

Inter-Annual Lightning Variability within the TRMM LIS Dataset Using an ENSO Perspective

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ABSTRACT: The Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS) was used to investigate inter-annual variability of lightning from 1998-2014 within the 38° S – 38° N range. Previous studies have indicated that the El-Niño/Southern Oscillation (ENSO) phenomenon is one significant contributor to inter-annual lightning variability, potentially the dominant mechanism on the global scale. This period of 16 years contained 4 warm- (El Niño), 8 cold- (La Niña), and 4 neutral-phase ENSO years based on the Oceanic Niño Index. Large magnitude lightning anomalies were found during the warm phase of ENSO, with mean warm-phase anomalies of $> 10 \text{ Fl (1000 km)}^{-2} \text{ min}^{-1}$ in north-central Africa and Argentina. This includes a $+35 \text{ Fl (1000 km)}^{-2} \text{ min}^{-1}$ anomaly in Argentina during the 2009 El Niño. In general, large-scale anomalies of thermodynamic properties and upper atmospheric vertical motion coincided with the lightning anomalies observed in both Africa and South America. The anomaly over north-central Africa however was characterized by a 6-week shift in the annual lightning maximum with the warm phase, a result of the more complex environmental response to ENSO over the Sahel. The most consistent ENSO anomalies with appreciable lightning were found in southeastern Africa, northwestern Brazil, central Mexico, and the southern Red Sea. Of these, all but the Mexico region had enhanced lightning with the cold phase and suppressed lightning with the warm phase.

1. Introduction

Intra-annual trends of lightning flash rate are generally quite predictable at large scales, following the environmental evolution of the local dynamic and thermodynamic conditions. Those factors control the intensity and frequency of deep convection capable of producing lightning. However, inter-annual trends of lightning activity are far less predictable at large scales, with the causes not always intuitively related to environmental shifts from one year to the next. Part of the predictability gap can be attributed to the difficulty of conducting investigations into large-scale lightning variability, associated environmental patterns, and causal mechanisms due to the limited amount of suitable climatological lightning data.

Four quasi-global climatological lightning investigations have highlighted lightning relationships with the El Niño/Southern Oscillation (ENSO), noting a wide variety of impacts dependent on the location(s) investigated and the extent of the study period (Sátori and Zieger (1999); Chronis et al. (2008); Sátori et al. (2009); Dowdy (2016)). A baseline correlation between sea surface temperature anomaly patterns in the NINO3.4 region and quasi-global lightning activity was established by Chronis et al. (2008) for the period from December 1997 - April 2006. Chronis et al. found that rainfall did not always covary with lightning activity as a result of ENSO. Dowdy (2016) built upon the ENSO/lightning correlations, finding that ENSO had the largest percentage of land area with statistically significant correlations to lightning between $\pm 35^\circ$ latitude over the period 1996-2013 when compared to several other modes of variability. Sátori et al. (2009) observed that the global lightning centroid shifted northeastward with two warm-phase events and southwestward with two cold phases, potentially indicating a relationship between ENSO and lightning production as a function of land/ocean contrast. This followed with the hypothesis of Sátori and Zieger (1999) where ENSO land surface temperature perturbations could yield shifts in large-scale lightning activity. Regional lightning shifts were also identified by Sátori et al. (2009) with zonal movements over the maritime continent and latitudinal changes in South America. They hypothesized these large-scale shifts in lightning production with ENSO could potentially be associated with shifts in atmospheric subsidence as a function of varying Hadley and Walker Cells.

Two additional global studies examined climatological trends of convection. Liu et al. (2019) investigated the intensity and size of convection within the Tropical Rainfall Measuring Mission (TRMM) domain from an ENSO perspective. They compared the horizontal size, vertical depth,

and convective vigor of TRMM precipitation features for the warm and cold phases of ENSO (using the Multivariate ENSO index) as proxies for changes in the character of deep convection. They found particularly noteworthy shifts in convective vigor with ENSO phase in north-central Africa, subtropical South America, much of the equatorial Pacific, and the Great Plains of the US into northern Mexico. In particular, they noted increased vigor during El Niño events for Argentina and the Sahel region of Africa, with reduced convective intensity with La Niña. The most noteworthy changes of precipitation feature size with ENSO phase were confined to the Pacific and the Maritime Continents. Lavigne et al. (2019) compared TRMM LIS flash rate trends with observed thunder days and mean lightning produced by TRMM precipitation features. They found generally increasing trends of thunder day occurrence for most locations including Argentina, the Amazon, and the Congo, especially during the local active convective season. However, some regions had decreasing trends of thunder day occurrence, including the Sahel and Australia. Furthermore, while most areas had strong relationships between thunder day, flash rate, flash rate density, and precipitation feature count, others had poor correlation between these inter-related parameters. This indicated that lightning production in these regions may be more complex, however it should be noted that these correlations were calculated from annual means (e.g., 16 points), which may not completely describe the patterns.

In addition to the quasi-global studies, there have been a number of shorter term and/or more regionally focused investigations that have identified some additional localized ENSO lightning responses and mechanisms, e.g., Goodman et al. (2000); Hamid et al. (2001); LaJoie and Laing (2008); Laing et al. (2008); Bovalo et al. (2012); Murray et al. (2012); Kumar and Kamra (2012); Yuan et al. (2016); Bruick et al. (2019a). In general, these studies corroborate the larger-scale investigations where applicable and supplement the lightning observations with more detailed examinations of the lightning/environment relationship for the respective subset of the global observations. Some, but not all, of these studies included the record El Niño (warm-phase) event in 1997-1998. This warm-phase event did produce large lightning anomalies, however it is uncertain just how representative those anomalies are of a typical warm-phase event. Sători et al. (2009) noted that the two warm-phase episodes that they examined (97/98 and 02/03) had generally the same sign anomalies, but the magnitudes were significantly different.

The primary focus of our study is to build on the understanding of lightning inter-annual variability and attempt to diagnose a 'typical' quasi-global (from 38° S to 38° N) lightning response to ENSO phase, then use this typical response to identify specific magnitude anomalies and potential causal environmental shifts. After examining the quasi-global patterns of lightning relationships with ENSO, this paper details four particular regions that had the largest amplitude or most consistent lightning anomalies during ENSO phases. These four regions – northern Argentina, northwestern Brazil, north-central Africa, and southeastern Africa – are listed in Table 1, along with a summary of other regions that had noteworthy inter-annual variability in the LIS lightning record.

TABLE 1. Summary of identified regions. Bold locations are discussed in the text.

Locations	Classifications	Anomaly (Fl (1000km) ⁻² min ⁻¹)	Figure
Argentina	Warm phase enhancement, cold phase suppression	+17/-7; +35 in Jan of 2010	6a
Brazil	Cold phase enhancement, Warm phase suppression	+3/-5	6b
North Central Africa	Warm phase enhancement, seasonal shift	~Sep max in warm phase, ~July max in cold phase	6c
Southeastern Africa	Cold phase enhancement, Warm phase suppression	+2.5/-3.5	6d
S. Mexico	Warm phase enhancement, cold phase suppression	+6/-4.5	S1a
Iraq	Warm phase enhancement, cold phase suppression	+3/-2.5	S1b
S.W. Africa	Warm phase enhancement	+5	S1c
N. Australia	Cold phase enhancement, Warm phase suppression	+3/-7.5; +20 in Oct 1998	S2a
Red Sea	Cold phase enhancement, Warm phase suppression	+3/-5	S2b
E. Equatorial Atlantic	Cold phase enhancement, Warm phase suppression	+2.5/-3.5	S2c
E. China	Possible warm phase enhance- ment	Not Consistent	S3a
Sydney, Australia	No discernible link to ENSO	+24 in Jan 2004	S3b
Cuba	Possible warm phase suppression	Not Consistent	S3c
Pakistan	No discernible link to ENSO		S3d
S.W. Atlantic	No discernible link to ENSO	Large inter-annual variability	S3e
Thailand	No discernible link to ENSO	Ambiguous ENSO signal	S3f
Bhutan	Possible warm phase enhance- ment; Anomaly in 2010	+38 in Apr 2010	S4a
N.W. Mexico (Baja)	Anomaly in 2000	+25 in Jul 2000	S4b
Bermuda	Anomaly in 1998; slight warm phase suppression	+16 in May 1998	S4c
Panama	Slight warm / cold phase enhancement/suppression	+20 in Jun 2012	S4d

2. Data

The lightning data presented in this study were from the TRMM Lightning Imaging Sensor (LIS). The LIS was a passive optical instrument in low Earth orbit from late 1997 to early 2015, sampling the domain between $\pm 38^\circ$ latitude with an estimated total lightning detection efficiency between 65-70% (Katrina Virts 2022, personal communication). During an orbit, a given location would remain within the field of view for ~ 90 seconds, and the full diurnal cycle for a location was sampled every ~ 49 days. Additional details of the LIS instrument are given by Boccippio

et al. (2002). It is important to note that despite the LIS dataset spanning a 17-year period, the accumulated LIS observation duration at any location was on the order of a few hundred hours (~ 200 near the equator, ~ 450 near the inflection points), or roughly 0.2% of the full length of the study period (Cecil et al. (2015)). Thus the LIS data may be considered a representative sample of the study period lightning patterns, but not a complete lightning record. This sampling issue is an unavoidable limitation when using the LIS data to relate lightning production to environmental conditions. However, the TRMM LIS dataset is the longest duration and most spatiotemporally consistent lightning record from a quasi-global perspective that is currently available.

The primary lightning datasets are the Low-Resolution [Monthly] Time Series (LRTS, LRMTS; Cecil et al. (2014); Cecil et al. (2017)). The LRTS is derived from the LIS observations and is a daily, smoothed, $2.5^\circ \times 2.5^\circ$ gridded climatological lightning product, with boxcar smoothing over 7.5° and two LIS diurnal sampling periods (99 days) before a low pass digital filter was applied (Cecil et al. (2017); Cecil et al. (2014)). As such, the LRTS represents a moving seasonally-averaged flash rate density, with separate entries for each day. The LRMTS is then extracted from the LRTS using the methodology of Cecil et al. (2014), with the exception that the LRMTS herein only contains LIS data rather than incorporating the OTD for the early LIS years. The LRTS was used to detail the lightning temporal patterns while the LRMTS was used for comparisons to the Oceanic Niño Index (ONI) and environmental data. The Low Resolution Diurnal Climatology (LRDC) was used to determine the peak lightning production time of day for each location.

While additional lightning datasets were available for portions of the TRMM LIS period, the present study elected to focus exclusively on the TRMM LIS due to the longevity and consistency of its record, as well as to eliminate inter-instrumental comparisons. In particular, we chose to avoid methods with uneven geographic or temporal detection efficiencies, such as ground networks or weather observation stations. Furthermore, the Optical Transient Detector (OTD) was avoided due to the roughly halved detection efficiency and substantial impacts of the South Atlantic Anomaly when compared to LIS (Christian et al. (2003)). The LIS on the international space station (ISS) was briefly examined to potentially extend the spatial and temporal coverage of the study (Lang (2022)). The five full years of ISS LIS data available contained 3 cold-phase years and only one warm phase, which limited the ENSO investigations that could be conducted. Furthermore, despite ISS LIS being a copy of TRMM LIS, it does have additional limitations due

to its platform such as solar panel/radiator obscuration and occasional orbital variations, which may introduce spatiotemporal patterns (Timothy Lang 2023, personal communication). ISS LIS also has a reduced detection efficiency compared to TRMM LIS by $\sim 5\%$ (Katrina Virts 2023, personal communication). Ultimately, with the limited record from ISS LIS, notable differences between the LIS instruments, and lack of a published climatological ISS LIS product, the present study limited in-depth analysis to the TRMM LIS patterns alone. Further investigation of the ISS LIS from an inter-annual perspective is planned in the near future.

Besides the gridded flash rate products, orbit-level lightning flash data from LIS (Blakeslee et al. (1998)) were used for computing ENSO-specific flash rate climatologies, frequency of thunderstorm occurrence, and conditional flash rates from methodologies similar to those described by Cecil et al. (2014, 2015). These ENSO-specific lightning climatologies are described further in the ONI methodology section. The conditional flash rate (consisting of only satellite overpasses that had lightning present within a grid box) is a proxy for the vigor of thunderstorms, as distinct from the number of thunderstorms. The conditional flash rate here is computed only from overpasses that observe a given 0.5° grid box for at least 80 s, i.e., a nominal overpass of the grid box for LIS. The flash count for each of these overpasses is scaled by the diurnally-varying LIS detection efficiency, then averaged for the overpasses with nonzero flash counts (Boccippio et al. (2002); Cecil et al. (2014, 2015)). This averaged conditional flash rate is then scaled from the 0.5° grid box size and the mean observation duration (usually around 90 s) for the grid box to a uniform 3000 km^{-2} area and 60 s duration, then smoothed to a 2.5° grid. A caveat to the conditional flash rate is that it is very sensitive to low mean flash rates and to low sample times. Therefore it is masked herein only where Fig. 1c is greater than $0.1 \text{ FI (250km)}^{-2} \text{ min}^{-1}$. It also excludes a region in proximity of the South Atlantic Anomaly where the number of acceptable overpasses with sufficient observation time is sometimes (substantially) reduced. More details about the conditional flash rate and the unit approximation are available from Cecil et al. (2015).

The Oceanic Niño Index (ONI), calculated using the Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5) and downloaded from the Climate Prediction Center (CPC), was used for ENSO phase (Huang et al. (2017)). The ONI is the mean monthly sea surface temperature anomaly from the 30-year mean within the NINO3.4 region (5°N - 5°S ; 120 - 170°W), with a 3-month boxcar averaging. An ENSO event is classified as 5 or more consecutive months with an

anomaly of at least $\pm 0.5^{\circ}$ C, following the CPC definition (Larkin and Harrison (2005)). This definition was used to calculate the ENSO-specific climatologies.

Environmental data were from the ERA5 reanalysis product derived from the ECMWF (Hersbach et al. (2020)). There were two datasets used: a monthly, 2.5° resolution format that was spatiotemporally smoothed to match the lightning products; and an hourly 0.25° dataset pulled for one time each day which corresponded to the peak lightning hour within the diurnal cycle for each of the four primary locations. These data were used to identify the environment that would be most closely associated with the deep convection. While these hourly reanalysis data were unable to resolve thunderstorm-scale environments, they do provide far more detail than the monthly averaged and seasonally smoothed data. For example, in order to find a value of CAPE that may be representative of the potential thunderstorm environment, we use the 90th percentile value at the time of climatological peak lightning activity each day. I.e., if lightning peaks near 00 UTC in a region, and that region contains 2400 reanalysis grid cells, then we use the 240th-highest CAPE value within that region at 00 UTC each day, and average the resulting daily values for warm-phase, cold-phase, and neutral-phase years. This approach avoids damping the values by averaging over the entire region or over the entire diurnal cycle, but also avoids the noisy and unrepresentative results from focusing on daily extrema. The monthly data however were much better suited for displaying the general synoptic scale environmental shifts that occur with ENSO. Twenty-eight total variables from the ERA5 were examined in relation to ENSO and lightning: 24 downloaded directly from the Copernicus Climate Data Store (CDS) and 4 which were calculated from the other products. The calculated products were a vertical profile of virtual temperature, zonal and total bulk wind shear, and total column saturation fraction.

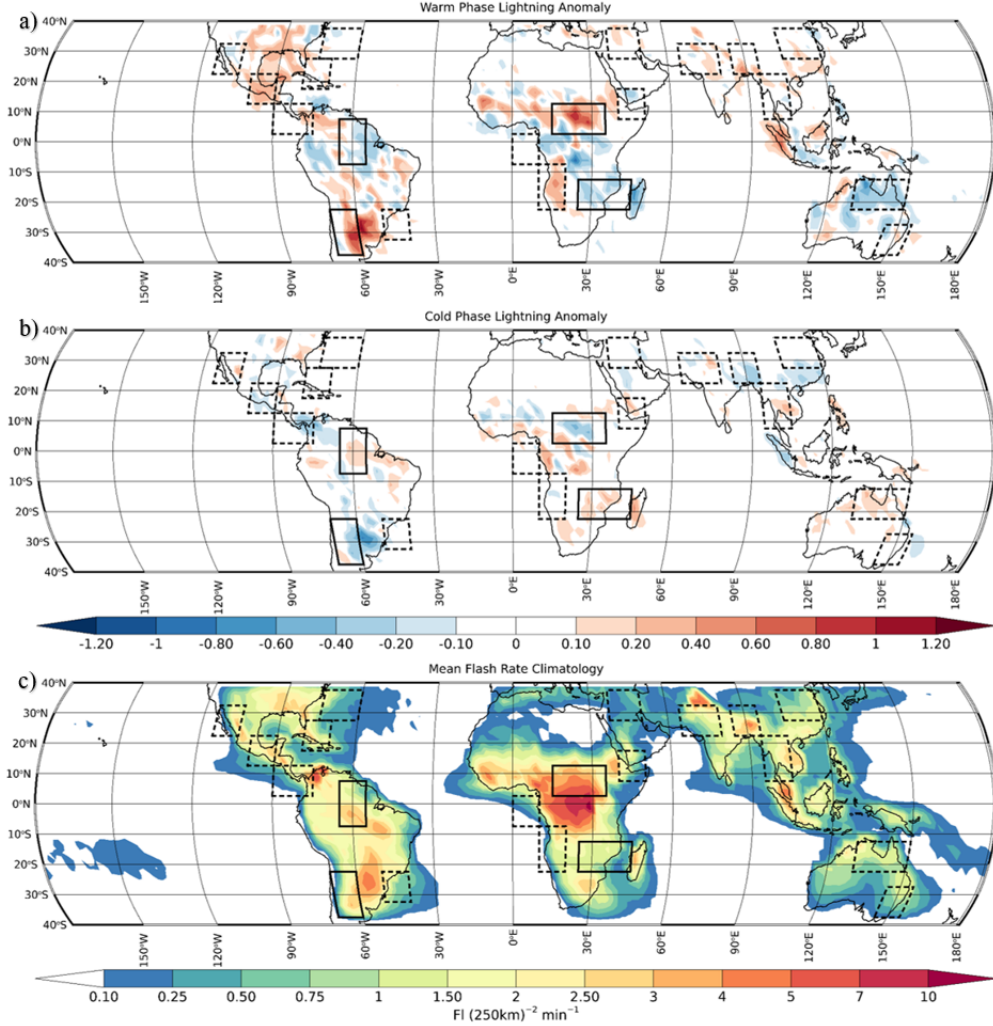


FIG. 1. Lightning flash rate density anomalies for the (a) warm phase and (b) cold phase, and (c) the mean study period flash climatology, all in $\text{Fl (250 km)}^{-2} \text{ min}^{-1}$. Anomalies are computed for each month relative to the mean flash rate density for the corresponding month from the full 16-year study period, then those anomalies are averaged for all ONI warm-phase (a) or cold-phase (b) periods. The boxes represent the 20 identified regions in Table 1- the solid boxes are the primary regions discussed in this study.

3. Methods

Lightning anomalies for each month were computed relative to the mean annual cycle, and then those anomalies were averaged for all warm-phase Fig. 1a and cold-phase Fig. 1b months (the asterisks in Fig. 2). These patterns are shown using units of $\text{Fl (250km)}^{-2} \text{ min}^{-1}$ to represent the grid box size. Anomalies of environmental parameters were treated similarly, with mean anomalies

computed relative to the mean annual cycles of those parameters (Table 2). The correlation analysis was completed using the anomaly time series, in an effort to remove as much of the seasonality as possible and directly compare the ONI (an anomaly) to the lightning anomaly. There are some associated caveats with this approach: potential lagged relationships between ONI and lightning are not accounted for; there were two instances of cold-phase events spanning multiple years which could introduce other inter-annual variability; and mean values taken over the full study period are biased toward the cold phase.

The time series of lightning and environmental data were then partitioned into ENSO years (EYRs). Herein an EYR is simply a redefined calendar year spanning April - March to capture individual ENSO episodes within a single year, framed around the preferential ENSO start/end period (Trenberth (1984); Trenberth and Caron (2000)). The ONI was used to then classify each EYR in order to group similar ENSO events together and examine the annual patterns at a regional resolution. The study period was thus defined using the available lightning record and the EYR framework as April 1998 - March 2014, a total of 16 EYRs. This methodology does introduce some ambiguity in the MAM season around the start of the EYR, however the intent of using this was similar to the usage of a 'water year' and was simply meant to group similar events together and compare their annual cycle. An EYR was designated as either warm- or cold- phased if, within it, the CPC criteria for an ENSO episode were met- otherwise the year was classified as neutral- 'phase' year. This approach allows for a thorough examination of the inter-annual patterns including a comparison of like-phased events as well, e.g., the two periods where the ONI met the CPC definition of a cold phase continuously for consecutive years.

The TRMM LIS period ultimately consisted of 4 warm- (2002, 2004, 2006, 2009) and 4 neutral- (2001, 2003, 2012, 2013) phase EYRs, with 8 cold- (1998, 1999, 2000, 2005, 2007, 2008, 2010, 2011) phase years rounding out the study period (Fig. 2). The average ONI magnitudes for the phases were $+0.61^{\circ}\text{C}$, -0.08°C , and -0.79°C respectively. An important note about the warm-phase years in this study is that all four of them were consistent with Central Pacific or 'warm pool' type ENSO events (Larkin and Harrison (2005)). The differences between conventional ENSO episodes (such as the 1997/98 or 2015/16 El Niño) and Central Pacific events are still not fully understood and could result in ENSO anomalies that do not necessarily represent all ENSO episodes (Larkin and Harrison (2005); Capotondi et al. (2015)). This study does not distinguish between ENSO

TABLE 2. ENSO environmental anomalies (presented as a percentage of standard deviation) from monthly mean ERA5 environmental variables. This is computed individually for each 2.5° grid point across each full region then averaged into one value for a season centered on the peak lightning anomaly times of both the warm and cold phases (if different) for Brazil, Argentina, and Southeastern Africa. The warm- and cold-phase anomalies in north-central Africa are both valid at the time of the warm-phase anomaly.

	Argentina		Brazil		N. Cent. Africa		S.E. Africa	
	Warm	Cold	Warm	Cold	Warm	Cold	Warm	Cold
CAPE	97	-66	-57	66	36	8	-46	35
CIN	-33	31	81	-39	81	-42	58	-44
Z 500hPa	24	-20	46	-45	57	-51	64	-43
Z 850hPa	-61	56	21	-49	42	-70	64	-40
ω 500hPa	-52	-3	94	-50	53	-64	85	-45
ω 850hPa	-26	15	-35	22	28	-14	80	-28
q 500hPa	31	-49	-53	23	1	23	-17	5
q 850hPa	76	-60	-48	36	36	-11	-8	9
Tv 500hPa	41	-73	58	-41	6	-3	41	-21
Tv 850hPa	27	-45	40	-9	77	-29	-16	4
TT Index	-9	16	-81	67	128	-47	-59	35
K Index	5	-13	-88	56	96	-15	-21	15
Tot. Precip	77	-48	-86	56	-57	57	-70	36
Conv. Precip	93	-56	-87	53	-42	57	-70	38
MSLP	-54	62	-25	-18	0	-46	54	-33
Sat. Fraction	62	-23	-78	36	-63	42	-10	10
Tv SFC	9	-37	69	-33	81	-36	23	-15
Bulk Wind Diff	67	-35	81	-49	-54	0	-9	-8
LRMTS	95	-42	-47	24	78	-23	-49	35

types or magnitudes when grouping events due to low sample size and no available conventional warm-phase events. There is very little LIS coverage of conventional warm-phase events from either instrument, with TRMM LIS observing the tail end of the '97/98 event and the '15/16 event falling between TRMM and the LIS on the ISS.

The individual EYRs were then manually examined for 5° x 5° grid boxes. Regions were subjectively identified where a group of at least four contiguous grid boxes (i.e., at least 10° x 10°) had consistent patterns of lightning production, seasonality, and inter-annual variability. The lightning time series for these regions are shown in $\text{Fl (1000km)}^{-2} \text{ min}^{-1}$ to reflect their averaged area. These regions do not necessarily outline the largest anomalies in Fig. 1, because of the requirements for consistent seasonality and inter-annual patterns within a region. Only regions

averaging at least $0.1 \text{ FI (250 km)}^{-2} \text{ min}^{-1}$ were considered, which eliminated about 62% of the LIS domain (including most ocean areas) from this part of the analysis. This constraint was put into place to mitigate the influence of LEO sampling from LIS and the subsequent smoothing into a climatological dataset, the effects of which can be most pronounced in regions with little lightning production. A subjective approach was favored because the sporadic nature of lightning activity, in conjunction with the observational constraints of a low Earth orbit sensor and intra-annual variability of ENSO impacts, could mask valid signal in a more objective correlation analysis. Additionally, it allowed for identification of a wider range of meteorologically/climatologically significant lightning patterns, e.g., substantial changes in lightning production for a location.

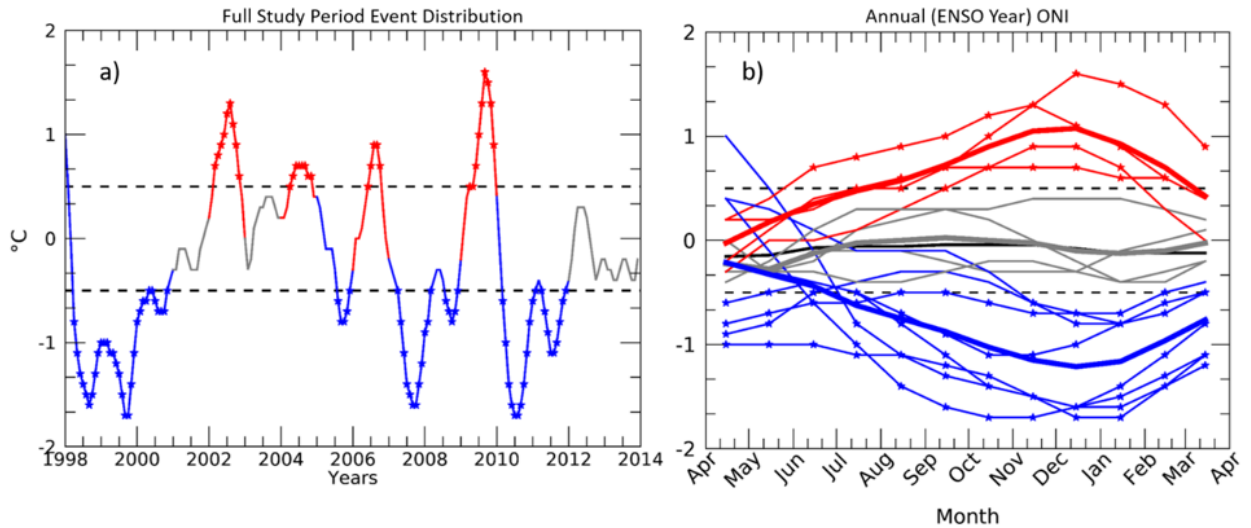


FIG. 2. ONI time series for the study period over (a) the full time period and (b) individual ENSO Years (EYR). Red lines indicate warm-phase ENSO Years, blue lines indicate cold-phase ENSO years, and gray lines indicate neutral ENSO years. Thick lines represent the mean values for each ENSO phase, and the dashed lines represent $\pm 0.5^\circ \text{C}$. Asterisks indicate months where the CPC criteria for an ENSO event are satisfied within an ENSO Year.

A region was classified as an ENSO study area if at least 75% of the corresponding phase years (i.e., 3 warm-phase or 6 cold-phase years) were enhanced/suppressed within the same season of the annual cycle. There was no specific magnitude threshold for an ENSO anomaly pattern to be considered. As such, there was some room for interpretation as to which phase years were notably affected by ENSO, especially given the relatively few warm-phase years within the study period.

However, the ENSO regions generally had good agreement for both magnitude and timing for at least 75% of the phase years. The criteria for a singular anomaly event were more straightforward, using either an instantaneous anomaly in lightning production of at least 75% for the region and/or an anomaly of at least $\pm 15 \text{ Fl (1000 km)}^{-2} \text{ min}^{-1}$ from the mean annual cycle at that instant. All identified regions are described in Table 1, with the top four entries (in bold) being the primary regions discussed in this paper. All regions are included in Fig. 1 and Table 1 as they each may merit further investigation- but for a succinct and compelling discussion, only the most consistent and highest magnitude ENSO anomalies are analyzed herein.

Ultimately, there are multiple assumptions employed or caveats associated with any attempted approach to diagnose near global lightning variability, especially with regard to an irregular phenomenon such as ENSO, over a long period. These often correspond to handling data gaps or evolving detection abilities, and how the detection abilities of one instrument compare with another at different places or times. Given the near-uniform spatiotemporal detection efficiency of TRMM LIS, the most significant caveat associated with the data itself is from the LEO sampling. Within this study, we have assumed that the heavy smoothing and coarse spatial resolution of the climatological lightning products are able to generally mitigate the LEO sampling biases enough within regions of appreciable lightning production to allow for synoptic-scale spatiotemporal trends to be observed. This assertion is corroborated by the generally good agreement between climatological lightning products from LIS and ground networks within regions for which said networks have a nominal network of sensors. An additional caveat is that this study utilized a subjective methodology to identify study areas rather than focus exclusively on the correlation analyses to diagnose ENSO sensitivity. While the general agreement between the two methods is good (i.e., most subjectively identified ENSO regions also have some patch of significant ONI correlation within them), we demonstrate that this subjective approach allows for a wider and more thorough examination of potential ENSO teleconnections and highlight patterns that correlation analyses can overlook. It also provided a way to examine additional lightning variability controls and test the previous assertion that the smoothing applied to the LIS data are sufficiently handling the LEO sampling.

4. Results

The largest phase anomalies observed were in the warm phase of ENSO (Fig. 1a) over Argentina ($+1.25 \text{ Fl (250 km)}^{-2} \text{ min}^{-1}$) and the southern Democratic Republic of the Congo ($-0.95 \text{ Fl (250 km)}^{-2} \text{ min}^{-1}$), equating to relative anomalies of roughly +46% and -22% of the mean annual flash rate density at those locations. Broad lightning enhancements during the warm phase are also found between the African Sahel and tropical rainforest, across much of China, Mexico, the Gulf of Mexico, the southern plains in the US, and the Himalayas. Gross cold-phase lightning enhancements (Fig. 1b) were not as large, and were generally confined to the Southern Hemisphere in Africa, Australia, and northeastern Brazil. The largest cold-phase enhancements were found over the Democratic Republic of the Congo and Madagascar at $+0.52$ and $+0.46 \text{ Fl (250 km)}^{-2} \text{ min}^{-1}$, and the largest cold-phase suppressions were found in Argentina $-0.82 \text{ Fl (250 km)}^{-2} \text{ min}^{-1}$ (Fig. 1b).

A number of these locations did have statistically significant Pearson correlations ($p \leq 0.01$) between the monthly lightning anomaly and the ONI, as shown in Fig. 3. The largest region of significant correlations in Fig. 3 exists in the central and western Pacific, in the general region of the most direct ENSO influence. Over land, regions of statistically significant correlations occur over Australia, the Middle East, South America, and southeastern Africa. Broad conditional flash rate anomalies (Fig. 4a-b) were generally confined to the Sahel, Central America/Gulf of Mexico, Argentina, and the Himalayas with increased convective strength in the warm phase and decreased convective strength with the cold phase. Percentage of observations with lightning (Fig. 5) displayed broad regions of increased thunderstorm frequency in Central America and southern North America, the Gulf of Mexico, the Sahel, and the eastern Indian Ocean/Sumatra during the warm phase. Cold-phase enhancements of thunderstorm frequency were found in central Australia extending north into the Philippines, southeastern Africa, and northeastern Brazil into the Caribbean.

From the quasi-global patterns four primary regions were identified- Argentina, northwestern Brazil, North-central Africa, and southeastern Africa, which are shown with the solid black boxes in Figs. 1, 3, 4, and 5, and time series of their lightning patterns are shown in Fig. 6. Argentina has a substantial warm-phase enhancement of lightning (Fig. 6a), driven by a large anomaly in January of 2009. Northwestern Brazil (Fig. 6b) and southeastern Africa (Fig. 6d) have enhancements

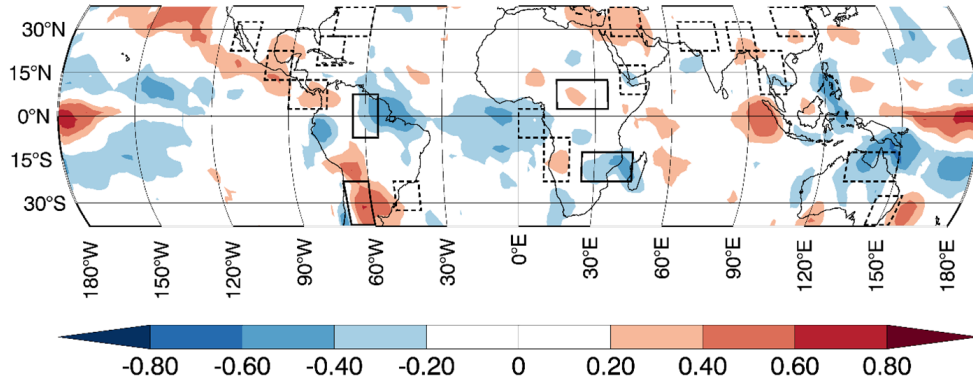


FIG. 3. Zero-lag Pearson (linear) correlation map between the monthly lightning (LRMTS) anomaly and the ONI for the study period; $p \leq 0.01$ (shaded).

of lightning during the cold phase that were smaller in magnitude than Argentina but displayed a clean separation between the warm- and cold- phase years. North-central Africa (Fig. 6c) has an overall enhancement of lightning during the warm phase, which manifests as a shift in seasonality. These results are described further in the discussion. In addition to the four primary regions, 16 other areas with notable patterns of inter-annual lightning production were identified, as shown by the dashed boxes in Figs. 1, 3, 4, and 5 and described in Table 1. Their annual lightning patterns are shown in supplemental figures 1-4. These locations may merit future further study to evaluate ENSO teleconnections (e.g., Southern Mexico; Australia; Iraq; Red Sea), additional controls on inter-annual lightning production across the globe (e.g., Cuba; Thailand; Northwest Mexico), and also the potential impact that irregular LEO sampling may have on a lightning climatology (e.g., Bhutan; Southwest Atlantic).

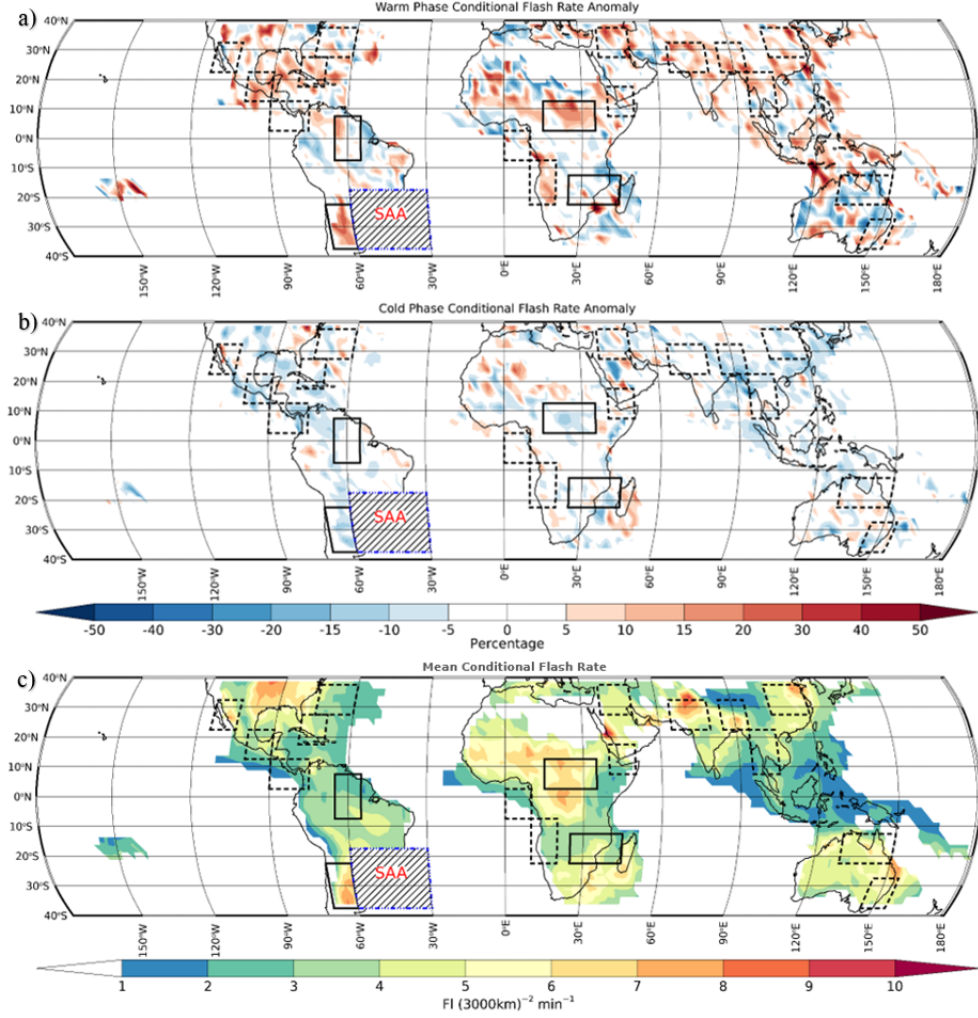


FIG. 4. Conditional flash rate anomalies for (a) warm ENSO Years and (b) cold ENSO Years as a percentage of (c) the mean study period conditional flash rate. Due to the sensitivity of the conditional flash rate to small mean flash rates, areas with a mean flash climatology in Fig. 1c of less than $0.1 \text{ FI (250 km)}^{-2} \text{ min}^{-1}$ have been masked out of (a) and (b). A portion of the SAA region is also masked out as shown due to a limitation of view-time from the LIS instrument in that area.

5. Discussion

a. Overview of Lightning Anomalies

Within the LIS domain, a northward trend of lightning production was observed with the warm phase during the SON season, driven in large part by the shift of the lightning max in Africa northward into the Sahel. A southward shift was also observed with the cold phase from the

335 Congo, Australia, and southeastern Africa. South America opposed this trend, with increased
336 lightning observed around Argentina and decreased lightning in the Amazon during the warm
337 phase, which is flipped during the cold phase. These large-scale results are consistent with Satori
338 et al. (2009). Broad anomalies of lightning production with ENSO phase were generally noted in
339 some of the same locations as previous studies, e.g., the Gulf of Mexico and surrounding areas;
340 southeast Asia; and Australia in particular. Southwest Africa also had a region of warm-phase
341 enhanced lightning similar to Dowdy (2016), however this region was far smaller than what was
342 observed from their study.

343 Warm-phase anomalies were, on average, larger than those from the cold phase. However, some
344 portion of the magnitude differential between the phases for the climatology maps is explained by
345 the inherent bias in the study period toward cold phases, as half of the study period was classified as
346 ENSO cold phase. In other words, Fig. 1c includes twice as many cold-phase years as warm-phase
347 years, and thus anomalies calculated from it should be smaller during the cold phase and larger
348 during the warm phase for locations with ENSO sensitivity. Additionally, Fig. 1 does not take
349 into account seasonal differences in response to ENSO phase, which could reduce potential annual
350 anomalies. However, this does not appear to play a significant role for most locations, potentially
351 because the anomaly maps are calculated only from periods where the CPC criteria for an ENSO
352 episode are satisfied.

356 Correlations between the lightning anomaly and the ONI are comparable to previous literature,
357 which was to be expected given the similarities in datasets used. The departures from prior studies
358 include the lack of a negative correlation in the southwestern US, broad positive correlation in
359 southeast Asia, and the lack of a positive correlation in southwestern Africa. Additionally, Dowdy
360 did not show the negative correlation spanning much of Australia that both Figure 3 and Chronis
361 et al. displayed. Period of record differences, especially pertaining to the inclusion of the extreme
362 El Niño in 1997/1998, are likely the cause of this divergence, although the different calculation
363 methods are also contributing. Some of the contrast could also be due to the reduced observational
364 capabilities of the Optical Transient Detector (OTD) versus the LIS, as any observations prior to
365 1998 in the studies by Chronis et al. and Dowdy originate from the OTD.

366 There are multiple factors that could limit the magnitudes of correlations between ONI and
367 observed lightning rates. The most likely factors are sampling biases, lagged relationships between

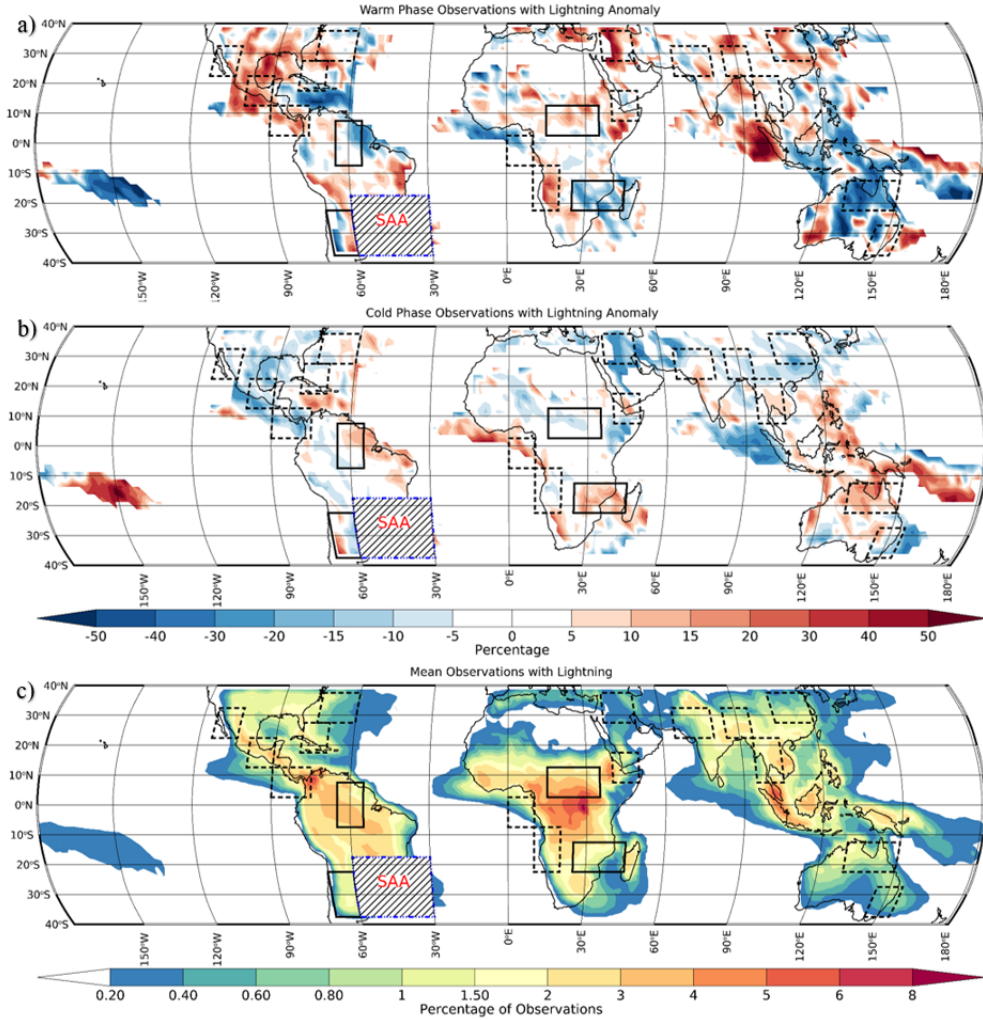


FIG. 5. Percentage of observations with lightning, anomalies for (a) the warm phase and (b) the cold phase, expressed as a percentage of (c) the mean study period percentage of observations with lightning. Both (a) and (b) are masked where the mean (c) is less than 0.2%. The SAA is also masked out as shown.

lightning and ONI, and the nonlinearity of the response to ONI in years having the same phase. Some regions, such as the western Pacific near the Philippines and the Red Sea / Horn of Africa, seem to have opposite signed responses to the same ENSO phase at different times in the year. These sign reversals could reduce the strength of the lightning/ONI correlations. Additionally, there are likely multiple other contributing factors to lightning production at each location, varying independently from ENSO. This is particularly true for the two cold-phased events that span multiple years (98-01 and 10-11). While no other single mode of inter-annual variability was quite

as prominent as ENSO, Dowdy (2016) did note several other influential factors or combinations of factors for certain regions.

The variations in flash rate on the scales considered here could result from differences in the number, spatial extent, or vigor of individual thunderstorms, or some blend of these attributes. Cecil et al. (2015) displayed mean quasi-global patterns of the frequency of thunderstorm occurrence, and the conditional flash rate when thunderstorms do occur. Fig. 4c similarly plots conditional mean flash rates, with percentage anomalies for the ENSO warm phase in Fig. 4a and cold phase in Fig. 4b. Figure 4c bears a strong likeness to an alternate lightning intensity calculation method using TRMM precipitation features by Lavigne et al. (2019). In general, higher conditional mean flash rates can be indicative of stronger thunderstorms.

Notable regions with conditional flash rate anomalies include the Sahel and much of north-central Africa (stronger thunderstorms in the warm phase), Argentina (stronger thunderstorms in the warm phase), the southeast and mid-Atlantic US (stronger thunderstorms in the cold phase), south-central Mexico and the Gulf of Mexico (stronger thunderstorms in the warm phase), the western Himalayas (stronger thunderstorms in the warm phase), and Australia (stronger thunderstorms in the cold phase). Most of these locations all had conditional flash rate shifts that aligned with the observed total flash rate changes with ENSO in Fig. 1, with the notable exception of the southeastern US. Those found in Argentina and north-central Africa with the warm phase and in Argentina and the US for the cold phase represent the largest magnitude anomalies. These locations have some of the highest mean conditional flash rates, and the anomalies were generally found along gradients in conditional flash rate from Fig. 4c, indicating a slight geographic shift in the conditional flash rate.

Conditional flash rates can be paired with the percentage of observations with lightning (Fig. 5), to determine if changes in storm intensity or frequency explain the shift in flash rate density. The percentage of observations with lightning in Fig. 5 is indifferent to flash rate and is simply a measure of how often thunderstorms are observed in each grid box. Unlike the conditional flash rate, regions with the most frequent thunderstorms are generally confined to the deep tropics, with a maximum in central Africa (Fig. 5c). The ENSO anomalies of thunderstorm occurrence are much more cohesive than anomalies of conditional flash rate. Spatially continuous patterns depict more thunderstorms in the warm phase across parts of the Middle East, Central America, the Gulf

of Mexico, and more storms in the cold phase across much of northern and central Australia, the Caribbean, northeastern Brazil, and southeastern Africa. These anomalies tend to be more mirrored between the phases than either the flash rate or conditional flash rate, which is also reflected in their correlations to the ONI (Fig. S5).

Most regions that have a noticeable ENSO-related increase in thunderstorm occurrence also have a noticeable increase in conditional flash rate for the same ENSO phase, e.g., south-central Mexico, Australia, the Gulf of Mexico, and north-central Africa. This indicates that the flash rate density anomalies in Fig. 1 are mostly driven by a combination of both more storms and more intense storms during the same ENSO phase. Regions with conflicting anomalies of thunderstorm occurrence and conditional flash rate are not as pronounced. The most noticeable example may be the southeastern US (stronger but overall fewer thunderstorms during the cold phase, comparing Figs. 4a and 5a). As a result, the total lightning anomaly is near zero there for the cold phase.

6. Regional Analyses

The four selected regions represent some of the strongest and most consistent ENSO teleconnections found in the TRMM LIS record. The north-central Africa and the Argentina regions are two of the highest lightning producing locations in the TRMM domain. The southeastern Africa region has not been discussed as a lightning teleconnection to ENSO, yet displayed a consistent sensitivity. The percentage anomalies discussed in this section and listed in Table 2 are expressed as a percentage of the standard deviation (σ) for the month in the annual cycle when the respective phase anomaly peaked. For example, imagine a warm-phase flash rate anomaly that peaks in September for a given region with a magnitude of $+9 \text{ Fl (1000 km)}^{-2} \text{ min}^{-1}$ more than the mean September flash rate. If the standard deviation for all September lightning is $12 \text{ Fl (1000 km)}^{-2} \text{ min}^{-1}$, then that anomaly represents a 75% of the standard deviation increase or the warm phase. This approach was used because some monthly-mean (or seasonal-mean) environmental parameters only vary by small magnitudes, but even small anomalies can be important on those time scales.

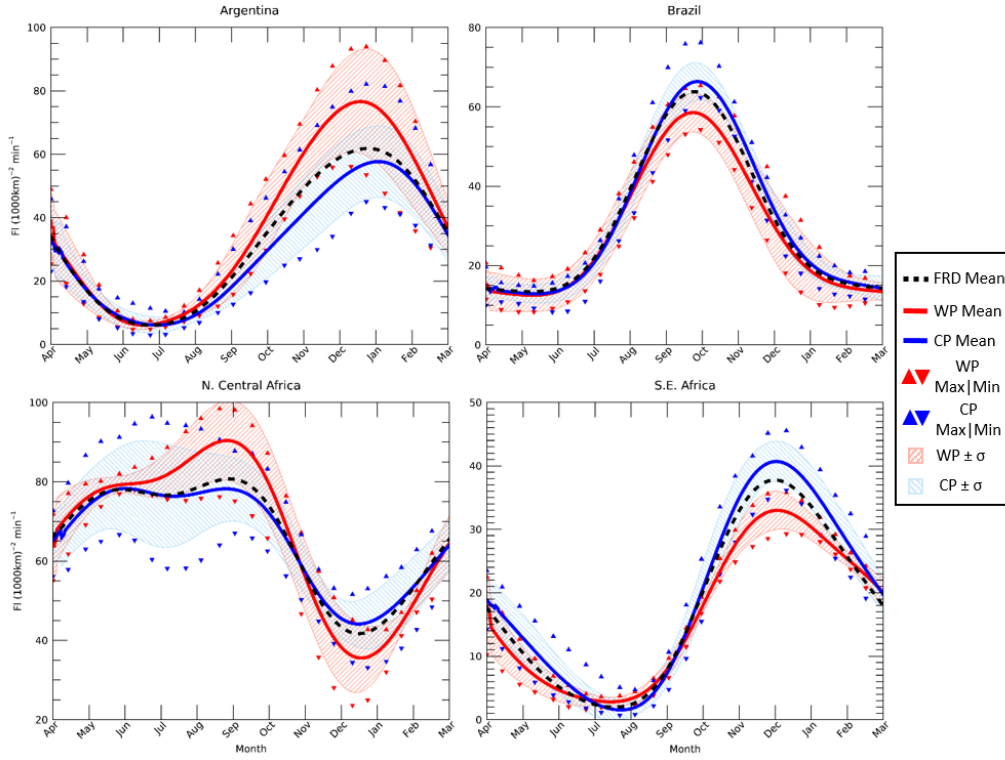


FIG. 6. Lightning flash rate density time series along an ENSO Year (EYR) for the four primary study locations, (a) Argentina, (b) northwestern Brazil, (c) north-central Africa, and (d) south eastern Africa. The red line is the mean of all 4 warm-phase ENSO Years; the blue line is the average of all 8 cold-phase ENSO years; and the dotted black line is the average for all 16 EYRs in the study. Shading represents $\pm$ one standard deviation (σ) for the warm- [red] or cold- [blue] phase years at that point in the EYR. Up (down) arrows indicate the maximum (minimum) flash rate density of any warm- [red] or cold- [blue] phase year.

a. South America

The two selected South American locations showcase both the unique tropical lightning seasonality of the Amazon River Basin as well as the intense subtropical lightning that has been observed in Argentina. Given the geographic proximity of South America to the sea surface temperature anomalies generally associated with ENSO, it has been shown that the phase of ENSO can have a substantial impact on the environmental conditions over much of the continent. Our Argentina region, which is to the west of the area investigated by Liu et al. (2019) and encompasses that examined by Lavigne et al. (2019), exhibited strong seasonality with a peak near $63 \text{ FI } (1000 \text{ km})^{-2}$

min^{-1} in January decreasing to $2.5 \text{ FI (1000 km)}^{-2} \text{ min}^{-1}$ in July. The Brazil region is situated in the northwestern portion of the country, incorporating the Brazil regions from both Dowdy (2016) and Lavigne et al. (2019), and has a strong peak in the mean annual cycle of lightning with over $65 \text{ FI (1000 km)}^{-2} \text{ min}^{-1}$ in October during the pre-monsoon season (Williams et al. (2002)).

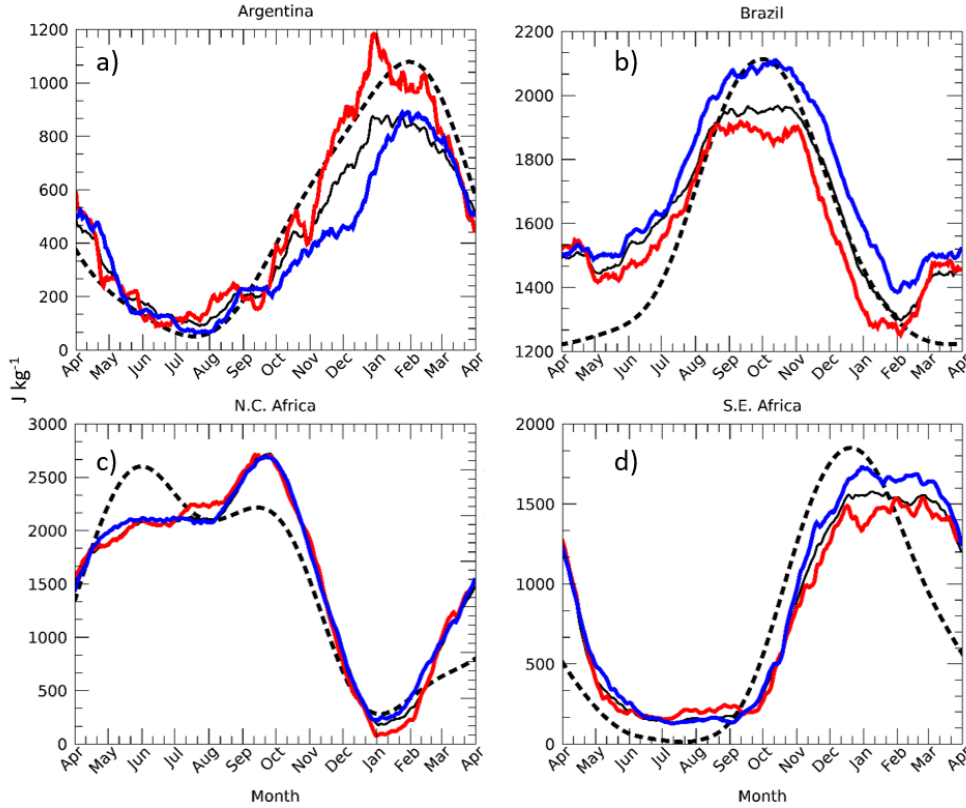


FIG. 7. 90th percentile of CAPE within each region, each day of the year, averaged over warm-phase ENSO Years (red), cold-phase ENSO Years (blue), along with the mean annual pattern (thin black line). For each region, CAPE is taken from ERA reanalysis at the time of day with maximum lightning: (a) Argentina at 00 UTC, (b) northwestern Brazil at 18 UTC, (c) north-central Africa at 14 UTC, and (d) southeastern Africa at 12 UTC. The black dashed line is the mean annual cycle of lightning flash rate density.

1) ARGENTINA

The mean anomaly for the four warm-phase years peaked at $+17 \text{ FI (1000 km)}^{-2} \text{ min}^{-1}$ in January (Fig. 6a), the largest regionally-averaged (i.e., on the scale of the boxes marked in Figs. 1, 3, 4, and 5 – about $[1000 \text{ km}]^2$) anomaly for any of the regions or ENSO phases. This was a 0.95σ increase compared to the overall mean January flash rate. Part of this large warm-phase enhancement was

from DJF of 2009/2010 with a $+35 \text{ FI (1000 km)}^{-2} \text{ min}^{-1}$ anomaly (6a), following the strongest warm-phase event in the study. However, both EYRs 2002 and 2006 also had positive anomalies of at least $+16 \text{ FI (1000 km)}^{-2} \text{ min}^{-1}$ during the DJF season, while 2004 did not. Argentina had a cold-phase suppression during boreal spring and summer in seven of the eight cold-phase years, although the peak magnitude of this suppression ($-7 \text{ FI (1000 km)}^{-2} \text{ min}^{-1}$ or -0.42σ) was smaller than the warm-phase enhancement and occurred earlier, in late November. The neutral phase in Argentina also had a large negative anomaly, peaking at $-8.5 \text{ FI (1000 km)}^{-2} \text{ min}^{-1}$ just after the maximum warm-phase enhancement.

Some of this lightning enhancement was likely driven by the increase in CAPE during the DJF season in Argentina, as noted in Figs. 7a and 8a. The 90th percentile CAPE is between 200-300 J kg^{-1} higher than the DJF mean during the warm phase, indicative of an enhanced environment for deep convection in Argentina (Fig. 7a). This coincides with a seasonal increase of CAPE for DJF across the entire Argentina region (Fig. 8a; Table 2), and a positive ONI correlation to CAPE (Fig. 9). At 700 hPa, there is anomalous easterly and southeasterly flow in the cold phase (Fig. 8b, 8d), with enhanced northerly and northwesterly flow in the warm phase (Fig. 8a, 8c). This wind pattern also extends to the 500hPa and 850hPa levels, importing additional moisture from the tropics into the region during the warm phase, noted in Table 2 with increases in 500 and 850hPa specific humidity. Both total and convective precipitation also have 0.77σ and 0.93σ enhancements respectively during the warm phase.

Decreased convective inhibition together with increased CAPE and upward motion favors increased convective development. This region is known for having some of the strongest thunderstorms on earth (e.g., Zipser et al. (2006); Cecil and Blankenship (2012); Cecil et al. (2015)), with ample thermodynamic instability often present to begin with (Bruick et al. (2019b)). Assuming that the favored convective mode remains the same, changes to the volatility of the environment would manifest as more (or less) intense storms. Fig. 4 suggests more intense storms in this region during the warm phase based on the conditional flash rates. These results are consistent with those from Liu et al. (2019), with more vigorous storms during El Niño and less vigorous storms during La Niña for Argentina, with little change to precipitation feature size from ENSO. It should be noted their specific Argentina region only contains a small portion of the one herein, as ours extends further to the north and west.

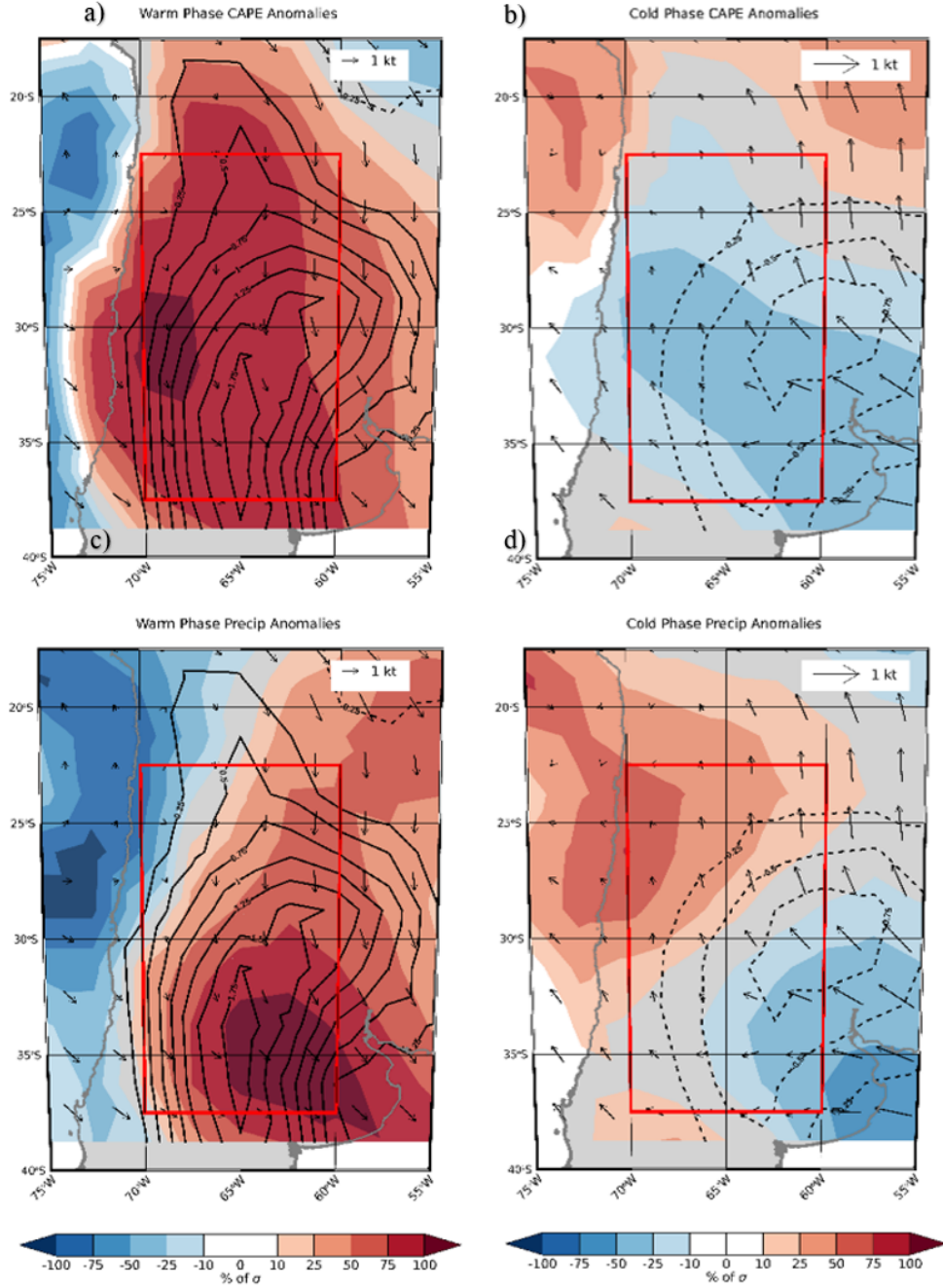


FIG. 8. Mean anomalies of lightning (contoured) and ERA 700hPa wind (vectors) along with shaded anomalies of CAPE (a,b) and total precipitation (c,d) in Argentina centered on a season around January 15th for the warm phase (a,c) and the cold phase (b,d). The red box outlines the study region. Lightning anomalies are contoured in $0.25 \text{ Fl } (250 \text{ km})^{-2} \text{ min}^{-1}$ increments where solid (dashed) lines are positive (negative) anomalies. Shaded anomalies are shown relative to the standard deviation of each grid point across the study period.

	Argentina		Brazil		N. Central Africa		S.E. Africa	
	LRMTS	ONI	LRMTS	ONI	LRMTS	ONI	LRMTS	ONI
CAPE	0.65	0.33	0.49	-0.22	0.55	-0.22	0.38	-0.01
CIN	-0.37	0.11	-0.29	0.29	-0.33	0.21	0.04	0.07
Z 500hPa	0.05	0.23	-0.15	0.63	-0.21	0.35	0.03	0.67
Z 850hPa	-0.35	-0.33	-0.08	0.49	-0.22	0.37	-0.04	0.65
ω 500hPa	-0.19	0.05	-0.14	0.45	-0.34	0.23	-0.01	0.13
ω 850hPa	-0.15	-0.04	0.12	-0.08	-0.09	0.05	0.22	0.04
q 500hPa	0.13	0.23	0.08	-0.11	0.22	-0.08	-0.02	0.23
q 850hPa	0.32	0.15	0.04	0.32	0.32	-0.01	0.28	0.09
Tv 500hPa	0.19	0.37	-0.21	0.52	-0.11	0.12	-0.01	0.42
Tv 850hPa	0.12	0.30	-0.08	0.41	0.04	0.20	0.14	0.30
TT Index	0.00	-0.12	0.38	-0.39	0.28	-0.02	0.29	-0.13
K Index	0.10	0.01	0.23	-0.11	0.27	0.01	0.23	0.07
Tot. Precip	0.35	0.04	0.12	-0.36	0.30	-0.27	-0.02	-0.20
Conv. Precip	0.48	0.09	0.22	-0.38	0.40	-0.30	0.02	-0.17
MSLP	-0.31	-0.41	0.03	0.13	-0.21	0.24	-0.09	0.46
Sat. Fraction	0.23	-0.01	0.21	-0.29	0.29	-0.11	0.11	-0.07
Tv SFC	0.02	0.24	-0.18	0.52	0.00	0.29	0.17	0.35
Bulk Wind Diff	0.15	0.16	-0.29	0.43	-0.07	-0.08	-0.17	-0.05

FIG. 9. Zero-lag Pearson (linear) correlations of the selected reanalysis variables to monthly lightning (LRMTS) and the ONI for the full study period. For the 99% confidence interval, $|R_c| \geq 0.20$ is color coded: red text indicates significant positive correlations, and blue indicates significant negative correlations.

2) BRAZIL

The mean flash rate anomalies are smaller at +3 Fl $(1000 \text{ km})^{-2} \text{ min}^{-1}$ ($+0.24\sigma$) for the cold phase and -5 Fl $(1000 \text{ km})^{-2} \text{ min}^{-1}$ (-0.47σ) for the warm phase (Fig. 6b). Most of the cold-phase years have enhanced lightning between August and December, and three of the four warm-phase years have decreased lightning during this time (Fig. 6b). The other warm-phase year, 2004, was an outlier for both Brazil (with enhanced lightning in January) and Argentina (with decreased lightning in February-March). 2004 was also the weakest of the warm-phase events in terms of ONI (Fig. 2).

The Brazil region has more environmental parameters with statistically significant correlations to the ONI than the other regions (Fig. 9). This is fairly intuitive as a direct result of the impact ENSO has on the Walker Circulation in South America, and contributes to the consistency of the lightning patterns. Most of these relationships are supportive of an enhanced convective environment during

the cold phase and suppressed environment with the warm phase, and the 90th percentile CAPE also supports this with a large and consistent separation between the phases of $\sim 250 \text{ J kg}^{-1}$ (Fig. 7b). Total precipitation is not significantly correlated with lightning in this part of Brazil. This stems from the annual cycles of lightning and precipitation being out of phase with one another. Although lightning is maximized during the pre-monsoon season around October, the subsequent months have abundant precipitation associated with weaker convection (Williams et al. (2002)).

The pre-monsoon environment limits the amount of widespread convection, favoring a smaller number of stronger systems rather than the more numerous weaker systems found in January and February. However, increases to both total and convective precipitation were noted during the cold phase and reductions during the warm phase at the lightning peak, consistent with negative correlations to ONI. The northeastern half of our Brazil region did have increased thunderstorm frequency during the cold phase and fewer thunderstorms during the warm phase (Fig. 5). With little difference in the conditional flash rates between ENSO phases (Fig. 4), this suggests the overall increase in lightning during the cold phase is driven by an increase in the number of thunderstorms, not by a change in their intensities.

b. Africa

At these synoptic and seasonal scales, Collier and Hughes (2011) found that the ITCZ is the dominant contributing factor to lightning production within tropical Africa, and particularly along the southern edge of the ITCZ for the Boreal summer. The ITCZ progresses across most of central Africa, from the Sahel in June - September into the southern Congo River Basin and Mozambique during the Austral summer. The ITCZ traverses and generally stops within our North-Central Africa region, then usually stops on the northern edge of our southeastern Africa region. The north-central Africa region is right on the cusp of the global lightning maximum, found just to the south in the Congo River Basin. It has a bimodal annual lightning pattern, with the highest mean flash rate density of all selected regions in the study at $\sim 80 \text{ Fl (1000 km)}^{-2} \text{ min}^{-1}$ in June and September. The mostly subtropical southeastern Africa region meanwhile has a more modest mean annual cycle of lightning of $43 \text{ Fl (1000 km)}^{-2} \text{ min}^{-1}$, peaking in December.

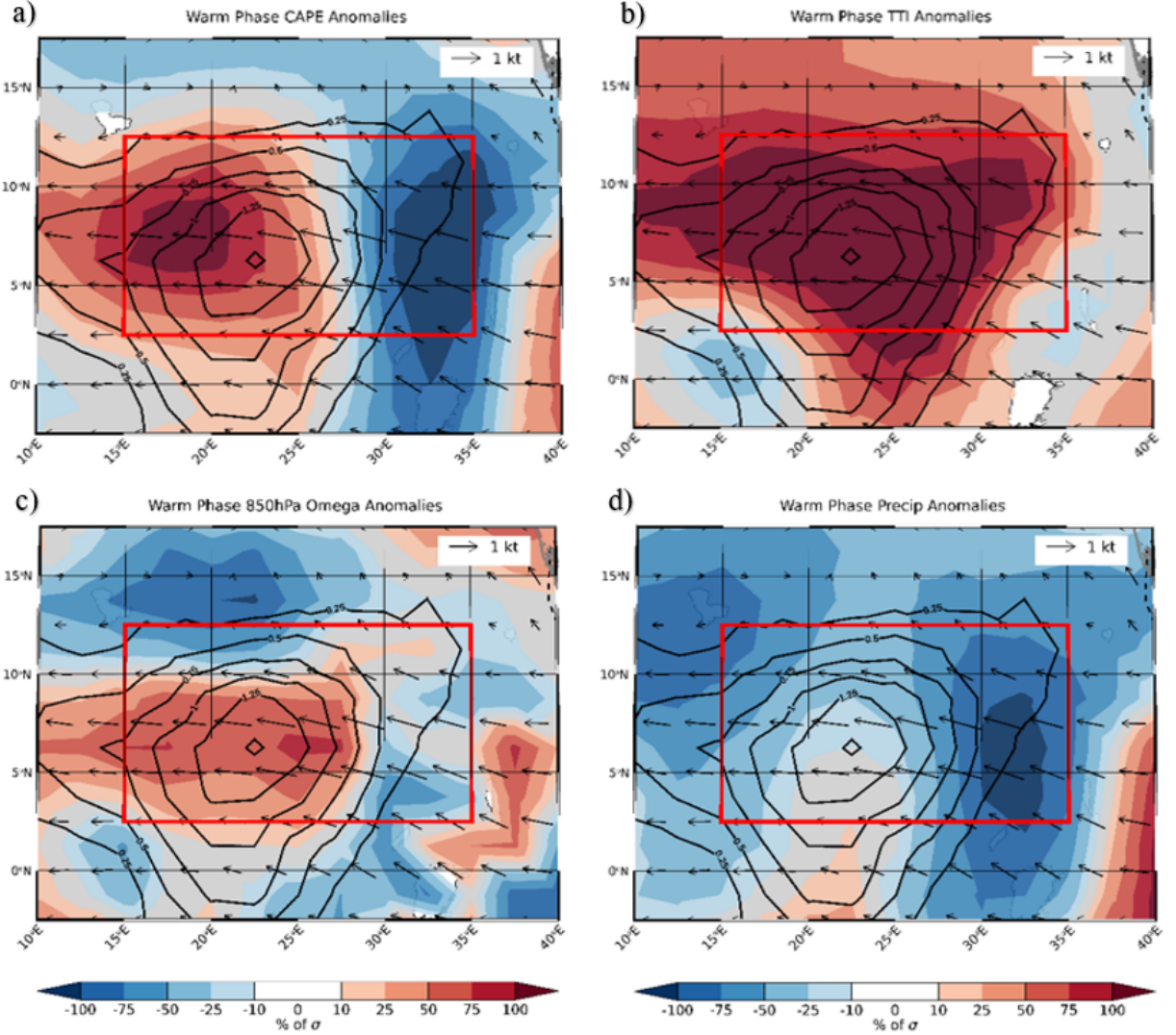


FIG. 10. Mean warm-phase anomalies of lightning (contoured) and ERA 700hPa wind (vectors) along with shaded anomalies of CAPE (a), total totals index (b), 850 hPa omega (c), and total precipitation (d) in north-central Africa centered on a season around September 15th. The red box outlines the study region. Lightning anomalies are contoured in 0.25 Fl (250km)⁻² min⁻¹ increments where solid (dashed) lines are positive (negative) anomalies. Shaded anomalies are shown relative to the standard deviation of each grid point across the study period.

1) NORTH-CENTRAL AFRICA

The inter-annual variability here was much more complex than in the other regions. Lightning anomalies in the cold-phase years did not have any consistent pattern. Three of the four warm-phase

years had enhanced lightning in the August-October timeframe, with the annual cycle peaking then during those years. The lone exception was 2006, which was the shortest-lived warm-phase event in the study (Fig. 2b), lasting only the minimum 5 months. Three cold-phase years had peak lightning production just as high if not higher than their warm-phase counterparts, however all these years peaked earlier in the annual cycle between June to mid-August (Fig. 6c). Therein is what set this region apart- that the seasonality of the lightning varied with ENSO phase (Fig. 6c). Cold-phase and neutral years typically peaked in May-June-July, while warm-phase years produced the most lightning around September. This shift resulted in a mean warm-phase lightning enhancement for September of $+10 \text{ Fl (1000 km)}^{-2} \text{ min}^{-1}$, a 0.78σ increase (Table 2). The cold-phase lightning anomaly was relatively small compared to the warm phase, $-3 \text{ Fl (1000 km)}^{-2} \text{ min}^{-1}$ in October, a 0.23σ decrease at that time. The ~September lightning peak was coincident with a seasonal peak of CAPE regardless of ENSO phase (Fig. 7c), although during the warm-phase CAPE was further enhanced in the western part of the region and reduced in the eastern part (Fig. 10a).

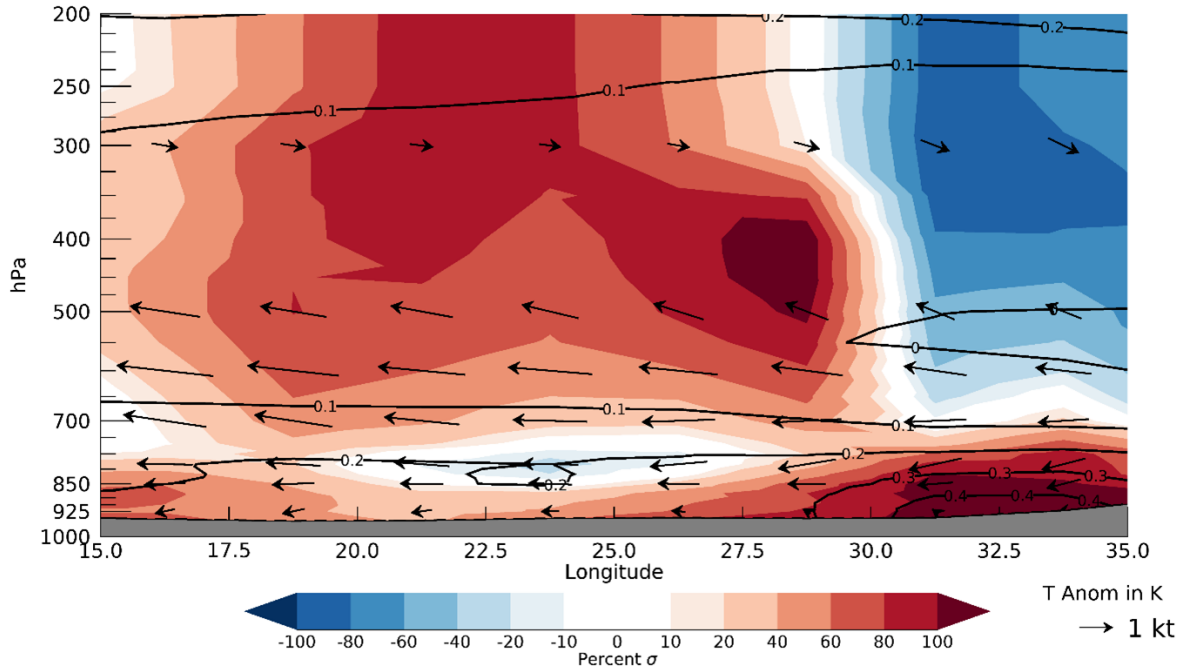


FIG. 11. Zonal cross section at 11.25°N in the north-central Africa box with ERA monthly averaged omega (ω) anomalies (shaded), temperature anomalies (contours), and wind anomalies (vectors) for August during the warm phase. Note, ω is negatively related to upward motion and thus a positive anomaly indicates more descending motion in the atmosphere.

There is a clear separation in environmental conditions during the warm phase between the western portions of the region and the far eastern side in Fig. 10a and Fig. 11. East of about 30° E, the near-surface environment is less favorable for convection, with stronger downward motion (Fig. 11), lower CAPE (Fig. 10a), and greater CIN (not shown). However, the upper-level environment is generally more favorable with large-scale upward motion above the 700-hPa level. This is in contrast to the generally better thermodynamic environment and less favorable upper-level synoptic-scale lifting in the center and western sides of the domain, where the lightning anomalies are maximized. The precipitation reduction is most evident on the eastern side (Fig. 10d), almost perfectly collocated with the reduced CAPE (Fig. 10d). That said, both the K-index (Table 2) and total totals index (Fig. 10b) are enhanced across almost the entire box at 0.96σ and 1.28σ respectively, and there is a strong enhancement of the easterly wind with the warm phase. The correlations between ONI and environmental parameters (Fig. 9) do not add clarity for this region, since the main ENSO impact we see is a shift in the seasonal patterns only during the warm phase.

The patterns seen in Figs. 10 and 11 lead to speculation that the upper level dynamic support and mid-level thermodynamic environment during the warm phase help initiate convection in the eastern portions of the region. These cells are then advected westward by the stronger easterly shear into a more favorable thermodynamic region, allowing for some of them to intensify and produce a limited number of strong updrafts, capable of vigorous lightning rates. The enhanced conditional flash rates (Fig. 4a) and fraction of observations with lightning (Fig. 5a) during the warm phase indicate that the overall lightning anomaly is driven by increases in both storm count and storm intensity. Given this region's proximity to the global lightning maximum coupled with the traversal of the African ITCZ (Collier and Hughes (2011); Nicholson (2018)), this August/September period appears to represent an extension of the lightning maximum northward along the southern edge of the ITCZ. While speculative, it is possible that the enhanced thermodynamic environment and the southward progression of the ITCZ in August and September could favor this period for more vigorous convection during the warm phase. A combination of both the advection and ITCZ mechanisms could help describe the timing, shape, and spatial extent of the lightning anomaly observed in north-central Africa.

2) SOUTHEASTERN AFRICA

The southeastern Africa region, centered near Mozambique, had especially consistent separation between the phases with reduced lightning in the warm phase and enhanced lightning in the cold phase (Fig. 6d). All four warm-phase years had reduced lightning during December and January while all eight cold-phase years had positive lightning anomalies during this time. However, the cold-phase years had some temporal variability, peaking anywhere from October through February. The raw magnitude of the anomalies is smaller here than in Argentina or north-central Africa, but the mean annual flash rate is also lower. The $+2.5/-3.5 \text{ Fl (1000 km)}^{-2} \text{ min}^{-1}$ phase-mean anomalies represent $+0.35 / -0.49\sigma$ departures from the mean (Fig. 6d, Table 2).

The anomalies for nearly all environmental parameters in Table 2 seem consistent with straightforward expectations of a more favorable convective environment and increased lightning in the cold phase and decreased lightning in the warm phase. Table 2 indicates a better dynamic and thermodynamic environment in the cold phase and an almost equally worse environment in the warm phase. This is echoed by Fig. 7d, with a CAPE increase of $\sim 100 \text{ J kg}^{-1}$ in the cold phase at the diurnal lightning peak (1200 UTC). Interestingly, the correlation between ONI and CAPE is near zero, despite noticeable increases in mean (Table 2) and 90th percentile (Fig. 7d) CAPE anomalies during the cold phase (Fig. 9). Correlations between ONI and geopotential height are extremely strong, consistent with both height and ω anomalies in Table 2, with higher heights (upper-level ridging) in the warm phase. The flow pattern in Fig. 12 reveals anomalous southerly flow from the subtropics into the region during the warm phase (Fig. 12a, c), with anomalous northerly flow from the tropics during the cold phase (Fig. 12b, d). This wind shift would explain the environmental improvements, with advection of deep moisture and thermodynamic instability during the cold phase. Besides the increased CAPE, both total and convective precipitation also all have positive anomalies for this region during the cold phase and larger negative anomalies during the warm phase (Table 2).

The lightning enhancement during the cold phase appears to be an expansion of the area of climatologically higher flash rates (Fig. 1c) and more frequent thunderstorm occurrence (Fig. 5c) typically found to the north and west of this region. The pattern reverses in the warm phase, with southerly flow and higher pressure bringing a drier, more stable environment and the gradient of precipitation and lightning shifting toward the northern tier of this region. This same northerly

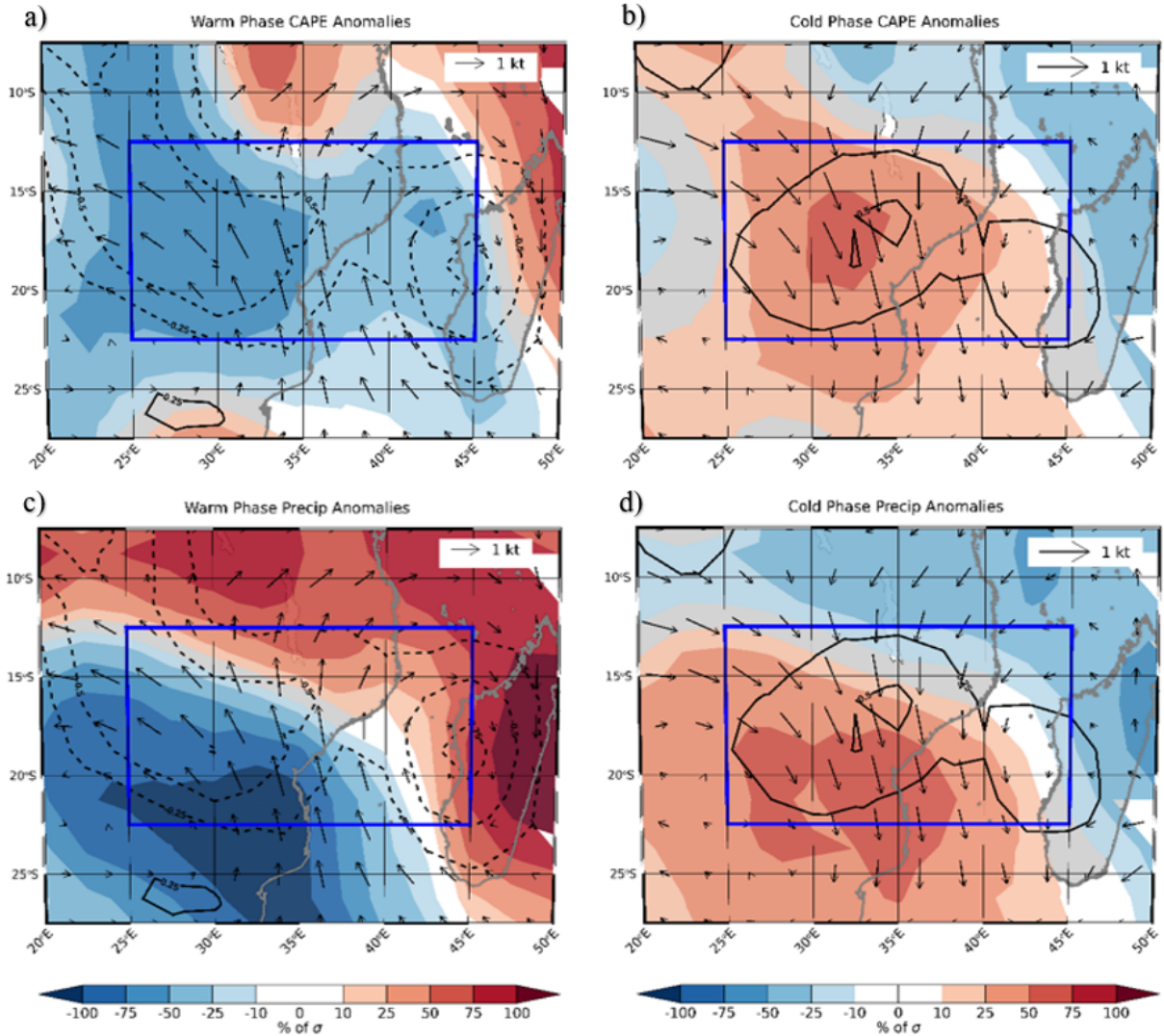


FIG. 12. As in Figure 8 for the southeastern Africa region during a season centered around December 15th.

momentum bringing a more tropical environment could also allow the ITCZ to push further south, favoring more convection and lightning along it with the enhanced environment of the cold phase. In the warm phase, the ITCZ potentially remains further north and does not enhance the lightning here. This could help explain the consistency observed between the phases, but more investigation is necessary. While the conditional flash rate anomalies (Fig. 4) are not large or consistent across this region, there is a clear increase in the frequency of thunderstorm occurrence during the cold phase and a decrease during the warm phase (Fig. 5). This supports the notion that thunderstorm

intensity is potentially unchanged with ENSO, but that the increased (decreased) lightning is driven by more (fewer) thunderstorms with the cold (warm) phase.

7. Summary and Conclusions

Inter-annual variability of lightning on regional scales was identified and examined using the full TRMM LIS climatology. Consistent patterns of inter-annual variability generally aligned with the phases of ENSO in the four regions highlighted here: northern Argentina, northwestern Brazil, north-central Africa, and southeastern Africa. Relationships between lightning variability, ENSO, and environmental patterns in the TRMM LIS domain were examined. Table 1 serves as a brief summary of the identified lightning patterns. From the study as a whole, ENSO impacts are seen as increasing lightning during the warm phase in Subtropical South America, north-central Africa and the Sahel, parts of Asia and the Middle East, and southern Mexico. The ENSO cold phase has increased lightning in the south-central and southeastern Africa, much of Australia, and much of Brazil. In some of these places, relationships to atmospheric stability and vertical motion are straightforward; in others they are unclear or complex. The results here are valid for a period of record dominated by ENSO cold phase and Central Pacific warm phase events, without including more canonical, large-magnitude warm phase events such as those in 1997-98 and 2015-16.

This study offers insight into several new regions of ENSO lightning impacts that were previously either unrecognized or not widely known. Analysis of lightning anomalies composited by ENSO phase (Fig. 1) or ENSO Year (Fig. 6) allowed for ENSO-related signals to be identified that would be difficult to distinguish or somewhat muted by more traditional correlation analyses (e.g., Fig. 3), and also opened the door for identifying other significant lightning patterns as well. While the environments for all of these locations were not examined in detail, each represents an area for further research to improve our understanding of how patterns of inter-annual lightning variability differ across the globe. Inclusion of the conditional flash rate and percentage of observations with lightning provides additional details about how the lightning anomalies themselves are manifested. Locations known for intense thunderstorms, such as north-central Africa and Argentina, have notable changes to the vigor of individual storms with ENSO. Several other regions, including the southeastern Africa study region, had clear changes to the frequency of thunderstorm occurrence

with ENSO. In Africa, the observed lightning patterns are potentially related to ENSO modulation of the ITCZ.

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658 ics program (NNH16ZDA001N-WEATHER) and NASA’s Earth from ISS program. Additional
659 thanks to Drs. Phillip Bitzer and Larry Carey for guidance and advice throughout the study.

660 *Data availability statement.* All data used in this study are freely available online. TRMM
661 LIS orbital and climatological data are available from the NASA GHRC DAAC at:
662 <https://ghrc.nsstc.nasa.gov/hydro/details/lislip>, doi: <http://dx.doi.org/10.5067/LIS/LIS/DATA201>
663 and <https://ghrc.nsstc.nasa.gov/hydro/details/lolrts>, doi: [http://dx.doi.org/10.5067/LIS/LIS-](http://dx.doi.org/10.5067/LIS/LIS-OTD/DATA311)
664 OTD/DATA311. ERA5 data are available from the Copernicus Climate Data Store
665 (<https://cds.climate.copernicus.eu#!/home>). The ONI data are available from the CPC at:
666 https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI.v5.php.

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