Response to Earle Williams's Comments

(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*:

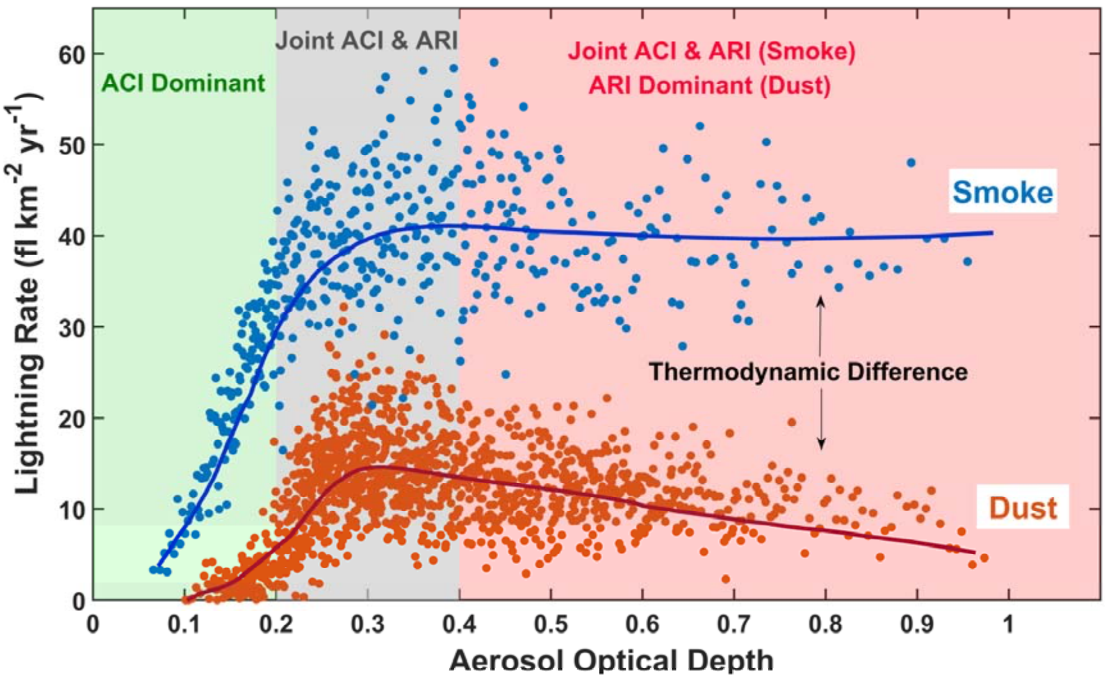

Fig. R1 (Figure 9 in the paper). Lightning flash rate as a function of aerosol optical depth (AOD) in the dust- (orange points) and smoke-dominant regions (blue points). Note that all data pairs (i.e., a three-month mean lightning rate and a three-month mean AOD) are first ordered by AOD from small to 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 $\in$ (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.

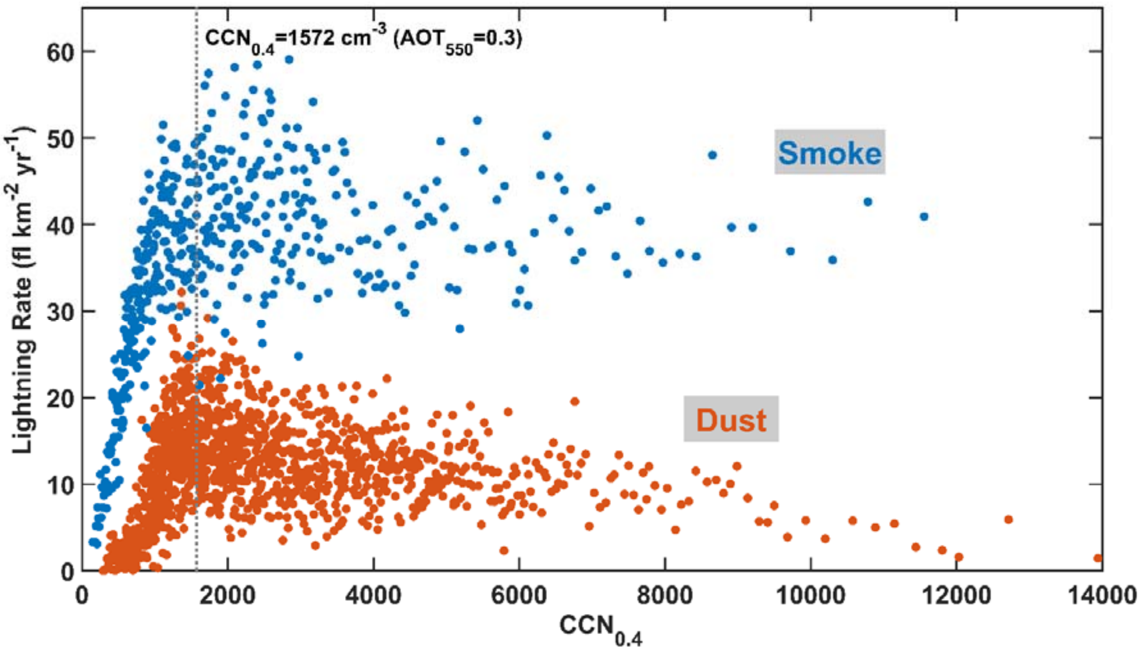

Fig. R2. The response of the lightning flash rate to dust and smoke aerosols in the dust- and smoke-dominant regions. The turning points are around $CCN_{0.4}$ =1600 cm^{-3}.

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 441–445).

Fig. R2 is added to the supplemental material (see Fig. S10).

(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.

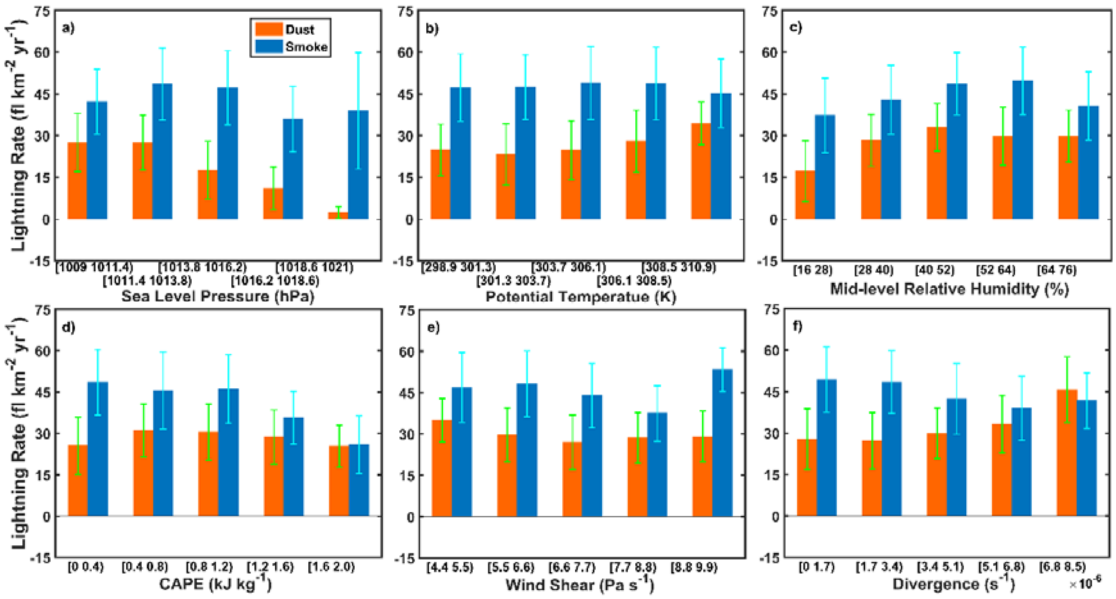

Fig. R3. Differences (polluted minus clean subsets of data) in lightning flash rate as a function of (a) sea level pressure, (b) potential temperature, (c) mid-level relative humidity, (d) convective available potential energy (CAPE), (e) vertical wind shear, and (f) 200-hPa divergence in the dust- (in 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.

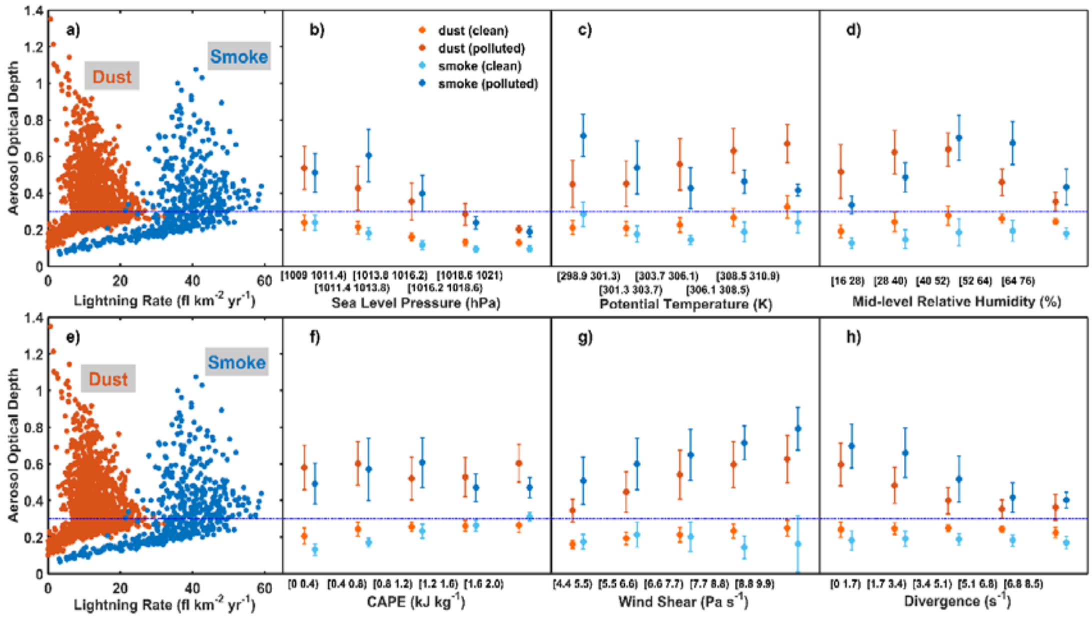

Fig. R4. (a, e, duplicated) Mean aerosol optical depth (AOD) as a function of the lightning flash rate in the dust- (in orange) and smoke-dominant (in blue) regions, and under clean and polluted conditions for five ranges of (b) sea level pressure, (c) potential temperature, (d) mid-level relative humidity, (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).

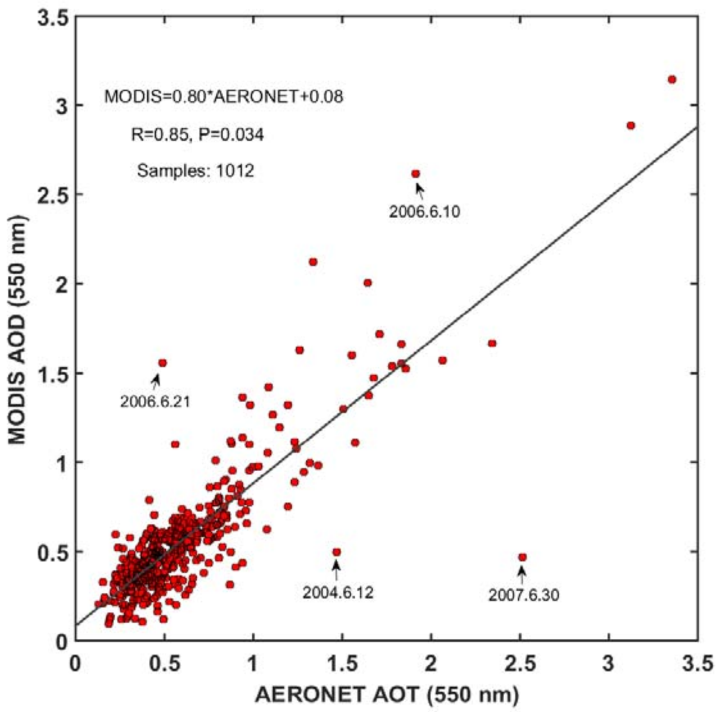

Fig. R5. Daily mean Aqua/MODIS AOD at 550 nm (local time ~13:30) as a function of AERONET AOD (averaged from 12:00–15:00 local time) over the dust-dominant region for the period 2003–2013 (May, June, July of each year). The AERONET site is located at Banizoumbou (2.66°E, 13.54°N), and the region covered 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.

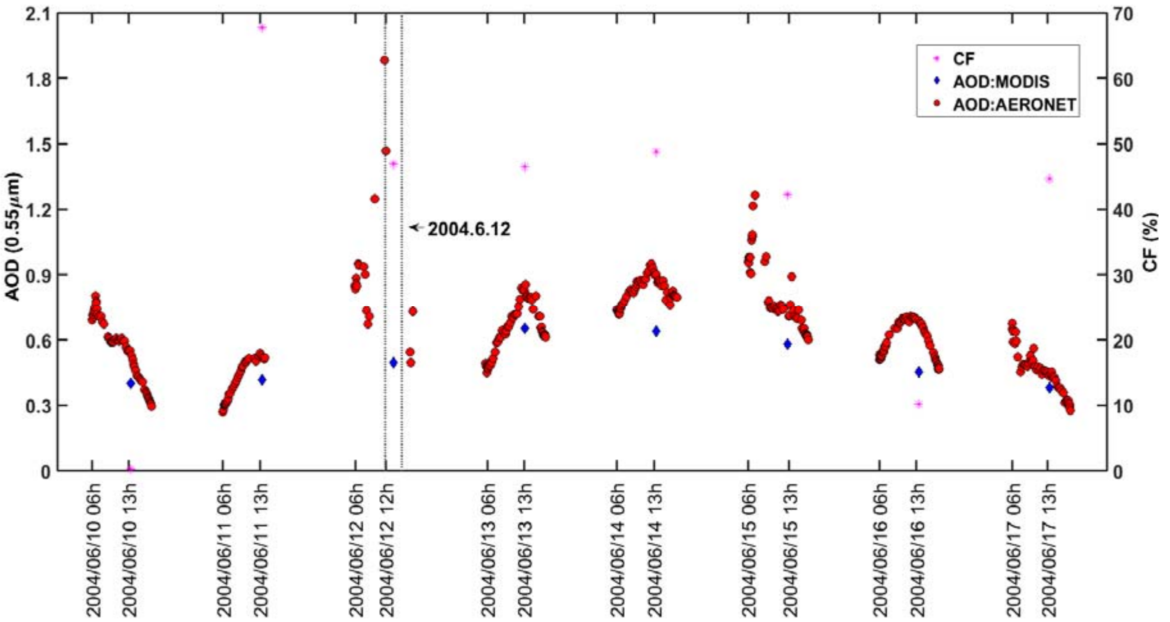

Fig. R5-1. Times series (10 – 17 June 2004) of daily mean Aqua/MODIS AOD at 550 nm (local time ~13:30 averaged over (2°E-3°E,13°N-14°N), blue triangles), high resolution (~7 min) AERONET AOD retrievals made at Banizoumbou (2.66°E, 13.54°N, averaged from 12:00–15:00 local time, red dots), and cloud fraction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

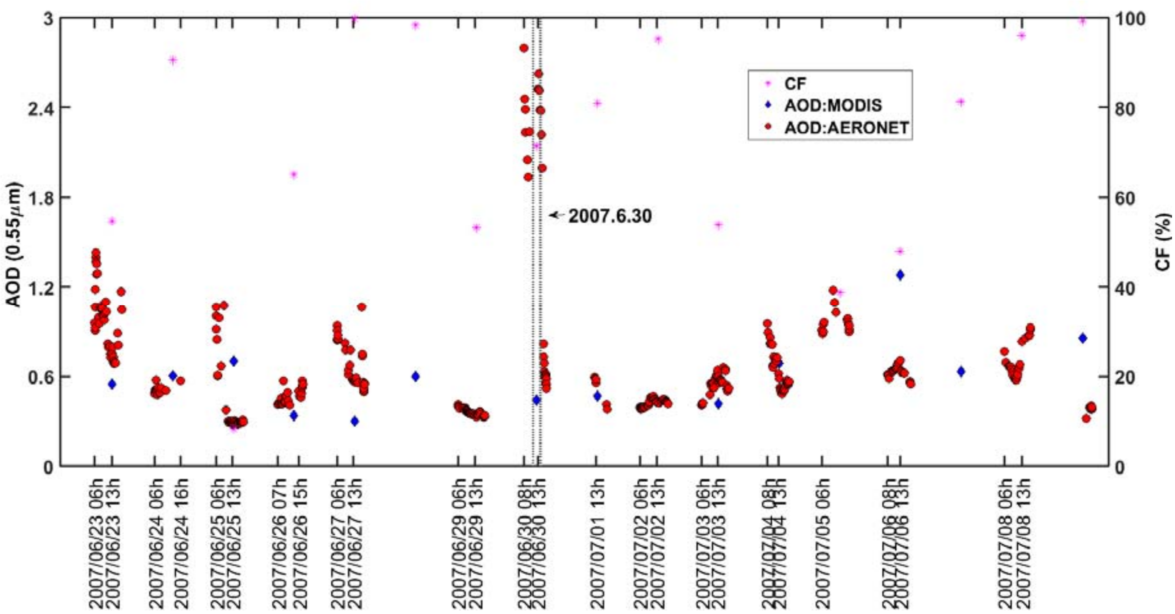

Fig. R5-2. Times series (23 June – 8 July 2007) of daily mean Aqua/MODIS AOD at 550 nm (local time ~13:30 averaged over (2°E -3°E,13°N -14°N), blue triangles), high resolution (~7 min) AERONET AOD retrievals made at Banizoumbou (2.66°E, 13.54°N, averaged from 12:00–15:00 local time, red dots), and cloud 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.

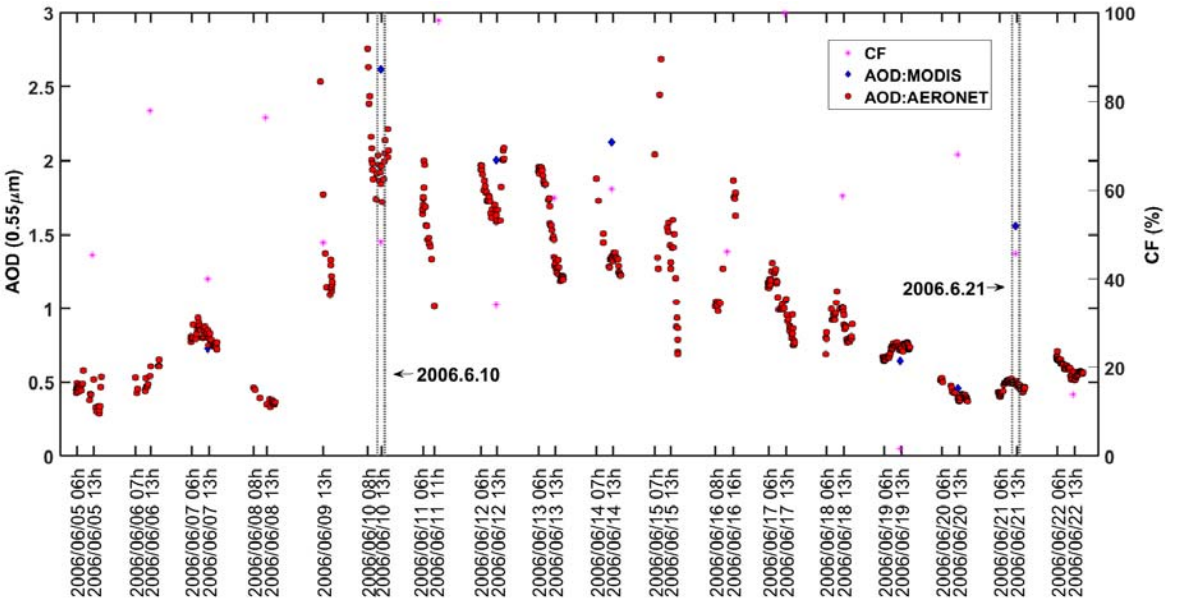

Fig. R5-3. Times series (5–22 June 2006) of daily mean Aqua/MODIS AOD at 550 nm (local time ~13:30 averaged over (2°E -3°E,13°N-14°N), blue triangles), high resolution (~7 min) AERONET AOD retrievals made at Banizoumbou (2.66°E, 13.54°N, averaged from 12:00–15:00 local time, red dots), and cloud fraction (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 Figures S8 and S8-1, 2, 3 in the supplemental material)..*" is added to the revised paper (see Lines 261–267).

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

Fig. R4 is added to the supplement material (see Fig. S11).

Fig. R5, and R5-1, 2, 3 are added to the supplement material (see Figs. S8 and S8-1, 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.*"(dded to the paper, see Lines 367–371). *This is shown in Tables R1-1 and R1-2 and is added to the supplemental material (see Tables S1-1 and S1-2). This is shown in Table R1 and is added to the supplemental material (see Table S1).*

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:

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

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:

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

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 633–634).

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:

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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.

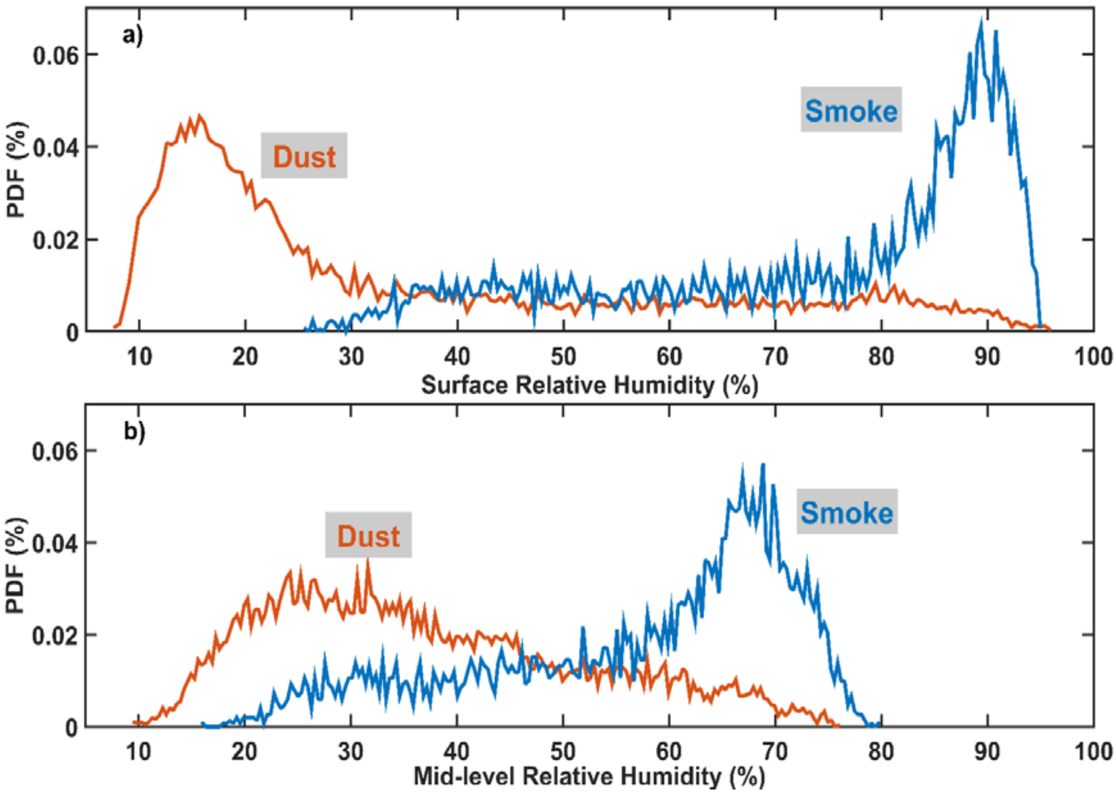

Fig. R6. The probability density function (PDF) of (a) surface and (b) mid-level relative humidity in the dust- and smoke-dominant regions.

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 (Figure 3). Mean relative humidity values at 700 and 500 hPa levels are used in this study." is added to the revised paper (see Lines 196–220).

Fig. R6 is added to the supplemental material (see Fig. S5) and the revised paper (see Figure 3).

(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.

1) 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.
2) 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.
3) 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.
4) 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 329–330).
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.

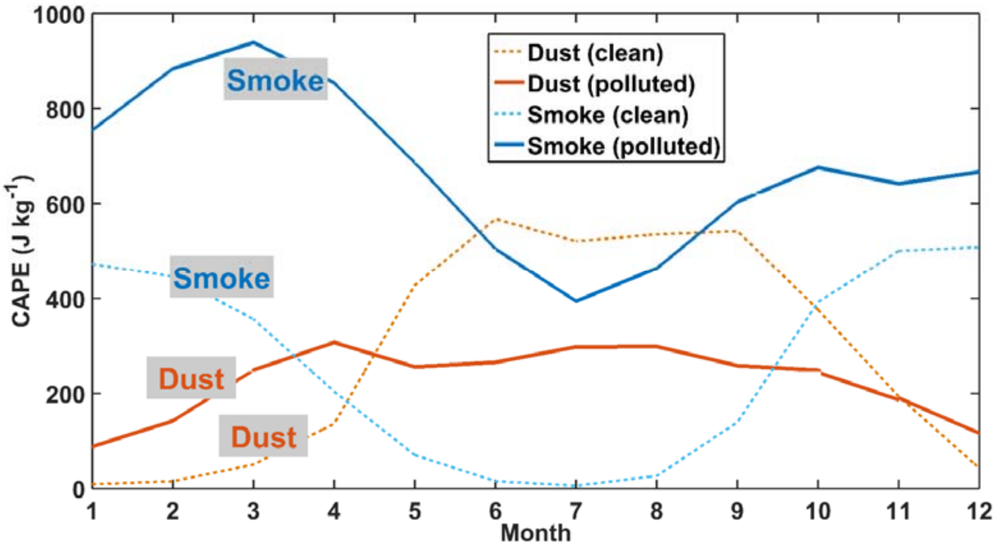

Fig. R7. Seasonal variations in CAPE under relatively clean and polluted conditions in the dust- and smoke-dominant regions. Clean (polluted) cases are defined as those CAPE values corresponding to the lowest (highest) third of the aerosol optical depth (AOD) range [AOD ∈ (0, 1)].

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 supplemental material (see Fig. S6) and the revised paper (see Figure 4).

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).

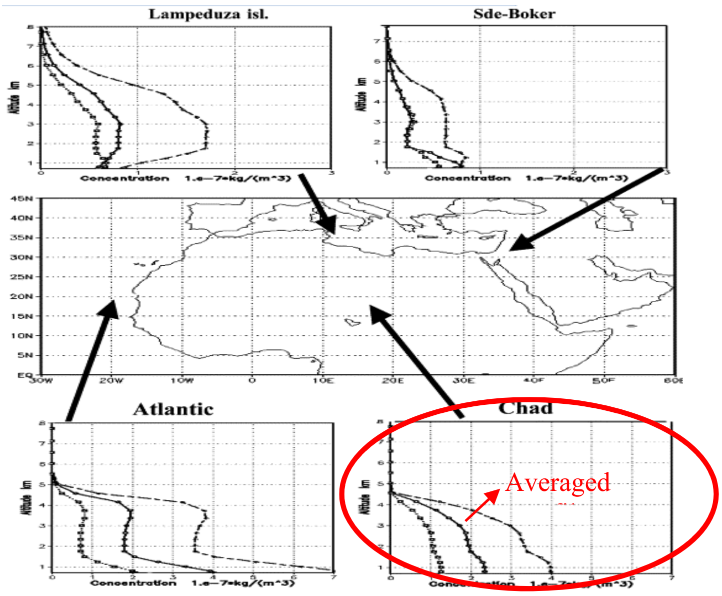

Fig. R8-1 (from Alpert et al., 2004). Mean vertical profiles of dust concentration (unit: 10^{-7} kg m^{-3}) for the month of June at 12:00 UTC over Sde-Boker (Israel) in the eastern Mediterranean (29.5°N–31.5°N, 34°E–36°E), Lampedusa Island in the central Mediterranean (34.5°N–36.5°N, 11.5°E–13.5°E), 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.

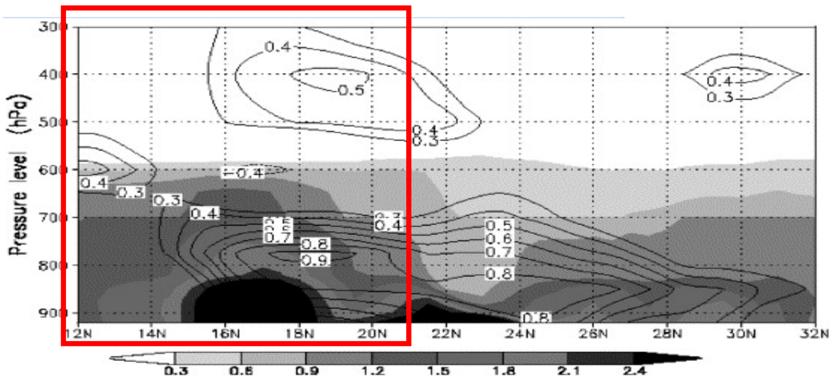

Fig. R8-2 (from Alpert et al., 2004). Vertical distribution of mean model dust concentration and the one of correlation within the latitudinal cross-section zonal averaged over the positive correlation area, both in the daytime (12:00 UTC) in the month of April. Solid lines show the correlation between 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.

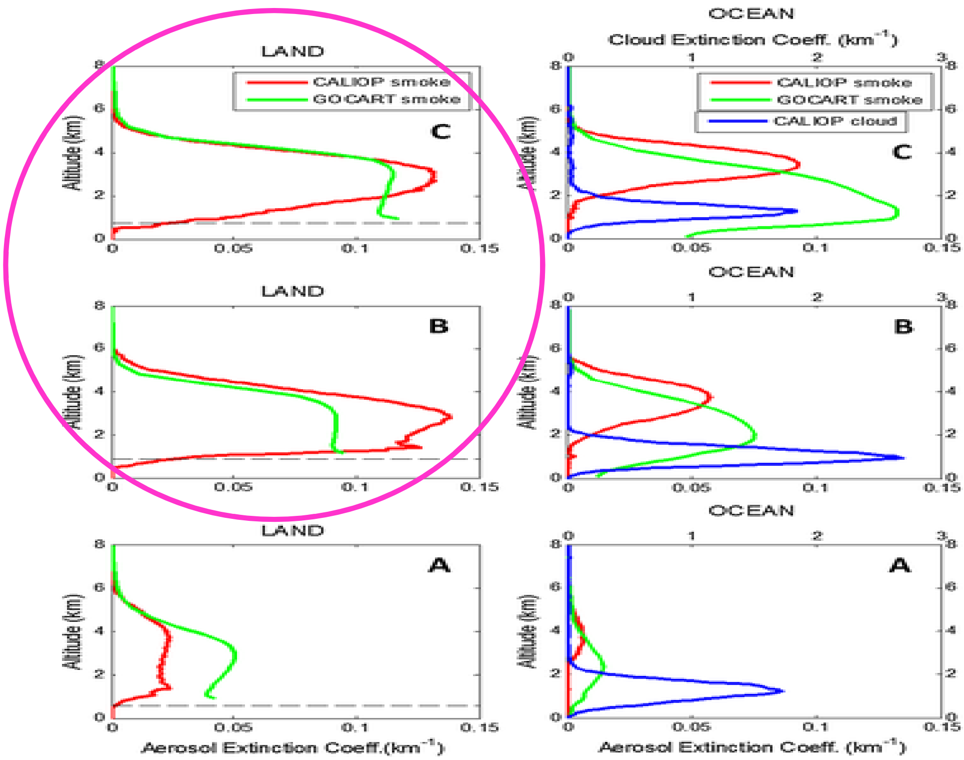

Fig. R8-3 (from Das et al., 2007). Comparisons of mean (August–September) smoke extinction profiles (km^{-1}) from CALIOP (in red) and GEOS-5-GOCART (in green) over land (13°E–35°E) and oceanic (13°E–15°W) parts of the three sub-regions, viz., A (30°S–20°S), B (20°S–10°S), and C (10°S–0°) of the domain. 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.

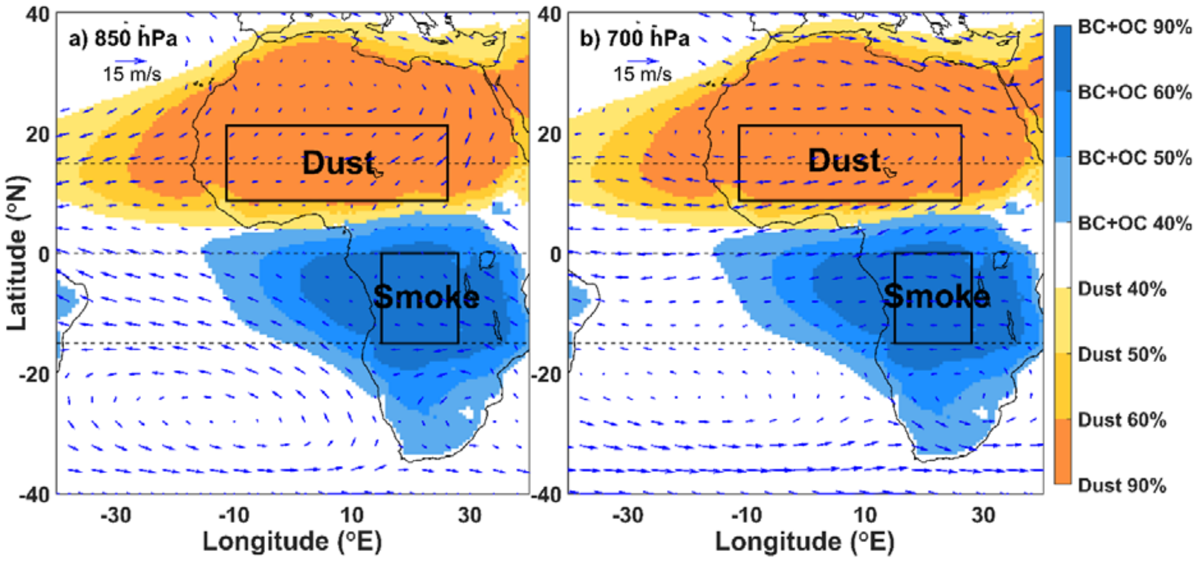

Fig. R9. Comparison of the prevailing wind directions at (a) 850 hPa and (b) 700 hPa over Africa.

Fig. R9 is added to the supplemental material (see Fig. S2).

(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 413–426).

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 Fig. 2. BR is mentioned on lines 353 and 354.

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 261–267)

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 273)*

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 324–326)

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 444)

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 456–471)*

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 633–634).

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.

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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	$y = 0.07x_1 + 0.08x_2 + 0.49x_3 + 0.49x_4 + 0.01x_5 + 0.09x_6 - 0.02x_7 - 1.52 \times 10^{-14}$						
	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	$y = 0.11x_1 + 0.15x_2 + 0.34x_3 + 0.54x_4 - 0.02x_5 + 0.15x_6 + 0.02x_7 - 5.44 \times 10^{-14}$						
	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	$y = -0.21x_1 - 0.06x_2 + 0.32x_3 + 0.42x_4 + 0.13x_5 - 0.08x_6 + 0.25x_7 - 5.28 \times 10^{-14}$						
	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	$y = -0.07x_1 + 0.09x_2 + 0.31x_3 + 0.51x_4 + 0.02x_5 + 0.17x_6 + 0.04x_7 - 1.02 \times 10^{-14}$						

	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, 2018