Atmospheric Pollution Research 14 (2023) 101860

Contents lists available at ScienceDirect

Atmospheric Pollution Research

journal homepage: www.elsevier.com/locate/apr

Spread COVID-19 during Godzilla African dust in June 2020 on the Colombian Caribbean region

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ARTICLE INFO

Keywords:
SARS−CoV−2
Saharan dust intrusion
Godzilla dust cloud
Pollution indicators
Long range particulate matter transport
Aerosol

ABSTRACT

Recent studies show that aerosols are highly linked to the spread of the COVID−19 pandemic. Furthermore, during this pandemic, the largest Saharan dust intrusion event has reached the Caribbean region in the last 20 years, called "Godzilla" African Dust or GAD. This study aims to analyze the correlation between the spread of COVID−19 and the GAD event in the main cities of the Colombian Caribbean region. The results showed a positive correlation between the spread of COVID−19 and the GAD event in most cities. Our findings could serve as input for the development of a strategy in the prevention of COVID−19 and other similar viral diseases during the Saharan dust intrusion events that reach the Caribbean region each year from Africa. Our results may help design strategies to prevent future outbreaks of COVID-19 and reduce the risk of future pandemics of similar viral diseases. Especially during the Saharan dust intrusion events that reach the Caribbean region each year.

1. Introduction

A great pandemic spread through almost all countries in 2020, called the Coronavirus disease 2019 (COVID-19) (WHO, 2020b). It is generated by the severe acute respiratory syndrome novel coronavirus 2 (SARS-CoV-2). This terrible pandemic has generated millions of infections and deaths around the world (WHO, 2020a). Since its initiation, many measures have been implemented to reduce the risk of COVID-19 contagion. These measures have been mainly related to limiting person-to-person contact, such as closing schools and universities, encouraging working from home, prohibiting mass public events, and closing borders (Franch-Pardo et al., 2020; He et al., 2020; Kwok et al., 2021; Li et al., 2020; Thu et al., 2020). The first case of COVID-19 in Colombia was reported on March 6, 2020 (INS, 2020). Since then, it has spread rapidly throughout the country. As of July 31, 2020, there were a total of 295,548 cases and 10,551 deaths due COVID-19 in Colombia (INS, 2021).

The transmission of SARS-CoV-2 virus has several routes. Wiersinga et al. (2020) affirm that SARS-CoV-2 is transmitted mainly by respiratory droplets during face-to face contact, i.e., speaking, shouting, coughing, or sneezing (Wiersinga et al., 2020). This spread due to the direct transmission from infected people is known human-to-human mechanism (Anand et al., 2021; Bontempi, 2020). Other researchers like Ram et al. (2021), and Bontempi (2020b) performed a classification of two different modes of person-to-person transmission of SARS-CoV-2 in COVID-19, namely, droplet transmission (>5–10 μm) and transmission by droplet nuclei (≤5 μm, also called aerosol transmission). Particularly aerosols play an essential role in COVID-19 infections, due to the fact to the coronavirus can remain viable and suspended in the air for hours (van Doremalen et al., 2020). Coccia (2020b) found that high aerosol contamination can interact with viral agents and increase the number of people infected with COVID-19. In addition, studies

Peer review under responsibility of Turkish National Committee for Air Pollution Research and Control.
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https://doi.org/10.1016/j.apr.2023.101860
Received 9 March 2023; Received in revised form 16 July 2023; Accepted 16 July 2023
Available online 24 July 2023

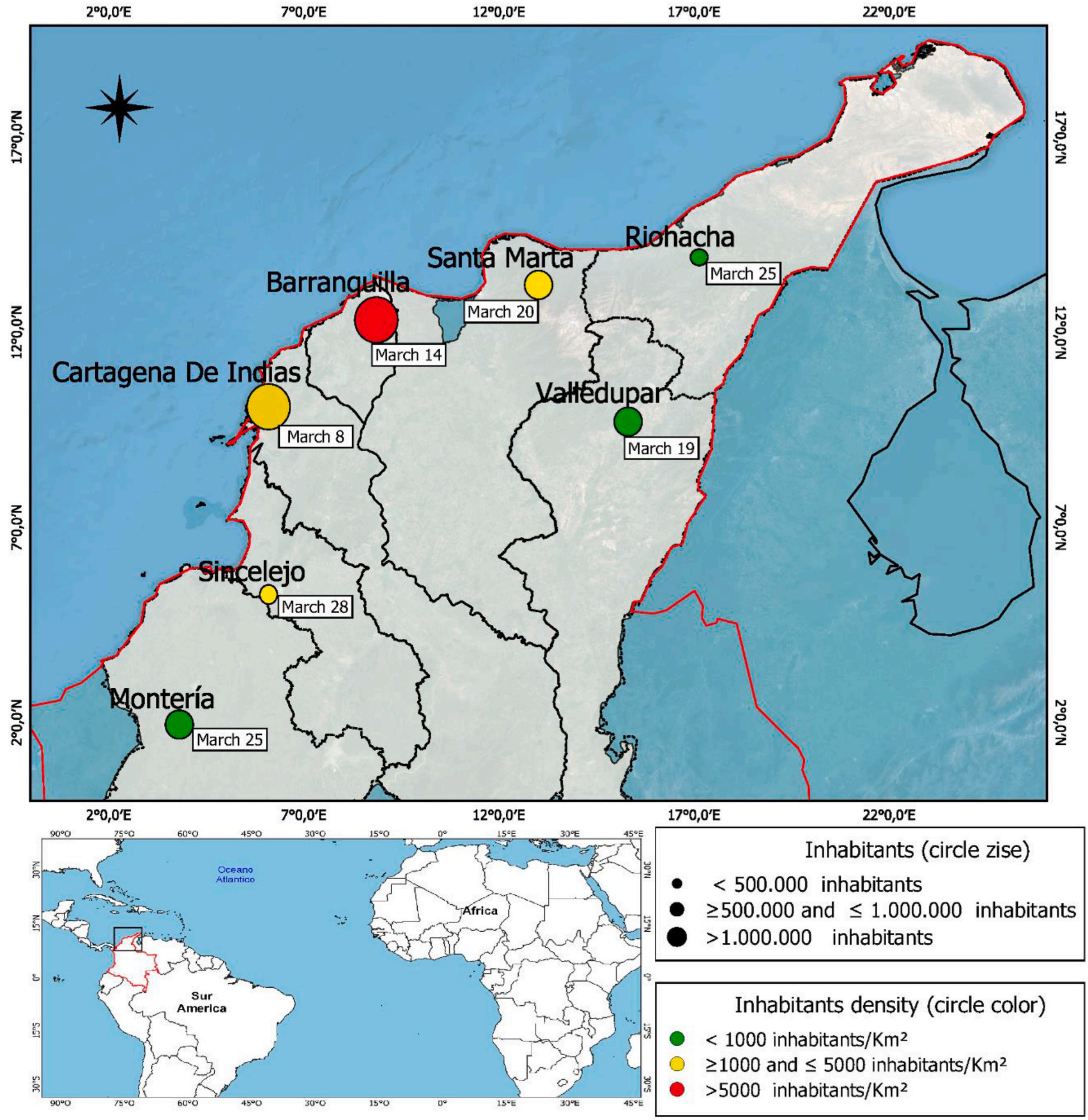

Fig. 1. Location of the main cities in the Colombian Caribbean region, the size of population (size of circle), density (color of circle) and the date of first case of COVID-19.

conducted in Singapore (Lorenzo et al., 2021), the United States (Wu et al., 2020a), and Pakistan (Ali et al., 2021) showed that a greater spread of COVID-19 can be associated with elevated aerosol levels such as $PM_{2.5}$. Thus, particulate matter aerosols appear to be functioning as vehicles to transport SARS-CoV-2 virus (Chakrabarty et al., 2021; Chen et al., 2020b; Fears et al., 2020; Jayaweera et al., 2020), until it is inhaled by people inhale it, and they become infected with COVID-19 (Ram et al., 2021).

Several studies have suggested transmission mechanisms of SARS-CoV-2 virus associated with meteorological conditions, which are known as environment-to-human transmission (Al Huraimel et al., 2020; Coccia, 2020a; Bontempi et al., 2021; Bontempi and Coccia, 2021). Tosepu et al. (2020) found that average temperature was significantly correlated with daily COVID-19 cases. Menebo (2020) showed that temperature and precipitation are associated with the incidence of daily COVID-19 cases in Oslo, Norway. At the same time, studies conducted by Bashir et al. (Bashir et al., 2020a, 2020b) suggest that climatic and fluctuating variables are correlated with the spread of COVID-19 in New York City and the state of California, both in the United States. Also, previous research showed the spread of COVID-19 was correlated statistically with climatic and pollutant variables throughout Latin America and the Caribbean (Auler et al., 2020;

Bolaño-Ortiz et al., 2020a, 2020b).

Other works have proposed that climatic and pollution variables affect the spread and deaths due to COVID-19 (Anand et al., 2021; Conticini et al., 2020; Lembo et al., 2021; Urrutia-Pereira et al., 2020). Some studies suggest that cities with high pollution levels and specific meteorological conditions can register further spread of the virus (Coccia, 2020a). So, this would be the third transmission mechanism, known as pollution-to-human way (Bontempi, 2020b). It suggests that coronavirus could join to dust and particulate matter (Zoran et al., 2020). Multiple studies reported that the main pollutants associated with COVID-19 spread, besides particulate matter, are carbon monoxide, nitrogen oxides, sulfur dioxide, and ozone (Bashir et al., 2020b; Lembo et al., 2021). Also, Lembo et al., 2021 concluded that the high pollution levels in 33 European countries were a potential risk for SARS-CoV-2 related death, and $PM_{2.5}$ and nitrogen oxides with stronger correlations for both positive cases and deaths. Air pollution is one of the causes of prolonged inflammation; prolonged exposure to atmospheric pollution sources leads to chronic inflammation. This explains the high prevalence and mortality of SARS-CoV-2 among the populations that live in highly polluted areas (Conticini et al., 2020). Besides, the Centre for Research on Energy and Clean Air (CREA) final report concluded that high air pollution affects the body's defenses, increasing the potential of contract viral diseases such as COVID-19 (Myllyvirta and Thieriot, 2020). Vergadi et al. (2022) conducted a review of scientific literature related to desert dust and disease. They found that desert dust outbreaks are vehicles for a significant number of pathogenic or opportunistic microorganisms. In addition, atmospheric dust is also associated with an increase in diseases, such as meningococcal meningitis, ambient influenza, avian influenza, COVID-19, etc. (Chen et al., 2010; Núñez-Delgado et al., 2021; Rohrer et al., 2020; Tobías et al., 2011). Broomandi et al. (2022) found a positive correlation between a dust intrusion from the Middle East and the daily increase of COVID-19 infections in southwest Iran. While other studies found that high COVID-19 mortality may be associated with dust events in rural municipalities in northwestern Mexico (Páez-Osuna et al., 2022).

Saharan dust intrusions are air masses that drag eroding dust from the Sahara Desert in North Africa. It is usually generated in the months of boreal summer (from June to July) (Russo et al., 2020). In addition, it usually crosses the Atlantic Ocean until it reaches the Caribbean region and the north of South America (Sakhamuri and Cummings, 2019). However, the number of aerosols transported is a source of nutrients in the Amazon rainforest (Yu et al., 2015). It also generates high levels of particulate matter that can affect the health of the exposed population (Ramírez-Romero et al., 2021). Méndez et al. (2018) studied a Saharan dust intrusion event into the Colombian atmosphere in 2014. Their results confirm that the high pollution episode was due to the intrusion of Saharan dust into the ambient air of Colombia, with its Caribbean region being the most affected. During the COVID-19 pandemic in 2020, there were several events of Saharian dust intrusion that reached the Colombian Caribbean (IDEAM, 2020). In fact, the largest Saharian dust intrusion event recorded in the last 20 years (called "Godzilla" African Dust) was generated in this period (Mayol-Bracero et al., 2020; Warren Cornwall, 2020).

The main objective of our research was to estimate the correlation between the inhalable and respirable dust, expressed as $PM_{2.5\text{-dust}}$, during the Saharan intrusion, and the reported daily cases of COVID-19, in the main cities in the Colombian Caribbean region (from June 1 to July 31, 2020). In addition, we analyze the interaction between climatic variables, the density of inhabitants, and daily cases of COVID-19. This study explains how meteorological and pollution variables controlled the spread of COVID-19 in the Colombian Caribbean, during the Saharan dust intrusion. Results provide results to design strategies to prevent future outbreaks of COVID-19 and reduce the risk of future pandemics of similar viral diseases (Coccia, 2020b). Especially during events of Saharan dust intrusion that reach the Caribbean region each year (Colarco et al., 2003; Euphrasie-Clotilde et al., 2020; Petit et al., 2005).

2. Materials and methods

2.1. Sample and data

We have studied the largest provincial capital cities, namely, Riohacha, Santa Marta, Valledupar, Barranquilla, Cartagena, Sincelejo, and Montería, located in the Colombian Caribbean. This is the northernmost region of Colombia and South America (See Fig. 1). The continental area of this region covers 130,955 km^2 (IGAC- National Geographical Institute, 2021). Its population in 2021 according to projections of the 2018 population census is 11,550,067 inhabitants (DANE, 2021). Also, these cities have the largest population in the Colombian Caribbean, and they had the daily data of COVID-19 infections available.

2.2. Measures of variables

In accordance with the objective, in the present investigation information was collected on cases of COVID-19, contamination by particulate matter, meteorology, and population density of each of the cities under study. Daily COVID-19 data reported were obtained from the web platform of the national government (https://www.datos.gov.co/Salud-y-Protecci-n-Social/Casos-positivos-de-COVID-19-en-Colombia/gt2j-8ykr/data). In the case of PM, and due to PM_{10} and $PM_{2.5}$ not being available in the cities analyzed, we used PM_{10} and $PM_{2.5}$ data from The Copernicus Atmosphere Monitoring Service (CAMS) (Copernicus Earth, 2021). It is worth clarifying that transmission by droplet nuclei (dried nano-droplet nuclei) or aerosol-laden virus, both with diameter ≤ 5 μm. This is synonymously and interchangeably referred to as aerosol transmissions in literature (Ram et al., 2021). Hence, we refer to this as aerosols or aerosol transmission in this work. In addition, we use particles that have diameters less than 2.5 μm ($PM_{2.5}$). The $PM_{2.5}$ air quality criterion is suitable for considering aerosols with a diameter of ≤ 5 μm. It used $PM_{2.5\text{-dust}}$ as a fraction only from dust retrieved from The Modern−Era Retrospective analysis for Research and Applications, Version 2 (MERRA−2) (Buchard et al., 2017). These data have proven to be adequate for studying air quality and adequately represent the air quality variables such as $PM_{2.5}$ (GMAO, 2015; Navinya et al., 2020). We also analyzed the trajectory of the CALIPSO satellite (NASA, 2020) when it crossed the study area, in order to check the presence of dust in the vertical profile of the study area during a Saharan intrusion event (see Figure A1). In addition, we analyze some meteorological variables such as average temperature, relative humidity, absolute humidity, rainfall, and wind speed. In all cases, data corresponded to the period from June 1 to July 31, 2020, in these weeks there were several events of intrusion of Saharan dust. And we made emphasized the subperiod from June 22 to June 25, 2020, where is the peak value of GAD.

2.3. Models and data analysis procedure

Spearman's rank correlation test was used to examine the correlation between daily COVID-19 and $PM_{2.5}$ dust fractions ($PM_{2.5-\text{dust}}$). Previous studies used the Spearman rank correlation test, which proved suitable for correlation studies of COVID-19 cases and pollution/climatic variables (Bashir et al., 2020b; Bolaño-Ortiz et al., 2020a, 2020b; Menebo, 2020; Tosepu et al., 2020). In addition, up to 14 days of delay were considered due to the incubation times of SARS-CoV-2 (Bontempi, 2020; Chen et al., 2020a; Jüni et al., 2020). On the other hand, a correlation is performed using the Spearman rank correlation test with daily average data of the $PM_{2.5\text{-dust}}$ concentration and the summed contagions of all the cities for the same days, which allows us to have a regional estimate of the GAD effect on the COVID-19 contagion rate. We also analyzed the correlation between climatic variables and new cases of COVID-19 (as shown in). Additionally, the one-way ANOVA test (Balding, 2019; Tabachnick and Fidell, 2007) was used to evaluate the variations between the correlation coefficients (shown in Table 2 and Table A1) during the study period. Then the Games-Howell (Bird, 2011; Hand and

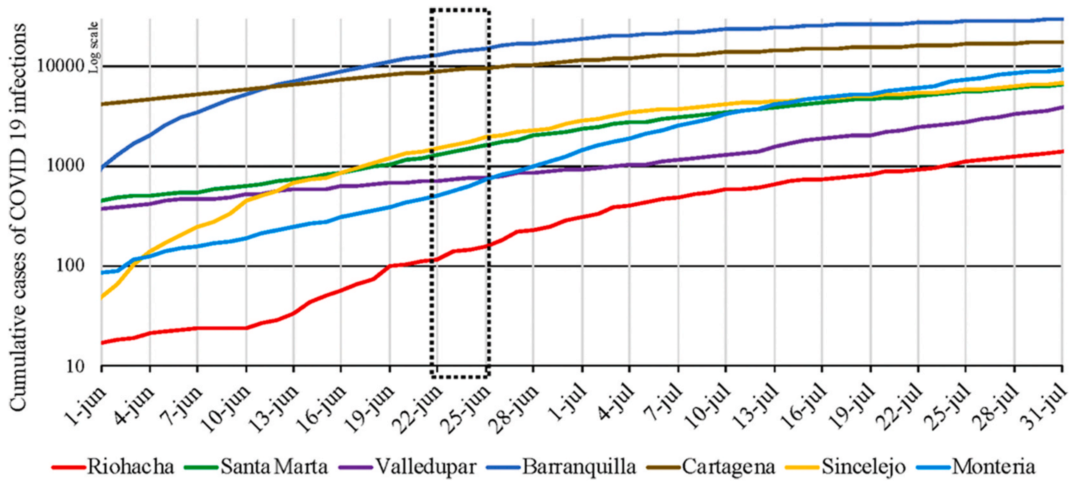

Fig. 2. Increase in COVID−19 cases in the cities studied during June–July 2020 in the Caribbean of Colombia.

Table 1
Descriptive statistics variables for climatic and air quality indicators during June–July 2020 in the Colombian cities were analyzed.

Cities analyzed	Descriptive statistics	Climatic indicators [a]					Air Quality		
		Temperature Average (°C)	Humidity relative (%)	Absolute humidity (gr m^{-3})	Rainfall (mm)	Wind Speed (m s^{-1})	PM_{10} [b] (μg m^{-3})	$PM_{2.5}$ [b] (μg m^{-3})	$PM_{2.5-dust}$ [c] (μg m^{-3})
Riohacha	Minimum	27.00	45.30	0.013	0.00	2.17	7.00	4.00	3.79
	Mean	31.97	59.73	0.019	0.22	4.10	20.23	11.93	10.87
	Maximum	34.67	77.00	0.025	5.97	5.40	74.00	49.00	48.20
Santa Marta	Minimum	27.90	58.63	0.021	0.00	2.00	16.00	10.00	2.07
	Mean	31.35	71.53	0.023	0.27	3.21	36.75	22.80	11.17
	Maximum	34.56	87.89	0.025	12.95	4.90	66.00	44.00	39.66
Valledupar	Minimum	26.50	52.50	0.017	0.00	1.67	24.00	17.00	1.66
	Mean	29.59	72.15	0.021	4.38	3.07	42.61	29.34	10.61
	Maximum	31.90	87.00	0.027	93.97	5.77	79.00	56.00	37.57
Barranquilla	Minimum	26.17	73.20	0.021	0.00	1.40	21.00	11.00	2.23
	Mean	28.27	82.44	0.023	0.00	2.93	74.66	51.43	12.58
	Maximum	29.78	91.83	0.024	0.00	4.60	133.00	93.00	44.80
Cartagena	Minimum	26.39	70.51	0.021	0.00	2.40	9.00	6.00	0.89
	Mean	29.96	78.46	0.024	3.12	3.31	34.33	20.97	12.10
	Maximum	31.67	89.15	0.026	101.60	4.90	71.00	41.00	43.56
Sincelejo	Minimum	24.90	49.00	0.011	0.00	1.05	9.00	6.00	0.87
	Mean	28.97	61.22	0.017	3.93	1.78	28.05	19.05	10.57
	Maximum	31.40	90.00	0.024	56.50	9.54	79.00	50.00	40.60
Montería	Minimum	24.72	65.16	0.020	0.00	1.00	5.00	3.00	0.89
	Mean	29.03	77.32	0.022	3.80	1.98	26.10	18.33	9.93
	Maximum	32.22	91.13	0.024	56.90	2.80	78.00	50.00	35.02

[a] Weather database used were obtained from the hydrology and meteorology data management system of Colombia (DHIME− IDEAM: http://dhime.ideam.gov.co/webgis/home/). Absolute humidity was estimated using the Clausius Clapeyron equation (Iribarne and Godson, 1973).
[b] PM_{10} and PM2.5 surface concentration estimates from Earth (CAMS/Copernicus/European Commission + ECMWF) (Copernicus Earth, 2021).
[c] $PM_{2.5}$ Dust Estimation from Reanalysis from MERRA−2 (Buchard et al., 2017; Randles et al., 2017).

Taylor, 1987), a nonparametric post hoc analysis approach for performing multiple comparisons for two or more sample populations, was used. In this manner, it was possible to statistically separate the variables into homogeneous groups and confirm the importance between variables.

3. Results and discussion

Fig. 2 shows the cumulative increase in COVID−19 cases in the Colombian cities analyzed during the period under study. Data show that since June 1st of 2020, the cases have constantly increased, corresponding with the first of four COVID-19 waves in Colombia. As of July 31, 2020, the cities with the highest number of new cases registered were Barranquilla (27,684), Cartagena (12,428) and Montería (7,644). Table 1 shows the maximum, minimum, and means for the meteorological and air quality indicators. Maximum temperature was recorded in Santa Marta, while the minimum temperature in Montería. The highest relative humidity recorded was in Barranquilla and the lowest in Riohacha. The highest precipitation and wind speed were observed in Cartagena and Montería, respectively. Air quality data showed that maximum values were recorded that were above the Colombian air quality standard, PM_{10}: 75 μg m^{-3} and $PM_{2.5}$: 37 μg m^{-3} (MADT, 2017). In particular, the fraction of $PM_{2.5}$ from dust exceeded this standard for the maximum values in all the cities analyzed.

Fig. 3 shows the temporal variations of the $PM_{2.5}$ concentration due to dust. Through the study period (from June 1 to July 31, 2020), there were three peaks of dust concentrations caused by Saharan dust intrusion. In fact, the highest concentrations were observed during the "Godzilla" African dust event from June 22 to 25, 2020 (see Table 1). Furthermore, Fig. 4 shows how the "Godzilla" African dust event expands, from Africa to the Caribbean reaching all the cities of the Colombian Caribbean analyzed.

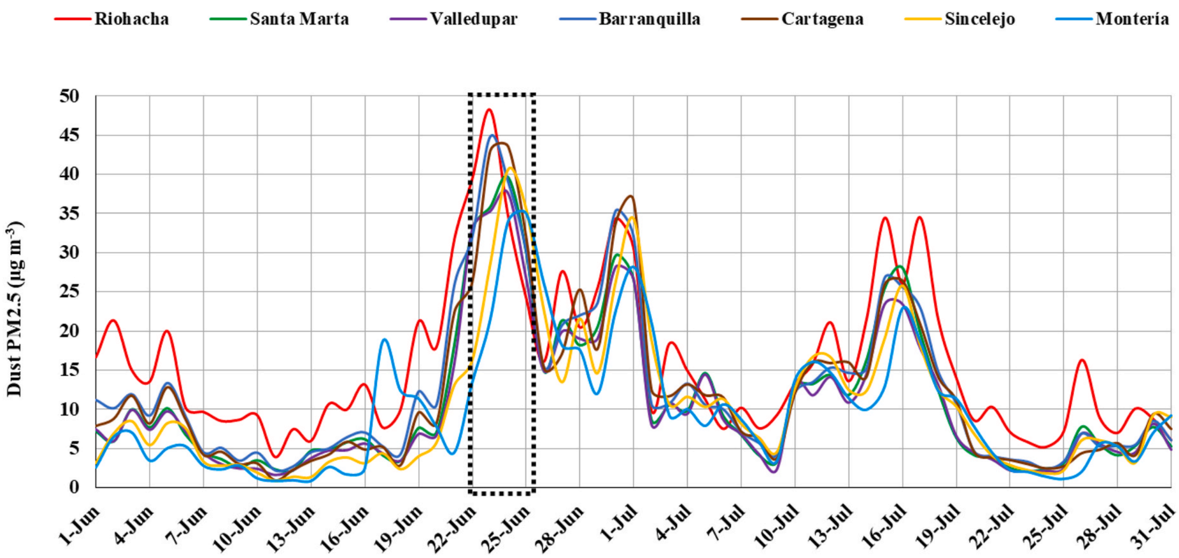

Fig. 3. Temporal variation of the surface dust fraction as $PM_{2.5}$ during June–July 2020 from MERRA−2 for the analyzed cities. The red dotted line indicates the highest concentration during the "Godzilla" African dust event (June 22–25, 2020).

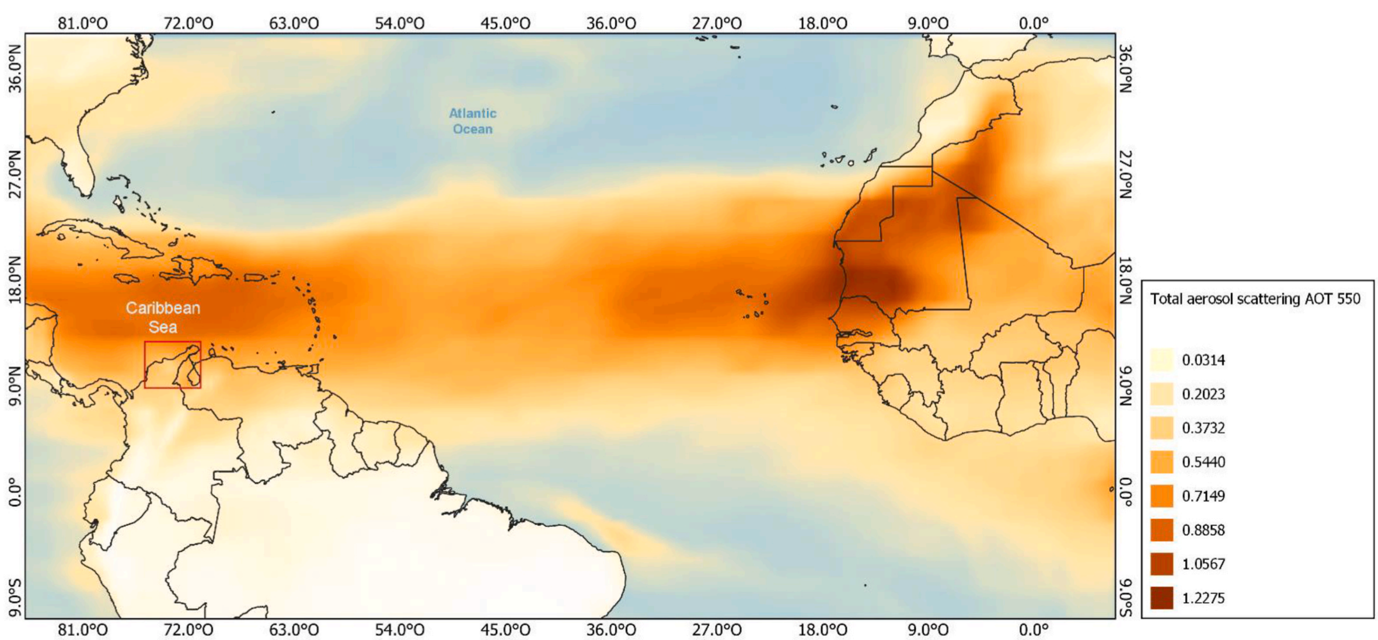

Fig. 4. Time average map of total aerosol scattering AOT 550 mm (June 22–25, 2020) from MERRA−2. Note the Saharan Dust Intrusions that travel from North Africa, crosses the Atlantic Ocean, and reaches the Caribbean region in America. Red box indicates the location of the Colombian Caribbean region where the analyzed cities are located (as shown in Fig. 1).

Table 2 shows the highest significant positive correlations in Montería, Sincelejo, Cartagena, Santa Marta, and Barranquilla. While the lowest correlations are observed in Riohacha and Valledupar. Regarding the days of delay to consider the incubation period of the SARS−CoV−2 virus (up to 14 days prior), the highest correlations were observed in Montería (lag day −14), Santa Marta (lag day −14) and Sincelejo (lag day −8). Barranquilla showed its highest significant correlation on day 0, and one of the highest concentrations of $PM_{2.5-dust}$ (mean: 12.58 μg m^{-3}; maximum: 44.80 μg m^{-3}). Overall, Fig. 5 showed that considering data from all cities and same days analyzed, $PM_{2.5\text{-dust}}$ was correlated up to 69% with the increase in the rate of COVID−19 infections in the Colombian Caribbean. This figure also showed that for each average increase of 5 μg m^{-3} dust such as $PM_{2.5}$, the infection rate increased in 8 cases/100,000 inhabitants in all the cities analyzed. The effect of dust on COVID−19 infections could be driven by population density. For example, Sincelejo was the second city with the highest positive correlation, and a high population density (1014.66 pop km^{-2}). Instead, Riohacha presented the lowest correlation, and the lowest population density of 33.44 pop km^{-2}.

Previous studies showed the high contamination in the ambient air from an atypical intrusion of Sahara dust in Colombia, mainly affecting its Caribbean region (Méndez et al., 2018). Also, the review by Ram et al. (2021) shows the droplets with a diameter ≤5 μm are mainly associated with airborne/aerosol transmission in COVID-19. These droplet nuclei generally result from the evaporation of a larger droplet containing SARS-CoV-2 or from the surface binding of the virus with particulate matter (PM), i.e., virus-laden PM. They also clarify that it should be noted that there is no "cut-off size" between the droplet nuclei and the

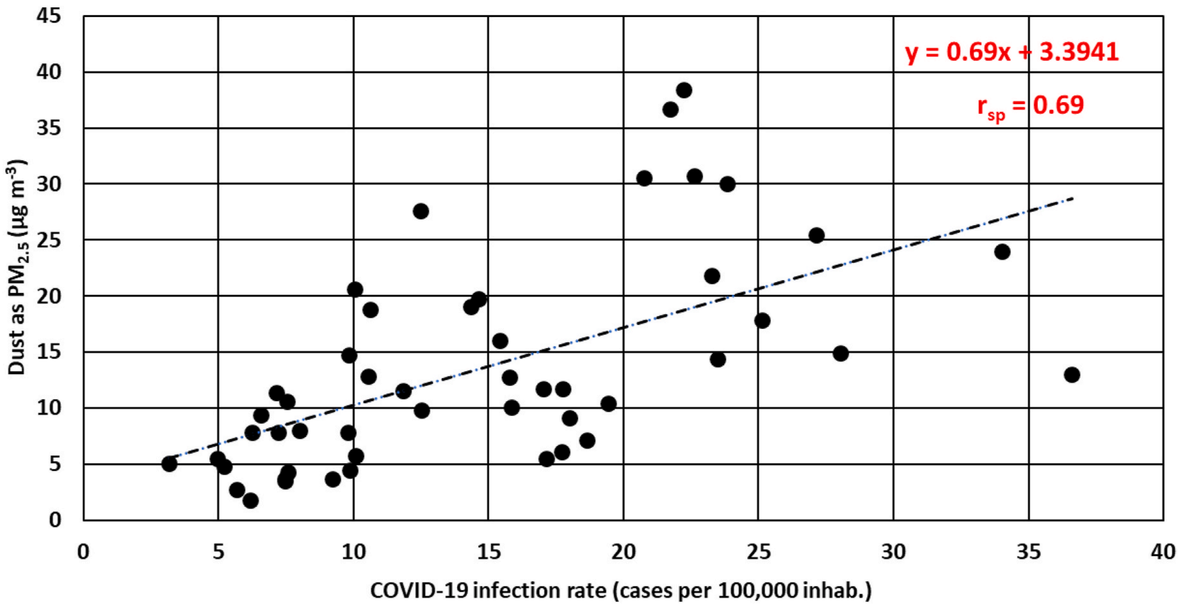

Fig. 5. Mean values of $PM_{2.5\text{-dust}}$ and COVID−19 infections rate of all cities analyzed in the Colombian Caribbean. Spearman's correlation coefficient in red (*p<0.001*).

smaller droplets floating in the air, however, both are ≤5 μm in size. In this way, Lorenzo et al. (2021) found for every 1 μg m^{-3} increase in $PM_{2.5}$ there was a 22.6% higher number of daily confirmed cases of COVID-19 in Singapore. While studies conducted by Ali et al. (2021) showed a higher rate of COVID-19 spread in major cities with poor air quality conditions in Pakistan. While our results and during the GAD episode the results show a mean of 6% of increasing, where the cities with annual low concentrations of PM, show a high percentage of increase (Monteria and Riohacha), which is evidence of GAD influence ($PM_{2.5\text{-dust}}$ increasing concentration) in the new cases of COVID-19. Likewise, the results are high compared with a study in London (Ayoub Meo et al., 2021), but low compared with those in Italy (Zoran et al., 2020), France (Tchicaya et al., 2021), and Poland (Czwojdzińska et al., 2021).

A study carried out in 10 cities in Latin America and the Caribbean showed that $PM_{2.5}$ was significantly correlated with the spread of COVID-19 (Bolaño-Ortiz et al., 2020a). Local studies were carried out in New York City, the United States (Bashir et al., 2020b) Buenos Aires, Argentina (Bolaño-Ortiz et al., 2020b), Italy (Kotsiou et al., 2021; Zoran et al., 2020), Germany (Bilal et al., 2020) also showed an impact of air quality on the spread of COVID-19. Studies show a delay in the $PM_{2.5}$ exposition and new cases of COVID-19. In New York, a lag between nine to 13 days shows a strong correlation (Adhikari and Yin, 2021), similar to South Korea with six to seven delay days (Hoang et al., 2021), and Chine with three and 12 delay days (Liu et al., 2023). Results consistent with our finding show significance from six days of delay. In the case of delayed exposure $PM_{2.5}$ in COVID-19 in Europe is only related to the death rate (Shao et al., 2022; Tchicaya et al., 2021). These novel results should be investigated in Colombia, Only, long-term exposition to $PM_{2.5}$ and mortality risk by COVID-19 was investigated, and the results show did not have an influence (Rodriguez-Villamizar et al., 2021). On the other hand, as remarkable aspect the studies used in the discussion correspond to anthropogenic sources, while the finding of this investigation associates the increase of $PM_{2.5}$ concentration from natural sources with the development of new cases of COVID-19.

Our results show that the maximum concentration of $PM_{2.5\text{-dust}}$ was above 35 μg m^{-3} in all cities (see Table 2). In addition, the vertical profile of aerosols observed through a CALIPSO satellite image confirms the presence of Saharan dust intrusion at the surface level (0–4000 m.a.s.l.), and therefore, breathable by the population of the study area (see Figure A1). Other studies showed that fine particle peaks can modulate the spread and virulence of COVID-19 (Ram et al., 2021; Rohrer et al., 2020). Additionally, aerosols in the open air could be possible routes of spread of COVID-19 (Fattorini and Regoli, 2020; Wang et al., 2020; Wu et al., 2020b; Zhu et al., 2020b; Zoran et al., 2020). Being thus consistent with previous investigations conducted in Iran (Ahmadi et al., 2020), India (Bhadra et al., 2020), Japan (Rashed et al., 2020), England (Tammes, 2020), and the United States (Sy et al., 2020). In this sense, our work shows that during the Saharan dust intrusion events, people living in cities with high population density in the Colombian Caribbean region, would be exposed to droplet nuclei or dust particles ($PM_{2.5\text{-dust}}$) that carry the SARS-CoV-2 virus (Guzman, 2020; Ram et al., 2021; Tang et al., 2020), and people have a higher probability of coming into close contact with others, consequently, COVID-19 is expected to spread rapidly in dense cities (Bhadra et al., 2020). The Copernicus $PM_{2.5}$ concentration was used in Colombia (Ballesteros-González et al., 2020; Bolaño-Ortiz et al., 2020; Y. Camargo-Caicedo et al., 2021; Mendez-Espinosa et al., 2020; Rodriguez-Villamizar et al., 2021). Their reliability needs to be investigated deeply, however, there is sufficient scientific literature to allow infer the certainty of this data in the present research. Some works showed the association between dust and diseases. Lauer et al. (2020) showed that exposure to dust increases the risk of valley fever disease in California, USA. Although other studies showed that there is no consistent link between dust storms and valley fever (Comrie, 2021). Kellogg et al. (2004) found 19 genera of bacteria and 3 genera of fungi isolated from air samples in a known source region of dust storms and over which large dust storms travel in Mali. Chen et al. (2010) found a significantly higher concentration of Avian Influenza Virus during dust storm days in Taiwan. While Tobías et al. (2011) showed the effects of Saharan dust intrusions on the risk of meningococcal meningitis in Barcelona city (Spain).

Moreover, a correlation was found between daily cases and climatic variables, namely, wind speed (Monteria: up to 0.43, $p < 0.001$; Valledupar: up to −0.30, $p<0.05$; Riohacha: 0.22, $p<0.01$), rainfall (Sincelejo: up to −0.32, $p<0.05$), average temperature (Cartagena; up to 0.38, $p<0.001$; Santa Marta: up to −0.36, $p<0.001$), relative humidity (Barranquilla: up to −0.31, $p<0.05$; Sincelejo: up to 0.27, $p<0.05$), and absolute humidity (Santa Marta: up to 0.28, $p<0.05$) as shown in Appendix A, Table A1. These results are consistent with previous studies conducted in Turkey and Italy, that showed that wind speed influenced

Table 2
Empirical results of the Spearman rank correlation tests between new cases and $PM_{2.5-dust}$ concentrations on every city analyzed. The *, ** and *** indicate stands for 10%, 5%, and 1% level of significance, respectively.

Lag day	Riohacha	Santa Marta	Valledupar	Barranquilla	Cartagena	Sincelejo	Montería
−14	0.12	**0.22***	0.04	0.01	0.08	−0.08	**0.62*****
−13	0.06	**0.26***	0.06	−0.01	0.10	−0.02	**0.59*****
−12	0.05	0.21	0.09	0.01	0.13	−0.03	**0.52*****
−11	0.09	**0.25***	0.11	0.02	0.18	0.06	**0.47*****
−10	0.14	0.19	0.08	0.06	0.14	0.17	**0.40*****
−9	0.12	0.19	0.04	0.04	0.15	0.18	**0.39*****
−8	0.07	0.15	0.04	0.00	0.05	**0.23***	**0.37*****
−7	0.01	0.13	−0.01	−0.01	0.05	**0.22***	**0.33****
−6	−0.10	0.10	−0.03	−0.02	0.03	0.17	**0.26****
−5	−0.10	0.13	−0.06	0.04	0.08	**0.23***	**0.23***
−4	−0.13	0.10	−0.06	0.10	0.06	**0.27****	0.20
−3	−0.06	0.17	−0.05	0.13	0.18	**0.30****	0.18
−2	−0.09	−0.09	−0.07	0.14	0.19	**0.26****	0.16
−1	−0.17	−0.09	−0.10	0.17	**0.24***	**0.30****	0.18
0	−0.09	−0.09	−0.05	**0.24***	**0.29****	**0.26****	0.19

the spread of COVID-19 (Coccia, 2020a; Coşkun et al., 2021; Rendana, 2020). In addition, work conducted by Coccia (2021a) suggests that atmospheric stability with low wind speed reduces the dispersion of gases and atmospheric particulate pollution, which can act as carriers of SARS-CoV-2 in the air to sustain the spread of COVID-19 in the environment, thus generating public health problems. Thus, our findings could indicate that the wind speed increased the dispersion of the dust that carried the SARS-CoV-2 virus, and therefore an increase in COVID-19 infections. These results also coincide with previous work that showed correlation between COVID-19 cases with temperature (Tosepu et al., 2020), relative humidity (Bolaño-Ortiz et al., 2020b), absolute humidity (Jüni et al., 2020; Zhu et al., 2020a), rainfall (Bolaño-Ortiz et al., 2020a; Menebo, 2020) and wind speed (Coccia, 2020c). These climatic variables appear to be modulating the effect of dust on the spread of COVID-19. Primarily, we observe that Montería and Sincelejo, the two cities with the highest positive correlation of dust vs. COVID-19 (Table 2), were those with the significant positive correlation of wind speed vs COVID-19 (Table A1). In fact, the results obtained with the one-way ANOVA test detected a significant interaction between the estimated Spearman coefficients, which means that the variations of the correlation between the new cases and some of the analyzed variables (air quality and climatic indicators) were statistically different ($p < 0.001$) during the study period. Therefore, the Games Howell test confirmed that the correlation between new cases and $PM_{2.5-dust}$ was the most important, given that its variation does not depend on the variations of all climatic variables correlated with the daily infections rate analyzed (as shown in Table A2). While the correlation between new cases and Rainfall was the second most important because it was independent of the correlations between daily COVID-19 infection with Dust, Average temperature, and Absolute humidity, respectively.

Our study shows that exposure to air pollution due to high concentrations of $PM_{2.5}$, specially during Saharan intrusion events in the Colombian Caribbean region. Showed a direct correlation with an increased case of COVID-19. Also shown by other research, that lockdown shows an improvement in air quality and consequently helps reduce the rate of COVID-19 infections (Bolaño-Ortiz et al., 2020b; Camargo-Caicedo et al., 2021). Then, vulnerability-based approaches for human mobility reduction strategies (Akan and Coccia, 2022; Benati and Coccia, 2022; Bolaño-Ortiz et al., 2020b, 2020c; Coccia, 2021a, 2021b, 2022, 2023; Pratap et al., 2021; Sasidharan et al., 2020), they could help develop strategies to restrict human mobility during future Saharan intrusion events to prevent future outbreaks of COVID-19 and similar diseases.

4. Conclusions and outlook

Overall, this study has provided evidence of the relationship between the increase in COVID-19 infection rate and the GAD dust intrusion event through Colombian Caribbean mainland. Our data showed that Saharan intrusions, and mainly the GAD, were an important factor in determining the incidence rate of COVID-19 in the main cities of the Colombian Caribbean. Our study showed that increased dust was significantly correlated with an increased number of new COVID-19 cases. In general, our findings accentuate the importance that during Saharan intrusion events, air pollution in the studied cities can serve as one of the indicators to assess vulnerability to COVID-19. We have also shown that dust ($PM_{2.5\text{-}dust}$) was the most crucial variable in the spread of COVID-19 in the cities analyzed. In line with the aforementioned, we suggest strategies like avoiding leaving home and wearing face masks outdoors during these events. Also, restrict human mobility during Saharan dust intrusion events to prevent future outbreaks of similar diseases. Finally, this work identified manifold limitations, such as the lack of meteorological and air quality data in all the cities analyzed that would allow for adequate long data to build multivariate models that could help to more accurately assess the links between air pollution, climatic variables and respiratory disease contagion. In addition, our results suggest that the implementation of an early warning system is essential to increase public awareness and help minimize loss of life and property from potentially devastating dust storms (Wu et al., 2021).

Credit author statement

Tomás R. Bolaño-Ortiz: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft, Review, Visualization. Jelaine I. Constante-Ballestas: Data Curation, Validation, Formal analysis, Visualization. S. Enrique Puliafito: Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft, Review, Visualization. Andrés M. Vélez-Pereira: Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft, Review, Visualization. Fredy A. Tovar-Bernal: Investigation, Review, Visualization. Yiniva Camargo-Caicedo: Conceptualization, Methodology, Investigation, Writing - Original Draft, Project administration, Review, Funding acquisition.

Declaration of competing interest

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

Acknowledgments

We would like to thank the MERRA-2 and CALIPSO scientific teams, and their associated personnel for producing the data used in this

research effort.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apr.2023.101860.

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