Ambient air pollutants and their effect on COVID-19 mortality in the United States of America

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ABSTRACT

Objective. To examine the impact of four ambient air pollutants on the COVID-19 mortality rate in the United States of America.

Methods. Using publicly accessible data collected by the United States Census Bureau, Environmental Protection Agency, and other agencies, county-level mortality rates were regressed on concentration values of ground-level ozone, nitrogen dioxide, carbon monoxide, and sulfur dioxide. Four confounder variables were included in the regression analysis: median household income, rate of hospital beds, population density, and days since first confirmed case.

Results. Regression analysis showed that ground-level ozone is positively correlated with county-level mortality rates regardless of whether confounders are controlled for. Nitrogen dioxide is also shown to have a direct relationship with county-level mortality rates, except when all confounders are included in the analysis.

Conclusions. High ground-level ozone and nitrogen dioxide concentrations contribute to a greater COVID-19 mortality rate. To limit further losses, it is important to reflect research findings in public policies. In the case of air pollution, environmental restrictions should be reinforced, and extra precautions should be taken as facilities start reopening.

Keywords   Coronavirus infections; air pollution; mortality; ozone; nitrogen dioxide; United States.

The 2019 novel coronavirus (SARS-CoV-2) has negatively impacted a great number of people physically, mentally, and economically. First reported in early December in Wuhan, China, COVID-19 is a respiratory disease with flu-like symptoms and pneumonia. Given its incubation period and modes of transmission, the virus is highly infectious and spread quickly globally, claiming many lives. As of 27 May 2020, the death toll in the United States of America had reached 100 000 (1).

Globally, studies have proved that COVID-19 is more lethal among certain groups, for instance, adults aged ≥65 years and people with underlying respiratory and cardiovascular health conditions (2). It is crucial to investigate the variables that influence COVID-19 deaths, in order to prevent the mortality rate from increasing. This study aims to evaluate a possible correlation between COVID-19 mortality and four ambient air pollutants.

The five major tropospheric air pollutants are ground-level ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO),

sulfur dioxide (SO_2), and particulate matter 2.5 microns or less in diameter ($PM_{2.5}$). All these pollutants are known to be associated with adverse and sometimes fatal effects on health, including lung cancer, stroke, and cardiovascular disease (3). For example, NO_2 is detrimental to human health by damaging lung linings and stimulating other acute respiratory illnesses (4). Ground-level ozone also damages cells and airway lining fluid, inducing immune-inflammatory responses in the lungs and the cardiovascular system (5). Essentially, air pollution dysregulates antiviral immune responses and exacerbates respiratory and cardiovascular conditions (6). Since these pollution-induced health conditions are the very same conditions that increase the likelihood of COVID-19 death, it is reasonable to hypothesize that higher ambient air pollutant concentrations are associated with higher COVID-19 mortality rates.

A study by Wu et al. proved a positive correlation between COVID-19 mortality rates and long-term $PM_{2.5}$ exposure using

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United States county-level data, showing that an increase of 1 $\mu g/m^3$ in $PM_{2.5}$ is associated with an 8% increase in the COVID-19 mortality rate (7). Recent studies evaluating the correlation of NO_2 and mortality rates in northern Italy (8) and regions of England (9) also showed a direct relationship. Surprisingly, a study analyzing ground-level ozone levels in regions of England found an inverse relationship between ozone and COVID-19 mortality rates (9). The authors argued that the unexpected relationship might have been caused by the conversion of ozone into secondary hazardous gaseous species. Therefore, lower levels of ozone could be linked to higher levels of ozone oxidation products, and subsequently a higher COVID-19 mortality rate.

Besides the study on $PM_{2.5}$ by Wu et al., there has not been any study evaluating the effect of the other four main air pollutants on mortality rates in the United States. This paper fills the gap by exploring the relationship between U.S. Environmental Protection Agency (EPA) county-level design values of O_3, NO_2, CO, and SO_2 with the county-level COVID-19 mortality rate.

MATERIALS AND METHODS

Data

We obtained county-level air pollutant design values for O_3, NO_2, CO, and SO_2 from the EPA website.[1] For ground-level ozone (O_3), the design value was the 3-year average (2017, 2018, and 2019) of the annual fourth highest daily maximum 8-hour ozone concentration, measured in parts per million (ppm). For nitrogen dioxide (NO_2), the design value was the annual (2019) average of the hourly concentration values measured in parts per billion (ppb). For carbon monoxide (CO), the design value was the higher of each year's (2018 and 2019) annual second maximum, non-overlapping 8-hour average, measured in parts per million (ppm). For sulfur dioxide (SO_2), the design value was the annual 99th percentile of the daily maximum 1-hour concentration values, averaged over three consecutive years (2017, 2018, and 2019), measured in parts per billion (ppb). Concentrations affected by exceptional events such as wildfires and volcanic eruptions were not included in these air pollutant values.

For mortality rates, we obtained the number of COVID-19 deaths from the USAFacts website,[2] which aggregates data from the U.S. Centers for Disease Control and Prevention (CDC) and reference state and local agencies, and expressed each county's total COVID-19 deaths up until 14 May 2020 as a percentage of the county's total 2019 population estimate, as obtained from the U.S. Census Bureau website.[3]

We included multiple confounder variables in our linear regression analysis. From the 20 county-level variables evaluated by Wu et al., we selected the four variables that showed significance in their analysis: median household income, rate of hospital beds, population density, and days since first confirmed case.

We obtained median household income data from the U.S. Department of Agriculture's Economic Research Service

(USDA ERS) website[4] and used their latest 2018 median household income in dollars. The rate of hospital beds is the number of hospital beds per county adjusted for county population. Hospital bed data were obtained from Homeland Infrastructure Foundation-Level Data Geoplatform (HIFLD Open Data).[5] For the population density variable, we divided the county's total 2019 population estimate by its area in square miles, both data being obtained from the U.S. Census Bureau website.[3] For the days since first confirmed case variable, we obtained data from the USAFacts website,[2] which aggregates data from the CDC and reference state and local agencies. For this variable, we set the final date of reported confirmed COVID-19 cases to be 14 May 2020 to ensure consistency with our calculation of mortality rates.

All data used in this study are publicly available for further investigation and verification of our results.

Descriptive statistics

The descriptive statistics for all of the above variables are presented in Table 1.

It is important to note that although the United States has a total of 3 141 counties including the District of Columbia, only 2 522 counties (80.29%) have complete data for all four confounders, because the rate of hospital beds data source (HIFLD) excludes counties without intensive care hospital beds. The varying number of county observations for each of the four pollutants was due to the fact that the EPA only collects pollutants data for selected counties that validly represent certain regions of the United States, and the counties reported vary for each of the four pollutants.

Correlation matrix

Pearson correlation tests were conducted among all variables except mortality rate for the datasets containing each of the four pollutants. Correlation matrices are presented in Table 2.

Regression model

Using R statistical software, we regressed mortality rate on O_3, NO_2, CO, and SO_2 concentrations using the following model:

$$Y_{(Mortality\ rate)} = \alpha + \beta_1 X_{1\ (Pollutant\ concentration)} + \beta_2 X_{2\ (Median\ household\ income)} + \beta_3 X_{3\ (Rate\ of\ hospital\ beds)} + \beta_4 X_{4\ (Population\ density)} + \beta_5 X_{5\ (Days\ since\ first\ case)}$$

This model was run for the dataset containing each pollutant separately, with X_1 representing O_3, NO_2, CO, and SO_2 concentrations, respectively.

RESULTS

Table 3 summarizes the regression results with all confounders included in the model.

Out of the four air pollutants, only ground level ozone (O_3) shows a significant and positive correlation with COVID-19

TABLE 1. Descriptive statistics

	No. of observations	Mean	Median	Minimum	Quantile 25%	Quantile 50%	Quantile 75%	Maximum	Standard deviation
Mortality rate (%)	2 522	0.01	0.002	0	0	0.0021	0.0093	0.3098	0.024
O_3 (ppm)	713	0.07	0.07	0.041	0.062	0.065	0.069	0.111	0.01
NO_2 (ppb)	232	8.17	7	1	4	7	11	30	5.53
CO (ppm)	168	1.27	1.1	0.2	0.8	1.1	1.6	6.4	0.83
SO_2 (ppb)	241	17.44	7	1	4	7	18	639	46.79
Median household income ($)	2 522	53 360	51 052	25 385	44 367	51 052	59 262	140 382	13 917
Rate of hospital beds (%)	2 522	0.37	0.27	0.0029	0.1602	0.2695	0.4277	9.9470	0.47
Population density (people per mi^2)	2 522	263.44	50.94	0.1870	20.318	50.939	146.03	47 903.1	1 392.61
Days since first confirmed case	2 522	67.02	65	50	62	65	68	112	12.21

Source: Prepared by authors from study data.

TABLE 2a. Correlation matrix for dataset containing O_3

	O_3 ppm	Population density	Median household income	Rate of hospital beds	Days since first confirmed case
O_3 ppm	1				
Population density	0.13***	1			
Median household income	0.21***	0.14***	1		
Rate of hospital beds	-0.13	0.08	-0.27	1	
Days since first confirmed case	0.28***	0.21	0.39***	-0.08	1

TABLE 2b. Correlation matrix for dataset containing NO_2

	NO_2 ppb	Population density	Median household income	Rate of hospital beds	Days since first confirmed case
NO_2 ppb	1				
Population density	0.39***	1			
Median household income	0.14*	0.07	1		
Rate of hospital beds	-0.05	0.06	-0.34	1	
Days since first confirmed case	0.57***	0.24***	0.31***	-0.22	1

TABLE 2c. Correlation matrix for dataset containing CO

	CO ppm	Population density	Median household income	Rate of hospital beds	Days since first confirmed case
CO ppm	1				
Population density	0.07	1			
Median household income	0.09	0.1	1		
Rate of hospital beds	0.01	0.15	-0.32	1	
Days since first confirmed case	0.30***	0.17*	0.35***	-0.07	1

TABLE 2d. Correlation matrix for dataset containing SO_2

	SO_2 ppb	Population density	Median household income	Rate of hospital beds	Days since first confirmed case
SO_2 ppb	1				
Population density	-0.06	1			
Median household income	-0.12	0.07	1		
Rate of hospital beds	-0.03	0.04	-0.36	1	
Days since first confirmed case	-0.07	0.28***	0.34***	-0.17	1

Source: Prepared by authors from study data.
Note: significance level: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

mortality rates, with an increase of 1 ppm in ozone concentration associated with an increase of 0.382% in mortality rate.

To account for collinearity between independent variables, confounders that show significant correlation from the Table 2 matrices were excluded from the regression analysis. The regression analysis results are presented in Table 4.

With correlated variables excluded, both O_3 and NO_2 concentrations show significant relationships with COVID-19 mortality rate. Specifically, when concentrations of O_3 increase by 1 ppm, the mortality rate increases by 0.857%. When concentrations of NO_2 increase by 1 ppb, the mortality rate increases by 0.002%. This finding for NO_2 is consistent with

TABLE 3. Regression analysis with all confounders

		O₃ regression results (713 obs.)		NO₂ regression results (232 obs.)		CO regression results (168 obs.)		SO₂ regression results (241 obs.)	
		Coeff.	p-value	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value
X_1	O_3	0.382	0.016*						
	NO_2			0.0003	0.602				
	CO					0.001	0.759		
	SO_2							-0.000	0.654
X_2 Median household income		0.0000002	0.019*	-0.000	0.887	-0.000	0.222	0.000	0.003**
X_3 Rate of hospital beds		0.002	0.652	-0.012	0.206	-0.016	0.266	-0.004	0.567
X_4 Population density		0.000006	<0.000***	0.00001	<0.000***	0.000006	<0.000***	0.00001	<0.000***
X_5 Days since first confirmed case		0.0002	0.017*	-0.000	0.829	0.0002	0.544	-0.000	0.635
Adjusted R-squared			0.270		0.451		0.351		0.538

Source: Prepared by authors from study data.
Note: obs., observations; coeff., coefficient; significance level: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

TABLE 4. Regression analysis excluding correlated confounders

		O₃ regression results (713 obs.)		NO₂ regression results (232 obs.)		CO regression results (168 obs.)		SO₂ regression results (241 obs.)	
		Coeff.	p-value	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value
X_1	O_3	0.857	<0.000***						
	NO_2			0.002	<0.000***				
	CO					0.002	0.619		
	SO_2							-0.00002	0.662
X_2 Median household income						-0.000	0.277	0.0000004	0.004**
X_3 Rate of hospital beds		0.004	0.368	-0.002	0.879	-0.016	0.270	-0.004	0.591
X_4 Population density						0.000	<0.000***	0.00001	<0.000***
X_5 Days since first confirmed case									
Adjusted R-squared			0.033		0.074		0.354		0.540

Source: Prepared by authors from study data.
Note: obs., observations; coeff., coefficient; significance level: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

studies conducted in northern Italy (8) and London (9), which also found a positive relationship between NO_2 and increased risk of COVID-19 death. The regression results for CO and SO_2 remain insignificant, suggesting no impact on COVID-19 mortality rate.

As a robustness test, an unadjusted regression analysis was conducted to evaluate the relationship between pollutant concentrations and mortality rate. These results are presented in Table 5.

Excluding all confounders, both O_3 and NO_2 concentrations still show significant relationships with COVID-19 mortality rate. When concentrations of O_3 increase by 1 ppm, the mortality rate increases by 0.836%. When concentrations of NO_2 increase by 1 ppb, the mortality rate increases by 0.002%.

DISCUSSION

It is important to note that ground-level ozone and stratospheric ozone are very different in their effects and formation. While stratospheric ozone makes up the ozone layer that blocks out harmful ultraviolet radiation from the sun and is formed from natural chemical processes, ground-level ozone is a constituent of smog and is formed from nitrogen oxides

(NO_x) commonly emitted into the atmosphere through man-made processes such as industrial emissions and motor vehicle exhaust. Given that NO_2 is a form of nitrogen oxide (NO_x), it explains the dual significance of the impact of O_3 and NO_2 on the COVID-19 mortality rate.

Multiple studies conducted on ground-level ozone have described its direct association with negative respiratory and cardiovascular health outcomes. In China, where high levels of smog have created hazardous living conditions, an estimated 230 000 to 403 000 respiratory-related deaths were attributable to long-term O_3 exposure in 2016 (10). The preexisting adverse health effects caused by exposure to O_3 render individuals more susceptible to COVID-19-related death, due to weakened respiratory, cardiovascular, and immune functions. This relationship was discovered during the 2002 SARS outbreak, in which a study showed that SARS patients from Chinese regions with moderate air pollution index (API, in which ozone is included) had an 84% increased risk of dying than those from regions with low APIs (11).

With the recent mandated lockdowns and stay-at-home orders, there has been a global improvement in air quality due to the temporary closure of factories and the decrease in vehicle usage. Despite the reduction in NO_x and PM

TABLE 5. Regression analysis without confounders

		O_3 regression results (713 obs.)		NO_2 regression results (232 obs.)		CO regression results (168 obs.)		SO_2 regression results (241 obs.)	
		Coeff.	*p*-value	Coeff.	*p*-value	Coeff.	*p*-value	Coeff.	*p*-value
X_1	O_3	0.836	<0.000***						
	NO_2			0.002	<0.000***				
	CO					0.004	0.390		
	SO_2							-0.00006	0.251
Adjusted R-squared			0.033		0.078		-0.002		0.001

Source: Prepared by authors from study data.
Note: obs., observations; coeff., coefficient; significance level: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

concentrations, a study evaluating four European cities and Wuhan found an increase in O_3 of 17% in Europe and 36% in Wuhan due to the decreased NO titration of O_3 (12). As countries such as the United States reopen, pollution levels will slowly start to return to pre-COVID-19 levels. Despite a semi-centennial shift toward a cleaner atmosphere and greener alternatives, air pollutants still play a large role in causing adverse health effects, and stricter measures must be taken to limit emissions. Ozone has been overlooked when it comes to regulation. In the United States in 2016, 90% of noncompliance to the national ambient air quality standards was in relation to ozone, whereas only 10% was in relation to particulate matter and other pollutants (5). The COVID-19 pandemic only more clearly highlights the significant and detrimental outcomes of air pollution, which has been a looming problem for decades.

Very recently, to combat the economic crisis, United States air pollutant restrictions are being eased to allow recovery and incentivize production. It is extremely difficult to balance economic vitality with COVID-19 casualties, but taking preventive measures by further limiting pollution may be more economically and socially effective in the long run. A recent study by Wang et al. estimated that if drastic measures are taken to reduce greenhouse gas emissions and air pollution in California, there will be a projected 14 000 premature deaths prevented in the state in 2050, as well as reduced respiratory and cardiovascular related hospital visits (13). By adopting measures such as implementing more green energy alternatives and incentives for electric vehicle ownership, ground-level ozone can be significantly reduced alongside other pollutants.

Conclusion

This study provides empirical evidence that ground-level ozone is positively correlated with COVID-19 mortality rate, regardless of whether the confounders are controlled for. NO_2 is also significantly correlated with the COVID-19 mortality rate except when all confounders are included in the regression analysis.

This study was subject to multiple limitations that could result in inaccuracies. There are still other confounder variables that were not accounted for, such as racial demographic, education level, and days since stay-at-home order. The sample size was also small, as the number of county-level observations extracted from the EPA public data was a fraction of the United States' total 3 141 counties. Within this limited number of counties there were outliers that resulted from the geographic and demographic diversity, ranging from extremely densely populated hotspot counties to isolated and sparsely populated counties. Given these and other limitations, further study and research on the correlation of air pollution and COVID-19 should be conducted to bring about a thorough understanding of this novel virus, as a possible second wave is on the horizon.

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Contaminantes del aire ambiental y su efecto en la mortalidad por COVID-19 en los Estados Unidos de América

RESUMEN

Objetivo. Examinar el impacto de cuatro contaminantes del aire ambiental en la tasa de mortalidad por la COVID-19 en los Estados Unidos de América.

Métodos. Utilizando datos de acceso público recopilados por la Oficina del Censo de los Estados Unidos, la Agencia para la Protección del Medio Ambiente y otros organismos, se llevó a cabo análisis de regresión para evaluar la relación entre las concentraciones de ozono, dióxido de nitrógeno, monóxido de carbono y dióxido de azufre a nivel del suelo y las tasas de mortalidad a nivel de condado. En el análisis de regresión se incluyeron cuatro variables confusoras: la mediana de los ingresos familiares, la tasa de camas de hospital, la densidad de población y los días transcurridos desde el primer caso confirmado.

Resultados. El análisis de regresión mostró que el ozono a nivel del suelo se correlaciona de manera positiva con las tasas de mortalidad a nivel de condado, independientemente de si los factores de confusión están controlados. El dióxido de nitrógeno también tiene una relación directa con las tasas de mortalidad a nivel de condado, excepto cuando se incluyen todos los factores de confusión en el análisis.

Conclusiones. Las concentraciones elevadas de ozono y dióxido de nitrógeno a nivel del suelo contribuyen a una mayor tasa de mortalidad por COVID-19. Para limitar los daños, es importante que los resultados de investigación se reflejen en las políticas públicas. En el caso de la contaminación del aire ambiental, deben reforzarse las restricciones ambientales y deben tomarse precauciones adicionales cuando los establec-imientos empiecen a reabrirse.

Palabras clave Infecciones por coronavirus; contaminación del aire; mortalidad; ozono; dióxido de nitrógeno; Estados Unidos.