Impact of a strong Saharan dust outbreak in the Caribbean

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Abstract: In June 2020, a dust storm crossed the Atlantic, from Africa to the Caribbean, within a few days, becoming one of the greatest dust events in the last two decades. A second dust plume, albeit less intense, was observed on 26-28 June. High and low values of aerosol optical depth and Angstrom exponent, respectively, were recorded from 21 June to 23 June in the Caribbean. On 22 June aerosol optical depth peaked at 1.9 in Guadeloupe. An isentropic layer was observed in dusty days, bounding the dust over the isles. A strong dust uplift over Africa, the subsequent accumulation on the West African coast and high-altitude winds led to large amounts of dust transport.

I. INTRODUCTION

The Sahara and the Sahel are the main sources of dust in the planet. This dust reaches regions in different continents such as Southern US, South America, Caribbean Basin, Mediterranean and Middle East, among others. Moreover, African dust has been observed even in Scandinavia and Japan. Particularly, dust transport from Africa to the Caribbean Basin was analysed in three papers between mid-1950s and mid-1960s [1]. Since then, mainly from the 1980s, the interest on this kind of events has grown with several studies about particular and general characteristics. Millions of tons of dust are transported across the Atlantic from Arica with a defined annual cycle, being maximum in boreal summer and minimum in winter. Desert dust makes up 75% of atmospheric aerosol particles [2] and it is of great importance for many aspects. It affects Caribbean climate since dust has radiative effect due to its albedo and the interaction with clouds. It also contributes to phosphorus concentration and nutrients to the Amazon Basin [3] and its role on tropical cyclones [4] is also a matter of discussion because it is not yet clear whether it facilitates its formation or not. There is also certain interest in the role of climate change in future dust outbreak emissions.

In the Caribbean during low-dust seasons, marine aerosols are the main source of suspended particles, due to its less urbanized regions, unlike Europe. Hence, when dust plumes reach the Caribbean most of it corresponds to African dust. Atmospheric aerosol particles are referred as particulate matter (PM): microscopic particles suspended in the air that are categorized in two modes. There are coarse mode particles PM_{10}, with a 10 μm size or less, and fine mode particles $PM_{2.5}$, average size of 2.5 μm or less. The most abundant dust particles after the transport in peak periods are PM_{10} [5], hence larger particles. Finer particles are less common in the dust plume. In a broader picture, coarse mode particles are also small, and the dust associated to it has aftermaths on human health [6] as well. The fact that coarse mode corresponds to microscopic particles makes them more penetrative in the human body than other bigger particles that are filtered out by cilia and mucus in the nose and the throat.

In June 2020 there was a dust outbreak, called the "Godzilla dust plume", which was considered one of the greatest dust events in the last decades [7]. This study aimed to analyse the event regarding aerosols, thermodynamic properties, and long-range transport due to synoptic weather patterns.

II. METHODS

Four data sources were used to study the event: sun photometry, meteorological sounding, air backward trajectories and synoptic analysis. As a complement, satellite imagery was used to keep track of the dust transport.

FIG 1: AERONET stations (green). Sounding stations next to or close to AERONET stations are in red.

Five photometric stations were selected for this study, the only ones that had data in the area and in the period of interest (Fig. 1). For this reason, two of them are quite close. La Parguera station is an island (Isla Magueyes) next to a small urban area. Guadeloup station is located at the University of the French Antilles. Ragged Point is found at the east coast in a rural area, away from the only city in Barbados, Bridgetown. Cape San Juan station is in Cabezas de San Juan, a natural reserve. No human activity close to this area is found. Similarly, to the latter, Neon Guan is off anthropogenic sources, in the Guánica State Forest (forest reserve).

A. Photometric ground-based measurements

A sun photometer is a device that estimates the atmospheric extinction from measurements of the Sun and sky radiances. The instrument automatically points at the Sun. The incident solar radiation at the top of the atmosphere (TOA) is modified by absorption and scattering from gases and aerosols. The Beer's law relates the attenuated radiation at a point with the atmospheric extinction via an exponential law.

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$$V(\lambda) = V_o(\lambda)e^{-m\tau(\lambda)}, \quad (1)$$

where V(λ) is the monochromatic solar intensity measured at any level, $V_o(\lambda)$ is the solar intensity at the TOA estimated by calibration, m is the optical air mass and τ is the total optical depth (TOD), which is defined vertically and includes the effect of air molecules, gases, aerosols, and clouds. The calibration is calculated by a linear adjustment of equation (1) using logarithms and plotting the intensity as a function of the air mass. With clear-sky homogenous days data, the extrapolation to zero air mass gives the intensity at the TOA. The TOD under cloud-free conditions has three main sources: gas absorption (τ_{GAS}), Rayleigh scattering (τ_R) and aerosols. The τ_{GAS} and τ_R are calculated from concentrations and optical properties. Therefore, the aerosol optical depth (AOD) can be deduced by subtracting τ_{GAS} and τ_R from the TOD. Aerosols attenuate the incident radiation at the TOA, and it depends on the wavelength. This spectral dependence of the AOD is presented by the Angstrom's law [8]:

$$AOD(\lambda) = \beta\lambda^{-\alpha}, \quad (2)$$

where β is the turbidity coefficient and α is the Angstrom exponent (AE). This exponent is quite useful since it is inversely proportional to the average size of the aerosol particles. The bigger the particles, the smaller the exponent. This relationship helps to confirm the data suspected to be dust. High AOD and low AE values are two of the features that characterize strong Saharan dust extinction.

The sun photometers used in this study belong to the Aerosol Robotic Network (AERONET) [9]. It is a dense net of stations worldwide that provides optical and physical properties of aerosols, such as AOD, AE, and fine mode fraction. This net is made up of CIMEL Electronique model CE318 sun photometers. By selecting properly AERONET stations, variations of these parameters throughout the intense event were analysed. We used quality level 1.5, in which an automatic cloud-screening is performed to each observation. We could not use level 2.0, manual post-processed control, since not enough time has passed to properly evaluate data from last year, 2020. AERONET requires 12 months or even longer to publish quality-assured data.

B. Sounding

An atmospheric sounding is a vertical profile of thermodynamic properties, even though it has some horizontal displacement. It provides temperature, humidity, pressure, wind direction and wind speed, among other properties. These measurements were helpful when detecting a dusty layer over the Caribbean Basin. Two properties of the sounding were studied to characterize the atmospheric situation in dusty days: the potential temperature and the mixing ratio. The potential temperature of an air parcel is the temperature it would get if it were expanded or compressed adiabatically to a reference pressure Po (1000hPa).

$$\theta = T\left(\frac{P_o}{P}\right)^{\frac{R_d}{C_p}}, \quad (3)$$

A constant potential temperature along the vertical is associated with neutral stability and adiabatic layers called isentropics. Neutral stability means that if a force is applied to an air parcel, it moves until the initial force is retreated. The motion does not keep any longer.

The mixing ratio is the fraction between mass of water vapor and mass of dry air in a certain volume. It is often expressed as grams of water vapor divided by kilograms of dry air.

$$w = \frac{m_v}{m_d}, \quad (4)$$

This parameter is useful to detect drier layers, which are a characteristic of Saharan Air Layers (SAL), and to indicate neutral stability in well-mixed layers when it remains constant. The sounding data of this study was provided by the Department of Atmospheric Science of the University of Wyoming [10].

C. Air mass backward trajectories

The backward trajectory is a tool to estimate the origin of air masses through the analysis of the previous position of an air parcel according to the meteorological conditions. It does not give any information about the particles, only about their possible origin. There are plenty of models that follow a foreigner air parcel backwards in time. In this study Hybrid Single Particle Lagrangian Integrated Trajectory model (HYSPLIT) [11] was used. This model belongs to NOAA's Air Resources Laboratory and uses a Lagrangian approach, following the air parcels, and a Eulerian approach, where pollutant concentration in a 3D grid is analysed. The input dataset used to initialize the trajectories with observational data was the Global Data Assimilation System (GDAS1). GDAS1 corresponds to 1-degree resolution that is equal to approximately 100 km x 100 km grid cells.

A transatlantic transport requires air travelling with altitude. Dust particles cannot travel close to the surface otherwise they would deposit quite fast due to gravity. Backward trajectories were done from two initial levels, 1500 m, and 3000 m to evaluate the difference and confirm whether dust transport was associated to the 3000 m level over the Caribbean and 1500 m level was associated to a local origin or not. This methodology has some uncertainties related to the model, the meteorologic input data and even the selected resolution [12], but it was a good resource to complement and give back-up to the other methods used in this study.

D. Synoptic maps

Weather maps conform an essential tool when discussing long-range air transport. Surface pressure, vector wind and geopotential height at different altitudes were considered to analyse the situation that led to the Saharan dust air transport.

Tropical waves are low-pressure regions characteristic around the Atlantic Ocean and are related to the dust uplift in Africa. This phenomenon is the origin of most of the tropcial cyclones. A cyclone is counterclockwise in the northern hemisphere (NH) and it is related to strong winds, instabilities, and vertical air development. In contrast, anticyclones are large-scale air masses around high-pressure centres, clockwise in the NH, and are related to subsidence, therefore stability and sunny weather. Saharan air dust transport requires of an anticyclone over the Atlantic.

NCEP/NCAR Reanalysis 1 [13] was used in this study. It provides constantly updated datasets and enables to create and costume reanalysis weather maps all over the globe.

III. DUST OUTBREAK ANALYSIS

On 17-18 June, a Saharan dust plume departed from the west coast of Africa towards the Atlantic Ocean. A few days later it reached the Caribbean. The day of maximum dust concentration did not coincide in all the stations. The peak was recorded on 22 June in four out of the five stations used and one day before in the most eastern station, Ragged Point, as it is shown by the temporal evolution of the AOD (Fig. 2a).

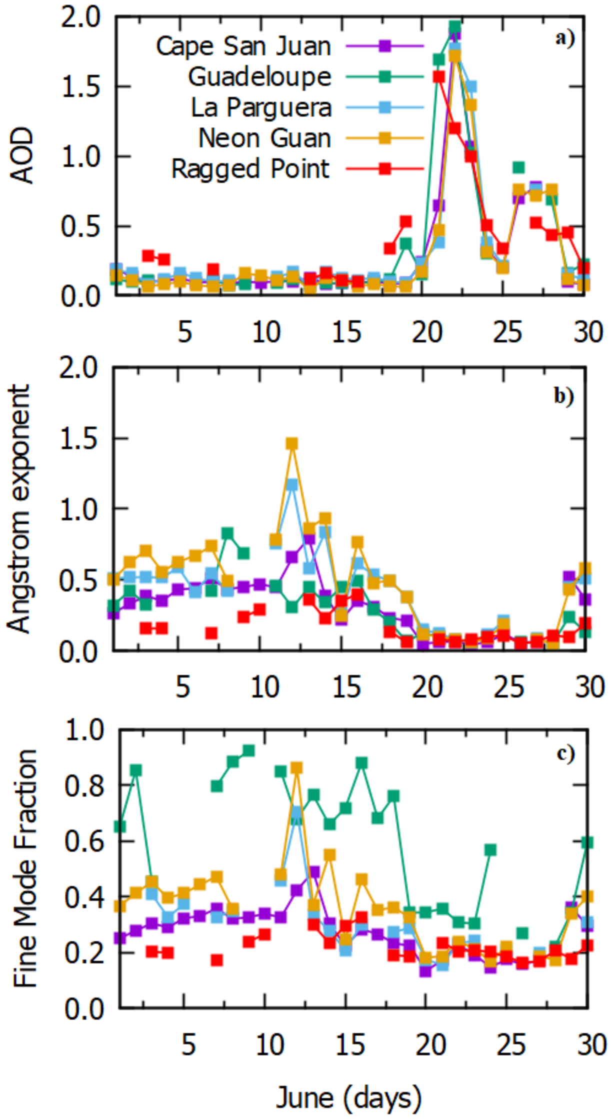

FIG. 2: Daily values in June 2020 in the Caribbean of AOD at 440 nm (a), of AE between 440 and 870 nm (b) and of fine mode fraction (c). The missing data is due to the cloud-screening.

Low values of AOD, relatively high values of AE (Fig. 2b) and presence of small particles characterized the first three weeks of June in all the stations. In the period 20-24 June, enormous values of AOD accompanied by low values of AE were recorded. Furthermore, a decrease in the fine mode fraction values, as it is observed in Fig. 2c, characterized a dominance of larger particles. This abrupt change in the data indicated the strength of the event. In those days AOD reached almost two while AE was close to zero. As aforementioned, all these features characterize dust presence. They are valuable indicators and provide strong evidence and support to the dust outbreak over the Caribbean. In the last days of June (26-28), a less intense dust plume was observed over the Caribbean with AOD values ranging between 0.5 and 1.0, depending on the stations but with AE as low as in the first episode. This was verified via NASA's EOSDIS satellite imagery (https://worldview.earthdata.nasa.gov), which showed a retard departure of a second dust plume from the west-coast of Africa on 21 June.

Soundings were performed on two stations separated 900 km away. Maximum dust days at each station and dust-free days were chosen to notice the differences (Fig.3). Potential temperature presented an almost vertical profile from 2500 to 4000 m in both dusty days. This corresponds to neutral stability and a well-mixed layer, as aforementioned. Low values of mixing ratio at the adiabatic layer (2-3g/kg) were also observed, corresponding to drier layers as well. This characteristic is typical of a SAL profile [14]. Temperature profile analysis (not displayed) showed that the SAL was located between thermal inversions and isotherm layers. In Barbados (21 June) the top layer was between 1500-2000m, and the bottom layer was between 5200-5600 m. In Cape San Juan, an isotherm layer at around 2350-2500 m limited the bottom of the SAL and the top was bounded by an inversion located between 4790-4900 m. In dust-free days these inversions were not found, at least not both.

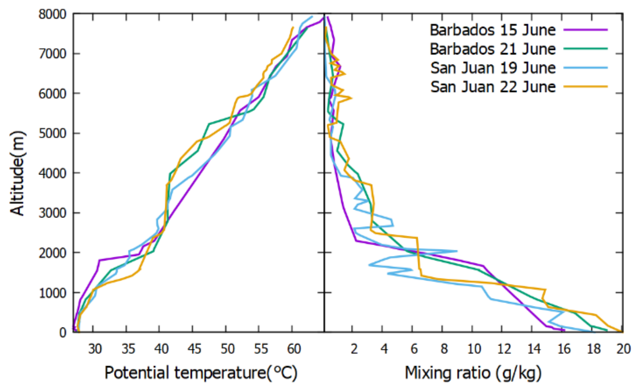

FIG. 3: Meteorological soundings at 12UTC in Ragged Point and Cape San Juan for two different days.

Long-range transport requires height, otherwise large particles deposit quickly by gravity. To trace the origin of the dust, two air mass parcels were followed with different initial heights but with the same starting point, one at 1500 m and the other at 3000 m.

For the 3 km-height backward trajectory Fig. 4 shows the uplift of the air parcel from surface in June 16 at around 18 UTC and how it reached 4500 m a couple of hours later. Then a light progressive subsidence motion came in and after that the parcel finally reached the 3 km-height in Barbados. This evidence supports a Saharan dust source. The low-altitude trajectory followed a similar path though it did not show any uplift. This may suggest the transport was held at many different levels, consistent with the amount of dust observed and the SAL profile.

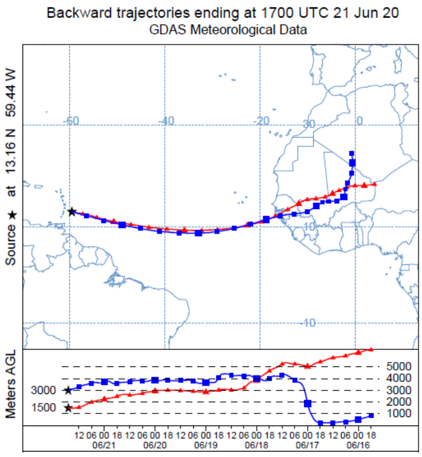

FIG. 4: Backward trajectories with starting point in Ragged Point, Barbados.

But which was the cause of the uplift, the transport, and the great magnitude of this unprecedented event in the last decades? Synoptic maps were quite useful when these questions were addressed. On 12-13 June low pressures were observed over Africa (Fig 5). These are related to convective updraft; therefore, they may have been the trigger for the dust uplift.

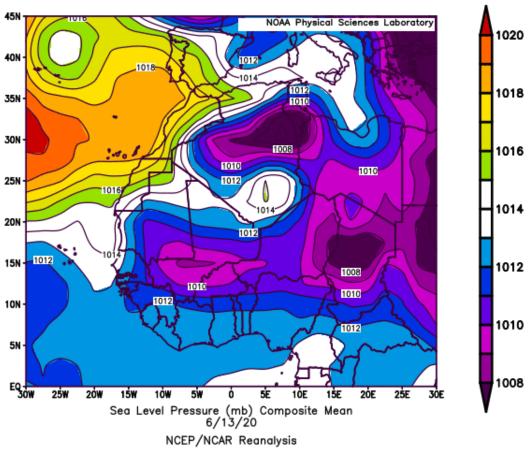

FIG. 5: Sea level pressure over Africa on 13 June.

Synoptic situation played a key role in transporting such large amounts of dust over the Atlantic leading to the high values of AOD in the Caribbean. The difference with other previous events was the presence of a close circulation 'loop'. From 14 to 17 June, the North Atlantic Subtropical High (NASH) was accompanied by a low-pressure system to the southwest and a high-pressure system over Africa. Looking at this disposition and the wind maps (Fig. 6a, 6b) an almost closed wind circulation that did not let dust to start crossing the Atlantic was identified. That is why the Saharan dust accumulated for days on the African coast. Finally, when the NASH lost strength the closed loop broke up (June 18) and the dust plume moved rapidly towards the Caribbean, with the help of the African Easterly Jet (AEJ). Fig. 6c,6d show the strong westward winds that transported the dust and the presence of the high across the Atlantic. East winds were observed every day from departure to arrival of the dust intrusion.

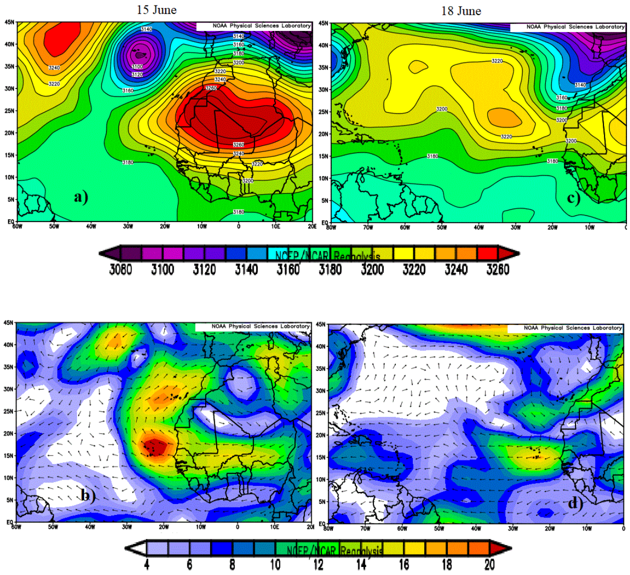

FIG. 6: Synoptic situation that maintained the dust for days in the African west coast (a, b). Transport of the Saharan dust once the circulation instability weakened (c, d). Geopotential height and wind magnitude are expressed in m and m/s, respectively. Source: psl.noaa.gov/data/composites/day/

In this study further analysis and conclusions about the origin and uplift of the dust plume were out of reach. Other studies used different synoptic maps from reanalysis and did not go beyond this basic level either [15]. Nonetheless, all methods used have clearly throw light to the Godzilla event of 2020. Other authors have treated this aspect, as for example Yu et al. [7] who focused on mesoscale analysis relating dust plumes to haboobs, a kind of dust storm that occurs in dry land. Francis et al. [16] also dealt with this topic focusing on synoptic situation and suggesting there were uninterrupted dust emissions for days due to strong north-easterly winds, linked to the anomalous high-pressure system in west Africa, and a pressure difference between the high and the Saharan heat low (SHL). To have more information and different insights about the uplift, the aforementioned articles and Remini et al. [17] may be of interest.

IV. CONCLUSIONS

This work focused on one of the strongest episodes of the latest years, 'Godzilla', which took place in June 2020 and involved two dust plumes over the Caribbean Basin. The techniques used were helpful and appropriate to discuss the departure of the dust, the arrival, and the location of the dust vertically. From this study we took out three major conclusions.

- AOD and AE characterized the dust plume over the Caribbean in peak days. Not only AOD reached huge values, but AE also was clearly low indicating the intrusion of dust in the Basin. Coarse mode particles were dominant during the event.

- Unlike dust-free days, a SAL was observed over the islands in dusty days bounded with inversions. Most of the dust was found in this layer and some of it deposited and reached the surface.
- Long-range transport of huge amounts of dust was due to a synoptic situation that favoured the accumulation of dust over the African coast for days until it departed.

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