Observed Impact of Smoke Aerosols on the Stratocumulus-to-Cumulus Transition in the Equatorial Atlantic

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Key Points:

- Transport of smoke aerosols within the equatorial Atlantic impact the stratocumulus to cumulus transition.
- Aerosol radiative effects alter lower tropospheric stability and moisture availability throughout the tropical and subtropical Atlantic.

Abstract

The impact of smoke aerosols on the stratocumulus-to-cumulus transition (SCT) in the equatorial Atlantic is studied using observation-based data for the month of June. Boundary layer deepening and increasing sea surface temperatures put the location of the SCT within the Gulf of Guinea. Satellite retrievals indicate that the bulk of aerosols occurs at 1500m in altitude, either above or below the boundary layer depending on latitudinal position. Changes in smoke loading over the Gulf of Guinea due to greater transport from regions of biomass burning leads to increased low-level cloud cover and lower surface temperatures when aerosol optical depth anomalies exceed 0.1. Similar results opposite in sign are obtained during lesser transport. Further south, we find significant changes to cloud top height, tropospheric stability and moisture availability. These effects combine to alter the SCT during increased loading, which is consistent with previous modeling studies.

1 Background/Introduction

Differential heating due to Earth's axial tilt causes excess energy in the form of shortwave radiation in the tropics that must be transported poleward. This sets up regions with considerable meridional sea surface temperature (SST) gradients. In addition, locations with eastern boundary currents that transport cooler waters equatorward coupled with large-scale subsidence are dominated by persistent stratocumulus decks [*Klein and Hartmann*, 1993]. As these decks follow the mean trade wind circulation equatorward, the cloud regime transitions from predominantly stratocumulus to trade cumulus [*Bretherton*, 1992; *Bretherton and Wyant*, 1997; *Bretherton et al*., 1999; *Teixeira et al.*, 2011]. A better understanding of this Stratocumulus-to-Cumulus transition (SCT) is important for modelling cloud interactions in a changed climate.

Factors that may potentially influence this transition has been studied using both observations [*Albrecht et al.*, 1995; *Albrecht et al.*, 2019; *Wood et al.*, 2018] and model simulations [*Chung et al.*, 2012; *Sandu and Stevens*, 2011]. The major factors controlling cloud coverage in these transition regions are lower tropospheric static stability (LTS) [*Wood and Bretherton*, 2006] and the typical advection of a cloud system over increasing SST. These two factors have been identified as important for all the ocean basins and they both lead to larger surface latent heat fluxes, buoyancy fluxes and boundary layer deepening.

Aerosols alter earth's radiation budget in three different ways, all of which can contribute to changes in cloud properties. First, aerosols directly impact the planetary energy balance through the absorption and scattering of incoming radiation [*Ramanathan*, 2001; *Haywood and Boucher* 2000], which is known as the "direct effect". Second, some aerosols act as cloud condensation nuclei (CCN), thereby influencing cloud droplet size and consequently the likelihood of coalescence and the accumulation of liquid water and ice in clouds, thus altering cloud albedo and lifetime [*Albrecht*, 1989; *Ferek et al.*, 2000; *Ghan et al.*, 2012]. This is the so-called "indirect effect". Third, solar absorbing aerosols such as black carbon can alter heating rates, the vertical temperature profile, and atmospheric stability, which can lead to cloud adjustments. The radiation flux associated with this adjustment is termed the aerosol "semi-direct effect" [*Hansen et al.*, 1997].

Observations have been used to understand the influence of smoke aerosols on boundary layer clouds in the southeastern Atlantic [*Painemal et al.*, 2014; *Wilcox*, 2010, 2012]. The consensus from such studies is that the location of the smoke layer relative to the cloud deck ultimately determines the resulting effect. When smoke resides above the cloud deck, there tends to be a strengthening of the inversion layer and cloud radiative effect whereas smoke within the boundary layer leads to decreased cloud fraction and increased temperatures within the boundary layer.

There have been few studies that look into how smoke aerosols may impact the SCT [*Sandu and Stevens*, 2011; *Yamaguchi et al*., 2017; *Terai et al*., 2014; *Painemal et al*., 2015; *Zhou et al*., 2015] and fewer studies that use observations in the Atlantic Ocean. The Atlantic Stratocumulus Transition Experiment-ASTEX [*Albrecht et al*., 1995] conducted in 1992 resulted in data leading to a coherent understanding as well the first measurements of its kind for cloud microphysical properties in the SCT of the northeastern subtropical Atlantic but did not investigate the impact of smoke aerosols.

In the southeastern subtropical Atlantic, there has not been an observational study looking at how aerosols may impact the SCT. Some studies that use large-eddy simulations (LES) to better understand this phenomenon

[*Yamaguchi et al*., 2015; *Zhou et al*., 2017] incorporate observed data from the northeastern subtropical Pacific and knowledge of smoke aerosols from active fires interacting with stratocumulus clouds off the coast of Southern Africa. Both studies find evidence of aerosols impacting the SCT but through contrasting mechanisms and end results. *Yamaguchi et al.,* [2015] attribute a delay of the SCT to increased LTS due to aerosol heating above the cloud layer, while *Zhou et al*., [2017] find a hastened transition due to increased cloud droplet number concentration and cloud water evaporation.

The scientific questions motivating this study are:

1. Can we clearly see a SCT region where black carbon aerosol emissions impact low-level cloud fraction?
2. What are the important mechanisms of black carbon aerosols possibly impacting the spatial structure of the SCT?

Knowing that these transitions occur in all four subtropical ocean basins, not many locations can satisfy the added component of solar-absorbing aerosols (black carbon) being present. We have located a region in the equatorial Atlantic with various cloud types transitioning from stratocumulus to trade cumulus and even deep convective cumulonimbus that have the potential to be influenced by local smoke aerosol emissions. This study will be extremely important for designing future field campaigns and testing global climate models (GCMs) abilities to simulate the SCT.

2 Data Sources and Methods

In order to determine the impact of smoke aerosols on cloud structure and precipitation processes, daily-averaged data are utilized from a variety of sources (with the exception of aerosol extinction). Utilizing daily intervals of data allows for a better sampling resolution as well as capturing mesoscale and synoptic-scale weather processes that would not be resolved with monthly data output.

Daily aerosol optical depth (AOD) for the years 2003-2015 are obtained from Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) at 0.5°x0.625° resolution [*GMAO,* 2015]. Having missing AOD data can lead to large errors when undergoing statistical analysis. Using reanalysis data reduces such errors as data not captured by observations are assimilated using a numerical algorithm to create a synthesized estimate of the state of the climate system (*Bengtsson et al*., 2004). Observations, such as the aerosol index and aerosol absorption optical depth obtained from the Ozone Monitoring Instrument (OMI) measurements and aerosol retrievals from the AErosol RObotic NETwork (AERONET) [*Buchard, et al*., 2015] validated the MERRA data obtained from reanalysis used in our study. This data is based on a version of the NASA Goddard Earth Observing System version 5 (GEOS5) model that is radiatively coupled to the Goddard Chemistry, Aerosol, Radiation, and Transport (GOCART) aerosol module and includes assimilation of observations from satellites.

To analyze the effect of aerosols on cloud cover, we obtained cloud coverage data during the study period from Clouds and the Earth's Radiant Energy System (CERES) data, which is available, daily-averaged, at 1-degree resolution [*Doelling et al*., 2013; *Doelling et al*., 2016]. This data is broken down into 4 vertical cloud levels (low [surface-700mb], mid-low [700mb-500mb], mid-high [500mb-300mb] and high [300mb-tropopause]). Cloud properties are determined using simultaneous measurements by other EOS and S-NPP instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible and Infrared Sounder (VIRS).

High resolution (0.25°x0.25°) daily SST data is provided by the National Oceanic and Atmospheric Administration's (NOAA) Earth System Research Laboratory (ESRL) Physical Sciences Division [*Reynolds et al*., 2007]. NOAA's 0.25° daily Optimum Interpolation Sea Surface Temperature (OISST) data is compiled from observational platforms taking into account bias adjustments.

Daily wind, temperature, specific humidity, convective available potential energy (CAPE), and cloud liquid water content data at 0.75° by 0.75° resolution were obtained at multiple pressure levels ranging from the surface to 500hPa from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis product [*Berrisford et al*., 2011] at a local time of 6 A.M. UTC. This is consistent with the analysis of *Tosca et al*., [2015], who studied

the changes in cloud fraction associated with variability in fire emissions and compared meteorological variables in control and high fire scenes using ECMWF reanalysis at a 6 A.M. local time to better understand the influence of mesoscale dynamics. Furthermore, mid-level clouds have been found to dominate cover over West Africa during the monsoon season early in the morning [*Bourgeios et al*., 2018].

In order to quantify the magnitude and location of anomalous changes in rainfall, daily data at 1-degree resolution is obtained from the Global Precipitation Climatology Project, Version 1.2 (GPCP 1.2). All the GPCP products are produced by optimally merging precipitation estimates computed from microwave, infrared, sounder data observed on board satellites, and ground-based rain gauge analysis, taking advantage of the strengths of each data type [*Huffman et al*., 2016]. These satellite datasets have been validated against rain gauges on land in West Africa, particularly on sub-monthly time scales [*Nicholson et al*., 2003].

Monthly smoke aerosol extinction coefficients are acquired from NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) platform for the years 2003-2015 using the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument. CALIPSO lidar level 3 aerosol data product reports monthly mean profiles of aerosol optical properties on a 2°x5° spatial grid [Winker, 2015] and 60m resolution in the vertical direction. We use monthly data because the return time between overpasses is too long at daily intervals.

Data analysis is conducted for June, representing monsoon onset as well as the establishment of a cold tongue in the eastern equatorial Atlantic Ocean as the intertropical convergence zone (ITCZ) migrates northward, intensifying trade winds and creating large meridional SST gradients. Our study region comprises of the boundary between 15°N-15°S and 10°W-10°E (Figure 1a). Also, to note, SST's decrease 2°C in the Gulf of Guinea (GoG) from the beginning to end of June. As a result, all data used in this study are detrended by the mean monthly June trend to remove variability arising solely from the seasonal cycle.

For each of the 13 years, the 30 days in each June were classified into pentiles according to the magnitude of AOD averaged between 5°N-5°S and 10°W-10°E in the GoG for that day. The top and bottom pentiles aggregated from each June resulted in 78 days that are referred to as "clean" (lowest AOD) and "dirty" (highest AOD) days. All dates associated with these dirty and clean days are averaged together to create composites that track how aerosol loading evolves with other meteorological variables of interest. Trends are then removed from composited data to reveal detrended, anomalous changes. By utilizing this method, we attempt to determine which variables are impacted by variations in aerosol transport. Statistical significance of results was determined by the 95% confidence interval according to a 2-tailed Student's t-test accounting for serial correlation by using the effective sample size, $n(1-r_1)(1+r_1)^{-1}$, where n is the number of days and r_1 is the lag-1 autocorrelation coefficient leading to ~3 day decorrelation time.

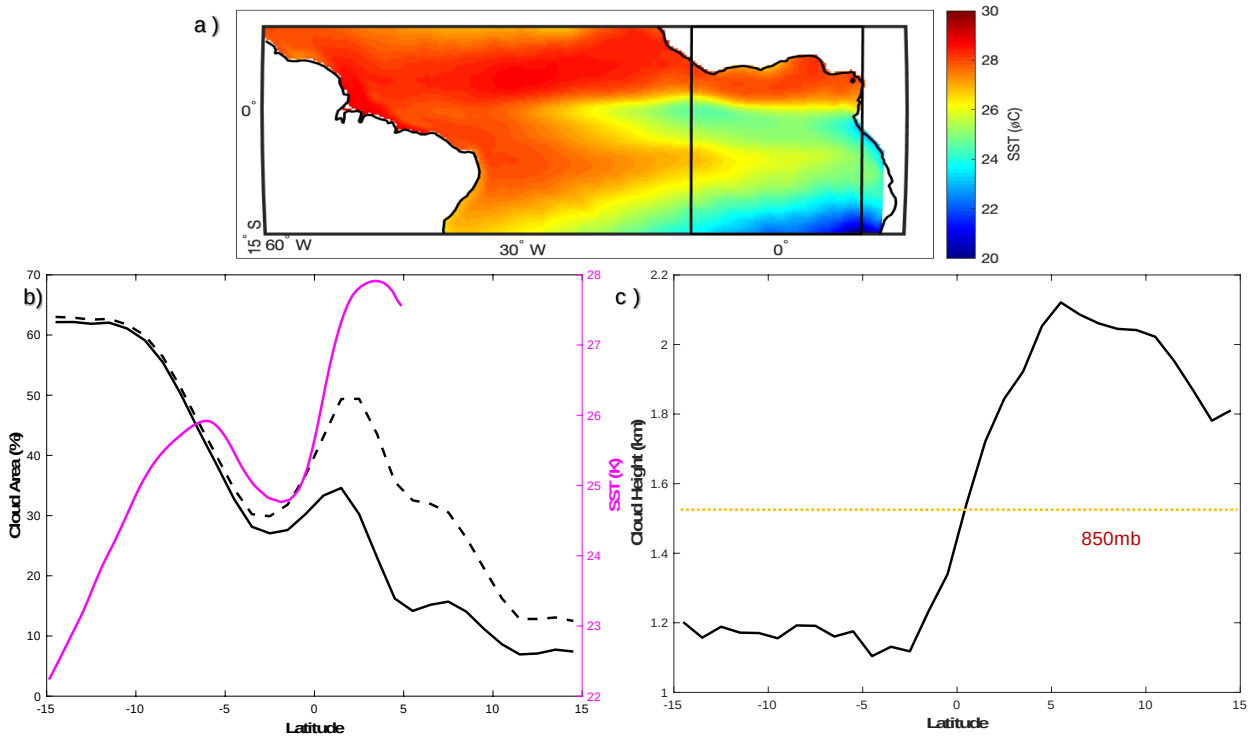

Figure 1. (a) Climatological June SST, (b) zonally-averaged low cloud area fraction and SST and (c) corresponding cloud top height for the years 2003-2015. The black box in **(a)** represents longitudinal boundaries used to average data in **(b)** and **(c)** as well as subsequent figures. Dashed black lines in **(b)** represent cloud area fraction accounting for obscurity from high level clouds.

3 Results

3.1. Study Region Overview

For the month of June, climatological conditions in the Eastern equatorial Atlantic are excellent for studying the SCT. Between the ITCZ migration and trade wind intensification, a large, meridional SST gradient sets up a corresponding cloud structure aloft. Starting in the southern subtropical Atlantic moving equatorward, we see an inverse relationship between increasing SST and decreasing low-level cloud fraction (Figure 1b). Of particular interest, we notice two locations where cloud fraction decreases to half the value it had farther south (7°S-3°S and 1°N-5°N). We note that this decrease is not as pronounced when accounting for obscurity from high-level clouds. Within the Gulf of Guinea (GoG), we examine the structure of cloud top height and find a ~700m increase (Figure 1c) in the same location that the cloud fraction decreases. We believe this is where the boundary layer deepens due to increasing SST in GoG and where the stratocumulus deck transitions into cumulus clouds. Further aloft, increases in higher level clouds (Fig 2 a) occur within the GoG in addition to precipitation rates rising to a maximum.

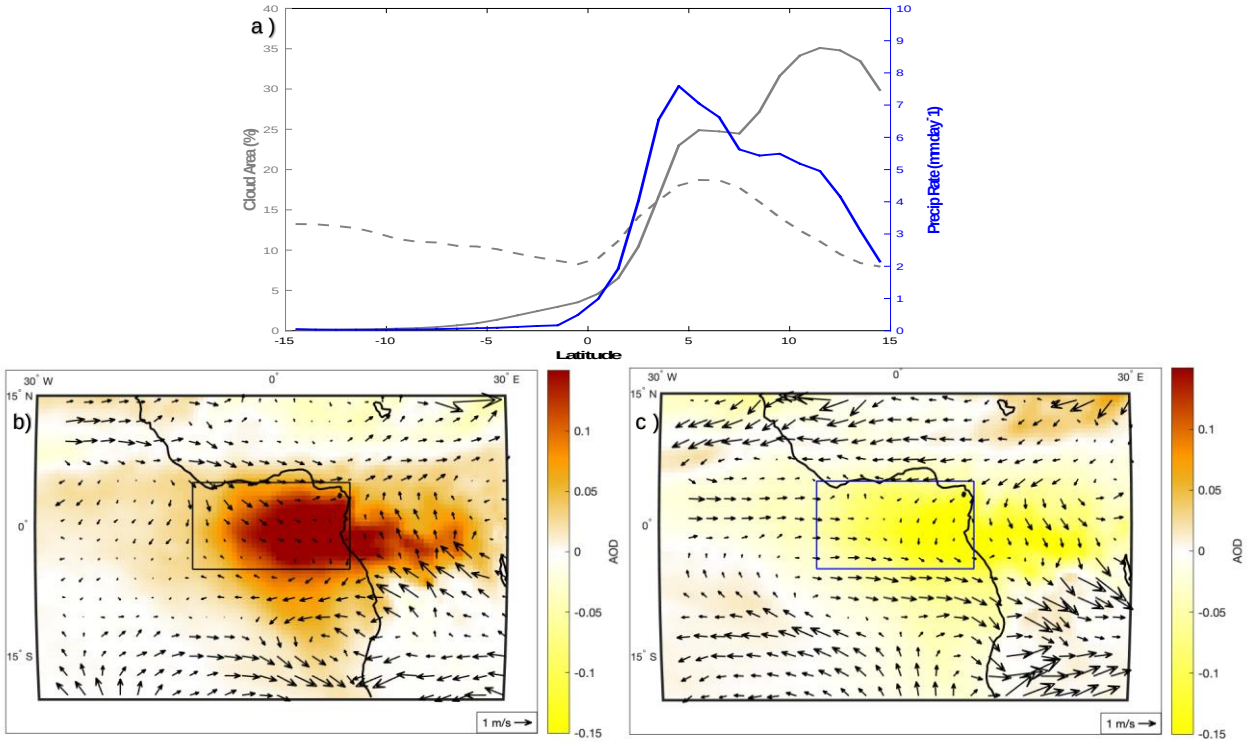

Figure 2. (a) Climatological, zonally-averaged mid-high (gray, dashed) and high (gray, solid) cloud fraction overlain with precipitation rates for the years 2003-2015, see Figure 1 for averaging area. AOD and 850 hPa wind anomalies for dirty **(b)** and **(c)** clean days during the same time period. Rectangular boxes in **(b)** and **(c)** represent averaging areas for composite analysis.

3.2. Aerosol-Low Cloud-SST Feedback

In order to understand aerosol-cloud interactions, first we must visualize at what altitude smoke aerosols are located. Long-term mean vertical aerosol extinction profiles representing locations in our study region are shown in figure 3a. We see the largest values at 4°S and the equator at an altitude just below 1500 meters. This extinction maximum occurs above the low cloud top height (Fig 1c). Further north, we notice decreases in mean extinction as aerosols enter the boundary layer. Regardless of location, values taper toward 0 near 5.5 km. Figure 3b shows that most of the smoke along the Prime Meridian is located between 1000m-3000m specifically where AOD anomalies exceed 0.1(~25% of the monthly mean) on dirty and clean days (Fig 2 b, c).

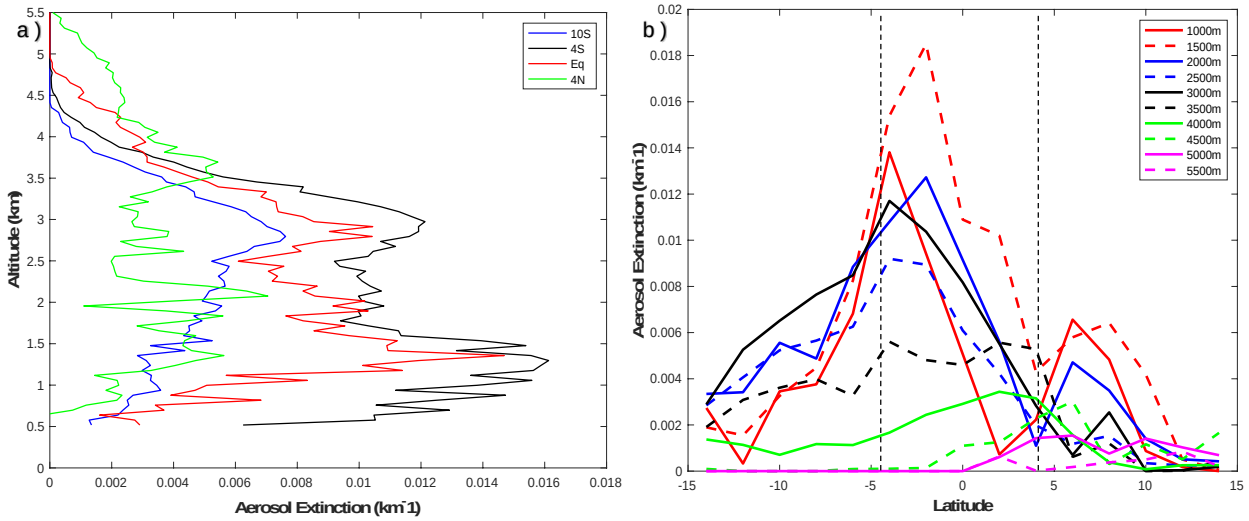

Figure 3. (a) Long-term mean single point and (b) zonally-averaged smoke aerosol extinction profiles for the month of June (2003-2015). Data in panel **(a)** represent values along the Prime Meridian. Dotted lines in panel **(b)** represent the boundary where AOD anomalies exceed 0.1. See Figure 1 for averaging area.

During dirty/clean smoke episodes, we find evidence of increased/decreased low-cloud fraction specifically within the equatorial Atlantic cold tongue zone and within the area where maximum aerosol loading occurs. As low cloud fraction increases, it is possible the amount of shortwave radiation reaching the ocean surface diminishes as is reflected by changes in SST (Fig 4). It is difficult to discern whether this is due to the cloud radiative effect (CRE) or aerosol radiative effect (ARE) with pure observations. However, we find positive low cloud fraction anomalies where cloud top heights reach a minimum near the cold tongue. Figure 3b shows that the bulk of smoke aerosols resides above this height. Thus, our results are in agreement with previous studies that find evidence of stratocumulus thickening above smoke layers with enhanced loading [*Wilcox, 2010*; *Wilcox*, 2012; *Li et al*., 2013]. As smoke travels north or south within the boundary layer, cloud fraction decreases, as found in *Zhang and Zuidema* [2019, in review]. Significant decreases are found south of 5°S as recent evidence shows that the boundary layer is often smoky especially in June [*Zuidema et al.*, 2018], although we can rule out the influence of meteorological parameters [*Adebiyi and Zuidema*, 2018].

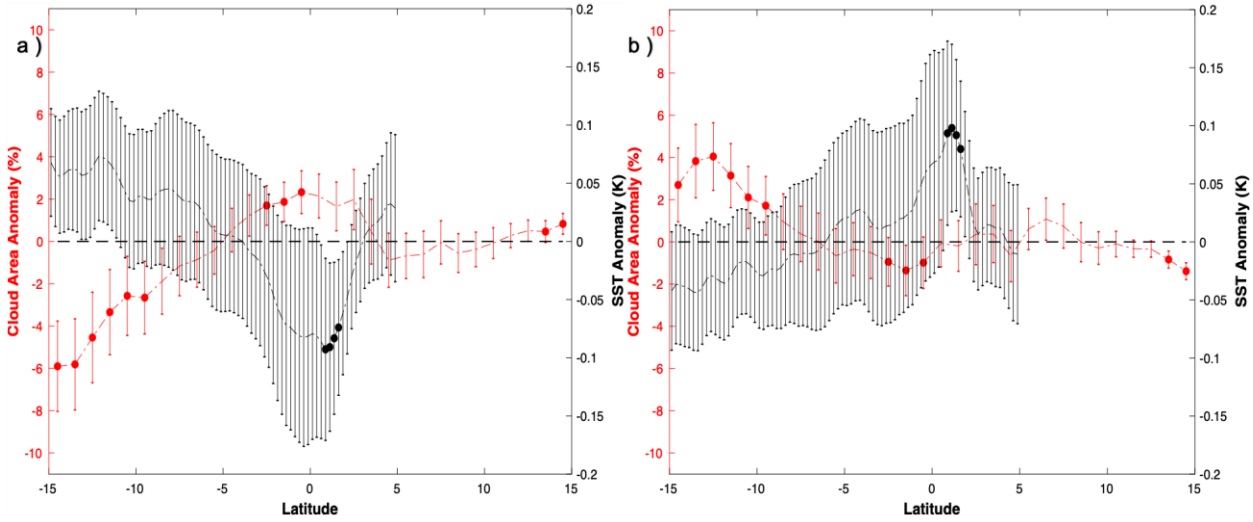

Figure 4. Zonally averaged low cloud area fraction and SST anomalies for **(a)** dirty and (**b)** clean smoke episodes. See Figure 1 for averaging area. Error bars range 1 standard error and filled circles represent locations where the difference between sampled means exceed the 95% confidence level.

3.3. Stability vs. Moisture Aloft

Yamaguchi et al., [2015] find that smoke aerosols delay the SCT by strengthening of the inversion layer. In accordance with this study and others that look at LTS as a controlling factor for low cloud amount within SCT regions [*Wood and Bretherton*, 2006; *Sandu and Stevens*, 2011], we examined changes in potential temperature (θ) profiles and cloud top height anomalies (Fig 5). Here, we can clearly see the effects of anomalous smoke loading on atmospheric stability. During dirty smoke episodes, we find significant decreases in low-level cloud top height between 25-100 meters from the cold tongue southwards (Fig 5a). By analyzing θ anomalies along the Prime Meridian transect, we can infer where aerosols impact stability within the lower troposphere (Fig 5b). As expected, the largest response occurs near 850hPa, which corresponds to ~1500m above sea level (Fig 1c). In the subtropics (10°S and 4°S), we find the largest changes in cloud height and θ anomalies although smoke aerosol extinction values do not vary much between 750m-4000m. Further north, these changes are less pronounced. We note significant surface cooling during dirty episodes, particularly at the equator where low cloud anomalies peak.

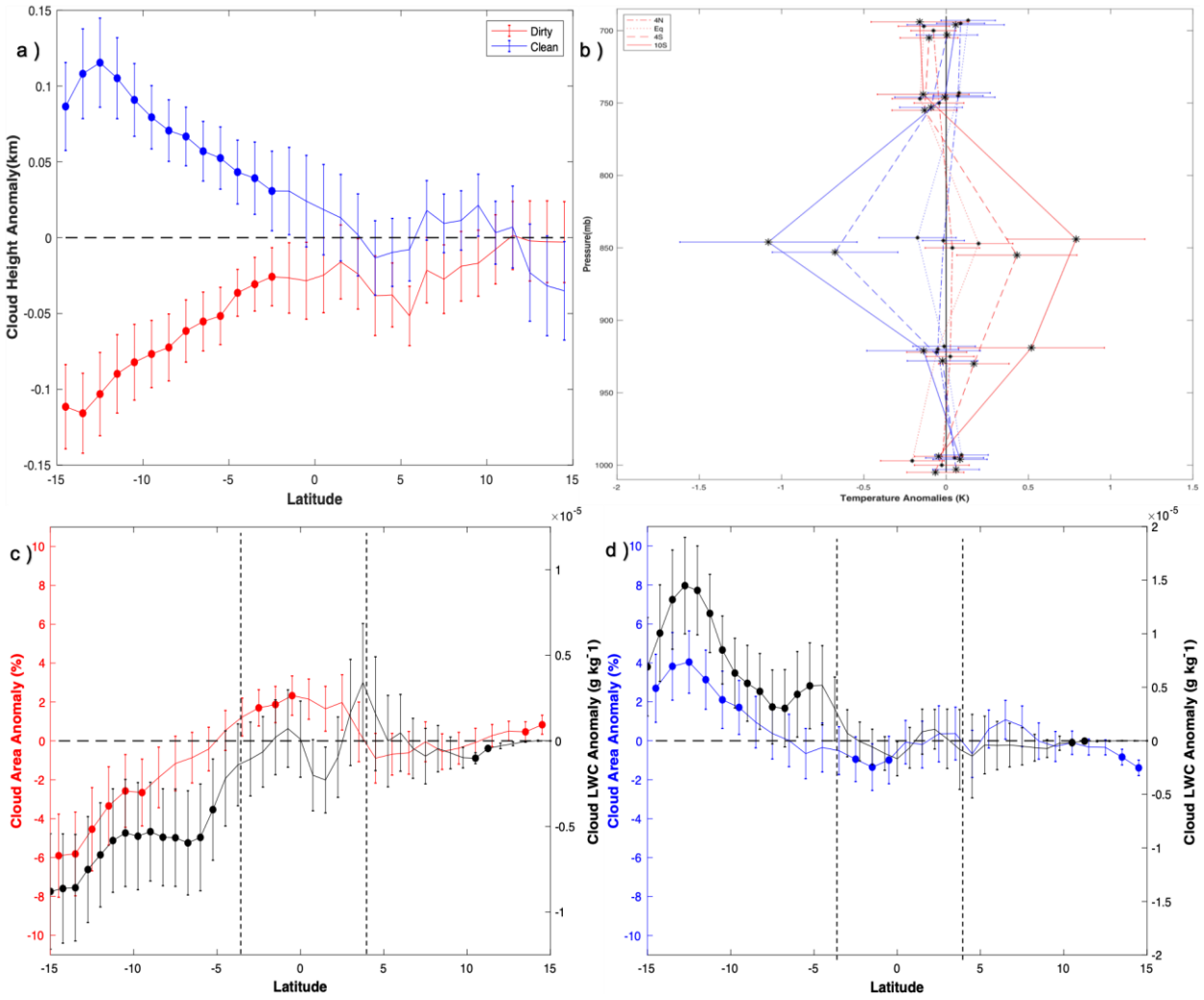

Figure 5. Anomalous changes in meteorological variables representing atmospheric stability and moisture: **(a)** cloud top height, **(b)** θ at various latitudes and cloud liquid water content at 850hPa for dirty**(c)** and clean**(d)** conditions. Data plotted in panel **b** are taken along the Prime Meridian. Panels **c** and **d** contain dotted lines representing the boundary where AOD anomalies exceed 0.1. See Figure 1 for averaging area. Error bars range 1 standard error and filled circles represent locations where the difference between sampled means exceed the 95% confidence level.

Using a large eddy simulation (LES), *Zhou et al.*, [2017] find a hastened SCT linked to increased cloud droplet number concentration (due to smoke aerosols) that leads to faster evaporation of cloud water which enhances entrainment. Their complementary experiments that included additional moisture aloft, which is believed to accompany biomass burning plumes relative to surrounding air [*Adebiyi et al*., 2015], revealed a more hastened SCT. In their study, absorbing aerosols above the cloud layer strengthens the inversion and reduces boundary layer height, in agreement with our findings. However, as aerosols enter into the boundary layer, they find that enhanced entrainment of surrounding warm, dry air reduces cloud cover. North of the equator, we observe low cloud cover and cloud liquid water content (CLWC) at 850hPa slightly change simultaneously (Fig 5 c-d) where smoke enters into the boundary layer (Fig 1c) but are not significant. During dirty episodes, we find 10-20% (0.1-0.2 g kg^{-1}) of moisture increases at 850hPa within our region of max AOD loading (Fig 5d) relative to recent observational studies [*Adebiyi et al*., 2015; *Haywood et al*., 2003]. However, those studies occurred in the southern Atlantic so our estimates may not be directly comparable.

4 Conclusions

Using observational data, we have isolated a mechanism for modulating the SCT in the equatorial Atlantic that has not yet been discussed in the literature. This transition is located within the GoG and thus we conducted our AOD composite analysis at this location.

In the subtropical Atlantic (15°S-5°S), we attribute reductions in cloud cover during dirty conditions to smoke mixing within the boundary layer (Fig3b), possibly reflecting a boundary layer positive semi-direct effect [*Zhang and Zuidema*, 2019, in review]. Within the equatorial Atlantic(4°S-2°N), elevated smoke levels lead to increases (1-2%) in low cloud cover along with decreases in SST (~0.1K) and potential temperature (~0.2K) at the surface. Also, cloud top heights decrease 20-100m, consistent with *Deaconu et al*., 2019. Boundary layer deepening reflected by increases in cloud top height (Fig 1c) within the GoG allow for smoke to mix and reduce low cloud cover between 0°-5°N, agreeing with hastened SCT from model results [*Zhou et al*., 2017]. Anomalous 850hPa winds (Fig 2b) do not reflect a pattern that would control both aerosol and cloud structures.

We attribute the switch from less low cloud for dirty conditions south of the cold tongue to more low clouds over the cold tongue to special air-sea interactions unique to this region. In the subtropics, trade winds advect the boundary layer over increasing SST's, which favors upward moisture flux from the surface to sustain cloud formations. Here, aerosol heating in the boundary layer can cause the clouds to evaporate. In contrast, when the boundary layer reaches the cold tongue, the atmosphere develops near-surface stratification which cuts off the upward moisture flux needed to sustain clouds from dry air entrainment of the free troposphere. Here, it is possible that aerosol heating may increase stratification in the upper part of the boundary layer which would reduce dry air entrainment and lead to longer lasting clouds.

Our study region offers more possibilities for research as we see cumulus clouds transitioning into deep-convective clouds within the GoG. Aerosols do not ascend high enough to have a direct influence on high-level clouds but may do so indirectly via hastening of the SCT and boundary layer moisture adjustments below. Subsequent changes in higher-level clouds and precipitation are small, but still worthy to note.

We acknowledge that this research relies on observations and so may be subjected to uncertainties associated with satellite data. It is our hope that these findings will serve as a foundation for designing future field campaigns and testing modeling studies that investigate the SCT.

Acknowledgments, Samples, and Data

All data supporting the conclusions of this research study are available through the references mentioned in the data sources and methods sections.

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