8.3 AFRICAN DUST AND SMOKE INFLUENCES ON RADIATIVE EFFECTS IN THE TROPICAL ATLANTIC USING CERES AND CALIOPSO DATA

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1. INTRODUCTION

Aerosols can have numerous effects on the atmospheric radiation budget. During cloud-free conditions, aerosols such as desert dust and smoke from biomass burning reflect solar radiation to space and absorb radiation, processes known as the aerosol direct radiative effect (Haywood et al., 2000). Uncertainty in understanding aerosol effects on the radiation budget results from complex interactions between aerosols and clouds. High concentrations of dust and smoke particles act as ice nuclei (IN) in cirrus clouds and cloud condensation nuclei (CCN) in water clouds (Kaufman et al., 1997; DeMott et al., 2003). Consequently, clouds that form in the presence of high aerosol concentrations tend to contain more numerous but smaller droplets that can increase cloud albedo and suppress precipitation (Ackerman et al., 2000; Rosenfeld et al., 2001). These phenomena are defined as the aerosol indirect radiative effect (Twomey, 1977; Albrecht, 1989). The aerosol semi-direct effect arises when aerosols heat the atmosphere, evaporating low-level clouds (Grassl, 1975; Su et al., 2008). Also, dust and smoke layers elevated above low-level clouds can inhibit solar radiation from reaching a cloud layer through aerosol absorption. These interactions between aerosols and clouds can have an important effect on the Earth's radiation balance in regions such as the Tropical Atlantic due to the large spatial and temporal extent of desert dust and smoke in the atmosphere. During the biomass burning season (June-September) in southern Africa, anticyclonic systems cause stagnant conditions and extend aerosol residence time (Ross et al., 2003). Along coastal regions, trade winds transport smoke aerosols over the Atlantic Ocean between the Equator and 20 S (Myhre et al., 2003). Africa also contains the Earth's largest desert, the Sahara, a significant source for atmospheric desert dust which heavily influences the Northern Tropical Atlantic (5 N-30 N) in July (Kaufman et al., 2005). Despite the high concentrations of dust and smoke aerosols, there have been few investigations of the radiative effects of these aerosols over the Tropical Atlantic as seen from recent satellite observational data.

In recent years, several studies have investigated the radiative effects of clouds and Asian dust. Huang et al. (2006a) used Clouds and the Earth's Radiant Energy System (CERES) and the Moderate Resolution Imaging Spectroradiometer (MODIS) data to examine the impacts of Asian dust storms on radiative forcing and cloud microphysics in cloudy conditions. Su et al. (2008) conducted a similar study by using additional Asian dust storm cases and the Fu-Liou radiative model. Both studies found that, on average, SW and net instantaneous top-of-atmosphere (TOA) radiative forcing in regions with dust and clouds present are less negative than aerosol-free cloudy regions. It is also revealed from these studies that changes in cloud microphysical properties such as decreases in optical depth and water droplet radius correspond to weakening in SW and net radiative forcing. However, identifying dust-contaminated ice clouds using imagers such as MODIS may introduce additional uncertainties. The identification of dust-contaminated clouds in these studies assumes the cloud is dust-contaminated when the brightness temperature for ice clouds at the 11 μm becomes larger than the brightness temperature at 12 μm. However, if water clouds are located beneath the ice cloud layer, a situation commonly observed in the tropics, this assumption is invalid. In this study, we will examine data from the CERES instrument and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument on the Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) satellite to; quantify the impacts of African dust and smoke on radiative properties of clouds, resolve the prominent aerosol radiative effects in the Tropical Atlantic, and demonstrate the ability of the CALIOP lidar to more

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Table 1. Description of Profile Types

Profile Type	Constraints	Total Samples
Pristine	no cloud or aerosol layers present	722
Cirrus	aerosol-free profile with cirrus cloud	1447
Low Cloud	aerosol-free profile with low cloud	5682
Dust	cloud-free profile with dust layer	2505
Smoke	cloud-free profile with smoke layer	8476
Dust-Low Cloud (DLC)	profile with a low cloud and dust layer	3014
Smoke-Low Cloud (SLC)	profile with a low cloud and smoke layer	1261
Dust-Cirrus Cloud (DC)	profile with a cirrus cloud and dust layer	304
Smoke-Cirrus Cloud (SC)	profile with a cirrus cloud and smoke layer	244

accurately determine the aerosol layer height and type. Ultimately, this lidar data should lead to a better understanding of aerosol-cloud-climate interactions over the Tropical Atlantic.

2. DATA AND METHODOLOGY

The NASA A-Train satellite constellation, a group of six satellites that fly in close proximity, allows examination of Earth's climate system by combining the CALIPSO data set with other platforms such as CERES (Winker et al., 2003). The CALIPSO satellite was launched in April 2006 with an objective to explore aerosol-cloud interactions through parameters such as cloud and aerosol layer height, optical depth and depolarization ratio. The CALIOP lidar, the primary instrument on the CALIPSO satellite, is the dual wavelength, polarization-sensitive backscatter lidar that measures vertical profiles of cloud and aerosol optical properties in the atmosphere with a vertical resolution of 60 meters (Winker et al., 2003). The level 2 cloud and aerosol data with 5 km horizontal resolution is analyzed in this study. CERES, a payload on another A-Train satellite (Aqua), supplies the science community with global radiance measurements. The instrument measures broadband TOA radiances at a spatial resolution of 20 km at nadir in three spectral regions; 0.2 to 5 μm, 8 to 12 μm, 0.2 to 100 μm. CERES Single Scanner Footprint (SSF) data sets combine CERES radiative flux and MODIS cloud microphysical retrievals to create a set of 140 parameters for studying the role of clouds in the Earth's radiation budget.

We have collocated the CALIOP 5km laser footprint and the CERES SSF 20km nadir pixel for the month of July for three years, 2006 through 2008. This data fusion is possible because the CALIPSO and Aqua satellites are so close in proximity that a point on the ground will be observed by the CALIOP and CERES instruments with an average time separation of 1.5 minutes (Winker et al., 2003). The collocation is achieved via a two-step process. Data is first collocated in time, and then in space. The CALIOP position information is used to find the best matching CERES footprint within 0.25 degrees from its footprint. Once a match is found, a location offset from the CALIOP footprint is calculated and stored. All selected SSF parameters are merged with the CALIOP 5km data product for further analysis.

The CERES-CALIOP collocated data set offers many advantages compared to the measurements provided by the CERES-MODIS SSF data. First, CALIOP provides vertical profiles with higher vertical resolution (60 m) than MODIS. The CALIOP vertical resolution allows the instrument to correctly detect multiple cloud and aerosol layers in a single profile, an important issue when studying cloud-aerosol interaction that can be difficult using an imager such as MODIS. Once these cloud and aerosol layers are detected, it is essential to identify the type of cloud or aerosol, since all clouds and aerosols influence radiative effects differently. CALIOP parameters such as layer height, depolarization ratio, color ratio, and extinction-to-backscatter ratio (S-ratio) allow for more accurate determination of cloud and aerosol type than MODIS. However, combining two data sets with varying horizontal and vertical resolution can introduce some uncertainties. Therefore, horizontal homogeneity must be assumed across the 20 km CERES footprint to make direct comparisons between instruments. To uphold this assumption, only cloud layers detected by CALIOP with cloud optical depth greater than 0.1 and the CERES subpixel percent area overcast value is between 85% and 100% are considered cloudy profiles. In order to obtain cloud and aerosol optical depths from the CALIOP lidar, the multiple scattering must be accurately corrected (Zardecki et al., 1983). For opaque clouds that completely attenuate the signal, the multiple scattering effects can lead to errors in the CALIOP cloud optical depth computation. Consequently, this study only examines transparent clouds.

The local daytime CALIPSO track (typically around 1400 to 1600 UTC) of the collocated data is analyzed and separated into nine profile types. These profile types, explained in Table 1, are based on the optically thickest

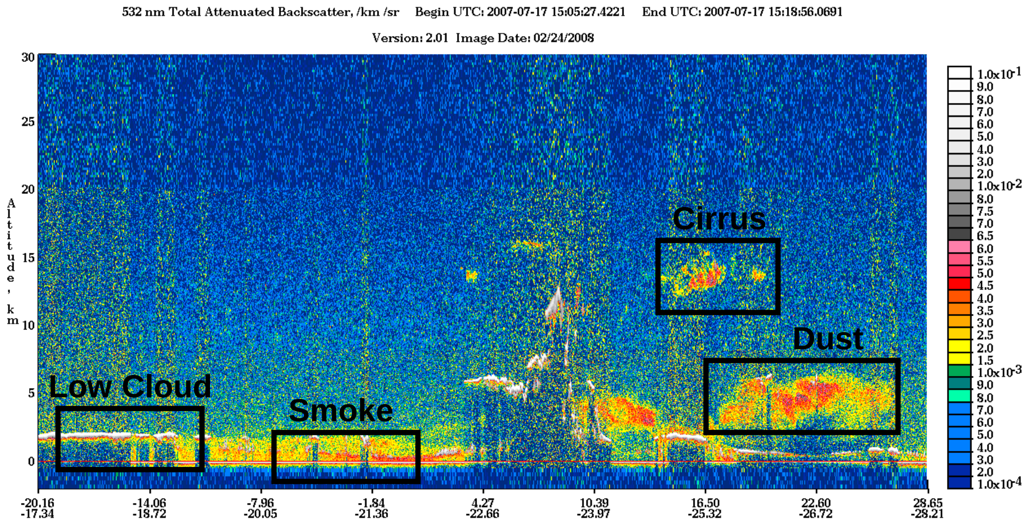

Figure 1. The 532 nm total attenuated backscatter (km-1/sr) image from the CALIOP lidar for the daytime CALIPSO track over the Tropical Atlantic on 17 July 2007. The black boxes identify the cloud and aerosol layers which serve as the basis of the nine profile types used in this study (http://www-calipso.larc.nasa.gov/products/lidar/browse_images/show_calendar.php).

cloud and aerosol layers detected in the profile. The 532 nm total attenuated backscatter (km^{-1}/sr) from CALIOP for 17 July, 2007 appears in Figure 1, with black boxes to demonstrate the cloud and aerosol layers used to define the ten profile types. A cirrus cloud is defined as a cloud with optical depth between 0.1 and 1.0 and a base height higher than 8 km. It should be noted that cirrus clouds can have optical depths above 1.0, however, aerosol layers located underneath these thicker cirrus are difficult to detect. Clouds below 5 km with an optical depth greater than 0.1 are designated “Low Cloud”. Dust, typically lofted as shown in Figure 1, is classified as an aerosol layer with a depolarization ratio greater than 0.20, or between 0.07 and 0.20 with an S-ratio between 40 and 60. When the depolarization ratio is less than 0.07 or between 0.07 and 0.20 with an S-ratio greater than 60, these layers are assigned as “Smoke”. CERES radiative fluxes and CALIPSO cloud and aerosol properties for all ten profile types are compared to investigate the influence of clouds and aerosols on radiative effects.

3. RESULTS

3.1 Cloud and Aerosol Observations

Dust and smoke from Africa is prominent over the Tropical Atlantic during July 2006 to 2008, creating the opportunity for cloud-aerosol interactions. To determine the location of the cloud and aerosol layers and confirm the layers used in this study are correctly identified, the frequencies of the latitudinal occurrence of these layers are plotted in Figure 2. Low clouds, mostly marine boundary layer cumulus clouds, are detected throughout the Tropical Atlantic on all days analyzed (Figure 2). Statistically, cirrus clouds are observed in the region of the ITCZ, centered at about 7 N, and the southern Tropical Atlantic (Figure 2). These cloud locations are also observed in Figure 1, with a cirrus cloud north of the ITCZ. On 17 July 2007, an elevated, optically-thick dust layer is observed off the northwestern coast of Africa between 27 N and 17 N (Figure 1). Typically in July, the Northern Tropical

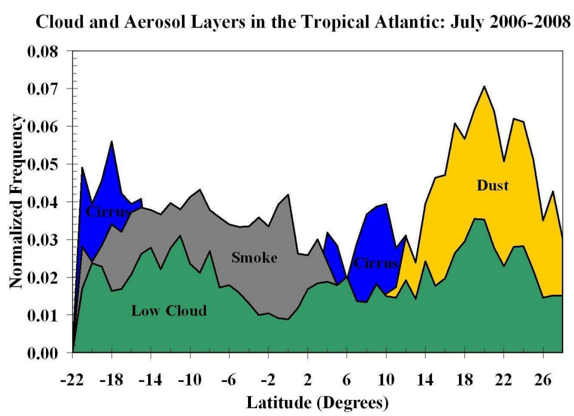

Figure 2. The frequency of the latitudinal occurrence of low cloud (green), dust (yellow), smoke (grey), and cirrus (blue) profiles for all 3 years of July data.

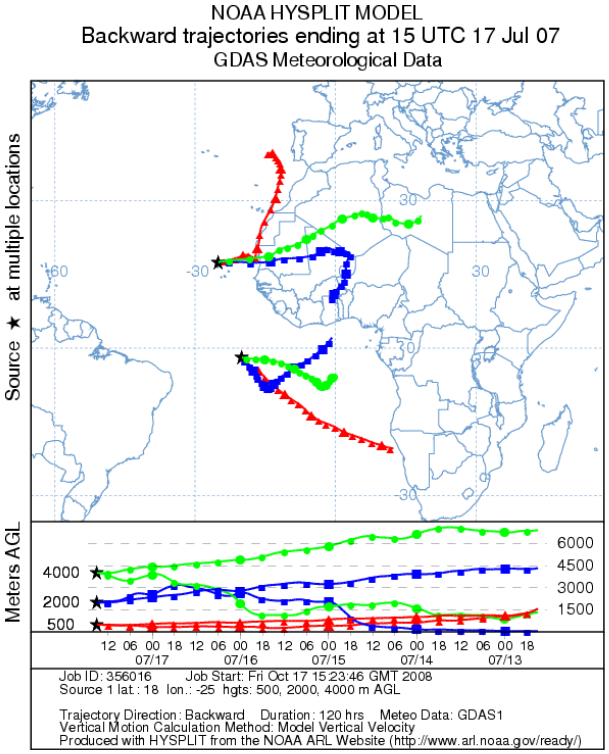

Figure 3. Back trajectories from NOAA HYSLPIT (http://www.arl.noaa.gov/ready/hysplit4.html) and EDAS 40 km Meteorological fields initialized at 18 N, 25 W and 2 S, 20 W for 17 July 2007 at 1500 UTC.

Atlantic (28 N to 10 N) is heavily influenced by dust (Figure 2). Back trajectories initialized at 18 N, 25 W for 17 July 2007 at 1500 UTC reveal 4 km flow from the low-level Sahara Desert region, further verifying the lofted layer is dust from Saharan sources (Figure 3). Back trajectories for all other days studied also suggest the Saharan boundary layer as the source of the dust layers observed in Figure 2, which compares favorably with the results of Kaufman et al. (2005). In addition, smoke layers are prevalent during July in the marine boundary layer from 4 N to 22 S (Figure 2), similar to the findings of Myhre et al. (2003). The source of these smoke layers in Figure 1 and 2 are likely attributed to biomass burning in southern Africa. On 17 July 2007, back trajectories initialized at 2 S, 20 W demonstrate low-level (500 m) flow from southern Africa (Figure 3). Carbon Monoxide (CO) increases during the month of July compared to previous months in southern Africa have been modeled and observed due to savanna burning in Sahel (Bremer et al., 2004). The locations of cloud and aerosol layers determined in this study are consistent with previous results and can be used to evaluate differences in radiative fluxes.

In the absence of clouds, aerosols such as smoke and dust scatter solar radiation back to space, causing a cooling effect compared to clear, pristine conditions. Figure 4 shows the 2006, 2007, 2008 and 3-year mean instantaneous TOA SW radiative fluxes for all cloud-free profiles. Over the Tropical Atlantic, clear and pristine skies have a 3-year mean SW radiative flux of 74.0 W/m^2. Cloud-free profiles containing smoke and dust layers yield a 3-year mean of 141.5 and 161.9 W/m^2, respectively, increases of 90% and 118% compared to clear and pristine conditions. It was expected that dust scatters more SW radiation than smoke, given their respective single scattering albedo. Cess (1985) reports a single scattering albedo at 550 nm of 0.70 for smoke, lower than the 0.98 value of dust. In the longwave, the introduction of aerosols causes a decrease in TOA radiative flux, but only by about 5%. Therefore, when aerosols are observed in the Tropical Atlantic, the scattering of solar radiation back to space is more dominant than the greenhouse effect.

The presence of clouds in the atmosphere can have a large impact on radiative effects. To compare the impact on radiative effects for different profile types, the 2006, 2007, 2008 and 3-year mean instantaneous SW radiative fluxes for all cloud profiles is displayed in Figure 5a. The 3-year mean SW radiative flux for low cloud and cirrus cloud profiles are 271.5 and 208.0 W/m^2, respectively. The low cloud profiles have a greater cooling effect than the optically thin cirrus clouds observed in this study, likely a characteristic of the larger optical depths observed in low clouds. Table 2 shows a 3-year mean optical depth of 2.00 for low clouds, but only 0.53 for the cirrus profiles. Rajeevan et al. (1999) demonstrated that clouds with large optical depths have a large negative (cooling) net cloud forcing because the effect of cloud albedo exceeds the cloud greenhouse effect. However, cirrus clouds have a

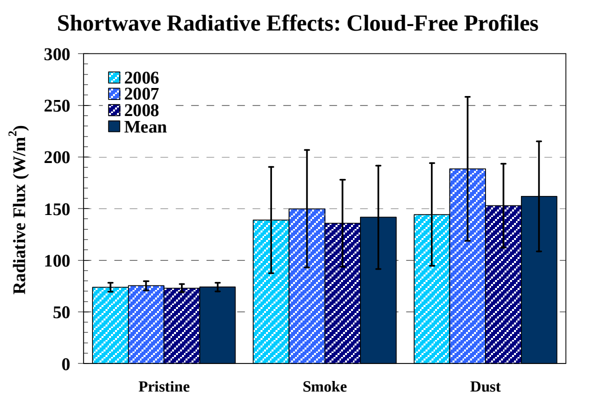

Figure 4. The 2006, 2007, 2008 and 3-year mean instantaneous SW TOA radiative fluxes (W/m2) for all cloud-free profiles (Pristine, Smoke, Dust). The black error bars represent +/- one standard deviation.

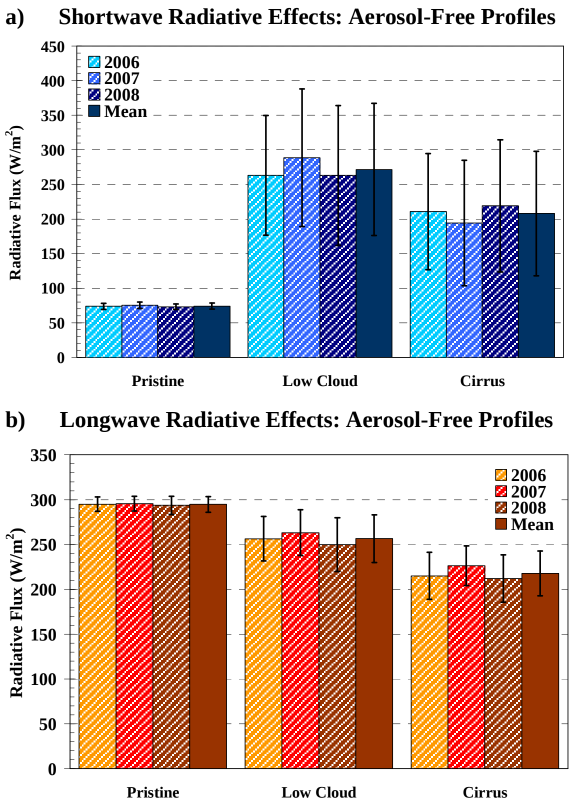

Figure 5. The instantaneous SW (a) and LW (b) TOA radiative fluxes (W/m2) for all cloud profiles for 2006, 2007, 2008 and 3-year mean. The black error bars represent +/- one standard deviation.

stronger greenhouse effect than low clouds. The 3-year mean LW radiative flux for cirrus clouds is 217.8 W/m^2, which is 15% lower than Low Cloud profiles and 26%lower than clear, pristine profiles (Figure 5b). This is likely attributed to the difference in cloud height between cirrus (11.75 km) and low clouds (1.91 km) in Table 2, an association that has been shown by Weare (1997). The stronger greenhouse effect of cirrus indicates a weaker net cooling effect compared to low clouds, which ultimately demonstrates the importance of low clouds on the climate system. When these low clouds are formed in air laden with aerosols, the radiative effects become more complex.

3.3 Cloud and Aerosol Interactions

The presence of aerosols in profiles with low clouds or cirrus clouds weakens the SW cooling effect of these clouds. However, these radiative effects could originate from different mechanisms due to the aerosol characteristics of dust and smoke layers over the Tropical Atlantic.

Profiles in which both dust and low clouds are observed yield a 3-year mean SW radiative flux of 209.3 W/m^2, about 25% less than aerosol-free low cloud profiles (Figure 6). The normalized frequency of the altitude of the dust and cloud layers from DLC profiles (Figure 7a) and smoke layers from SLC profiles (Figure 7b) suggest the height of the aerosol layer plays a significant role in the aerosol-cloud interaction. In both DLC and SLC profiles, over 85% of cloud layers are observed below 3 km. Approximately 70% of dust layers are found above 3 km and above the majority of cloud layers. These dust layers absorb solar radiation, which decreases the amount of solar radiation that reaches the cloud and evaporates cloud particles located in the upper part of the cloud (the semi-direct effect). The presence of dust in low cloud profiles decreases the values of mean optical depth (1.63) and cloud integrated attenuated backscatter (CIAB, 0.489 sr^{-1}) by nearly 20% and 50%, respectively (Table 2). It has been shown that a decrease in cloud optical depth and water path partially reduces the cloud cooling effect, dominated by the aerosol semi-direct effect (Huang et al. 2006b). The influence of aerosols on LW radiative effects of low clouds, already weak forcing compared to cirrus clouds, is minimal because aerosols only increase LW radiative flux by less than 5%. Ultimately, the weakening of net low cloud cooling is dictated by two factors; dust absorption above the cloud and changes in cloud microphysics.

Similar to dust layers, the SW radiative flux of low clouds decreases in the presence of smoke layers while the LW flux is relatively insensitive to the presence of smoke layers in low cloud profiles. The 3-year mean SW radiative flux for SLC profiles is 243.0 W/m^2, nearly 30 W/m^2 less than Low Cloud profiles (Figure 6). However, 72% of smoke layers are found below 3 km,

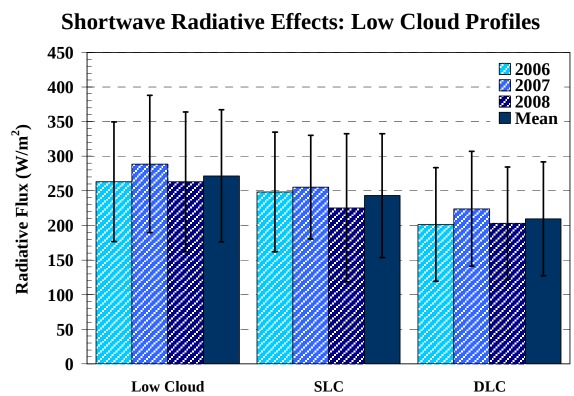

Figure 6. The 2006, 2007, 2008 and 3-year mean instantaneous SW TOA radiative fluxes (W/m2) for all low cloud profiles (Low Cloud, Smoke-Low Cloud, Dust-Low Cloud). The black error bars represent +/- one standard deviation.

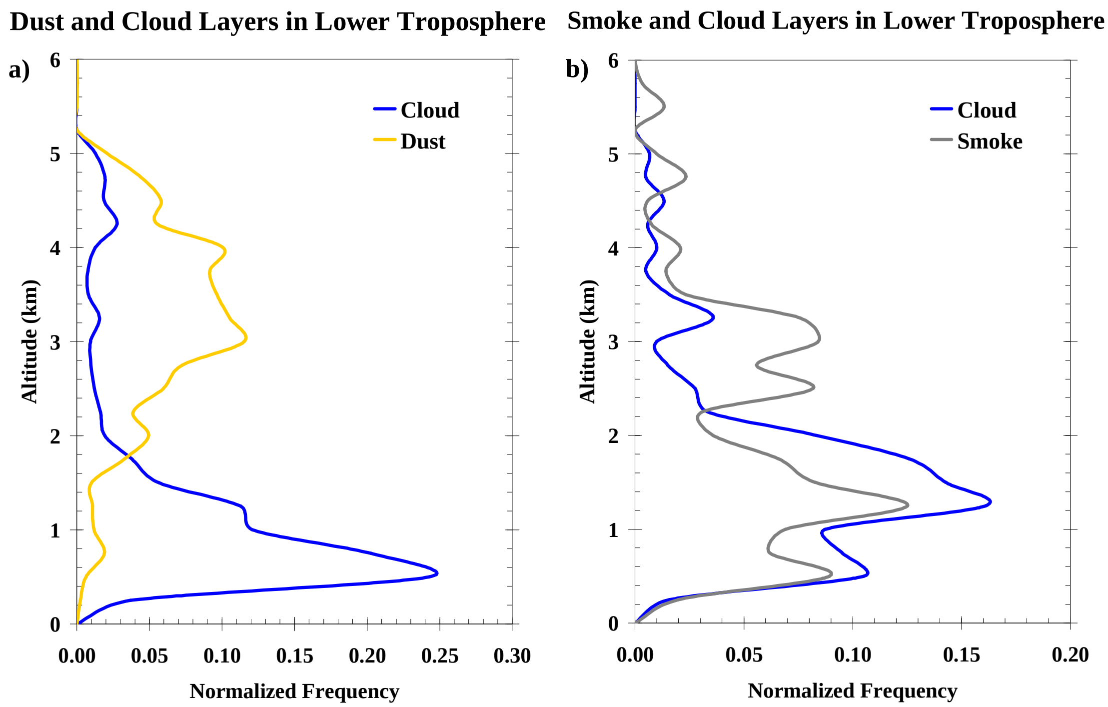

Figure 7. The frequency of the altitude (km) of low cloud and dust layers from DLC profiles (a) and low cloud and smoke layers from SLC profiles (b) for all 3 years of July data. The frequency is normalized using the total number of profiles shown in Table 1.

at the same level as the majority of the cloud layers (Figure 7b). Since the smoke and cloud layers are at the same level, changes in cloud microphysics are prominent. Values of mean optical depth (1.55) and cloud integrated attenuated backscatter (0.493 sr^{-1}) for SLC profiles are nearly 25% and 50%, respectively, lower than Low Cloud profiles (Table 2). Mean cloud particle radius derived by CERES-MODIS data are also lower for SLC profiles, although not statistically significant. Therefore, the decrease in low cloud cooling when smoke is present may be dominated by changes in cloud microphysics due to the smoke aerosol semi-direct effect.

It is possible that radiative effects of cirrus clouds could be influenced by dust and smoke layers, despite the fact that cirrus clouds are typically 5-9 km higher than these aerosol layers. The 3-year mean SW radiative fluxes for DC and SC profiles are 183.8 W/m^2 and 167.7 W/m^2, respectively. These values are 12% and 20% less than the 208.0 W/m^2 of Cirrus profiles. The greenhouse effect of cirrus clouds is also significant and impacted by aerosols. SC and DC profiles have mean LW radiative fluxes of 235 W/m^2, nearly 7% greater than the value of 217.8 W/m^2 for aerosol-free cirrus cloud profiles. Su et al. (2008) suggest that reduced cooling due to the existence of dust under clouds can be considered as a warming effect of these aerosols from dust absorption. It is possible that changes in cloud microphysics also contribute to changes in SW and LW radiative flux observed but because of the small sample sizes of the DC and SC bins (Table 1), the changes in cloud microphysics could be induced by the aerosols themselves (semi-direct effect) or the meteorological conditions in which the dust and smoke layers were transported. The exact origin to these changes in cloud microphysical properties is outside of the scope of this study, but does warrant future investigation.

4. CONCLUSION

Dust and smoke from African sources are transported into the Tropical Atlantic atmosphere, where they interact with marine boundary layer and cirrus clouds. These cloud-aerosol interactions influence the atmospheric radiation budget and climate system. Phenomena such as aerosol indirect and semi-direct effects can occur, but few studies have demonstrated these effects as seen from observational data. Therefore, cloud-aerosol interaction remains a major uncertainty in understanding the climate system. The launch of the CALIPSO satellite has made it possible to

Table 2. Three Year Mean of Cloud Microphysical Properties

Cloud Type	Optical Depth	CIAB (532 nm, sr-1)	Particle Radius (μm)	Height (km)
Cirrus	0.53	0.0152	18.80	11.75
SLC	1.55	0.0493	14.82	1.35
DLC	1.63	0.0489	16.35	1.21
Low Cloud	2.00	0.0858	15.58	1.91

detect aerosol and cloud layers in high-resolution vertical profiles using the CALIOP backscatter lidar. To quantify African dust and smoke influences on radiative effects in the Tropical Atlantic, collocated CALIOP data and CERES radiative fluxes from the month of July for three years (2006-2008) are separated into ten profiles types and mean SW and LW radiative fluxes are compared for each profile type.

Individual aerosol and cloud layers over the Tropical Atlantic result in stronger SW radiative cooling, and stronger greenhouse effects compared to clear and pristine conditions. These radiative effects are altered when African dust and smoke layers interact with marine boundary layer and cirrus clouds over the Tropical Atlantic. The most profound impact is found at the lower levels, where aerosols can lead to a weakening of low cloud cooling in excess of 30%, exhibiting the importance in understanding the influence of cloud-aerosol interactions on the radiation budget and climate system. Profiles with dust and low clouds present have a 3-year mean SW radiative flux of 209.3 W/m^2, about 25% less than aerosol-free low cloud profiles. This appears to be a result of elevated dust layers absorbing solar radiation, which can inhibit radiation from reaching the cloud and evaporate cloud particles within the cloud. Similarly, the SW radiative flux for SLC profiles are 12% less than Low Cloud profiles. However, changes in cloud microphysics are likely the dominant effect since values of mean optical depth and cloud integrated attenuated backscatter for SLC profiles are nearly 25% and 50% lower than aerosol-free low cloud profiles, and smoke layers are found at the same altitude as the low clouds. The aerosol layer height and type are critical factors in determining the type of cloud-aerosol interaction and are better detected using the CALIOP lidar than any other A-Train instrument.

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