\Delta I\%$ resulting from the 2017, 2018, and 2019 baselines were averaged to yield the final $\Delta I\%$ shown in Table 1. The EPA Air Quality System (https://www.epa.gov/aqs) provided the CAPs data for 2017–2019.

Averaging over consecutive 6 weeks for P1 and P0 minimizes daily or seasonal variability due to meteorology. Changes of local emissions and/or measurement protocols from year to year should not affect the inter-annual comparison because those effects are mostly canceled in the P1/P0 ratio. P1 and P0 with more than one third of missing data (i.e., >14 days out of the 42-day period) were excluded. For the 28 sites selected, $[I]'_{\text{baseline}}$ resulted from at least 2 years of valid data. To estimate the confidence interval of $\Delta I\%$, a bootstrapping procedure (Mooney and Duval, 1993) based on 12,000 resampling/recalculation of the data were carried out using the Matlab® Statistics Toolbox. The type I error was set to 5%.

3. Results

Twenty-eight NCore sites with 2017–2020 NO_2, O_3, and $PM_{2.5}$ data mostly available through the end of April 2020 were identified for this analysis. These sites are in or proximate to 28 different metropolises among 23 states. CO and PM_{10} were also reported from 21 and 13 of the 28 sites, respectively. Table 1 lists the site- and pollutant-specific $\Delta I\%$, ranked by $\Delta NO_2\%$, whereas the detailed site information can be found in the supplemental Table S1.

Decreasing NO_2 concentrations occurred throughout the U.S. during the lockdown, with $\Delta NO_2\%$ ranging from −49% at the Las Vegas, Nevada to −5% at the Cheyenne, Wyoming site. Reductions that exceed 19% (18 sites) are all statistically significant. The CO levels also declined broadly except at two sites (Raleigh and Indianapolis) where the positive changes were not significant. For $PM_{2.5}$, only 7 sites reported significant decreases while 3 sites (Indianapolis, Seattle, and Cheyenne) actually saw significant increases. The mixed results reflect relatively small changes in $PM_{2.5}$, if any, due to the lockdown, compared with the normal inter-annual variability at many locales. Since $\Delta PM_{2.5}\%$ and $\Delta PM_{10}\%$ are correlated (Spearman $r = 0.78$, 95% CI: [0.35, 0.93]) and generally have the same sign, the changes in PM_{10} might mostly be attributed to $PM_{2.5}$.

There are also significant associations among $\Delta NO_2\%$, $\Delta CO\%$, and $\Delta PM_{2.5}\%$ (see Table S2). For the top 9 sites in Table 1 with the most reductions in NO_2 concentration, all the other pollutants except O_3 also declined. As a secondary pollutant, O_3 did not show a clear pattern across the country, with significant increases and decreases observed at 2 and 7 sites, respectively, for the lockdown period.

4. Discussion

The lockdown appeared to lower NO_2 and CO more broadly and significantly than PM, consistent with declining mobile and power plant emissions and similar to observations in Europe (Sicard et al., 2020; Tobías et al., 2020). On a national scale both $PM_{2.5}$ and PM_{10} are predominately attributed to Industrial and Other Sources, such as residential fuel combustion, waste management, and fugitive dust (Chow et al., 2010; U.S. EPA, 2016), which were not particularly targeted by government policies against COVID-19. Sites reporting significant $PM_{2.5}$ reductions represent major urban areas in either Northeastern U.S. (New York, Boston, and Province) or California/Nevada (Fresno, San Jose, Los Angeles, and Las Vegas), where the traffic fractions of $PM_{2.5}$ emissions likely exceed the national average and lockdown policies are known to be stringent from the beginning. California, Nevada, New York, and Massachusetts were among the first 10 states to close non-essential businesses and ban mass gathering statewide (Raifman et al., 2020). For example, Nevada had enforced closure of all schools and non-essential businesses including casinos and restaurant dine-ins since March 17 (Messerly et al., 2020) and banned gathering of 10 or more people since March 24 (Komenda, 2020). This is in contrary to states such as North Dakota and Wyoming where schools were closed but businesses remained open (no stay-at-home order). Significant CO reductions nonetheless were observed at Bismarck, ND and Cheyenne, WY during the lockdown (Table 1).

There could also be an urban-rural contrast in how the lockdown affects air quality, as fewer non-essential commercial activities occur in rural and suburban areas than in urban centers. Enforcing lockdown policies in rural areas is also more difficult. Population density of the zip code where a site is located serves as a surrogate of urbanization and is plotted against $\Delta NO_2\%$ in Fig. 1. All sites with population

Table 1
Locations of 28 U.S. EPA NCore sites and percentage changes of criteria air pollutants by site due to the COVID-19 lockdown (3/15–4/25, 2020). Numbers in the brackets are 95% confidence intervals. The dark and light green shades highlight significant and insignificant reductions, respectively, while dark and light orange shades denote significant and insignificant increases, respectively.

Site ID*	Metropolis/City**	NO_2	CO	$PM_{2.5}$	PM_{10}	O_3
NV1	Las Vegas	-49 (-60, -36)	-28 (-43, -10)	-41 (-55, -25)	-55 (-66, -43)	17 (0, 35)
UT1	Salt Lake City	-43 (-55, -31)	-	-5 (-30, 24)	-	25 (8, 45)
CA1	Fresno	-42 (-52, -30)	-31 (-40, -21)	-25 (-44, -1)	-54 (-65, -42)	-9 (-20, 3)
CA2	San Jose	-41 (-53, -27)	-29 (-40, -15)	-45 (-58, -29)	-	-10 (-21, 2)
NY1	New York	-40 (-53, -25)	-37 (-50, -22)	-29 (-48, -7)	-	8 (-7, 25)
VA1	Richmond	-37 (-51, -21)	-13 (-22, -3)	-	-	-8 (-19, 3)
MA1	Boston	-36 (-48, -22)	-22 (-31, -12)	-23 (-40, -2)	-	8 (-5, 23)
CA3	Los Angeles	-34 (-50, -16)	-34 (-46, -21)	-41 (-59, -17)	-57 (-69, -42)	-17 (-26, -6)
CA4	Sacramento	-34 (-51, -12)	-20 (-34, -4)	-19 (-41, 8)	-	-15 (-24, -5)
NC1	Raleigh	-33 (-48, -16)	1 (-12, 14)	-	12 (-18, 47)	-8 (-17, 2)
IN1	Indianapolis	-28 (-43, -10)	14 (-2, 33)	47 (17, 81)	29 (4, 59)	-15 (-25, -4)
RI1	Providence	-26 (-45, -2)	-	-31 (-49, -9)	-	20 (-1, 47)
AZ1	Phoenix	-25 (-36, -12)	-9 (-21, 5)	-22 (-41, 0)	-45 (-55, -33)	-12 (-20, -3)
MO1	St. Louis	-25 (-38, -9)	-13 (-24, -1)	6 (-15, 30)	-	-2 (-17, 14)
MD1	District of Columbia	-21 (-38, -2)	-	-1 (-22, 23)	-	-7 (-17, 4)
OK1	Tulsa	-21 (-37, -2)	-29 (-38, -19)	1 (-20, 27)	-	-14 (-26, -0)
OH1	Cincinnati	-20 (-34, -4)	-4 (-14, 8)	19 (-4, 47)	18 (3, 36)	-8 (-20, 5)
NM1	Albuquerque	-19 (-34, -3)	-2 (-13, 9)	-14 (-28, 1)	-10 (-25, 7)	8 (-3, 19)
MN1	Minneapolis	-15 (-39, 14)	-	-1 (-25, 27)	14 (-15, 49)	-13 (-21, -5)
GA1	Atlanta	-15 (-33, 6)	-7 (-25, 14)	18 (-7, 47)	14 (-5, 35)	-1 (-16, 16)
OR1	Portland	-11 (-33, 15)	-	21 (-19, 74)	-	6 (-12, 26)
WA1	Seattle	-11 (-31, 13)	-1 (-11, 10)	44 (1, 96)	-	0 (-14, 16)
OH2	Cleveland	-10 (-32, 16)	-16 (-28, -2)	22 (-11, 63)	-15 (-35, 10)	-15 (-25, -4)
HI1	Honolulu	-10 (-28, 13)	-	-8 (-25, 11)	-14 (-28, 2)	-
KS1	Kansas City	-9 (-29, 15)	-	5 (-21, 38)	-	3 (-13, 21)
MD2	Grantsville	-6 (-23, 14)	-7 (-14, -1)	13 (-9, 39)	-	-13 (-21, -4)
ND1	Bismarck	-6 (-22, 13)	-12 (-17, -7)	5 (-17, 30)	-	7 (-1, 16)
WY1	Cheyenne	-5 (-39, 43)	-16 (-21, -10)	112 (41, 210)	12 (-15, 45)	-6 (-14, 3)

*The first two letters of Site ID indicate state where the site is located. Detailed site information is in Table S1.
**The greater metro area each site represents.

density > 4000 per mile^2 observed significant decreases of NO_2, except the Portland site in Oregon. For those <4000 per mile^2, only half saw significant changes, possibly reflecting distinct local emissions and/or responses to the pandemic. Population density does explain the different $\Delta NO_2\%$ between the two OH sites and between the two MD sites that bore a uniform lockdown policy within the respective state. In both cases, NO_2 reduction increased with the local population density (Fig. 1). Some counties or municipalities implemented stricter measures to curb COVID-19, creating in-state disparity. Utah, for example, did not enforce a statewide lockdown, despite of a mandatory stay-at-home order for all residents in Salt Lake City, the state's capital (Stevens and Harkins, 2020), where significant NO_2 reductions were observed. Future studies are warranted to elucidate how various policies (e.g., stay-at-home versus business closure) and their enforcement impact emissions in urban and rural communities.

Earlier studies reported increases of O_3 concentrations in Europe, Brazil, and India metropolises during the COVID-19 lockdown (Dantas et al., 2020; Sharma et al., 2020; Sicard et al., 2020). In the NO_x-rich urban air, O_3 can be more limited by VOCs than NO_x, and thus reducing NO_x emissions would elevate O_3 unless VOCs are reduced at a higher rate simultaneously (Kleinman et al., 2005). Reducing NO_x in suburban or rural airs which are NO_x-limited, however, results in lower O_3 levels. The U.S. sites in this study covered both urban and suburban areas, where O_3 were generally low and not the leading pollutant in March–April. Although VOCs were not measured at every NCore site for a photochemical assessment, Table 1 indicates both O_3 enhancing and depressing scenarios. The two sites with significant O_3 increases happened to be in Las Vegas and Salt Lake City, where NO_2 reduced the most. All $\Delta O_3\%$ are within 20% regardless of the sign and significance, with the exception of Salt Lake City at 25%. The lockdown appears to only slightly affect the ambient O_3 level, as shown in Sommer et al. (2020).

5. Conclusion

The lockdown or stay-at-home orders issued by the U.S. government to counter the COVID-19 pandemic have nonuniformly impacted air pollution in the U.S. More consistent NO_2 and CO declines than other pollutants coincide with reduced transportation and utility demands, while inter-site differences reflect not only the local lockdown policy but also population density. The first phase of lockdown in general affected urban more than suburban air quality. Although these effects are temporary, public health benefits from more aggressive air quality management should be considered in the recovery efforts, such as accelerating the transition into cleaner fuels and mass transportation.

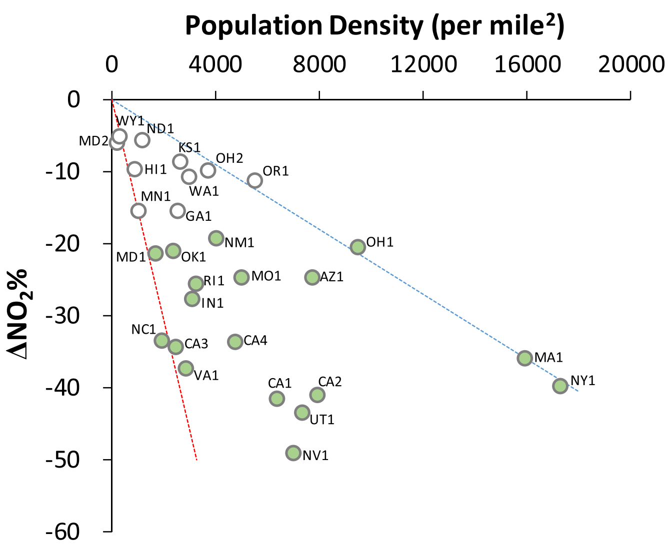

Fig. 1. Change in ambient NO_2 concentration (ΔNO_2 %) due to the COVID-19 lockdown versus local population density based on a site's zip code. Site IDs are as noted in Table 1. Significant reductions are marked in green. The upper and lower dashed lines are visual guide for comparing the two OH and two MD sites, respectively.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.141105.

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