Effects of air pollution and climatology on COVID-19 mortality in Spain

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Abstract

The health, economic, and social impact of COVID-19 has been significant across the world. Our objective was to evaluate the association between air pollution (through NO_2 and $PM_{2.5}$ levels) and COVID-19 mortality in Spanish provinces from February 3, 2020, to July 14, 2020, adjusting for climatic parameters. An observational and ecological study was conducted with information extracted from Datadista repository (Datadista, 2020). Air pollutants (NO_2 and $PM_{2.5}$ levels) were analyzed as potential determinants of COVID-19 mortality. Multilevel Poisson regression models were used to analyze the risk of mortality after severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection. Models were adjusted by four climatic variables (hours of solar radiation, precipitation, daily temperature and wind speed) and population size. The mean levels of $PM_{2.5}$ and NO_2 across all provinces and time in Spain were 8.7 µg/m³ (SD 9.7) and 8.7 µg/m³ (SD 6.2), respectively. High levels of $PM_{2.5}$ (IRR = 1.016, 95% CI: 1.007–1.026), NO_2 (IRR = 1.066, 95% CI: 1.058–1.075) and precipitation (IRR_{NO2} = 0.989, 95% CI: 0.981–0.997) were positively associated with COVID-19 mortality, whereas temperature ($IRR_{PM2.5}$ = 0.988, 95% CI: 0.976–1.000; and IRR_{NO2} = 0.771, 95% CI: 0.761–0.782, respectively) and wind speed (IRR_{NO2} = 1.095, 95% CI: 1.061–1.131) were negatively associated with COVID-19 mortality. Air pollution can be a key factor to understand the mortality rate for COVID-19 in Spain. Furthermore, climatic variables could be influencing COVID-19 progression. Thus, air pollution and climatology ought to be taken into consideration in order to control the pandemic.

Keywords SARS-CoV-2 · COVID-19 · Mortality · Risk factors · Air pollution

Introduction

On December 31, 2019, the Municipal Health Commission in Wuhan (Hubei province, China) reported 27 cases of pneumonia of unknown etiology that included seven serious cases, with common exposure to a seafood, fish, and live animal wholesale market located in Wuhan city (Isolate and Wuhan-Hu-1, 2020). Onset of symptoms of the first case occurred on December 8, 2019. On January 7, 2020, Chinese authorities identified a new type of virus of the Coronaviridae family as the agent causing of the outbreak. Named as Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), this new virus is the pathogen responsible for this infectious respiratory disease called Coronavirus Disease 2019 (COVID-19). On March 11, the World Health Organization (WHO) declared the COVID-19 pandemic.

Studies on past coronavirus outbreaks highlighted the impact of meteorological conditions in the virus dissemination (Casanova et al. 2010). The transmission of SARS-CoV-2 by aerosol is under consideration (Doremalen et al. 2020). This mechanism of spreading can be affected by climatology and air quality conditions. Setti et al. demonstrated that air pollution can contribute to spread the disease (Setti et al. 2020). Moreover, air pollution was studied as a key factor in leading to a more severe form of the disease (Cui et al. 2003). Recent studies assessed the impact of air quality in the spread and consequences of the COVID-19 pandemic (Wu et al. 2020). Some of these works evaluated the changes in air pollution due to traffic restrictions (Briz-Redón et al. 2020; Baldasano 2020) and how these modifications can have contributed to a reduction in mortality by COVID-19

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(Chen et al. 2020; Achebak et al. 2020; Urrutia-Pereira et al. 2020).

All these investigations met in pointing out the importance of air pollution and climatic parameters in the evolution of the pandemic. However, the connection between air quality, climatological (e.g., the impact of wind), and epidemiological variables, as well as the long-term impact of these parameters, are still controversial (Fattorini and Regoli 2020). In this study, we examined the association between air pollution and COVID-19 mortality in Spanish regions, adjusting for climatic parameters. Studying these factors and associations could be useful to a better understanding about the importance of air quality in terms of severity and mortality of the disease. We hypothesized that residents living in regions with higher long-term exposure to high concentrations of air pollutants would experience more severe COVID-19 outcomes, thus resulting in a higher mortality among more heavily polluted provinces.

Methods

Sample

This study was based on mortality data from Spanish provinces (groups of municipalities). The analysis included data from February 3, 2020, to July 14, 2020. We obtained the number of daily deaths from the Datadista repository (Datadista, 2020), which captures COVID-19 statistics data (ordered by days and Spanish regions) from the Ministerio de Sanidad, Consumo y Bienestar Social.

$PM_{2.5}$ (22 units) and NO_2 (50 units) levels were available from the Andalusian Office of Agriculture, Livestock, Fisheries, and Sustainable Development (Junta de Andalucía, 2020) for the different Andalusian monitoring stations and from the European Air Quality Portal (European Environment Agency, 2020) for the rest of the Spanish monitoring stations. These data were processed by DatAC, which is a visual analytics platform to explore air quality and climatic indicators.

Outcome

The outcome of this work was the number of COVID-19 deaths per day in Spanish provinces. Considering that the mean incubation period of COVID 19 infection was 6 days (China 2019) and the average time from onset of symptoms to death was 18 days (Verity et al. 2020), we estimated 24 days as the average time from the infection to death. Therefore, daily deaths were accordingly moved back 24 days based on the estimation of the probable date of infection.

Exposures

Air pollution

We obtained air quality data from DatAC (available at https://covid19.genyo.es). We used daily mean concentrations of NO_2 in 50 provinces, a traffic-related air pollutant, and a major component of urban smog, and of $PM_{2.5}$ in 22 provinces, a heterogeneous mixture of fine particles in the air.

Other variables

Climatic and population variables such as temperature (°C), precipitation (measured in liters per square meter, l/m2), wind speed (meters per second, m/s), and insolation (hours) for each province were also downloaded from DatAC (available at https://covid19.genyo.es). Population information was obtained from the Spanish Statistics Institute (INE), updated on January 1, 2020.

Statistical analysis

We described daily average levels of NO_2 and $PM_{2.5}$ in tertiles, over the period from February 3 to July 14, 2020. The estimation of the variability of air pollution and mortality across time within each province was explored through a multilevel model with daily repeat province $PM_{2.5}$ or NO_2, including random effects for each region.

For a Poisson distributed variable Y_i, if the variance is greater than the mean, then over-dispersion is present. Given over-dispersion in mortality data, we applied a negative-binomial regression model to estimate the association of $PM_{2.5}$ and NO_2 trends with the number of deaths using a log link function. The model used was as follows:

$$\log\left(Y_{ij}\right) = \beta_0 + \sum_{k=1}^{n} \beta_k X_{ki} + \sum_{l=1}^{m} \beta_l z_{lj} + \log\left(T_l\right) + u_j$$

Y_{ij} is the number of deaths per day for day i in the province j, β_0 represents the intercept, and β_k represents the percentage of change from baseline for NO_2, $PM_{2.5}$, and each climatic parameter (temperature, precipitation, wind speed, and hours of solar radiation). β_l is the vector of random effects for the sample variables Z_l, X_i is the set of explanatory variables at the individual level (level 1), and Z_j is the set of explanatory variables defined for the provinces (level 2), being u_j the residuals of level 2, for which it is assumed that they are independent and follow a normal distribution with mean 0 and variance σ_u^2. And $\log(T_l)$ is the number of inhabitants of each province as an offset term.

A null model was fitted to estimate the median odds ratio (MOR), which is a measure of the variation of mortality across different provinces that is not explained by the modeled factors. It was obtained with the following formula:

$$MOR = \exp\left[\sqrt{(2 * V_A)} * 0.6745\right] \approx \exp\left(0.95 \sqrt{V_A}\right)$$

V_A is the province-level variance. If the MOR is 1, there is no variation between municipalities; a larger MOR indicates considerable between-province variation.

We estimated whether increases in NO_2 and $PM_{2.5}$ were associated with changes in mortality over time by using mixed-effects models (with random effects for provinces). For NO_2 and $PM_{2.5}$, a set of adjusted models were then fitted separately for each climatic parameter. A final model, including all climatic variables from the previous step plus the offset term, was fitted for NO_2 and $PM_{2.5}$, separately.

We used z-score transformation to compare levels of PM2.5 and NO2 and climatic variables with the number of daily deaths. This transformation was successfully used as a normalization procedure. A z-score is the result of dividing the amount that a raw score differs from the mean of the distribution by the standard deviation.

We used Stata 14.0 (StataCorp, Stata Statistical Software, 2015) for the data analysis. The significance level was set at 0.05.

Results

Table 1 summarizes the daily average concentrations of $PM_{2.5}$ by tertiles over the study period. The mean $PM_{2.5}$ across all provinces and time was 8.7 μg/m³ (SD 9.7). The mean mortality across all provinces and time was 4.8 deaths (SD 20.4). Provinces with higher levels of $PM_{2.5}$ tended to have more hours of solar radiation, less precipitation and wind speed, and higher population size than those with lower levels. A description of the compiled data by provinces is shown in Supplementary Table S1.

Table 2 summarizes daily average concentrations of NO_2 by tertiles over the study period. The mean of NO_2 concentration across all provinces and time was 8.7 μg/m³ (SD 6.2). Provinces with higher levels of NO_2 were associated with more hours of solar radiation, less precipitation and wind

Table 1 Characteristics of provinces by tertiles of average of $PM_{2.5}$ over the period from February 3rd to July 14th, 2020

Variables, mean (SD)	Total	Daily average concentrations of $PM_{2.5}$			P-value
		< 5.7 μg/m3	≥ 5.7 and < 9.12 μg/ m3	≥ 9.12 μg/m3	
Deaths	4.8 (20.4)	5.6 (28)	5.8 (22.5)	8.6 (29.2)	< 0.001
PM 2.5	8.7 (9.7)	4.1 (1.1)	7.3 (1)	14.7 (14.9)	< 0.001
Hours of solar radiation	7.8 (4.1)	6.8 (4.1)	7.3 (4.1)	7.9 (4)	< 0.001
Rainfall	1.8 (4.6)	2.3 (5)	2.1 (5.2)	1.2 (3.4)	< 0.001
Temperature	16.3 (5.4)	15.5 (4.7)	15.4 (4.6)	16 (5.3)	0.241
Wind speed	3 (1.3)	3.3 (1.4)	3.1 (1.4)	3 (1.3)	< 0.001
Population size (per 100,000 residents)	9.3 (12.2)	10.3 (12.2)	11.8 (14.8)	12.0 (15.2)	0.006

Table 2 Characteristics of provinces by tertiles of average of NO_2 over the period from February 3rd to July 14th, 2020

Variables, mean (SD)	Total	Daily average concentrations of NO_2			P-value
		< 5.46 μg/m3	≥ 5.46 and < 8.95 μg/ m3	≥ 8.95 μg/m3	
Deaths	4.8 (20.4)	1.9 (4.1)	2.9 (10.4)	10.4 (33.8)	< 0.001
NO2	8.7 (6.2)	3.8 (1.1)	7 (1)	15.2 (6.8)	< 0.001
Hours of solar radiation	7.8 (4.1)	7 (4)	7.6 (4.1)	8.1 (3.9)	< 0.001
Rainfall	1.8 (4.6)	2.4 (5.1)	1.9 (4.6)	1.3 (4.2)	< 0.001
Temperature	16.3 (5.4)	15.1 (4.6)	16.2 (5.2)	15.9 (5.6)	< 0.001
Wind speed	3 (1.3)	3.1 (1.3)	3 (1.3)	2.8 (1.2)	< 0.001
Population size (per 100,000 residents)	9.3 (12.2)	5.8 (5.3)	8.4 (9.2)	14.7 (17.3)	< 0.001

speed, and higher population size than those with lower levels. Temperature was high in tertile 2 and we inferred that it had a positive correlation with mortality. A description of the compiled data by provinces is shown in Supplementary Table S2.

Figure 1 shows the evolution of the daily number of deaths moved back 24 days, daily levels of $PM_{2.5}$ and NO_2, and climatic variables (the quantities were standardized to be comparable), and we compared z-scores of $PM_{2.5}$ and NO_2, and climatic variables with z-scores of the number of deaths.

Table 3 shows the association of daily mortality changes with $PM_{2.5}$, adjusted for climatic parameters (hours of solar radiation, precipitation, temperature, and wind speed). The increase in one μg/m³ of $PM_{2.5}$ was associated with 1.6% more mortality (IRR = 1.016, 95% CI: 1.007–1.026). However, the increase in temperature was associated with 1.2% (IRR = 0.988, 95% CI: 0.976–1.000) less mortality for COVID-19.

Table 4 presents the results of the multilevel model to estimate the association between mortality and NO_2,

Table 3 Adjusted associations between mortality and $PM_{2.5}$

Predictors	Effect of $PM_{2.5}$ on mortality**	
	OR	95%CI
$PM_{2.5}$	1.016*	1.007—1.026
Hours of solar radiation	1.005	0.986—1.025
Precipitation	0.988*	0.976—1.000
Temperature	0.762*	0.747—0.777
Wind speed	1.036	0.994—1.080

* Significant values ($p < 0.05$)

** All the models were adjusted by the population size

adjusted for climatic parameters (hours of solar radiation, precipitation, temperature, and wind speed). The increase in one μg/m³ of NO_2 levels was associated with a 6.6% increase in mortality for COVID-19 (IRR = 1.066, 95% CI: 1.058–1.075). Also, the increase in precipitation (l/m²) and temperature (°C) levels were associated with a lower risk of COVID-19 mortality (IRR precipitation = 0.989,
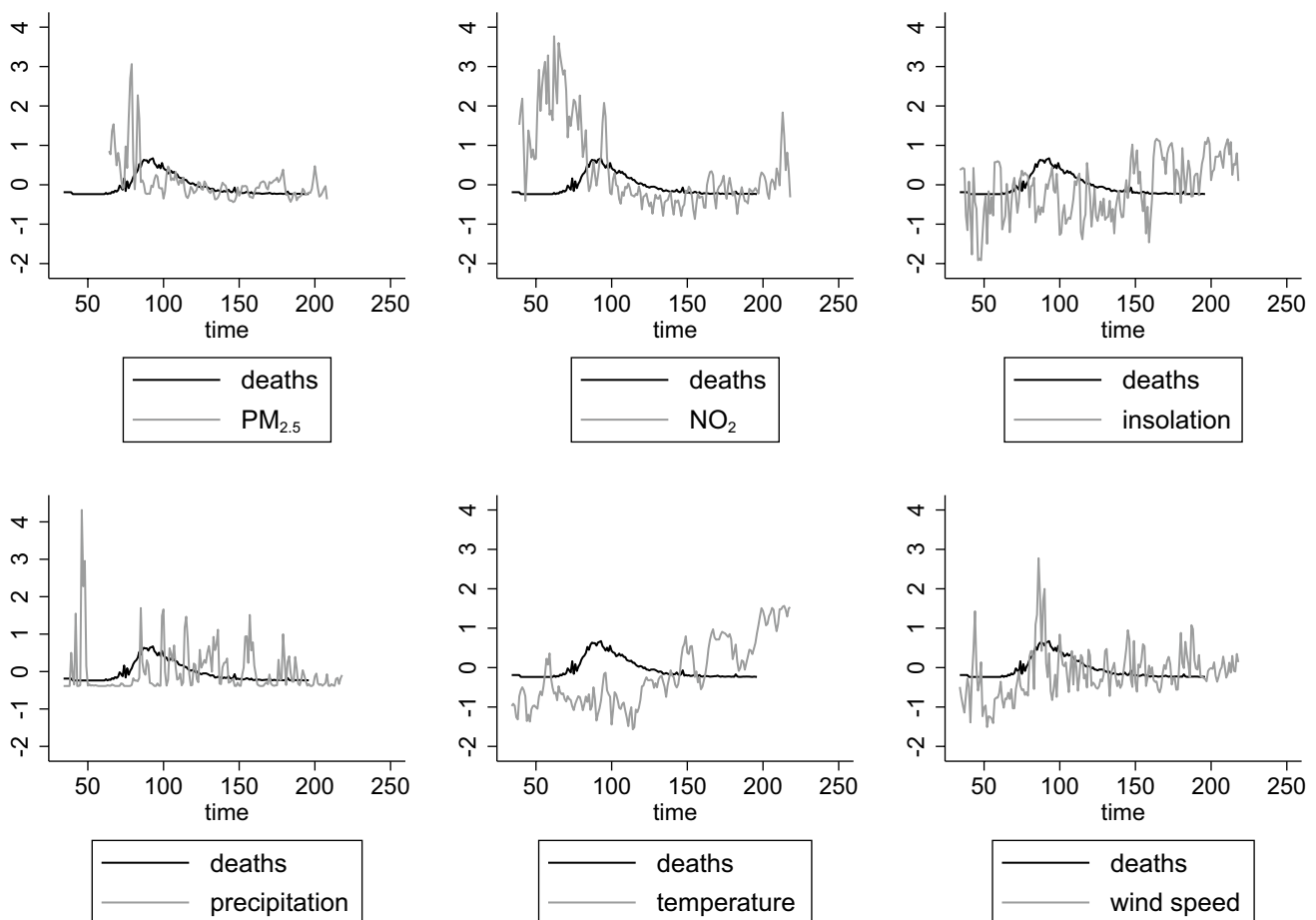

Fig. 1 Z-scores (on Y axis) of fluctuations in $PM_{2.5}$, NO_2 and climatic parameters, and in daily deaths estimated by possible day of infection (t + 24 days)

Table 4 Adjusted associations between mortality and NO_2

Predictors	Effect of NO_2 on mortality**	
	OR	95%CI
NO_2	1.066*	1.058—1.075
Hours of solar radiation	0.994	0.981—1.008
Precipitation	0.989*	0.981—0.997
Temperature	0.771*	0.761—0.782
Wind speed	1.095*	1.061—1.131

* Significant values ($p < 0.05$)

** All the models were adjusted by the population size

95% CI: 0.981–0.997; IRR temperature = 0.771, 95% CI: 0.761–0.782, respectively). Wind speed (m/s) was associated with a 9.5% increase (IRR = 1.095, 95% CI: 1.061–1.131) in COVID-19 mortality.

Discussion

The most relevant finding of this work was a significant association between air pollution levels and increases in mortality in Spanish provinces, after considering climatic parameters (temperature, insolation, precipitation, wind speed). This finding was driven by an association of increases in $PM_{2.5}$ and NO_2 levels with increases in COVID-19 mortality. Temperature and wind speed were key factors to understand COVID-19 lethality.

The impact of pollutants on fatality caused by the SARS-CoV2 was studied previously (Ali and Islam xxxx). We found an association between NO_2 levels and COVID-19 mortality in Spain. Ogen et al. demonstrated that European regions with the highest NO_2 concentrations were associated with the highest mortality ratios (Ogen 2020). This work also studied the impact of airflow on the severity of the infection and found that downwards airflow, which prevents efficient dispersion of air pollution, could be associated with fatality. However, these results are still controversial due to methodological limitations (Pisoni and Dingenen 2020; Chudnovsky 2020). Wind speed was evaluated in our NO_2 model and we found no association with COVID-19 mortality. The effect of NO_2 concentration over deaths caused by COVID-19 was studied in other regions. Pacheco et al. found a strong correlation between air NO_2 concentrations and the cases/mortality caused by COVID-19 in Ecuador (Pacheco et al. 2020). Another analysis from India suggests that exposure to NO_2 may increase the COVID-19 pandemic fatality (Chakraborty et al. 2020). A work aimed at analyzing the association between COVID-19 evolution and the air quality index, comorbidities, and sociodemographic factors in the USA found that NO_2 levels could be one of the key factors to understand COVID-19 susceptibility and mortality

(Sarmadi et al. 2020). In particular, Marques et al. described and studied the effect of PM_{10}, NO_2, and O_3 on COVID-19 infection in Catalonia (Spain). They found a potential association between air pollution and COVID-19 outcomes (Marquès et al. xxxx).

The role of PM2.5 levels is still controversial. We found an association with COVID-19 mortality. This was not found in previous works based on England data. Konstantinoudis et al. showed a strong effect of long-term NO_2 exposure on COVID-19; however, this work did not find evidence about an association between $PM_{2.5}$ and COVID-19 mortality (Konstantinoudis et al. 2020). There was no evidence of a significant association between $PM_{2.5}$ and COVID-19 mortality in a multivariate analysis from Bray et al. (Bray et al. 2020). However, Zoran et al. found similar results; there was a strong association between COVID-19 daily new cases and $PM_{2.5}$ levels in Italy (Zoran et al. 2020). Evidence from the Netherlands suggested that $PM_{2.5}$ was a highly significant predictor of COVID-19-related hospital admissions (Andree 2020). Other preliminary studies pointed out that $PM_{2.5}$ levels may be affecting disease evolution, according to available data in areas with worse prior air quality (Hendryx and Luo 2020). All investigations agree on the need to continue evaluating the role of $PM_{2.5}$ levels in the evolution of COVID-19. Some previous works found that COVID-19 mortality presented geographical differences, especially when the analysis considered data from urban and rural areas (Fattorini and Regoli 2020; Marquès et al. 2020). This finding may be partially explained considering the effect of air pollution in more industrialized cities. With regard to other climatic factors related to COVID-19 mortality, our findings are consistent with a growing body of evidence suggesting that these variables are essential to understand the pandemic. We found a negative association between temperature and mortality. This finding is similar to the results of Ma et al. in China (Ma et al. 2020). This work found that the temperature variation may be one key factor affecting the death rate caused by COVID-19. Temperature was also associated with the apparition of new confirmed cases related to COVID-19 in the USA, although there was

no evidence about the connection between temperature and COVID-19 mortality (Adhikari and Yin 2020; Bashir et al. 2020). A study based on a machine learning approach demonstrated that the higher the value of temperature, the lower the number of infection cases, confirming the relevance of temperature in the spread of the virus (Malki et al. 2020). Regarding the role of wind speed in COVID-19 outcomes, the existing evidence is controversial (Bashir et al. 2020; Şahin 2020; Ahmadi et al. 2020).

This study has strengths and limitations. Firstly, we did not use information from COVID-19 case counts because they were underestimated. However, data from mortality have been used to estimate the association, as the underestimation is substantially lower for death counts than for case counts. Secondly, we lack data to know the long-term exposure levels of $PM_{2.5}$ and NO_2, but these levels in the period used can be considered as a proxy of urbanity. Finally, we could not take into account the number of hospitalized patients or patients in intensive care units with COVID-19, socio-economic and demographic characteristics, and information regarding comorbidities due to the lack of province-level data. However, although we controlled for climatic variables and population size, the exclusion of these variables did not vary the associations.

Our findings could have implications for the control and prevention of this disease. So that, this research could lead to a better knowledge of the effect of climatic parameters on COVID-19 spread, contributing to improve future public health strategies. Therefore, further extensive research is recommended to reach a more comprehensive understanding of the factors associated with COVID-19 mortality.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11869-021-01062-2.

Data availability The datasets generated during and/or analysed during the current study are available in:

(1) Air pollutants (NO2 and PM2.5 levels) and climatic variables: the DatAC repository, https://covid19.genyo.es.

(2) Mortality: https://github.com/datadista/datasets/tree/master/COVID%2019.

Declarations

Conflict of interests The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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