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African Lightning and its Relation to Rainfall and Climate Change in a Convection-Permitting Model

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Key Points:

- Lightning and its relationship to rainfall vary considerably across Africa, with indication of dry lightning in arid regions
- Opposite changes in lightning days and intensity lead to little change in total flashes under climate change, unlike many past studies
- Graupel increases are smaller than column water increases, and therefore, lightning intensity mostly increases less than rain intensity

Supporting Information:

- Supporting Information S1

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Abstract Global climate models struggle to simulate both the convection and cloud ice fundamental to lightning formation. We use the first convection-permitting, future climate simulations for the lightning hot spot of Africa, at the same time utilizing an ice-based lightning parametrization. Both the model and observations show that lightning over Africa's drier areas, as well as the moist Congo, have more lightning per rainfall than other regions. Contrary to results in the literature, the future projection shows little increase in total lightning (~10^7 flashes (or 2%) per degree warming). This is a consequence of increased stability reducing the number of lightning days, largely offsetting the increased graupel and updraft velocity driving an increase in lightning per lightning day. The next step is to establish if these results are robust across other models and, if combined with parametrized-convection models, whether ensemble-based information on the possible responses of lightning to climate change can be investigated.

Plain Language Summary Lightning depends on ascending air in thunderstorms and the collision of cloud ice particles, which charge the thundercloud. Many climate models have too coarse a resolution to reliably capture these processes. We focus on Africa, which has some of the most frequent lightning in the world. We use a model that is much higher resolution than usual, and this allows us to explicitly simulate the deep convection associated with thunderstorms as well as provide more detailed representation of the distribution of cloud ice particles. Our results show that in drier regions, as well as the much wetter Congo, there is relatively more lightning per kilogram of surface rainfall than there is in other parts of the continent. Lightning does increase across the continent under climate change, but by a relatively small amount. This is despite the number of days with lightning decreasing as the lower atmosphere becomes more stable. On days with lightning, there are more lightning flashes because there is an increase in cloud ice and intensity of convection. This study gives much more detailed information about African lightning than previous work. However, it is a single simulation. Future research should look at these results across other climate models.

1. Introduction

Lightning is a serious hazard in many parts of Africa, being one of the main global hot spots of lightning activity (Albrecht et al., 2016). As well as the risk to people and infrastructure, lightning can be a natural cause of wildfires and affects key features of atmospheric chemistry such as ozone production in the upper troposphere (Finney, Doherty, Wild, Young, & Butler, 2016; Schumann & Huntrieser, 2007).

As with many weather phenomena, lightning is likely to respond to climate change. The majority of studies suggest there will be an increase in lightning (Clark et al., 2017; Finney, Doherty, Wild, & Abraham, 2016; Romps et al., 2014; Schumann & Huntrieser, 2007; Williams, 2005). Clark et al. (2017) does present 2 out of 16 projections that show a small decrease in lightning, but these lightning schemes are not widely used and perform poorly in evaluation. The studies listed use proxies for lightning activity such as cloud top height, convective available potential energy or cloud condensation nuclei (Clark et al., 2017; Finney, Doherty, Wild, & Abraham, 2016; Romps et al., 2014), or they study lightning-temperature relationships in the current climate (Williams, 2005).

The widely accepted mechanism for thunderstorm charging is based upon the collision of different ice particles within clouds (Latham et al., 2007; Reynolds et al., 1957). To fully simulate lightning activity, a model would include prognostic charging through ice particle collisions, evolution of the electric field, and breakdown of the field which leads to the lightning flash (e.g., Barthe et al., 2012; Fierro et al., 2013). On global or continental spatial scales, and over climate timescales, it is unfeasible to simulate the full complexity of these processes. Instead, three past studies take an intermediate approach and implement empirical relationships between lightning flashes and the fundamental components of the charging process, notably including aspects of cloud ice and updraft strength (Finney et al., 2018; Jacobson & Streets, 2009; Romps, 2019). These papers all find decreases in tropical lightning activity under climate change, which is contrary to the majority of non-ice-based approaches of simulating lightning (Clark et al., 2017; Finney, Doherty, Wild, & Abraham, 2016; Romps et al., 2014; Schumann & Huntrieser, 2007; Williams, 2005).

Jacobson and Streets (2009) and Finney et al. (2018) use coarse resolution models which parametrize convection, thereby limiting their ability to simulate tropical convective storms. Romps (2019), who investigated cloud-to-ground lightning, uses a much higher resolution model. However, the model is based upon radiative-convective equilibrium and consequentially only applies over the tropical ocean, where there is relatively weak lightning activity. Therefore, recently completed high-resolution, convection-permitting simulations over Africa, which use a cloud ice-based lightning scheme, offer the chance to investigate lightning and climate change in a lightning hot spot with unprecedented detail. The high resolution and explicit convection, when compared to a comparable model with parametrized convection, has already been shown to improve the representation of storms, extreme rainfall, and dry spells (Finney et al., 2019; Jackson et al., 2019; Kendon et al., 2019) and affect projections of these metrics (Finney et al., 2020; Fitzpatrick et al., 2020; Jackson et al., 2020; Kendon et al., 2019).

2. Data

2.1. Convection-Permitting 4.5 km Simulations Over Africa (CP4A)

Two decade-long regional UK Met Office Unified Model simulations, one of current climate (January 1997–February 2007) (Stratton et al., 2018) and one of a future climate (~2,100 s)(Kendon et al., 2019), have been performed at 4.5-km grid spacing with explicit convection over the entirety of the African continent. To summarize, a recent version of the global UK Met Office Unified Model provides the horizontal boundary conditions. Sea surface temperatures (SSTs) use observed values for current climate with a change applied to current climate SSTs from the HadGEM2-ES simulated change for future climate. The SSTs used by global driving model are the same as for the regional models. The first 2 months of simulation are disregarded as spin-up. The future climate simulation is for the end of century under Representative Concentration Pathway 8.5 (RCP8.5) (van Vuuren et al., 2011), and with aerosol and ozone climatologies kept constant at current climate values, and consequently, the cloud condensation nuclei distribution is also kept constant between the two simulations. Therefore, this study is focused solely on the impact of changes in long-lived greenhouse gases. A complete description of the simulations is provided by Stratton et al. (2018) and Kendon et al. (2019), and we provide some details of the cloud and microphysics schemes in supporting information Text S1.

2.2. Lightning Parametrization

The lightning scheme used is based upon that of McCaul et al. (2009) and has been shown to produce useful forecasts of lightning for the UK (Wilkinson, 2017; Wilkinson & Bornemann, 2014) as well as reproducing the global climatology of lightning (Field et al., 2018). McCaul et al. (2009) developed empirical relationships between the lightning flash rate and fundamental components of the cloud charging process:

$$F = 0.95F1 + 0.05F2, \tag{1}$$

$$F1 = 0.042\left(wq_g[-15°\mathrm{C}]\right), \tag{2}$$

$$F2 = 0.2\int\rho\left(q_g + q_s + q_i\right)\mathrm{d}z, \tag{3}$$

where F is the total lightning flash rate in flashes per minute (per grid cell), $wq_g[-15°\mathrm{C}]$ represents the product of vertical velocity and graupel mixing ratio at the $-15°\mathrm{C}$ isotherm, and $\int\rho(q_g + q_s + q_i)\mathrm{d}z$ is the integral of air density and the sum of graupel, snow, and cloud ice mixing ratios. All input variables are in SI units. The equations of $F1$ and $F2$ represent individually determined relationships (McCaul et al., 2009). McCaul et al. (2009) then determined that the graupel-based approach ($F1$) should have the greatest weighting in order to best represent the Alabama storms they studied. Using an isotherm as in McCaul et al. (2009) appeals since it sits within the thunderstorm charging zone (approximately −10 to −25°C) (Solomon & Baker, 1994). Use of this ice-based lightning parametrization in convection-permitting, climate change simulations is a first and provides a significant step beyond previous models used for investigating the climate change effect on tropical continental lightning. The same formulation is applied over land and ocean grid cells.

2.3. Lightning and Rainfall Satellite Observation Products

For lightning evaluation, we use the Lightning Imaging Sensor (LIS) Very High Resolution Monthly Climatology product with data from 1998–2013 measured from on board the Tropical Rainfall Measurement Mission (TRMM) satellite. Data are available on a 0.1° grid and provide an estimate of total lightning (cloud-to-ground and intracloud/intercloud lightning) (Albrecht et al., 2016). For evaluation of rainfall we use TRMM 3B42 v7 product from 1998 to 2006, which uses retrievals from the TRMM satellite and other microwave and infrared satellite instruments to estimate rainfall (Huffman et al., 2007). The satellite swaths used in each of the products are not directly comparable, but it is assumed that more than a decade of observations allows for useful broad comparisons of the two data sets.

3. Evaluation of Simulated Lightning Over Africa and its Relationship to Rainfall

Figures 1a–1c provide an evaluation of the total annual lightning distributions over Africa from the current climate simulation against the climatology from the LIS lightning observational product. Figures 1d–1f then divide these fields by the total annual surface rainfall from the model and the TRMM rainfall observation product to offer a different perspective on storm activity over the continent. Such a metric has been studied before, where Petersen and Rutledge (1998) have shown that the amount of convective rainfall per lightning flash can vary greatly by location.

CP4A has similar total flashes over Africa's land to LIS, with only 14% more flashes over the continent. There is a notable overestimation of lightning over the ocean, as well as over large lakes such as Lake Victoria (Figures 1a and 1b). There is also rainfall overestimation over the ocean (supporting information Figure S1), likely arising from too intense convection due to the lack of coupling between atmosphere and ocean, and too coarse a grid spacing for tropical oceanic convection (Berthou et al., 2019; Willetts et al., 2017). Lightning parametrizations often overestimate oceanic lightning (Finney et al., 2014; Tost et al., 2007). This can be in part due to biases in underlying meteorology, as is implied by similar biases in rainfall fields here, but the high biased lightning/rain ratio (Figures 1d and 1e) suggests that there are aditional high biases in the lightning scheme itself. Since our interest in this study is continental Africa, where the majority of people experience the impacts of thunderstorms, and here the CP4A model generally improves upon a comparable model with parametrized convection (Berthou et al., 2019; Finney et al., 2019; Kendon et al., 2019), ocean and lake results will not be discussed for the remainder of analysis. The zonal mean plot of lightning over the continent (Figure 1c) shows that there is also an overestimate of lightning between 10° and 20°S. The better representation of the zonal mean lightning/rain ratio (Figure 1f) implies that this is a result of underlying meteorology, likely due to too much deep convective rainfall compared to stratiform rainfall. Despite biases, the lightning climatological spatial distribution (Figure 1b) and zonal mean distribution (Figure 1c) of CP4A is strongly correlationed with the observational data: 0.85 and 0.94, respectively (significant at 1% level). The unique value of this data set comes from its explicit simulation of convection at high resolution over a key tropical continent, more closely linking the climate change response of relevant processes to physical laws.

We draw attention to two general features of the lightning/rain ratio analysis (Figures 1d–1f):

1. Observations show relatively high amounts of lightning in drier regions such as the Sahara (15°–30°N) and Kalahari (25°–30°S) deserts and the Arabian Peninsula. The higher lightning/rain ratio suggests that in these drier locations a large proportion of rainfall evaporates during its descent (consistent with observations of Miller et al. (2008)). This kind of lightning (sometimes called "dry lightning") carries particular risk of wildfires (Rorig & Ferguson, 1999). It has been shown that evaporation of rainfall in such dry

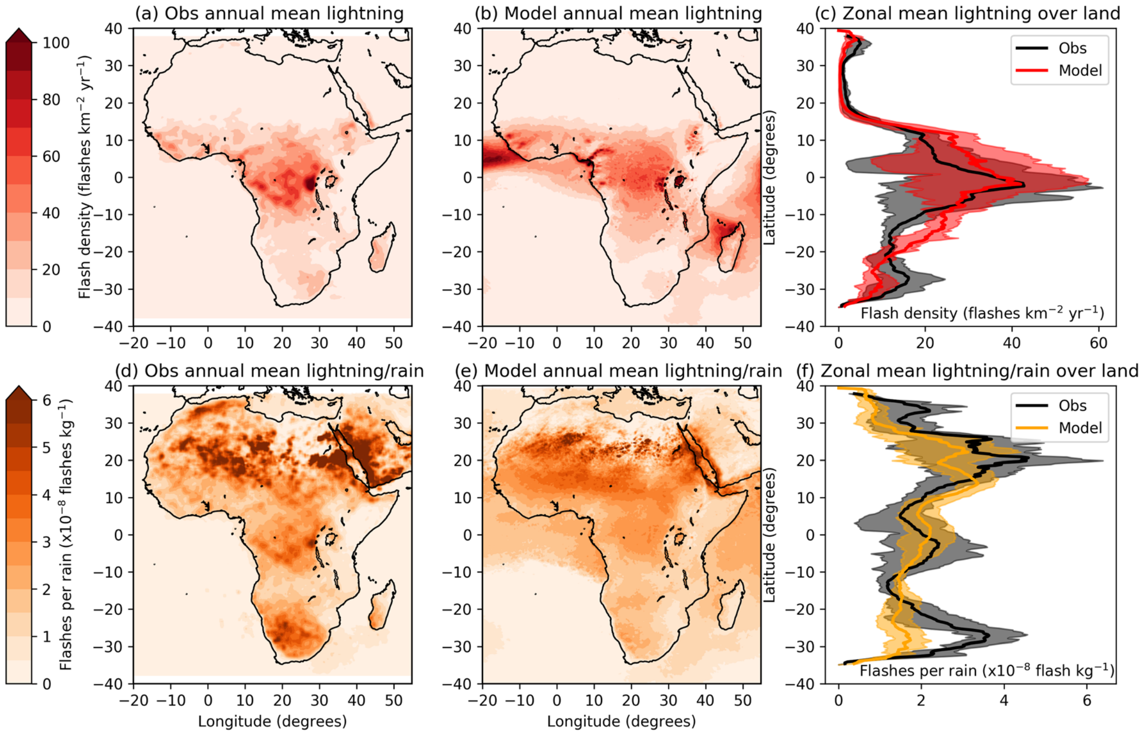

Figure 1. Evaluation of the (a–c) annual climatology lightning and (d–f) lightning flashes per kilogram of rain. Using LIS lightning (1998–2013) and TRMM rainfall (1998–2006) observations ("Obs") (section 2.3) and CP4 simulations ("Model") (March 1997 to Feb 2007) (section 2.1). Panels (c) and (f) show the zonal mean of land grid cells at each latitude, with shading to indicate the 25th to 75th percentiles of the grid cell values within the zonal band.

locations causes large cold pool dust storms in the Sahara and Sahel (Marsham et al., 2013) with lightning being a useful proxy for such dust storms (Pope et al., 2016).

2. The East African Rift Valley (30°E, 10°S–5°N) divides eastern and western equatorial Africa. The eastern region shows a much lower number of lightning flashes per rainfall (67% and 35% less than the western region in observations and model, respectively, supporting information Text S2). This is consistent with results of Field and Heymsfield (2015) who show the frequency of rainfall events originating from the ice phase has an east-west gradient across equatorial Africa ranging from 15% along the eastern coast to 85% in central Africa of rainfall events. Similar consistency exists for a north-south gradient in West Africa. The lightning-rainfall ratio is related to the ratio of cloud ice melting to form rain to total rain, thereby physically justifying the consistency between results here and those of Field and Heymsfield (2015).

It is encouraging to see that the model approximately reproduces the higher ratios in the Sahara and the Congo (10°E–30°E, 10°S–5°N), though in some other regions where lightning is underestimated there is an also an underestimation of the lightning-rainfall ratio. There are higher modeled ratios for the western Sahel (10°W–10°E, 15°N), potentially highlighting a bias in storm type for this region. Crook et al. (2019) show that the convection-permitting model has fewer organized long-lived, fast-moving storms in the Sahel compared to those in a satellite rainfall product. Such storms produce a high proportion of rainfall for the region (Crook et al., 2019), but results here suggest that they may be relatively less intense in terms of lightning activity or that the higher number of short-lived storms in CP4A, which trigger in the afternoon and evening, is too intense in terms of lightning. Overall, the CP4A model captures the broad picture of the relationship between lightning and rainfall, and we have highlighted some areas of bias which may help direct future model development.

4. Projected Change in African Lightning Under Climate Change

The future scenario here (RCP8.5) can be considered a high-end, business-as-usual case with a global mean 1.5-m temperature rise in the driving model of 5.2°C between 1997–2006 and end of century (Kendon et al., 2019). Once correcting for the small overestimation of total flashes (supporting information

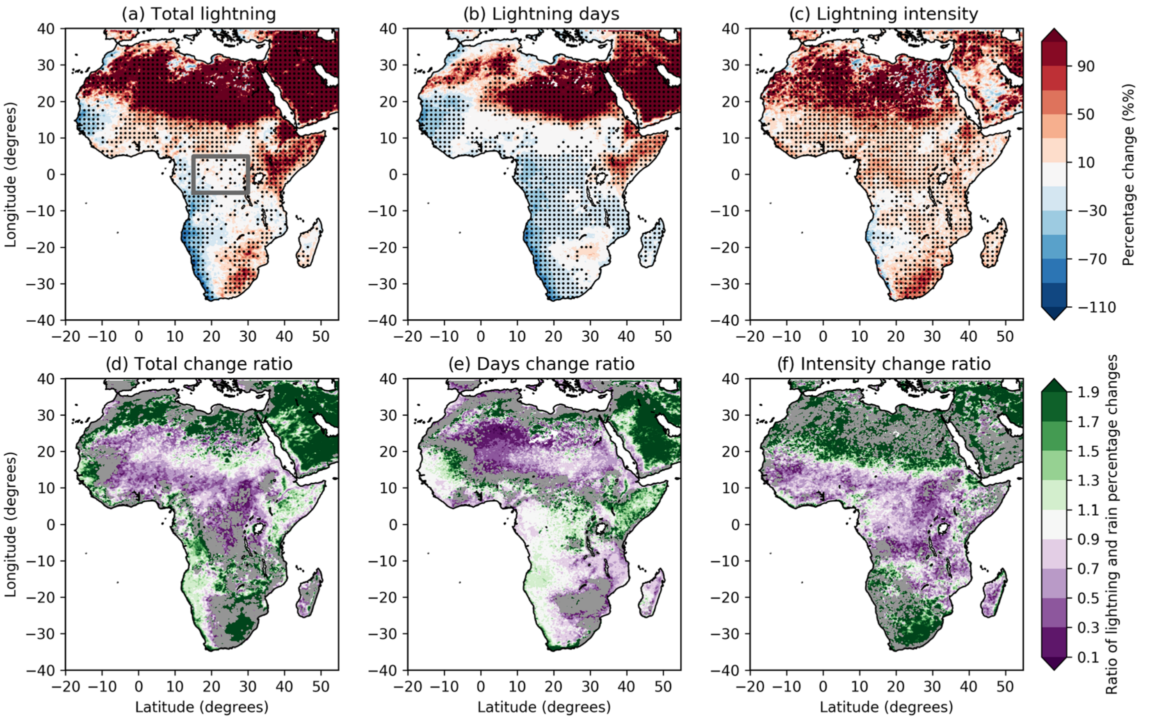

Figure 2. Percent changes in lightning (a) total, (b) days, and (c) intensity in 2100 RCP8.5, and ratios of each lighting metric percentage change to the equivalent rainfall metric percentage change. Lightning days are any day with nonzero flashes. (d–f) The changes in (a)–(c) divided by changes in the equivalent metrics of rainfall (supporting information Figure S2). Rain days are any days with greater than 1 mm/day rainfall. Rain intensity is total rain divided by number of rain days (likewise for lightning, using flashes). Stippled regions of panels (a)–(c) show significant changes at the 5% level based on a paired *t* test on the differences between the 10 annual mean values for current and future climate. Gray masks where there are opposite signs in the rainfall and lightning changes. Ocean and lake values are not plotted. Supporting information Figure S3 shows equivalent plots using an absolute scale.

Text S3), the CP4 data projects an increase of about 10^7 flashes/K over Africa. Evidence from Finney, Doherty, Wild, and Abraham (2016) would suggest that a linear relationship is likely, which as a percentage the change is equivalent to 2.3% ± 0.2% of the current climate flashes per degree warming, where the range is the standard error calculated from a bootstrap resampling of the annual mean changes. Figures 2a–2c shows the spatial change. The mean change is particularly low in the Congo (Figure 2a box, <1%/K), a region that accounts for ~20% of current climate lightning in the model and observations. Most of the continent does show an increase of the intensity of lightning on lightning days (Figure 2c), but this is offset in many locations by a decrease in the number of lightning days. The spatial distribution of lightning changes is much more complex than the results of Finney et al. (2018), who projected decreases across the entirety of equatorial Africa. This highlights the challenges of using coarse-resolution climate models with parametrizations of convection when investigating convective storms.

Whether the change in total lightning, lightning intensity, or lightning days is of more interest in a region will depend on the impact of interest. Another metric of interest is the frequency of “strong” lightning days, identified by various thresholds. Supporting information Figure S4 shows that the reduction in lightning days under climate change is predominantly from days with less intense lightning activity (≤200 flashes/cell/day), while days with more intense lightning activity (≥500 flashes/cell/day) generally become more frequent in this simulation, consistent with the intensification of storms under climate change (Finney et al., 2020; Kendon et al., 2019). Studies of the response of lightning to climate change should consider different metrics of lightning activity since, as we demonstrate here, they can respond differently.

Figures 2d–2f show the ratio of the lightning percentage change (Figures 2a–2c) to rainfall percentage change (supporting information Figure S2). The sign of lightning and rainfall change is similar in all metrics with only a few regions with a gray mask. Of the three metrics, the intensity shows the clearest difference in lightning and rainfall changes (Figure 2f). Lightning intensity changes are larger than rainfall intensity changes in more arid regions at the north and south ends of the continent (Figure 2f, green), while in more tropical regions they are less (purple). As shown in Figure 1, the more arid regions have a higher flash rate per rainfall, likely because rainfall evaporates in the dry boundary layer. Under climate change such air will be of higher temperature and could cause a greater fraction of rainfall to evaporate, thereby limiting rainfall intensity increase. Closer to the equator, lightning intensity is increasing less than rainfall intensity (Figure 2f, purple). The following section explores this further.

5. Projected Changes in Drivers of Simulated Lightning

To understand a potential driver of lightning (and rainy) day change, we consider the difference between the saturated equivalent potential temperature at 700 hPa (θ_{es}^{700}) and the equivalent potential temperature at 850 hPa (θ_{e}^{850}), which we refer to as the conditional stability (supporting information Text S4). The metric has been calculated from 3-hourly instantaneous data and averaged over all times. Supporting information Figure S5 shows the average value of conditional stability over all times to be positive, indicating an inhibition to convection on average, but as expected this inhibition is lowest where lightning days are most frequent.

Figure 3 considers the change in different variables, including conditional stability, between each month in the current climate time series and the equivalent month in the future climate simulation. The sea surface temperature monthly variability in the future climate is the same as in current climate (section 2.1), so this is an appropriate comparison. Only grid cells which had at least one lightning day in the month are included in the monthly averages, and then the averages of current and future climate were first standardized by the current climate monthly climatology.

Figure 3a shows the average lightning days across the land points in the domain decreases in many months. This decrease has a significant anticorrelation with average conditional stability, which increases in almost all months, consistent with results of Chen et al. (2020). A similar significant, but weaker, anticorrelation (Figure 3c) also exists for the Congo domain (Figure 2a, box). Supporting information Figure S6 provides maps of change of these metrics in different seasons, highlighting that such relationships are widespread.

Average lightning intensity across Africa increases (Figure 2c). A major component of the McCaul et al. (2009) scheme is the cloud graupel content (Equation 2). The maximum daily column graupel has been composited, on a grid cell basis, for days on which lightning occurs. There is a strong significant correlation between the two variables over all land points and the Congo domain, as would be expected (Figures 3b and 3d). However, the average percentage increase in lightning intensity over Africa is 28%, despite only a 17% increase in composited daily maximum column graupel content. The likely reason being that updraft velocity (the other main component of Equation 2) is also increasing, driving further increase in lightning intensity. It is not computationally practical for us to process the very large quantity of archived model level data needed to analyze the updraft velocity specifically at −15°C (supporting information Text S5), the isotherm used in the McCaul et al. (2009) scheme. However, results from Finney et al. (2020), Jackson et al. (2020), and Fitzpatrick et al. (2020) do show an increased strength of updrafts in the CP4A future simulations. Furthermore, it is generally expected that convective available potential energy, which is related to the maximum potential updraft velocity, will increase under climate change (Chen et al., 2020; Romps, 2016). There is a small contribution to the lightning scheme from cloud ice (Equation 3), but for tropical locations it is reasonable to expect this to have a minor impact on results.

Finally, we note that the percentage increase in graupel is smaller than the increase in total column water (TCW) averaged over all times (supporting information Figure S5). If we assume any changes in updraft velocity impact rainfall and lightning similarly, then the smaller change in graupel compared TCW offers an explanation for why rainfall intensity would increase more than lightning intensity within the tropical region. There are theoretical reasons to think graupel content would increase less than TCW under climate change. While both are likely to increase in response to the increasing saturation vapor pressure (O'Gorman et al., 2012), a counteracting effect of increasing freezing level height may lead to a decrease, or reduce the increase, in graupel. Graupel does increase in the CP4A model, but this may not be the case in other models since there are many other factors that affect graupel such as aerosol changes (aerosol concentrations are unchanged in the future scenario here). Clearly, there are reasons to believe that the response of graupel

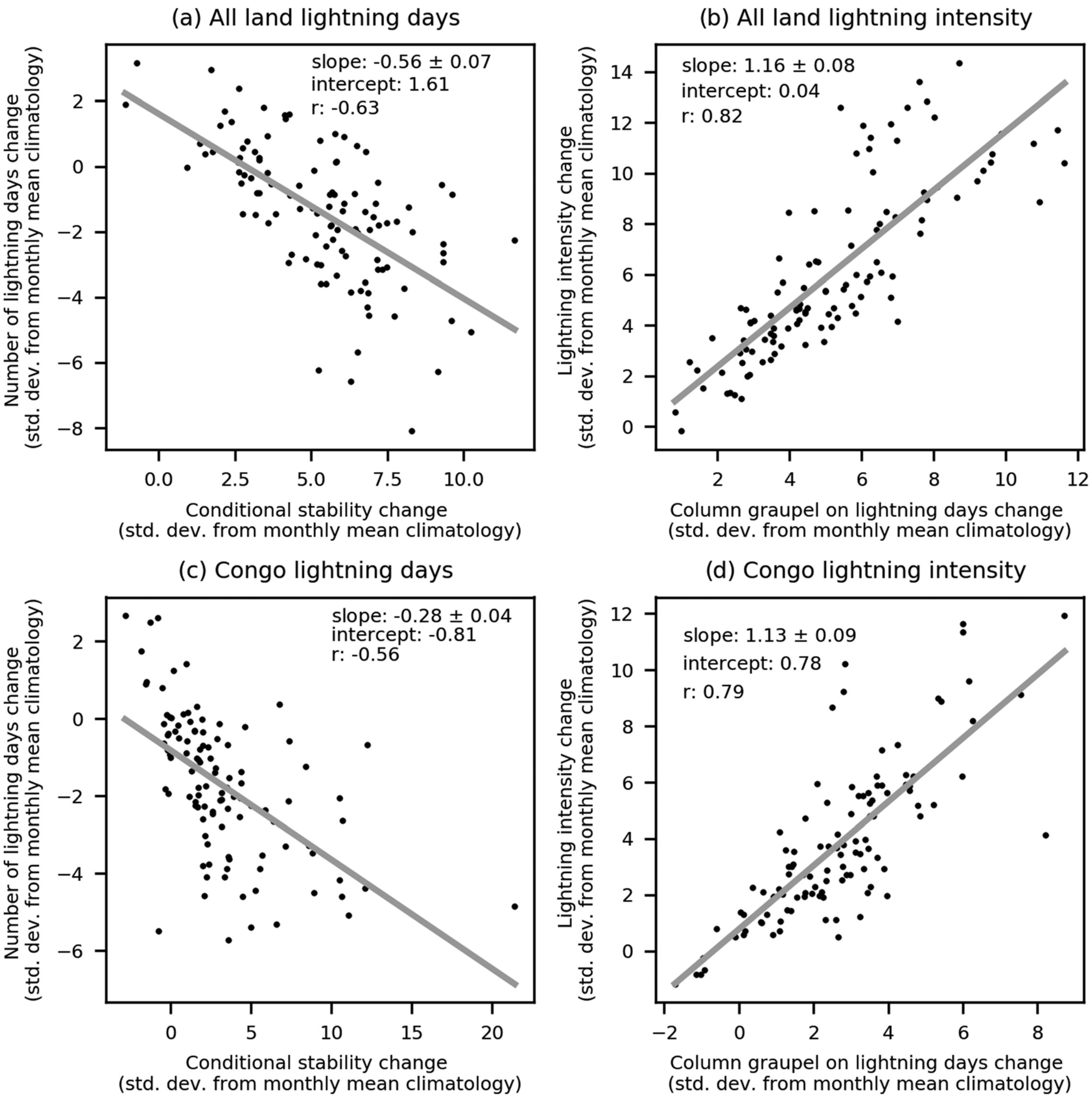

Figure 3. Average monthly future changes in number of lightning days against conditional stability and lightning intensity against daily maximum column graupel on lightning days. Conditional stability is defined as $\theta_{es}^{700} - \theta_{e}^{850}$ (section 5). Each month in the current climate time series from January 1998 to December 2006 is compared to the change in the equivalent month in the future time series. The monthly average changes are calculated from land grid cells in the (a, b) full domain and (c, d) Congo region (Figure 2a, gray box). Only land grid cells which have at least one lightning day in the month are used in averaging. The current and future climate monthly averages are first standardized by the current climate monthly climatology before calculating the future change. Gray lines and text in the panels show the linear regression of the 108 points. All Pearson correlations (r) are significant at the 5% level. The standard errors for the regression slopes are also shown in the figure text.

content, and therefore lightning intensity, to climate change is not as straightforward as the conceptual view of rain rate response.

6. Conclusions

This study provides novel insights into the nature of lightning and climate change due to its focus on the underinvestigated region of Africa, its use of new convection-permitting climate simulations, and its use of an ice-based lightning parametrization. These advanced approaches for simulating lightning are rarely present in the literature, and to date, there has been no such study over Africa.

In observations, drier regions have a higher ratio of lightning to rainfall. This is largely captured by the model and is likely a consequence of rainfall evaporating before reaching the surface. There is also a higher ratio in the Congo, a global lightning hot spot. Consistency with Field and Heymsfield (2015) suggests that this is due to the balance of cold versus warm rainfall.

Many studies of the lightning response to climate change propose that total lightning flashes increase by ~10% per degree of global warming. Using state-of-the-art climate simulations, we find that the African continent may have a much weaker response of around 2%/K. Although this varies by location, the physical mechanisms for the overall weak response are likely relevant across the tropics. The use of percentage implies this is a nonlinear response, but with only two time slice simulations, our data cannot inform on the functional form of the response, and as such we would assume linearity, given results of Finney, Doherty, Wild, and Abraham (2016). The risk of lightning to people may not only be related to total lightning; more days of lightning would likely increase exposure, but more intense thunderstorms may increase the chance of being struck during a specific event. We find that the intensity of lightning events does increase but not as much as rainfall intensity in equatorial regions (Figure 2f). And in such locations, the Congo for instance, this is offset by a reduction in the number of days with thunderstorms (Figures 2a and 2b), which arises from increased stability in the lower atmosphere (Figures 3a and 3c) under climate change inhibiting the frequency of convection. There is, however, an increase in the frequency of strong lightning days, as storms intensify.

Results presented here are based on a single model and future scenario and time slice and also use fixed aerosol concentrations. This limits the application as a projection for impact studies, and a few previous studies which used an ensemble of data (Clark et al., 2017; Finney, Doherty, Wild, Young, & Butler, 2016; Romps et al., 2014) should not be disregarded. However, it still provides unique and new information. Namely, our results show that lightning days and intensity may not have the same sign of change, and therefore, the experience of thunderstorms in Africa could change in future, even if the total number of flashes does not. These details are lost when referring to global increases in total lightning. The spatial variation in storm days and intensity cannot be ignored, as these are important for the risk to life. Furthermore, the importance of gathering lightning observations in building understanding of storms is clear, especially for aspects such as inferring the behavior of updrafts, which are difficult to observe.

Convection-permitting studies of climate change are becoming more frequent (Prein et al., 2015), and the high resolution of these models provides a good opportunity to use ice-based lightning parametrizations to simulate the lightning response to climate change. Including such lightning schemes in global models is challenging, but the use of regional higher-resolution models may be able to assist the development of approaches that can be applied at coarser resolution. Alongside this, lightning schemes which explicitly model the evolution of the electric field should be used to test the conclusions from convection-permitting models using lightning parametrizations. These lines of research are vital in order to reliably simulate the future risk of lightning strikes as well as aspects of climate change such as wildfires and tropospheric ozone.

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Data Availability Statement

The CP4A data set generated under the FCFA IMPALA project is publicly available, with currently a limited set of monthly mean variables downloadable from the Centre for Environmental Data Analysis (CEDA) archive (http://archive.ceda.ac.uk/ and search for CP4A).

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