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RESEARCH ARTICLE

Particulate matter concentrations and their association with COVID-19-related mortality in Mexico during June 2020 Saharan dust event

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Abstract

The present study evaluated the impact of Saharan dust event on particulate matter (PM: PM_{10} and $PM_{2.5}$) concentrations by analyzing the daily average PM data between Saharan dust days (June 23–29, 2020) and non-Saharan dust days (June 15 to June 22 and June 30 to July 12, 2020) for four majorly affected regions in Mexico and by comparing with three major previous events (2015, 2018, and 2019). The results showed that PM_{10} and $PM_{2.5}$ concentrations were 2–5 times higher during the Saharan dust event with the highest daily averages of 197 μg/m^3 and 94 μg/m^3, respectively, and exceeded the Mexican standard norm (NOM-020-SSA1-2014). When comparing with the previous Saharan dust episodes of 2015, 2018, and 2019, the levels of PM_{10} and $PM_{2.5}$ considerably increased and more than doubled across Mexico. The correlation analysis revealed a positive association of PM levels with the number of daily COVID-19 cases and deaths during Saharan dust event. Furthermore, the human health risk assessment showed that the chronic daily intake and hazard quotient values incremented during Saharan dust days compared to non-Saharan days, indicating potential health effects and importance of taking necessary measures to ensure better air quality following the COVID-19 pandemic.

Keywords Air pollution · $PM_{2.5}$ · PM_{10} · Air quality index · Public health · Hazard quotient

Introduction

Air pollution remains a global environmental threat and a public health risk. The World Health Organization (WHO) estimated that exposure to polluted air alone caused around 4.2 million deaths worldwide in 2016 (WHO 2018). Particulate matter (PM) is one of the most common air pollutants which comprises particles of various sizes (PM_{10} and $PM_{2.5}$) with associated adsorbed substances (i.e., chemicals and metals). PM can be naturally originated (i.e., sea spray, volcanoes, forests, and deserts) and anthropogenic originated (i.e., vehicles, combustion, industry, and power plants) (Hernández-Escamilla et al. 2015; Ali-Khodja et al. 2017). With the increase in anthropogenic activities and ambient PM concentrations, their exposure to short-term and long-term period affects human health and contributes breathing problems, respiratory diseases, chronic diseases, cancer, and premature mortality (Kim et al. 2015; Loxham and Nieuwenhuijsen 2019). The impact of desert dust events on the PM concentrations and human health has received worldwide attention in the last decades. Sahara Desert is the largest source of atmospheric mineral dust and dust storms are a common meteorological phenomenon, happening especially between late Spring and early Fall, peaking in late June to mid-August (Querol et al. 2019; Çapraz and Deniz 2020). It has been estimated that about 800 millions of metric tons of dust from North Africa travel and impact across the Atlantic Ocean, the Mediterranean Sea, and the Red Sea, to the Caribbean, South America, North America, Europe, and the

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Middle East every year (Querol et al. 2019; Çapraz and Deniz 2020). Owing to the frequent long-range transport of large amounts of dust, a number of studies have evaluated the impact of Saharan dust events on PM concentrations (Querol et al. 2009; Achilleos et al. 2014; Moroni et al. 2015; Dimitriou and Kassomenos 2018; Querol et al. 2019). It is understood from these studies that Sahara dust events greatly increase the ambient concentration of PM contributing to air pollution and may be associated with adverse health effects.

According to NOAA's (National Oceanic and Atmospheric Administration) Atlantic Oceanographic and Meteorological Laboratory, the June 2020 Saharan dust event was around 60–70% dustier than an average event happened in 20 years. Most notably, the June 2020 Saharan dust occurred at a critical time when the world is already facing Coronavirus disease 2019 (COVID-19), a global health crisis. COVID-19 is an acute respiratory disease caused by SARS-CoV-2 (WHO 2020); it has been suggested that environmental factors, such as ambient air pollution, could increase the severity of the health outcomes (e.g., hospitalization and death) among individuals with COVID-19 (Coker et al. 2020). Recent researchers have corroborated the presence of SARS-CoV-2 viral RNA on coarse PM and associations with COVID-19 mortality cases (Setti et al. 2020; Wu et al. 2020). Several studies identified positive association between higher $PM_{2.5}$ and PM_{10} and COVID-19 deaths globally (Yao et al. 2020; Wu et al. 2020). With the rapid emergence of the novel COVID-19 disease, which by itself is a respiratory disease, it will be important to evaluate the impact of June 2020 Saharan dust event on PM levels and to determine if any relevant associations with COVID-19 cases and deaths. The Saharan dust event occurred between June 23 and June 29, 2020 in Mexico, right after the withdrawal of COVID-19 lockdown, has drawn our attention. Air pollution has been a primary issue in Mexico, exceeding the WHO-recommended level in relation to various types of air pollutants, including the PM, in most of its major cities (Molina et al. 2019). The Saharan dust-affected regions include the parts of northeastern Mexico and Yucatan Peninsula (Fig. 1), where they already have higher levels of air pollution due to industrialization and urbanization activities (González-Santiago et al. 2011; Bretón et al. 2018; CONAGUA 2020). Thus, the main objectives of this study are (1) to examine the relative contribution of Saharan dust on PM_{10} and $PM_{2.5}$ concentrations, (2) to assess the variations in PM concentrations when compared with previous major dust episodes (2015, 2018, and 2019), (3) to explore the association of PM concentrations with COVID-19 cases and deaths, and (4) to evaluate the human health risk associated with PM exposure via inhalation. To the best of our knowledge, this is the first research to document the impact of Saharan dust event in relation to PM levels (PM_{10} and $PM_{2.5}$) and human health in Mexico and during COVID-19 crisis.

Methodology

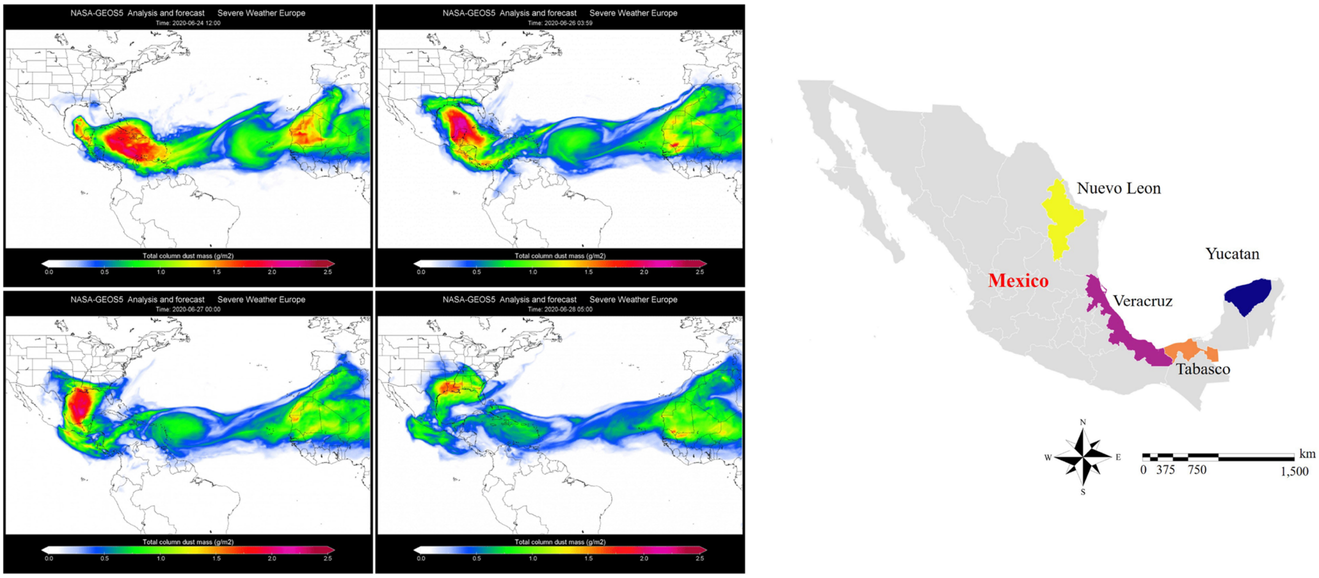
Site description and data collection

In this study, the PM levels (PM_{10} and $PM_{2.5}$) for a total of 28 days between June 15, 2020 and July 12, 2020 were assessed in four majorly hit regions of Mexico, namely, Nuevo Leon, Veracruz, Tabasco, and Yucatan (Fig. 1b). The period between June 23 and June 29, 2020 when the event took place in Mexico was considered as Saharan dust days, whereas the periods prior (June 15 to June 22) and after the event (June 30 to July 12, 2020) were collectively considered as non-Saharan dust days. For our analysis, we used the daily concentrations of PM_{10} and $PM_{2.5}$ as well as the meteorological data (i.e., temperature, relative humidity, and wind speed) during the study period from 15 air monitoring stations located in Nuevo Leon (n = 11), Veracruz (n = 2), Tabasco (n = 1), and Yucatan (n = 1), respectively. The details and data availability of the monitoring stations are provided in Table 1. The previous major Saharan dust episodes in Mexico, recorded in the years of 2015, 2018, and 2019, were considered for the comparison of PM levels with that of 2020. The PM data for Saharan dust events during 2015, 2018, 2019, and 2020 was downloaded from the website of Sistema Nacional de Información de la Calidad del Aire (SINAICA, https://sinaica.inecc.gob.mx/index.php), operated by Instituto Nacional de Ecologia y Cambio Climatico, Government of Mexico.

To find associations, if any, of PM levels with COVID-19 cases and mortality, we collected the data of confirmed COVID-19 cases and deaths (June 15, 2020 to July 12, 2020) from the official website of the Government of Mexico (https://coronavirus.gob.mx/datos/). We preferred to carry out this analysis only for Nuevo Leon as the dataset available from monitoring stations (n = 11) covers the wider province comparatively higher than other states selected in this study. Additionally, it represents the third most populated region in Mexico. Statistical analysis was conducted using Statistica software (version 8.0). The whole data set was varimax normalized to minimize the number of variables with a high loading on each component. Correlation matrix with p < 0.5, 0.01, 0.001 values was obtained to investigate the relationships between the PM levels and COVID-19 cases and deaths.

Air quality index

Air quality index (AQI) by USEPA (1999) was employed for the effective assessment of air quality. We calculated AQI for PM_{10} and $PM_{2.5}$ obtained from each monitoring stations using the following equation:



(a) (b)

Fig. 1 **a** Dust forecast obtained from the NASA GEOS-5 model showing the June 2020 Saharan dust event. **b** Map showing the study regions for the demonstration of Saharan dust event in Mexico

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}} \left(C_p - BP_{Lo}\right) + I_{Lo}$$

where I_p = index for pollutant p; C_p = rounded concentration of pollutant p; BP_{Hi} = the breakpoint that is greater than or equal to C_p; BP_{Lo} = the breakpoint that is less than or equal to C_p; I_{Hi} = the AQI value corresponding to BP_{Hi}; I_{Lo} = the AQI value corresponding to BP_{Lo}. The AQI ranges from 0 to 500 and categorized into following six intervals: 0–50: good (air quality is good with no risk); 51–100: moderate (air quality is acceptable; however, for some pollutants, there may be a moderate health concern like for people having respiratory diseases); 101–150: unhealthy for sensitive groups (members of sensitive groups may experience health effects); 151–200: unhealthy (everyone may begin to experience health effects); 201–300: very unhealthy (health warnings of emergency conditions and the entire population is more

Table 1 List of air monitoring stations from the Saharan dust-affected regions for the period of assessment (June 15–July 12, 2020) in Mexico

State	Air monitoring station	Short name	Data availability	Latitude and longitude
Nuevo Leon	Apodaca	MAS 1	PM_{10}, $PM_{2.5}$, temperature, wind speed and relative humidity	25.78 N, 100.19 W
	Cadereyta	MAS 2	PM_{10}, $PM_{2.5}$, temperature, wind speed and relative humidity	25.60 N, 99.99 W
	Garcia	MAS 3	PM_{10}, $PM_{2.5}$, temperature, wind speed and relative humidity	25.78 N, 100.59 W
	Juarez	MAS 4	PM_{10}, $PM_{2.5}$, temperature and wind speed	25.65 N, 100.1 W
	La Pastora	MAS 5	PM_{10}, $PM_{2.5}$, temperature, wind speed and relative humidity	25.67 N, 100.25 W
	Obispado	MAS 6	PM_{10}, temperature, wind speed and relative humidity	25.68 N, 100.34 W
	Pueblo Serena	MAS 7	PM_{10}, temperature, wind speed and relative humidity	25.58 N, 100.25 W
	San Bernabe	MAS 8	PM_{10}, $PM_{2.5}$, temperature, wind speed and relative humidity	25.76 N, 100.37 W
	San Pedro	MAS 9	PM_{10}, $PM_{2.5}$, temperature, wind speed and relative humidity	25.67 N, 100.41 W
	Santa Catarina	MAS 10	PM_{10}, $PM_{2.5}$, temperature, wind speed and relative humidity	25.68 N, 100.46 W
	Universidad	MAS 11	PM_{10}, temperature, wind speed and relative humidity	25.73 N, 100.31 W
Veracruz	Universidad Veracruzana	VAS 1	PM_{10}, $PM_{2.5}$, temperature, wind speed and relative humidity	20.51 N, 97.45 W
	Minatitlan Tecnologico	VAS 2	$PM_{2.5}$, temperature, wind speed and relative humidity	18.01 N, 94.56 W
Tabasco	Instituto Tecnologico de Villahermosa	TAS	PM_{10}	18.02 N, 92.9 W
Yucatan	Merida SDS01	YAS	$PM_{2.5}$, temperature and relative humidity	20.97 N, 89.62 W

likely to be affected); and 301–500: hazardous (everyone may experience more serious health effects).

Human health risk assessment on exposure to particulate matter (PM_{10} and $PM_{2.5}$)

Exposure dose

Human health risk assessment (USEPA 1989) was performed to understand the nature and probability of adverse health effects in humans exposed to PM during the June 2020 Saharan dust event. We concentrated on the health risk estimation through inhalation route for both children and adults. Chronic daily intake (CDI) was estimated for assessing the human health risk upon exposure to PM through inhalation pathway. It was calculated as follows (USEPA 2009):

$$CDI_{\text{inh}} = C_{\text{UCL}} \times \frac{R_{\text{inh}} \times F_{\text{exp}} \times T_{\text{exp}}}{ABW \times T_{\text{avrg}}}$$

where CDI = chronic daily intake (μg kg^{-1} day^{-1}); R_{inh} = inhalation rate at 20 m^3 day^{-1} for adults and 7.6 m^3 day^{-1} for children; F_{exp} = exposure frequency (days $year^{-1}$); in the present study, exposure frequency was considered as 28 days $year^{-1}$ corresponding to the June 2020 Saharan dust event; T_{exp} = the exposure duration 6 years for children and 24 years for adult; ABW = average body weight, 15 kg for children and 70 kg for adults; T_{avrg} = averaging time, for non-carcinogens T_{avrg} = T_{exp}* 365 days and for carcinogens T_{avrg} = 70 × 365.

C is the concentration of particulate matter (μg/m^3). C_{UCL} estimates the reasonable maximum exposure, which is the upper limit of the 95% confidence interval for the mean. C_{UCL} was calculated based on the central limit theorem (adjusted) by USEPA (2002):

$$C_{\text{UCL}} = \overline{X} + \left(Z + \frac{\beta}{6\sqrt{n}} \left(1 + 2 \times z^2\right) \right) STD/\sqrt{n}$$

where $\overline{X}$ = arithmetic mean; Z = statistic constant 1.645; β = skewness; n = number of samples; and STD = standard deviation.

Risk characterization

Risk assessment for the carcinogenic and non-carcinogenic risk of PM was calculated using the parameter called hazard quotient (HQ), the ratio of CDI to reference dose (RfD) by using the following equation:

$$\text{Hazard quotient (HQ)} = \text{CDI/RfD (USEPA 1989, 2011)}$$

HQ of 1.0 is considered safe. HQ that is < 1.0 indicates a negligible risk, i.e., the pollutant is not likely to induce adverse health effects, even to a sensitive individual. HQ > 1.0 indicates that there may be some risks to sensitive individuals as a result of exposure (USEPA 1989, 2011). Given the lack of information regarding RfD of PM_{10} and $PM_{2.5}$ in Mexico, we calculated RfD using the following equation:

$$\text{RfD} = \text{RfC} \left(\text{inhalation reference concentration } \mu\text{g/m}^3\right) \times \text{Assumed inhalation rate } \left(\text{m}^3/\text{day}\right) \times 1/\text{BW (kg)}$$

We used RfC values of 50 μg/m^3 for PM_{10} and 5 μg/m^3 for $PM_{2.5}$ (de Oliveira et al. 2012; Li et al. 2017; Yunesian et al. 2019) to assess the probability of adverse health impacts.

Results and discussion

The daily average concentration of PM_{10} and $PM_{2.5}$ during the June 2020 Saharan dust event from 15 monitoring stations is shown in Figs. 2 and 3. The daily average PM_{10} and $PM_{2.5}$ levels were high during Saharan dust event and exceeded the annual limit of 75 μg/m^3 and 45 μg/m^3 set up by the Mexican standard Norm (NOM-020-SSA1-2014; DOF 2014). It also exceeded the WHO air quality guidelines for the annual mean concentrations of 50 μg/m^3 and 25 μg/m^3 for PM_{10} and $PM_{2.5}$, respectively (WHO 2006).

In general, the PM_{10} and $PM_{2.5}$ were at low concentrations before the dust event. As shown in Figs. 2 and 3, there was a significant increase in the daily average concentration of PM_{10} and $PM_{2.5}$ in all the stations of Mexico under the examination period of Saharan dust event (23rd to 29th, June 2020). The elevated PM concentrations were as a result of received Saharan dust cover which is generally a rich source of PM_{10} and $PM_{2.5}$. TAS and VAS 2 stations recorded the highest daily average concentration of 197 μg/m^3 and 94 μg/m^3 for PM_{10} and $PM_{2.5}$, respectively. In contrast, MAS 6 and MAS 10 stations registered the lowest daily average concentration of 49 μg/m^3 and 35 μg/m^3 for PM_{10} and $PM_{2.5}$, respectively. After the dust event, a considerable decrease in the PM concentrations (Figs. 2 and 3) was noted but the concentration of PM_{10} and $PM_{2.5}$ remained high to those observed before the event. It can be explained by the fact that the effect of a Saharan dust event can extend to days succeeding the event as fine particulates can remain airborne for long durations.

Considering all days, PM_{10} (μg/m^3) average concentrations were 47, 42, and 53 for Nuevo Leon, Veracruz, and Tabasco; $PM_{2.5}$ (μg/m^3) average concentrations were 20, 24, and 25 for Nuevo Leon, Veracruz, and Yucatan, respectively. It is noted that the increase in the concentration of PM was more significant on Saharan dust days as compared with the non-Saharan dust days. On Saharan dust days, average concentrations were 1.2, 2.2, and 2.2 times higher for PM_{10} than on non-Saharan dust days, with the values reaching 52 μg/m^3, 68 μg/m^3, and 86 μg/m^3 for Nuevo Leon, Veracruz, and

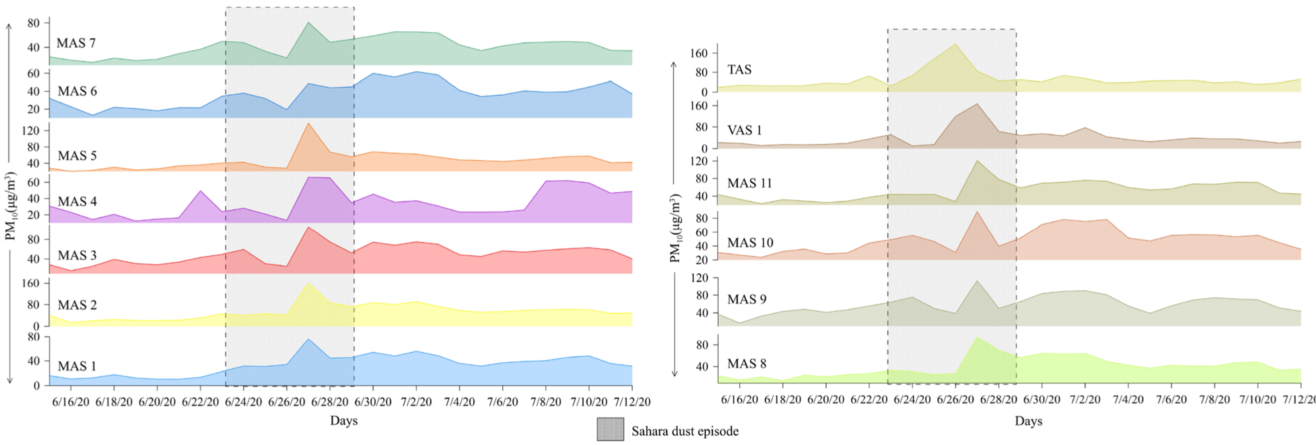


Fig. 2 Average PM_{10} concentrations from June 15 to July 12, 2020 recorded in air monitoring stations located in Nuevo Leon, Veracruz, and Tabasco of Mexico

Tabasco, respectively. Compared to non-Saharan dust days, the average concentrations of $PM_{2.5}$ were 1.3, 1.8, and 2.4 times higher for Nuevo Leon, Veracruz, and Yucatan, with the values reaching 25 $\mu g/m^3$, 37 $\mu g/m^3$, and 44 $\mu g/m^3$, respectively. The results suggest that Tabasco and Yucatan have the highest average value of PM_{10} and $PM_{2.5}$, followed by Veracruz and Nuevo Leon.

Next, we estimated the changes (%) in PM_{10} and $PM_{2.5}$ concentrations for the period of assessment, i.e., non-Saharan dust vs Saharan dust (Fig. 4). The first thing to note is that the variations of PM concentrations were obvious among the study regions, but it was uneven. The stations located in the coastal regions of Tabasco, Veracruz, and Yucatan presented higher increase percentage of PM levels in Saharan dust days than non-Saharan days. The station that registered the greatest change percentage was VAS 1 (118%), followed by TAS (115%) for PM_{10}. YAS station recorded a maximum increase of about 59% for $PM_{2.5}$. In contrary, the increase percentage of PM_{10} and $PM_{2.5}$ concentrations varied between 5 and 45%, respectively, in Nuevo Leon, displaying an overall increase of 20% of PM levels for the study period. For example, the increase of PM levels was higher in MAS 2 and MAS 1 between Saharan dust days and non-Saharan days, while it was least significant in MAS 10 station (Fig. 4). MAS 8 station displayed no significant variation between non-Saharan and Saharan dust days. It can be said that Nuevo Leon (located northeast) is less affected by Saharan dust event compared to other regions that are located on the southeast side of Mexico. This may be likely due to the differences in the dust intensity (significantly thicker dust), gravitational settling velocities, and distribution of Saharan dust across Mexico.

Additionally, the changes (%) in PM_{10} and $PM_{2.5}$ concentrations were examined with respect to previous major Saharan dust episodes in Mexico (Table 2). The lack of data availability from few air monitoring stations for previous year events, however, rendered a complete comparison to understand the effect of PM_{10} and $PM_{2.5}$ concentrations between Saharan dust episodes. With available data, the first thing to note is that the PM_{10} and $PM_{2.5}$ concentrations did not show

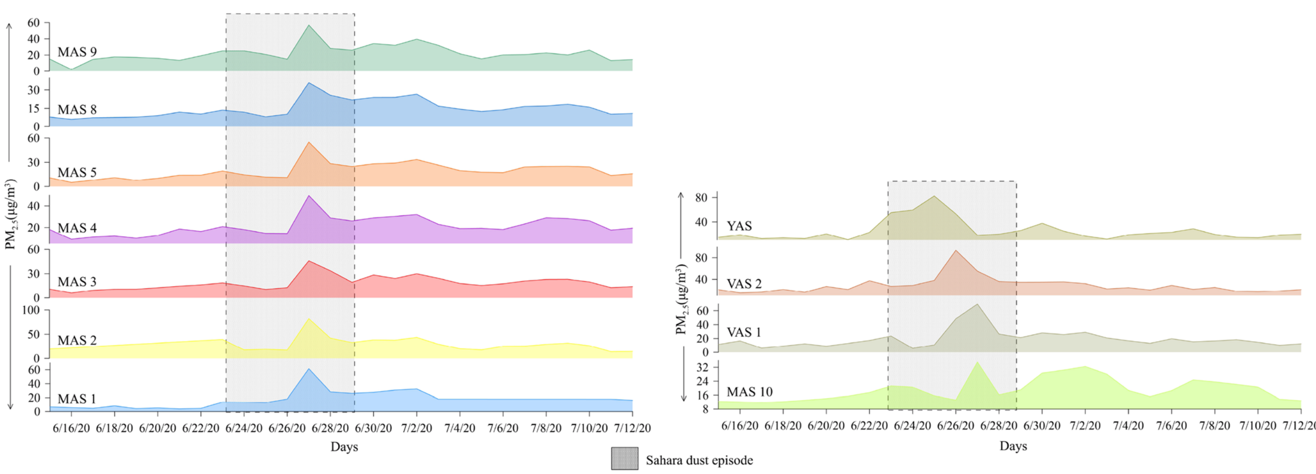


Fig. 3 Average $PM_{2.5}$ concentrations from June 15 to July 12, 2020 recorded in air monitoring stations located in Nuevo Leon, Veracruz, and Yucatan of Mexico

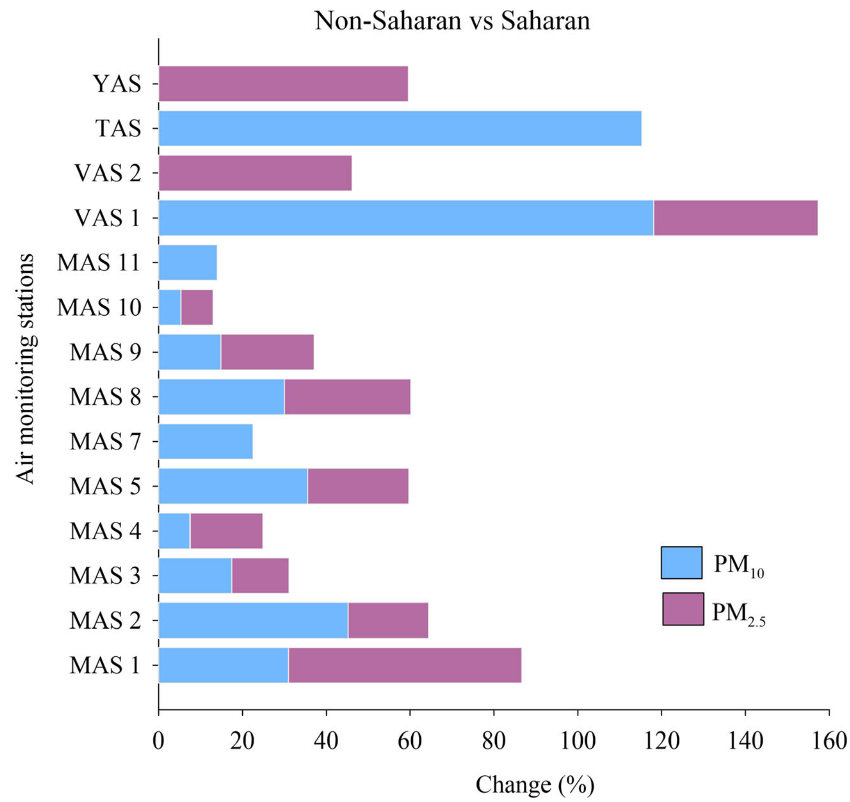


Fig. 4 Bar chart displaying the changes (%) in PM concentrations between non-Saharan and Saharan days

similar trends in each of the Saharan dust episodes. Despite certain differences observed in the concentrations, it is seen in Table 2 that all stations exceeded the concentrations of PM_{10} and $PM_{2.5}$ with those of 2015, 2018, and 2019, except for MAS 1. The change was noticeable with considerable increase, and it was well pronounced compared to previous Saharan dust episodes. For example, an average increase of PM_{10} by 8% and 71% was noted compared to years 2018 and 2019 in Nuevo Leon; in contrary, $PM_{2.5}$ increased by 166% compared to 2019. When comparing 2019 with 2020, VAS1

Table 2 Comparison of PM concentrations between Saharan dust episodes for years 2015, 2018, 2019, and 2020 in Mexico

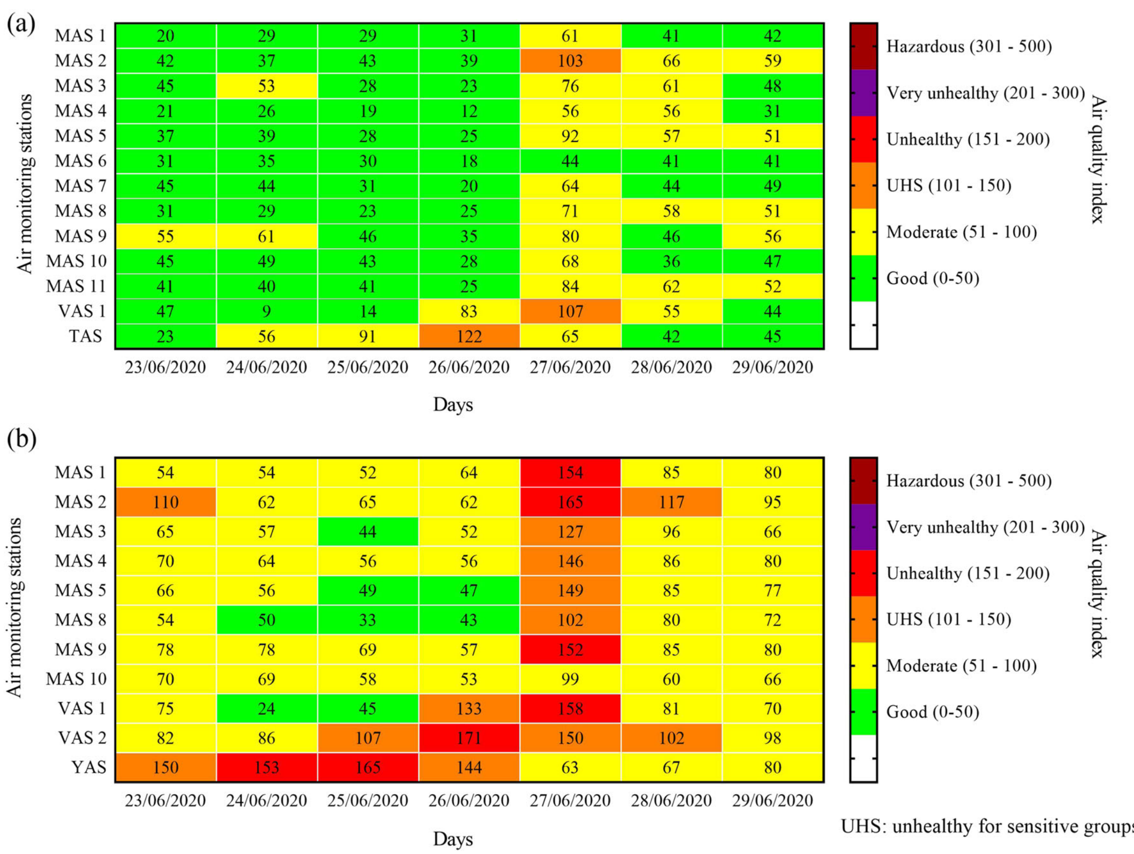
PM_{10} (µg/m^3)							
Stations	2020	2019	2018	2015	Relative change		
					A (% change)	B (% change)	C (% change)
MAS 1	76	80	105	101	− 5	− 27	− 24
MAS 2	160	66	97	-	143	65	-
MAS 3	106	55	103	96	93	3	11
MAS 4	66	46	89	87	44	− 26	− 24
MAS 5	139	49	93	98	183	49	42
MAS 6	49	41	89	87	19	− 45	− 44
MAS 7	81	62	71	-	31	14	-
MAS 8	95	73	109	113	30	− 13	− 16
MAS 9	113	60	85	104	89	33	9
MAS 10	89	50	96	116	79	− 7	− 23
MAS 11	121	67	85	-	81	43	-
VAS 1	167	69	90	-	142	86	-
TAS	197	57	90	-	246	119	-

$PM_{2.5}$ (µg/m^3)							
Stations	2020	2019	2018	2015	Relative change		
					A (% change)	B (% change)	C (% change)
MAS 1	62	25	-	42	146	-	47
MAS 2	82	24	21	38	243	291	116
MAS 3	46	19	32	-	142	43	-
MAS 4	50	19	-	-	161	-	-
MAS 5	55	18	-	-	206	-	-
MAS8	36	-	-	-	-	-	-
MAS 9	57	21	-	-	171	-	-
MAS 10	35	18	-	47	95	-	− 25
VAS 1	70	31	11	-	125	533	-
VAS 2	94	31	45	40	203	109	135
YAS	83	52	35	49	59	136	69

A: change percentage with respect to PM concentrations between 2020 and 2019; B: change percentage with respect to PM concentrations between 2020 and 2018; C: change percentage with respect to PM concentrations between 2020 and 2015. The change in negative shows decreased contents and positive shows increased contents and VAS2 stations recorded 124% and 202% increase of $PM_{2.5}$. The result of the analysis confirmed that the observed changes in the PM_{10} and $PM_{2.5}$ concentrations are more severe during the June 2020 Saharan dust compared to previous episodes in Mexico.

It is reasonable to assume that the amount of dust entering the atmosphere in the region could worsen by the increased particulate concentrations. Therefore, it is critical to estimate air quality index for the Saharan dust period. As shown in Fig. 5, in general, the distribution of air quality trend between the stations for PM_{10} remained good for most of the days but based on $PM_{2.5}$, the dominance of moderate category was observed. In terms of $PM_{2.5}$ estimations, it is suggested that the population of study area is exposed with more than 50% of the days with significant impact on health. It is important to note an elevated value in the category, "unhealthy" for all the stations on the maximum dusty day (June 27), leading to adverse air quality. The consequences of these inflations in air quality might have impact on health, especially on elderly and sensitive groups during COVID-19 pandemic.

Similar to our findings, variations in PM_{10} and $PM_{2.5}$ levels during the Saharan dust events especially in the proximity of the source areas have been widely reported. Spain and Nicosia displayed PM_{10} concentrations reaching 250 μg/m^3 and up to 470 μg/m^3 respectively, during Saharan dust events (Querol et al. 2009; Achilleos et al. 2014). Moroni et al. (2015) identified 22 dust intrusions in Monte Martano (central Italy) in 2009 and estimated the impact of dust on PM_{10} at 22 μg/m^3 per intrusion. Kabatas et al. (2014) also found a significant contribution of dust to high levels of PM_{10} in Turkey. Likewise, Dimitriou and Kassomenos (2018) observed extreme concentrations of PM_{10} in Athens (Greece) during April 2008 Saharan dust. We acknowledge here that our results of PM levels in Mexico were way lower compared to other regions during Saharan dust episodes (i.e., 2015, 2018, 2019, and 2020) due to its geographical location away (~ 7000 km) from the source area. In addition, the lack of investigations for North American region closer to our study area, however, hinders a detailed comparison. In relation to meteorological conditions, Saharan dust events usually occur during warmer months (i.e., summer) characterized with higher temperatures and low relative humidity (Weinzierl et al. 2017; Ramírez-Romero et al. 2021). However, this region did not show any significant changes in temperature and relative humidity between Saharan dust days and non-Saharan dust days (Supplementary Material Table S1) similar to dust episodes witnessed in Athens, Greece, during 2001–2006 (Samoli et al. 2011), while a decrease in wind speed was observed during Saharan dust days favoring the accumulation of dust particles in atmosphere for a prolonged time.



(a)	23/06/2020	24/06/2020	25/06/2020	26/06/2020	27/06/2020	28/06/2020	29/06/2020
MAS 1	20	29	29	31	61	41	42
MAS 2	42	37	43	39	103	66	59
MAS 3	45	53	28	23	76	61	48
MAS 4	21	26	19	12	56	56	31
MAS 5	37	39	28	25	92	57	51
MAS 6	31	35	30	18	44	41	41
MAS 7	45	44	31	20	64	44	49
MAS 8	31	29	23	25	71	58	51
MAS 9	55	61	46	35	80	46	56
MAS 10	45	49	43	28	68	36	47
MAS 11	41	40	41	25	84	62	52
VAS 1	47	9	14	83	107	55	44
TAS	23	56	91	122	65	42	45

(b)	23/06/2020	24/06/2020	25/06/2020	26/06/2020	27/06/2020	28/06/2020	29/06/2020
MAS 1	54	54	52	64	154	85	80
MAS 2	110	62	65	62	165	117	95
MAS 3	65	57	44	52	127	96	66
MAS 4	70	64	56	56	146	86	80
MAS 5	66	56	49	47	149	85	77
MAS 8	54	50	33	43	102	80	72
MAS 9	78	78	69	57	152	85	80
MAS 10	70	69	58	53	99	60	66
VAS 1	75	24	45	133	158	81	70
VAS 2	82	86	107	171	150	102	98
YAS	150	153	165	144	63	67	80

Fig. 5 AQI levels for PM_{10} and $PM_{2.5}$ concentration for the period of assessment (June 23–29, 2020)

Owing to the fact that the COVID-19, by itself a respiratory disease and spread quickly among the community and SARS-CoV-2 would remain viable and infectious in aerosols for hours (van Doremalen et al. 2020), this study determined the possible interrelationship between PM and COVID-19 cases and deaths for Nuevo Leon. By July 12, 2020, Nuevo Leon reported 12,322 confirmed COVID-19 cases and 694 deaths (Government of Mexico: https://coronavirus.gob.mx/datos/). The correlation analysis was performed for the entire study period (June 15, 2020 to July 12, 2020) considering the longer residence of PM levels in the atmosphere after the dust event (Figs. 2 and 3). Table 3 summarizes the association between PM and COVID-19 cases and death for the study period. Our results provided preliminary evidence showing that there is a prominent association of PM with COVID-19 cases and deaths during the Saharan dust event but only that of PM_{10} is significant. The fine fraction of PM ($PM_{2.5}$) in our case did not present a substantial relation with COVID-19 cases and deaths (Table 3). Few studies reported similar results of less statistically significant association of $PM_{2.5}$ particles with total or specific mortality. For example, in Barcelona (Spain), the effects of short-term exposure to $PM_{2.5}$ were not significant during Saharan dust days (Perez et al. 2008). It was found, in Madrid and Italy, that the daily mean $PM_{2.5}$ concentrations displayed no statistically significant association with total mortality, circulatory, and respiratory causes on Saharan dust days (Jiménez et al. 2010; Tobías et al. 2011; Mallone et al. 2011). Under reduced anthropogenic activities during pandemic measures, PM_{10} have presented strong relationship with COVID-19 mortality rate in many parts of the world (Yao et al. 2020; Setti et al. 2020; Shakoor et al. 2020; Kutralam-Muniasamy et al. 2020). Similarly, in this study, PM_{10} is positively correlated with COVID-19 cases and deaths (r^2 = 0.53; 0.50), suggesting that exposure to such PM levels may affect COVID-19 prognosis, and thus, more comprehensive studies should be conducted on this subject.

Furthermore, to understand the human health risks associated with PM exposure during the study period, non-carcinogenic and carcinogenic risks in both children and adults via inhalation for Saharan dust and non-Saharan dust days were estimated by calculating the average CDI and HQ. The results are shown in Table 4. The CDI values for non-carcinogenic risk of PM in children were comparatively higher than adults during Saharan period. For instance, the maximum CDI values (μg kg^{-1} day^{-1}) of non-carcinogenic risk for PM_{10} and $PM_{2.5}$ in children were 4.4 and 0.38 (Tabasco), while for adults was only 2.48 (Tabasco) and 1.16 (Yucatan), respectively. It has been documented that children are highly vulnerable to environmental pollutants than adults for numerous reasons, including their relatively higher amount of air inhalation (the air intake per weight unit of a resting infant is twice that of an adult), and their immune system and lungs not being fully developed (Thabethe et al. 2014; Morakinyo et al. 2017). Contrarily, for carcinogenic risks, adults displayed maximum CDI values (μg kg^{-1} day^{-1}) of 0.85 (Tabasco) and 0.40 (Yucatan), and children exhibited 0.38 (Tabasco) and 0.18 (Yucatan) values for PM_{10} and $PM_{2.5}$. Among regions studied, Veracruz, Tabasco, and Yucatan during Saharan dust days presented nearly one-fold to two-fold increase in CDI values for both children and adults compared to non-Saharan dust days. Nuevo Leon also presented greater CDI values; however, it was in lesser extent compared to other regions. As mentioned earlier in this study, it could be attributed to the location of Nuevo Leon (northeast), which experienced lesser impact from Saharan dust event in comparison with other three regions (southeast) in Mexico. In case of HQ, both children and adults displayed values higher for $PM_{2.5}$ compared to PM_{10} (Table 4). It is important to mention here that the AQI values for $PM_{2.5}$ fell into the category of moderate-unhealthy for most Saharan dust days. Fine fraction of PM particles ($PM_{2.5}$) are more resident in the atmosphere and they more

Table 3 Correlation between daily confirmed COVID-19 cases and deaths and particulate matter in Nuevo Leon (Mexico)

	PM_{10}	$PM_{2.5}$	Total number of cases	Male cases	Female cases	Total number of deaths	Male deaths	Female deaths
PM_{10}	1.00							
$PM_{2.5}$	0.96*†‡	1.00						
Total number of cases	0.53*†	0.33	1.00					
Male cases	0.48*†	0.33	0.69*†‡	1.00				
Female cases	0.43*	0.27	0.75*†‡	0.96*†‡	1.00			
Total number of deaths	0.50*†	0.30	1.00*†‡	0.68*†‡	0.75*†‡	1.00		
Male deaths	0.40*	0.25	0.73*†‡	0.57*†‡	0.62*†‡	0.73*†‡	1.00	
Female deaths	0.45*	0.31	0.78*†‡	0.57*†‡	0.65*†‡	0.79*†‡	0.57*†‡	1.00

* $p < 0.05$

† 0.01

‡ 0.001

Table 4 Health risk assessment for PM exposure via inhalation during the June 2020 Saharan dust event in Mexico

Region	Period	Particulate matter	C (95% UCL) (μg/ m^{-3})	Exposure pathway	Children CDI values (μg kg^{-1} day^{-1})		Hazard quotient (HQ)		Adult CDI values (μg kg^{-1} day^{-1})		Hazard quotient (HQ)	
					Non-carcinogenic	Carcinogenic	HQ non-carcinogenic	HQ carcinogenic	Non-carcinogenic	Carcinogenic	HQ non-carcinogenic	HQ carcinogenic
Nuevo Leon	Non-Saharan	PM_{10}	50.87	Inhalation	2.12	0.18	0.08	0.01	1.19	0.41	0.08	0.03
	Saharan		67.58		2.81	0.24	0.11	0.01	1.59	0.54	0.11	0.04
	Non-Saharan	$PM_{2.5}$	19.72		0.82	0.07	0.32	0.03	0.46	0.16	0.32	0.11
	Saharan		32.94		1.37	0.12	0.54	0.05	0.77	0.27	0.54	0.19
Veracruz	Non-Saharan	PM_{10}	37.51	Inhalation	1.56	0.13	0.06	0.01	0.88	0.30	0.06	0.02
	Saharan		90.52		3.77	0.32	0.15	0.01	2.13	0.73	0.15	0.05
	Non-Saharan	$PM_{2.5}$	20.73		0.86	0.07	0.34	0.03	0.49	0.17	0.34	0.12
	Saharan		44.57		1.86	0.16	0.73	0.06	1.05	0.36	0.74	0.25
Tabasco	Non-Saharan	PM_{10}	48.61	Inhalation	2.02	0.17	0.08	0.01	1.14	0.39	0.08	0.03
	Saharan		105.56		4.40	0.38	0.17	0.02	2.48	0.85	0.17	0.06
Yucatan	Non-Saharan	$PM_{2.5}$	20.71	Inhalation	0.86	0.07	0.34	0.03	0.49	0.17	0.34	0.12
	Saharan		49.26		2.05	0.18	0.81	0.07	1.16	0.40	0.81	0.28

easily penetrate the respiratory system (Xing et al. 2016) which is a deep concern and demands in-depth investigation of health risks associated with $PM_{2.5}$. In general, HQ values were similar on non-Saharan days, whereas a potential increase in HQ values closer to 1 was seen in all the four studied regions during Saharan dust days. Therefore, our results from human health risk assessment about the levels and risks of PM could make useful contributions to government, environmental, and health professionals in taking good steps to protect and promote human health during this pandemic situation.

Limitations of the study

Although our study data and correlational analysis showed significant impacts of PM from Saharan dust in COVID-19, this short communication has a few limitations: (1) additional information on meteorological factors such as temperature, precipitation, and relative humidity were not examined, and future studies need to explore these factors for a comprehensive investigation. (2) PM samples from the June 2020 Saharan dust event were not analyzed by scanning electron microscopy with energy dispersive X-ray spectrometry and inductively coupled plasma mass spectrometry for morphological and chemical characterization. These results would have been greatly helpful but could not be accomplished as the COVID-19 pandemic hindered the analyses. Accordingly, the chemical composition of PM was not considered for assessing the health associated risks, and as a result, the exposure to the combination of the pollutants could not be determined. Thus, the toxic effects of these PM particles during the short-term dust episodes should be further investigated. (3) This study could not consider population density, mobility trends from the regions studied in the analysis. Future studies can investigate on these aspects to provide more useful insights into the spread of COVID-19. (4) The lack of studies for comparison demands future studies from other world regions that are similarly affected by the June 2020 Saharan dust event.

Concluding remarks

In summary, this study is the first to quantitatively assess the importance of the June 2020 Saharan dust event over PM concentrations in Mexico, as well to investigate its relationship with COVID-19 pandemic. As a consequence of the June 2020 Saharan dust event, we observed a sudden hike in both PM_{10} and $PM_{2.5}$ concentrations from northeastern and southeastern regions of Mexico. Also, in these regions, the PM levels were higher in many orders of magnitude compared to previous major Saharan dust episodes. Based on our results, it is confirmed that the Saharan dust transported from longer distances had a significant effect on the PM concentrations in Mexico. The correlational analysis revealed that the Saharan dust contributions to increased PM_{10} levels present positive association with the daily number of COVID-19-confirmed cases and deaths. In parallel, this study provided a valuable evaluation of the human health risks associated with exposure to PM via inhalation in both children and adults during the dust event. Overall, the main findings of this study underline that the Saharan dust events cannot be ignored during global health crisis. Taking together, this study could serve as a reference data for government authorities to design appropriate strategies for mitigating such unforeseen episodes to improve air quality.

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Availability of data and materials The datasets generated and/or analyzed during the current study are available in the Sistema Nacional de Información de la Calidad del Aire repository, operated by Instituto Nacional de Ecologia y Cambio Climatico, Government of Mexico (SINAICA, https://sinaica.inecc.gob.mx/index.php).

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Declarations

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