Response to Reviewer 1 （Anonymous Referee）

General comments:

This work investigated impacts of meteorology and aerosols on lightning activities in Africa based on products from TRMM, MODIS and MERRA and so on. Authors examined six meteorological variables to analyze the dominant role by thermodynamics and attributed the differences in lightning under clean and polluted conditions to aerosol effect. They separated the northern Africa and the southern Africa dominated by dust and smoke aerosols, respectively. And they found different radiative effects of different aerosol species. This work presents valuable information to understand aerosol effects on lightning. Some minor questions/suggestions need to be solved are listed in the following.

General response:

We thank the reviewer for the valuable comments and suggestions that have helped us improve the paper. Our detailed responses to the reviewer's questions and comments are listed below.

Comment and Question:

(1) Both MODIS and MERRA can provide aerosol optical depth and aerosol species, why did authors choose two datasets than one? How did authors combine aerosols, lightning and meteorological information from different platforms together?

Response:

1.1) We did take into account which data to use and compared MODIS AOD and MERRA total AOD (60°S–70°N) which shows a good correlation with R=0.88. For total AOD, these two products are well correlated. We believe that MODIS is closest to the real value among so many AOD products. So we used MODIS AOD in the statistical analysis. However, MODIS cannot measure the magnitudes of different aerosol species which contribute to total AOD. So in the process of determining study areas, we used MERRA total AOD and the AOD of different aerosol species to ensure that dust and biomass burning aerosols are dominant in these two areas.

1.2) In order to match lightning data (2.5°×2.5°), all AOD (MODIS: 1°×1°) and meteorological (now called dynamic-thermodynamic) data (1°×1°) are resampled to 2.5°×2.5° resolution grids in the analysis. For each variable, the value in each grid is the mean value of the closest grids within a 1.25°radius.

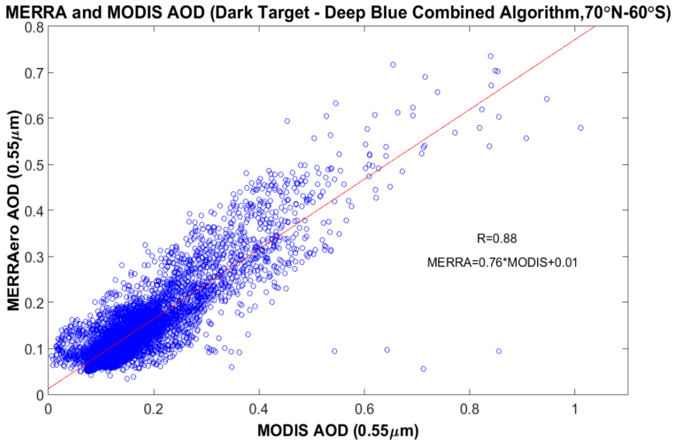

Fig. R1. Comparison of global MODIS and MERRA monthly aerosol optical depth (AOD) at 550 nm for the period 2003–2013 (May, June, July of each year). R is the correlation coefficient.

(2) Page 5, Line 85: Referring to dust effect on drought, following articles should be cited.

Huang, J., T. Wang, W. Wang, Z. Li, and H. Yan, Climate effects of dust aerosols over East Asian arid and semiarid regions, Journal of Geophysical Research: Atmospheres, 119 (2014), 11398–11416, doi:10.1002/2014JD021796.

Huang J., Y. Li, C. Fu, F. Chen, Q. Fu, A. Dai, M. Shinoda, Z. Ma, W. Guo, Z. Li, L. Zhang, Y. Liu, H. Yu, Y. He, Y. Xie, X. Guan , M. Ji, L. Lin, S. Wang, H. Yan and G. Wang, 2017: Dryland climate change recent progress and challenges. Reviews of Geophysics, 55, 719-778, doi:10.1002/2016RG000550.

Response:

Indeed, these two papers are closely related to our study and have been cited/added to the reference list.

(3) The potential temperature is conserved for a parcel of air that is unsaturated and remains unsaturated as it rises and sinks. For deep convection condition, it is far away from adiabatic process. So why don't use the pseudo-equivalent potential temperature?

Response:

1) Yes, in unstable convection, two processes are involved: the dry process under the cloud base and the moist process above the cloud base. Potential temperature is conserved in the dry

process, but in the real troposphere, it usually increases with increasing altitude. In this study, potential temperature is calculated to correct the effect of altitude on the 2-m temperature. Its horizontal distribution can reflect the thermal condition at the level of equal altitudes: In places with higher potential temperature, warm air rises. Although potential temperature appears to have nothing to do directly with the moist process, places with higher potential temperatures have larger updrafts when the moisture is fixed. Therefore, when there is enough moisture, places with higher potential temperatures are more favorable for convection.

2) The pseudo-equivalent potential temperature includes both temperature and moisture and may be the better choice when investigating the correlation between deep convection (lightning activity) and a thermodynamic parameter. But in our study, we examine the relative roles of several parameters and their total contribution to lightning activity, so we selected potential temperature to reduce the repeatability of humidity information. In an ongoing study, we are selecting parameters more carefully and evaluating them.

Response: 2018/7/23

Response to Reviewer 2: Earle Williams

(Note that the text in italics is text appearing in the revised paper).

General comments:

This paper is an excellent contribution to the literature on the effects of thermodynamics and aerosol on lightning activity, and gets high marks for its efforts to study simultaneously the roles of multiple variables. Only in this way can aerosol and thermodynamic effects get disentangled. Figure 7 is a remarkable result in showing a consistent optimal AOD value (=0.3) for effect of aerosol on lightning, on the basis of climatological datasets alone as I understand it. The two areas in greatest need of attention are the procedures used in the paper to organize the data sets and make specific plots, and the discussion and interpretation of same plots. Further details are provided below through an emphasis on Substantive Issues. This discussion is followed by a detailed editing of the manuscript.

General Response:

We deeply appreciate your exceptionally informative and constructive comments on our manuscript. We have studied them carefully and have addressed all the issues raised with several additional analyses. The changes are explained in the following responses, and also marked in the revised manuscript. Please excuse us for the exceptionally long responses (44 pages) as a result.

Substantive Issues:

(1) Data sampling

Coming back to Figure 7, the most important single result in the paper, some comments are in order about data sets and sampling. Maybe the most remarkable aspect of Figure 7 is that it shows consistent behavior with AOD for two regions with very different aerosol characteristics. And somewhere it needs to be stated clearly that the data points in that plot do not represent simultaneous lightning and aerosol measurements on the same storm or in the same grid square, but instead points drawn from two independent climatologies developed over many years of observations, one for lightning and one for aerosol. But still I am confused about the last sentence in the Figure 7 caption which attempts to explain how this figure was created. More details are needed here. For example, are the 10 samples mentioned drawn from only the AOD data set or both the LIS and AOD data sets? And since both lightning and AOD data sets have samples through all the seasons (though with resolution degraded from monthly), are all seasons represented in this plot (and other plots, see below)?

Response:

1.1) Yes, lightning and aerosol data are not simultaneous measurements. They are from two independent observational climatologies developed over many years (the TRMM LIS climatology, the LRMTS dataset, and the MODIS monthly products), and collocated in the same grid square (2.5°×2.5°).

1.2) The last sentence in Figure 7 caption means that we first ordered samples (each sample includes a pair of AOD and lightning data) by AOD from small to large, then calculated mean values (for both AOD and lightning rate) in each 10-sample bin to reduce the uncertainty caused by the large dispersion in the data. Samples from all seasons are used.

Figure 7 is now recreated and reordered as Figure 9 in the revised paper. *The caption has been rewritten to explain more clearly*:

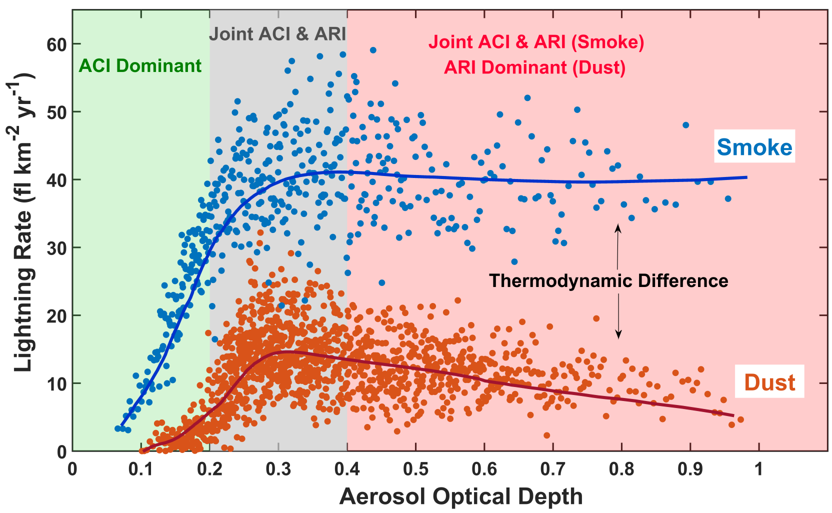

Fig. R1 (Figure 9 in the paper). Lightning flash rate as a function of aerosol optical depth (AOD) in the dust- (orange points) and smoke-dominant regions (blue points). Note that all data pairs (i.e., a three-month mean lightning rate and a three-month mean AOD) are first ordered by AOD from small to large. Mean values of both AOD and lightning flash rate in each 10-sample bin are then calculated to reduce the uncertainty caused by the large dispersion of data. The two curves are created by applying a 100-point moving average (50-point) thrice to the mean values of lightning flash rate in each 30-sample bin for the dust- (smoke-) dominant region. Note that data used here are for the entire AOD range but only shown for the range AOD ∈ (0, 1). Turning points in the boomerang shapes are around AOD = 0.3. Aerosol-cloud interactions (ACI) play a dominant role in lightning activity under relatively clean conditions (green zone). As AOD exceeds 0.3, both ACI and aerosol-radiation interaction (ARI) effects come into play with different magnitudes. For dust aerosols, ACI and ARI have the same same effect of suppressing convection in the dry environment favorable for evaporating cloud droplets. The moist environment of central Africa strengthens aerosol invigoration that offsets the suppression due to ARI, leading to a nearly flat line in the grey and red zones.

(2) Meteorology versus aerosol

This study is comparing the effects of meteorology (including six meteorological variables) and aerosol on lightning rate. However, to any physical meteorologist, aerosol is a subset of meteorology. Shouldn't the authors be pitting aerosol effects versus thermodynamic effects? I guess then we have a problem because SLP is a variable outside the thermodynamic realm. Please consider.

Response:

Yes, aerosols can also be considered a meteorological variable. Previous studies have proposed two hypotheses—the thermal hypothesis and the aerosol hypothesis—to explain the variability in lightning and convective intensity. In this study, we investigate the relative roles of thermodynamics and aerosols from a climatological perspective. Sea level pressure determines the weather pattern which may be advantageous or disadvantageous to the development of convection and lightning activity. Therefore, in our study, we take the sea level pressure (SLP) into account. However, as you point out, SLP is not a thermodynamic factor, which, combined with other thermodynamic factors, are considered meteorological variables. To enable a separate statistical analysis of the aerosol effect, especially the different dust and smoke aerosol effects, we do not lump aerosols and other meteorological variables together. As you suggested, it may be better to divide the influential factors into two groups: (1) dynamic-thermodynamic variables and (2) aerosols.

The term "meteorology" is replaced by the term "dynamics-thermodynamics", and the phrase "meteorological variables" is replaced by the phrase "dynamic-thermodynamic variables" in the revised paper.

(3) The lightning quantity is a rate

Lightning is often referred to in this work but the real metric for lightning is a flash rate obtained from the LIS. Hence the suggestion for a slight modification of the paper's title.

Response:

We have modified the paper's title per your suggestion: *"The Climate Impact of Aerosols on the Lightning Flash Rate: Is it Detectable from Long-term Measurements?"*

(4) "Severe storm" terminology

In a couple of places (lines 59, 162), the severe storm usage appears. The problem here is that a severe storm in USA meteorology is a storm in which very specific thresholds are exceeded: surface wind speed, hailstone size, and the occurrence of a tornado on the ground.

The great majority of storms studied here will not be in the severe storm category.

Response:

We now use the term "*strong convection*" instead of "severe storms".

(5) Linking AOD with CCN concentration in per cc

Figure 7 is one of the highlights of this work in showing maximum values of AOD near 0.3 for the impact of aerosol on lightning rate. The value of these results could be extended by linking with CCN, a parameter more closely allied with the cloud microphysics pertaining to lightning and now getting increased attention by virtue of Rosenfeld's satellite method to measure CCN at cloud base height. Towards this end, the work by Andreae et al. (2009, Atmos. Chem. Phys.) should be cited. According to the least squares fit in Figure 1, for an AOT of 0.3, the corresponding CCN value is a little less than 2000 per cc. These values are close to what Hu et al. (2018, manuscript in preparation) are finding for optimal values in the lightning context.

Response:

The tight relationship between $CCN_{0.4}$ and AOD_{500} has been fitted with the power law function

$AOD_{500} = 0.0027{CCN_{0.4}}^{0.64}$ with a very high degree of correlation ($r^2 = 0.88$; Andreae et al., 2009). According to the regression equation, we can deduce CCN concentrations at a supersaturation of 0.4% (a value commonly used for convective clouds) from retrievals of AOD at 500 nm. When AOD_{550} = 0.3, the corresponding $CCN_{0.4}$ is about 1600 cm^{-3} which is close to 1200 cm^{-3} (Rosenfeld et al., 2008). The maxima of the scattering and extinction efficiency functions often fall near or above the maximum of the mass size distribution of the aerosol between 400 and 1000 nm so that this part of the size distribution usually has the strongest influence on AOD_{500}. In addition, in regions with high loadings of dust and sea salt aerosols, the coarse mode (>1 μm) may also contribute strongly to AOD_{500}. Samples dominated by dust plumes were excluded when fitting the regression equation. Therefore, $CCN_{0.4}$ estimated for the smoke-dominant region is more reliable than that for the dust-dominant region. However, without any other available CCN data from the dust aerosol-dominant region, we use $CCN_{0.4}$ =1600 cm^{-3} as a reference value. We will try to estimate CCN with other methods in a future study.

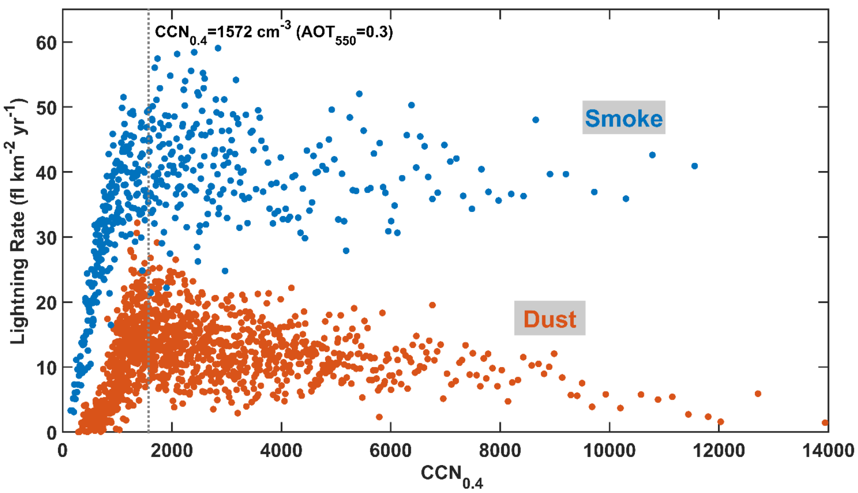

Fig. R2. The response of the lightning flash rate to dust and smoke aerosols in the dust- and smoke-dominant regions. The turning points are around $CCN_{0.4}$ ≈ 1600 cm^{-3}.

The following "*We deduce that the CCN concentration is more closely allied with the cloud microphysics pertaining to lightning based on the equation fitted by Andreae (2009). The turning point of the CCN concentration at a supersaturation of 0.4% is 1600 cm*$^{-3}$ *which falls within the range of 1000–2000 cm*$^{-3}$ *(Mansell and Ziegler, 2013) and is close to 1200 cm*$^{-3}$ *(Rosenfeld et al., 2008).*" is added to the paper (see Lines 445–449).

Fig. R2 is added to the supplemental material (see Fig. S3).

(6) AOD boundaries, defining regimes

Given the central importance of the AOD=0.3 value in Figure 7 (that the reader does not learn about when AOD boundaries are first discussed in lines 201-205), and the linkage to CCN in Figure 1 of Andreae et al. (2009), more care should be given to explaining, justifying and bounding the three regions (clean, intermediate?, and polluted) that are used in this work. All three regions should be named, and possibly illustrated in Figure 7 where the full range of AOD is shown, and with early notice about the special transitional value taken from Figure 7. I am confused in returning to this important Figure because there you show equations for just two AOD intervals (AOD< 0.3 and AOD>0.3) rather than the three given mention in the text. It seems to this reviewer that all ambiguities on this topic can be resolved by appropriate modification of the AOD range in this figure. My recollection is that Altaratz et al. (2017) did something similar with the AOD scale in their work. This paper on the same topic (lightning and AOD-measured aerosol) should also be consulted and cited.

Response:

6.1) We choose AOD = 0.3 to separate relatively clean and polluted cases when performing regression analyses (Figure 7 and Figure 10 are now Figure 9 and 12). *The regression analyses are removed in the revised paper.* However, since aerosol loadings change over the seasons/dynamic-thermodynamic conditions, this threshold value (AOD = 0.3) cannot be used for every month in the comparison of the lightning rate seasonal variability under clean and polluted conditions (Figure 2) and in the analysis of the environmental dependence of the aerosol effect on lightning activity (Figure 9, now Figure 11). Therefore, all data are sorted by AOD and divided into three equal-sample subsets to retain a good sampling size. The top third of the AOD range [AOD ∈ (0, 1)] is labeled as polluted, and the bottom third is labeled as clean. Analyses are only performed between clean and polluted subsets to create sufficient contrast between the groups (Koren et al., 2012).

6.2) Because clean and polluted regions vary by seasons and by dynamic-thermodynamic condition, we cannot show them in Figure 7 (now Figure 9). But in Figures 2c and 2d, we have shown monthly mean AOD values under clean and polluted conditions. Figure R3 is the same as Figure 9 (now Figure 11) in the manuscript except that only those data associated with the AOD range (0, 1) are shown to maintain consistency with the analysis of the seasonal variability in Figure 2. Figure R4 shows mean AOD as a function of the lightning flash rate and as a function of the six dynamic-thermodynamic variables under clean and polluted conditions.

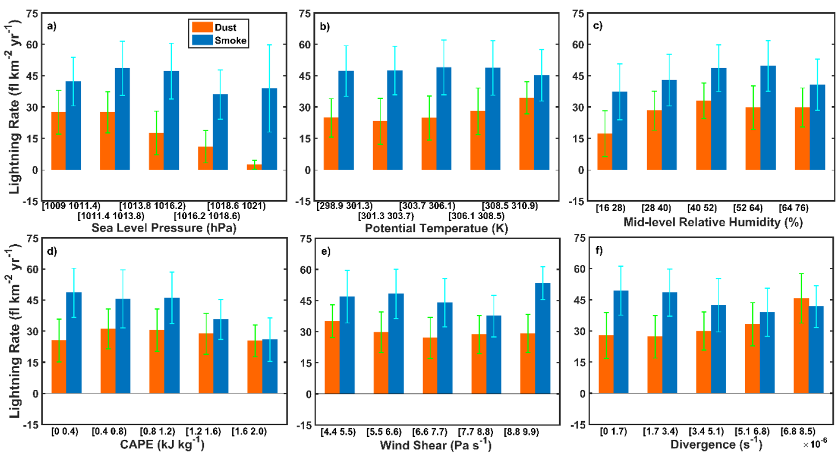

Fig. R3. Differences (polluted minus clean subsets of data) in lightning flash rate as a function of (a) sea level pressure, (b) potential temperature, (c) mid-level relative humidity, (d) convective available potential energy (CAPE), (e) vertical wind shear, and (f) 200-hPa divergence in the dust- (in orange) and smoke-dominant region (in blue). Note that the top third of aerosol optical depth (AOD) values [AOD ∈ (0, 1)] is labeled as polluted, and the bottom third is labeled as clean. Vertical error bars represent one standard deviation.

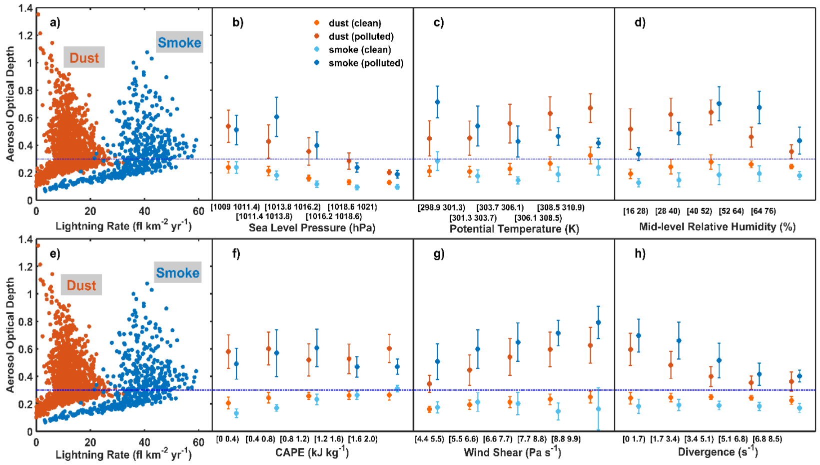

Fig. R4. (a, e, duplicated) Mean aerosol optical depth (AOD) as a function of the lightning flash rate in the dust- (in orange) and smoke-dominant (in blue) regions, and under clean and polluted conditions for five ranges of (b) sea level pressure, (c) potential temperature, (d) mid-level relative humidity, (f) convective available potential energy (CAPE), (g) vertical wind shear, and (h) 200-hPa divergence.

6.3) The decision to divide data into two subsets centered on the value AOD = 0.3 and to divide data into three equal-sample subsets is not random. The latter choice is explained in 6.2) above. The value of AOD = 0.3 that is the location of the turning point is selected from the scatterplot. We then perform regression analyses before and after the turning point to reduce the non-linear effect of AOD.

6.4) The range of AOD, i.e., AOD ∈ (0, 1), was carefully thought out. To avoid a higher probability of misclassification of clouds and aerosols in high AOD regimes (Platnick et al., 2003) such as AOD < 0.6 (Kaufman et al., 2005), and to minimize the influence of hygroscopic growth in a humid environment (Feingold and Morley, 2003), differing threshold values of AOD have been selected [e.g., AOD < 0.8 in Koren et al. (2008), AOD < 0.3 in Koren et al. (2012), and AOD < 0.4 in Altaratz et al. (2017)]. To have some knowledge of the MODIS AOD reliability and to retain enough samples, especially in the lightning-deficient region ROI_1, daily mean AERONET AOD data (averaged over 1200–1500 local time) from the Banizoumbou site (2.66°E, 13.54°N) during the most polluted months (May-June-July, 2003–2013) were used to evaluate Aqua/MODIS AOD at around 13:30 local time (2°E–3°E, 13°N–

14°N). Results are shown in Figures R5, R5-1, 2, and 3. The high correlation (R = 0.85) suggests that MODIS AOD retrievals are reliable in the dust-dominant region for the total AOD range with just a few days having large biases. Four days are selected to see if the large biases are caused by cloud contamination. As shown in Figures R5-1, 2 (MODIS AOD << AERONET AOD) and R5-3 (MODIS AOD > AERONET AOD), high MODIS AOD values under high cloud fraction (CF) conditions are not found, so the influence of cloud contamination is considered to be small in the dust-dominant region. Dust storms are frequent in spring and summer and can last a few days to about two weeks, so the odds of AOD > 0.5 is then very likely as is the probability of AOD > 0.8. To retain enough data, we finally chose all data with AOD < 1.0 (~99% of total samples) in the dust-dominant region. For ease of comparison of the aerosol effect between dust and smoke aerosols, the same AOD range is selected for the smoke-dominant region (~99% of total samples).

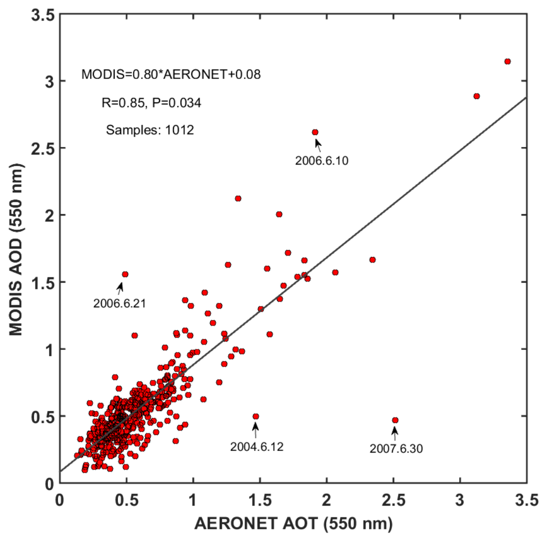

Fig. R5. Daily mean Aqua/MODIS AOD at 550 nm (local time ~13:30) as a function of AERONET AOD (averaged from 12:00–15:00 local time) over the dust-dominant region for the period 2003–2013 (May, June, July of each year). The AERONET site is located at Banizoumbou (2.66°E, 13.54°N), and the region covered by MODIS is (2°E -3°E,13°N -14° N). The four dots marked with dates (yyyy.mm.dd, where yyyy = year, mm = month, and dd = day) have relatively large biases.

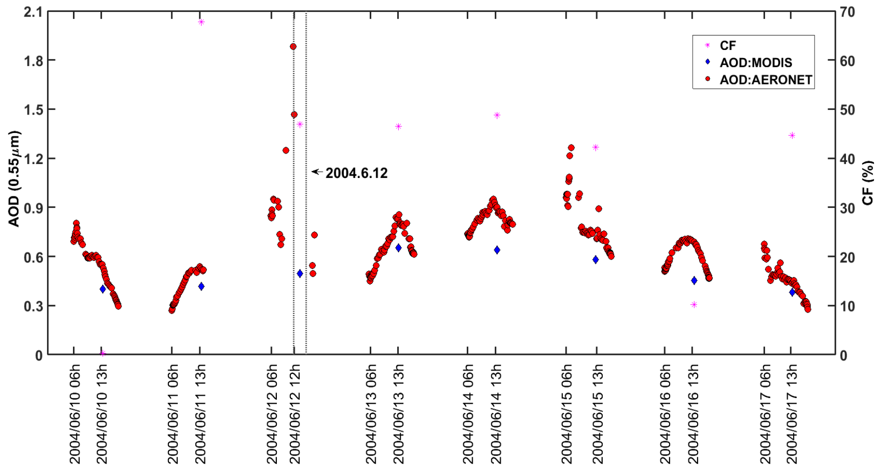

Fig. R5-1. Times series (10 – 17 June 2004) of daily mean Aqua/MODIS AOD at 550 nm (local time ~13:30 averaged over (2°E-3°E,13°N-14°N), blue triangles), high resolution (~7 min) AERONET AOD retrievals made at Banizoumbou (2.66°E, 13.54°N, averaged from 12:00–15:00 local time, red dots), and cloud fraction (CF, pink stars). The largest deviation appears on 12 June 2004. The two vertical dotted lines present the period 12:00–15:00 local time.

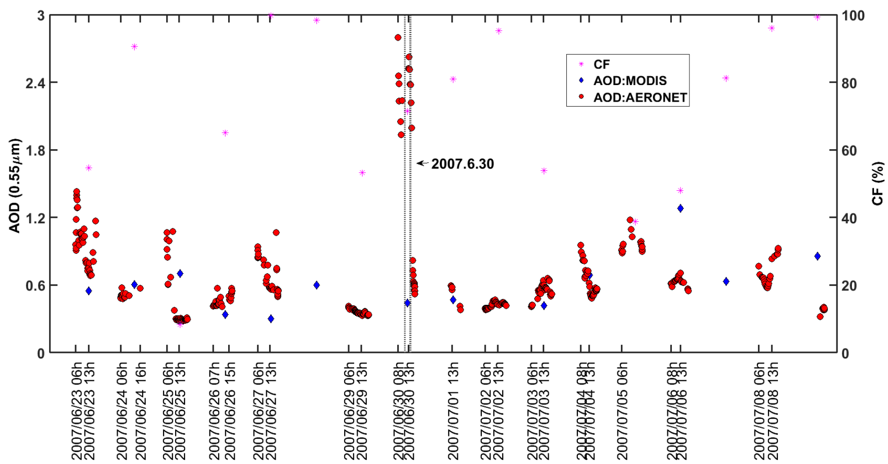

Fig. R5-2. Times series (23 June – 8 July 2007) of daily mean Aqua/MODIS AOD at 550 nm (local time ~13:30 averaged over (2°E -3°E,13°N -14°N), blue triangles), high resolution (~7 min) AERONET AOD retrievals made at Banizoumbou (2.66°E, 13.54°N, averaged from

12:00–15:00 local time, red dots), and cloud fraction (CF, pink stars). The largest deviation appears on 30 June 2007. The two vertical dotted lines present the period 12:00–15:00 local time.

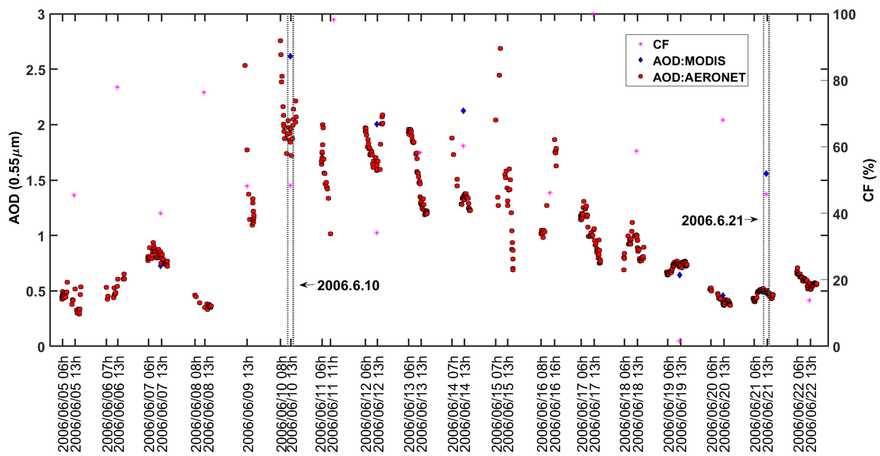

Fig. R5-3. Times series (5–22 June 2006) of daily mean Aqua/MODIS AOD at 550 nm (local time ~13:30 averaged over (2°E -3°E,13°N-14°N), blue triangles), high resolution (~7 min) AERONET AOD retrievals made at Banizoumbou (2.66°E, 13.54°N, averaged from 12:00–15:00 local time, red dots), and cloud fraction (CF, pink stars). The largest deviations appear on 10 June 2006 and 21 June 2006. The two vertical dotted lines present the period 12:00–15:00 local time on each of these days.

Totally, the following "*To avoid a higher probability of misclassification of clouds and aerosols in high AOD regimes (Platnick et al., 2003), to minimize the influence of hygroscopic growth in a humid environment (Feingold and Morley, 2003) and to retain enough samples especially in the lightning-deficient region, the AOD range in this study is set between 0 and 1, following the work of Kaufman et al. (2005, AOD<0.6), Koren et al. (2008, AOD < 0.8; 2012,AOD<0.3) and Altaratz et al. (2017, AOD<0.4). In addition, MODIS AOD is evaluated using daily AERONET AOD data (see Figs. S1 and S1-1, 2, 3 in the supplemental material).*." is added to the revised paper (see Lines 260–266).

Fig. R3 is added to the revised paper (see Figure 11).

Fig. R5, and R5-1, 2, 3 are added to the supplement material (see Figs. S1 and S1-1, 2, 3).

(7) Selection of variables

The authors choose meteorological variables to investigate, but the physical meaning/ justification for this selection gets short shrift. Furthermore, other studies have considered different (but more physically relevant to the questions at hand) variables (CBH and warm cloud depth) that the authors chose to bypass without explanation. It should also be noted that certain variables will work better in Africa than elsewhere (RH is one), and others will work poorly in Africa (potential temperature). The linkage between lightning and shear has been considered in previous studies (Fan et al., 2009; Yoshida et al. (2009, have relevant data but do not address it directly) and Bang and Zipser (who have a positive relationship but overlook it). These findings are mixed and so new looks (like this one) are most welcome.

Response:

7.1) We strongly agree with the reviewer's comment. There are many variables that can be selected, and some of them are more physically relevant to lightning activity than others. Since we are trying to examine the possible effects of dynamic-thermodynamic factors on lightning activity from a climate perspective, we chose the more commonly used ones that have been identified and explained previously to be associated with lightning activity (sea level pressure, potential temperature, mid-level relative humidity, CAPE, wind shear, and divergence) to represent the influences of dynamics and thermodynamics. Thanks for your comments, more references are cited. Among them, sea level pressure describes weather patterns, potential temperature describes the surface thermal condition, mid-level relative humidity represents mid-level tropospheric humidity which contains information about clouds, and CAPE denotes the instability of the atmosphere which is determined by the temperature and humidity profiles. The cloud base height and warm cloud depth can also be derived from surface temperature and humidity (i.e., dew-point temperature) information. So, to reduce the duplication of information about temperature and humidity, we selected relative humidity and potential temperature and did not consider cloud base height and warm cloud depth.

"*However, as statistical theory indicates, more factors will introduce more random noise and thus undermine the stability of the regression equation. When the sample size is fixed, the contribution of factors to the multiple regression equation changes little between 5–10 factors (Klein and Walsh, 1983; see Tables S1-1 and S1-2 in the supplemental material), so 5–6 factors should be the best choice.*" (added to the paper, see Lines 369–373). *This is shown in Tables R1-1 and R1-2 and is added to the supplemental material (see Tables S1-1 and S1-2)*.

However, the importance of these factors still needs to be assessed, not only through analyses and some speculation, but also through quantification with statistical methods. This will be considered in a future study.

Assume that the Pearson correlation coefficients between the predictor (y) and factors (x_1, x_2, ⋯ , x_{10}) and Pearson correlation coefficients between factors are all equal to r. The sum of squared residuals (Q) can be derived as:

$$Q = S_{yy}\left(1 - \frac{pr^2}{1+(p-1)r}\right) \quad . \qquad (1)$$

Here, p is the number of factors ($p = 1, 2, \ldots, 10$). If we set the sum of squares of deviations $S_{yy} = 1$, then Q can be calculated using different p and r. Results are shown in Table R1-1.

Assume that the Pearson correlation coefficients between the predictor (y) and factors (x_1, x_2, ⋯ , x_{10}) are equal to r, and Pearson correlation coefficients between factors are equal to $r/2$. The sum of squared residuals (Q) can be derived as:

$$Q = S_{yy}\left(1 - \frac{pr^2}{1+(p-1)\frac{r}{2}}\right) \quad . \qquad (2)$$

Here, p is the number of factors ($p = 1, 2, \ldots, 10$). If we set the sum of squares of deviations $S_{yy} = 1$, then Q can be calculated using different p and r. Results are shown in Table R1-2.

Table R1-1. The relationship between the sum of squared residuals (Q) and the number of factors.

Q \ p, r	1	2	3	4	5	6	7	8	9	10
0.2	0.96	0.93	0.91	0.90	0.89	0.88	0.87	0.87	0.86	0.86
0.3	0.91	0.86	0.83	0.81	0.80	0.78	0.78	0.77	0.76	0.76
0.4	0.84	0.77	0.73	0.71	0.69	0.68	0.67	0.66	0.66	0.65
0.5	0.75	0.67	0.63	0.60	0.58	0.57	0.56	0.56	0.55	0.55
0.6	0.64	0.55	0.51	0.49	0.47	0.46	0.45	0.45	0.44	0.44
0.7	0.51	0.42	0.39	0.37	0.36	0.35	0.34	0.34	0.33	0.33
0.8	0.36	0.29	0.26	0.25	0.24	0.23	0.23	0.22	0.22	0.22
0.9	0.19	0.15	0.13	0.12	0.12	0.12	0.11	0.11	0.11	0.11

Table R1-2. The relationship between the sum of squared residuals (Q) and the number of factors.

Q \ p, r	1	2	3	4	5	6	7	8	9	10

0.2	0.96	0.93	0.90	0.88	0.86	0.84	0.83	0.81	0.80	0.79
0.3	0.91	0.84	0.79	0.75	0.72	0.69	0.67	0.65	0.63	0.62
0.4	0.84	0.73	0.66	0.60	0.56	0.52	0.49	0.47	0.45	0.43
0.5	0.75	0.6	0.50	0.43	0.38	0.33	0.30	0.27	0.25	0.23
0.6	0.64	0.45	0.33	0.24	0.18	0.14	0.10	0.07	0.05	0.03

In general, the sum of squared residuals decreases little when the number of factors is greater than five, so 5–6 factors should be the best choice. Another finding is that if the factors are approximately independent, they contribute much to the decrease in the sum of squared residuals.

7.2) Yes, wind shear affects the dynamical flow structures around and within a deep convective cloud. Lightning activity or convection responds to shear in different ways under different conditions. But from a climatological perspective, shear has no significant effect, maybe because these mixed impacts cancel each other in the long term.

The following "*The influences of other variables such as wind shear and convergence/divergence are insignificant from a climatological perspective.*" is added to the revised paper (see Lines 635–636).

The following papers are cited in section 2.1.3 and added to the reference list:

About wind shear: Bang and Zipser, 2016; Richardson and Droegemeier, 2007; Takemi, (2007)

(8) RH as a favored variable in Africa

I did not grasp immediately that you were considering the RH in mid-troposphere, rather than the surface RH. Please clarify this wherever appropriate. If it is the RH in mid-troposphere that is selected, some physical interpretation of the importance of this variable should be discussed, and especially how that can influence the erosion of moist convection by entrainment. I do not see any discussion on the entrainment issue at all in the present version. The text below on this RH topic was prepared when I was still under the impression that the authors were using surface RH. I think I will leave this text in, just for further consideration of the important thermodynamic side of this challenging problem. When one considers the full meteorological dynamic range of this variable, it' s limitations as a correlate to lightning rate should be clear. The largest values during lightning episodes are ~80% and this is a prevalent value over tropical oceans where lightning is least likely. The contrast between weak lightning activity in the high RH tropical monsoon and in the strong lightning activity of the low RH pre-monsoon/break period is also widely recognized

(Williams et al., 1992; Rutledge et al., 1992). The reason RH works as a positive correlate with lightning in Africa is because RH is low and CBH is already high. See for example Williams and Satori (2004) and follow up work by Venevsky et al. (2014) that are not now cited.

Venevsky, S., Importance of aerosols for annual lightning production at global scale, Atmos. Chem. Phys. Discuss., 14, 4303-4325, 2014.

Williams, E.R. and G. Sátori, Lightning, thermodynamic and hydrological comparison of the two tropical continental chimneys, J. Atmos. Sol. Terr. Phys., 66, 1213-1231, 2004.

Response:

Thank you for pointing out highly relevant studies that were not cited in our original manuscript. They have now been added.

The following papers are added to section 2.1.3 and the reference:

About temperature: Reeve and Toumi, 1999; Jayaratne and Kuleshov, 2006; Markson, 2007

About relative humidity: Williams et al., 1992; Redelsperger et al., 2002; Derbyshire et al., 2004; Xiong et al., 2006; Zhang 2009; Chakraborty et al., 2018

The following papers are cited in section 4.2 and added to the reference list:

About cloud base height: Williams and Satori, 2004; Venevsky, 2014

Yes, in our study, mid-tropospheric relative humidity is used instead of surface relative humidity.

Both surface and mid- to upper-level relative humidity are closely correlated with convection:

1) Moderately wet underlying surfaces are recognized as an important factor in facilitating deep convection. A higher relative humidity results in more lightning activities in dry regions and less lightning activities in wet regions with a watershed value of relative humidity of ~72–74% (Xiong et al., 2006). This result can be explained through the development of unstable convection. Large CAPE and the high conversion efficiency of CAPE to kinetic energy (large updrafts) are essential to thunderstorms. Williams and Stanfill (2002) suggest that the transformation from CAPE to kinetic energy can be reflected by the cloud base height (CBH). Both CAPE and CBH are a function of temperature and relative humidity, but the change in CBH depends almost only on the variation in relative humidity (Williams and Satori, 2004). When temperature is fixed, the moist environment produces large CAPE and a low CBH. So in the development of convection (the production of lightning activities), a moderately wet underlying surface is needed.
2) Mid-tropospheric moistening is important for the evolution of deep convection. A sensitivity test of moist atmospheric convection to mid-tropospheric humidity shows

strong deep convection in moist cases and only shallow convection in the driest case (Derbyshire et al., 2004). By simulating a dry intrusion event, strong positive associations were found between mean humidity (between 2–6 km) and convective cloud top heights (Redelsperger et al., 2002). Anomalously high humidity in the free troposphere (between 850–400 hPa), which tends to increase plume buoyancy, was observed prior to a shallow-to-deep convection transition (Chakraborty et al., 2018). Wall et al. (2014) also demonstrated significant differences in convective intensity with respect to variations in average relative humidity in the 700–500 hPa layer based on proximal thermodynamic soundings. They also noted that relatively dry air in the middle troposphere could contribute to increased temperature lapse rates and a hostile environment for weak convection to develop in. Developing plumes that overcome convective inhibition tend to be subsequently stronger.

Shallow and congestus cumulus clouds are important means of transporting moisture from the atmospheric boundary layer to the lower mid-troposphere, thus allowing for the development of deep convection which can bring moisture to the upper troposphere. Mid-to-upper tropospheric moisture (between 200–600 hPa) is more likely to be an effect of convection (Sobel et al., 2003). Moistening the mid-tropospheric environment can also reduce the dilution effect on CAPE which depends strongly on the degree of sub-saturation of the entrained air: the drier the entrained air, the larger the effect (Zhang, 2009), thus facilitating deep convection. So we think there may be no turning point in the response of lightning to mid-tropospheric relative humidity. Even if there is one, the three-month smoothed mid-tropospheric relative humidity is less than the surface relative humidity in the long term. In the dust-dominant region (the smoke-dominant region), less than 1.3% (8.3%) of mid-level relative humidity values are greater than 73%. The probability of mid-level relative humidity > 73% is much lower than that of surface relative humidity (see Fig. R5). Finally, to avoid the nonlinear response of convection (lightning activity) on surface humidity, we chose mid-tropospheric relative humidity instead of surface relative humidity.

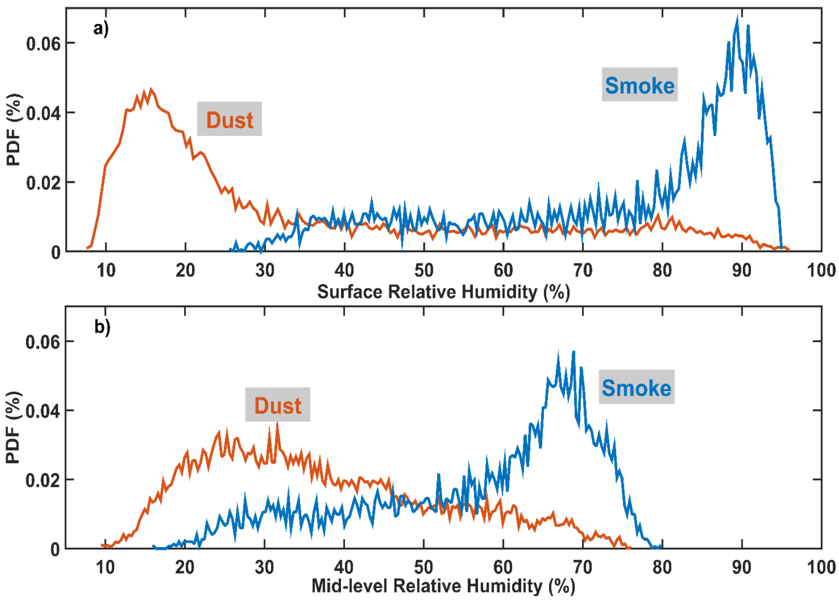

Fig. R6. The probability density function (PDF) of (a) surface and (b) mid-level relative humidity in the dust- and smoke-dominant regions.

The following "*Moderately wet underlying surfaces are an important factor in facilitating deep convection due to the compromise between instability energy (when temperature is fixed, the atmosphere is wetter, and CAPE is larger) and the transformation efficiency from instability energy to kinetic energy (when the boundary layer is wetter, the cloud base height is lower, and updrafts are weaker). Higher surface relative humidity results in more lightning activities in dry regions and less lightning activities in wet regions with the watershed of surface relative humidity values at ~72 % to 74 % (Xiong et al., 2006). However, for mid-level humidity, only shallow convection occurs in the driest case while strong deep convection occurs in more moist cases (Derbyshire et al., 2004). Strong positive relations are found between mean humidity (between 2–6 km) and convective cloud top heights (Redelsperger et al., 2002). Anomalously high humidity in the free troposphere (between 850–400 hPa), which tends to increase plume buoyancy, is observed prior to a shallow-to-deep convection transition (Chakraborty et al., 2018). Different from surface moisture as a cause of deep convection, mid-to-upper tropospheric moisture (between 200–600 hPa) is more likely to be an effect of convection (Sobel et al., 2003). In addition, moistening the mid-tropospheric environment can also reduce the dilution effect on CAPE, which depends strongly on the degree of sub-saturation of the entrained air: the wetter the entrained air, the smaller the effect (Zhang 2009) which tends to facilitate ensuing deep convection. Therefore, there may*

be no turning point regarding the response of lightning to mid-level relative humidity. Even if there is, three-month-moving-averaged mid-level relative humidity (less than 1 % and 9 % of the total in the dust- and smoke-dominant regions,
respectively, surpass relative humidity = 73 %) is less than the surface relative humidity (12 % and 63 % of the total in the dust- and smoke-dominant regions surpass relative humidity =73 %) in the long-term. Mean relative humidity values at 700 and 500 hPa levels are used in this study." is added to the revised paper (see Lines 195–219).

Fig. R6 is added to revised paper (see Figure 4).

(9) Potential temperature

Potential temperature is selected as another variable, presumably as a test of earlier work that

considered global lightning/temperature relationships and not just Africa. Here is the problem with the use of this quantity for Africa. The linkage between lightning rate and thermodynamics clearly involves moist processes. In much of the African continent, there is insufficient moisture to allow ANY condensation, much less deep moist convection of the kind productive of lightning. Accordingly, elevated potential temperature is not serving to enhance moist processes. A second (but related) problem with the use of potential temperature is that in elevated terrain, the air temperature can be high by virtue of sensible heat flux, but because the boundary layer height (containing the rich water vapor) is comparable, the air is still moisture starved and so little lightning producing convection can occur. A good example is the Rocky Mountains west of Denver. The positive correlation between lightning and theta in the Sahara Desert (Figure 5) is puzzling to me and deserves additional explanation. Wet bulb potential temperature includes both temperature and moisture. We ought to be measuring global warming in that quantity rather than dry bulb temperature. Why isn't this variable being considered in the present context?

Response:

We appreciate the reviewer's comments on this point which helped us think through this issue more deeply.

3) Potential temperature is selected based on the work "Lightning, thermodynamic and hydrological comparison of the two tropical continental chimneys" (Williams and Satori, 2004) whose study regions are the Amazon and Congo River basins. We note that ROI_1 was not included in that study.
4) Yes, in unstable convection, two processes are involved: the dry process under the cloud base and the moist process above the cloud base. Potential temperature is conserved in the dry process, but in the real troposphere, it usually increases with increasing altitude. In this study, potential temperature is calculated to correct the effect of altitude on the 2-m temperature. Its horizontal distribution can reflect the thermal condition at the level

of equal altitudes: In places with higher potential temperature, warm air rises. Although potential temperature appears to have nothing to do with the moist process directly, places with higher potential temperatures have larger updrafts when the moisture is fixed. Therefore, when there is enough moisture, places with higher potential temperatures are more favorable for convection.

5) The wet-bulb potential temperature includes both temperature and moisture and may be the better choice when investigating the correlation between deep convection (lightning activity) and a thermodynamic parameter. But in our study, we examine the relative roles of several parameters and their total contribution to lightning activity, so we selected potential temperature to reduce the repeatability of RH information. In an ongoing study, we are selecting parameters more carefully and evaluating them.
6) We think the positive correlation between the lightning flash rate and potential temperature in the Sahara Desert is mainly because we use data from all seasons. Higher potential temperatures in warmer seasons are also accompanied by higher RHs which are more likely to produce deep convection compared to the situation in cold seasons. We note that the absolute number of deep convection events in warmer seasons is not large. We also note that when we controlled RH, the positive correlation between potential temperature and the lightning flash rate disappeared.

The following "*Taking into account that the linkage between lightning activity and thermodynamics involves moist processes, some others use wet-bulb temperature or wet-bulb potential temperature which includes both temperature and moisture (Williams, 1992; Reeve and Toumi, 1999; Jayaratne and Kuleshov, 2006). It has been demonstrated that CAPE increases linearly with wet-bulb potential temperature (Williams et al., 1992). In this study, we would like to examine the relative roles of several parameters and their total contribution to lightning activity. In order to select more independent variables and reduce the duplication of temperature and humidity information, potential temperature is selected. Although it does not reflect moist processes directly, when the moisture level is high enough, places with higher temperatures are more favorable for convection.*" is added to the revised paper (see Lines 183–192).

(10) Figure 2 backup

Figure 2 is a useful contribution to this work but more attention is needed to justify it when it is first introduced and more details are needed for how the curves computed from the observations in the clean and polluted conditions. An additional sentence or two should suffice here. This also links with the Substantive Issue on AOD boundaries. It also seems that no attention is given to thermodynamic variations on either the diurnal or the seasonal times scale here, so how are the authors disentangling the two contributions. Also some justification is needed for the selection of the wind parameter and the elevation of 850 mb.

As a general remark, the figures in this paper are full of information but are deserving of greater

discussion either in the text or in the respective captions.

Response:

1) About the curves: Firstly, we collocate AOD with lightning data (each sample: one AOD-one lightning rate) and remove those samples with AOD > 1.0. We then order the samples by AOD from small to large and separate them into three equal sample groups (the first group with smallest AOD is labeled as clean; the third group with largest AOD is labeled as polluted).
2) And an additional sentence "*The seasonal and diurnal cycles of the lightning flash rate and AOD are first examined over the dust- and smoke-dominant regions (Figure 2a)*." is added to the beginning of section 4.1 (see Lines 328–329).
3) Disentangling diurnal and seasonal contributions.

   Fig. R7 shows that CAPE varies throughout the year over both regions with maximum values in local summer (boreal summer in the dust-dominant region and austral summer in the smoke-dominant region) and minimum values in local winter. In the dust-dominant region, CAPE under relatively clean conditions increases in magnitude more than under polluted conditions in warmer months (from May to October). In the smoke-dominant region, CAPE under polluted conditions increases in magnitude more than under clean conditions throughout the whole year. The seasonal variations in CAPE over both regions show similar seasonal patterns in lightning activity. This supports the idea of the dominant role of thermodynamics on the seasonal variation in lightning activity.

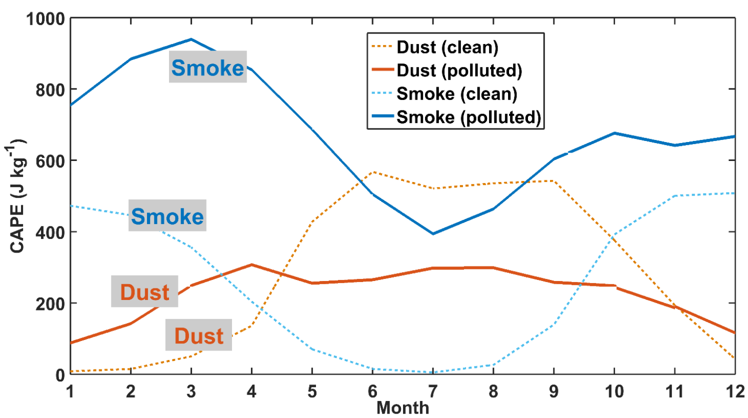

Fig. R7. Seasonal variations in CAPE under relatively clean and polluted conditions in the dust- and smoke-dominant regions. Clean (polluted) cases are defined as those CAPE values corresponding to the lowest (highest) third of the aerosol optical depth (AOD) range [AOD ∈ (0, 1)].

Due to the lack of hourly CAPE data, we do not present the diurnal variation in CAPE. Instead, we report findings from other studies about the diurnal variation in CAPE. Ratnam et al. (2013) found a strong diurnal variation in CAPE with a maximum in the afternoon and a minimum in the early morning hours in all seasons except in winter over a tropical station based on microwave radiometer measurements. Nesbitt and Zipser (2003) examined the diurnal cycle of rainfall and convective intensity using TRMM measurements. They found that land areas have a large rainfall cycle with a marked minimum in the midmorning hours and a maximum in the afternoon. This is similar to the patterns of the diurnal variation in lightning activity found in our study. And as they indicated, this is attributed to convective enhancement by afternoon heating.

Fig. R7 is added to the revised paper (see Fig. S3).

4) The selection of 850-hPa winds.

Alpert et al. (2004) showed the vertical distribution of Saharan dust based on 2.5-year model predictions (Fig. R8-1 and Fig. R8-2). The dust-dominant region (8.75°N–21.25°N, 11.25°W–26.25°E) is closest to the Chad Basin in the Sahara Desert (15°N–17°N, 15°E–17°E, see Fig. R8-1). From these two figures (Fig. R8-1 and Fig. R8-2), we find that dust aerosols are mainly distributed within the 1–4.5 km layer and are densest under 800 hPa.

The vertical distribution of biomass burning aerosols over the South African-Atlantic region is shown Fig. R8-3 (from Das et al., 2017). The smoke-dominant region (0°–15°S, 15°E–28°E) is close to B (20°S–10°S) and C (10°S–0°) in Fig. R8-3. GOCART data show that smoke aerosols are mainly distributed within the 1–3.5 km layer in regions B and C (see Fig. R8-3). By contrast, CALIPSO data show that aerosol extinction coefficients decrease sharply below 2 km. However, this is due to the large attenuation of signals at lower altitudes. So GOCART data are more reliable in reflecting the aerosol vertical distribution.

Dust and biomass burning aerosols distributed within the altitude range of 1–3.5 km form the major portion of total aerosols. Therefore, wind fields at 850 hPa and 700 hPa are both reasonable choices to show the prevailing wind direction which affects the aerosol transport path. We chose 850 hPa because there was little difference between the prevailing wind directions at the two levels (see Fig. R9).

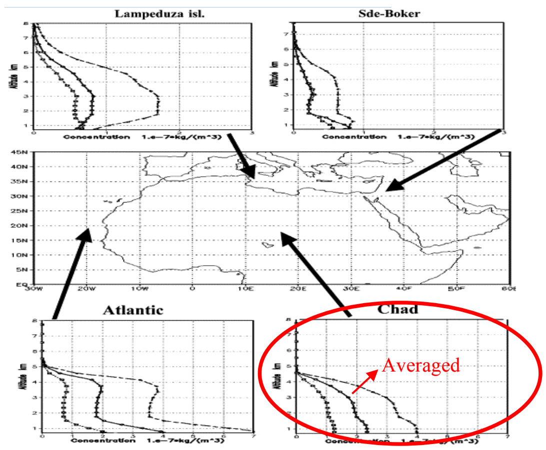

Fig. R8-1 (from Alpert et al., 2004). Mean vertical profiles of dust concentration (unit: 10^{-7} kg m^{-3}) for the month of June at 12:00 UTC over Sde-Boker (Israel) in the eastern Mediterranean (29.5°N–31.5°N, 34°E–36°E), Lampedusa Island in the central Mediterranean (34.5°N–36.5°N, 11.5°E–13.5°E), the Chad Basin in the Sahara Desert (15°N–17°N, 15°E–17°E), and a domain within the eastern Atlantic (17°N–19°N, 17°W–19°W). Solid lines show mean profiles calculated from all available profiles for this specific month that have dust loadings greater than 0.1 g m^{-2}. Dashed (dotted) lines show mean profiles representing high (low) dust activity, calculated from only those vertical profiles with dust loadings greater (less) than normal.

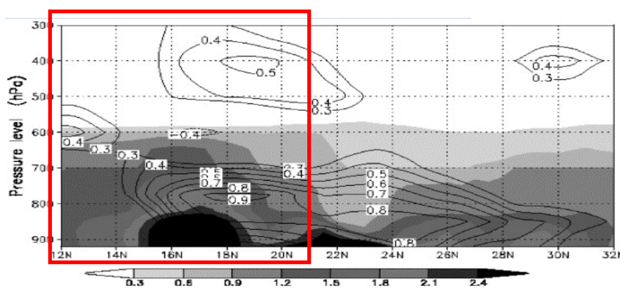

Fig. R8-2 (from Alpert et al., 2004). Vertical distribution of mean model dust concentration and the one of correlation within the latitudinal cross-section zonal averaged over the positive correlation area, both in the daytime (12:00 UTC) in the month of April. Solid lines show the correlation between the ECMWF temperature increments at the ERA model levels and the TOMS aerosol index during the period from 1979 to 1993. The model dust concentration (10^{-7} kg m^{-3}) averaged for the month of April 2001–2002 is shown by grayscale shades.

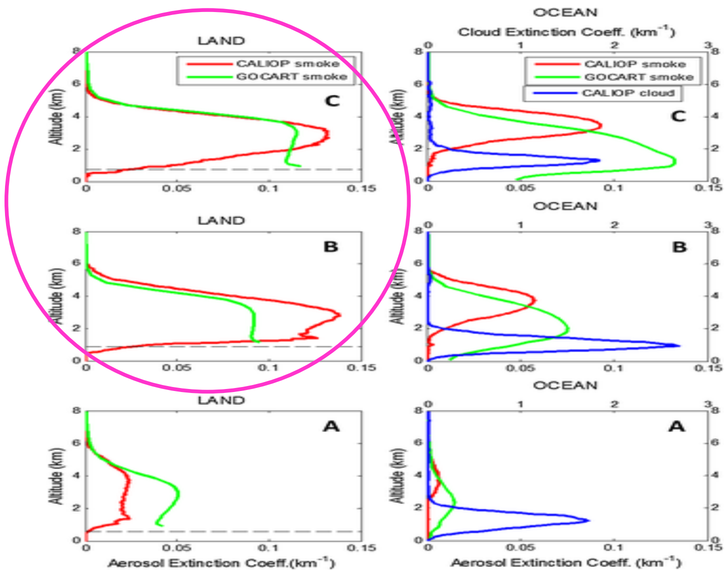

Fig. R8-3 (from Das et al., 2007). Comparisons of mean (August–September) smoke extinction profiles (km^{-1}) from CALIOP (in red) and GEOS-5-GOCART (in green) over land (13°E–35°E) and oceanic (13°E–15°W) parts of the three sub-regions, viz., A (30°S–20°S), B (20°S–10°S), and C (10°S–0°) of the domain. CALIOP-retrieved cloud extinction profiles (in blue) are plotted using the upper *x*-axis for profiles over the ocean to show relative altitudes of smoke and cloud layers. The mean surface elevations retrieved from CALIOP are shown using dashed lines on profiles over land.

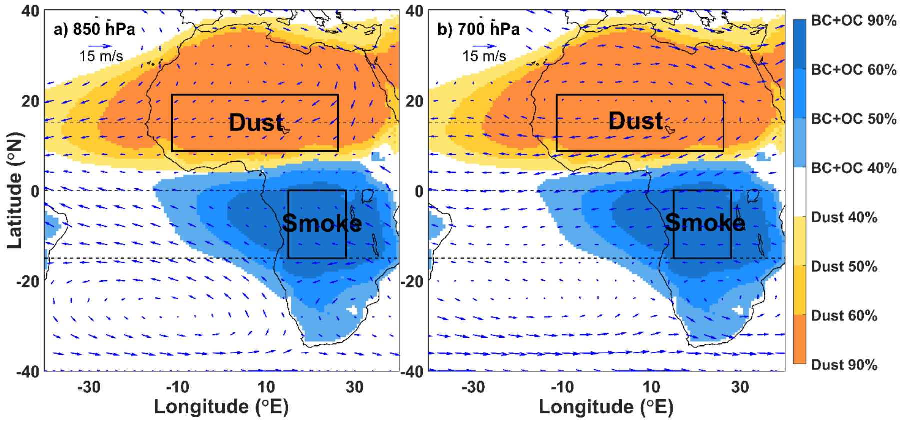

Fig. R9. Comparison of the prevailing wind directions at (a) 850 hPa and (b) 700 hPa over Africa.

(11) Figures 3 and 4

Sufficient details should be included in the text and/or figure captions for Figures 3 and 4 to enable anyone to replicate the plots. At present, I could not do it. For example, are data from all seasons used to make these plots, or only the respective lightning seasons? Were data points taken from every grid square in the two selected regions of interest?

Response:

One sentence "*Data used here are from every grid square (2.5°×2.5°) through the whole year from 2003 to 2013. Dynamic-thermodynamic variables are processed using three-month running mean filters to match with lightning data.*" is added to the caption of Figure 3 (now Figure 5) in the revised paper.

(12) Figure 5 discussion and interpretation

Only four sentences appear in the text to describe what one finds over Africa in the six panels of Figure 5. Some unaddressed questions: why is the correlation with SLP positive only in a narrow range of latitude? Why is lightning positively correlated with over wide areas of the Sahara where there is little lightning, and where hotter conditions are often accompanied by less moisture? Why is there a narrow belt of zero correlation in the RH plot? What is the significance of the blue spot in central Africa for the CAPE plot? Why is the correlation with wind shear positive in much of extratropical Africa but positive in the equatorial region? What is the nature of the blue zone in the map involving divergence?

Figure 5 (now is Figure 7) has been described again in the revised paper as "*Figure 7 shows that lightning flash rates are well correlated with mid-level relative humidity, CAPE, and divergence throughout both the dust- and smoke-dominant regions (most parts R > 0.6), while for other variables, the correlations vary from region to region. In particular, the correlations between the lightning flash rate and sea level pressure (positive), potential temperature (negative), and wind shear (positive) near the Earth's equator are distinctly different from those over other regions. We infer that this is because the hot and humid environment year-round favors deep convection. Wind shear helps organize mesoscale convection in moist deep convection which produces more lightning. Regarding potential temperature, rich precipitation helps cool the surface, which causes the negative correlation between the lightning flash rate and potential temperature. Different from the frontal system-dominant strong convection in the mid-latitudes, thermal convection more likely occurs in the tropics with a much smaller air pressure change. The frequent precipitation may also help create low and high pressure centers on the ground. These two points may lead to the positive correlation between the lightning flash rate and sea level pressure*." (see Lines 415–428).

Detailed edits and comments on the text:

Major editing is needed for this manuscript. The important and innovative scientific content of the paper has justified a detailed editing as the authors are not English-speakers, but in the future they should make a more concerted effort to clean their manuscript text prior to submission. Errors abound.

Title: Given that lightning rate rather than lightning is the key observable, shouldn't the title be: "The climate impact of aerosols on lightning rate: Is it detectable from long-term aerosol and meteorological data?"

Response: Yes. We have changed the title to: "The Climate Impact of Aerosols on the Lightning Flash Rate: Is it Detectable from Long-term Measurements?"

Page 2

Abstract

Line 34 "based on the 11-year dataset of lightning

Sentence rewritten as **"**by analyzing 11-year datasets of lightning, …" (Line 35)**.**

Line 35 "from the Moderate Resolution…"

Response: Modified.

Line 38 Why wasn't CBH or warm cloud depth selected, given earlier published results of Williams et al.(2005) and Stolz et al (2017)?

Response:

One goal of this study is to investigate the relative roles of several variables using the multi-regression method. As statistics textbooks suggest, when the sample size is fixed, 5–6 factors are the best choice for developing a multi-regression equation. More factors will introduce more random noise and thus undermine the stability of the regression equation. CAPE is the vertical integral of the buoyancy of an air parcel lifted from the boundary layer to the neutral buoyancy level which contains temperature and humidity information. Observational studies indicate that temperature and humidity in the boundary layer determines the variability in CAPE (Donner and Phillips, 2003). CBH can be derived from surface temperature and humidity and is mainly determined by surface RH (Williams and Satori, 2004). The warm cloud depth (WCD) is defined as the distance between the cloud base and the local height of the 0°C isotherm. So, to reduce the duplication of information about temperature and humidity, we chose to use the fundamental variables mid-level relative humidity, potential temperature, and CAPE, and did not consider CBH or WCD. However, the importance of these factors still needs to be assessed, not only through analyses and some speculation, but also through quantification with statistical methods. This will be considered in a future study.

Lines 48-49 Why is this so?

Response: From our statistical analysis, RH and CAPE are the top two factors modulating lightning activity and have the top two highest correlation coefficients and standardized regression coefficients.

Page 3

Line 51 Need to check this special value of AOD = 0.3 in the context of the Andreae et al. study linking AOD and CCN.

Response: Refer to the response to Substantive Issue (5).

Line 51 "lightning flash rate increases monotonically…"

Corrected.

Line 54 "enhance and suppress" without further explanation is confusing here

Response: Modified and removed.

Page 4

Introduction

Line 59 "accompanied with a concomitant" is redundant; be careful about use of "severe". This has a well-defined formal meaning in meteorology, and by those definitions the great majority of thunderstorms investigated here will not be in the severe category. Suggest not to use this term.

Response: We have changed the sentence to "Lightning can be considered a key indicator of strong atmospheric convection".

Line 60 Just a comment on this pairing: For many physical meteorologists, aerosol is part of meteorology. These are not two distinct categories.

Response: As you suggested, it may be better to divide the influential factors into two groups: (1) dynamic-thermodynamic variables and (2) aerosols. For more details, see the response to Substantive Issue (2).

Line 63 There was also pioneering work on aerosol effects on lightning in the 1990s by the cloud microphyscis group in Guadeloupe. See for example the following reference:

Michalon, N, A. Nassif, T. Saouri, J.F. Royer and C. Pontikis, Contribution to the climatological study of lightning, Geophys. Res. Lett., 26, 3097-3100, 1999.

Response: We have added this reference (Line 60).

Line 73 I don't understand "constrained" in this context.

Response: The phrase "the constrained water" is replaced by "a fixed liquid water content".

Line 76 Better if authors can quantify "conspicuous"

Response: We have added two sentences to quantify "conspicuous": "*More than a 150 % increase in lightning flashes accompanied a ~60 % increase in aerosol loading. Aerosol emissions from ships enhanced the lightning density by a factor of ~2 along two of the world's main shipping lanes in the equatorial Indian Ocean (Thornton et al., 2017).*" (Lines 77–80)

Page 5

Line 80 "and a simple parcel calculation" stops short. What is the authors' intended meaning here. Most readers will not understand.

Response: We wanted to say that previous studies found an optimal aerosol concentration in the response of clouds to aerosols through observations and theory. To help readers understand, "a simple parcel calculation" is replaced by "a theoretical calculation".

Line 83 "rainfall in southern China and drought in northern China"

Corrected.

Line 88 Here and elsewhere in the paper: "lightning activity"

Corrected.

Line 89 ", prompting us to perform…"

Corrected.

Line 91 Markson (BAMS, 2007) also considered temperature sensitivity of lightning in global circuit context.

Response: We have added this reference (Lines 98, 179).

Line 94 Bang and Zipser also considered influence of shear in a recent paper. Yoshida et al. (2009) has indirect evidence for positive shear effects on lightning flash rate.

Response: Yes, Bang and Zipser (2016) examined whether wind shear helps to differentiate between flashing and non-flashing convective systems and found no significant differences in shear. The effect of shear has been added to section 2.1.3.

Line 96 Given these physically-based connections with aerosol, why don' t the present authors also consider these same variables?

Response: See the response to Substantive Issue (7) on the selection of variables.

Page 6

Lines 99-100 A reference would be valuable here.

Response: A reference has been added: Fan et al., 2009.

Line 100 "forming in relatively dry conditions"

Corrected.

Lines 103-104 Authors are non-committal about the SIGN of the effect of shear. That is appropriate given different results in the literature, but given that, this situation should be clarified.

Response: We have added some details in Section 2.1.3.

Line 104 "from the invigoration effect"

Corrected.

Line 106 Williams et al. (2005) found the same effect but in CBH rather than in warm could depth. They are closely related. But it is in this line that I was left with the impression that you were looking at SURFACE RH rather than mid-tropospheric RH. Please make this clear in the text, everywhere.

Response: The reference has been added. Throughout this paper, all RH used in the statistical analysis is mid-tropospheric RH. We now use the full name "mid-level relative humidity" in the revised paper.

Lines 108-109 See earlier comments on "meteorology and aerosol"

Response: We have used "aerosol and dynamic-thermodynamics" instead.

Page 7

Line 118 “onboard the Tropical Rainfall…”

Corrected.

Line 119 “(TRMM) satellite which was designed…”

Corrected.

Line 120 “and span all longitudes”

Corrected.

Line 127 “with the same spatial resolution”

Corrected.

Lines 130-143 Somewhere the full time period of the AOD data set should be given, for comparison with the eleven year period provided for the LIS lightning data

Response: We have added the time period of AOD “from 2003–2013” (Line 145).

Line 131 “onboard the Aqua satellite…”

Corrected.

Line 133 “based on a dark target-deep…”

Corrected.

Line 136 “data from 1979 till present”

Corrected.

Line 139 “into the Aerosol Robotic…”

Corrected.

Line 140 “…(AERONET)-calibrated…”

Corrected.

Page 8

Line 142 Is the particle size aspect used in this paper? If not, why bring this up?

Response: The total Ångström exponent is used in creating Fig. 1b to show the significant differences in particle size over southern and northern Africa.

Line 148 “Convective Available Potential Energy”, given the acronym in CAPS.

Corrected.

Line 151 Ditto

Corrected.

Line 151 The "most commonly used thermodynamic parameter" for what purpose? Be specific.

For climate studies, ordinary temperature is much more commonly used than CAPE.

Modified as "*CAPE is a thermodynamic parameter commonly used in strong convection analysis and forecasting.***"**

Line 153 "of the atmosphere"

Corrected.

Line 154 "the more unstable is the atmosphere" ; "and more likely is strong vertical air motion"

Corrected.

Line 156 Williams et al., JGR, 2002 or Williams, 2012, AGU Franklin Lecture are better references.

Corrected.

Lines 157-158 Suggest rewording to "Unfortunately, reliable updraft measurements are lacking toward illuminating this role in the present study."

The sentence was changed to: *"However, reliable updraft measurements that would illuminate this role in the present study are lacking." (Lines 170–171)*

Page 9

Line 162 Ditto on use of "severe weather" . Please check formal definition of this term.

Corrected.

Line 166 Markson (BAMS, 2007) should be added here for his investigation of the UT diurnal dependence of the DC global circuit on temperature.

Added.

Line 168 "temperature systematically declines with altitude"

Corrected.

Line 172

Use of RH as a parameter for lightning rate can bring confusion. When lightning contrast between monsoon and break period convection is considered, increased RH is associated with dramatically reduced lightning activity. In Africa, which is moisture started, increased

RH is associated with increased lightning activity.

Response: Yes. In the development of convection (the production of lightning activities), a moderately wet underlying surface is needed. In this study, we chose to use mid-tropospheric RH instead to avoid the non-linear effect of surface RH on lightning activity. For more details, see the response to Substantive Issue (8).

Line 176 Consider including the same references you had before in lines 99-101 here.

Corrected.

Page 10

Line 181-182 I experience same confusion here as in the Abstract. Please elaborate here.

Modified and removed.

Line 187 Add space before "Mapes"

Corrected.

Line 191 "In addition, the Bowen ratio (BR) is calculated from the SHF and the LHF to describe a surface property"; on completion of the reading of the paper, it appears that these variables are never discussed again. If that was the intention, why not delete this information?

Response: BR is calculated to indicate the type of surface so that we can understand the climatological behavior of the lightning flash rate over the dust- and smoke-dominant regions in Figure 2. BR is shown in Fig. R10, mentioned on lines 352, 353, and is added to the supplemental material (Fig. S2).

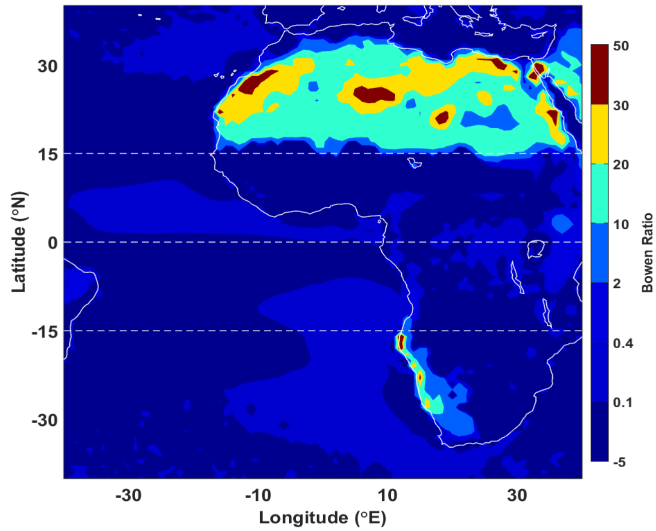

Fig. R10. Spatial distribution of the mean Bowen ratio during the period 2003–2013. Significant regional differences in surface properties over the African landmass are seen.

Line 195 "three-month smoothed average is chosen in this study"; I am confused about "three-month" period when an 11 year period was mentioned earlier.

Response: Yes, 11-year datasets are used in this study. But each dataset goes through three-month moving average smoothing. For example, data for January 2003 is the average of data from December 2002, January 2003, and February 2003, and so on.

Lines 195-196 Suggest rewording: "allow the LIS to progress twice through the diurnal cycle at a given location"

Corrected.

Line 196 "and to show"

Corrected.

Line 199 If the gridding of the basic data is 2.5 x 2.5 deg, why does the sampling in Figures 5 and 6 appear to be finer than this? (Please be careful on procedure throughout this document. Sampling info should go into the captions of every figure for which this is appropriate.)

Response: We have checked that the spatial resolution in Fig. 5 and Fig. 6 (now Fig. 7 and Fig. 8) is indeed 2.5°×2.5°. In these two figures, the longitude range is 20°W–40°E and the latitude range is 37°S–40°N.

Page 11

Line 199 "taking a 3-month running mean and resampling to…"

Corrected.

Line 200 change "climatic" to "climatological"

Corrected.

Line 202 Justify the choice here.

Response: We have added the following to justify the choice made here: "*To avoid a higher probability of misclassification of clouds and aerosols in high AOD regimes (Platnick et al., 2003), to minimize the influence of hygroscopic growth in a humid environment (Feingold and Morley, 2003) and to retain enough samples especially in the lightning-deficient region, the AOD range in this study is set between 0 and 1, following the work of Kaufman et al. (2005, AOD < 0.6), Koren et al. (2008, AOD < 0.8; 2012, AOD < 0.3) and Altaratz et al. (2017, AOD < 0.4). In addition, MODIS AOD is evaluated using daily AERONET AOD data (see Figures S8 and S8-1, 2, 3 in the supplemental material).*" (Lines 260–266)

Line 203 "top third of the AOD range" ; "and the bottom (lowest) third"

Corrected.

Line 207 "to measure the strength of a relationship between lightning flash rate and individual

predictors"

Corrected.

Line 208 Need reference for 'Pearson correlation'

Response: *We have added the following reference: "Pearson, K. (1896), "Mathematical Contributions to the Theory of Evolution. III. Regression, Heredity and Panmixia," Philosophical Transactions of the Royal Society of London, 187, 253-318." (Line 272)*

Line 211 "test at the 0.05 level"

Corrected.

Line 213 "use a multiple-linear regression method following previous studies"

Corrected.

Line 214 "and establish a standardized regression…"

Corrected.

Line 215 At this stage of the paper, we do not yet understand the importance of 0.3 so perhaps some foreshadowing is needed; "reduce the nonlinear effect"

Modified and removed.

Line 216 how does this sorting relate to the three categories of AOD noted above (lines 202-203)?

Response: When we began investigating the climatological behavior of the lightning flash rate under relatively clean and polluted conditions, we had no idea about the turning point. AOD varies seasonally, so to make sure there are enough samples in the clean and polluted scenarios, we divided the data into three categories according to the AOD range of each month. After we combined data from all seasons and created the scatterplot seen in Fig. 7 (now Fig. 9), we found a turning point at around AOD = 0.3. So in the following regression analysis, we divided the data into two groups (AOD < 0.3 and AOD > 0.3) to reduce the effect of nonlinearity.

Page 12

Lines 228 to 229 Wording and meaning are unclear to me here.

Response: It means we use normalization on each variables to remove the effect of units on the slope value.

Section 3 Shouldn't it be "Regions of Interest (ROI)"?

Corrected.

Line 231 "Northern and southern Africa have high…"

Response: The sentence was rewritten "*High loadings of dust and smoke aerosols are found in northern and southern Africa, respectively, as seen in Figure 1*."

Line 234 "It has been estimated that about…"

Response: The sentence was rewritten: "*About 2–4 billion tons of blown dust is estimated to be removed from the Sahara Desert annually (Goudie and Middleton, 2001*)."

Line 235 Shouldn't "globally" be "annually"?

Corrected.

Line 238 "accounting for roughly 30 to 50 %"

Corrected.

Page 13

Line 244 "onboard the Aqua satellite"

Corrected.

Lines 246-247 "at a spatial resolution of 0.625o x 0.5o"

Corrected.

Line 249 "have excessive uncertainties over land. The African continent stands out…" ; quantify "very large"

Response: We could not find a published study quantifying this uncertainty. However, information is given in the introduction to the MODIS Collection 6 product (https://darktarget.gsfc.nasa.gov/products/ocean). The preliminary estimated error for the Ångström exponent over oceans is 0.45; pixels with an AOD > 0.2 are expected to have a more accurate Ångström exponent. The Ångström exponent over land is no longer included in Collection 6.

Line 251 "Africa dominated by smoke"

Corrected.

Line 252 change "they…." to "these two regions ROI_1 and ROI_2 have been selected for study"

Response: The sentence was rewritten "*Due to their distinct differences in aerosol species, the dust- and smoke-dominant regions (Figures 1c, 1d) are selected as the study regions for dust and smoke.*"

Line 255 "to study multiple aerosol effects on lightning rate"

Corrected.

Line 257 The use of "long-term" here suggests you will study time series and trends, but I think you are focused only on climatology; suggest new section title: "Climatological behavior of lightning rate and aerosol optical depth"

Corrected per your suggestion.

Line 258 Discussion of details of Figure 2a begins abruptly. Some introductory sentences are needed to show reader where you are headed with this Figure.

Response: The following sentence was added: *"The seasonal and diurnal cycles of the lightning flash rate and AOD are first examined over the dust- and smoke-dominant regions (Figure 2a)."*

Page 14

Line 259 "over Africa" ; "neighboring" ; "over the red rectangle shown in Fig.1"

Response: The sentence was rewritten: "*Also shown in Figures 1c and 1d are mean wind* *vector at 850 hPa over Africa and its neighboring oceans (the area outlined in red in the left panel), which represent the prevailing wind direction.*" (Lines 323–325)

Line 260 delete one "the"

Corrected.

Line 262 "over the dust-dominant region"; "aerosol-dominant region"

Corrected.

Line 266 Williams (2000, JAM) is relevant here.

Added.

Line 270 "simulations by Lee et al. (2016)"

Response : This sentence has been rewritten "*This is well consistent with the finding of an aerosol-induced delay in precipitation and lightning activity revealed from observations (Guo et al., 2016) and model simulations (Lee et al., 2016) in southern China.*"

Line 274 "shows a pronounced seasonal variation with a huge…"

Corrected.

Line 275-276 The basis for this claim is not entirely clear to me.

Response: *We have provided a figure to help disentangle the contribution of thermodynamics on the seasonal variation in lightning activity. For more details, see the response to Substantive Issue (8).*

Lines 277-278 Need to be more specific about what features you are calling attention to.

Response: We have added the subgraph information to the show where we are talking about *"Figure 2 also shows an apparent enhancement in lightning activity under smoky conditions superimposed on both the diurnal (Figure 2b) and seasonal cycles (Figure 2d)."*

Line 278 "the impact is much weaker than for smoky conditions"

Corrected.

Page 15

Line 280 "dominating the region"

Response: *Modified and removed.*

Line 280 "A key factor…" Authors are not giving the physical basis here for the importance of relative humidity. See also earlier Substantive Comments

Response: We have added several sentences to Section 2.1.3. See the response to Substantive Issue (8).

Line 283 A reference that could be added here pertains to oceanic conditions where RH is greatest—Thornton et al. (GRL, 2017)

Added.

Line 284 "is located in the vicinity…"

Corrected.

Line 285 "is located in the ITCZ"

Corrected.

Line 286 "and leads to differences in wind shear and instability between the two regions"

Response: The sentence was rewritten. "*The dust-dominant region is located in the vicinity of the African easterly jet (Burpee, 1972) and the smoke-dominant region is located in the ITCZ (Waliser and Gautier, 1993). Differences in wind shear and instability thus arise between the two regions.*"

Line 287 Aerosol is a part of meteorology

Response: We have replaced the term "meteorology" with "dynamics-thermodynamics".

Line 288 "Thermodynamic conditions are considered to play the main role in the diurnal and seasonal variation of lightning"

Response: The sentence was rewritten: "*Diurnal and seasonal variations in lightning activity depend on dynamic-thermodynamic conditions.*"

Line 290 "which are characterized"; Add CBH or warm cloud depth, or say why they have not been included.

Response: See the response to Substantive Issue (7).

Line 291 "The violin plot…"

Corrected.

Line 292 "of distributions"

Corrected.

Line 296 Authors mean to say "linear correlations" rather than "linear relationships". (The relationships themselves can be non-linear."

Corrected.

Line 298 "lightning flash rates"

Corrected.

Line 298 Not in the ocean regime. If RH is too high, warm rain will kill the lightning activity. The authors need to consider the full dynamic range of the variables they select, and the limitations for regimes outside of the dry African continent.

Response: Moderately high surface RH is more favorable for lightning activity with a watershed value of 72–74% (Xiong et al., 2006). Mid-level relative humidity is lower than surface humidity. As shown in Fig. R6, there is a very low probability that mid-level relative humidity surpasses 73% (< 1% in the dust-dominant region, < 9% in the smoke-dominant region). So we think there may be no turning point in the response of lightning to mid-tropospheric RH. Even if there is one, the three-month smoothed mid-tropospheric relative humidity is less than the surface relative humidity in the long term. For more details, see the response to Substantive Issue (8).

Page 16

Line 300 I don't understand "variable density shape"

Removed.

Line 303 "characterizes"

Corrected.

Line 305 What can one expect, with author's use of potential temperature variable?

Response: See the response to Substantive Issue (9).

Line 306 "that the variables cannot be considered correlated"

Response: The sentence was rewritten" *The small correlation coefficients of the regressions between the lightning flash rate and sea level pressure, wind shear, and potential temperature suggest little correlation between these variables and the lightning flash rate*."

Line 307 Yes, "linear correlation" is correct, not "linear relationship"

Corrected.

Line 313 "which is also the case"

Corrected.

Line 314 "lightning"

Corrected.

Lines 314-315 This statement is ignoring the physics.

Response: We have added the following as a possible explanation: "S*imulations done by Weisman and Klemp (1982) show that weak, moderate, and high wind shear produces short-*

lived single cells, secondary development, and split storms, respectively. The coarse time resolution may be why no significant correlation is found between shear and the lightning flash rate."

Line 316 "and cannot imply causal relationships"

Corrected.

Line 318 "To provide a visual comparison…"

Corrected.

Figure 5 has altogether too little discussion. (It is getting just four sentences.)

Response: See the response to Substantive Issue (9). We have added more discussions.

Page 17

Lines 321-322 What is meant here?

Response: We performed partial correlations between lightning rate and each dynamic-thermodynamic variable while controlling AOD and the other five dynamic-thermodynamic variables.

Line 323 "activity"

Corrected.

Line 324 "lightning"

Corrected.

Line 325 "lightning activity by participating in …"

Corrected.

Line 328 "the peak times for lightning" ; Please note that thermodynamics will also change here.

Response: Yes. Thermodynamics may change with pollution load. Thermodynamics under relatively clean and polluted conditions are quite different, especially in the smoke-dominant region. Although we cannot determine the cause-and-effect relationship between aerosols and thermodynamics, there should be some interplay between them.

Lines 329-330 Why?

Response: Yes, thermodynamics under relatively clean and polluted conditions are quite different, especially in the smoke-dominant region. Although we cannot determine the cause-and-effect relationship between aerosols and thermodynamics, they should be some interplay between them.

Line 331 "condition the lightning response to AOD shows an…"

Response: Modified as "*The response of the lightning flash rate to AOD is shaped like a boomerang* …."

Line 332 "dust- and smoke aerosol-dominant regions"

Corrected.

Line 333 "the data are divided"

Corrected.

Line 334 "performing correlation and regression"

Response: Modified and removed.

Line 35 "lightning flash rate increases monotonically"

Corrected.

Line 337 "lightning flash rate is strongly…"

Corrected.

Line 338 "implying that under large…"

Response: The sentence was rewritten as "*implying that aerosol-cloud interactions (ACI) play the dominant role in lightning activity.*"

Line 339 "lightning rate is mainly influenced"

Response: Modified and removed.

Line 339 At large aerosol loading, the cloud microphysics changes. See modelling efforts in Mansell and Ziegler (2013?)

Response: This paper helped us explain the boomerang shape in more detail so has been cited. (Line 448)

Line 340 quantify "under smoky conditions" in AOD.

Response: From the scatterplot, the turning point is around AOD=0.3. Smoky conditions means AOD > 0.3 here.

Page 18

Line 341 "significant" is repeated; I don't understand the rest of this line. Please clarify.

Response: Modified and removed.

Line 343 If I am not mistaken, the Farias studies would pertain to smoke rather than dust aerosol, as they were carried out in South America.

Response: Yes, Farias et al. (2014) used PM_{10} data collected in the metropolitan region of

Sao Paulo. We cited this work to show a similar suppression effect of aerosols on lightning. However, the aerosol type is different so this reference was deleted.

Line 344 "we can easily find" : This claim is unclear. Did the authors find it? Are you able to find it.

Response: Modified and removed.

Line 345 "a smoke aerosol-dominant region that is located in the ITCZ"

Response: Modified and removed.

Line 346 "the dust-dominant region sis much drier and so is not so easy…"

Response: Modified and removed.

Line 354 "lightning flash rate increase"

Corrected.

Line 356 change "around" to "near"

Corrected.

Line 358 You mean to say that half the CAPE values are < 100 J/kg?

Response: Yes. All data used have undergone three-month moving average smoothing. The means represent climatological features including information about lightning and non-lightning days.

Line 359 How do you know that the effect is entirely thermodynamic?

Response: Thermodynamics play an important role, but we cannot say the effect is entirely thermodynamic.

Line 360 "the lightning flash rate response to RH in different ways…"

Corrected.

Page 19

Line 361 "In the dust-dominant region, flashes increase monotonically…"

Corrected.

Line 363 "constraint on lightning activity"

Corrected.

Line 364 "for the smoke aerosol-dominant region, large lightning flash rates appear…"

Corrected.

Line 365 "response of lightning rate to…"

Corrected.

Line 367 "…remain high." ; "The data distribute…"

Corrected.

Line 368 Best to remind the reviewer that you are talking about mid-level RH rather than surface RH.

Response: We replaced RH with mid-level relative humidity throughout the paper.

Line 371 "are still conducive to …" ; "but data variance is larger, suggesting…"

Corrected.

Line 372 "is not as high" ; "the restriction on RH…"

Response: Corrected, "restriction" is replaced by "dependence"

Line 374 "also contribute to different climate conditions" : the meaning here is unclear to this reviewer

Response: It has been changed to "*… be attributed to different dynamic-thermodynamic conditions.*"

Line 378-379 "Generally, the lightning rates are greater for all these…"

Corrected.

Line 380 "lightning" (typo)

Corrected.

Line 381 "is highly significant (>99%), based on the Student' s test."

Corrected.

Page 20

Line 383 "In addition, we note that, when SLP decreases and mid-level RH increases, the differences in lightning rate…"

Corrected.

Line 384 "conducive conditions"

Corrected.

Line 385 "participate in the cloud microphysics and convective development, and thus to modulate…"

Corrected.

Line 388 "response of lightning rate"

Corrected.

Line 389 "impacting aerosol loadings"

Corrected.

Line 392 "the aerosol-meteorological variables" and add "the turning point (AOD=0.3, Figure 7)"

Corrected.

Line 393 Start new sentence: "The results are shown in…"

Corrected.

Line 394 "For clean conditions"

Corrected.

Line 401 Excellent to constrain all the others.

Thank you.

Page 21

Line 402 "regression equation, the coefficients of this equation represent…"

Corrected.

Line 405 "anymore"; "envisaged"?

Response: The sentence was rewritten" … are no longer significant.". "Envisaged" is removed.

Line 406 "lightning activity through the modulation of meteorological variables…" Not clear what is the physical meaning here.

Response: The weak partial correlation of the AOD-lightning flash rate relationship, the high Pearson correlation of the AOD-CAPE relationship, and the high partial correlation of the CAPE-lightning flash rate relationship all suggest that the lightning rate does not respond much to dust aerosols directly, but dust can affect convection and lightning activity through the modulation of the thermodynamic variables in aerosol-cloud interactions.

Line 408 "for the dust-dominant region"

Corrected.

Line 411 "The main interplay is between AOD and…"

Corrected.

Line 412 "and the coefficients"

Corrected.

Line 413 "The standardized multiple regression equation reveal the top three factors…"

Corrected.

Line 414 "as the top restraint factor in the dust-dominant region…"

Corrected.

Line 415 "In addition, AOD becomes more important…"

Corrected.

Line 416 "meteorology" (typo); What is the meaning here? Correlate well with what meteorology?

Response: Aerosols correlate well with CAPE (R > 0.75) under clean conditions (AOD < 0.3).

Line 417 I am not sure what the tight cluster distribution is in Figure 9. Please clarify.

Response: In both regions, aerosols correlate well with CAPE (R > 0.75) under clean conditions (AOD < 0.3) which suggests that aerosols might participate in cloud microphysical processes: more aerosols acting as CCN leads to a narrower cloud droplet size spectrum, delays the warm-rain process and allows more liquid water to ascend higher into the mixed-phase cloud, thus releasing more latent heat, molulating environmental variables (such as increasing temperature, updraft and CAPE in and above clouds) and producing a more unstable atmosphere conducive to convective development. The aerosol invigoration effect may play the key role during this stage (AOD < 0.3). The same directions of the impacts of aerosols and thermodynamics such as CAPE on the lightning flash rate may be the reason for the tightly clustered distribution under clean conditions seen in Figure 9.

Line 417-418 CAPE and moist static energy are not the same, so CAPE does not measure it.

Response: This sentence has been deleted.

Line 422 "more latent heat

Corrected.

Page 22

Line 423 "conducive to convective development"

Corrected.

Line 426 "meteorology" (typo)

Corrected.

Line 427 "is weakened" ; "meteorology" (typo)

Corrected.

Line 430 I think you have the causality turned around: a dry environment enables dust aerosol.

Response: We appreciate this comment. Ackerman et al. (2000) demonstrated that dark haze enhances the solar heating of aerosol layers, increases temperatures, thereby lowering RH, leading to cloud burning. Under dusty conditions, high dust loadings produce more cloud droplets which are easy to evaporate and may reduce cloudiness. As the absorption strength of dust is much smaller than soot, this hardly happens. Perhaps the reviewer' s suggestion is more reasonable. We have modified the text "*This suggests two things: (1) drier environments are more favorable for dust emission, and (2) drier mid-level environments produce a more stable atmosphere and rapid evaporation of the condensate, leading to the suppression of convection and lightning.*"

Line 431 "and the atmosphere more stable through the aerosol radiative effect"

Corrected.

Line 433-434 "in making the environment drier"

Corrected.

Line 434-435 This finding is surprising to me, but is also what Stolz et al. (2017) concluded.

Response: "*The lightning flash rate seems to be saturated in the smoke-dominant region but is strongly suppressed in the dust-dominant region. This is likely associated with difference in both aerosol properties and dynamics/thermodynamics which are coupled to jointly affect lightning. The different dynamic and thermodynamic conditions between the two regions may play important roles: 1) The drier the mid-level atmosphere, the more likely that there is evaporation of cloud droplets that are smaller under heavily polluted conditions. The aerosol-microphysical-effect-induced evaporation tends to suppress the development of clouds and inhibits lightning activity in combination with the aerosol radiative effect which causes surface cooling and leads to an increase in atmosphere stability. Together, the two factors are compounded, leading to a sharp decline in lightning rate under heavy dusty conditions in the desert-dominant region. 2) However, clouds in the moister region of central Africa are less susceptible to evaporation and suppression. The strongly absorbing smoke aerosols also heat up the aerosol layers (usually below deep convective clouds that produce lightning), destabilizing the atmosphere above, thus dampening the suppression effect of the aerosol-radiation interactions. The development of convection and associated lightning is thus sustained." (Lines 460–474)*

Line 439 "convection-induced" ; "case-based"

Corrected.

Page 23

Line 445 "dust- and smoke-dominant regions"

Corrected.

Line 447 "from the ECMWF…"

Corrected.

Line 448 "features of the diurnal…" ; "show the peak in …"

Corrected.

Line 449 "role of thermodynamics"

Corrected.

Line 452 "lightning flash rates are larger" ; "than under clean ones"

Corrected.

Line 453 "increase much more than when the SLP…" Clarify where this is shown in the paper.

Response: When we constrain AOD to the range of (0, 1) and recreate Figure 9 (now Figure 11), this feature is no longer seen. This sentence has thus been deleted.

Line 456 "show a boomerang shape"

Corrected.

Line 457 "in an attempt…"

Corrected.

Line 458 "and to quantify"

Corrected.

Line 459 "Under relatively clean conditions"

Corrected.

Line 461 "two top determinants" ; "in the dust-dominant region"

Corrected.

Line 462 "in the smoke aerosol-dominant region"

Corrected.

Line 463 "on lightning activity"

Corrected.

Page 24

Line 464 "through a cloud microphysical effect which may modulate the meteorological …"

Corrected.

Line 465 "lightning rate shows a more dispersed…"

Corrected.

Line 466 "of a competition between the aerosol microphysical effect and the radiative…"

Corrected.

Line 469 "cools the surface"

Corrected.

Line 470 "warms the mid-level atmosphere"

Corrected.

Line 471 "dusty conditions"

Corrected.

Line 472 "the aerosol radiative effect"

Corrected.

Line 473 "to a stable atmosphere" ; "lightning" (typo)

Corrected.

Lines 474-475 How do you know this?

Response: There is a large difference in mid-level relative humidity: 1) The mean RH in ROI_1 is ~36%, while the mean RH in ROI_2 is ~74%; 2) There is a much lower probability that relative humidity surpasses 73% (< 1% in the mid-level troposphere, < 12% at the surface) in the dust-dominant region than in the smoke-dominant region (~9% in the mid-level troposphere, ~63% at the surface). This large moisture difference may lead to the difference in the response of lightning to aerosols.

Line 475 "for the dust-dominant region" ; "and high CAPE"

Corrected.

Line 476 "help to intensify…" ; "For the smoke-dominant region…"

Corrected.

Line 477-478 You could list the state variables and the transient variables here.

Response: This sentence is rewritten "*The influences of other variables such as wind shear and convergence/divergence are insignificant from a climatological perspectiv*e." (Lines

635–636).

Line 479 “cannot totally filter them out”

Corrected.

Line 482 “model simulations”

Corrected.

Page 25

Line 487 “lightning flash information”

Corrected.

References

Suggest adding:

Altaratz O., B. Kucienska, A. Kostinski, G. B. Raga, and I. Koren, Global association of aerosol with flash density of intense lightning, Env. Res. Lett., 114037, 2017.

Andreae (2009) relating AOD and CCN

Fan et al. (Science, 2018) is relevant, even though the Amazon is the main target rather than Africa.

Williams et al. (JAM, 2000), Williams et al. (JGR, 2002), Williams and Satori (2004)

Venevsky (cited above)

Response: We have added the following references:

Ackerman, A. S., Toon, O. B., Stevens, D, E., Heymsfield, A. J., Ramanathan, V., and Welton, E. J.: Reduction of tropical cloudiness by soot, Science, 288(5468), 1042-1047, 2000.

Altaratz, O., Kucienska, B., Kostinski, A., Raga, G. B., and Koren, I.: Global association of aerosol with flash density of intense lightning, Environ. Res. Lett., 12, 114037, https//doi.org/10.1088/1748-9326/aa922b, 2017.

Andreae, M. O.: Correlation between cloud condensation nuclei concentration and aerosol optical thickness in remote and polluted regions, Atmos. Chem. Phys., 9(2), 543–556, https//doi.org/10.5194/acp-9-543-2009, 2009.

Bang, S. D. and Zipser, E. J.: Seeking reasons for the differences in size spectra of electrified storms over land and ocean, J. Geophys. Res.-Atmos., 121(15), 9048–9068, https//doi.org/ 10.1002/2016JD025150, 2016.

Chakraborty, S., Schiro, K. A., Fu, R., and Neelin, J. D.: On the role of aerosols, humidity, and vertical wind shear in the transition of shallow to deep, Atmos. Chem. Phys. Discuss., https://doi.org10.5194/acp-2018-249, 2018.

Derbyshire, S. H., Beau, I., Bechtold, P., Grandpeix, J. Y., Piriou, J. M., Redelsperger, J. L., and Soares, P. M. M.: Sensitivity of moist convection to environmental humidity, Q. J. Roy. Meteorol. Soc., 130(604), 3055-3079, 2004.

Fan, J., Zhang, R., Tao, W. K., and Mohr, K.: Effects of aerosol optical properties on deep convective clouds and radiative forcing, J. Geophys. Res.-Atmos., 113(D8), https://doi.org/10.1029/2007JD009257, 2008.

Fan, J., Rosenfeld, D., Zhang, Y., Giangrande, S. E., Li, Z., Machado, L. A., ⋯, and Barbosa, H. M.: Substantial convection and precipitation enhancements by ultrafine aerosol particles, Science., 359(6374), 411-418, 2018.

Feingold, G. and Morley, B.: Aerosol hygroscopic properties as measured by lidar and comparison with in situ measurements, J. Geophys. Res.-Atmos., 108(D11), 4327, doi:10.1029/2002JD002842, 2003

Jayaratne, E. R., and Kuleshov. Y.: The relationship between lightning activity and surface wet bulb temperature and its variation with latitude in Australia, Meteorol. Atmos. Phys. , 91(1-4), 17-24, 2006.

Koren, I., Altaratz, O., Remer, L. A., Feingold, G., Martins, J. V., and Heiblum, R. H.: Aerosol-induced intensification of rain from the tropics to the mid-latitudes, Nat. Geosci., 5(2), 118, 2012.

Mansell, E. R. and Ziegler, C. L.: Aerosol effects on simulated storm electrification and precipitation in a two-moment bulk microphysics model, J. Atmos. Sci., 70(7), 2032–2050, https://doi.org/10.1175/JAS-D-12-0264.1, 2013.

Markson, R.: The global circuit intensity–its measurement and variation over the last 50 years, B. Am. Meteorol. Soc., 88(2), https://doi.org/10.1175/BAMS-88-2-223, 2007.

Pearson, K.: Mathematical contributions to the theory of evolution. III. Regression, heredity and panmixia, Philos. T. R. Soc. Lond. S-A, 187, 253–318, https://doi.org/10.1098/rsta.1896.0007, 1896.Price, C.: Global surface temperatures and the atmospheric electrical circuit, Geophys. Res. Lett., 20(13), 1363–1366, https://doi.org/10.1029/93GL01774, 1993.

Platnick, S., King, M. D., Ackerman, S. A., Menzel, W. P., Baum, B. A., Riedi, J.C., and Frey, R. A.: The MODIS cloud products: Algorithms and examples from Terra, IEEE Trans. Geosci, Remote Sens, 41(2), 459-473.

Redelsperger, J. L., Parsons, D. B., and Guichard, F.: Recovery processes and factors limiting cloud-top height following the arrival of a dry intrusion observed during TOGA COARE, J. Atoms. Sci, 59(16), 2438-2457, 2002.

Reeve, N., and Toumi, R.: Lightning activity as an indicator of climate change. Q. J. Roy. Meteorol. Soc., 125(555), 893-903, 1999.

Takemi, T.: A sensitivity of squall-line intensity to environmental static stability under various shear and moisture conditions, Atoms. Res., 84,374-389, doi:10.1016/j.atmossres.2006.10.001, 2007.

Venevsky, S.: Importance of aerosols for annual lightning production at global scale, Atmos. Chem. Phys. Discuss., 14, 4303–3325, https://doi.org/10.5194/acpd-14-4303-2014, 2014.

Weisman, M. L. and Klemp, J. B.: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy, Mon. Weather Rev., 110(6), 504–520, https://doi.org/ 10.1175/1520-0493(1982)110<0504:TDONSC>2.0.CO;2, 1982.

Williams, E. R., Rosenfeld, D., Madden, N., Gerlach., J., …, and Avelino, E.: Comparison convective regimes over the Amazon: Implications for cloud electrification, J. Geophys. Res.-Atmos., 107(D20), https://doi.org/10.1029/2001JD000380, 2002.

Williams, E. R., Rothkin, K., Stevenson, D., and Boccippio, D.: Global lightning variations caused by changes in thunderstorm flash rate and by changes in the number of thunderstorms, J. Appl. Meteorol., 39(12), 2223–2230, https://doi.org/ 10.1175/1520-0450(2001)040<2223:GLVCBC>2.0.CO;2, 2000.

Xiong, Y. J., Qie, X. S., Zhou, Y. J., Yuan, T., and Zhang, T. L.: Regional response of lightning activities to relative humidity of the surface, Chin. J. Geophys., 49(2), 311-318, 2006.

Zhang, G. J.: Effects of entrainment on convective available potential energy and closure assumptions in convection parameterization, J. Geophys. Res. - Atmos, 114(D7), 2009.

Figures

Figure 1

Line 574 "from the MERRA dataset"

Corrected.

Line 758 "from the MERRAAero data set" Caption needs to clarify whether pictures are seasonally integrated. And what is "BC+OC"?

Response: Corrected. All figures in this paper cover the period 2003–2013 and include all seasons. "BC+OC" means black carbon and organic carbon.

Figur 2

2nd line of caption: "neighboring"

Corrected.

5th line of caption: “enables”

Corrected.

7th line of caption: “calculated” (typo)

Corrected.

8th line of caption: “in the dust-dominant region”; “smoke-dominant region”

Corrected.

Last line: “Cecil et al., …”

Corrected.

Figures 3 and 4 The caption should tell what time frame is examined and how the monthly sampling is handled. Why are the CAPE values so low here?

Response: Corrected. All data used here are for the period 2003–2013 and are processed using a three-month running mean smoothing filter to match with lightning data. Each sample represents a three-month mean value and includes data with and without lightning activity. The mean CAPE value is therefore much lower than it is in a lightning case.

Figure 5 The caption should explain exactly how the plots were made. See also other questions about details of each sub-figure.

Response: We have added more explanations about how the plots were made: “Data used here are from every grid square (2.5°×2.5°) through the whole year from 2003 to 2013. Dynamic-thermodynamic variables are processed using three-month running mean filters to match with lightning data.”

Figure 7 You have excellent opportunity here to show your three ranges of AOD, including the “clean” and “polluted” range, and the one in between. Also important to explain exactly what a single point represents on these important plots. The last sentence of the caption I do not completely understand.

First of all, what is one “sample”?

Response:

1) It is a good idea to show three ranges of AOD in Figure 7 (now Figure 9). However, the problem is that clean and polluted regions vary by season (Figure 2) and dynamic-thermodynamic condition (Figure 9, now Figure 11), so we cannot show them together in Figure 7 (now Figure 9). In Figures 2c and 2d, mean values of AOD under clean and polluted conditions are shown for each month. Figure R4, which shows mean AOD as a function of the lightning flash rate and as a function of the six meteorological variables under clean and polluted conditions, has been added here to help explain and analyze Figure 9 (now Figure 11). See the response to Substantive Issues (6) for more details.

2) One sample, or data point, means a pair of data in each month, e.g., the three-month mean (e.g., April-May-June) lightning rate and the three-month mean (e.g., April-May-June) sea level pressure for May 2007.
3) The last sentence means that we first ordered samples by AOD from small to large, then calculated mean values (for both AOD and lightning rate) in each 10-sample bin to reduce the uncertainty caused by the large dispersion of data.

Figure 8 What exactly is one "cell" here relative to the climatological maps you are taking data from? (This gets at the criticism on Procedure again.) Why is CAPE so small?

Response:

1) In Figure 8 (now Figure 10), lightning data is divided into 100 discrete cells: ten decile bins of the horizontal axis variable and ten decile bins of the vertical axis variable. The intersection of a specific bin along the x-axis and a specific bin along the y-axis defines a cell in x-y space.
2) All variables here are processed using a three-month running mean smoothing filter and include data with and without lightning activity. The mean CAPE value is therefore much lower than it would be in a lightning-only case.

Figure 9 This is an impressive result, with all differences (no exception) taking on a positive sign. Still confused about "the top third of AOD". Is that the top third of a full range of 0.9 (0.6 to 0.9), or the top third of a full range of 1.0 (0.66 to 1.0)?

Response:

The top third of AOD is the top third of the full range of values. The full range of values is 0–1.7 for ROI_1 and 0–1.2 for ROI_2 in Figure 9. Figure 9 (now Figure 11) was recreated using the AOD range 0–1 for both dust- and smoke-dominant regions. Note that the top third of the range 0–1 does not mean 0.66–1. Data are ordered by AOD from small to large first then data are divided into three subsets with an equal number of samples in each subset. So under different dynamic or thermodynamic conditions, the top third of the AOD range varies.

Figure 10 is too complicated for me to understand.

Response:

Here is a table listing the regression coefficients. This may help in understanding Figure 10 (now Figure 12) and has been added to the supplemental material (see Table S2).

Table R2: Linear regression correlations between lightning flash rate and dynamic-thermodynamic factors (x_1–x_6) and AOD (x_7) before and after the turning point (AOD = 0.3) for the dust- and smoke-dominant regions.

ROI	Correlation	SLP (x_1)	Θ (x_2)	RH (x_3)	CAPE (x_4)	SHEAR (x_5)	Div (x_6)	AOD (x_7)

dust (AOD<0.3)	Pearson_1	-0.62	0.52	0.96	0.96	-0.51	0.87	0.75
	Pearson_2	-0.74	0.63	0.81	0.76	-0.43	0.74	/
	Partial	0.12	0.02	0.44	0.57	0.02	0.16	-0.04
	Equation	$y = 0.07x_1 + 0.08x_2 + 0.49x_3 + 0.49x_4 + 0.01x_5 + 0.09x_6 - 0.02x_7 - 1.52\times10^{-14}$						
	Multiple	0.96 (standardized)						
dust (AOD>0.3)	Pearson_1	0.26	-0.18	0.89	0.91	-0.09	0.76	-0.41
	Pearson_2	-0.66	0.47	-0.51	-0.33	-0.07	-0.53	/
	Partial	0.10	0.16	0.41	0.66	-0.05	0.25	0.04
	Equation	$y = 0.11x_1 + 0.15x_2 + 0.34x_3 + 0.54x_4 - 0.02x_5 + 0.15x_6 + 0.02x_7 - 5.44\times10^{-14}$						
	Multiple	0.91 (standardized)						
smoke (AOD<0.3)	Pearson_1	-0.94	-0.37	0.74	0.96	-0.31	0.83	0.86
	Pearson_2	-0.80	-0.43	0.43	0.78	-0.02	0.59	/
	Partial	-0.27	-0.21	0.36	0.50	0.31	-0.10	0.50
	Equation	$y = -0.21x_1 - 0.06x_2 + 0.32x_3 + 0.42x_4 + 0.13x_5 - 0.08x_6 + 0.25x_7 - 5.28\times10^{-14}$						
	Multiple	0.96 (standardized)						
smoke (AOD>0.3)	Pearson_1	-0.67	-0.27	0.81	0.87	-0.07	0.82	-0.15
	Pearson_2	0.17	-0.74	-0.24	0	0.5	-0.3	/
	Partial	-0.12	0.11	0.36	0.51	0.04	0.21	0.05
	Equation	$y = -0.07x_1 + 0.09x_2 + 0.31x_3 + 0.51x_4 + 0.02x_5 + 0.17x_6 + 0.04x_7 - 1.02\times10^{-14}$						
	Multiple	0.88 (standardized)						

Columns from left to right: (1) Region of interest (ROI). (2) Correlation type: Pearson correlation coefficients of the linear regression relationships between the lightning flash rate and the six dynamic-thermodynamic variables and aerosol optical depth (AOD; Pearson_1), Pearson correlation coefficients of the linear regression relationships between AOD and any given dynamic-thermodynamic variable (Pearson_2), partial correlation coefficients of the relationships between the lightning flash rate and any influential factor (AOD or dynamic-thermodynamic variables) with the others as control variables (Partial). (3) Correlation coefficients, standardized multiple correlation coefficients (R_M) and standardized multiple regression equations of the lightning flash rate (y) to six dynamic-thermodynamic factors ($x_1 - x_6$) and AOD (x_7). The six dynamic-thermodynamic variables are sea level pressure [SLP (x_1)], potential temperature [θ (x_2)], mid-level relative humidity [RH (x_3)], mean convective available potential energy [CAPE (x_4)], vertical wind shear [SHEAR (x_5)], and 200-hPa divergence [Div (x_6)]. Correlation coefficients are shown in black if they pass the significance test at 99%. They are shown in red if they failed the significance test at the 0.05 level.

End of Review
Earle Williams
May 11, 2018

End of Response
July 23, 201

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The Climate Impact of Aerosols on the Lightning Flash Rate: Is it Detectable from Long-term Measurements?

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Revised July 23, 2018

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Abstract

The effect of aerosols on lightning has been noted in many case studies, but much less is known about the long-term impact, relative importance of dynamics-thermodynamics versus aerosol, and any difference by different types of aerosols. Attempts are made to tackle with all these factors whose distinct roles are discovered by analyzing 11-year datasets of lightning, aerosol loading and composition, and dynamic-thermodynamic data from satellite and model reanalysis. Variations in the lightning rate are analyzed with respect to changes in dynamic-thermodynamic variables and indices such as the convective available potential energy (CAPE), vertical wind shear, etc. In general, lightning has strong diurnal and seasonal variations, peaking in an afternoon and summer. The lightning flash rate is much higher in moist central Africa than in dry northern Africa presumably because of the combined influences of surface heating, CAPE, relative humidity, and aerosol type. In both regions, the lightning flash rate changes with AOD in a boomerang shape: first increasing with AOD, tailing off around AOD = 0.3, and then behaving differently, i.e., decreasing for dust and flattening for smoke aerosols. The deviation is arguably caused by the tangled influences of different thermodynamics (in particular humidity and CAPE) and aerosol type between the two regions. In northern Africa, the two branches of opposite trends seem to echo the different dominant influences of the aerosol microphysical effect and the aerosol radiative effect that are more pronounced under low and high aerosol loading conditions, respectively. Under low AOD conditions, the aerosol microphysical effect more likely invigorates deep convection. This may gradually yield to the suppression effect as AOD increases, leading to more

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and smaller cloud droplets that are highly susceptible to evaporation under the dry conditions of northern Africa. For smoke aerosols in moist central Africa, the aerosol invigoration effect can be sustained across the entire range of AOD by the high humidity and CAPE. This, plus a potential heating effect of the smoke layer, jointly offset the suppression of convection due to the radiative cooling at the surface by smoke aerosols. Various analyses were done that tend to support this hypothesis.

1 Introduction

Lightning can be considered a key indicator of strong atmospheric convection (Betz et al., 2008). Lightning activity has been linked to two major factors: dynamics-thermodynamics and aerosols (e.g., Lucas et al., 1994; Michalon et al., 1999; Boccippio et al., 2000; Orville et al., 2001; Williams and Stanfill, 2002; Christian et al., 2003; Williams et al., 2004, 2005; Bell et al., 2008, 2009; Guo et al., 2016).

Since the pioneering work by Westcott (1995) who attempted to link summertime cloud-to-ground lightning activity to anthropogenic activities, the roles of aerosols in lightning have been increasingly recognized, as comprehensively reviewed on the topic associated with aerosol-cloud-precipitation interactions (e.g., Tao et al., 2012; Fan et al., 2016; Li et al., 2016, 2017a). The aerosol effect encompasses both radiative and microphysical effects (Boucher et al., 2013; Li et al., 2017b). The radiative effect suggests that aerosols can heat the atmospheric layer and cool the surface by absorbing and scattering solar radiation, thereby reducing the latent heat flux and stabilizing the atmosphere (Kaufman et al., 2002; Koren et al., 2004, 2008; Li et al., 2017a). Convection and electrical activities are thus likely inhibited (Koren et al., 2004). By acting as cloud condensation nuclei (CCN) with fixed liquid water content, increasing the aerosol loading tends to reduce the mean size of cloud droplets, suppress coalescence, and delay the onset of warm-rain processes (Rosenfeld and Lensky, 1998). This permits more liquid water to ascend higher into the mixed-phased region of the atmosphere where it fuels lightning. A conspicuous enhancement of lightning activity was found to be tightly connected to volcanic ash over the western Pacific Ocean (Yuan et

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al., 2011). More than a 150 % increase in lightning flashes accompanied a ~60 % increase in aerosol loading. Aerosol emissions from ships enhanced the lightning density by a factor of ~2 along two of the world's main shipping lanes in the equatorial Indian Ocean (Thornton et al., 2017). In terms of the response of clouds to aerosols, an optimal aerosol concentration was found to exist based on observational analyses (Koren et al., 2008; Wang et al., 2015) and a theoretical calculation (Rosenfeld et al., 2008). Biomass-burning activities, anthropogenic emissions, and desert dust are the three major atmospheric aerosol sources (Rosenfeld et al., 2001; Fan et al., 2018) that have different climate effects. The increased rainfall in southern China and drought in northern China are thought to be related to an increase in black carbon aerosols (Menon et al., 2002). The effect of dust on cloud properties tends to decrease precipitation through a feedback loop (Rosenfeld et al., 2001; Huang et al., 2014a, b, 2017) especially for drizzle and light rain.

Most studies on aerosol-convection interactions account for the aerosol burden (i.e., aerosol optical depth (AOD), the number concentration of aerosols, particulate matter that have a diameter less than 2.5 μm, or CCN) rather than aerosol size or species. It was not until recently that ultrafine aerosol particles were found to intensify convective strength by being activated to cloud droplets under excess supersaturation environmental conditions (Fan et al., 2018). Regarding aerosol species, recent studies have underscored the urgent need to consider the effect of different aerosol species in modulating lightning activity (e.g., Stolz et al., 2015, 2017), prompting us to perform more detailed analyses in this study.

Lightning and convection strength are controlled by various dynamic-thermodynamic variables and indices such as air temperature (Price, 1993; Williams, 1994, 1999; Markson, 2007),

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convective available potential energy (CAPE) and its vertical distribution (normalized CAPE, NCAPE) (Stolz et al., 2015; Bang and Zipser, 2016), vertical wind shear (Khain et al., 2008; Fan et al., 2009, 2013; Igel and Heever, 2015; Bang and Zipser, 2016), relative humidity in the lower and middle troposphere (Fan et al., 2007; Wall et al., 2014), cloud base height (Williams et al., 2005), updraft velocity (Zipser and Lutz, 1994; Williams et al., 2005), and warm cloud depth (Stolz et al., 2015, 2017).

Depending on aerosol properties and atmospheric conditions, aerosols may enhance (Khain et al., 2005, 2008; Fan et al., 2007) or suppress convection (Rosenfeld et al., 2001; Khain et al., 2004; Zhao et al., 2006). In general, aerosols tend to suppress convection for isolated clouds forming in relatively dry conditions but invigorate convection in convective systems within a moist environment (Fan et al., 2009). Under conditions of strong vertical wind shear, aerosols tend to reduce the strength of single deep convective clouds due to higher detrainment and larger evaporation of cloud hydrometeors (Richardson et al., 2007; Fan et al., 2009). The increase in evaporation and cooling intensifies downdrafts and fosters the formation of secondary clouds, cloud ensembles, and squall lines (Altaratz et al., 2010). Apart from the invigoration effect induced by aerosols, lightning activity is enhanced by increases in NCAPE, cloud base height, and vertical wind shear, but inhibited by the increasing cloud base height (Williams and Satori, 2004; Williams, 2005), mid-tropospheric relative humidity, and warm cloud depth (Stolz et al., 2015).

Most previous studies were based on short-term data. Here, we investigate and quantify the relative roles of aerosols and dynamics-thermodynamics on the lightning flash rate using long-term (11 years) lightning, AOD, and dynamic-thermodynamic data. Section 2 describes the

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datasets and method used in this study, section 3 shows the regions of interest, and section 4 examines (1) the climatological behavior of the lightning flash rate and AOD, (2) the response of the lightning flash rate to dynamics and thermodynamics, (3) the contrast in the response of the lightning flash rate to dust and smoke, (4) the environmental dependence of the aerosol effect, and (5) the relative roles of dynamics, thermodynamics, and AOD on the lightning flash rate. A summary of key findings is given in section 5.

2 Data and method

2.1 Data

2.1.1 Lightning data

We use lightning data from the Lightning Imaging Sensor (LIS) onboard the Tropical Rainfall Measuring Mission (TRMM) satellite which was designed to acquire and investigate the distribution and variability of total lightning (i.e., intra-cloud and cloud-to-ground) on a global basis and spans all longitudes between 38°N–38°S during the day and night (Boccippio, 2002; Christian et al., 2003). The LIS on TRMM monitors individual storms and storm systems at a nadir field of view exceeding 580 km×580 km with a detection efficiency of 69 % to 90 %. Also used are the low-resolution monthly time series (LRMTS) from 2003–2013, a gridded lightning climatology dataset that provides the flash rate per month at a 2.5°×2.5° spatial resolution and is recorded in coordinated universal time. The low-resolution diurnal climatology provides the mean diurnal cycle in local solar time (LT) with the same spatial resolution (Cecil et al., 2001, 2006, 2014).

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2.1.2 Aerosol data

Aerosol loading is characterized by AOD which is obtained from observations collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua satellite that crosses the equator at ~13:30 LT. Here, the monthly level 3 global product (MYD08_M3) on a 1°×1° grid from 2003–2013 is used. The AOD at 0.55 µm is retrieved using the Dark Target-Deep Blue combined algorithm which is particularly suitable over desert regions (Levy et al., 2013; Hubanks et al., 2015). The Modern Era–Retrospective analysis for Research and Application (MERRA) is a NASA meteorological reanalysis that takes advantage of satellite data from 1979 till the present using the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5). The assimilation of AOD in the GEOS-5 involves very careful cloud screening and data homogenization by means of a neural net scheme that translates MODIS radiances into Aerosol Robotic Network (AERONET)-calibrated AODs. The MERRA Aerosol Re-analysis (MERRAero) provides dust, black carbon, organic carbon, and total extinction AODs, and the total Ångström exponent at a spatial resolution of 0.625°×0.5° (da Silva et al., 2015). These data characterize aerosol species and particle size.

2.1.3 Dynamic-thermodynamic data

Dynamic-thermodynamic data used are from the Medium-Range Weather Forecasting (ECMWF) ERA-Interim reanalysis product (Dee et al., 2011). Of interest to this study are the surface upward sensible heat flux, the surface upward latent heat flux, sea level pressure, 2-m temperature, CAPE, relative humidity at 700 and 500 hPa, the wind fields at 925 and 500 hPa, and

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divergence at 200 hPa, all with a spatial resolution of 1°×1°. With reference to the findings from previous studies, we choose the following factors to characterize the dynamics and thermodynamics:

1) CAPE. CAPE is a thermodynamic parameter commonly used in strong convection analysis and forecasting. It describes the potential buoyancy available to idealized rising air parcels and thus denotes the instability of the atmosphere (Riemann-Campe et al., 2009; Williams, 1992). The stronger is CAPE, the more unstable is the atmosphere, and the more likely is there strong vertical air motion. Lightning activity increases with CAPE (Williams et al., 2002). The conversion efficiency of CAPE to updraft kinetic energy depends on the strength and width of updrafts (Williams et al., 2005). However, reliable updraft measurements that would illuminate this role in the present study are lacking.

2) Sea level pressure. Atmospheric pressure is a key dynamic factor affecting weather because it defines basic weather regimes. Low-pressure systems are usually associated with strong winds, warm air, and atmospheric lifting and normally produce clouds, precipitation, and strong convective disturbances such as storms and cyclones. An examination of summertime sea level pressure anomalies in the tropical Atlantic region shows an inverse relationship between sea level pressure and tropical cyclones (Knaff, 1997).

3) Potential temperature. Many researchers have studied the role of temperature in influencing lightning activity (Williams, 1992, 1994, 1999; Williams et al., 2005; Markson, 2003, 2007). However, the direct comparison of air temperatures for different regions is problematic because air temperature systematically declines with altitude. We choose potential temperature instead

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which corrects for the altitude dependence and provides a more meaningful comparison. Taking into account that the linkage between lightning activity and thermodynamics involves moist processes, some others use wet-bulb temperature or wet-bulb potential temperature which includes both temperature and moisture (Williams, 1992; Reeve and Toumi, 1999; Jayaratne and Kuleshov, 2006). It has been demonstrated that CAPE increases linearly with wet-bulb potential temperature (Williams et al., 1992). In this study, we would like to examine the relative roles of several parameters and their total contribution to lightning activity. In order to select more independent variables and reduce the duplication of temperature and humidity information, potential temperature is selected. Although it does not reflect moist processes directly, when the moisture level is suitable, places with higher temperatures are more favorable for convection. Here, potential temperature (θ; in units of K) is calculated from 2-m air temperature (T; in units of K) and pressure (p; in units of hPa):

$$\theta = \mathrm{T}\left(\frac{1000}{p}\right)^{0.286} \qquad (1)$$

4) Mid-level relative humidity. Moderately wet underlying surfaces are an important factor in facilitating deep convection due to the compromise between instability energy (when temperature is fixed, the atmosphere is wetter, and CAPE is larger) and the transformation efficiency from instability energy to kinetic energy (when the boundary layer is wetter, the cloud base height is lower, and updrafts are weaker). Higher surface relative humidity results in more lightning activities in dry regions and less lightning activities in wet regions with the watershed of surface relative humidity values at ~72 % to 74 % (Xiong et al., 2006). However, for mid-level humidity, only shallow convection occurs in the driest case while strong deep

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Deleted: <#>Relative humidity (RH). As one of the important thermodynamic factors, RH has been identified to affect the relationship between aerosols and convection (Fan et al., 2007; Fan et al., 2009; Khain and Lynn, 2009). It was found that for isolated clouds formed in a relative dry condition convection is suppressed by aerosols, whereas for convective systems inside a moist environment convection is invigorated (Khain and Lynn, 2009; Khain et al., 2008). The mean RH values at 700 and 500 hPa levels are employed in this study.
Wind shear

convection occurs in more moist cases (Derbyshire et al., 2004). Strong positive relations are found between mean humidity (between 2–6 km) and convective cloud top heights (Redelsperger et al., 2002). Anomalously high humidity in the free troposphere (between 850–400 hPa), which tends to increase plume buoyancy, is observed prior to a shallow-to-deep convection transition (Chakraborty et al., 2018). Different from surface moisture as a cause of deep convection, mid-to-upper tropospheric moisture (between 200–600 hPa) is more likely to be an effect of convection (Sobel et al., 2003). In addition, moistening the mid-tropospheric environment can also reduce the dilution effect on CAPE, which depends strongly on the degree of sub-saturation of the entrained air: the wetter the entrained air, the smaller the effect (Zhang 2009) which tends to facilitate ensuing deep convection. Therefore, there may be no turning point regarding the response of lightning to mid-level relative humidity. Even if there is, three-month-moving-averaged mid-level relative humidity (less than 1 % and 9 % of the total in the dust- and smoke-dominant regions, respectively, surpass relative humidity = 73 %) is less than the surface relative humidity (12 % and 63 % of the total in the dust- and smoke-dominant regions surpass relative humidity = 73 %) in the long-term. Mean relative humidity values at 700 and 500 hPa levels are used in this study.

5) Wind shear. The vertical shear of horizontal wind, hereafter simply referred to as wind shear, not only affects dynamical flow structures around and within a deep convective cloud (Rotunno et al., 1988; Weisman and Rotunno, 2004; Coniglio et al., 2006), but also qualitatively determines whether aerosols suppress or enhance convective strength (Fan et al., 2009). Bang and Zipser (2016) found no significant visible differences in wind shear (the lowest 200 hPa)

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between flashing and non-flashing radar precipitation features in the central Pacific. Others have suggested that vertical wind shear can suppress cloud vertical development for isolated convection (Richardson and Droegemeier, 2007), but is critical in organizing mesoscale convection systems (Takemi, 2007). In this paper, wind shear (SHEAR; in units of Pa s^{-1}) is calculated from daily wind fields [(U, V); in units of Pa s^{-1}] at 925 hPa and 500 hPa as follows:

$$\text{SHEAR} = \sqrt{(U_{500} - U_{925})^2 + (V_{500} - V_{925})^2} \qquad (2)$$

6) Divergence. Air divergence is especially useful because it can be linked to adiabatic heating processes, of which the non-uniformity gives rise to atmospheric motion (Mapes and Houze, 1995; Homeyer et al., 2014). Fully developed clouds are usually accompanied by upper-level divergence, especially in raining regions (Mapes and Houze, 1993). A pronounced divergence maximum exists between 300 and 150 hPa due to deep convective outflow (Mitovski et al., 2010).

The surface property which determines the contribution of latent heat versus sensible heat is described by the Bowen ratio. In warm and wet climates, the large potential for evapotranspiration creates small Bowen ratios. In dry regions, a lack of water to evaporate creates large Bowen ratios. The Bowen ratio is calculated as:

$$\text{Bowen ratio} = \frac{Surface\ upward\ sensible\ heat\ flux}{surface\ upward\ latent\ heat\ flux} \qquad (3)$$

2.2 Methodology

2.2.1 Data collocation

A roughly three-month running mean filter is used to smooth lightning data (i.e., the LRMTS

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dataset), allowing the LIS to progress twice through the diurnal cycle at a given location (Cecil et al., 2014), and to show the normal annual variation in lightning activity due to the seasonal meridional migration of the intertropical convergence zone (ITCZ; Waliser and Gautier, 1993; Thornton et al., 2017). A three-month running mean is also applied to all AOD and dynamic-thermodynamic data which are then resampled onto 2.5°×2.5° resolution grids in the climatological analysis. To make the comparison within the same AOD range and to increase the number of data samples, climatological features of lightning, AOD, dynamics, and thermodynamics under polluted and clean conditions are limited to cases with AOD < 1.0 over the regions of interest. Since there are large differences in aerosol loading in different seasons and under different dynamic-thermodynamic conditions, we cannot use a specific set of values to distinguish between clean and polluted cases applicable to all months and all dynamic-thermodynamic conditions. So for each month and under each fixed dynamic-thermodynamic condition, all data are sorted according to AOD and divided into three-equal-sample subsets where the top third of the AOD range is labeled as polluted, and the bottom third is labeled as clean. To avoid a higher probability of misclassification of clouds and aerosols in high AOD regimes (Platnick et al., 2003), to minimize the influence of hygroscopic growth in a humid environment (Feingold and Morley, 2003) and to retain enough samples especially in the lightning-deficient region, the AOD range in this study is set between 0 and 1, following the work of Kaufman et al. (2005, AOD < 0.6), Koren et al. (2008, AOD < 0.8; 2012, AOD < 0.3) and Altaratz et al. (2017, AOD < 0.4). In addition, MODIS AOD is evaluated using daily AERONET AOD data (see Figs. S1 and S1-1, 2, 3 in the supplemental material). Analyses are performed between clean and

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2.2.2 Statistical analysis method

Correlation coefficients are used to measure the strength of the relationship between the lightning flash rate and individual predictors (sea level pressure, potential temperature, mid-level relative humidity, CAPE, wind shear, divergence, AOD). The Pearson correlation (Pearson, 1896) is commonly used to measure linear correlation. Partial correlation is done to control the other predictors and to study the effect of each predictor separately. The correlation is significant when it passes the significance test at the 0.05 level.

To explore the relative roles of dynamic-thermodynamic variables and AOD on lightning activity, we use a multiple-linear regression method following previous studies (e.g., Igel and van den Heever, 2015; Stolz et al., 2017). Since there is an optimal value of aerosol loading in terms of the response of the lightning flash rate to aerosols (Koren et al., 2008; Rosenfeld et al., 2008), we establish standardized regression equations for AOD greater than and less than the turning point value. This is done to reduce the nonlinear effect of AOD. Note that all data used here are processed by averaging 10 samples sorted by AOD from small to large to mitigate data uncertainties. The standardized regression equation with seven predictor variables x_1, x_2,…, x_7 (sea level pressure, potential temperature, mid-level relative humidity, CAPE, wind shear, divergence, AOD) and the response y (lightning flash rate) can be written as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_i x_i, \quad i = 1, \ldots, 7 \qquad (4)$$

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Here, y and x_i are standardized variables derived from the raw variables Y and X_i by subtracting the sample means ($\overline{Y}$, $\overline{X_i}$) and dividing by the sample standard deviations (δ_Y, δ_i):

$$y = \frac{Y-\overline{Y}}{\delta_Y}, \quad x_i = \frac{X_i-\overline{X_i}}{\delta_i}, \qquad i=1,\dots,7 \qquad (5)$$

The sample mean of N valid samples is calculated as:

$$\overline{Y} = \frac{\sum_1^N Y_j}{N}, \quad \overline{X_i} = \frac{\sum_1^N X_{ji}}{N}, \qquad i=1,\dots,7; \quad j=1,\dots,N \qquad (6)$$

The sample standard deviation is:

$$\delta_Y = \sqrt{\frac{1}{N-1}\sum_1^N (Y_j-\overline{Y})^2}, \quad \delta_i = \sqrt{\frac{1}{N-1}\sum_1^N (X_{ji}-\overline{X_i})^2}, \quad i=1,\dots,7; \; j=1,\dots,N \qquad (7)$$

Standardized regression coefficients ignore the independent variables' scale of units, which makes the slope estimates comparable and shows the relative weights to the changes in lightning flash rate.

3 Regions of Interest (ROIs)

High loadings of dust and smoke aerosols are found in northern and southern Africa, respectively, as seen in Figure 1. Northern Africa is the world's largest source of mineral dust (Lemaître et al., 2010) with the most widespread, persistent dust aerosol plumes and the densest particulate contribution found on Earth (Prospero et al., 2002). About 2–4 billion tons of blown dust is estimated to be removed from the Sahara Desert annually (Goudie and Middleton, 2001). Dust particles of relevance to atmospheric processes are minerals with particle sizes up to 70 µm that can be readily suspended by the wind (Shao, 2008). Africa is also the single largest source of smoke emissions due to widespread biomass burning, accounting for roughly 30 to 50 % of the total amount of vegetation burned globally each year (Andreae, 1991; van der Werf et al., 2003, 2006; Roberts et al., 2009). In central and southern Africa, biomass burning due to wildfires and

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human-set fires has strong diurnal and seasonal variabilities (Roberts et al., 2009; Ichoku et al., 2016).

Figure 1a shows the global distribution of mean AOD from the MODIS onboard the Aqua satellite from 2003 to 2013. Figure 1b shows the Ångström exponent obtained from the MERRAero at a spatial resolution of 0.625°×0.5° used for the analysis of contributions from different aerosol species, chiefly, dust, black carbon (BC), and organic carbon (OC), and total extinction AODs. Note that satellite retrievals of the Ångström exponent have excessive uncertainties over land so are not included in the MODIS Collection 6 product. The African continent stands out with very large AOD in two regions: the Sahara Desert covered by dust (Figure 1c) and central to southern Africa dominated by smoke (Figure 1d), characterized by small and large values of the Ångström exponent, respectively (Figure 1b). Due to their distinct differences in aerosol species, the dust- and smoke-dominant regions (Figures 1c, 1d) are selected as the study regions for dust and smoke. The ratios of dust (dust-dominant region) or (BC+OC) (smoke-dominant region) extinction AOD to total extinction AOD are greater than 50% averaged over the period 2003–2013, which enables us to study multiple aerosol effects on lightning activity. Also shown in Figures 1c and 1d are mean wind vectors at 850 hPa over Africa and its neighboring oceans (the area outlined in red in the left panel) which represent the prevailing wind direction.

4 Results and Discussion

4.1 Climatological behavior of the lightning flash rate and AOD

The seasonal and diurnal cycles of the lightning flash rate and AOD are first examined over

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Deleted: Figure 2a shows the mean wind vector at 850 hPa from the ERA-Interim re-analysis at a spatial resolution of 1°×1° over the Africa and the neighbouring ocean the dust- and smoke-dominant regions (Figure 2a). Figure 2 also shows the diurnal cycle (Figure 2b) and monthly variations in MODIS-retrieved AOD and lightning flash rate (Figures 2c, 2d) calculated under relatively clean and polluted (dusty/smoky) conditions over the dust-dominant region and the smoke-dominant region. The same afternoon peaks in lightning activity are seen in Figure 2b, suggesting strong convection in the afternoon over land (Williams et al., 2000; Nesbitt and Zipser, 2003). Peaks in lightning activity over both the dust- and smoke-dominant regions under polluted (dusty/smoky) conditions occur 1 h later than those under clean conditions. This is consistent with the finding of an aerosol-induced delay in precipitation and lightning activity revealed from observations (Guo et al., 2016) and model simulations (Lee et al., 2016) in southern China. Numerous studies have noted that aerosols modulate convection and lightning activity through both radiative and microphysical processes, as reviewed extensively in Asia (Li et al., 2016) and around the world (Li et al., 2017b). Monthly variations in dust loading change little throughout the year (Figure 2c), while smoke shows a pronounced seasonal variation with a large contrast between dry and wet seasons (Figure 2d). Lightning activity in both regions is most active in summer and rarely occurs in winter, which is consistent with the seasonal feature of CAPE (especially for the smoke-dominant region; see Figure 3), implying that the seasonal variation in lightning activity is mainly controlled by thermodynamic conditions. Figure 2 also shows an apparent enhancement in lightning activity under smoky conditions superimposed on both the diurnal (Figure 2b) and seasonal cycles (Figure 2d). Under dusty conditions, however, the impact is much weaker than under smoky conditions. Apart from different aerosol effects, different climate conditions that exist between the dust- and smoke-dominant regions, as well as between

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heavy and light loading seasons/conditions for the same type of aerosol, may also contribute. A key factor is moisture which is much lower over the dust-dominant region (Bowen ratio > 10, see Fig. S2 in the supplemental material) than over the smoke-dominant region covered with rainforests (Bowen ratio < 0.4, see Fig. S2 in the supplemental material). The significantly higher probabilities of high relative humidity over the smoke-dominant region than over the dust-dominant region for both middle troposphere and surface are shown in Figure 4. The mean mid-level relative humidity for the dust-dominant region is ~36 % and for the smoke-dominant region is ~74 %. High values of relative humidity favor the invigoration effect (Fan et al., 2008, 2009; Khain et al., 2008; Khain, 2009; Thornton et al., 2017), which is likely a major cause for the intense lightning activity in the smoke-dominant region. The dust-dominant region is located in the vicinity of the African easterly jet (Burpee, 1972) and the smoke-dominant region is located in the ITCZ (Waliser and Gautier, 1993). Differences in wind shear and instability thus arise between the two regions.

4.2 Response of lightning to dynamics and thermodynamics

Diurnal and seasonal variations in lightning activity depend on dynamic-thermodynamic conditions. We first look at the response of the lightning flash rate to dynamic-thermodynamic conditions which are characterized by six variables (sea level pressure, potential temperature, CAPE, mid-level relative humidity, wind shear, and divergence). The cloud base height and warm cloud depth are also both physically relevant to lightning activity (Williams and Satori, 2004; Venevsky, 2014; Stolz et al., 2017). However, as statistical theory indicates, more factors will

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introduce more random noise and thus undermine the stability of the regression equation. When the sample size is fixed, the contribution of factors to the multiple regression equation changes little between 5–10 factors (Klein and Walsh, 1983; see Tables S1-1 and S1-2 in the supplemental material), so 5–6 factors should be the best choice. However, the importance of these factors still needs to be assessed. Since cloud base height and warm cloud depth can be derived from temperature and humidity, to reduce the duplication of information about temperature and humidity, we choose to use only the fundamental variables relative humidity and potential temperature. The violin plot is an effective way to visualize the distribution of data and the shape of distributions that allows the quick and insightful comparison of multiple distributions across several levels of categorical variables. It synergistically combines the box plot and the density trace into a single display (Hintze and Nelson, 1998).

Figure 5 shows linear correlations between the lightning flash rate and the six dynamic-thermodynamic variables for the dust-dominant region. CAPE, mid-level relative humidity, and divergence are the top three dynamic-thermodynamic variables strongly and positively correlated with lightning flash rate (R > 0.7). This suggests that high mid-level relative humidity and CAPE are conducive to the development of intense convection and that the lightning occurrence is associated with high-level divergence. One thing to notice is the shape of the density traces in Figure 5f. The bimodal distribution indicates that small to moderate high-level divergence may be due to clear-sky atmospheric movement or in-cloud with a small updraft velocity that does not produce lightning. Large divergence usually characterizes the strong upward movement closely associated with lightning activity. Inverse correlations between the lightning flash rate and sea

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level pressure and between the lightning flash rate and wind shear are seen in Figures 5a and 5e. Figure 5b shows a weak, positive correlation between the lightning flash rate and potential temperature. The small correlation coefficients of the regressions between the lightning flash rate and sea level pressure, wind shear, and potential temperature suggest little correlation between these variables and the lightning flash rate.

Figure 6 shows the linear correlations between the lightning flash rate and the six dynamic-thermodynamic variables associated with strong convection for the smoke-dominant region. Mid-level relative humidity, CAPE, and divergence are positively correlated with the occurrence of lightning as opposed to sea level pressure, potential temperature, and wind shear which are negatively correlated with the lightning flash rate. In particular, Figures 6a, 6c, 6d, and 6f show that CAPE, mid-level relative humidity, divergence, and sea level pressure are significantly correlated with the lightning flash rate ($|R| > 0.75$, $p < 0.05$; in order of the correlation strength), suggesting that these four variables may be the major factors modulating changes in the lightning flash rate. By comparison, a moderate linear relationship exists between the lightning flash rate and potential temperature (R=-0.47), which is also the case for the relationship between the lightning flash rate and wind shear (R=-0.08), suggesting their minor effects on the lightning flash rate (Figures 6b and 6e). Simulations done by Weisman and Klemp (1982) show that weak, moderate, and high wind shear produces short-lived single cells, secondary development, and split storms, respectively. The coarse time resolution may be why no significant correlation is found between shear and the lightning flash rate. Note that the correlation coefficients obtained here can only describe the possible dependencies between the lightning flash rate and dynamic-

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thermodynamic variables and cannot imply causal relationships.

To provide a visual comparison of the dust- and smoke-dominant regions, we show the spatial distributions of the correlation coefficients of the regressions between the lightning flash rate and dynamic-thermodynamic variables. Figure 7 shows that lightning flash rates are well correlated with mid-level relative humidity, CAPE, and divergence throughout both the dust- and smoke-dominant regions (most parts R > 0.6), while for other variables, the correlations vary from region to region. In particular, the correlations between the lightning flash rate and sea level pressure (positive), potential temperature (negative), and wind shear (positive) near the Earth's equator are distinctly different from those over other regions. We infer that this is because the hot and humid environment year-round favors deep convection. Wind shear helps organize mesoscale convection in moist deep convection which produces more lightning. Regarding potential temperature, rich precipitation helps cool the surface, which causes the negative correlation between the lightning flash rate and potential temperature. Different from the frontal system-dominant strong convection in the mid-latitudes, thermal convection more likely occurs in the tropics with a much smaller air pressure change. The frequent precipitation may also help create low and high pressure centers on the ground. These two points may lead to the positive correlation between the lightning flash rate and sea level pressure. However, partial correlation analyses show that only CAPE and mid-level relative humidity are the top two factors affecting lightning activity (Figure 8).

4.3 Contrast in the response of the lightning flash rate to dust and smoke aerosols

Aerosols can modulate lightning activity by participating in radiative and microphysical

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Deleted: Aerosols can modulate lightning activities through participating in radiative and microphysical processes. The roles of dust and smoke aerosols in modulating lightning activity are examined in Fig. 2 and Fig. 7. The diurnal cycle of lightning flashes in Fig. 2 shows that, for both dust and smoke aerosols, the lightning peak times under polluted conditions are delayed by about 1h. Besides, smoke aerosols tend to apparently enhance lightning activity on both diurnal and seasonal cycles, while the impact of dust is much weaker.

4.4 Environmental dependence of

processes. Besides the finding that the peak time for lightning under polluted conditions is delayed by about 1 h or so (see Figure 2), more informative and revealing features of the impact of aerosols on lightning are presented in Figure 9. The scatterplot and two curves (100-point and 50-point running means are applied thrice to the mean values of lightning flash rate in each 30-sample bin for the dust- dominant region and the smoke-dominant region, respectively) show that lightning activity is much more intense in the smoke-dominant region located in the ITCZ where the air is hot and humid regardless of aerosol loading. By contrast, the dust-dominant region is much drier, making it difficult to produce intense convection and lightning. The response of the lightning flash rate to AOD is shaped like a boomerang (Koren et al., 2008) with a turning point around AOD = 0.3, and the turning point in the dust-dominant region is slightly ahead of that in the smoke-dominant region. This is mainly because fewer aerosols are needed to produce small droplets likely to evaporate in the drier dust-dominant region so the optimal AOD will be lower. We deduce that the CCN concentration is more closely allied with the cloud microphysics pertaining to lightning based on the equation fitted by Andreae (2009). The turning point of the CCN concentration at a supersaturation of 0.4 % is ~1600 cm^{-3} (see Fig. S3 in the supplemental material), which falls within the range of 1000 – 2000 cm^{-3} (Mansell and Ziegler, 2013) and is close to 1200 cm^{-3} (Rosenfeld et al., 2008). Figure 9 is separated into three zones (green, grey, red) to show the dominant roles of the aerosol microphysical effect and the aerosol radiative effect. In the green zone, the lightning flash rate increases sharply with increasing aerosol loading in both dust- and smoke-dominant regions. Data are clustered around the regression lines tightly, and the lightning flash rate is strongly and positively correlated with AOD, implying that aerosol-cloud interactions

(ACI) play a dominant role in lightning activity. However, as AOD approaches the turning point (the grey zone), data become more scattered and the trend is reversed likely because of the joint impact of the aerosol microphysical effect and the aerosol radiative effect that have opposite signs of compatible magnitude (Koren et al., 2008; Rosenfeld et al., 2008). However, other dynamic-thermodynamic effects cannot be ruled out. In the red zone, the response of the lightning flash rate to aerosol loading is different between dust and smoke aerosols. The lightning flash rate seems to be saturated in the smoke-dominant region but is strongly suppressed in the dust-dominant region. This is likely associated with the differences in both aerosol properties and dynamics/thermodynamics which are coupled to jointly affect lightning. The different dynamic and thermodynamic conditions between the two regions may play important roles: 1) The drier the mid-level atmosphere, the more likely that there is evaporation of cloud droplets that are smaller under heavily polluted conditions. The aerosol-microphysical-effect-induced evaporation tends to suppress the development of clouds and inhibits lightning activity in combination with the aerosol radiative effect which causes surface cooling and leads to an increase in atmosphere stability. Together, the two factors are compounded, leading to a sharp decline in the lightning rate under heavy dusty conditions in the dust-dominant region. 2) However, clouds in the moister region of central Africa are less susceptible to evaporation and suppression. The strongly absorbing smoke aerosols also heat up the aerosol layers (usually below deep convective clouds that produce lightning), destabilizing the atmosphere above, thus dampening the suppression effect of the aerosol-radiation interactions. The development of convection and associated lightning is thus sustained.

4.4 Environmental dependence of the aerosol effect

To further clarify the joint influences of dynamics, thermodynamics, and aerosols on lightning activity, the distribution of the lightning flash rate with AOD and the top two influential thermodynamic variables, i.e., mid-level relative humidity and CAPE (based on the results in Figures 5-8), are examined in Figure 10. Lightning flash rates are classified into 100 discrete cells by ten decile bins of horizontal axis variable – ten decile bins of vertical axis variable (AOD – CAPE, AOD – mid-level relative humidity, and CAPE – mid-level relative humidity) which ensures approximately equal sample sizes among the cells. The mean values are calculated in each cell. Looking at the CAPE bins, the lightning flash rate generally increases with increasing AOD under relatively clean conditions but decreases after the turning point near AOD = 0.3 in both regions (Figures 10a and 10d). When AOD is fixed, the lightning flash rate monotonically increases with CAPE. Irrespective of aerosol loading and region, lightning rarely occurs when CAPE is less than 100 J kg^{-1}. Half of the CAPE data in the dust-dominant region falls below this value. Systematically higher CAPE in the smoke-dominant region plays an important role in inducing more intense lightning activity than in the dust-dominant region. However, the lightning flash rates in the dust- and smoke-dominant regions respond to mid-level relative humidity in different ways when AOD is fixed (Figures 10b and 10e). In the dust-dominant region, the lightning flash rate increases monotonically as mid-level relative humidity increases for all AOD, but changes little as AOD increases in each relative humidity bin. This suggests that apart from CAPE, relative humidity is another restraint on lightning activity in the dust-dominant region. In the smoke-dominant region, large lightning flash rates appear in the environment of moderate mid-

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level relative humidity and high aerosol loading. When relative humidity is fixed, the response of the lightning flash rate to AOD also shows a turning point in AOD around AOD = 0.3. Beyond this value, the lightning flash rate remains high. When looking into the common roles of relative humidity and CAPE on lightning, the data distribution along the diagonal shows that mid-level relative humidity is highly correlated with CAPE and that they affect lightning activity in the same direction. In general, intense lightning activity occurs under high mid-level relative humidity (> 40 %) and high CAPE (> 100 J kg^{-1}) conditions in the dust-dominant region. In the smoke-dominant region, high CAPE and high mid-level relative humidity are still conducive to lightning production, but the data variance is larger, suggesting that the correlation involving mid-level relative humidity and CAPE is not as high as in the dust-dominant region, and the dependence on relative humidity is reduced.

As shown in Figures 2, 9, and 10, differences in the lightning response to aerosols in the dust- and smoke-dominant regions may also be attributed to different dynamic-thermodynamic conditions. To isolate the signal attributed to aerosol loading from that attributed to environmental forcing, lightning flash rates are categorized according to six dynamic-thermodynamic variables (sea level pressure, potential temperature, mid-level relative humidity, CAPE, wind shear, and divergence). Figure 11 shows the differences in lightning flash rate between polluted and clean conditions (polluted minus clean datasets) as a function of these six variables. In general, lightning flash rates are greater for all these dynamic-thermodynamic variables under polluted conditions compared with clean conditions in both the dust- and smoke-dominant regions. Lightning enhancement under polluted conditions is highly significant (> 99 %) based on the Student's t-test.

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The differences in lightning flash rates between polluted and clean conditions are smaller in the dust-dominant region than in the smoke-dominant region. Note that in the dust-dominant region, when sea level pressure decreases and potential temperature increases, differences in the lightning flash rate (polluted minus clean datasets) become larger. This suggests that under conductive conditions (such as a thermal depression which is likely the main synoptic system introducing lightning activity in this region), aerosols are more likely to participate in cloud microphysics and convective development, thus modulating lightning activity.

4.5 Relative roles of dynamics-thermodynamics and AOD on the lightning flash rate

The response of the lightning flash rate to changes in AOD may indicate an aerosol effect on lightning activity, but it can also be the result of dynamics or thermodynamics impacting aerosol loadings and the cloud microphysical process that is closely associated with lightning production. To further explore this complex process, the correlations between aerosol − lightning rate, dynamic-thermodynamic variables − lightning rate, and aerosol — dynamic-thermodynamic variables were examined before and after the turning point (AOD=0.3, see Figure 9). Results are shown in Figure 12 (correlation coefficients are listed in Table S2 in the supplemental material).

Under clean conditions (AOD < 0.3) in the dust-dominant region, all dynamic-thermodynamic variables and AOD show good correlations with the lightning flash rate (｜R｜> 0.5). Considering the interaction between aerosols and dynamics-thermodynamics, the correlation coefficients between AOD and the six dynamic-thermodynamic variables were calculated. Results show strong positive correlations between AOD and mid-level relative humidity, CAPE, divergence, and

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potential temperature (R > 0.6) and a negative correlation between AOD and sea level pressure and wind shear (in order of correlation strength). To investigate the relative roles of these variables (AOD and the six dynamic-thermodynamic variables), we carry out partial correlation analyses between the lightning flash rate and any of its influential factors while constraining all the others. We then establish standardized multiple regression equations where the coefficients of these equations represent the relative importance of each factor. After the common effects are constrained, the partial correlation coefficients are much smaller than the Pearson correlation coefficients, and the correlations between the lightning flash rate and sea level pressure, potential temperature, and AOD are no longer significant. The weak partial correlation of the AOD-lightning flash rate relationship, the high Peason correlation of the AOD-CAPE relationship, and the high partial correlation of the CAPE-lightning flash rate relationship all suggest that the lightning flash rate does not respond much to dust aerosols directly, but dust can affect convection and lightning activity through modulation of the thermodynamic variables involved in ACI. From these analyses, the top three factors are found to be mid-level relative humidity, CAPE, and divergence for the dust-dominant region under relatively clean conditions. For the clean smoke-dominant region, analyses show strong positive correlations between the lightning flash rate and CAPE, AOD, and divergence (｜R｜>0.7), a strong negative correlation between the lightning flash rate and sea level pressure (R = -0.94), and weak negative correlations between the lightning flash rate and potential temperature and wind shear (｜R｜< 0.4). The main interplay is between AOD and sea level pressure and CAPE (｜R｜> 0.75). The partial correlation coefficients and the coefficients of the standardized multiple regression equations reveal the top three factors: CAPE,

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AOD, and mid-level relative humidity (R > 0.35). Different from relative humidity as the top restraint factor in the dust-dominant region, here it plays a smaller role in the humid environment. AOD also becomes more important in this region. In both regions, aerosols correlate well with CAPE (R > 0.75) under clean conditions (AOD < 0.3) which suggests that aerosols might participate in cloud microphysical processes: more aerosols acting as CCN leads to a narrower cloud droplet size spectrum, delays the warm-rain process and allows more liquid water to ascend higher into the mixed-phase cloud, thus releasing more latent heat, modulating environmental variables (such as increasing temperature, updrafts, and CAPE in and above clouds) and producing a more unstable atmosphere conducive to convective development. The aerosol invigoration effect may play the key role during this stage (AOD < 0.3). The same directions of the impacts of aerosols and thermodynamics such as CAPE on the lightning flash rate may be the reason for the tightly clustered distribution under clean conditions seen in Figure 9.

Under polluted conditions, CAPE and mid-level relative humidity are still of paramount importance for lightning activity (Pearson: R > 0.8; Partial: R > 0.35), but the correlation between aerosols and dynamics-thermodynamics is weakened. This weak connection between aerosols and dynamics-thermodynamics results in a large dispersion of lightning flash rates under polluted conditions in both regions. The most important finding appears to be the negative correlation between AOD and CAPE (R = -0.51) and between AOD and mid-level relative humidity (R = -0.33) in the dust-dominant region. This suggests two things: (1) drier environments are more favorable for dust emission, and (2) drier mid-level environments produce a more stable atmosphere and rapid evaporation of the condensate, leading to the suppression of convection and

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lightning. In the smoke-dominant region, AOD is negatively correlated with mid-level relative humidity (R = -0.24) which suggests the similar role of drier environments in producing more smoke aerosols. The negative correlation between AOD and potential temperature (R = -0.74) reflects the surface cooling that is caused by the radiative effect. No significant correlation is found between AOD and CAPE (R = 0, p > 0.05) which may imply that the radiative effect and the microphysical effect are comparable under heavy smoke aerosol loading conditions.

5 Conclusions

Depending on specific environmental conditions, aerosols are able to invigorate or suppress convection-induced lightning activity. This has been noted in previous case-based studies. This study attempts to 1) answer a key question of whether aerosol effects on lightning are of long-term climate significance, 2) disentangle the complex influences of aerosols and dynamics/thermodynamics on lightning activity and their mutual dependencies, and 3) investigate different roles played by different types of aerosols (dust versus smoke) on lightning. Here, dynamics and thermodynamics are characterized by six variables: sea level pressure, potential temperature, mid-level relative humidity, convective available potential energy (CAPE), vertical wind shear, and 200-hPa divergence. Eleven years (2003–2013) of coincident data are used, including lightning data from the LIS/TRMM, aerosol optical depth (AOD) from the MODIS/Aqua, and dynamic-thermodynamic variables from the ECMWF ERA-Interim reanalysis. Climatological features of the diurnal and seasonal variations in lightning flash rate show a peak in the afternoon and during the local summer, respectively, which suggests the dominant role of

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thermodynamics, while differences in lightning flash rate under relatively clean and polluted conditions signify the potential influences of aerosols. In general, differences in lightning flash rates are larger in moist central Africa dominated by biomass burning than in dry northern Africa with much dust. Despite the complex and diverse climatic conditions, the response of the lightning flash rate to dust and smoke aerosols has a boomerang shape with a turning point at AOD ≈ 0.3. As AOD increases towards the threshold, the flash rate first increases sharply with increasing AOD for both the dust and biomass-burning regions. As AOD exceeds the threshold, the response turns to negative and is more pronounced for dust aerosols than for smoke aerosols. Grossly speaking, such a pattern echoes the joint influences of the aerosol microphysical effect and the aerosol radiative effect with the former and latter being more significant under low AOD and high AOD conditions, respectively. Around the turning point, the two effects are comparable.

We performed a correlation analysis and a standardized multiple regression analysis in an attempt to quantify the relative roles of AOD and dynamic-thermodynamic factors in modulating lightning activity. Under relatively clean conditions (AOD < 0.3), standardized multiple regression coefficients of dynamics, thermodynamics, and AOD on the lightning flash rate in both regions have $R_M^2 \geq 0.92$, with mid-level relative humidity and CAPE being the top two determinant factors. The contributions of relative humidity and CAPE are comparable in the dust-dominant region and less so in the smoke-dominant region. The impact of AOD on lightning activity is likely to be exerted through a cloud microphysical effect that may modulate the dynamics and thermodynamics. Under smoky conditions (AOD > 0.3), R_M^2 for the standardized multiple regression equation diminishes to 0.77 with a strong negative correlation with potential

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temperature (R = -0.74), a weak negative correlation with mid-level relative humidity, and no correlation with CAPE (R = 0). Note that aerosols cool the surface and warm the mid-level atmosphere through the radiative effect which may be less than (for AOD < 0.3), more than (AOD > 0.3), or equal to (AOD = 0.3) the aerosol microphysical effect. Under dusty conditions (AOD > 0.3), the standardized multiple regression equation has a higher R_M^2 (0.83), and the aerosol radiative effect plays a dominant role, possibly leading to a stable atmosphere and suppression of convection and lightning. Lightning flash rates in the dust- and smoke-dominant regions respond to AOD in different ways mainly because of the different humidity conditions. For the dust-dominant region, moisture is the maximum constraint. High CAPE, high mid-level relative humidity, and moderate aerosol loadings help to intensify lightning activity. For the smoke-dominant region, large values of CAPE, mid-level relative humidity, and AOD (up to 0.3) fuel lightning. The influences of other variables such as wind shear and convergence/divergence are insignificant from a climatological perspective. Based on observations alone, however, we cannot totally filter them out but can constrain the confounding effect of dynamics and thermodynamics on lightning activity. More insightful analyses based on a combination of state-of-the-art observations and convection-revolved model simulations are warranted in the future.

Acknowledgements

We gratefully acknowledge the GES DISC, the NASA DAAC, and the ECMWF for providing aerosol information, lightning flash rate information, and dynamic-thermodynamic data via public access. MODIS AOD data can be downloaded from https://ladsweb.modaps.eosdis.nasa.gov/search/. MERRAero data are from

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https://disc.sci.gsfc.nasa.gov/MERRA/, lightning data are from https://ghrc.nsstc.nasa.gov/hydro/, and the ERA-Interim meteorological data are from http://apps.ecmwf.int/datasets/data/interim-full-moda/. We are most grateful to E. Williams of MIT for providing exceptionally informative and constructive comments and suggestions that helped improve the paper quality considerably. We thank Tie Yuan, Hugh Christian, and Richard Orville for their assistance in using and analyzing TRMM LIS orbit data in the early stage of this study. We acknowledge Wu Zhang at Lanzhou University for his suggestions to improve the statistical methodology. This work was supported by the National Natural Science Foundation of China under grants 91544217 and 41771399, the Ministry of Science and Technology under grants 2017YFC1501702 and 2017YFC1501401, and the Chinese Academy of Meteorological Sciences (2017Z005).

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References

References

Ackerman, A. S., Toon, O. B., Stevens, D, E., Heymsfield, A. J., Ramanathan, V., and Welton, E. J.: Reduction of tropical cloudiness by soot, Science, 288(5468), 1042–1047, 2000.

Altaratz, O., Koren, I., Yair, Y., and Price, C.: Lightning response to smoke from Amazonian fires, Geophys. Res. Lett., 37, L07801, https//doi.org/10.1029/2010GL042679, 2010.

Altaratz, O., Kucienska, B., Kostinski, A., Raga, G. B., and Koren, I.: Global association of aerosol with flash density of intense lightning, Environ. Res. Lett., 12, 114037, https//doi.org/10.1088/1748-9326/aa922b, 2017.

Andreae, M. O.: Biomass burning: its history, use, and distribution and its impact, in: Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications, MIT Press, Cambridge, MA, 3–21, 1991.

Andreae, M. O.: Correlation between cloud condensation nuclei concentration and aerosol optical thickness in remote and polluted regions, Atmos. Chem. Phys., 9(2), 543–556, https//doi.org/10.5194/acp-9-543-2009, 2009.

Bang, S. D. and Zipser, E. J.: Seeking reasons for the differences in size spectra of electrified storms over land and ocean, J. Geophys. Res.-Atmos., 121(15), 9048–9068, https//doi.org/10.1002/2016JD025150, 2016.

Bell, T. L., Rosenfeld, D., Kim, K. M., Yoo, J. M., Lee, M. I., and Hahnenberger, M.: Midweek increase in US summer rain and storm heights suggests air pollution invigorates rainstorms, J. Geophys. Res.-Atmos., 113(D2), https://doi.org/10.1029/2007JD008623, 2008.

Bell, T. L., Rosenfeld, D., and Kim, K. M.: Weekly cycle of lightning: evidence of storm

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invigoration by pollution, Geophys. Res. Lett., 36(23), https://doi.org/10.1029/2009GL040915, 2009.

Betz, H. D., Schumann, U., and Laroche, P.: Lightning: Principles, Instruments and Applications: Review of Modern Lightning Research, Springer Science & Business Media, 2008.

Boccippio, D. J.: Lightning scaling relations revisited, J. Atmos. Sci., 59(6), 1086–1104, https://doi.org/10.1175/1520-0469(2002)059<1086:LSRR>2.0.CO;2, 2002.

Boccippio, D. J., Goodman, S. J., and Heckman, S.: Regional differences in tropical lightning distributions, J. Appl. Meteorol., 39(12), 2231–2248, https://doi.org/10.1175/1520-0450(2001)040<2231:RDITLD>2.0.CO;2, 2000.

Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., Kerminen, V.-M., Kondo, Y., Liao, H., Lohmann, U., Rasch, P., Satheesh, S.K., Sherwood, S., Stevens, B., and Zhang, X.Y.: Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2013.

Burpee, R. W.: The origin and structure of easterly waves in the lower troposphere of North Africa, J. Atmos. Sci., 29(1), 77–90, https://doi.org/10.1175/1520-0469(1972)029<0077:TOASOE>2.0.CO;2, 1972.

Cecil, D. J.: LIS/OTD 2.5 Degree Low Resolution Diurnal Climatology (LRDC). Dataset available online from the NASA Global Hydrology Center DAAC, Huntsville, Alabama, U.S.A, doi:

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http://dx.doi.org/10.5067/LIS/LIS-OTD/DATA307, 2001.

Cecil, D. J.: LIS/OTD 2.5 Degree Low Resolution Monthly Climatology Time Series (LRMTS). Dataset available online from the NASA Global Hydrology Center DAAC, Huntsville, Alabama, U.S.A, doi: http://dx.doi.org/10.5067/LIS/LIS-OTD/DATA309, 2006.

Cecil, D. J., Buechler, D. E., and Blakeslee, R. J.: Gridded lightning climatology from TRMM-LIS and OTD: dataset description, Atmos. Res., 135, 404–414, https://doi.org/10.1016/j.atmosres.2012.06.028, 2014.

Chakraborty, S., Schiro, K. A., Fu, R., and Neelin, J. D.: On the role of aerosols, humidity, and vertical wind shear in the transition of shallow to deep, Atmos. Chem. Phys. Discuss., https://doi.org10.5194/acp-2018-249, 2018.

Christian, H. J., Blakeslee, R. J., Boccippio, D. J., Boeck, W. L., Buechler, D. E., Driscoll, K. T., Goodman, S. J., Hall, J. M., Koshak, W. J., and Mach, D. M.: Global frequency and distribution of lightning as observed from space by the Optical Transient Detector, J. Geophys. Res.-Atmos., 108(D1), https://doi.org/10.1029/2002JD002347, 2003.

Coniglio, M. C., Stensrud, D. J., and Wicker, L. J.: Effects of upper-level shear on the structure and maintenance of strong quasi-linear mesoscale convective systems, J. Atmos. Sci., 63(4), 1231–1252, https://doi.org/10.1175/JAS3681.1, 2006.

da Silva, A. M., Randles, C. A., Buchard, V., Darmenov, A., Colarco, P. R., and Govindaraju, R,: File Specification for the MERRA Aerosol Reanalysis (MERRAero). GMAO Office Note No. 7 (available from http://gmao.gsfc.nasa.gov/pubs/office_notes), 2015.

Dee, D. P., Uppala, S., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M., Balsamo, G., and Bauer, P.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. Roy. Meteorol. Soc., 137(656), 553–597, https://doi.org/10.1002/qj.828, 2011.

Derbyshire, S. H., Beau, I., Bechtold, P., Grandpeix, J. Y., Piriou, J. M., Redelsperger, J. L., and Soares, P. M. M.: Sensitivity of moist convection to environmental humidity, Q. J. Roy. Meteorol. Soc., 130(604), 3055–3079, 2004.

Fan, J., Zhang, R., Li, G., and Tao, W. K.: Effects of aerosols and relative humidity on cumulus clouds, J. Geophys. Res.-Atmos., 112(D14), https://doi.org/10.1029/2006JD008136, 2007.

Fan, J., Zhang, R., Tao, W. K., and Mohr, K.: Effects of aerosol optical properties on deep convective clouds and radiative forcing, J. Geophys. Res.-Atmos., 113(D8), https://doi.org/ 10.1029/2007JD009257, 2008.

Fan, J., Yuan, T., Comstock, J. M., Ghan, S., Khain, A., Leung, L. R., Li, Z., Martins, V. J., and Ovchinnikov, M.: Dominant role by vertical wind shear in regulating aerosol effects on deep convective clouds, J. Geophys. Res.-Atmos., 114(D22), https://doi.org/ 10.1029/2009JD012352, 2009.

Fan, J., Rosenfeld, D., Ding, Y., Leung, L. R., and Li, Z.: Potential aerosol indirect effects on atmospheric circulation and radiative forcing through deep convection, Geophys. Res. Lett., 39(9), https://doi.org/10.1029/2012GL051851, 2012.

Fan, J., Leung, L. R., Rosenfeld, D., Chen, Q., Li, Z., Zhang, J., and Yan, H.: Microphysical effects determine macrophysical response for aerosol impacts on deep convective clouds, P. Natl. Acad. Sci. USA, 110(48), E4581-E4590, https://doi.org/10.1073/pnas.1316830110, 2013.

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Fan, J., Wang, Y., Rosenfeld, D., and Liu, X.: Review of aerosol-cloud interactions: mechanisms, significance and challenges, J. Atmos. Sci., 73(11), 4221–4252., https://doi.org/10.1175/JAS-D-16-0037.1, 2016.

Fan, J., Rosenfeld, D., Zhang, Y., Giangrande, S. E., Li, Z., Machado, L. A., …, and Barbosa, H. M.: Substantial convection and precipitation enhancements by ultrafine aerosol particles, Science, 359(6374), 411–418, 2018.

Feingold, G. and Morley, B.: Aerosol hygroscopic properties as measured by lidar and comparison with in situ measurements, J. Geophys. Res.-Atmos., 108(D11), 4327, doi:10.1029/2002JD002842, 2003

Goudie, A. and Middleton, N.: Saharan dust storms: nature and consequences, Earth-Sci. Rev., 56(1–4), 179–204, https://doi.org/10.1016/S0012-8252(01)00067-8, 2001.

Guo, J., Deng, M., Lee, S. S., Wang, F., Li, Z., Zhai, P., Liu, H., Lv, W., Yao, W., and Li, X.: Delaying precipitation and lightning by air pollution over the Pearl River Delta. Part I: Observational analyses, J. Geophys. Res.-Atmos., 121(11), 6472–6488, https://doi.org/10.1002/2015JD023257, 2016.

Hintze, J. L. and Nelson, R. D.: Violin plots: a box plot-density trace synergism, The American Statistician, 52(2), 181–184, https://doi.org/10.1080/00031305.1998.10480559, 1998.

Homeyer, C. R., Schumacher, C., and Hopper Jr., L. J.: Assessing the applicability of the tropical convective–stratiform paradigm in the extratropics using radar divergence profiles, J. Climate, 27(17), 6673–6686, https://doi.org/10.1175/JCLI-D-13-00561.1, 2014.

Moved up [1]: Yuan, T., Comstock, J. M., Ghan, S., Khain, A., Leung, L. R., Li, Z., Martins, V. J., and Ovchinnikov, M.: Dominant role by vertical wind shear in regulating aerosol effects on deep convective clouds, J. Geophys. Res

Deleted: . - Atmos., 114(D22), https://doi.org/10.1029/2009JD012352, 2009.

Fan, J., Rosenfeld, D., Ding, Y., Leung, L. R., and Li, Z.:

Deleted: Aerosol-Cloud Interactions: Mechanisms, Significance and Challenges. Journal of the Atmospheric Sciences,

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Huang, J., Wang, T., Wang, W., Li, Z., and Yan, H.: Climate effects of dust aerosols over East Asian arid and semiarid regions, J. Geophys. Res. - Atmos., 119, 11,398–11,416, https://doi.org/10.1002/2014JD021796, 2014a.

Huang, J., Li, Y., Fu, C., Chen, F., Fu, Q., Dai, A., Shinoda, M., Ma, Z., Guo, W., Li, Z., Zhang, L., Liu, Y., Yu, H., He, Y., Xie, Y., Guan, X., Ji, M., Lin, L., Wang, S., Yan, H., and Wang, G.: Dryland climate change recent progress and challenges, Rev. Geophys., 55, 719–778, doi:10.1002/2016RG000550, 2014b.

Hubanks, P., Platnick, S., King, M., and Ridgway, B.: MODIS Atmosphere L3 gridded product algorithm theoretical basis document (atbd) & users guide, ATBD reference number ATBD-MOD-30, NASA, 125, 2015.

Ichoku, C., Ellison, L. T., Willmot, K. E., Matsui, T., Dezfuli, A. K., Gatebe, C. K., Wang, J., Wilcox, E. M., Lee, J., and Adegoke, J.: Biomass burning, land-cover change, and the hydrological cycle in Northern sub-Saharan Africa, Environ. Res. Lett., 11(9), https://doi.org/10.1088/1748-9326/11/9/095005, 2016.

Igel, M. R. and van den Heever, S. C.: The relative influence of environmental characteristics on tropical deep convective morphology as observed by CloudSat, J. Geophys. Res.-Atmos., 120(9), 4304–4322, https://doi.org/10.1002/2014JD022690, 2015.

Jayaratne, E. R., and Kuleshov. Y.: The relationship between lightning activity and surface wet bulb temperature and its variation with latitude in Australia, Meteorol. Atmos. Phys., 91(1-4), 17–24, 2006.

Kaufman, Y. J., Tanre, D., Holben, B., Mattoo, S., Remer, L., Eck, T., Vaughan, J., and Chatenet,

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B.: Aerosol radiative impact on spectral solar flux at the surface, derived from principal-plane sky measurements, J. Atmos. Sci., 59(3), 635–646, https://doi.org/10.1175/1520-0469(2002)059<0635:ARIOSS>2.0.CO;2, 2002.

Kaufman, Y. J., Koren, I., Remer, L. A., Rosenfeld, D., and Rudich, Y.: The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean, P. Natl. Acad. Sci. USA, 102(32), 11,207–11,212, 2005.

Khain, A. P.: Notes on state-of-art investigation of aerosol effects on precipitation: a critical review, Environ. Res. Lett., 4, 015004, https://doi.org/10.1088/1748-9326/4/1/015004, 2009.

Khain, A. and Lynn, B.: Simulation of a supercell storm in clean and dirty atmosphere using weather research and forecast model with spectral bin microphysics, J. Geophys. Res.-Atmos., 114(D19), https://doi.org/10.1029/2009JD011827, 2009.

Khain, A., Pokrovsky, A., Pinsky, M., Seifert, A., and Phillips, V.: Simulation of effects of atmospheric aerosols on deep turbulent convective clouds using a spectral microphysics mixed-phase cumulus cloud model. Part I: Model description and possible applications, J. Atmos. Sci., 61(24), 2963–2982, https://doi.org/10.1175/JAS-3350.1, 2004.

Khain, A., Rosenfeld, D., and Pokrovsky, A.: Aerosol impact on the dynamics and microphysics of deep convective clouds, Q. J. Roy. Meteorol. Soc., 131(611), 2639–2663, https://doi.org/10.1256/qj.04.62, 2005.

Khain, A., BenMoshe, N., and Pokrovsky, A.: Factors determining the impact of aerosols on surface precipitation from clouds: an attempt at classification, J. Atmos. Sci., 65(6), 1721–1748, https://doi.org/10.1175/2007JAS2515.1, 2008.

Deleted: https://doi.org/10.1175/1520-0469(2002)059<0635:ARIOSS>2.0.CO;2,

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Knaff, J. A.: Implications of summertime sea level pressure anomalies in the tropical Atlantic region, J. Climate, 10(4), 789–804, https://doi.org/10.1175/1520-0442(1997)010<0789:IOSSLP>2.0.CO;2, 1997.

Koren, I., Kaufman, Y. J., Remer, L. A., and J. V. Martins, J. V.: Measurement of the effect of Amazon smoke on inhibition of cloud formation, Science, 303(5662), 1342–1345, https://doi.org/10.1126/science.1089424, 2004.

Koren, I., Martins, J. V., Remer, L. A., and Afargan, H.: Smoke invigoration versus inhibition of clouds over the Amazon, Science, 321(5891), 946–949, https://doi.org/10.1126/science.1159185, 2008.

Koren, I., Altaratz, O., Remer, L. A., Feingold, G., Martins, J. V., and Heiblum, R. H.: Aerosol-induced intensification of rain from the tropics to the mid-latitudes, Nat. Geosci., 5(2), 118, 2012.

Lee, S. S., Guo, J., and Li, Z.: Delaying precipitation by air pollution over the Pearl River Delta, Part 2. Model simulations, J. Geophys. Res. - Atmos., 121(19), https://doi.org/10.1002/2015JD024362, 2016.

Lemaître, C., Flamant, C., Cuesta, J., Raut, J.-C., Chazette, P., Formenti, P., and Pelon, J.: Radiative heating rates profiles associated with a springtime case of Bodélé and Sudan dust transport over West Africa, Atmos. Chem. Phys., 10(17), 8131–8150, https://doi.org/10.5194/acp-10-8131-2010, 2010.

Levy, R., Mattoo, S., Munchak, L., Remer, L., Sayer, A., Patadia, F., and Hsu, N.: The Collection 6 MODIS aerosol products over land and ocean, Atmos. Measurement Tech., 6(11), 2989–3034, https://doi.org/10.5194/amt-6-2989-2013, 2013.

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Deleted: :

Li, Z., Lau, W. M., Ramanathan, V., Wu, G., Ding, Y., Manoj, M., Liu, J., Qian, Y., Li, J., and Zhou, T.: Aerosol and monsoon climate interactions over Asia, Rev. Geophys., 54(4), 866–929, https://doi.org/10.1002/2015RG000500, 2016.

Li Z., Guo, J., Ding, A., Liao, H., Liu, J., Sun, Y., Wang, T., Xue, H., Zhang, H., and Zhu, B.: Aerosol and boundary-layer interactions and impact on air quality, Natl. Sci. Rev., 4(6), 810–833, https://doi.org/10.1093/nsr/nwx117, 2017a.

Li, Z., Rosenfeld, D., and Fan, J.: Aerosols and their impact on radiation, clouds, precipitation, and severe weather events, Oxford Research Encyclopedias, https://doi.org/10.1093/acrefore/9780199389414.013.126, 2017b.

Lucas, C., Zipser, E. J., and Lemone, M. A.: Vertical velocity in oceanic convection off tropical Australia, J. Atmos. Sci., 51(21), 3183–3193, https://doi.org/10.1175/1520-0469(1994)051<3183:VVIOCO>2.0.CO;2, 1994.

Mansell, E. R. and Ziegler, C. L.: Aerosol effects on simulated storm electrification and precipitation in a two-moment bulk microphysics model, J. Atmos. Sci., 70(7), 2032–2050, https://doi.org/10.1175/JAS-D-12-0264.1, 2013.

Mapes, B., and Houze Jr., R. A.: An integrated view of the 1987 Australin monsoon and its mesoscale convective systems. II: Vertical structure, Q. J. Roy. Meteorol. Soc., 119(512), 733–754, https://doi.org/10.1002/qj.49711951207, 1993.

Mapes, B. E., and Houze Jr., R. A.: Diabatic divergence profiles in western Pacific mesoscale convective systems, J. Atmos. Sci., 52(10), 1807–1828, https://doi.org/10.1175/1520-0469(1995)052<1807:DDPIWP>2.0.CO;2, 1995.

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Markson, R.: Ionospheric potential variation from temperature change over continents, XII International Conference on Atmospheric Electricity, Versailles, France, 2003.

Markson, R.: The global circuit intensity–its measurement and variation over the last 50 years, B. Am. Meteorol. Soc., 88(2), https://doi.org/10.1175/BAMS-88-2-223, 2007.

Menon, S., Hansen, J., Nazarenko, L., and Luo, Y.: Climate effects of black carbon aerosols in China and India, Science, 297, 2250–2253, https://doi.org/10.1126/science.1075159, 2002.

Michalon, N., Nassif, A., Saouri, T., Royer, J. F., and Pontikis, C.: Contribution to the climatological study of lightning, Geophys. Res. Lett., 26, 3097–3100, https://doi.org/10.1029/1999GL010837, 1999.

Mitovski, T., Folkins, I., Von Salzen, K., and Sigmond, M.: Temperature, relative humidity, and divergence response to high rainfall events in the tropics: observations and models, J. Climate, 23(13), 3613–3625, https://doi.org/10.1175/2010JCLI3436.1, 2010.

Nesbitt, S. W. and Zipser, E. J.: The diurnal cycle of rainfall and convective intensity according to three years of TRMM measurements, J. Climate, 16(10), 1456–1475, https://doi.org/10.1175/1520-0442-16.10.1456, 2003.

Orville, R. E., Huffines, G., Nielsen-Gammon, J., Zhang, R., Ely, B., Steiger, S., Phillips, S., Allen, S., and Read, W.: Enhancement of cloud-to-ground lightning over Houston, Texas, Geophys. Res. Lett., 28(13), 2597–2600, https://doi.org/10.1029/2001GL012990, 2001.

Pearson, K.: Mathematical contributions to the theory of evolution. III. Regression, heredity and panmixia, Philos. T. R. Soc. Lond. S-A, 187, 253–318, https://doi.org/10.1098/rsta.1896.0007, 1896.

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Price, C.: Global surface temperatures and the atmospheric electrical circuit, Geophys. Res. Lett., 20(13), 1363–1366, https://doi.org/10.1029/93GL01774, 1993.

Platnick, S., King, M. D., Ackerman, S. A., Menzel, W. P., Baum, B. A., Riedi, J.C., and Frey, R. A.: The MODIS cloud products: Algorithms and examples from Terra, IEEE Trans. Geosci, Remote Sens, 41(2), 459-473, 2003.

Prospero, J. M., Ginoux, P., Torres, O., Nicholson, S. E., and Gill, T. E.: Environmental characterization of global sources of atmospheric soil dust derived from the Nimbus 7 TOMS absorbing aerosol product, Rev. Geophys., 40(1), https://doi.org/10.1029/2000RG000095, 2002.

Redelsperger, J. L., Parsons, D. B., and Guichard, F.: Recovery processes and factors limiting cloud-top height following the arrival of a dry intrusion observed during TOGA COARE, J. Atoms. Sci, 59(16), 2438–2457, 2002.

Reeve, N., and Toumi, R.: Lightning activity as an indicator of climate change. Q. J. Roy. Meteorol. Soc., 125(555), 893–903, 1999.

Richardson, Y. P., Droegemeier, K. K., and Davies-Jones, R. P.: The influence of horizontal environmental variability on numerically simulated convective storms. Part I: Variations in vertical shear, Mon. Weather Rev., 135(10), 3429–3455, https://doi.org/10.1175/MWR3463.1, 2007.

Riemann-Campe, K., Fraedrich, K., and Lunkeit, F.: Global climatology of convective available potential energy (CAPE) and convective inhibition (CIN) in ERA-40 reanalysis, Atmos. Res., 93(1-3), 534–545, https://doi.org/10.1016/j.atmosres.2008.09.037, 2009.

Roberts, G., Wooster, M., and Lagoudakis, E.: Annual and diurnal African biomass burning

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temporal dynamics, Biogeosci., 6(5), https://doi.org/10.5194/bg-6-849-2009, 2009.

Rosenfeld, D., and Lensky, I. M.: Satellite–based insights into precipitation formation processes in continental and maritime convective clouds, B. Am. Meteorol. Soc., 79(11), 2457–2476, https://doi.org/10.1175/1520-0477(1998)079<2457:SBIIPF>2.0.CO;2, 1998.

Rosenfeld, D., Rudich, Y., and Lahav, R.: Desert dust suppressing precipitation: a possible desertification feedback loop, P. Natl. Acad. Sci. USA, 98(11), 5975–5980, https://doi.org/10.1073/pnas.101122798, 2001.

Rosenfeld, D., Lohmann, U., Raga, G. B., O'Dowd, C. D., Kulmala, M., Fuzzi, S., Reissell, A., and Andreae, M. O.: Flood or drought: How do aerosols affect precipitation?, Science, 321(5894), 1309–1313, https://doi.org/10.1126/science.1160606, 2008.

Rotunno, R., Klemp, J. B., and Weisman, M. L.: A theory for strong, long-lived squall lines, J. Atmos. Sci., 45(3), 463–485, https://doi.org/10.1175/1520-0469(2004)061<0361:ATFSLS>2.0.CO;2, 1998.

Shao, Y.: Physics and Modelling of Wind Erosion, Springer Science & Business Media, 2008.

Stolz, D. C., Rutledge, S. A., and Pierce, J. R.: Simultaneous influences of thermodynamics and aerosols on deep convection and lightning in the tropics, J. Geophys. Res.-Atmos., 120(12), 6207–6231, https://doi.org/10.1002/2014JD023033, 2015.

Stolz, D. C., Rutledge, S. A., Pierce, J. R., and van den Heever, S. C.: A global lightning parameterization based on statistical relationships among environmental factors, aerosols, and convective clouds in the TRMM climatology, J. Geophys. Res.-Atmos., 122, 7461–7492, https://doi.org/ 10.1002/2016JD026220, 2017.

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Takemi, T.: A sensitivity of squall-line intensity to environmental static stability under various shear and moisture conditions, Atoms. Res., 84, 374–389, doi:10.1016/j.atmossres.2006.10.001, 2007.

Tao, W. K., Chen, J. P., Li, Z. Q., Wang, C., and Zhang, C. D.: Impact of aerosols on convective clouds and precipitation, Rev. Geophys., 50(RG2001), https://doi.org/10.1029/2011rg000369, 2012.

Thornton, J. A., Virts, K. S., Holzworth, R. H., and Mitchell, T. P.: Lightning enhancement over major oceanic shipping lanes, Geophys. Res. Lett., 44(17), 9102–9111, https://doi.org/10.1002/2017GL074982, 2017.

van der Werf, G. R., Randerson, J. T., Collatz, G. J., and Giglio, L.: Carbon emissions from fires in tropical and subtropical ecosystems, Glob. Change Biol., 9(4), 547–562, https://doi.org/10.1046/j.1365-2486.2003.00604.x, 2003.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Kasibhatla, P. S., and Arellano Jr., A. F.: Interannual variability in global biomass burning emissions from 1997 to 2004, Atmos. Chem. Phys., 6(11), 3423–3441, https://doi.org/10.5194/acp-6-3423-2006, 2006.

Venevsky, S.: Importance of aerosols for annual lightning production at global scale, Atmos. Chem. Phys. Discuss., 14, 4303–3325, https://doi.org/10.5194/acpd-14-4303-2014, 2014.

Waliser, D. E. and Gautier, C.: A satellite-derived climatology of the ITCZ, J. Climate, 6(11), 2162–2174, https://doi.org/10.1175/1520-0442(1993)006<2162:ASDCOT>2.0.CO;2, 1993.

Wall, C., Zipser, E., and Liu, C.: An investigation of the aerosol indirect effect on convective intensity using satellite observations, J. Atmos. Sci., 71(1), 430–447,

Deleted: Tao, W. K., Li, X., Khain, A., Matsui, T., Lang, S., and Simpson, J.: Role of atmospheric aerosol concentration on deep convective precipitation: cloud-resolving model simulations, J. Geophys. Res. - Atmos., 112(D24), https://doi.org/10.1029/2007JD008728, 2007.

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Wang, F., Guo, J., Zhang, J., Huang, J., Min, M., Chen, T., Liu, H., Deng, M., and Li, X.: Multi-sensor quantification of aerosol-induced variability in warm cloud properties over eastern China, Atmos. Environ., 113, 1–9, https://doi.org/10.1016/j.atmosenv.2015.04.063, 2015.

Weisman, M. L. and Klemp, J. B.: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy, Mon.Weather Rev., 110(6), 504–520, https://doi.org/10.1175/1520-0493(1982)110<0504:TDONSC>2.0.CO;2, 1982.

Weisman, M. L., and Rotunno, R.: "A theory for strong long-lived squall lines" revisited, J. Atmos. Sci., 61(4), 361–382, https://doi.org/10.1175/1520-0469(2004)061<0361:ATFSLS>2.0.CO;2, 2004.

Westcott, N. E.: Summertime cloud-to-ground lightning activity around major midwestern urban areas, J. Appl. Meteorol., 34(7), 1633–1642, https://doi.org/10.1175/1520-0450-34.7.1633, 1995.

Williams, E. R.: The Schumann resonance: a global tropical thermometer, Science, 256(5060), 1184–1187, https://doi.org/10.1126/science.256.5060.1184, 1992.

Williams, E. R.: Global circuit response to seasonal variations in global surface air temperature, Mon. Weather Rev., 122(8), 1917–1929, https://doi.org/10.1175/1520-0493(1994)122<1917:GCRTSV>2.0.CO;2, 1994.

Williams, E. R.: Global circuit response to temperature on distinct time scales: a status report, Atmospheric and Ionospheric Phenomena Associated with Earthquakes, 939–949, 1999.

Williams, E. R.: Lightning and climate: a review, Atmos. Res., 76(1-4), 272–287, https://doi.org/10.1016/j.atmosres.2004.11.014, 2005.

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Williams, E. R. and Stanfill, S.: The physical origin of the land–ocean contrast in lightning activity, Comptes Rendus Physique, 3(10), 1277–1292, https://doi.org/10.1016/S1631-0705(02)01407-X, 2002.

Williams, E. R. and Satori, G.: Lightning, thermodynamic and hydrological comparison of the two tropical continental chimneys, J. Atmos. Sol.-Terr. Phy., 66(13-14), 1213–1231, https://doi.org/10.1016/j.jastp.2004.05.015, 2004.

Williams, E. R., Rothkin, K., Stevenson, D., and Boccippio, D.: Global lightning variations caused by changes in thundersotmr flash rate and by changes in the number of thunderstorms, J. Appl. Meteorol., 39(12), 2223–2230, https://doi.org/ 10.1175/1520-0450(2001)040<2223:GLVCBC>2.0.CO;2, 2000.

Williams, E. R., Rosenfeld, D., Madden, N., Gerlach., J., …, and Avelino, E.: Comparison convective regimes over the Amazon: implications for cloud electrification, J. Geophys. Res.-Atmos., 107(D20), https://doi.org/10.1029/2001JD000380, 2002.

Williams, E. R., Chan, T., and Boccippio, D.: Islands as miniature continents: another look at the land-ocean lightning contrast, J. Geophys. Res.-Atmos., 109(D16), https://doi.org/10.1029/2003JD003833, 2004.

Williams, E. R., Mushtak, V., Rosenfeld, D., Goodman, S. and Boccippio, D.: Thermodynamic conditions favorable to superlative thunderstorm updraft, mixed phase microphysics and lightning flash rate, Atmos. Res., 76(1-4), 288–306, https://doi.org/10.1016/j.atmosres.2004.11.009, 2005.

Xiong, Y. J., Qie, X. S., Zhou, Y. J., Yuan, T., and Zhang, T. L.: Regional response of lightning

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activities to relative humidity of the surface, Chin. J. Geophys., 49(2), 311–318, 2006.

Yuan, T., Remer, L. A., Pickering, K. E., and Yu, H.: Observational evidence of aerosol enhancement of lightning activity and convective invigoration, Geophys. Res. Lett., 38(4), https://doi.org/10.1029/2010GL046052, 2011.

Zhang, G. J.: Effects of entrainment on convective available potential energy and closure assumptions in convection parameterization, J. Geophys. Res. - Atmos, 114(D7), 2009.

Zhao, C., Tie, X., and Lin, Y.: A possible positive feedback of reduction of precipitation and increase in aerosols over eastern central China, Geophys. Res. Lett., 33(11), https://doi.org/10.1029/2006GL025959, 2006.

Zipser, E. J. and Lutz, K. R.: The vertical profile of radar reflectivity of convective cells: a strong indicator of storm intensity and lightning probability? Mon. Weather Rev., 122(8), 1751–1759, https://doi.org/10.1175/1520-0493(1994)122<1751:TVPORR>2.0.CO;2, 1994.

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Williams, E. R.: Global circuit response to seasonal variations in global surface air temperature, Mon. Weather Rev., 122(8), 1917–1929, https://doi.org/10.1175/1520-0493(1994)122<1917:GCRTSV>2.0.CO;2, 1994.

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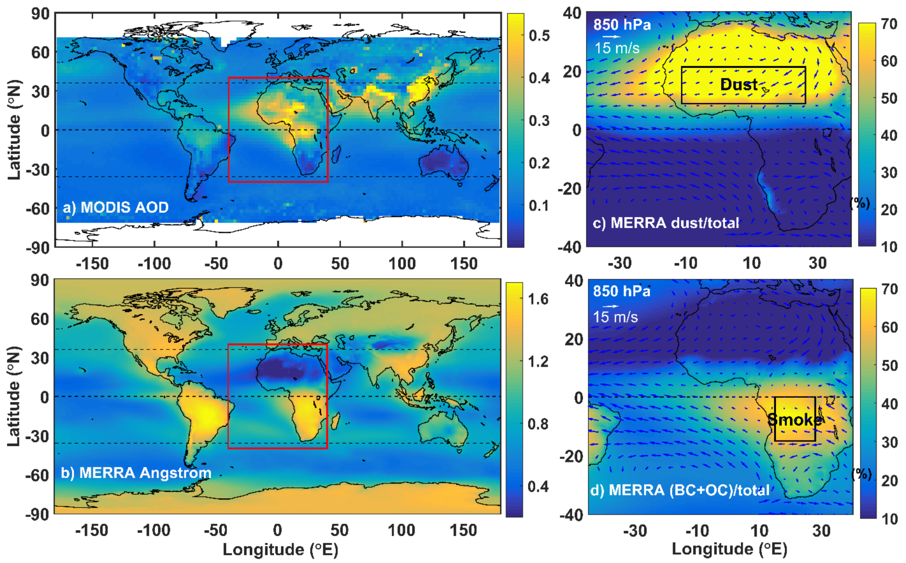

Figure 1. Spatial distributions of (a) aerosol optical depth (AOD) at 550 nm derived from the MODIS at a spatial resolution of 1°×1° and (b) the total aerosol Ångström parameter (470–870 nm) from the MERRA dataset on a 0.625°×0.5° grid for the period 2003–2013, including all seasons. The red rectangle outlines the region of interest. (c) The ratio of dust AOD to total AOD over the region of interest and (d) the ratio of carbonaceous aerosol [black carbon (BC) and organic carbon (OC): BC+OC] AOD to total AOD over the region of interest derived from the MERRAero dataset (da Silva et al., 2015). Also shown is the 850-hPa mean wind field from the ERA-Interim re-analysis with a spatial resolution of 1°×1° in panels (c) and (d).

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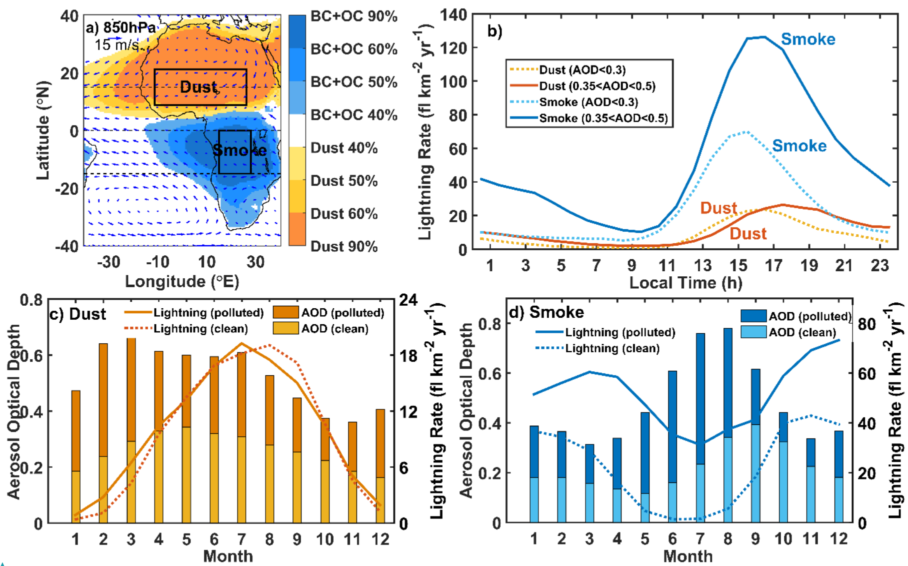

Figure 2. (a) The 850-hPa mean wind field from the ERA-Interim re-analysis with a spatial resolution of 1°×1° showing the prevailing wind direction over Africa and the neighboring ocean over the region of interest defined in Figure 1. The dust- and smoke-dominant regions (outlined by black rectangles) are defined as areas where the ratio of dust or carbonaceous aerosol (black carbon and organic carbon: BC+OC) extinction aerosol optical depth (AOD) to total extinction AOD is greater than 50% averaged over the period from 2003 to 2013 which enables us to better understand the potential effect of dust or smoke aerosols on lightning. Also shown are the (b) diurnal cycle and monthly variations in mean AOD and lightning flash rate calculated under relatively clean and polluted (dusty/smoky) conditions in the (c) dust-dominant region and the (d) smoke-dominant regions. Unless otherwise noted, the AOD used in this study is derived from the MODIS, and the lowest (highest) third of the AOD range [AOD ∈ (0, 1)] is labeled as clean (polluted). Lightning flash rates come from the low-resolution monthly time series and the low-resolution diurnal climatology products on a 2.5°×2.5° grid (Cecil et al., 2001, 2006, 2014). Data from all seasons are included.

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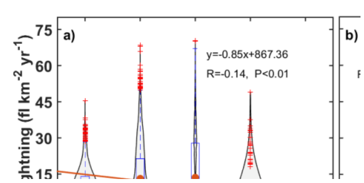

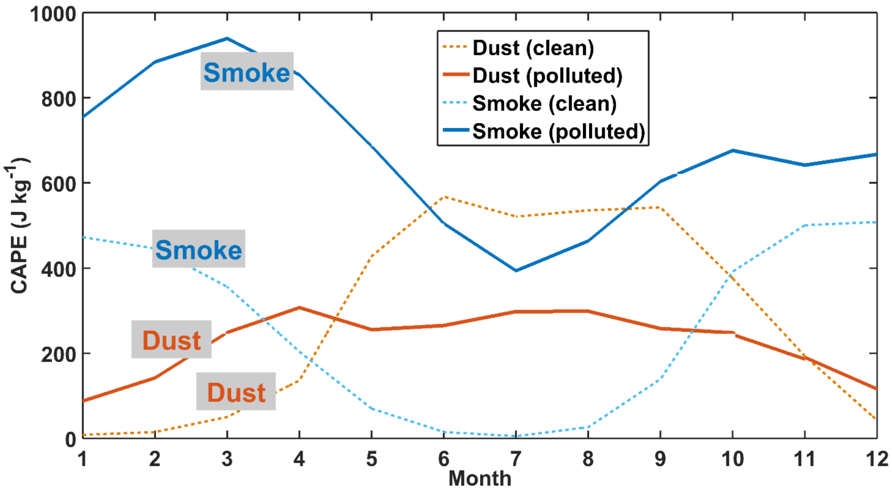

Figure 3. Seasonal variations in CAPE under relatively clean and polluted conditions in the dust- and smoke-dominant regions. Clean (polluted) cases are defined as those CAPE values corresponding to the lowest (highest) third of the aerosol optical depth (AOD) range [AOD ∊ (0, 1)].

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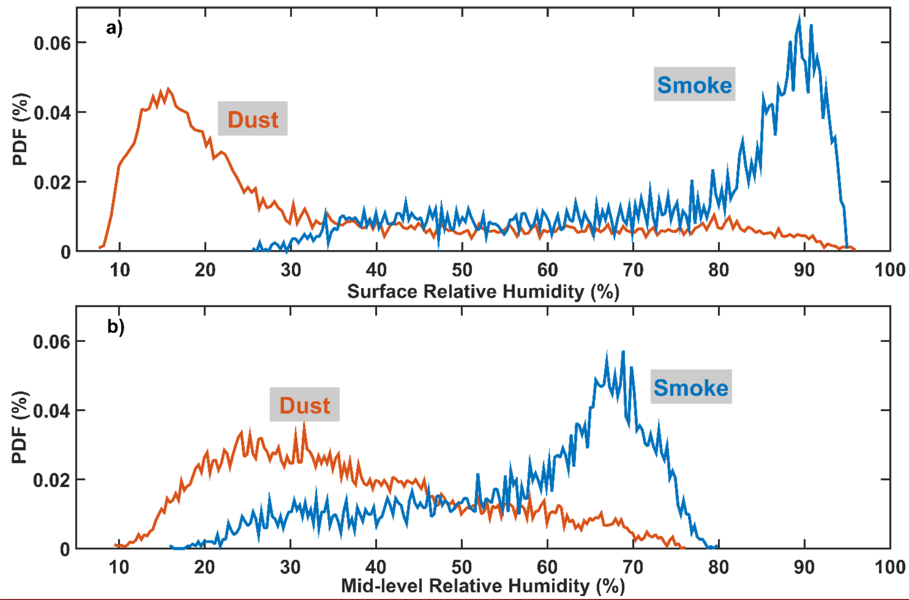

Figure 4. The probability density function (PDF) of (a) surface and (b) mid-level relative humidity in the dust- and smoke-dominant regions.

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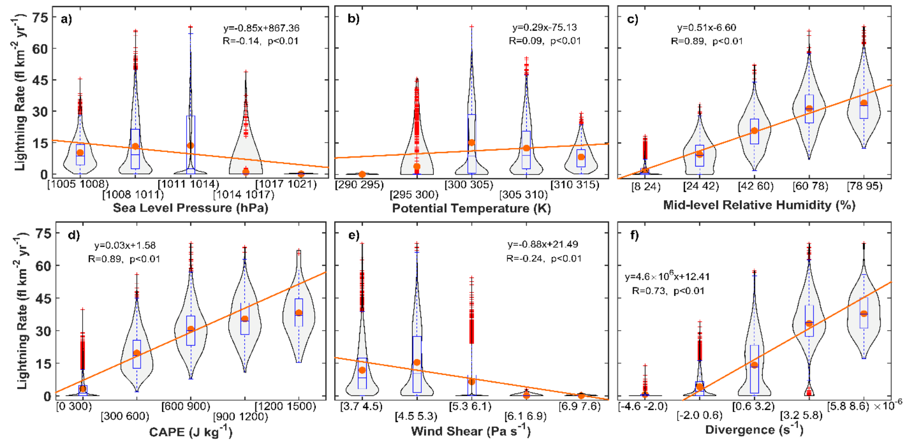

Figure 5. Violin plots of lightning dispersion showing the relationship between the lightning flash rate and six dynamic-thermodynamic variables: (a) sea level pressure, (b) potential temperature, (c) mid-level relative humidity, (d) convective available potential energy (CAPE), (e) vertical wind shear, and (f) 200-hPa divergence in the dust-dominant region. The five bins are equally spaced. Box plots represent the interquartile range (the distance between the bottom and the top of the box), the median (the band inside the box), the 95% confidence interval (whiskers above and below the box), the maximum (the end of the whisker above), the minimum (the end of the whisker below), and the mean (orange dot) in each bin. The plus signs represent outliers. On each side of the black line is the kernel estimation showing the distribution shape of the data. The estimate is based on a normal kernel function and is evaluated at 100 equally spaced points. Wider sections of the violin plot represent a high probability that members of the population will take on the given value; the skinnier sections represent a lower probability. The equations describe the linear correlations between the lightning flash rate and the dynamic-thermodynamic variables. Pearson correlation coefficients (R), p values, and the linear regression lines (in orange) are also shown. Data used here are from every grid square (2.5°×2.5°) through the whole year from 2003 to 2013. Dynamic-

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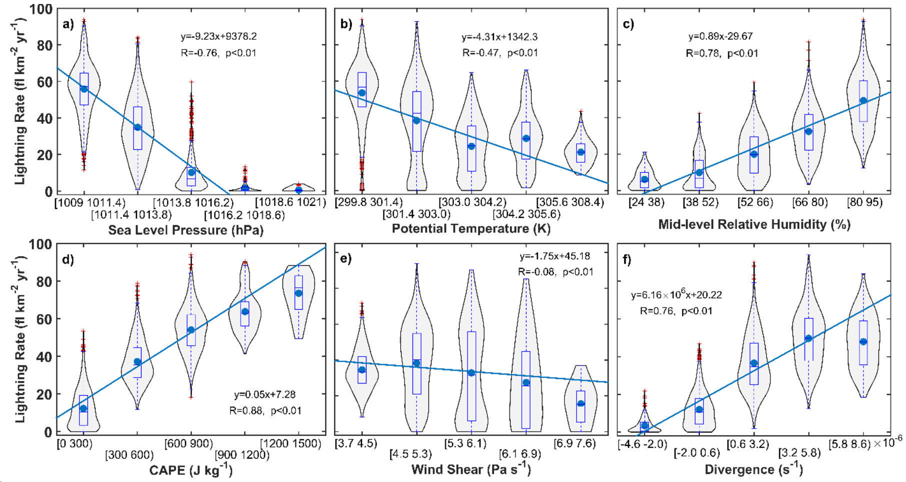

Figure 6. Same as in Figure 5, but for the smoke-dominant region. Mean values are represented by blue dots, and linear regression lines are shown in blue.

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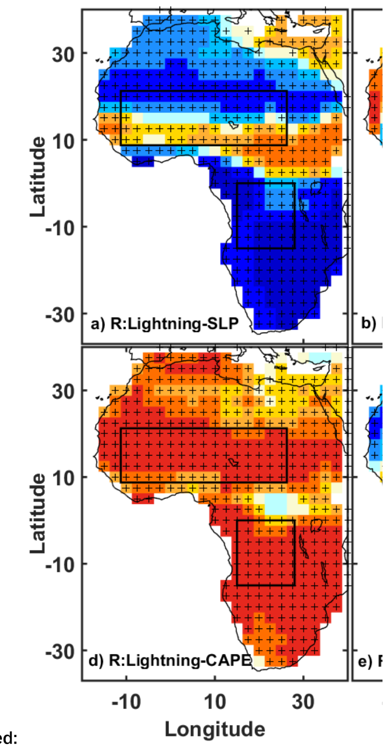

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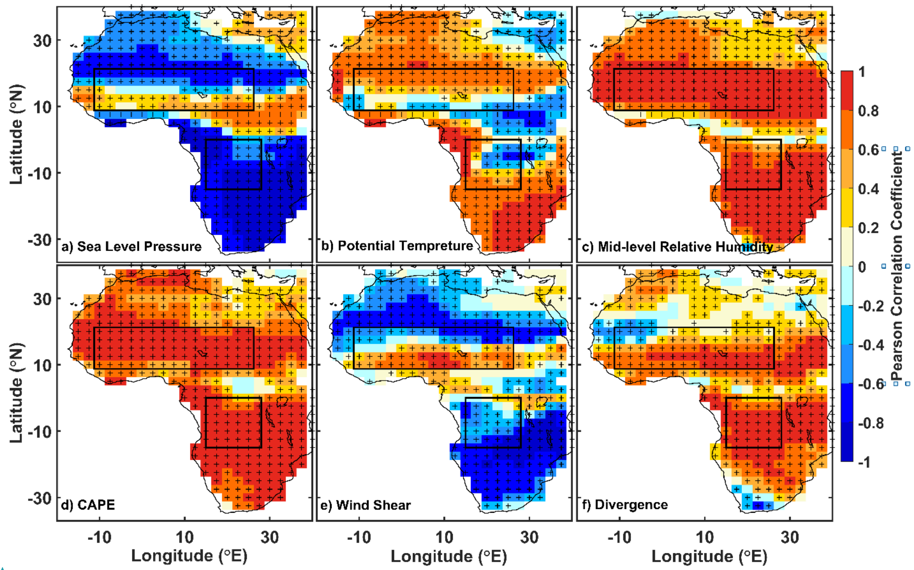

Figure 7. Maps of Pearson correlation coefficients between the lightning flash rate and (a) sea level pressure, (b) potential temperature, (c) mid-level relative humidity, (d) mean convective available potential energy (CAPE), (e) vertical wind shear, and (f) 200-hPa divergence over Africa at a spatial resolution of 2.5°×2.5° from 2003 to 2013 (including all seasons). In each grid, 132 samples are used to calculate the correlation coefficient. For each sample, variables are processed using three-month smoothing averages. The black rectangles outline the dust- and smoke-dominant regions (see Figure 2, left panel). Plus signs denote those grids that pass the significance test of 0.05.

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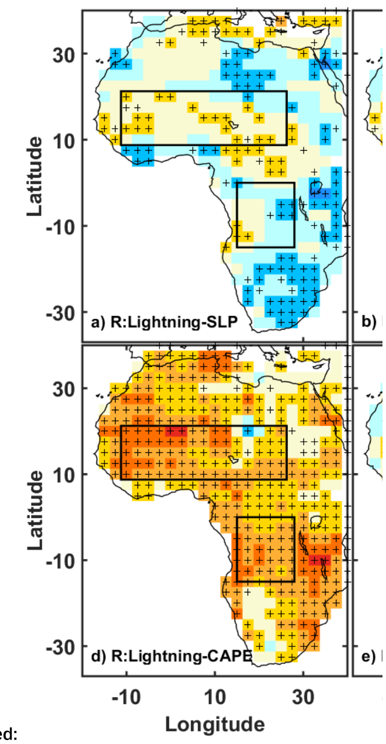

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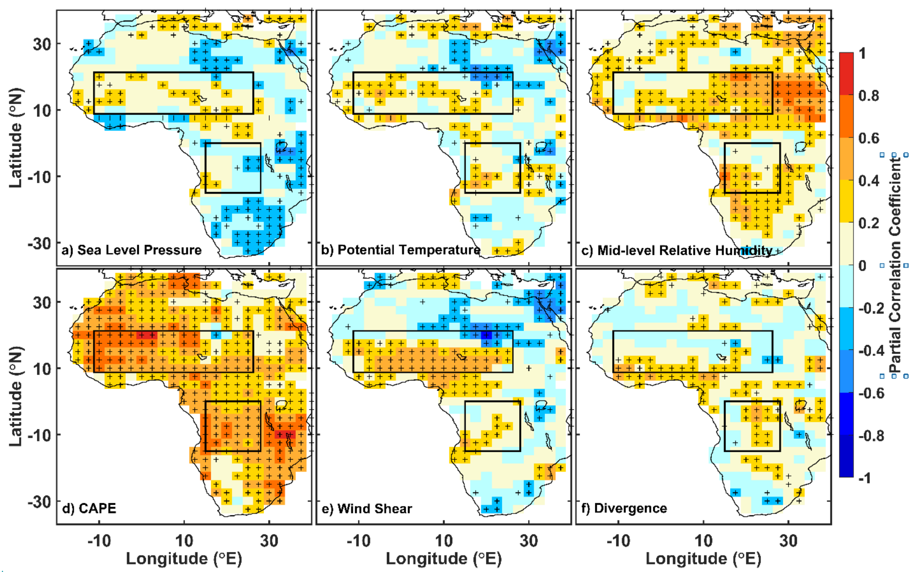

Figure 8. Same as in Figure 7, but for the partial correlation coefficients.

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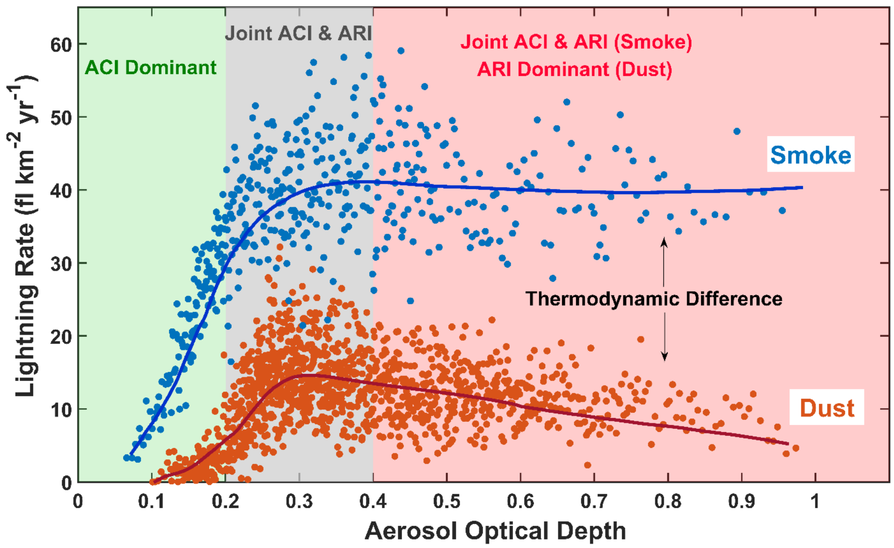

Figure 9. Lightning flash rate as a function of aerosol optical depth (AOD) in the dust- (orange points) and smoke-dominant regions (blue points). Note that all data pairs (i.e., a three-month mean lightning rate and a three-month mean AOD) are first ordered by AOD from small to large. Mean values of both AOD and lightning flash rate in each 10-sample bin are then calculated to reduce the uncertainty caused by the large dispersion of data. The two curves are created by applying a 100-point moving average (50-point) thrice to the mean values of lightning flash rate in each 30-sample bin for the dust- (smoke-) dominant region. Note that data used here are for the entire AOD range but only shown for the range AOD ∈ (0, 1). Turning points in the boomerang shapes are around AOD = 0.3. Aerosol-cloud interactions (ACI) play a dominant role in lightning activity under relatively clean conditions (green zone). As AOD exceeds 0.3, both ACI and aerosol-radiation interaction (ARI) effects come into play with different magnitudes. For dust aerosols, ACI and ARI have the same same effect of suppressing convection in the dry environment favorable for evaporating cloud droplets. The moist environment of central Africa strengthens

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aerosol invigoration that offsets the suppression due to ARI, leading to a nearly flat line in the grey and red zones.

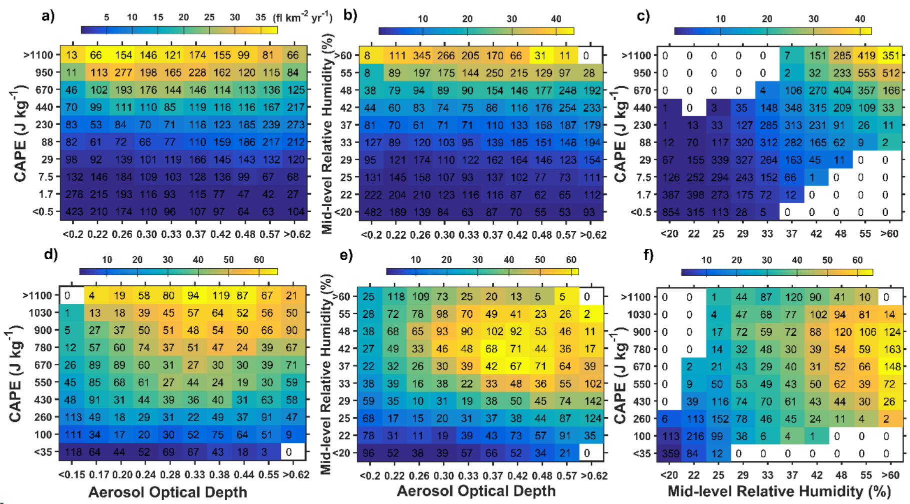

Figure 10. Joint dependence of the lightning flash rate on CAPE, mid-level relative humidity, and aerosol optical depth in the dust- (a-c) and smoke-dominant (d-f) regions. The bold number in each cell indicates the number of samples in the cell. The colorbar denotes the number of lightning flash rates averaged in each cell.

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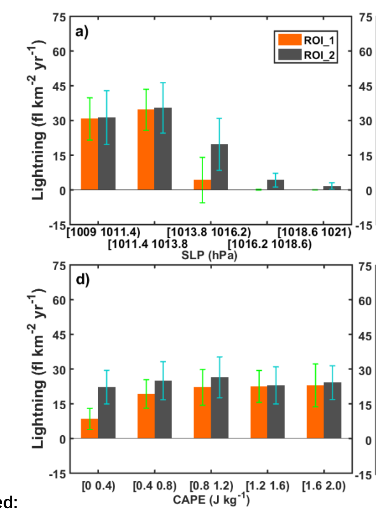

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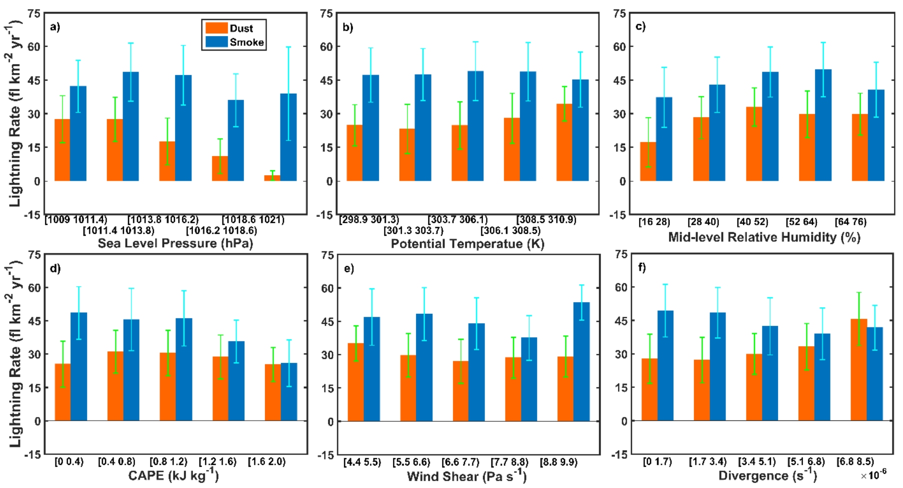

Figure 11. Differences (polluted minus clean subsets of data) in lightning flash rate as a function of (a) sea level pressure, (b) potential temperature, (c) mid-level relative humidity, (d) convective available potential energy (CAPE), (e) vertical wind shear, and (f) 200-hPa divergence in the dust- (in orange) and smoke-dominant regions (in blue). Note that the top third of aerosol optical depth (AOD) values [AOD ∈ (0, 1)] is labeled as polluted, and the bottom third is labeled as clean. Vertical error bars represent one standard deviation.

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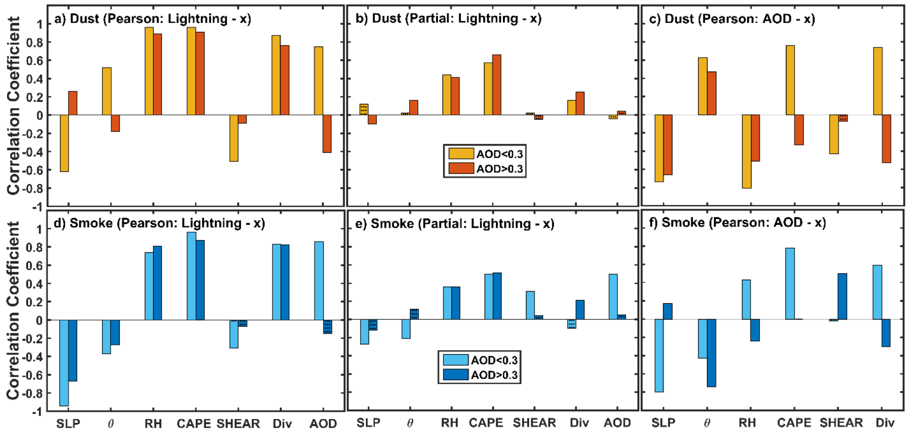

g) Standardized multiple regression equation : y(Lightning), x_1(SLP), x_2(θ), x_3(RH), x_4(CAPE), x_5(SHEAR), x_6(Div), x_7(AOD)

ROI_1 (AOD<0.3): $y=0.07x_1+0.08x_2+0.49x_3+0.49x_4+0.01x_5+0.09x_6-0.02x_7-1.52\times10^{-14}$ ($R_M=0.96$)

ROI_1 (AOD>0.3): $y=0.11x_1+0.15x_2+0.34x_3+0.54x_4-0.02x_5+0.15x_6+0.02x_7-5.44\times10^{-14}$ ($R_M=0.91$)

ROI_2 (AOD<0.3): $y=-0.21x_1-0.06x_2+0.32x_3+0.42x_4+0.13x_5-0.08x_6+0.25x_7-5.28\times10^{-14}$ ($R_M=0.96$)

ROI_2 (AOD>0.3): $y=-0.07x_1+0.09x_2+0.31x_3+0.51x_4+0.02x_5+0.17x_6+0.04x_7-1.02\times10^{-14}$ ($R_M=0.88$)

Figure 12. (a,d) Pearson correlation coefficients of the linear regression relationships between the lightning flash rate and the six dynamic-thermodynamic variables and aerosol optical depth (AOD). (b,e) Partial correlation coefficients of the relationships between the lightning flash rate and any influential factor (AOD or dynamic-thermodynamic variables) with the others as control variables. (c,f) Pearson correlation coefficients of the linear regression relationships between AOD and any given dynamic-thermodynamic variable. The top panels are for the dust-dominant region, and the bottom panels are for the smoke-dominant region. Those bars with dots on them signify success of the statistical significance test at the 95% confidence level. Also shown are standardized multiple regression equations of the lightning flash rate (y) onto the six dynamic-thermodynamic variables (x_1-x_6) and AOD (x_7) and standardized multiple correlation coefficients (R_M). The six dynamic-thermodynamic variables are sea level pressure [SLP (x_1)], potential temperature [θ (x_2)], mid-level relative humidity [RH (x_3)], mean convective available potential energy [CAPE (x_4)], vertical wind shear [SHEAR (x_5)], and 200-hPa divergence [Div (x_6)].

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narrow distribution and high correlation between aerosol and meteorology imply that the

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optimum value, lightning shows more dispersed distribution

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has much weaker dependence on AOD, which may be the consequence of competition between aerosol microphysical effect and radiative effect

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Fan, J., Rosenfeld, D., Ding, Y., Leung, L. R., and Li, Z.: Potential aerosol indirect effects on atmospheric circulation and radiative forcing through deep convection, Geophys. Res. Lett., 39(9), https://doi.org/10.1029/2012GL051851, 2012.

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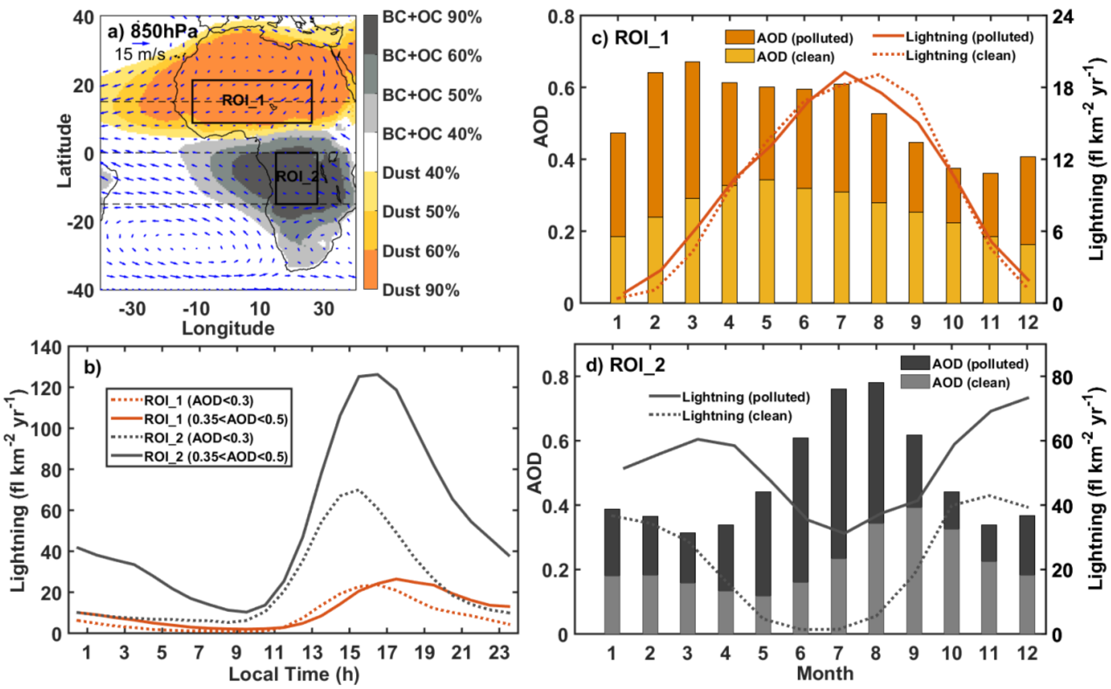

Figure 2. (a) The distribution of

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