Do Saharan Dust Intrusions Affect the Incidence and Severity of COVID-19 in Spain?

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Abstract

Scientific evidence suggests that Saharan dust intrusions in Southern Europe contribute to the worsening of multiple pathologies and increase the concentrations of particulate matter (PM) and other pollutants. However, few studies have examined whether Saharan dust intrusions influence the incidence and severity of COVID-19 cases.

To address this question, in this study we carried out generalized linear models with Poisson link between incidence rates and daily hospital admissions and average daily concentrations of PM_{10} and NO_2 in nine Spanish regions for the period from February 1, 2020 to May 31, 2020. The models were adjusted by maximum daily temperature and average daily absolute humidity. Furthermore, we controlled for trend, seasonality and the autoregressive nature of the series. The variable relating to Saharan dust intrusions was introduced using a dichotomous variable, NAF, averaged across daily lags in ranges of 0–7 days, 8–14 days, 14–21 days and 22–28 days.

The results obtained in this study suggest that chemical air pollutants, and especially NO_2, are related to the incidence and severity of COVID-19 in Spain. Furthermore, Saharan dust intrusions have an additional effect beyond what is attributable to the variation in air pollution; they are related, in different lags, to both the incidence and hospital admissions rates for COVID-19. These results serve to support public health measures that minimize population exposure on days with particulate matter advection from the Sahara.

1. Introduction

The 2019 coronavirus (COVID-19) outbreak in Wuhan, China was declared a pandemic by the World Health Organization (WHO) on March 11, 2020 (WHO, 2020a). Since that time, multiple studies have been carried out that aim to explain the different behavior of the virus in terms of transmission and severity that has been observed in different locations around the world. Studies take into account environmental factors such as temperature and humidity (Holtmann et al., 2020; CDC, 2020; Lipsitch & Phil, 2020; Tobías et al., 2020, Sajadi et al., 2020), solar radiation (Yao et al., 2020) and wind velocity (Islam et al., 2020).

If we take into account that the most severe symptoms have been observed in people over age 65 (Remuzzi & Remuzzi, 2020) with prior conditions such as cardiovascular diseases (Li et al., 2020; Onder et al., 2020) and respiratory, endocrine and digestive (Sohrabi et al., 2020; Wang et al., 2020) problems, chemical air pollution seems to be one of the factors that could be related to the development and severity of the disease. Air pollution predominantly affects these age groups and these conditions in particular (Landrigan et al., 2018). Thus, in recent months multiple studies have been published using different methodologies that relate air pollution to the incidence of COVID-19 (Bashir et al., 2020b; Fronza et al., 2020; Jiang et al., 2020; Ogen, 2020) and its severity (Wang et al, 2020a; Saez et al, 2020; Bilal et al, 2020; Zoran et al, 2020; Travaglio et al, 2021; Magazzino et al, 2020, Dominici et al., 2020). In addition, studies carried out in Italy (Setti et al., 2020) have pointed out that particles of up to 10 micros (PM_{10}) could act as a vector for transmission of the SARS-CoV-2 virus.

Despite much research on the transmission process and severity of the virus, there are practically no studies that analyze the role of a natural and relatively frequent phenomenon in the South of Europe, Saharan dust advection (Stafoggia et al., 2016). This natural event is an especially interesting topic for analysis for two reasons. First, the arrival of Sarahan dust produces a statistically significant increase in the concentrations of particulates and other contaminants that have an effect on transmission and severity, as has been shown previously. Furthermore, the days with Saharan dust intrusions have been shown to have a clear additional incidence in terms of the worsening of cardiovascular and respiratory diseases (Stafoggia et al., 206; Díaz et al.,2017; Pérez et al., 2012), especially among the most vulnerable groups (Jiménez et al., 2011). Therefore, the objective of this study was to analyze whether Saharan dust advection supposes an additional risk in terms of the impact that air pollution has on the incidence and severity of COVID-19 in Spain.

2. Materials And Methods

2.1. Dependent and independent variables

2.1.1 Dependent variables

The dependent variables were calculated based on the number of positive cases of COVID-19. Cases diagnosed as positive for COVID-19 were defined based on a positive PCR test result. Cases thus defined refer to daily cases that occurred in the provinces analyzed during the time period from February 1, 2020 through May 31, 2020. The state of alarm and subsequent confinement of the population went into effect on March 14, along with measures restricting movements and social interactions (BOE, 2020 a), and they remained in effect until June 21 (BOE, 2020b).

The data analyzed corresponded to the number of cases diagnosed as COVID-19 positive and the number of urgent hospital admissions due to COVID-19 and were provided by the National Center for Epidemiology at the Carlos III Health Institute. The population data at the province level were provided by the National Statistics Institute (INE). Based on these data, we calculated the following rates:

Incidence rate of COVID-19 per 1,000,000 inhabitants: (Number of positive COVID cases/population) x 1,000,000 inhabitants.

Rate of urgent hospital admissions due to COVID-19 per 1,000,000 inhabitants: (Number of urgent hospital admissions due to positive COVID-19 cases/population) x 1,000,000 inhabitants.

2.1.2 Independent variables

The independent variables were made up of both meteorological data and air pollution data, as well as the days with Saharan dust intrusion that occurred during the study period.

The meteorological data were the daily maximum temperature values (Tmax) and daily average relative humidity (HR) in percent form. Based on daily average relative humidity and daily average temperature, the values of daily average absolute humidity (HA) were obtained in g/m^3 (Gupta et al., 2020). Maximum daily temperature and daily average absolute humidity were used because they presented better behavior with the COVID-19 variables analyzed (Linares et al., 2021; Xie et al., 2020).

These values made up the average values of the observations corresponding to the AEMET stations located in the provinces considered in the study. They were provided by the State Meteorological Agency (AEMET).

Air pollution data were made up of the average daily values of concentrations of PM_{10} and NO_2 in $\mu g/m^3$, obtained as an average of the values measured in stations located in the different provinces analyzed. These data were provided by the Ministry for Ecological Transition and Demographic Challenge (MITECO).

The classification of the days with Saharan dust intrusion was determined based on information provided by the Ministry for Ecological Transition and Demographic Challenge in Spain (MITECO, 2020). According to MITECO methodology, Spain is divided into nine areas: North, North-East, North-West, Center, South-East, South-West, East, Canary Islands, and Balearic Islands, as shown in Figure 1. In order to identify the existence of a day with Saharan dust intrusion, a first evaluation of the advection process was carried out, based on an analysis of retro-trajectories of air masses, synoptic maps, satellite images and numerical prognosis models for mineral material. Later, there was an evaluation of the true impact of African dust in surface level registries, based on a statistical analysis applied to time series for average daily values of PM_{10} obtained at regional measurement stations in each of the studied areas. This is one of the official methods recommended by the European Commission for the evaluation of the occurrence of dust intrusions of African origin (CSWP,2011).

2.2. Variables used in the analysis:

In each of the nine regions described above, a representative province was selected based on the existence and quality of air pollution data, meteorological data and variables related to COVID-19. For the North region, the selected province was Vizcaya; Zaragoza province was selected for the North-East region; A Coruna was selected for the North-West region; Madrid was selected for the Center region; Malaga was selected for the South-East region; Seville was selected for the South-West region; Valencia was selected for the East region; Las Palmas was selected for the Canary Islands, and Mallorca was selected for the Balearic Islands region (see Figure 1). This selection has been used in prior studies related to the incidence of Saharan dust and morbidity and mortality in Spain (Moreira et al., 2020; Díaz et al., 2017; Russo et al., 2020).

In order to take into account the days with Saharan dust advection, a dichotomous variable was calculated, North African (NAF), which equals 1 on a day with advection and 0 on a day without it. Based on daily NAF, we calculated average values with lags of 0 to 7 days (NAF:0_7); 8 to 14 days (NAF:8_14); 15 a 21 days (NAF:15_21) and 22 to 28 days (NAF:22_28) with the objective of analyzing the lagged behavior of these intrusions on the COVID-19 variables registered.

2.3. Analysis methodology

For each of the mentioned provinces, generalized linear models with Poisson link (GLM) were carried out between the dependent (positive COVID rates) and independent (environmental) variables. In these models we controlled for the series trend and seasonality for 120, 90, 60 and 30 days and the autoregressive nature of the series. Also, we controlled for weekly seasonality by including the days of the week as dummy variables in the models. For example, when the data corresponded to Tuesday, the value in the cell data corresponding to the variable “day of the week” was equal to 1; and all the other weekdays for the same data were zero.

GLM were carried out between each dependent variable and the average daily values of the independent variables. In this way, time lags were established that produced statistically significant associations between the dependent variables and the independent variables.

The range of lag days considered in the analysis was from 0 days to 28 days, to account for the time that took place between the occurrence and worsening of symptoms and arrival at the hospital (Lauer et al., 2020; WHO 2020b). A weekly distributed lag model was used. In a first step, the lags were introduced corresponding to the independent variables, lagged from 0 to 7 days. In a second step, the lags corresponding to 8 to 14 days were introduced, keeping the variables lagged that were statically significant in the first step, and so on up to 28 days, to complete the range of lag days considered in the analysis. This methodology has been used in other, similar studies (Linares et al., 2021; Díaz et al., 2021).

Finally, all variable models were carried out between all of the dependent and independent variables, introducing the control variables described. Based on the absolute values of the estimators, Relative Risks (RR) were calculated in the form $RR = e^{\beta}$ with β as the absolute value of the estimator obtained in the Poisson modeling. A negative coefficient in the estimator indicated that an increase in the independent variable was associated with a decrease in the dependent variable. The RR was calculated using an increase of 10 $\mu g/m^3$ in PM_{10} and NO_2; 1 ºC in the maximum temperature (Tmax) and 1 g/m^3 in the absolute humidity (AH) value.

In the case of the NAF variable, the RR values obtained referred to increases of one unit in the values of NAF. That is to say, if, during the lagged days analyzed, all of the days had Saharan dust intrusion, the value of NAF would be equal to one, and if there had not been any days, it would be zero. In cases where some days had intrusion, the value of NAF would oscillate between zero and one, given that it refers to the weekly average of a dichotomous variable.

We used a back-stepwise process for variable selection, and statistical significance was set at a p-value of $p<0.05$. Over- and under-dispersion were controlled for.

3. Results

Table 1 shows the descriptive statistics that correspond to the dependent and independent variables analyzed in this study. Table 1 shows the values of these variables for the days with Saharan dust intrusion (NAF = 1), and those without intrusion (NAF = 0) appear marked with an asterisk when the values of the independent variables present statistically significant differences between the days with and without Saharan dust advection.

Table 1
Descriptive statistics of the dependent variables: Incidence rate and hospital admissions rate, and the independent variables: particles (PM_{10}), nitrogen dioxide (NO_2), maximum temperature (Tmax), relative humidity (AH) and Saharan dust advection (NAF) used in each city in the study.

Provincial capital		**INCIDENCE RATE Mean (SD)**	**HOSPITAL ADMISSIONS RATE Mean (SD)**	**PM_{10} (µg/m^3) Mean (SD)**	**NO_2 (µg/m^3) Mean (SD)**	**Tmax (ºC) Mean (SD)**	**AH (g/m^3) Mean (SD)**
LAS PALMAS	*Without NAF N = 69*	5.93 (9.51)	2.42 (4.02)	28.7 (9.1)	7.2 (3.1)	22.8 (1.5)	11.1 (1.2)
	With NAF N = 52	4.94 (8.86)	1.83 (5.41)	65.9 (93.2)*	11.0 (4.5)*	23.6 (2.0)	11.2 (1.7)
MALAGA	*Without NAF N = 85*	19.42 (21.85)	7.81 (13.3)	24.1 (8.8)	14.1 (8.3)	21.6 (3.7)	9.8 (1.6)
	With NAF N = 36	20.64 (27.82)	6.27 (11.79)	34.1 (8.8)*	14.7 (7.2)	22.6 (3.6)	11.0 (1.4)*
SEVILLA	*Without NAF N = 85*	12.63 (17.84)	5.60 (9.67)	11.6 (4.6)	12.6 (6.8)	22.6 (4.0)	9.3 (1.4)
	With NAF N = 36	12.94 (19.60)	4.00 (7.29)	23.2 (13.5)*	11.9 (5.4)	26.0 (6.0)*	10.5 (1.6)
VALENCIA	*Without NAF N = 86*	23.00 (27.76)	9.42 (15.57)	12.7 (6.8)	10.6 (6.9)	21.5 (4.2)	8.8 (1.7)
	With NAF N = 35	26.24 (34.08)	9.90 (18.31)	18.8 (15.7)*	10.3 (6.3)	21.9 (4.8)	9.7 (1.8)*
MADRID	*Without NAF N = 105*	83.25 (103.84)	37.43 (56.24)	12.8 (6.2)	18.3 (13.6)	17.7 (7.5)	7.3 (1.8)
	With NAF N = 16	110.10 (153.42)	69.24 (101.98)	35.1 (21.6)*	22.1 (14.0)*	16.9 (5.9)	6.9 (1.3)
BILBAO	*Without NAF N = 102*	54.95 (67.27)	20.19 (36.78)	15.6 (6.8)	14.7 (7.2)	19.1 (4.7)	9.0 (2.0)
	With NAF N = 19	90.23 (110.02)	42.51 (58.59)	26.2 (14.3)*	15.4 (6.6)	21.9 (4.8)	9.8 (2.4)
ZARAGOZA	*Without NAF N = 99*	390.35 (554.52)	165.96 (261.17)	11.1 (4.7)	17.1 (8.5)	20.0 (5.4)	7.7 (1.9)

* Statistically significant difference $p < 0.05$ between the days with and without advection of Saharan dust.

Provincial capital		INCIDENCE RATE Mean (SD)	HOSPITAL ADMISSIONS RATE Mean (SD)	PM_{10} ($\mu g/m^3$) Mean (SD)	NO_2 ($\mu g/m^3$) Mean (SD)	Tmax (ºC) Mean (SD)	AH (g/m^3) Mean (SD)
	With NAF *N = 22*	424.53 (395.27)	212.50 (296.20)	16.5 (8.3)*	17.3 (7.3)	20.15 (5.0)	7.9 (1.5)
MALLORCA	*Without NAF* *N = 105*	16.02 (22.59)	6.98 (11.80)	17.0 (5.0)	6.6 (4.0)	20.1 (3.5)	9.3 (1.8)
	With NAF *N = 16*	16.58 (26.68)	9.62 (13.70)	27.3 (13.9)*	4.6 (2.6)	20.7 (2.6)	10.8 (1.8)*

* Statistically significant difference $p < 0.05$ between the days with and without advection of Saharan dust.

A Coruna is not shown, given that the number of days with Saharan dust intrusion in the period was 10, which was lower than the limit established for the region. (There had to be intrusion on at least 10 percent of days.) The greatest percentage of days with Saharan dust intrusion was in Gran Canaria (43%), Malaga (30%), Seville (30%) and Valencia (29%), and the lowest levels were in Madrid (13%), Vizcaya (Bilbao) (16%) and Mallorca (13%).

As shown in Table 1, in all of the provinces considered, the values of PM_{10} were greater on the days where NAF = 1 than on the days without dust, and this difference was statistically significant in all cases. The cases of greater values, and that were statistically significant, were in the provinces of Las Palmas and Madrid. In the case of absolute humidity, the value was greater, and statistically significant, on days with intrusion in Malaga, Valencia and the Balearic Islands. In terms of maximum daily temperatures, there were only statistically significant differences in the province of Seville.

The results of the multivariate models in which the whole group of variables was introduced appear in Table 2. It is worth noting that daily concentrations of NO_2 is the air pollution variable that appears most frequently related to the dependent variables. In relation to the incidence rate, it appears in eight of the provinces, compared to four which are related to average daily concentrations of PM_{10}. In relation to hospital admissions, NO_2 appears to be related in five of the provinces and PM_{10} in three.

Table 2

Results of the multivariate models by city, between dependent variables: incidence rate and rate of hospital admissions for COVID-19, and the independent variables: particles (PM_{10}), nitrogen dioxide (NO_2), maximum temperature(Tmax), relative humidity (AH) and Saharan dust advection (**NAF) for its corresponding lags.** The relative risks (RR) are calculated for increases of 1µg/m^3 for the concentrations of NO_2 and PM_{10}; of 1ºC for the values of Tmax and of 1g/m^3 for the values of AH. For the variable NAF the RR corresponds to an increase of one unit in the value of NAF.

Provincial Capital	**INCIDENCE RATE**	**HOSPITAL ADMISSIONS RATE**
LAS PALMAS	NO_2 (28) RR: 1.053 (1.030 1.076) AH (18) RR: 1.184 (1.070 1.311) AH (24) RR: 1.190 (1.067 1.328) **NAF:15_21 RR: 4.175 (1.851 9.417)** **NAF:22_28 RR:2.541 (1.042 6.198)**	Without effect
MALAGA	PM_{10} (26) RR: 1.011 (1.005 1.016) NO_2 (14) RR: 1.014 (1.007 1.021) NO_2 (21) RR: 1.035 (1.027 1.043) Tmax (9) RR: 1.025 (1.005 1.047) Tmax (17) RR: 1.036 (1.014 1.057) Tmax (20) RR: 1.062 (1.040 1.082) **NAF:0_7 RR: 1.869 (1.222 2.859)**	PM10 (13) RR : 1.009 (1.000 1.017) NO2 (0) RR: 1.016 (1.000 1.032) **NAF:0_7 RR: 3.179 (1.212 8.343**) **NAF:8_14 RR: 3.016 (1.024 8.886**)
SEVILLA	PM_{10} (23) RR: 1.013 (1.008 1.018) PM_{10} (25) RR: 1.012 (1.008 1.018) PM_{10} (27) RR: 1.008 (1.003 1.013) NO_2 (28) RR: 1.034 (1.023 1.051) Tmax (20) RR: 1.028 (1.003 1.054) AH (24) RR: 1.105 (1.045 1.166)	NO_2 (0) RR: 1.058 (1.019 1.099) NO_2 (3) RR: 1.042 (1.003 1.083) NO_2 (12) RR: 1.026 (1.002 1.052) Tmax (10) RR: 1.031 (1.000 1.063) **NAF:0_7 RR: 4.169 (1.071 16.234)**
VALENCIA	NO_2 (0) RR: 1.025 (1.016 1.034) NO_2 (3) RR: 1.030 (1.022 1.039) NO_2 (6) RR: 1.029 (1.020 1.038) NO_2 (28) RR: 1.018 (1.011 1.026)	NO_2 (28) RR: 1.020 (1.007 1.033) **NAF:22_28 RR: 2.079 (1.169 3.697)**
MADRID	NO_2 (0) RR: 1.009 (1.006 1.011) NO_2 (13) RR: 1.002 (1.001 1.004) Tmax (14) RR: 1.031 (1.024 1.039) AH (18) RR: 1.097 (1.077 1.118) AH (23) RR: 1.074 (1.055 1.094)	PM_{10} (18) RR: 1.008 (1.006 1.010) Tmax (7) RR: 1.051 (1.043 1.060) Tmax (14) RR: 1.085 (1.076 2.489) AH (16) RR: 1.214 (1.175 1.256) AH (20) RR: 1.096 (1.070 1.124) **NAF:8_14 RR: 1.749 (1.279 2.391)**

Provincial Capital	INCIDENCE RATE	HOSPITAL ADMISSIONS RATE
BILBAO	PM_{10} (14) RR: 1.004 (1.001 1.007)	NO_2 (27) RR: 1.020 (1.013 1.027)
	PM_{10} (17) RR: 1.004 (1.002 1.007)	AH (13) RR: 1.038 (1.002 1.076)
	NO_2 (6) RR: 1.015(1.010 1.021)	**NAF:0_7 RR: 1.703 (1.147 2.529)**
	NO_2 (9) RR: 1.014 (1.010 1.019)	
	NO_2 (20) RR: 1.015 (1.010 1.019)	
	AH (7) RR: 1.034 (1.012 1.057)	
ZARAGOZA	PM_{10} (9) RR: 1.009 (1.006 1.012)	PM_{10} (3) RR: 1.009 (1.004 1.014)
	PM_{10} (13) RR: 1.007 (1.005 1.010)	PM_{10} (9) RR: 1.014 (1.010 1.019)
	NO_2 (7) RR: 1.021 (1.018 1.025)	NO_2 (14) RR: 1.032 (1.029 1.036)
	NO_2 (10) RR: 1.008 (1.005 1.012)	NO_2 (16) RR: 1.026 (1.022 1.030)
	TMax (8) RR: 1.026 (1.023 1.029)	TMax (7) RR: 1.020 (1.015 1.025)
	TMax (15) RR: 1.013 (1.010 1.016)	TMax (15) RR: 1.010 (1.004 1.016)
	TMax (21) RR: 1.026 (1.023 1.029)	TMax (21) RR: 1.012 (1.007 1.016
	AH (6) RR: 1.121 (1.108 1.136)	**NAF:15_21 RR: 1.593 (1.270 1.998)**
	AH (12) RR: 1.062 (1.048 1.075)	**NAF:22_28 RR: 1.324 (1.122 1.563)**
	AH (13) RR: 1.035 (1.022 1.047)	
	AH (17) RR: 1.101 (1.088 1.115)	
MALLORCA	NO_2 (7) RR: 1.054 (1.032 1.077)	Tmax (17) RR: 1.054 (1.001 1.113)
	NO_2 (18) RR: 1.023 (1.003 1.044)	AH (23) RR: 1.108 (1.046 1.175)
	Tmax (6) RR: 1.060 (1.025 1.096)	
	Tmax (25) RR: 1.069 (1.024 1.115)	

For the meteorological variables, maximum daily temperature (Tmax) was related to the incidence rate with a negative sign for five of the provinces considered. The same occurred with absolute humidity, also with a negative sign. In terms of hospital admissions for COVID-19, maximum daily temperature was associated with a negative sign in four of the provinces and absolute humidity (AH) in three.

In terms of the variables exclusively related to Saharan dust intrusions (NAF), only two provinces were associated with the incidence rate, compared to six provinces in relation to the rate of hospital admissions for COVID-19.

The lags in which associations appeared seem to be more short term for NO_2 than for PM_{10}, and in some cases there was even an association for lag 0, while in the case of PM_{10}, generally, associations were established beginning with lag 9. The same was true in the case of AH and Tmax for which associations were produced, in general, after lag 7.

In terms of the NAF variable, Fig. 2 shows the Relative Risks obtained for the COVID-19 incidence rate for the different NAF lags in which statistically significant associations were established. Figure 3 shows the Relative Risks for the hospital admissions rate for COVID-19 for the different NAF lags. From a quantitative perspective, the RR associated with values of NAF were greater than those found for the rest of the independent variables analyzed.

4. Discussion

In the case of the Saharan desert, the proximity to the source of advection and the trajectories that air masses follow in arriving in each of the provinces analyzed in this study explain the percentage of days with advection registered in the different provinces. This is shown in Table 1 (Russo et al., 2020).

Saharan dust intrusions contribute significantly to increasing levels of PM_{10} in the Mediterranean basin (Querol et al., 2009), which means that the concentrations of this pollutant experience an important increase even in urban air pollution measurement stations (Salvador et al., 2013), and especially in places like Las Palmas (Díaz et al., 2017; Viana et al., 2014), where there is practically a three-fold increase in PM_{10} on days with Sarahan dust. These results agree with the results of other studies.

Days with Saharan dust intrusion not only produce increases in concentrations of $PM_{10,}$ they also result in increases in the concentrations of other pollutants such as NO_2, although in our analysis, there were only statistically significant increases in Gran Canaria and Madrid. These results coincide with what has been found in other studies that analyze the evolution of primary pollutants on days with and without Saharan dust intrusion in the cities of Barcelona (Pandolfi et al., 2014) and Madrid (Salvador et al., 2019) and in other Spanish cities (Moreira et al., 2020). According to these studies, the reason for this increase is the existence of particulate material on days with Saharan dust intrusion, which produces a decrease in solar radiation and a consequent decrease in the convective turbulence processes that cause a vertical development of the mixing cap during the day. Thus, the thickness of the mixing cap diminishes, and the concentrations of pollutants and aerosols increase (Li et al., 2017).

The trajectories of different air masses explain the behavior detected for temperature and absolute humidity in some provinces, with increases on days with Saharan intrusion (Russo et al., 2019).

One of the relevant results of this study is the association produced between the pollutant variables NO_2 and PM_{10} and the COVID-19 variables. There are two biological mechanisms that could explain the existence of these associations (Domingo and Rovira, 2020). On one hand, it is clear that air pollution affects human health (WHO, 2013). On the other hand, Pothirat et al. (2019) investigated the association between daily average seasonal air pollutants and daily mortality of hospitalized patients and community dwellers, as well as emergency and hospitalization visits for serious respiratory, cardiovascular, and cerebrovascular diseases. It was found that air pollutants were associated with higher mortality in hospitalized patients and community dwellers, with varying effects on severe acute respiratory, cardiovascular, and cerebrovascular diseases. In relation to the age of the individuals who are affected by outdoor air pollution - in particular those with respiratory system issues - those of elderly ages are one of the most sensitive groups (Jimenez et al., 2011; Simoni et al.,2015; Kotaki et al., 2019). Thus, air pollution worsens the same type of pathology in the same vulnerable age groups that are impacted more severely by SARS-Cov2 (MSCBS, 2020).

The other mechanism is based on the fact that air pollution weakens the immune system in the short term. There is growing evidence that pollution can cause oxidative stress, resulting in the production of free radicals, which in turn may damage the respiratory system and reduce the resistance to viral and bacterial infections (Ciencewicki and Jaspers, 2007). Air pollutants could influence the immune system and affect its ability to limit the spread of infectious agents like Respiratory Syncytial Virus (RSV) (Vandini et al., 2013; Nenna et al., 2017). On the other hand, Zhao et al., (Zhao et al., 2016) established that short-term exposure to $PM_{2.5}$ could act on the balance of inflammatory M1 and anti-inflammatory M2 macrophage polarizations, which could be involved in air pollution-induced immune disorders and diseases.

The results found in this study, with associations in the very short term, even in lags 0 and 3, point to a worsening of pre-existing circulatory and respiratory pathologies. The associations observed in the later lags could be explained by the worsening of prior conditions as well as a possible weakening of the immune system that would favor infection by the virus (Linares et al., 2021).

The fact that it is the concentrations of NO_2 that show a greater association with COVID-19 variables compared to PM_{10} agrees with the fact that the impact on short-term mortality in Spain is greater for NO_2 (RR: 1.012 (1.010 1.014) (Linares et al., 2018) than for PM_{10} (RR: 1.009 (1.006 1.011) (Ortiz et al., 2017).

In terms of the meteorological variables, the GLM models show that the coefficients related to COVID-19 variables are negative. That is to say, low and humid temperatures are related to higher incidence rates. On the other hand, the serological study of the prevalence of SARS-CoV-2 in Spain (ENE-COVID) (Pollán et al., 2020) indicates that a lower prevalence of COVID-19 in Spain was produced in

coastal regions that, during the time of the study and in general, are characterized by higher temperatures and humidity than the interior areas of the peninsula (AEMET, 2020).

Beyond the role of air pollution or the meteorological variables included in the multivariate models, the days with Saharan dust intrusion produce a generalized increase in the rate of incidence and in COVID-19 hospital admissions in particular, which are also subject to the effect of NAF. One possible explanation of this additional effect of Saharan dust could be that there may be another possible mechanism related to the transmission of the virus. According to a study carried out in Lombardia (Setti et al., 2020), traces of RNA of SARS-CoV-2 were found in samples of PM measured both in industrial and urban settings in Bergamo. The authors suggest that the aerosol particles that contain the virus of between 0.1 and 1µm can travel further when they group together with pollutant particles of up to 10µm (PM_{10}). Given that the resulting particle is larger and a less dense respiratory droplet, the time it remains in the atmosphere could increase. However, other research also carried out in Italy suggests the opposite in terms of the possible transmission of the virus via material particles (Bontempi et al., 2020). The results found in our study, with a very short-term effect in some cases (lags 0–7), lower even than the virus incubation period of 5.2 days, does not support the hypothesis that PM can act as a vector for the virus. Rather, these results point to the possibility that days with Saharan dust advection could aggravate cardiovascular and respiratory conditions, as suggested in other studies (Stafoggia et al., 2016; Díaz et al., 2017).

One possible hypothesis that would explain why days with Saharan dust intrusion result in an exacerbation of the effect of the COVID-19 variables analyzed relates to the different composition of the particles and their reaction to the primary pollutants present in the urban atmosphere. Saharan dust particles are mineral in origin, and they are the result of stone erosion (Griffin 2007). Their chemical composition includes mineral elements such as: quartz (60%), oxides (SIO_2, FeO_2), carbonates ($CaCO_3$), steel, titanium, and vanadium, and in some cases sulfate peaks can appear, resulting from the chemical reaction between carbonate contained in the dust and the gases that result from locally present environmental pollution (NO_2 SO_2) (Tobías et al., 2011). Some studies in experimental toxicology in rats have shown that quartz, silica, aluminum and oxides contained in desert dust can cause bronchial and lung inflammation thanks to the hyper production of cytokines (Ichinose et al., 2008; Mancino et al., 1984). In the majority of patients severely affected by COVID-19, an increase was observed in interleukins: 6 (IL6) and 10 (IL10). This process is referred to as a cytokine storm (Tang et al., 2020), and it can rapidly lead to worsening of symptoms and even death. Currently, it is not precisely known which environmental mechanisms could contribute to initiating a cytokine storm in some patients and not in others. From an immunological point of view, the presence of Saharan dust, together with other endogenous factors in each patient (genetic profile, age, and other still unclear factors), could support the initiation of this severe process.

Another possible hypothesis could be related to the fact that a decrease in the mixing cap is produced when there is a Saharan dust intrusion (Pandolfi et al., 2017; Salvador et al., 2019). A decrease in the mixing cap not only affects the increase in primary pollutants, including those we have included in this study, PM_{10} and NO_2, but it also makes the dispersion of other pollutants and increase in aerosols more difficult (Li et al., 2017). Therefore, in introducing the variable related to Saharan dust, it is important to take into account the effect of other pollutant substances not considered as independent variables that have been shown to be associated with COVID-19 (Frontera et al., 2020) or other constituents of PM_{10} such as $PM_{2.5}$, that are also related to the incidence and severity of COVID-19 (Yao et al., 2020; Zhao et al.,2020; Zoran et al., 2020).

Finally, the greater RR for the NAF variables observed in this study can be explained by the fact that the range of variation in these variables is between zero and one, which does not occur for the rest of the variables considered in the multivariate models, as shown in Table 1.

Strengths and weaknesses of this study

One of the primary strengths of this study is the length of the series used. Even though it is a series of only 121 days, or roughly four months, it is longer than the majority of the series used in other studies carried out to date. On the other hand, the period analyzed corresponds to a period that was both prior to the state of alarm and during the state of alarm, which applied homogeneous restrictions to the zone of the study. Thus, the entire area considered in the study was subjected to the same conditions in terms of “physical distancing and other public health interventions” (Villeneuve & Goldberg 2020).

The duration of the series allowed for us to construct generalized linear models with control variables such as trend and seasonality and the autoregressive component. The study corresponds to an ecological time series design, with all the epidemiological limitations inherent in this type of study, especially the ecological fallacy, which is a key weakness, given that we cannot know which of the possible hypotheses that relate Saharan dust intrusions with COVID-19 variables is that which truly explains the association.

On the other hand, paradoxically, the length of the series is also considered a weakness, given that it is only four months and does not include complete annual variation. It was also period that was totally anomalous, given the decrease in pollutants that occurred with the confinement of the population. Thus, the exposure to external environmental variables represents an important bias. On the other hand, the conditions under which the data were obtained correspond to the definition of a positive COVID-19 case as one which took place only when a person already presented important symptoms associated with the disease.

Both of the above mentioned points require prudence in extrapolating the results of this study to time periods other than that of the study period. Later studies could analyze with greater depth the combined impact of climate variability, air pollution and other factors extrinsic to COVID-19. Other important factors should also be considered that were not included in this study, such as patterns of social relationships, the susceptibility of the population, and surveillance data on respiratory infections, for example.

5. Conclusions

The results of this study show that chemical air pollution, especially NO_2, is related to the incidence and severity of COVID-19 in Spain. Additionally, Saharan dust intrusions have an effect beyond that which can be attributed to air pollution. These results serve to support adoption of public health measures to minimize population exposure on days with advection of particulate material of Saharan origin.

6. Declarations

Ethical Approval

The manuscript should not be submitted to more than one journal for simultaneous consideration. The submitted work should be original and should not have been published elsewhere in any form or language (partially or in full), unless the new work concerns an expansion of previous work.

The researchers declare that they have no conflicts of interest that would compromise the independence of this research work. The views expressed by the authors do not necessarily coincide with those of the institutions whose affiliation is indicated at the beginning of this article.

Consent to Participate

This study works with aggregate data, therefore there are no individual data, therefore, the consent to participate is not applicable.

Consent to Publish

This study works with aggregate data, therefore there are no individual data, therefore, the consent to publish is not applicable.

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Availability of data and materials

It´s an ecological analysis so the study does not involve human subjects. The data in relation to COVID-19 used in this study are subject to statistical secrecy and, therefore, are not freely available.

Credit Author Statement:

Cristina Linares. Original idea of the study. Study design; Elaboration and revision of the manuscript.

Fernando Belda. Providing and Analysis of data; Elaboration and revision of the manuscript.

José A López-Bueno. Providing and Analysis of data; Elaboration and revision of the manuscript.

Yolanda Luna. Providing and Analysis of data; Elaboration and revision of the manuscript

Gerardo Sánchez-Martínez. Epidemiological study design. Elaboration and revision of the manuscript.

Beatriz Hervella. Providing and Analysis of data; Elaboration and revision of the manuscript.

Dante Culqui. Epidemiological study design. Elaboration and revision of the manuscript.

Julio Díaz. Original idea of the study. Study design; Elaboration and revision of the manuscript.

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Figures

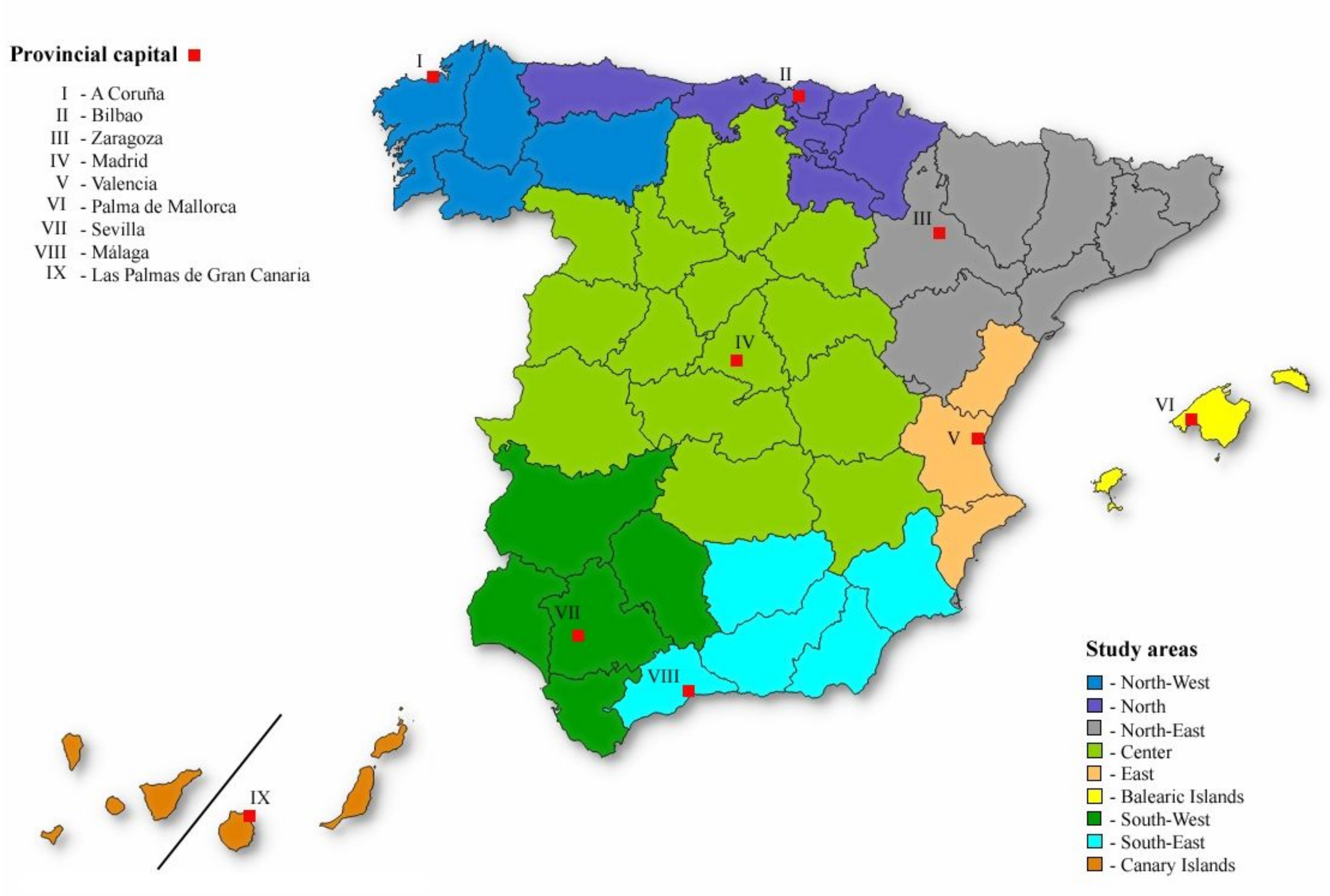

Figure 1

Location of the study areas and location of the province capitals selected for participation in the study. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

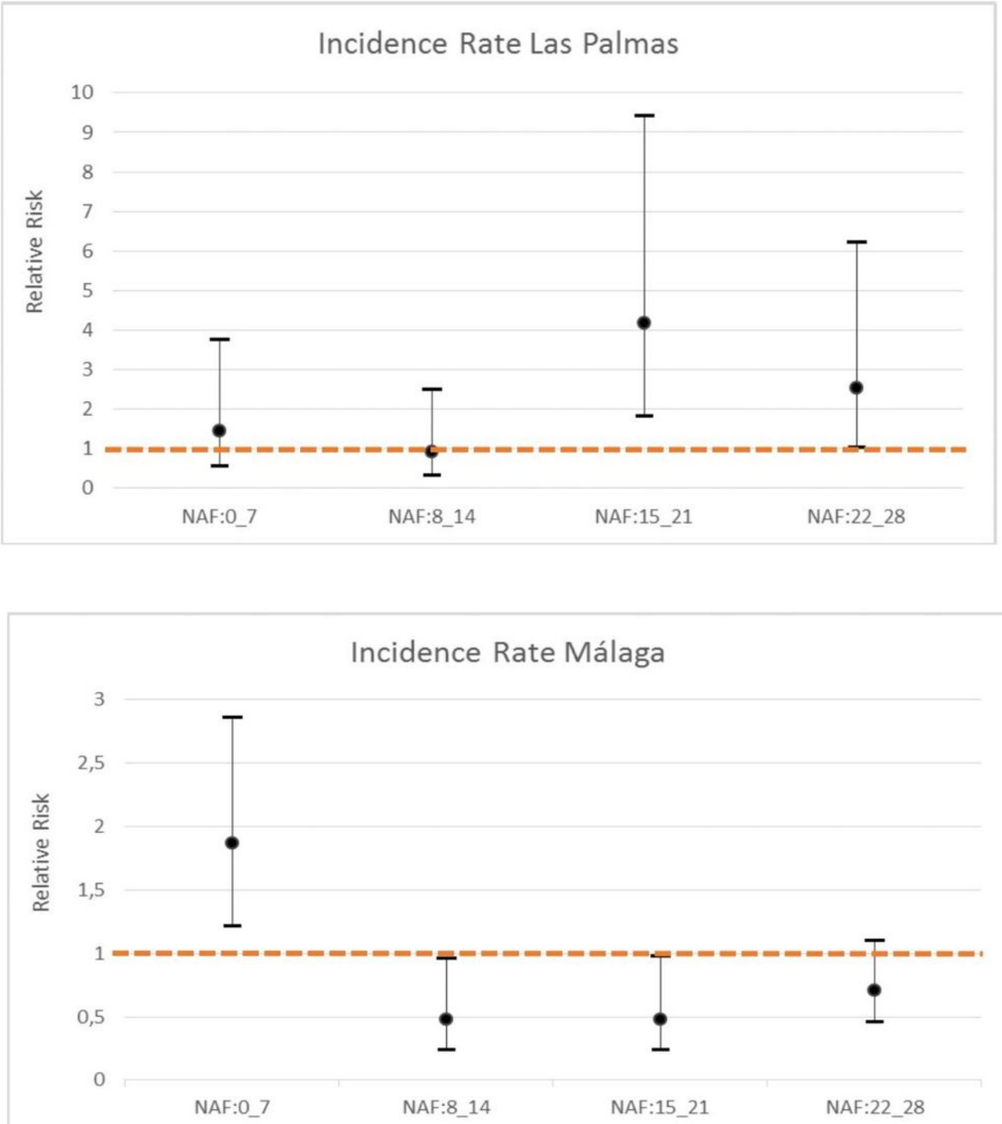

Figure 2

Relative Risks obtained for the COVID-19 incidence rate for different lags corresponding to Sarahan dust intrusion in Las Palmas (left) and Malaga (right). NAF:0_7 corresponds to the average value of the first 7 days of advection of Saharan dust. NAF:8_14 corresponds to the average value of the interval of 8 to 14 days after the Saharan dust advection. NAF:15_21 corresponds to the average value of the interval of 15 to 21 days after the Saharan dust advection, and NAF:22_28 corresponds to the average value of the interval of 22 to 28 days after the Saharan dust advection.

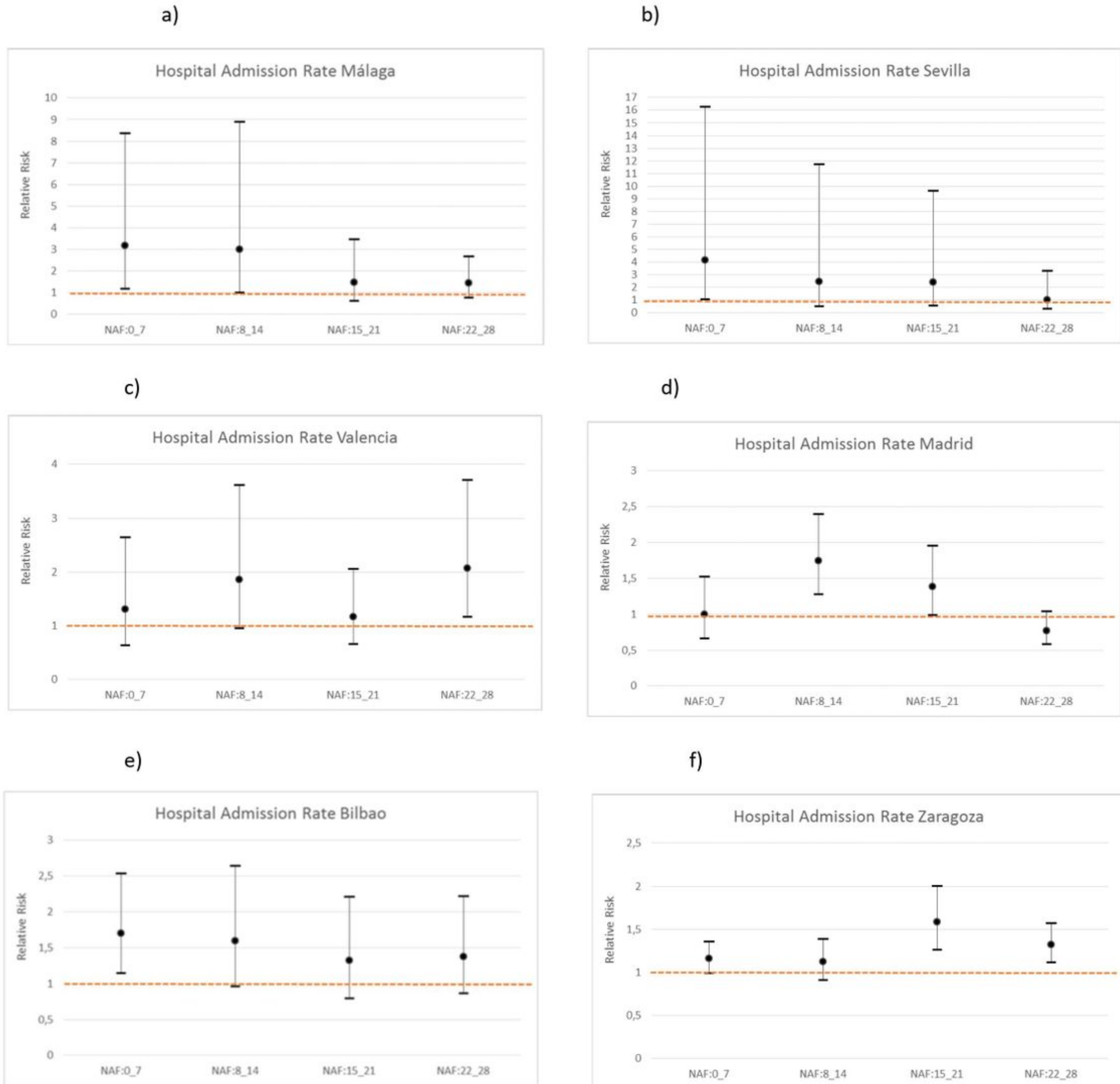

Figure 3

Relative Risks obtained for the rate of hospital admissions for COVID-19 for the lags corresponding to the intrusion of Saharan dust in a)Malaga, b)Seville, c)Valencia, d)Madrid, e)Bilbao and f)Zaragoza. NAF:0_7 corresponds to the average value of the first 7 days of advection of Saharan dust. NAF:8_14 corresponds to the average value of the interval of 8 to 14 days after the advection of Saharan dust. NAF:15_21 corresponds to the average value of the interval of 15 to 21 days after the Saharan dust advection and NAF:22_28 corresponds to the average value of the interval of 22 to 28 days after the advection of Saharan dust.