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Saharan Dust Detection in The Bahamas Using a Bistatic Camera Lidar

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A B S T R A C T

A low cost, low complexity bistatic camera lidar system (Clidar) was used to study atmospheric aerosols and long-range dusts in The Bahamas. The thick aerosol layers over Nassau detected by Clidar above 1.0 km altitude are attributed to the passing Saharan dust on June 28 and June 30, 2020 (UTC) which agrees with NASA-GEOS-5 model. The heights of the layers detected by Clidar fall within the altitude range of the dust plumes that are typically found at 1-6 km above sea level. NOAA-HYSPLIT back trajectories for dust layers above 1 km indicate their origins near North Africa.

1. Introduction

Since the discovery of African dust transport in 1950s, there is a great interest on dust research due to their role on climate change [Prospero et al. 2021]. Each year during the summer months, the nutrient-laden sand and soil in the Saharan desert are lifted by a strong wind into the atmosphere forming a very dry and hot Saharan air layer ranging from 1-6 km above the surface. Dust plumes are then carried by the easterly wind across the Atlantic reaching all the way to North America in few weeks [Adams, Prospero & Zhang 2012]. On its journey across the Atlantic, the mineral enriched dust particles can sprinkle on the land and ocean feeding the marine and plant life [Prospero, Olmez & Ames 2001]. Like the other type of natural and anthropogenic aerosols, dusts play a vital role by modulating the solar radiation and cloud properties [Valle-Diaz et al. 2016, Charlson et al. 1992]. Alongside the local aerosol sources, the long range dust particles degrade the local air quality impacting the health effects [Querol et al. 2019]. Dusts can suppress the formation and strengthening of the cyclones as well [Strong, Vecchi & Ginoux 2018]. While the earth's climate and ecology are influenced by the dust, the amount of dust emission is a factor of climate change [Knippertz & Todd 2012]. Due to the effects of the dust plumes on the climate and environment and interlinked dependencies between climate change and dust emission, there is an increased focus on the integrated approach for long range dust transport and aerosol research. Regular tracking and understanding the dust plumes and their effects is thus critical. In the past several decades, station at Barbados led by University of Miami and atmospheric station at Puerto Rico contributed extensively on the aerosol and long range dust transport research in the Caribbean regions. However, the distribution of aerosols and dust particles vary greatly over time and location making it challenging for in-situ characterization. Information of atmospheric aerosols and long range dusts in most parts of the Caribbean region including The Bahamas would be useful for better climate modeling and forecasting. Aircraft and balloon borne devices can be used for aerosol and dust studies, but cannot provide altitude dependent information at once and are not as suitable for frequent monitoring [Baumgardner 2011] due to cost and logistics. Satellite and ground based monostatic lidars are generally used for the remote sensing of aerosols and long range dust particles [Welton & Campbell, 2002]. NASA's Moderate Resolution Imaging Radio spectrometer (MODIS) Aqua satellite covers most of the regions on the earth to calculate aerosol optical depth (aerosol extinctions integrated along all altitudes from the top of the atmospheric layer to all the way to the ground) but does not monitor Nassau and nearby regions as frequently as desired. Further, in the monostatic lidar system where a pulsed laser and detector are colocated, the scattering altitudes are determined by measuring the travel time of the laser to the scatterers and the scattered light to the detector using an expensive time-gating electronics. It can detect aerosol extinction at high altitudes with excellent

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altitude resolution but is unable to detect aerosols near ground levels due to the colocation of the receiver and laser transmitter.

It is often desirable to have a remote sensing system which is low cost, low complexity, portable and which can provide in-situ environmental characterization in a variety of field settings. A bistatic system called the Clidar (Camera lidar), where the vertical laser transmitter and detector are widely separated, has been developed and used to study temporal and altitude dependent aerosols in The Bahamas [Barnes & Sharma 2012, Kabir et al. 2018]. Unlike the monostatic lidar system which has challenges in detecting aerosols near ground levels, the Clidar system provides excellent resolution at lower altitudes thus enabling to efficiently detect spatial and temporal variation of boundary layer aerosols in The Bahamas all the way to the ground. It is also crucial to determine the origins of the aerosol extinctions for climate and ecological studies. Previous studies of aerosol detections using Clidar system in The Bahamas illustrates that most aerosols reside within 1 km altitude from the surface and extinctions are nearly zero above this altitude. However, in the month of June 2020, a massive layer of dust originated from the Saharan desert was progressing through the Atlantic Ocean and expected to pass over Nassau according to NASA's (National Aeronautics and Space Administration) GEOS-5 model (Goddard Earth Observing System) [GMAO 2020]. Previous studies indicate that he heights of the passing Saharan dust plumes are typically at 1-5 kmasl (km above sea level) [Carlson & Prospero, 1975]. It was thus expected that aerosol extinctions measured by Clidar in late June 2020 would be higher above 1 kmasl due to the passing Saharan dust. The high aerosol extinctions above 1 km were further investigated using NOAA's (National Oceanic and Atmospheric Administration) HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) backtrajectory model to ratify if the large aerosol extinctions at higher altitudes in The Bahamas are attributed to the long range transport of the dust plumes that are originated from the Saharan desert [Stein et al. 2015].

2. Experimental Procedures

The Clidar system consists of a charge coupled device (CCD) camera fitted with a wide angle lens and a laser. In our experiments, a continuous wave (CW) laser of 3W power and 532 nm wavelength placed at the ground was set to transmit the laser beam vertically into the sky at night. While the laser travels through the atmosphere the particles in the beam path scatter light in all directions. The scattered lights off the particles in the laser beam path from ground to zenith is imaged at the CCD camera placed at the ground at ~93 m away from the laser source. A very wide angle lens is attached with the camera which enables to image the entire laser beam (the side scattered lights off the particles from all altitudes) at once from ground to zenith without orienting the camera for various angles (Fig.1a). A transmission filter at 532 nm was inserted between the lens and the camera to allow the scattered lights at 532 nm while blocking the lights at other wavelengths from the background. The setup is limited to nighttime measurements due to the negligible background lights at 532 nm compared to daylight conditions. Each section of the imaged vertical laser beam at the CCD camera corresponds to a scattering altitude. A traditional monostatic lidar (where a laser transmitter and receiver are placed at the same location) requires a pulsed laser and expensive electronics to determine the scattering altitude by measuring the total travel time of the laser beam to the scatterers and the backscattered light to the receiver.

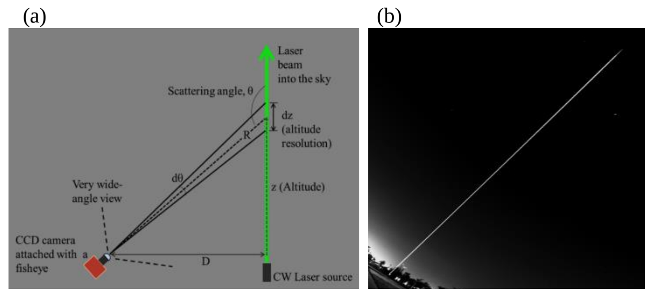

Figure 1 - (a) Clidar geometry consisting of a vertically transmitted laser and a CCD camera attached with a wide-angle lens. (b) The laser image captured onto the CCD chip at night. This is a sample raw data which is analyzed to calculate aerosol extinction.

For Clidar, the scattering altitudes are determined simply by utilizing the geometry without requiring expensive time-gating electronics. The uncertainty of the scatter altitude, dz varies with altitude z due to the constant angular field of view, dθ (0.030 deg./pixel) of the lens image on the CCD camera. Since dθ remains constant captured dz (the length of the laser beam at altitude z) is smaller at the ground levels compared to higher altitudes as can be seen from the Fig. 1a. Therefore, Clidar provides excellent resolution at the ground levels compared to traditional lidars which suffer low resolution at the ground levels due to the colocated laser transmitter and detector. Fig. 1b shows the image of the side scattered lights off the particles (laser beam) from ground to zenith on the CCD chip. This is an example of a raw data which is used for the extinction analysis. The scattered light signal on the CCD is calculated pixel by pixel along the imaged laser beam. The CCD image of the laser beam during a cloud free night, contains single-angle scattering from air molecules and all types of aerosols including the long range dusts. The aerosol portion is retrieved by subtracting a model of molecular scattering which is constructed using altitude dependent air molecule densities obtained from Nassau radiosonde data and from the NRLMSIS 2.0 atmospheric model (US Naval Research Laboratory's Mass Spectrometer and Incoherent Scatter Radar) [Upperair, Emmert et al. 2021]. Remote sensing of aerosols using lidar techniques requires an assumption of the ratio of extinction to 180 degree backscattered light in order to calculate extinction. Clidar requires the assumptions of the ratios of extinctions to the scattering angles (corresponds to the altitudes) ranging from 90 and 180 degrees. This dependence of the amount of scattered light to the scattering angle is called the aerosol phase function (APF). APFs can be obtained from CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) satellite measurements or from ground based radiometers operated by Aerosol Robotic network (AERONET). The Polluted Continental aerosol phase function obtained from CALIPSO satellite measurements is assumed to be representative to the experimental site and thus is used in this analysis [Omar et al. 2009]. Finally, a single scattering albedo which accounts for aerosol absorption is also assumed from CALIPSO database to convert total scatter to extinction (aerosol extinction = total scatter + absorption).

3. Results and Discussions

Transport of the dust plumes from the Saharan desert to all the way to north America is a natural phenomenon which occurs every year during summer months. During June 2020, a massive dust plume nicknamed “Godzilla” was observed to cross the Atlantic Ocean from the Sahara Desert [O’Brien 2020].

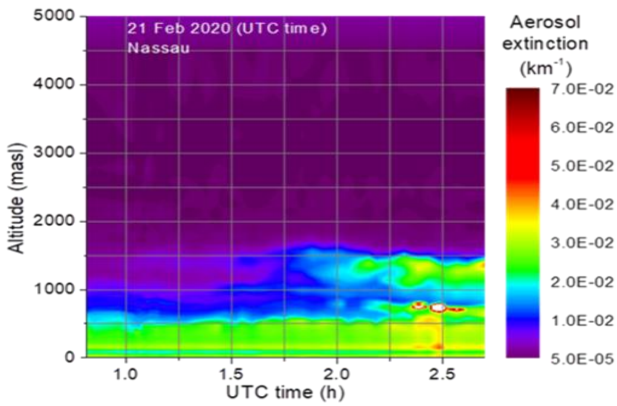

Figure 2 - Contour plot of Clidar aerosol extinction as a function of altitude in meters above sea level (masl) and UTC time (h) on February 21, 2020

NASA’s (National Aeronautics and Space Administration) GEOS-5 model (Goddard Earth Observing System) which is the world’s highest resolution global climate model, showed the origin of the dust plumes over the Saharan Desert in early June and its progress through the Atlantic Ocean, passing over the Caribbean and North America in late June [GMAO 2020]. Clidar measurements were conducted at the University of the Bahamas, Nassau at night for several hours on February 21, June 28 and 30, 2020 UTC time.

Several images of the scattered laser beam were captured with CCD exposure times 30 s and 120 s. Fig. 2 represents a contour plot for Clidar aerosol extinctions measured on February 21 UTC time that is similar to the profiles observed in other previous measurements (not reported here) in the absence of long range transport of Saharan dust plumes [Kabir et al. 2018]. On this day during 0.7 h to 2.7 h UTC time, aerosol extinction profile from ground to 600 m remains nearly similar with a peak value of ~ 0.035 km-1 at altitude 140 m. During 0.7 h to 1.5 h extinction drops off nearly to zero at 1.2 km. A layer of aerosol starts developing after 1.5 h above 1 km but the extinction becomes nearly zero at 1.6 km indicating the top of the atmospheric boundary layer beyond which the aerosol concentrations are very low on this day. The white spots around 2.5 h at altitude ~ 750 m is due to the passing cloud through the laser beam resulting in a high extinction value which is outside the maximum aerosol extinction value set for the contour plot.

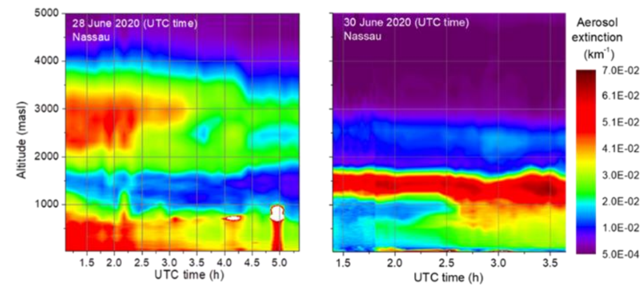

Figure 3 - Contour plots of Clidar aerosol extinction as a function of altitude in meters above sea level (masl) and UTC time (h) on June 28 and 30, 2020. Same color scale and altitude range were used for these plots as in figure 2.

Aerosol profiles measured on June 28 and 30 UTC time presented in fig. 3 are noticeably different from the profiles in fig. 2. While the aerosol extinctions became nearly zero above 1.6 km on February 21, aerosol layers of high extinctions at altitudes spanning from 1.7-4 km with a peak extinction value of 0.06 km-1 are detected on June 28. The white spots at 4.1 h and 5 h are due to the passing clouds. Two distinct thick aerosol layers ranging from 1.2-1.8 km with an extinction peak 0.07 km-1 and from 2-3 km with an extinction peak 0.008 km-1 are also observed on June 30. The thick layers of aerosols above 1.0 km altitude in the June data is attributed to the passing Saharan dust over the Bahamas on June 28 and June 30 which agrees with NASA’s GEOS-5 model [GMAO 2020].

The heights of the layers detected by Clidar fall within the altitude range of Saharan dust plumes that are typically found at 1-5 kmasl [Carlson and Prospero 1972]. During the months when Saharan dust transport do not occur, measured Clidar aerosol extinctions are very low above 1 km altitude as seen in the February data. Further, aerosol layers above 1 kmasl on the June data were investigated to identify their origins using NOAA’s HYSPLIT back trajectory model [Stein et al. 2015]. Back-trajectory analysis is broadly used to determine the trajectories of the pollutants from original locations and source-receptor relationships. Fig. 4a shows four weeks back trajectories for the measured Clidar extinction peak in Nassau at ~2.2 km and at 3 am UTC time on June 28. The top left figure shows the back trajectories of the peak for two weeks and the right figure shows the back trajectories for the last two weeks demonstrating the origin of the aerosol layer near North Africa dated back on June 2.

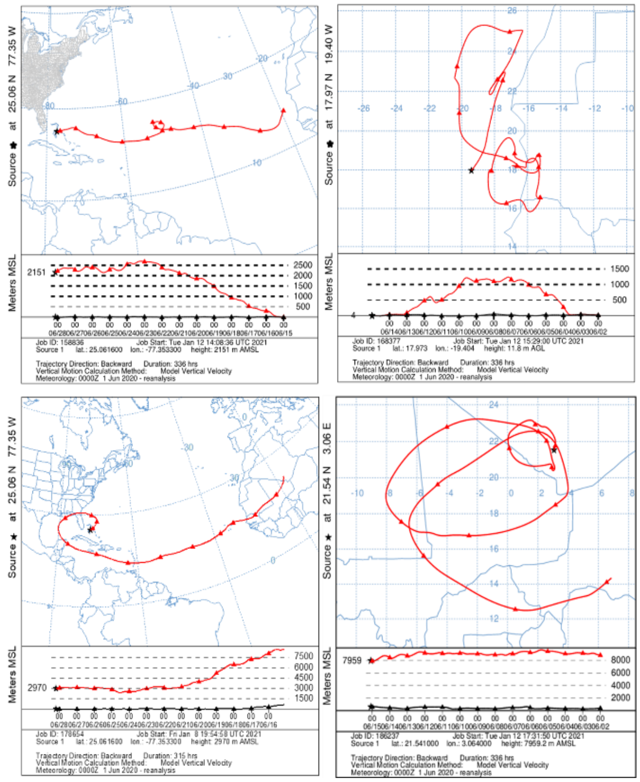

Figure 4 - (a) Top left plot shows NOAA-HYSPLIT two weeks back trajectory for the measured Clidar extinction peak in Nassau at ~2.2 km and at 3 am UTC time on June 28, 2020. The top right plot shows another two weeks of back trajectories extended from the first plot (b) the bottom two plots from left to right show four weeks back trajectories of the measured Clidar extinction peak in Nassau at ~3.0 km and at 5 am UTC time on June 28, 2020

Back trajectories in fig. 4b for the measured Clidar extinction peak in Nassau at ~3.0 km and at 5 am UTC time on June 28 demonstrates the origin of the aerosol layer from the Saharan desert as well. Most of the other NOAA-HYSPLIT back trajectories except for few (not shown) for the extinction peaks above 1 km on June 28 showed their origins from North Africa. Back trajectories for two extinction peaks (~2.4 km and ~1.4 km) above 1 km for two different times on June 30 data are presented in fig. 5a and 5b. The thick aerosol layers above 1 km over Nassau on June 30 are also seen to be transported from North Africa regions dated back on June 4. Similar to the back trajectories for June 28 data, most of the trajectories for extinction peaks above 1 km on June 30 in Nassau showed their origins from North Africa.

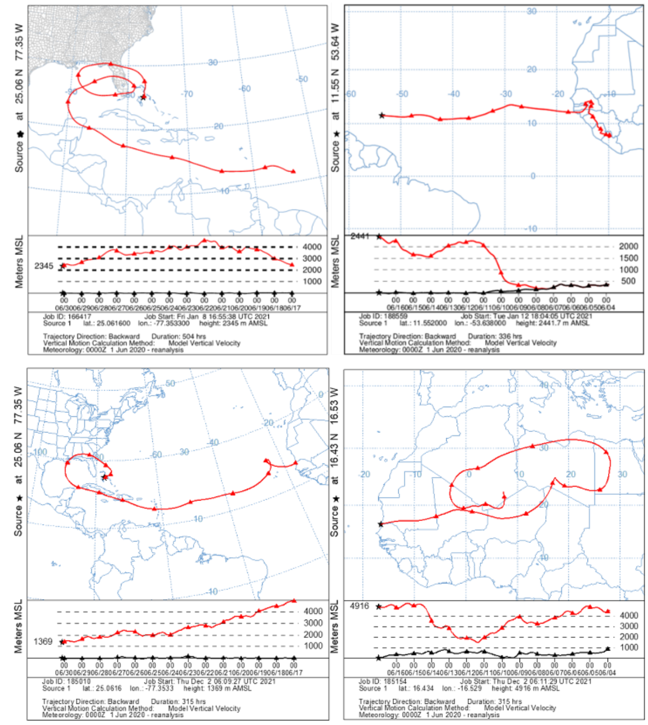

Figure 5 - (a) Top left plot shows NOAA-HYSPLIT two weeks back-trajectory for the measured Clidar extinction peak in Nassau at ~2.3 km and at 2 am UTC time on June 30, 2020. The top right plot shows another two weeks of back trajectories extended from the first plot (b) the bottom two plots from left to right show four weeks back trajectories of the measured Clidar extinction peak in Nassau at ~1.4 km and at 3 am UTC time on June 30, 2020

Aerosol optical depth (AOD) obtained from Moderate Resolution imaging SpectroRadiometer (MODIS) Aqua satellite measurements on the three experimental dates near Nassau were also compared with Clidar extinctions [Levy et al. 2015]. AOD is the integrated aerosol extinction for all altitudes along a vertical atmospheric column and thus depend on the total amount of aerosols in the column. Clidar aerosol profile illustrates the additional aerosol layers above 1 km on June 28 and June 30 compared to February 21 and thus AODs on those dates are expected to be larger.

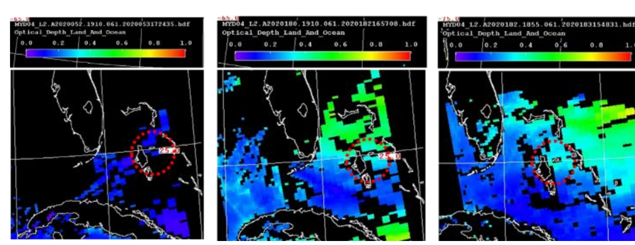

Figure 6 - From left to right: aerosol optical depth (AOD) obtained from NASA's MODIS Aqua satellite on February 21, June 28 and June 30, 2020 UTC time.

Fig. 6 demonstrates that the MODIS AOD values on February 21 ranges from 0.02- 0.15 which is much lower compared to the AOD values 0.3-0.5

on June 28 and 0.25-0.35 on June 30 which further support the detection of additional aerosol layers above 1 km altitude due to the passing Saharan dust plumes over Nassau in June 2020.

4. Conclusion

In conclusion, boundary layer aerosol profiles on three different days were monitored using a portable and an inexpensive imaging lidar called Clidar. June 28 and 30, 2020 data reveal thick aerosol layers above 1 km which is attributed to the passing Saharan dust over Nassau. The NOAA-HYSPLIT back trajectories of the measured Clidar extinction peaks above 1 km on June 28 and 30, 2020 shows their origins all the way from the Saharan desert in North Africa. Larger values of AOD measured by MODIS Aqua Satellite on 28 and 30 June 2020 compared to February 21 further supports passing Saharan dust over Nassau in June 2020. Nassau's aerosol profile in summer months is thus expected to be influenced by the Saharan dust during the dust transport from North Africa. In future, we plan to measure seasonal aerosol extinction profiles and AOD simultaneously using Clidar and star photometry technique in various family islands to study long range dusts and the aerosols originating from the local sources in The Bahamas [Leiterer 1995, Kabir et al. 2023]. The meteorological effects of the locally originated aerosols and the dusts transported from the Sahara Desert will be assessed as well. Work is in progress to measure the altitude dependent aerosol phase functions to enhance the accuracy of the conversion of measured single angle scatter to total scatter and extinction by employing a two-camera bistatic lidar system. Clidar measurements at the ground levels will be compared to the measurements from ground-based air quality devices as well.

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