Abstract

Saharan dust storms are major events that occur normally in the summer and affect the air quality in various regions of the world. In particular, Saharan regions in Morocco and Mauritania actively contribute to dust storms. The Saharan outbreak that took place between 14 and 19 of June 2020 was one of the most severe Saharan dust storms in recent years. This paper investigates the PM10 emissions and concentrations during the 4 days of the dust storm in the region of Western Sahara of Morocco and Mauritania and the transport of the PM10 from the area of study to the Caribbean Sea and the Gulf of Mexico using Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) software with PM10 emission model and cluster analysis. We also analyse the effect of the transported PM10 particles on the concentration level in the Southern parts of the United States and the Martinique islands. The results showed that the average PM10 concentration below the altitude of 100 m during the dust storm was higher than 100 $\mu$g/m$^3$ in most of the regions such as Dakhla in Morocco, Nouakchott, Adrar and Tiris Zemmour in Mauritania. This is confirmed by Aerosol Optical Depth (AOD) values between 0.7 and 1 retrieved by MODIS-Aqua for those areas. Furthermore, PM10 particles transported across the Atlantic Ocean affected the concentrations observed in the Caribbean Basin, where hourly PM10 reached 372 $\mu$g/m$^3$ and the dust top layer was found between 4 and 4.5 km above ground level. In addition, HYSPLIT cluster analysis results revealed several PM10 particle source areas in Western Sahara such as Bir Anzerane in Morocco, Nouakchott and Tichit in Mauritania that contributed to the increase of PM10 concentrations to an Unhealthy level in the Texas and Florida States in the United States.

KEYWORDS

correlation analysis, HYSPLIT, Mauritania, Morocco, PM10, Saharan dust storm

1 | INTRODUCTION

Dust storms are significant sources of suspended dust. Globally, arid and semiarid regions are responsible for the majority of dust emissions. The dust belt (Figure 1) consists of primary dust source regions that stretch from the west coast of North Africa, the Middle East, central and south Asia to China (Ashrafi et al., 2014). Sahara is
the major and most active dust source in the world. The approximate emission ranges from 400 to 2200 Tg yr\(^{-1}\) (Huneeus et al., 2011).

Saharan dust contains natural mineral particles, which by interaction with anthropogenic pollutants can exacerbate secondary aerosol formation (Ashrafi et al., 2014). However, the transported Saharan dust particle tends to be beneficial for the Amazon forests and the equatorial Atlantic Ocean by acting as fertiliser, due to the Iron (Fe) and Phosphorus (P) micronutrients content of those particles (Bristow et al., 2010). Dust particles in the atmosphere can affect climate and weather directly and indirectly. Directly through scattering and absorption, dust aerosols affect the shortwave and longwave radiative flux. Indirectly by influencing cloud microphysical processes. Dust particles that have been chemically or physically processed in the atmosphere can act as cloud condensation nuclei, impacting the radiative budget via aspects such as cloud albedo, precipitation efficiency, cloud lifespan and cloud height. Furthermore, mineral dust particles are the major natural ice-nucleating aerosol, causing convective clouds to glaciate quickly (Knippertz & Todd, 2012). Prospero et al. (2001) and Ginoux et al. (2012) found that around half of the African dust mass corresponds to PM2.5 (fine respirable particles with diameters of 2.5 μm or less) and more than 90% to PM10 (particles with diameters of 10 μm or less). Particulate matter (PM) is a mixture of small particles and liquid droplets such as sulphate, nitrate, ammonium, heavy metals, elemental and black carbon and sodium chloride. PM is also a harmful pollutant and chronic exposure to it has been shown to increase the risk of developing cardiovascular and lung diseases and heart attacks, with prolonged exposure to high concentrations leading to premature death (Kim et al., 2015).

Saharan dust particles can impact air quality in many parts of the world like the western and eastern Mediterranean, Europe, the Caribbean basin, United States and South America. Many studies used different approaches to determine and describe dust source zones, such as, remote sensing, surface dust observations, trajectory analyses and mineral tracers (Escudero et al., 2006; Kaskaoutis et al., 2019; Prospero & Mayol-Bracero, 2013; Weinzierl et al., 2017).

In this article, we carry out an investigation of the dust storm event that occurred in the period between 14 and 19 June 2020 using the Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) software dust storm model, focusing on PM10 emission from the Western Sahara regions in Morocco and Mauritania. Also, forward trajectory cluster analysis was performed for potential region sources in Mauritania, Western Sahara of Morocco and Southern region of Algeria to analyse the PM particle trajectories. The results of the dust storm model and the cluster analysis were compared and supported with MODIS-aqua aerosol optical depth.
(AOD) values and CALIPSO vertical aerosol profiles. In addition, analysis of the PM10 concentration measurements from the Martinique Islands and the United States were included to evaluate the impact of the dust storm.

2 | MATERIALS AND METHODS

2.1 | Event description

June 2020 was a month where a breaking record dust storm occurred over the Sahara and transported toward the Americas. According to Francis et al. (2020), the dust clouds that were generated in this event registered the highest record of AOD. The dust emission was continuous for 4 days and uplifted to 5–6 km above the ground surface, and transported across the tropical Atlantic oceans by the powerful mid-atmospheric winds that had a speed higher than 20 m/s (Francis et al., 2020).

For Francis et al. (2020), the primary objective was to determine the processes responsible for the lifting and transport of dust during the dust event, as well as their relationship to large-scale circulation, and focus on the characteristics of the atmospheric mechanisms that led to massive transport of the Saharan dust. In this article, the central goal is to locate the most active regions in Western Sahara during that event, and the contribution of those regions to PM10 concentration in some regions that are far away from the source region, such as the United States coastal part of the Gulf Mexico and the Martinique islands.

The dust clouds generated covered a huge space as shown in the true colour images of MODIS-Aqua satellite on the 14, 15, 16, 17, 18 and 19 June 2020 (Figure 2), where the dust in yellow colour is shown to spread from the Western Saharan region to the Atlantic Ocean.

2.2 | HYSPLIT model description

The HYSPLIT is a software developed by the ARL of the National Oceanic and Atmospheric Administration (NOAA) of the United States (Draxler & Hess, 1998). The model is a comprehensive system for simulating basic air parcel trajectories as well as complicated transport, dispersion, chemical transformation and deposition

FIGURE 2 MODIS-aqua true colour images on the (a) 14th, (b) 15th, (c) 16th, (d) 17th, (e) 18th and (f) 19th of June 2020 over western Africa and the northern tropical Atlantic Ocean. Clouds appear in white and Saharan dust in pale yellow/brown
scenarios. The model calculation method is a hybrid of the Lagrangian approach, which uses a moving frame of reference to calculate advection and diffusion as trajectories or air parcels move away from their initial location, and the Eulerian methodology, which uses a fixed three-dimensional (3D) grid as a frame of reference to compute pollutant air concentrations. More information can be found in Stein et al. (2015).

2.2.1 Dust Storm Model

HYSPLIT dust storm model is a model for the emission of PM10 dust that has been built using the theory of a surface-roughness-dependent threshold friction velocity (Draxler et al., 2001). When the local wind velocity exceeds the threshold velocity for the soil properties of that emission cell, a dust emission rate is computed from that model grid cell. The predominant mechanism for PM10 emission is ‘sandblasung,’ in which larger particles that cannot become airborne bounce along the surface (saltation), allowing additional smaller particles to become airborne (Draxler et al., 2010). This emission module makes use of HYSPLIT’s 1° × 1° land-use file, which assumes that a ‘desert’ grid cell corresponds to the roughness identification class ‘active sand sheet’. Only on dry days and when the friction velocity exceeds the threshold value (0.28 m s⁻¹ for an active sand sheet) do dust emissions occur. Once the emission strength is determined, the model emits Lagrangian particles with a mass calculated by multiplying the PM flow by the 1° × 1° area corresponding to a desert category in HYSPLIT’s land-use file. These Lagrangian particles are distributed and moved forward in time in response to NOAA’s GFS model’s meteorological fields with a horizontal resolution of 1°. A more specific description of particle dispersion and transport can be found in Draxler et al. (2001) and Escudero et al. (2006).

The meteorological data fields needed for the model can be accessed from the National Climatic Data Centre (NCDC) website which is NOAA’s National Centers for Environmental Information (NCI) that provides public access to remarkable archives for environmental data on Earth. In this article, we used the GDAS (Global Data Assimilation System) meteorological data (GDAS1) with a horizontal resolution of 1° × 1° corresponding to ~100 km × 100 km and 23 vertical layers. GDAS1 is chosen to match the resolution of the HYSPLIT land-use file resolution. GDAS is a system used by the global forecast system (GFS) model to insert observations into a gridded model space to initialise, weather predictions using observed data. Surface observations, balloon data, wind profiler data, airplane reports, radar observations and satellite observations are all added to a gridded, 3D model space by GDAS. GDAS data are provided as both GDAS input observations and GDAS gridded output fields. The GFS model can be started using gridded GDAS output data. Input data are accessible in a number of data formats due to the varying nature of the assimilated data types, notably Binary Universal Form for the Representation of Meteorological Data (BUFR) and Institute of Electrical and Electronics Engineers (IEEE) binary. World Meteorological Organisation (WMO) Gridded Binary is the GDAS output (GRIB) (Kleist et al., 2009). The GDAS dataset covers the entire globe and is freely available.

In the dust storm model, the study domain is defined from 15.0N–18.0E to 32.0N–05.0E (Domain covered with stars in Figure 3) which covers the Western Sahara of Morocco Mauritania, and a small part from Algeria. PM10 concentrations are averaged over every 12 h. The dust simulation Started on the 14th of June 2020 at 0000UTC until the 19th of June 2020 at 0000UTC. HYSPLIT dust storm modelling was set for 0.5° × 0.75° resolution for desert dust sources, with a total of 10 million particles or puffs released during one release cycle and a maximum of 5 million particles permitted to be carried at any time during the simulation. The release mode is sampled using 3D particles in both horizontal and vertical orientations.

2.2.2 Trajectory Cluster Analysis

Forward and Backward trajectory analysis are reliable methods to identify the long-range transport patterns with the use of archived meteorological data (Baker, 2010). However, considering the benefits of the trajectory model, individual trajectories are subject to errors due to the precision and quality of the meteorological data, as well as the simplifying assumptions employed in the trajectory model, which ultimately limits their utility. This problem was addressed by computing a large number of trajectories and then submitting them to cluster analysis.

Cluster analysis is a multivariate statistical approach that divides data collection into groups. Cluster analysis is sometimes presented as an objective classification approach; however, this is not true because the clustering algorithm, the distance measure specification and the number of clusters utilised are all subjective (Stohl, 1998). It is an approach that organises an ensemble’s individual trajectories into a user-specified number of clusters where the errors in the single trajectories tend to average out. Source receptor connections may thus be identified statistically, which aids in establishing knowledge of a location’s pollution climatology (Baker, 2010).
HYSPLIT forward trajectory cluster analysis was performed for the regions that are considered the most active sources of dusts and particles in the region of study as well as some surrounding regions. The list of the regions is presented in Table 1 with names, latitudes, longitudes and time periods.

FIGURE 3  Modelling results for the concentration of PM10 averaged across the 0–100 m altitude range in June (a) 14th from 0000 UTC to 1200 UTC, (b) 14th from 1200 UTC to 15th 0000 UTC, (c) 15th from 0000 UTC to 1200 UTC, (d) 15th from 1200 UTC to 16th 0000 UTC, (e) 16th from 0000 UTC to 16th 1200 UTC and (f) 16th from 1200 UTC to 17th 0000 UTC.
2.3 Satellite observations

Satellites are increasingly being utilised to collect data on aerosol features such as AOD, the columnar concentration of particles, and particle sizes, taking advantage of technological and scientific advances over recent years. There are various Earth-observing satellite instruments that developed many aerosols remote sensing algorithms for the retrieval of the AOD. One of those instruments is the MODIS. The MODIS instrument, which is mounted on both the Terra and Aqua satellites, measures upwelling radiances in 36 bands with wavelengths ranging from 0.4 to 14.5 μm. MODIS data, with spatial resolutions of 250, 500 m, or 1 km, have been used to construct the most detailed aerosol products, including AOD (Lee et al., 2009). The most recent MODIS collection 6 (C6) aerosol products feature enhanced Dark-Target (10 km DT) and Deep-Blue (10 km DB) AOD. The MODIS science team has carried out a few worldwide validation tests to demonstrate the cumulative impact of these adjustments and the discrepancies between the various parameters (Belle & Liu, 2016). DT was created to provide coverage over dense, dark vegetation, whereas DB was created to fill in the gaps in DT by providing coverage over bright surfaces (such as deserts) (Sayer et al., 2014). In this article, the MODIS-Aqua Deep Blue AOD 550 nm with a spatial resolution of 1° was retrieved as an average daily map from GIOVQNNI (https://giovanni.gsfc.nasa.gov, last accessed 21 October 2021), is an online platform created by NASA for displaying and analysing geophysical parameters, with easy access to provenance. MODIS-Aqua AOD average maps were compared with them with the average PM10 concentration maps at altitudes between 0 and 100 m from the HYSPLIT dust simulation results, due to the lack of PM10 ground measurements in the area of study.

In addition to the MODIS-Aqua AOD product, we also used data from CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations). CALIPSO’s mission is an ongoing collaboration between NASA Langley Research Center (LaRC) and the Centre National D’Etudes Spatiales (CNES) to explore the global radiative effects of aerosols and clouds on climate. CALIPSO has been providing nearly continuous measurements of the vertical structure and optical properties of clouds and aerosols since its launch on April 28, 2006, to improve our understanding of their role in the Earth’s climate system and the performance of a variety of models ranging from regional chemical transport to global circulation models used for climate prediction (Winker et al., 2010). CALIPSO Lidar Level 1532 nm total attenuated backscatter version 4.10 is the product used in this study, which describes the vertical aerosol profile and provides a clear vision about the altitude of the existing aerosols (including dust) in the troposphere and stratosphere level. Further details can be found in Getzewich et al. (2018), Kar et al. (2018), and Kim et al. (2018). The CALIPSO 532 nm total attenuated backscatter images were retrieved from the official website of CALIPSO (https://www-calipso.larc.nasa.gov) and used to get the altitude of the top layer of dust transported from the Saharan region over the Caribbean Sea and the South-eastern region of the United States.

3 RESULTS

3.1 Dust simulation results

Hysplit PM10 emission modelling results (Figures 3 and 4) show that the PM10 emission on the 14th of June 2020 started from the region of Tinduf, Algeria (Close to the Moroccan borders), Adrar, Tiris Zemmour and Tagant in Mauritania. While the dust storm was continuous for 4 days and the dust was transported to the North Atlantic Ocean, the average PM10 concentration between 0 and
100 m was between 100 μg/m³ and 10,000 μg/m³ in some critical regions like Tinduf, Algeria on the 14th and 17th of June 2020, Adrar, Mauritania on the 15th, Bir Anzarane, Morocco on the 16th, Tiris Zemmour, Mauritania on the 17th, Goundam Cercle, Mali on the 18th of June 2020. Comparing the average PM10 concentration maps between 0 and 100 m from the HYSPLIT modelling results and the MODIS Aqua Deep Blue AOD maps (Figure 5), it can be seen that in most of the regions where the PM10 concentration are high, the AOD index is also at a high level, which indicates a positive correlation between the PM10 concentration and the AOD index of MODIS Aqua.

Regions like Tiris Zemmour in Mauritania, Western Sahara of Morocco, Western and Southern regions of Algeria, are also characterised as source regions that influence the level of the PM10 concentration over the western Mediterranean Basin (Russo et al., 2020; Salvador et al., 2014). Moreover, all the areas that had a high concentration of PM10 in the HYSPLIT dust simulation results and high AOD values (between 0.7 and 1) according to time-averaged maps of MODIS-Aqua are considered as primary dust natural source regions (Ginoux et al., 2012), and they are active throughout the year, although their peak activity is between April and September (Prospero et al., 2002).

### 3.2 Cluster analysis results

The analysis of the trajectories of the PM10 particles emitted from numerous locations in the western Sahara during the June dust storm event using the HYSPLIT cluster analysis method is shown in Figures 6 and 7. A large percentage
of the PM10 trajectories analysed in the period between 10th and 30th of June 2020, reached the middle-upper troposphere of the Caribbean Sea and the Gulf of Mexico. 80%, 51%, 76% and 70% of the PM10 particle trajectories from Bir Anzarane Morocco, Nouakchott and Tichit Mauritania and Bordj Badji Mokhtar Algeria arrived to the

**FIGURE 5** MODIS aqua time-averaged map of aerosol optical depth 550 nm (deep blue, land-only) daily 1° in the region of western Sahara on the (a) 14, June 2020 (b) 15, June 2020 (c) 16, June 2020 (d) 17, June 2020 (e) 18, June 2020 (f) 19, June 2020
FIGURE 6  Forward trajectory cluster analysis results, each picture shows cluster mean trajectories with the percentage of trajectories in each cluster from (a) Dakhla, (b) Bir Anzarane, (c) Oum Dreyga, (d) Aousserd, (e) Nouakchott and (f) Tichit

FIGURE 7  Forward trajectory cluster analysis results, each picture shows cluster mean trajectories with the percentage of trajectories in each cluster from (a) Atar, (b) Toumbouctou cercle, (c) Bordj Badji Mokhtar and (d) Tamanrasset
Gulf of Mexico respectively. In addition, the backscatter vertical profile as measured by CALIPSO on June 21 and 23, 2020 (Figure 8) shows evidence of the high altitude of the dust particles transported from the Saharan region. The top layer altitude of the dust on June 21 and 23 were between 4 and 4.5 km, forming a massive dust cloud over the Windward and Leeward islands in the Caribbean Sea, and the effect was seen in the hourly measurements of the PM10 concentrations of the Fort de France station in Martinique Island where the PM10 daily average concentration was 181, 264 and 183 μg/m³ on the 21, 22 and 23 of June consecutively with an hourly concentration that reached 372 μg/m³, comparing to 42 μg/m³ that was registered at the beginning of that month. Furthermore, and after 11 days of the starting of the Saharan dust storm, the effect of the transported particles was clear in the United States coastal cities of the Gulf of Mexico. Texas and Florida states were the most affected by having an Unhealthy level of PM10 and PM2.5 concentrations (red colour in the maps of Figure 9), followed by Georgia, Alabama, Mississippi and Louisiana states that reached the level of Unhealthy for sensitive groups (orange colour in the maps of Figure 9) during the 26 and 27 June 2020, which is in correlation with the backscatter vertical profile measured by CALIPSO on June 27, 2020, showing dust cloud over Florida state with dust top layer altitude at 4 km.

Many studies state that during summer, and especially during Saharan dust events, the level of PM10 and PM2.5, the effect of the transported particles was clear in the United States coastal cities of the Gulf of Mexico. Texas and Florida states were the most affected by having an Unhealthy level of PM10 and PM2.5 concentrations (red colour in the maps of Figure 9), followed by Georgia, Alabama, Mississippi and Louisiana states that reached the level of Unhealthy for sensitive groups (orange colour in the maps of Figure 9) during the 26 and 27 June 2020, which is in correlation with the backscatter vertical profile measured by CALIPSO on June 27, 2020, showing dust cloud over Florida state with dust top layer altitude at 4 km.

Many studies state that during summer, and especially during Saharan dust events, the level of PM10 and

![Figure 8](image-url) CALIPSO 532 nm total attenuated backscatter version 4.10 images, the dust appears in yellow and red in the images. (a) Orbit map on 21, June 2020 with area covered in b image coloured in pink, (b) 532 nm total attenuated backscatter on 21, June 2020 with white arrows pointing at the dust top layer over the Caribbean Sea, (c) orbit map on 23, June 2020 with area covered in d image coloured in pink, (d) 532 nm total attenuated backscatter on 23, June 2020 with white arrows pointing at the dust top layer over the Caribbean Sea, (e) orbit map on 27, June 2020 with area covered in f image coloured in pink and (f) 532 nm total attenuated backscatter on 27, June 2020 with white arrows pointing at the dust top layer over Florida state.
PM2.5 concentration increased dramatically. Bozlaker et al., 2013 state that during the Saharan episode in 2008, the total dust contribution for PM10 increased by 85% in Houston, Texas, which shows a dominance of the transported PM10 particles from Sahara during dust episodes. Also, Bozlaker et al., 2019 found dust contributions of 19% to 48% of PM2.5 during the 9-day dust episode in 2014 to African dust. In addition, the results of the cluster analysis point out a number of source regions in the western Sahara that contributes to the rise in PM10 concentrations in the Southern Coast of the United States, such as Bir Anzarane Morocco, Nouakchott and Tichit Mauritania and Bordj Badji Mokhtar Algeria.

4 | CONCLUSION

Sahara is considered the dominant dust source in the world. Saharan dust storms can be transported far away in the North Atlantic Ocean and can hit North and south America depending on the meteorological conditions and can go even further to reach the North Pacific Ocean. Dust contains particles from different ranges of diameters, including 10 and 2.5 μm (PM10 and PM2.5), therefore Saharan dust storms can affect regional air quality dramatically and can be dangerous to sensitive and healthy people as well.

The extreme Saharan dust event that occurred on 14–19 June 2020 was the most intensive dust storm in the last 50 years. The use of the HYSPLIT PM10 emission model to simulate the Saharan storm in Mauritania and Saharan regions of Morocco, and the forward cluster analysis for the period of the Saharan event, alongside the MODIS-Aqua AOD and CALIPSO vertical aerosol profiles illustrate a positive correlation between the different approaches and provide evidence of the intensity of the dust storm and its effects of the level of PM10 concentrations.

The average PM10 concentration between 0 and 100 m reached severe levels according to the HYSPLIT dust
simulation results. Regions like Dakhla-Oued Ed-Dahab in Morocco, Adrar and Tiris Zemmour in Mauritania had high PM10 concentrations (higher than 100 μg/m³) and AOD values (between 0.7 and 1) during the 4 days of the dust storm.

Moreover, PM10 particles were transported over the Atlantic Ocean to the Caribbean Sea and the Gulf of Mexico, causing raise in the concentrations in those regions. The tropospheric level of the Caribbean Sea and the Gulf of Mexico was loaded with dust particles transported from the study area. Bir Anzarane Morocco, Nouakchott and Tichit Mauritania and Bordj Badji Mokhtar Algeria all contributed to the high PM10 concentrations observed in the Martinique islands and the southern United States, with the top altitude of the dust layer was between 4 and 4.5 km, according to the back-scatter vertical profile measured by CALIPSO. Therefore, PM10 concentration and AOD reached their peak values during June 2020 dust storm.

Finally, Saharan dust storm particles can be carried thousands of kilometres away from their originating regions, affecting air quality and posing significant health risks, particularly for vulnerable populations. The study’s findings reflect earlier research’s conclusion that African dust impacts a large area of the United States’ South, Southeast and East Coast. The prediction of similar events in the future can help to mitigate their effects on people and the environment, especially since the frequency of such severe Saharan dust outbreaks is predicted to increase in the future.

AUTHOR CONTRIBUTIONS
Achraf Qor-el-aine: Investigation; methodology; resources; software; visualization; writing – original draft; writing – review and editing. Gábor Géczi: Supervision; validation; writing – review and editing. András Béres András: Supervision.

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