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Deep Convection over Africa: annual cycle, ENSO, and trends in the hotspots

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ABSTRACT

Africa is one of the three key regions of deep convection in the global tropics. There is a wealth of information on the intensity, variability and change of convection and associated rainfall in regions across the continent but almost all of this literature is regionally focused and confined to specific seasons. This fragmented approach precludes a continent-wide view of deep convection leaving the following key issues unanswered: When is deep convection the most wide-spread across Africa? Where on the continent is deep convection most active? Where does wide-spread convection have the most interannual variability? This paper confronts these questions using a satellite-derived integral of deep convection. At the continental scale, March exhibits the most extensive deep convection while the West African monsoon during June-July exhibits the least. El Niño generally suppresses pan-African convective activity while La Niña enhances this activity. These pan-African signals are largely determined by regional hotspots: the eastern Congo hosts the most persistent wide-spread deep convection, southeastern southern Africa displays the highest interannual variability, and regional highlands maintain local convective activity hotspots. Furthermore, pan-African annual mean convective activity has increase ∼10% between 1983 and 2015 with increases of >20% recorded in local hotspots. Results in this study provide a climatological baseline for both observational and model-based studies of African climates and offer insights into when African convection has the greatest potential impact on the general circulation.

1. Introduction

Africa has long been known as one of three key regions of deep convection and diabatic heating that drives the global tropical circulation (Webster 1973). A striking characteristic of that deep convection is its almost perfect symmetry around the equator when averaged through the annual cycle such that convection spans 45 degrees of latitude with a peak near 2^{o}S (Waliser and Gautier 1993). This symmetry likely results from the equitable land area either side 0^{o} latitude. No other region in the global tropics has comparable symmetry. African convection is also distinct in being influenced on interannual and interdecadal timescales by all three ocean basins.

Through the annual cycle, solar heating and water vapour transport renders a broad swath of the atmosphere conducive to deep convection, although in most seasons and regions of Africa not through a recognisable Intertropical Convergence Zone (Nicholson 2018) – the exception being West Africa. The strong seasonality and regional location of the deep tropical convection results in distinctive responses to remote forcing. For example, El Niño events are generally dry in West Africa in July to September (Ward 1992), wet in East Africa from October to December (Ogallo 1988) and dry in southern Africa from January to March (Lindesay 1988). The upshot of the strong seasonality, wide latitudinal excursion of tropical convection through the annual cycle, and contrasting influence of remote modes, is that the understanding of deep convection in Africa is fragmented into specific regions and seasons. The primary regions are West Africa/Sahel which dominates the literature, East Africa, southern Africa and, occasionally, central Africa which is the region of most widespread convection. What is missing from this fragmented view, is an integrated assessment of African deep convection onto which maps some rather basic questions such as, what is the annual cycle of deep convection for the continent as a whole? Which month features the largest spatial extent of deep convection? Does deep convection dominate on the continent in La Niña or El Niño years and in which months? And is there a trend in deep convection over the satellite era? It is the purpose of this paper to engage with these concerns. The overall objective is to build a regionally integrated picture of Africa-wide deep convection which is long overdue. These questions can be summed up pictorally in Fig. 1. There is extensive literature covering convection during the austral (Fig. 1a) and

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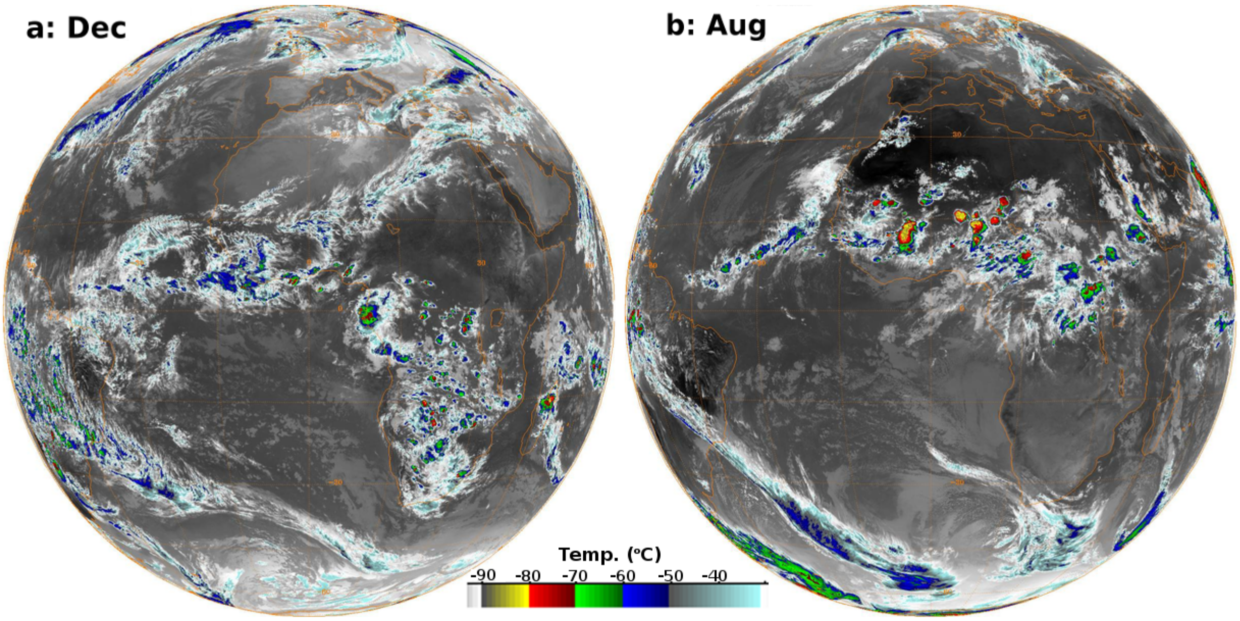

FIG. 1. Typical geostationary satellite imagery of convective outbreaks over Africa during (a) austral summer, taken at 18:12 UTC 21 December 2017, and during (b) boreal summer, taken at 18:12 UTC 21 August 2017. (Courtesy: NOAA-NCEI Global ISCCP B1 Browse System, Knapp 2008)

boreal (Fig. 1b) summers, but quantitatively which summer represents a more active season for deep convection? And what is the climatological spatial and temporal structure of convection during the transition between these two states?

The advent of convective-permitting climate models run at continental scale (eg. Stratton et al. 2018), whereby deep convection and its characteristics are beginning to be better represented, is a further impetus for this research. This study provides the observational assessment of the spatio-temporal distribution of wide-spread convection, which is needed to diagnose the fidelity of these models in simulating the climatology of African convection. A key part of this climatology is the consideration of regional hotspots for deep convection. Frequent outbreaks of organised deep convection in one locale will lead to repeated heating of the atmospheric column with associated adjustments in the regional circulation. As a result, deep convective hotspots may act as "engine-rooms" controlling regional climate. Diagnosing where and when these regional engine-rooms are active is the second objective of this paper.

Section 2, which follows, outlines the data and methods which underpin the rest of the paper. This section also motivates for studying wide-spread convection as specifically distinct from African rainfall. Presentation of the results are organised to address three central aspects of wide-spread convective activity across Africa:

- the annual cycle of convection across the continent (Section 3)
- the impact of ENSO on pan-African convective activity and highlight hotspots of deep convection (Section 4)
- contemporary changes in mean convective activity across Africa (Section 5)

Section 6 provides a summary of the salient results and the paper closes with conclusions that are drawn from these findings.

2. Diagnosis of wide-spread convective activity

The redistribution of energy by deep convection is a defining characteristic of the local and regional atmospheric circulation and water cycle across much of Africa, as in the global tropics, and is achieved both vertically and horizontally by complex interplays between latent heating, radiative cooling, and momentum transport through the full depth of the troposphere (for review see Roca et al. 2010).

In many studies, rainfall serves as a proxy for diabatic heating of the column. However, difficulties in estimating rainfall without an extensive rainfall station network, even with satellite observations (eg. Maidment et al. 2015; Awange et al. 2016), continue to hamper research efforts focused on African weather and climate. These difficulties are greatest in the most convectively active part of the continent, the Congo, where observations are sparse (Washington et al. 2013) and even recent datasets (Nicholson et al. 2018) have resolutions below those necessary to consider wide-spread convection directly. Irrespective of these difficulties, rainfall is good a proxy for the diabatic heating rates deep convection, but does not necessarily diagnose radiative cooling controlled by deep cloud (eg. Fiolleau and Roca 2013).

Therefore, there is a strong rationale for an alternative proxy to diagnose deep convection in a way that summarises the full potential of such convection to modify regional to global circulation. Such a proxy should highlight wide-spread convection rather than isolated convective cells, as it is organised mesoscale convection that is particularly effective at impinging on large-scale circulation in both the tropics (Houze 1982; Hartmann et al. 1984) and extratropics (Rodwell et al. 2013).

A key character of such organised convection is the cold cloud shields which develop characterised by tropopause-level cirrus and the even colder –deeper– clouds associated with the core convective updrafts. These cold cloud characteristics have been exploited in mesoscale convective system tracking algorithms typically applied to 15 minute to 3-hourly data (eg. Hodges and Thorncroft 1998; Carvalho and Jones 2001; Laing et al. 2011). However, mesoscale convection systems are a specific subclass of wide-spread convection (Houze 2004). They form a crucial part of convective activity, and indeed rainfall, over Africa, but are not the whole (Jackson et al. 2009; Laing et al. 2011; Roca et al. 2014). Our study seeks to answer questions about wide-spread deep convection more generally. Answering theses questions requires a summary diagnostic that provides a daily integral of deep convective activity across the continent.

a. Data

This integral of deep convection is provided by using the thermal infrared radiation observations made onboard the Meteosat geostationary satellites to compute daily cold cloud duration (CCD). CCD is expressed as number of minutes a pixel exhibits temperatures below a chosen brightness temperature threshold. Maidment et al. (2014) provides full details of a climate data record of CCD computed from thermal infrared imagery detected by Meteosat first and second generation satellites. CCD for cloud brightness temperatures below -30°C, -40°C, -50°C and -60°C were computed. This dataset underlies the TAMSAT product, which provides a long-term stable and routinely-updated estimate of African rainfall long-term stable and routinely-updated estimate of African rainfall (Maidment et al. 2014, 2017). The climate record quality of this CCD data, computed on a 0.0375° lat-lon grid ($\sim$4km) and used here for the 1983-2015 period, provides an appropriate dataset to answer the questions posed in this paper. CCD provides an effective integral of daily convective activity across Africa and is a more direct diagnostic of convection than rainfall, minimizing the additional uncertainties introduced by satellite-derived rainfall estimation.

A large-scale summary of the thermodynamic environments supporting convection across Africa is obtained by computing monthly mean moist static energy (MSE) from moisture and temperature variables estimated in the NCEP-DOE Reanalysis II (NCEP2, Kanamitsu et al. 2002). These data are available on a 2.5° x 2.5° lat-lon grid. Low-level MSE was diagnosed using variables on the 850 hPa level. Due to estimation from reanalysis which is poorly constrained in data-sparse parts of Africa, especially the Congo (Hua et al. 2019), this MSE should only be treated as indicative of the climatology for the continent.

The ENSO events considered in this study are obtained from years in which the NINO3.4 SST anomaly peak exceeds $\pm 0.7\sigma$ of a standard deviation from climatology during 1983-2015. The NOAA Optimally Interpolated SST was used to create this index (Reynolds et al. 2002). The El Niño events considered begin in 1986, 1987, 1991, 1994, 1997, 2002, 2006, and 2009 with La Niña events in 1983, 1984, 1988, 1995, 1998, 1999, 2000, 2007, 2010, and 2011.

b. Methodology

The goals of this study focus on wide-spread convection, especially convection which is of sufficient scale to have an impact on regional circulation. The CCD brightness temperature threshold of -50°C is chosen for use here as it is a well-established value appropriate for the identification of mesoscale convective systems (Jackson et al. 2009; Laing et al. 2011; Blamey and Reason 2012). Fig. 1 provides examples of this assertion: brightness temperatures lower than -50°C (dark blue) capture convectively active cloud shields, whereas the -40°C threshold (light blue) includes cirrus outflow. Such low brightness temperatures rarely last long in one location so a duration threshold of more than 30 minutes is applied to the CCD field at -50°C (CCD_{50}) to identify deep convection. Changing these thresholds modifies the magnitude of values output by the analysis in this study, but has negligible impact on climatology and interannual variability results in terms of when and where the most convection is observed. However, reported trends in convective activity are greater for the colder brightness temperature thresholds, as reported in the literature (Taylor et al. 2017; Raghavendra et al. 2018). This will be discussed in Section 5 and figures reproduced with the -60°C CCD data are included in supplementary material. While CCD_{50} is an appropriate thresh-

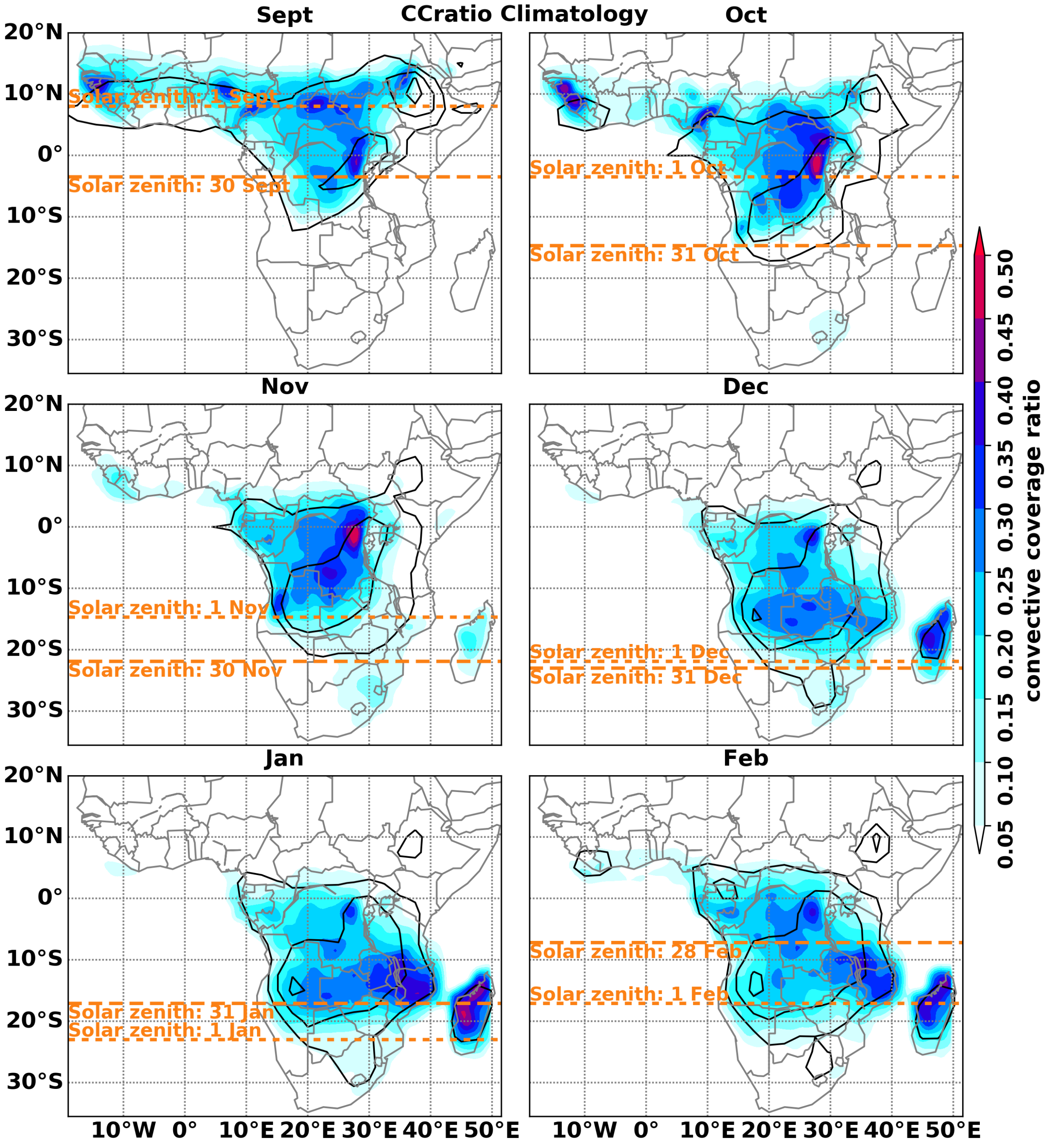

FIG. 2. September to February climatology (1983-2015) of monthly mean convective coverage. Climatology of highest low-level (850hPa) moist static energy contoured at 340, 345, and 350 kJ (black lines).

old for identifying the cloud shields of organised convective systems, this field does not summarise how wide-spread convection is in a region. To obtain this summary, we compute a convective coverage ratio defined as

$$ccratio = \frac{a}{\pi r^2} \tag{1}$$

where a is the area of CCD_{50}>30 mins within a circle defined by radius, r=1° latitude. This ccratio calculation is applied to the 4km gridded CCD_{50} and is only computed at every grid-point on a 0.5° latitude-longitude grid. The output is a coarse-grained diagnostic of daily convection which preferentially highlights wide-spread outbreaks of convective activity. This diagnostic is very similar to the ouput of regridding the CCD data to a 0.5° using a spatial smoother such as a bivariate spline. However, that approach loses the localization over high intensity orographic convection hotspots. The ccratio retains this localization. Monthly means of this metric are used to show the spatial and seasonal variation of wide-spread convective activity across the continent. The monthly mean of the ccratio quantifies the joint probability of the frequency and spatial extent of deep convection. For example, the ccratio would be 0.5 if 100% of the circle was covered by deep convection during half of the days in a month. The value of 0.5 would also be diagnosed if 70% of 1° circle surrounding a grid-point was covered by deep convective cloud during two thirds of days in a month. Thus, the monthly mean ccratio represents a simple way to diagnose the mean actvitity of wide-spread convective outbreaks.

A complementary object-based analysis was performed on the CCD_{50} data in order to explicitly separate long-term changes of areal extent from long-term changes in number of convectively active days. A standard connected component labelling algorithm (van der Walt et al. 2014) was applied to each daily $CCD_{50}>30$ min thresholded image. The "blobs" output from the algorithm were used to build a database of convective objects including area and location. These properties were then used to computed the monthly mean areal extent of convective objects and the total monthly count of these objects in convective activity hotspots. Long-term changes were computed from these means (presented in Section 5).

The ENSO events considered in this study are obtained from years in which the NINO3.4 SST anomaly peak exceeds $\pm 0.7\sigma$ of a standard deviation from climatology during 1983-2015. The NOAA Optimally Interpolated SST was used to create this index (Reynolds et al. 2002). The El Niño events considered begin in 1986, 1987, 1991, 1994, 1997, 2002, 2006, and 2009 with La Niña events in 1983, 1984, 1988, 1995, 1998, 1999, 2000, 2007, 2010, and 2011.

3. Annual progression of deep convection

September, the start of boreal autumn, is the month in which convection starts to progress southward across the continent as the West African peak of convection wanes. As such, we commence our analysis of the spatial migration of convection in this month.

a. Where and when is there wide-spread convective activity?

In September, large convective systems develop across West Africa, while wide-spread deep convection starts to extend southward into the Congo River Basin (Fig. 2). This extension closely matches the rapid southward migration of the latitude of maximum solar heating during September as shown by the latitudes of the solar zenith on the first and last days of the month are indicated in Fig. 2. Theory and observations show that the latitude of maximum tropical convection is to the first order controlled by the maximum surface moist static energy (MSE) (Neelin and Held 1987; Nie et al. 2010). The seasonal migration of the solar zenith is an important control on this MSE maximum and is therefore shown for reference on Figs. 2–3, along with contours for high MSE. To reiterate what was noted in Section 2(a), these MSE values should be interpreted as a useful but poorly-constrained estimate of the natural system since observations are so sparse in the region.

In October, southward migration of the rain belt brings wide-spread convective activity into southern Congo and Angola. A hotspot of activity develops along the Rwenzori-Virunga Mountains, the eastern boundary of the Congo basin (Fig. 2 Oct) with ccratios > 0.5. Notably, these convective episodes are confined to the west of the subcontinent. Wide-spread convection fails to form in East Africa where MSE remains lower than central Africa. The exception in convective activity is the small region on the southeastern coast near 30°S where convective outbreaks are occasionally observed (Fig. 2) in October. Such outbreaks are often supported by short episodes of synoptic-scale uplift in response to tropical-extratropical interactions (Hart et al. 2013).

Convective hotspots over the Angolan Highlands and East Congo are prominent in November (Fig. 2), despite the latitude of maximum solar heating moving well south of these locations by the end of the month. The more southerly position of the solar zenith provides the necessary forcing to support wide-spread convective episodes along the eastern half of subtropical southern Africa and Madagascar. The subtropical convective activity in south-eastern southern Africa is further invigorated in November and December as low-level MSE increases (Fig. 2). This is the peak season for the organisation of convection into mesoscale convective complexes over the lowland plains of South Africa and Mozambique (Blamey and Reason 2012).

During December, the most frequent convective outbreaks establish over countries along the southern tropical edge, broadly located between 10°S to 20°S (Fig. 2). This includes enhanced outbreak activity over Madagascar with ccratios exceeding 0.35. Diminished convective activity over the Angolan Highlands and East Congo hotspots is associated with the enhanced convective outbreaks along the tropical edge further south.

Fig. 2 shows that the most vigorous and persistent convective activity during January and February is found across eastern southern Africa. Zambia, Malawi, Tanzania, Mozambique and Madagascar become a regional hotspot for large-scale convective outbreaks. This region is known for intense tropical depressions which occasionally develop in to tropical cyclones (Mavume et al. 2009; Rapolaki and Reason 2018). This activity is associated with the large values of low-level MSE in the region. During March, the northward movement of the solar zenith is associated with a decrease in MSE, wide-spread convection in the eastern subcontinent, and invigoration of large outbreaks in Congo Basin and along the west coast of equatorial Africa (Fig. 3). Invigoration of wide-spread convection along the tropical west coast is amplified further in April, as is activity in the East Congo (Fig. 3). The Angolan Highlands and Madagascar maintain local convective hotspots during March but by April, these have subsided (Fig. 3). Convection becomes wide-spread along the west equatorial African coast in May (Fig. 3) with concentrations over the highlands of Cameroon and Guinea including parts of Sierra Leone and Liberia. During June, convective activity is confined to the Sahel despite the solar zenith lying well north in the Sahara (Fig. 3, out of frame). This moisture limitation north of $\sim$15$^{\rm o}$N is reflected in the low-level MSE with the 340 kJ contour effectively bounding the West African monsoonal convection. Similar to June, July (Fig. 3) has lower values of convective coverage (ccratio=0.15-0.25) when compared to values observed in central and southern Africa (ccratio=0.25-0.40) in peak warm season months (Fig. 2). If the frequency of convective outbreaks in both regions were similar at 10 days per month, these values indicate a typical spatial convective coverage of 100% over the eastern southern Africa hotspot versus 70% over West Africa, during the core months in each region. This is in part due to the low-level MSE which rarely exceeds 345 kJ, in contrast to southern Africa in January and February where MSE is widely above that value (Fig. 2).

The return of the latitude of maximum solar heating to the Sahelian belt, during August, enhances wide-spread convective activity (Fig. 3) by $\sim$ 20%. This invigoration is particular prevalent in hotspots in southern Chad and on the northwest edge of the Ethiopian Highlands (Fig. 3d). Early indication of the start of the Congo Basin convection season is also observed in August.

Figs. 2–3 demonstrate that the seasonal march of wide-spread convective outbreaks across Africa has marked asymmetries and distinct convective hotspots. The southward progression of convective activity during September-November is confined to the western parts of the continent associated with geographic asymmetries in rainfall onset reported in Dunning et al. (2016). During the core austral summer months (December-February) the convective rain belt extends across the southern tropical edge countries of southern Africa with the most extensive convective outbreaks observed in the east, adjacent to the Mozambique Channel. This dominance of wide-spread convection in eastern southern Africa persists into March as the rain belt returns northward during the onset of boreal summer. The patterns of onset and peak convective activity in boreal summer (June-August) have a markedly more even distribution across the zonal extent West Africa than those over southern Africa.

b. When is pan-Africa convection most vigorous?

The obvious differences in the extent of deep convective activity in Figs. 2–3, are further investigated in Fig. 4. Here, the histogram of ccratio values from all grid points across the continent is computed for each month. The dashed, grey curve shows the annual average for reference (Fig. 4). September shows a peak in moderate ccratio values (ccratio$\approx$0.22), but in October convective activity the distribution is weighted to more wide-spread activity. This is demonstrated by the fewer grid points with ccratios below 0.25, when compared to the annual average, but more grid points with values above 0.25 compared to the annual averaged (Fig. 4, Oct). April has an even more pronounced version of this pattern with substantially more wide-spread deep convection for those grid points that are convectively active (Fig. 4, Apr). October and April (Fig. 2) are also months in which convection is particularly confined to the Congo Basin.

The combination of wide-spread convection concentrated in the tropical centre of Africa suggests that these transition season months may be periods during which African tropical convection has the greatest potential impact on global circulation climatology. This transition season convection is also closely linked to the bimodal peak in equatorial African rainfall (Washington et al. 2013; Awange et al. 2016). This is in contrast to the June-July period (Fig. 3), when organised convection is spread widely across West Africa with generally lower values of convection coverage (Fig. 4) compared to the annual mean.

Fig. 4 shows, however, that January through March has more wide-spread convection across all magnitudes of the ccratio. As noted previously, Tanzania, Malawi and Mozambique host much of this convection during January and February, with the eastern and western Congo playing host in March, and into April (Fig. 3). This late austral summer activity is dominated by central African convection and lingering activity in the southeast. This is the period of highest convective activity across the continent as a whole, as discussed next.

What is the annual cycle of deep convection for the continent as a whole? The pan-African mean convective activity is shown Fig. 5 (a). March-April sees more wide-spread convection – averaged across the continent – than at any other time of the year. This pan-African activity peaks, as the central African hotspots become most active in austral autumn. In contrast, the June and July core months of the West African monsoon have the lowest values of pan-African convection (Fig. 5 (a)). This is a result

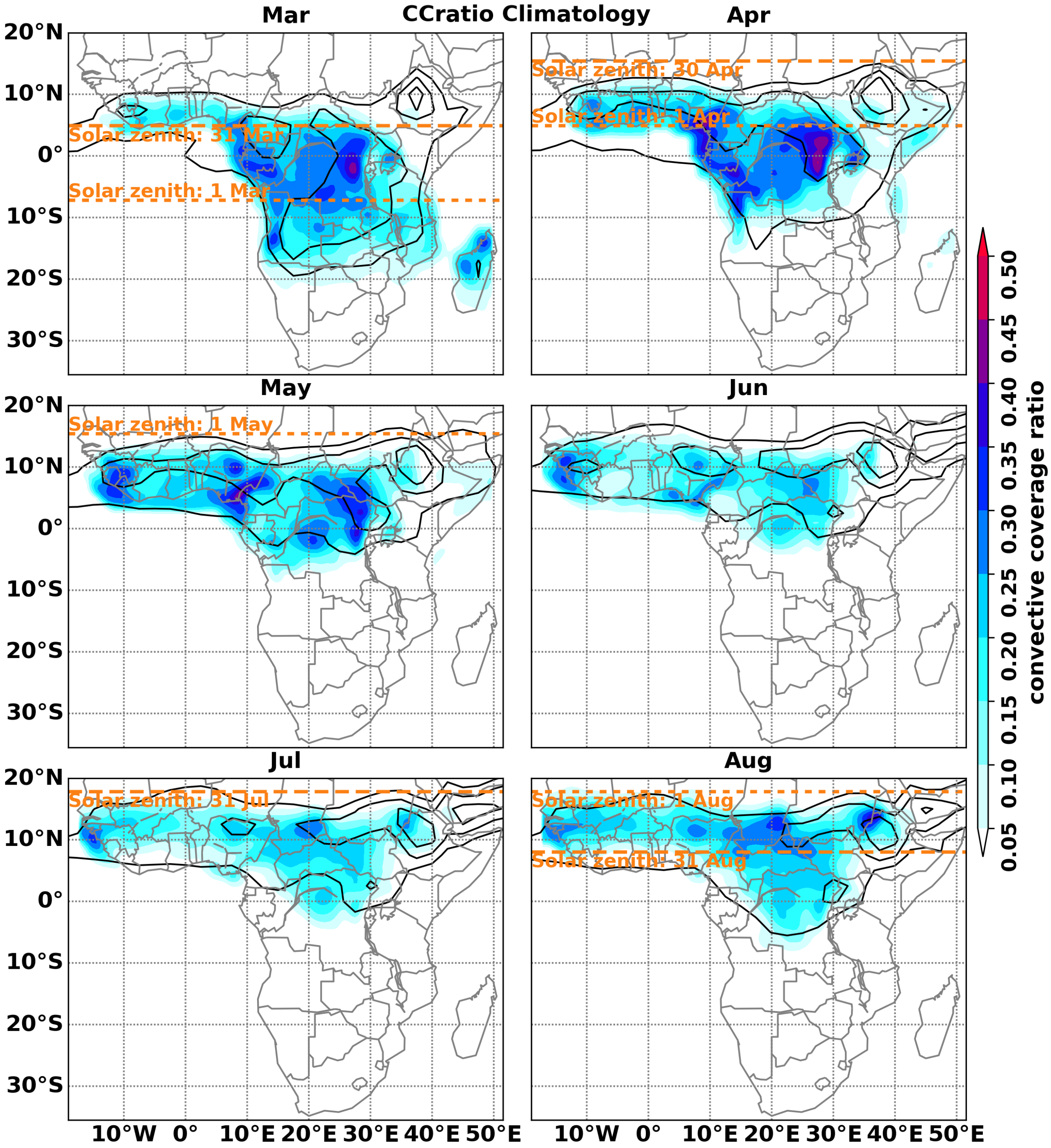

FIG. 3. March to August climatology (1983-2015) of monthly mean convective coverage. Climatology of highest low-level (850hPa) moist static energy contoured at 340, 345, and 350 kJ (black lines).

of the lower values of convective coverage across a narrower zonal band through West Africa, with little activity in central Africa (Fig. 3).

To summarise, pan-African activity in wide-spread convective outbreaks is at a peak in late austral summer during March. The combination of intensity and geographic coherence of this activity in these transition months of March/April, and October to some degree, suggest these are the periods when African convection has the greatest potential to influence the global general circulation.

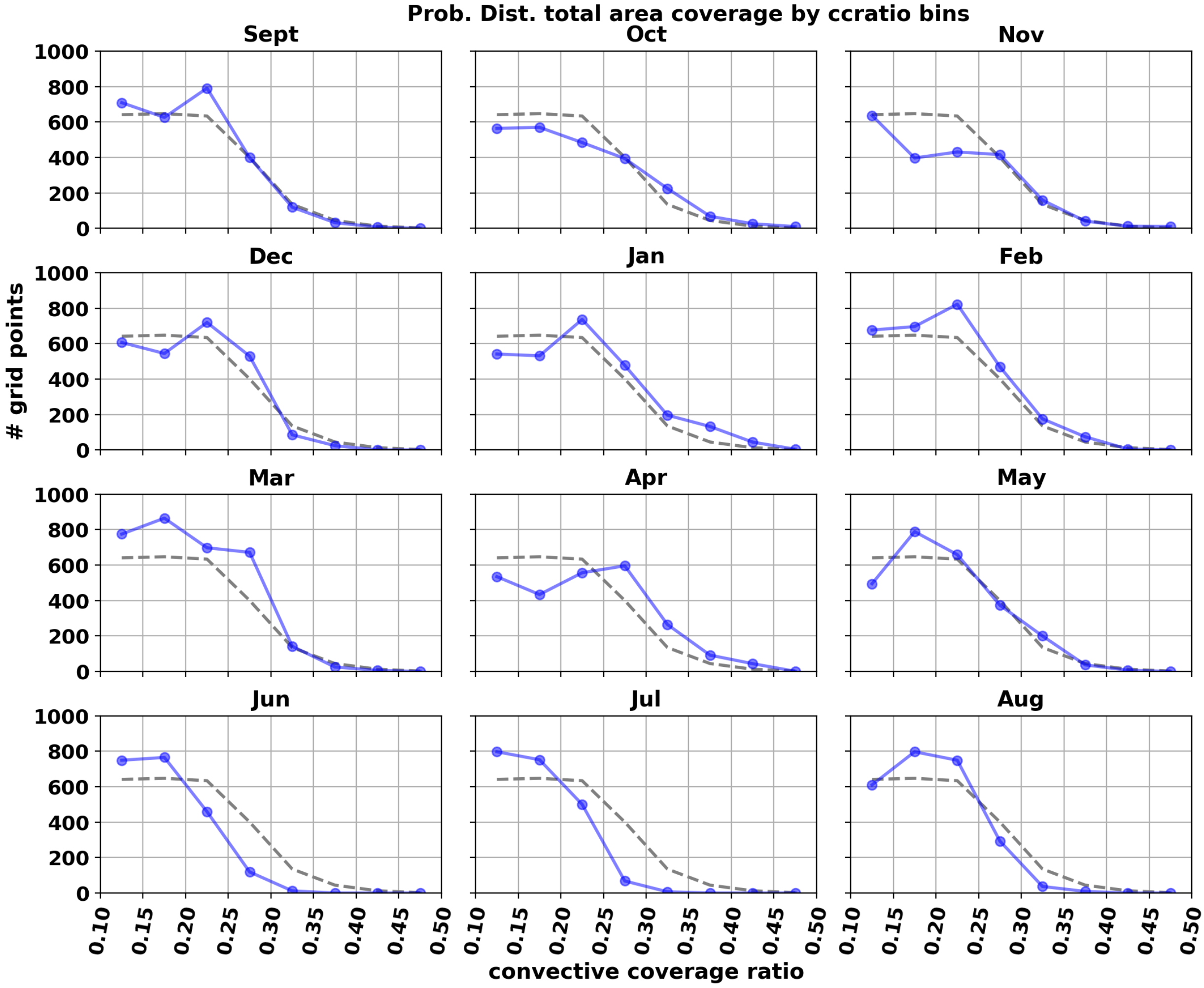

FIG. 4. Probability distribution of wide-spread convective coverage values across Africa for each month (blue lines). The annual mean distribution is shown for reference (grey dashed line).

4. The effect of ENSO on African convection

On interannual timescales, the strongest modification to the annual cycle of the global climate happens during El Niño Southern Oscillation (ENSO) events (eg. Bjerknes 1969; Rasmusson and Carpenter 1982). For many parts of Africa, ENSO is the first order control on interannual variability of the warm season rainfall (Ogallo 1988; Lindesay 1988; Ward 1992). SST variability in adjacent ocean basins has strong impact too, however much of this variability is intimately tied to ENSO variability (Nicholson and Kim 1997). This study therefore considers only this first order impact on the annual cycle of African deep convection.

Fig. 5 (b) shows that ENSO has a distinct impact on pan-African convective activity. The interquartile ranges shown are for annual cycles computed from August through July, to consider the development of the ENSO event during austral spring, the maximum tropical Pacific SST anomalies in austral summer, and decay during austral autumn. For pan-African convection, El Niño events demonstrate an general suppression of the annual cycle relative to La Niña events (Fig. 5b). The climatological peak in March is reduced and the lower activity during June and July is lowered further. The equally plausible alternative view is that these features of the annual cycle are enhanced during La Niña events. As will be shown next when viewed through anomaly maps, the response shown in Fig. 5 (b) is a combination of both responses.

a. Where is the ENSO response the strongest?

1) EL NIÑO COMPOSITE

The composite response in wide-spread convection over Africa to El Niño events is spatially and temporally com-

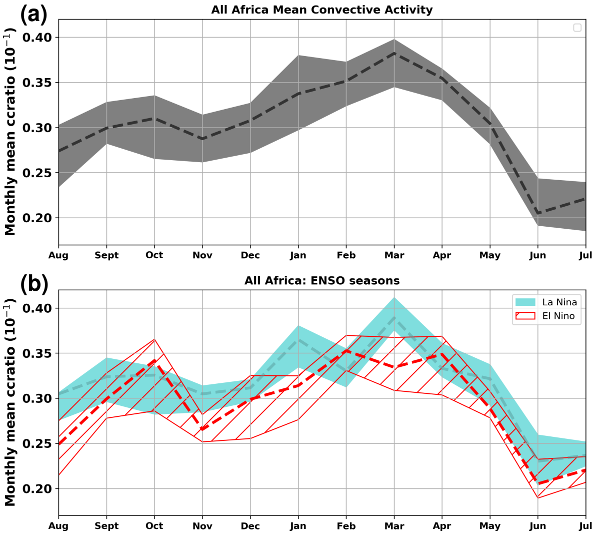

FIG. 5. The annual cycle in pan-African monthly-mean convective activity depicted by median (dashed line) with the interquartile range shaded in grey (a). (b) Seasons in which La Niña events (light blue shading) and El Niño events (red hatching) developed, as shown by the interquartile range in monthly-mean ccratio. Median shown in dashed curves. Seasons are consider from August to July during which ENSO-related SST anomalies reach a maximum in austral summer.

plex due to inter-ENSO event diversity and the stochasticity inherent in outbreaks of organised mesoscale convection (Fig. 6). Nevertheless, robust signals emerge in each month which have similarity to the broad understanding of the regional response to El Niño. Note that the false detection rate as used here (after Ventura et al. 2004) results in p-values ~0.01, so the shaded values are composite responses that are robust despite high levels of noise between different El Niño season responses.

During September of developing El Niño events, there is a weak and spatially discontinuous reduction in organised convective activity throughout the rain belt, consistent with the pan-African signal in Fig. 5 (b). This response switches in October to a weak enhancement of possible wide-spread outbreaks (Fig. 6). By November, a more coherent pattern emerges with enhanced convective activity over East Africa, at the expense of activity in the Congo and subtropical southern Africa. During December the enhancement over east Africa intensifies over Tanzania with strong reductions in wide-spread convection along the southern edge of the tropical rainbelt (Fig. 6). The widely reported (eg. Nicholson and Kim 1997; Dunning et al. 2016) East African rainfall dipole response–drying in the south with wetting in the northeast–is manifest here in December. Malawi and northern Mozambique are the fulcrum of this response in convection. Southern Zambia, Zimbabwe, Malawi, Mozambique and southern Madagascar all have reduced convective outbreak activity. Northeastern South Africa has a significant increase in the likelihood of wide-spread convection. In January, wide-spread convection is reduced in the region of Angola Low (Reason et al. 2006; Howard and Washington 2018) over northern Botswana and Namibia, with vigorous outbreaks over Madagascar (Fig. 6).

During February, spatial coherence of the El Niño response is lost but significant reductions in convective outbreaks are seen over northeastern Namibia and Zimbabwe, with increases over the Angolan Highlands, southern Congo and Tanzania (Fig. 6). Central Malawi again acts as a fulcrum between enhanced convection to the north and reduced to the south. By March convective outbreaks are reduced in regions peripheral to the convective core over the Congo, particularly in northern Namibia and Madagascar and along the central west African coast (Fig. 6).

As the rainbelt moves north during the decaying months of the El Niño events, small but significant decreases in convective activity are noted over west equatorial Africa in April (Fig. 6). In May and June, significant decreases are seen in northeastern Congo. By July, there are weak indications of increased activity across the Sahel, but again, the spatial coherence is weak (Fig. 6).

2) LA NIÑA COMPOSITE

The final months of the West and North African wet seasons experience enhanced wide-spread convection during the development of La Niña events, as shown in the August to October panels of Fig. 7. However, coherent anomalies in convective activity do not develop in southern Africa until January. The climatological hotspot for convection in eastern southern Africa is strongly amplified with more frequent and wide-spread convection over Mozambique, Malawi, and Tanzania,with a reduction to the west over the Angolan Highlands (Fig. 7). During February of La Niña events, convection at the southern tropical edge is enhanced associated with a reduction of wide-spread convection across Angola, the Congo and southern Tanzania (Fig. 7). The Malawi fulcrum in the wetting and drying signal seen during El Niño is also manifested in La Niña during February. However, during March increased wide-spread convection is likely throughout northern Mozambique, Malawi, and Tanzania. Small reductions in March convective outbreaks are also noted near the Angolan Highlands and eastern Congo (Fig. 7).

The northward migration of the rain belt during April of La Niña events is accompanied by strongly enhanced activity of organised convection over west equatorial Africa (Fig. 7). This enhancement persists along the West African coast during May and extends across the convective regions of North and West Africa during June and July (Fig. 7 Jun and Jul). It is this enhancement that is seen in the pan-African convective activity for June and July, relative to El Niño seasons (Fig. 5 (b)).

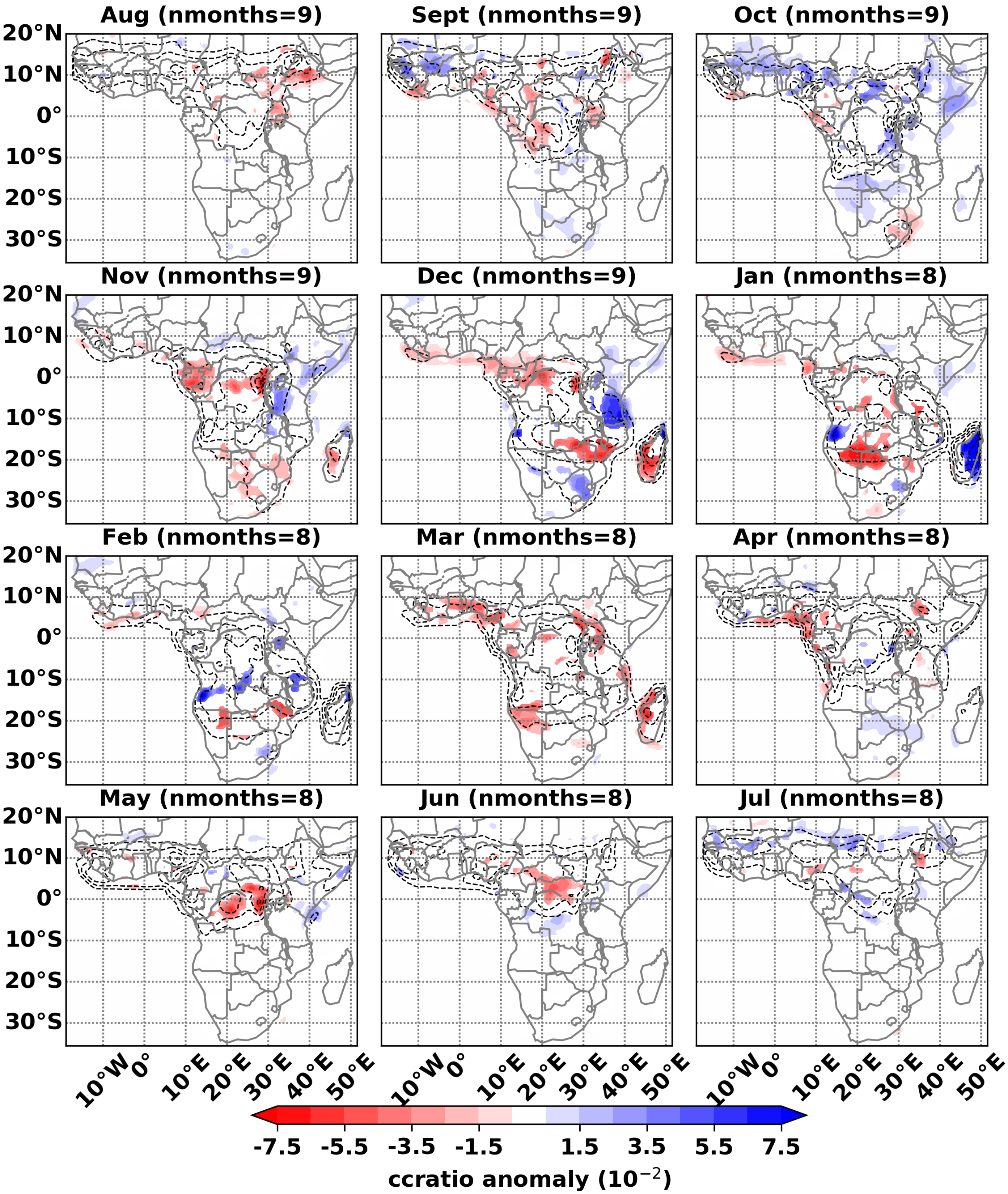

FIG. 6. Composite anomalies in monthly mean convective coverage during El Niño events sequenced from developing phase in Septmber. Anomalies are only shaded where statistically significant as determined by a student-t test with the false discovery rate controlled by the p^*_{FDR}-value computed with α_{FDR}=0.1. For reference, mean climate of ccratio, as in Fig. 1, is contoured from 0.05 at 0.1 increments (black, dashed).

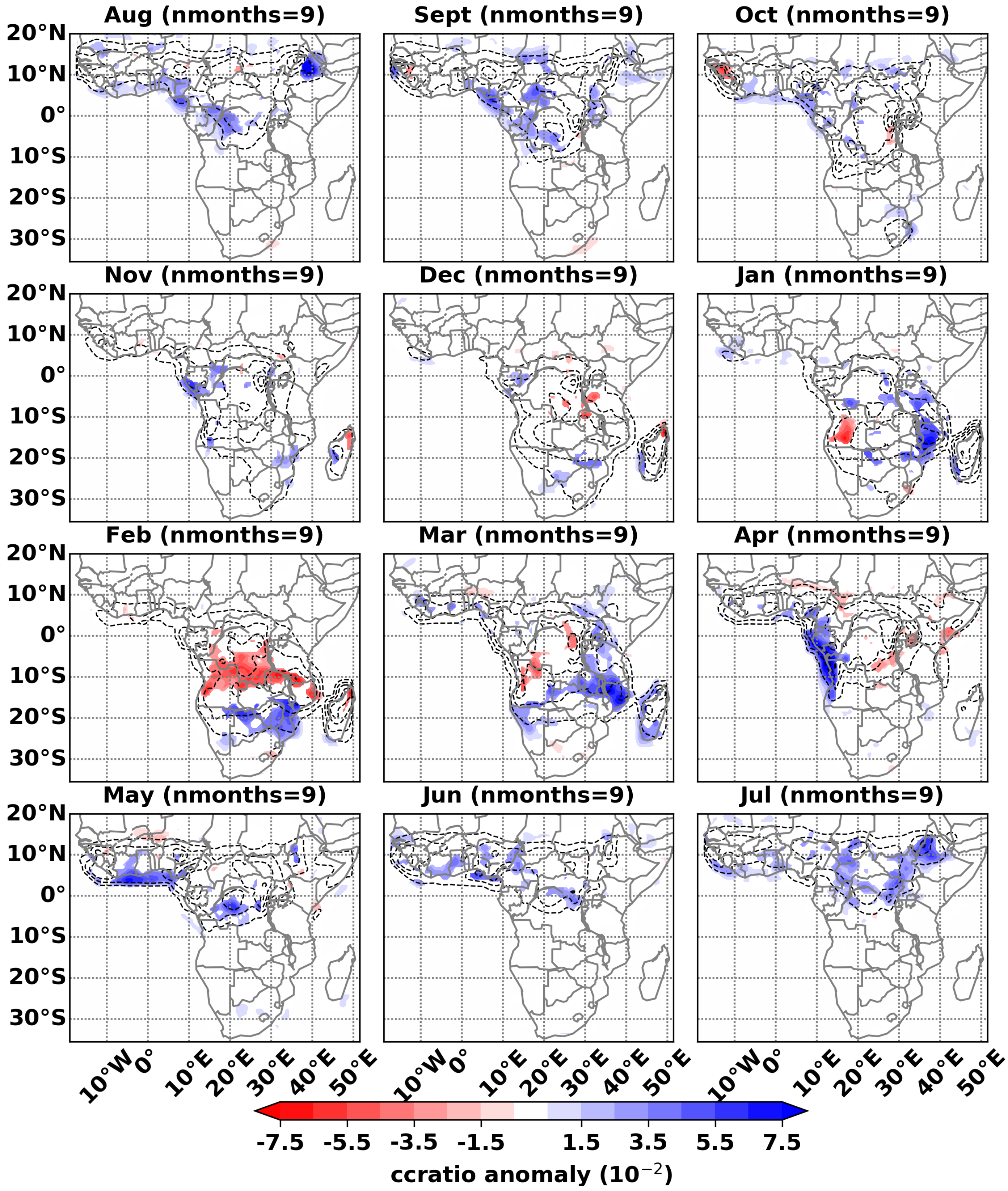

FIG. 7. As in Fig. 6, but for La Nña events.

Overall the response of wide-spread convection to ENSO events is similar to the rainfall response (eg. Nicholson and Kim 1997), but appears more complex. This however, is largely due to month-by-month analysis here. The wetting in East Africa drying in southern Africa summary ENSO signal emerges most clearly in seasonal mean anomalies (eg. October-March as in Dunning et al. 2016). But this summary signal hides the noise inherent in the ENSO response from month to month, as demonstrated in Figs. 6 and 7. The southern African summer response to ENSO has a clear fulcrum between enhanced and reduced convection located over central Malawi and northern Mozambique. The presence of the convective hotspot located in the southeastern Africa during December to February (Fig. 2) predisposes this region to exactly such a response. A hotspot bounded north and south by low convective activity will have north-south wanderings manifested as a north-south dipole in anomalies. The anomalies here show that this hotspot tends to locate further north during El Niño particularly in December and January (Fig. 6), whereas during La Niña the hotspot has amplified activity throughout January to March with a shift to the south during February (Fig. 7). Inter-event variations in the magnitude of the shift during ENSO results in a fulcrum region shown by blank shading separating the dipole anomalies. In these regions, the response to a given ENSO event is highly uncertain both at the seasonal and subseasonal time scales.

b. Identification of deep convection hotspots

Analysis of the regional distribution of convective activity (Section 3) and ENSO-related variability (Section 4a) highlighted convective hotspots across the continent. We now investigate the seasonality, variability and change in these hotspots. Fig. 8 shows the monthly mean widespread convective activity for the month in which climatological convective activity is greatest. This peak is computed individually at each grid point (shading) and the associated year-to-year standard deviation in convective activity for that corresponding peak month is shown in contours (Fig. 8). This figure shows the hotspot regions chosen due to either local maxima in wide-spread deep convective activity (shaded) or high interannual variability (contours) in peak convective activity.

Unsurprisingly, the convective activity hotspots and interannual variability hotspots are often coincident. These hotspots represent areas likely to receive substantial convective rainfall, which for the high-elevation hotspots is crucial to the head waters of regional rivers. Furthermore, given the spatial and temporal scale of convection diagnosed with this metric, it is likely that convective activity in these hotspots influences circulation on regional scales. Hotspots considered further are indicated by the boxes on Fig. 8.

We briefly note that there is potential to define a hotspot over a region in eastern Chad (15°N, 22°E), especially with regards to interannual variability in convective activity (Fig. 8). This roughly corresponds to the Darfur MCS hotspot shown by Jackson et al. (2009). This hotspot and the Ethiopian Highlands display similar annual cycles in convective activity and – as will be noted in Section 5 – similar contemporary increases in peak season activity.

c. What is the effect of ENSO on the annual cycle of convection in the hotspots?

The two equatorial hotspots, west equatorial Africa and east Congo, have a bimodal seasonal cycle in convective activity with relatively low interquartile range through the annual cycle Fig. 9.These correspond to the MCS activity hotspots studied in Jackson et al. (2009). West equatorial Africa has significantly less wide-spread convection during El Niño than during La Niña. This is expressed during the developing stages (September to November) and decaying stages (April to May) of ENSO events, co-incident with the two annual peaks. Convective activity in the East Congo is similarly reduced during May and June of decaying El Niño events.

Over the Angolan Highlands, the November and March peaks in wide-spread convective activity are unaltered during ENSO events. However, La Niña seasons have distinctly lower convective activity during mid-summer, relative to El Niño years. As noted in Section 4a, this demonstrates that the rain belt makes a great excursion into the subtropics during La Niña seasons and remains deeper in the tropics during El Niño seasons. This behaviour is well-captured in the convective activity along the southern African tropical edge: La Niña seasons have substantially enhanced wide-spread convection relative to El Niño seasons (Fig. 9d).

Section 4a discussed how the mid- to late summer ENSO impact was pronounced in the eastern southern Africa, as shown in the composite maps in Figs. 6 and 7. As discussed in Section 2, there is only one hotspot here but the nature of variability creates a response region to the north and the south. This impact is shown in Fig. 9 (e and f) with reduction in convective activity over southern Malawi and Mozambique during January of El Niño seasons and enhanced activity during February in southern Tanzania, relative to La Niña. However, the ENSO response in these two regions is highly unreliable as shown by the widest interquartile ranges in convective activity of all the hotspots across the continent (Fig. 9). These interquartile ranges show that from December through February, the measure of wide-spread convective activity can vary by up to 50% of the full annual range. Such variability is likely a combination of the strong ENSO influence here (Figs. 6-7) and likely geographic variation in the position of the fulcrum of the wet-dry dipole during individual ENSO events.

In contrast to the wide-range of response over eastern southern Africa, Madagascar shows a clearer modification of the annual cycle in convection during ENSO events.

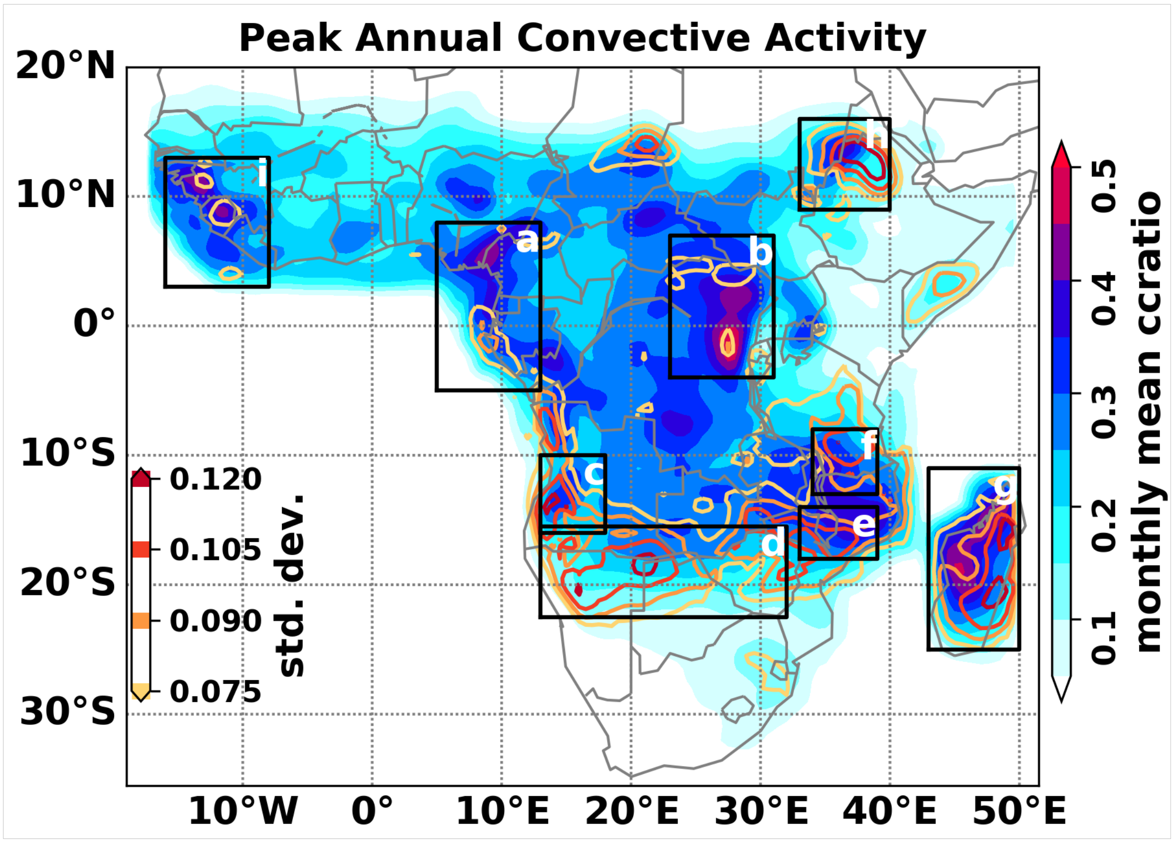

FIG. 8. Peak monthly mean convective activity for each grid point (shaded) and the associated standard deviation in convective activity for that corresponding peak month (contours). Boxes indicate hotspots considered in the annual cycle plots in Figs. 9, 11–13.

The interquartile ranges show enhanced convective outbreaks during January of El Niño seasons however this cannot be deemed statistically distinct from the range observed during La Niña events.

The impact of ENSO on east Africa north of the equator is seen over the Ethiopian Highlands, where outbreaks of wide-spread convection are enhanced in La Niña seasons relative to El Niño years, during the peak activity months of May, July and August (Fig. 9h). The Guinea hotspot, as shown in Fig. 9 (i), is the only hotspot with no discernible impact from ENSO events in any months.

5. Contemporary changes in African convection

There are a number of studies that demonstrate substantial changes in rainfall – including local increases – during the satellite observation record from 1980 to present (eg. Maidment et al. 2015). Increases in intense MCSs and associated rainfall extremes have been particularly pronounced in some locations (Taylor et al. 2017, 2018). Are such increases in convective extremes are reflected in the mean climatology of wide-spread convective outbreaks? We answer this here by considering the continental-scale mean and focusing on the convection hotspots highlighted in Fig. 8. Indeed pan-African wide-spread convection has increased by ∼10% over the last 30 years, shown by the low-pass filtered (blue dashed) annual activity in Fig. 10 (a). Intriguingly, this increase is well matched by the growing asymmetry between Northern and Southern Hemisphere averaged surface temperatures (grey curve, Fig. 10a). Taylor et al. (2017) noted the asymmetric increase in North African temperatures with Zhou (2016) and (Zhou et al. 2016) demonstrating the higher magnitudes of surface warming across the Northern Hemisphere. The result in Fig. 10 (a) demonstrates an association with the inter-hemispheric asymmetry related to the mean temperature of whole Northern Hemisphere. The increase in annual mean activity is distributed across all months as shown in Fig. 10 (b) by the differences in the interquartile ranges of monthly convective activity between the first (orange) and second (blue hatched) half of the record. The

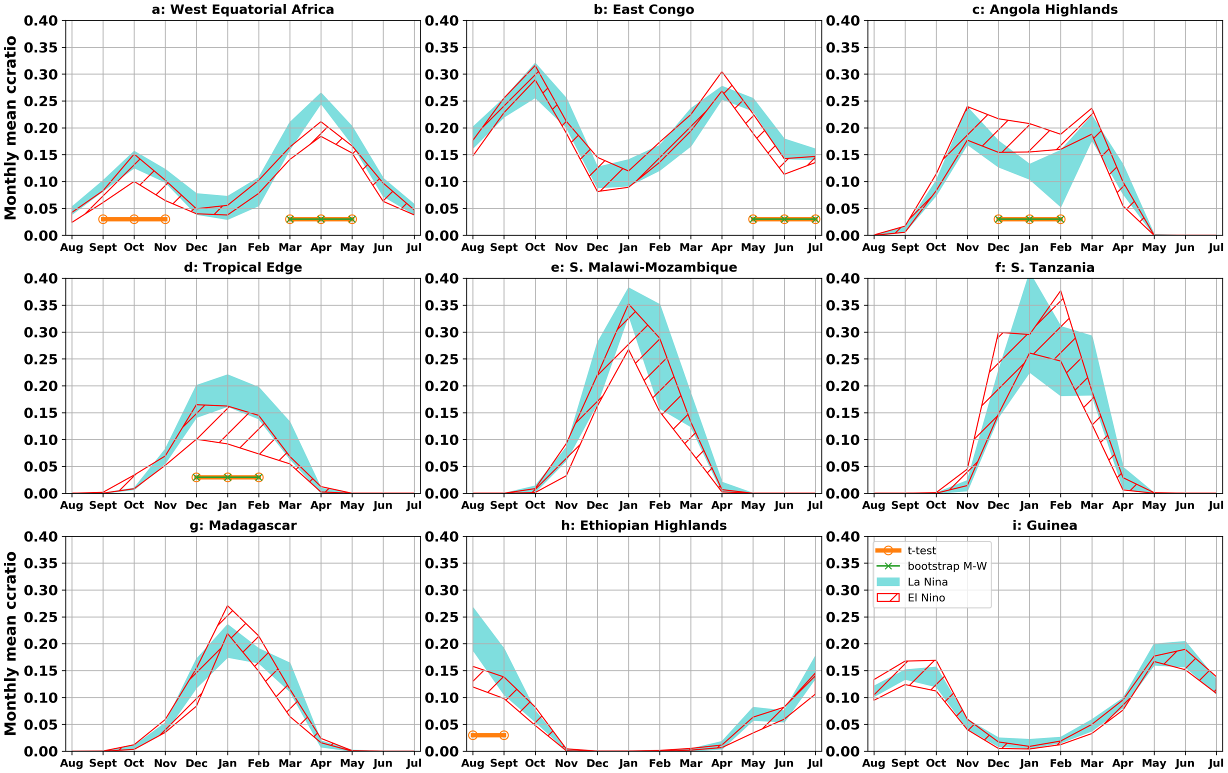

FIG. 9. ENSO impact on the annual cycle of area-averaged convective coverage ratio for the convection hotspots of the African rain belt (locations in Fig. 8). The interquartile range of monthly mean convective coverage is shown by the width of the curves for seasons that occurred during a La Niña events (light blue shading) and El Niño events (red hatching). Seasons are consider from August to July during which ENSO-related SST anomalies reach a maximum in austral summer. Periods in which El Niño and La Niña observations have less than 5% chance of being drawn from the same distribution, as determined by a bootstrapped Mann-Whitney U rank test in, are indicated by green line. Significance is additionally considered with a t-test (orange curve).

largest increase is from June to August and, as will be shown next, this is associated with enhanced convection in the East Congo, Ethiopian Highlands and over Guinea.

a. Contemporary changes in the annual cycles of African convective hotspots

Contemporary trends in African rainfall have been addressed by a number of authors, with most recent results demonstrating increases in ground water reserves – with a few decreases – in local regions across Africa (Rodell et al. 2018). This section specifically considers contemporary changes in the primary convective hotspots on the continent. As noted before, the changes in large-scale convective outbreaks over the hotspots would have implications for the regional water balances and potentially impact profoundly on regional circulation. Fig. 11 confronts the question whether hotspot annual cycles of convective activity sampled during 2000–2015 are distinct from activity observed between 1983 and 2000. Many of the hotspots have seen increased activity in wide-spread convection. Along west equatorial Africa, the increase is visible in the interquartile ranges November through February (Fig. 11a). In the East Congo, there have been notable increases in the mean convective activity in February – Taylor et al. (2018) showed robust February increases of the most intense MCSs – but the most significant increase has been during June to August. This increase makes an important contribution to the pan-African JJA increase shown in Fig. 12 (b). Paradoxically, rainfall has been reported decreasing in East Congo (Zhou et al. 2014). Raghavendra et al. (2018) has proposed that this paradox should be understood as taller and narrower convective storms producing less rainfall but cooler cloud top temperatures over the Congo. This is inline with conclusions in Hamada et al. (2015) that demonstrate a disconnect between extreme convection and extreme rainfall. Futhermore, an increase in vertical extent of tropical convection is a likely outcome of changes to the Hadley circulation in warmer climates, as reviewed by Fu (2015).

Distinct increases in convective activity over the Angolan Highlands and at the southern tropical edge have been observed (Fig. 11 c and d), which corroborates the 2000-2016 increase in ground water storage associ-

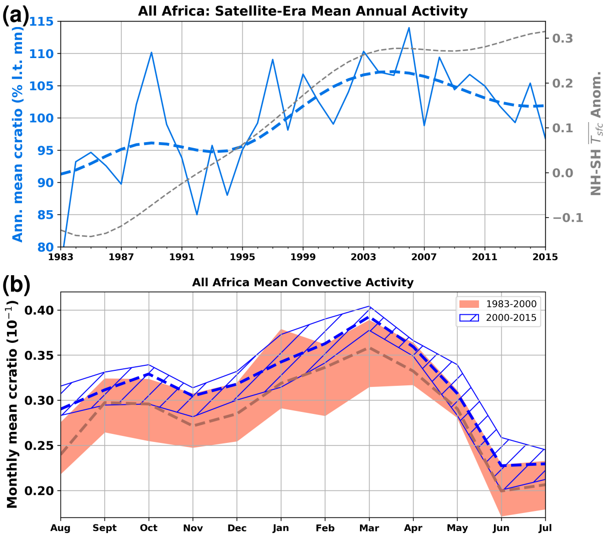

FIG. 10. (a) the annual mean of pan-African convective activity for the geostationary satellite record since 1983 (blue line). A Butterworth filter is applied to only retain the low-frequency variation (>6 years) across the period (blue dashed). The low-pass filtered inter-hemispheric surface temperature difference for the same period is shown in grey line. The distribution of this change across the annual cycle is shown in (b). The interquartile range of monthly mean convective coverage is captured by the width of the curves for the 1983–2000 period (coral shading) and the 2000–2015 period (blue hatching). Median shown in dashed curves.

ated with rainfall increase in this region (Rodell et al. 2018). Little change has been observed over Malawi-Mozambique, southern Tanzania, and Madagascar, which is not surprising since these regions have very large interannual variability which would increase the signal-to-noise ratio, thereby hindering detection of change (Fig. 11 e, f, g).

North African hotspot convective activity has also increased notably during boreal summer. This increase is reflected over the Ethiopian Highlands (Fig. 11h) and, even more prominently over Guinea from May through to October (Fig. 11i).

These increases in convective activity in some seasons at these hotspots is reflected in a general increase in annual mean convective activity too (Fig. 12; a low-pass filter has been used to exclude interannual variability in the signal). Over west equatorial Africa there has been a 10% increase in wide-spread convection, computed relative to climatology (Fig. 12a). These trends are even stronger when considering a ccratio computed from CCD_{60} data, both pan-African and for the hotspots (see supplementary Figs. 1 and 2). This is in agreement with the trends considered specifically for April to June of the Congo (Raghavendra et al. 2018) and the Sahel wet season of June to September (Taylor et al. 2017).

Notably, the two hotspots with the highest interannual variability, over southern Malawi/Mozambique and southern Tanzania, show wide variations in annual mean convection even on the decadal timescales considered here (Fig. 12 e, f). The large noise in the signal in these locations means negligible long-term change is observed. The most profound increases are observed along the southern African tropical edge and the Ethiopian Highlands (Fig. 12d and 12h, respectively), with nearly a third more convection in the 2000s relative to the 1980s. This suggests implications for African Easterly Wave initiation (Mekonnen and Rossow 2011). Indeed, Raghavendra et al. (2019) report increases in activity of the higher frequency tropical wave activity across the tropics, with the equatorial Rossby wave activity notably increasing downstream (westward) of the Ethiopian Highlands. Patterns in outgoing longwave radiation (OLR) over these highlands suggest a northwestward shift in the location of most intense convection (Raghavendra et al. 2019). However, change convective activity is only part of the total change OLR budget and therefore OLR may be a poor proxy for *changes* in convective activity.

The Angolan Highlands and Guinea hotspot have seen more modest increases of about 20%. We note that all of these increases track the disproportionate warming of the Northern Hemisphere relative to the Southern Hemisphere– grey-dashed curves on each panel of Fig. 12 – during the satellite observation era. This intriguing correspondence is in keeping with results of Taylor et al. (2017) related to the warming of the Sahara, but also suggests mechanisms of interhemispheric energy exchange may be at play (Todd and Washington 2004). Further investigation is needed and should build on the work on surface energy balance changes (Zhou et al. 2016; Zhou 2016).

These increases in monthly mean convective activity can be disaggregated into changes in number of convective episodes and the areal extent of these episodes (Fig. 13). Note, however, that increases in intensity (not explicitly considered in this study) would have some impact on areal extent as larger areas of cloud would fall below the -50°C threshold. Most of the hotspots have had increases in the number of convective objects observed annually with wider variability in the mean areal extent of these convective objects (Fig. 13). Increases in activity in West Equatorial Africa, the Angolan Highlands, the southern Tropical Edge, Madagascar, and Guinea seem all to be a result of general increase in the frequency and areal extent of convection (Fig. 13). However, increases over the Ethiopian Highlands are dominated by the growing size of convective objects (Fig. 13h). Both Malawi-Mozambique and Southern Tanzania are dominated by large slow-varying changes in areal extent of convective episodes, further highlighting the large variability inherent over this part of Africa (Fig. 13 e and f).

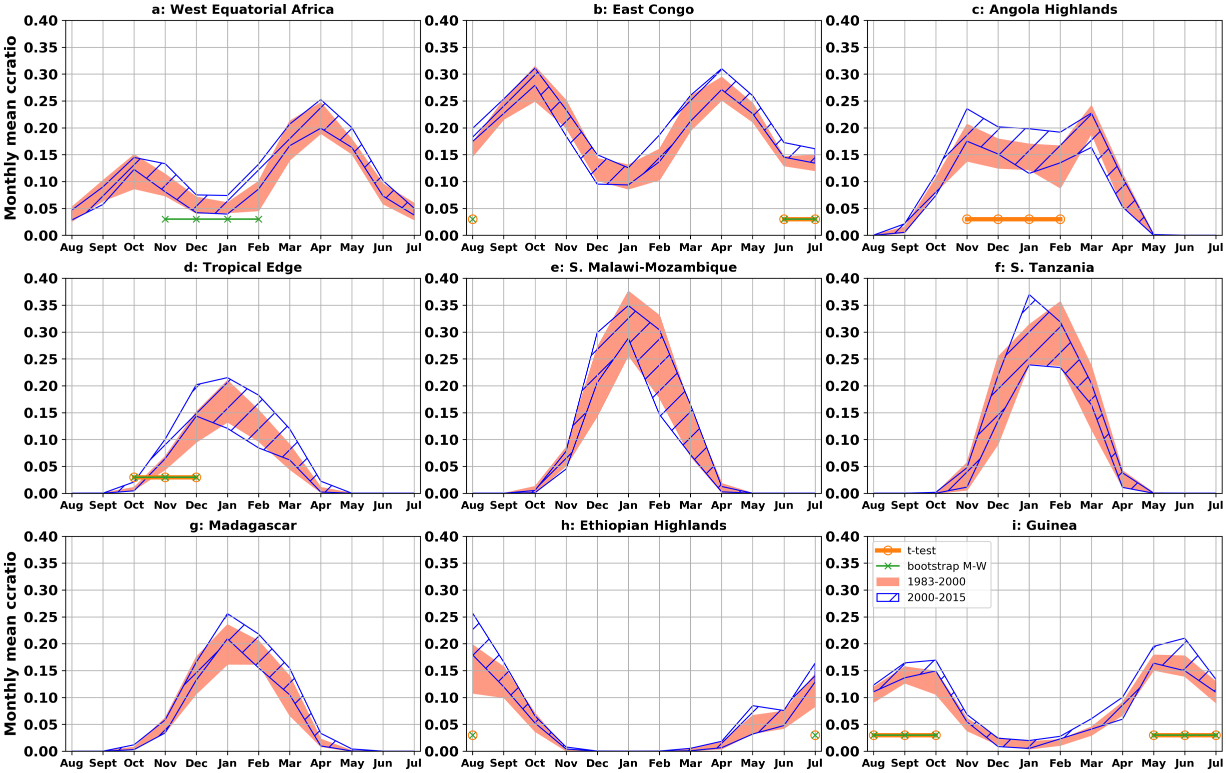

FIG. 11. Contemporary change in the annual cycle of area-averaged convective coverage ratio for the convection hotspots of the African rain belt (locations in Fig. 8). The interquartile range of monthly mean convective coverage is shown by the width of the curves for seasons that occurred during 1983–2000 (coral shading) and 2000–2015 (blue hatching). Months in which the two periods have less than 5% chance of being drawn from the same distribution is determined by a bootstrapped Mann-Whitney U rank test (green line). Significance is additionally considered with a t-test (orange line).

6. Summary

a. The annual cycle

Pan-African convective activity peaks in March, reflecting the vigorous and wide-spread outbreaks of convection across central and eastern southern Africa. Furthermore, our results have demonstrated that the most wide-spread and geographically coherent African convection occurs in the transition season months of October and March/April. This result suggests energy inputs into the general circulation by African convection may be greatest in the transition seasons.

At a more regional scale, the seasonal march of convective activity in the rain belt is meridionally asymmetric. This is especially true in southern Africa where convection advances primarily down the western half of the continent during October before becoming active in the east during January. This convective activity then retreats from the southeast back into the Congo before the West African monsoon begins. This seasonality of convection is further modulated by regional orographic features with the Angolan Highlands, Virunga/Rwenzori Mountains, Mount Cameroon, and the Ethiopian Highlands, all enhancing convective activity and extending the convective seasons relative to their surrounds.

The relatively low-lying plains and hills of southern Malawi, Mozambique, and Tanzania host the most vigorous convective hotspot of January and February. As highlighted next, this hotspot – with high MSE maintained by convergence of moisture off the Indian Ocean – is the most variable region for wide-spread convective activity anywhere on the continent.

b. ENSO-related interannual variability

The strongest ENSO impacts are during the southern African summer can be understood as an enhanced southward excursion of the convective activity during La Niña and more equatorward contraction during El Niño. This is in keeping with Nicholson (1986) who reported a mode of African rainfall variability in which the tropics and subtropics demonstrated anomalies of opposite sign. This mode is linked to interannual variability associated with ENSO (Nicholson and Kim 1997). The result is that countries along the southern tropical edge are particularly af-

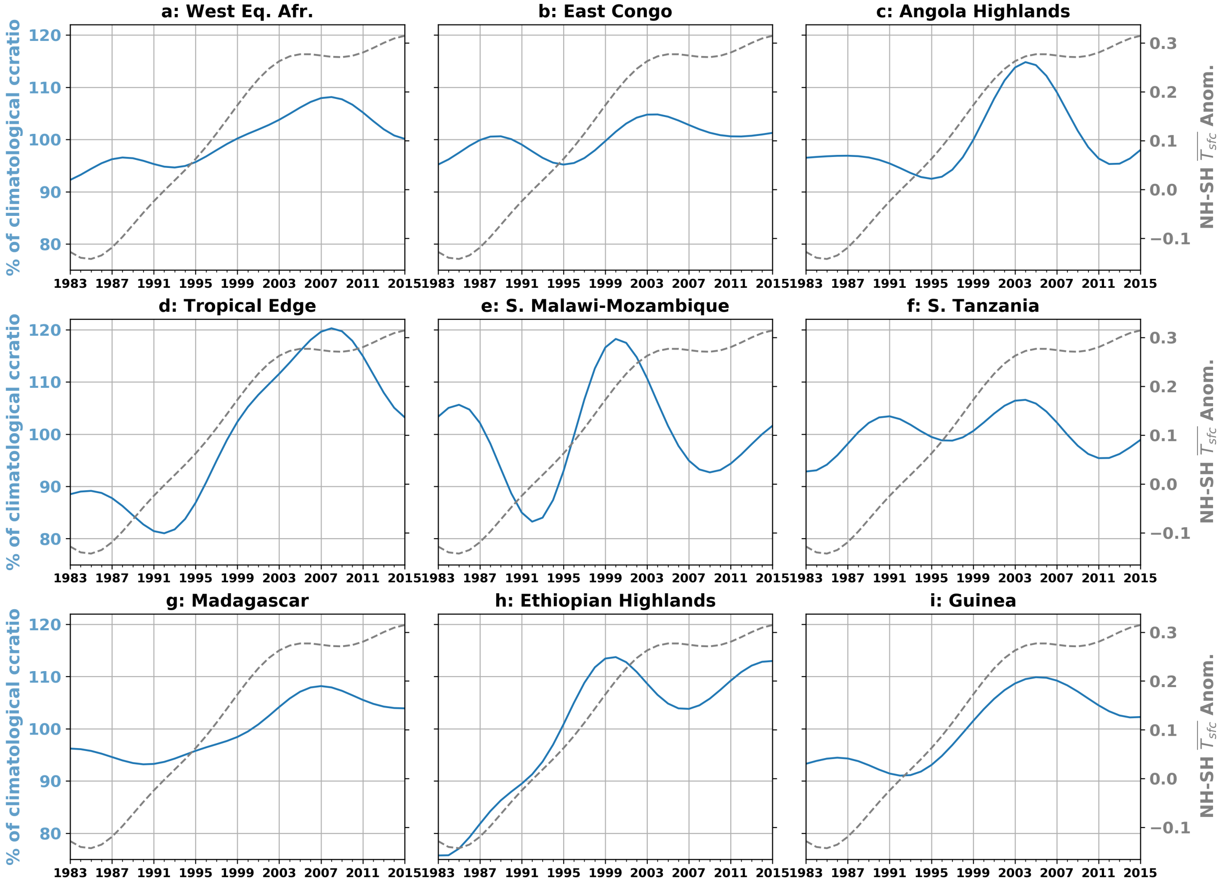

FIG. 12. Low-frequency variation in the annual mean wide-spread convective activity (% long-term mean) for convection hotspots (locations in Fig. 8), as diagnosed from a low-pass (>6 years) Butterworth filter applied to the satellite-era record (blue line). The low-pass filtered hemispheric surface temperature difference for the same period is shown for reference (grey line).

fected by positive and negative ENSO events. A similar yet muted response to ENSO is observed along the northern edge of the rainbelt in North Africa.

The largest ENSO reponses are observed in the occurrence of wide-spread convective outbreaks in eastern southern Africa. The hotspots in convection over southern Malawi/Mozambique and southern Tanzania have the highest observed variability of all the convective hotspots across the continent. These two regions straddle a climate boundary in east Africa, which is seen clearly as the fulcrum of the regional ENSO response: El Niño typically enhances wide-spread convection over Tanzania and reduces it over southern Malawi and northern Mozambique. La Niña typically enhances convection south of the fulcrum, at the expense of wide-spread convection to the north over Tanzania. However, these signals are discontinuous through core summer months, illuminating intraseasonal complexity that is lost in the typical seasonal mean anomalies.

These regional climates that straddle such a sharp climate boundary are inherently prone to high variability as relative small shifts in where this boundary locates year to year can result in large interannual departures in convective rainfall. The likely diversity in the simulated location of such a boundary by different climate models would require careful treatment in regional climate information provision.

c. Contemporary Changes

There has been a distinct increase, during the satellite-era, in pan-Africa wide-spread convection with changes in wide-spread convection of 10-20% of the climatology observed across deep convective hotspots. This broadly corresponds to a pan-African increase in rainfall, a mode identified in Nicholson (1986). But as shown in recent work on Congo rainfall change, more vigorous convection diagnosed by colder cloud tops may in fact be associated with less rainfall in the tropics (Zhou et al. 2014;

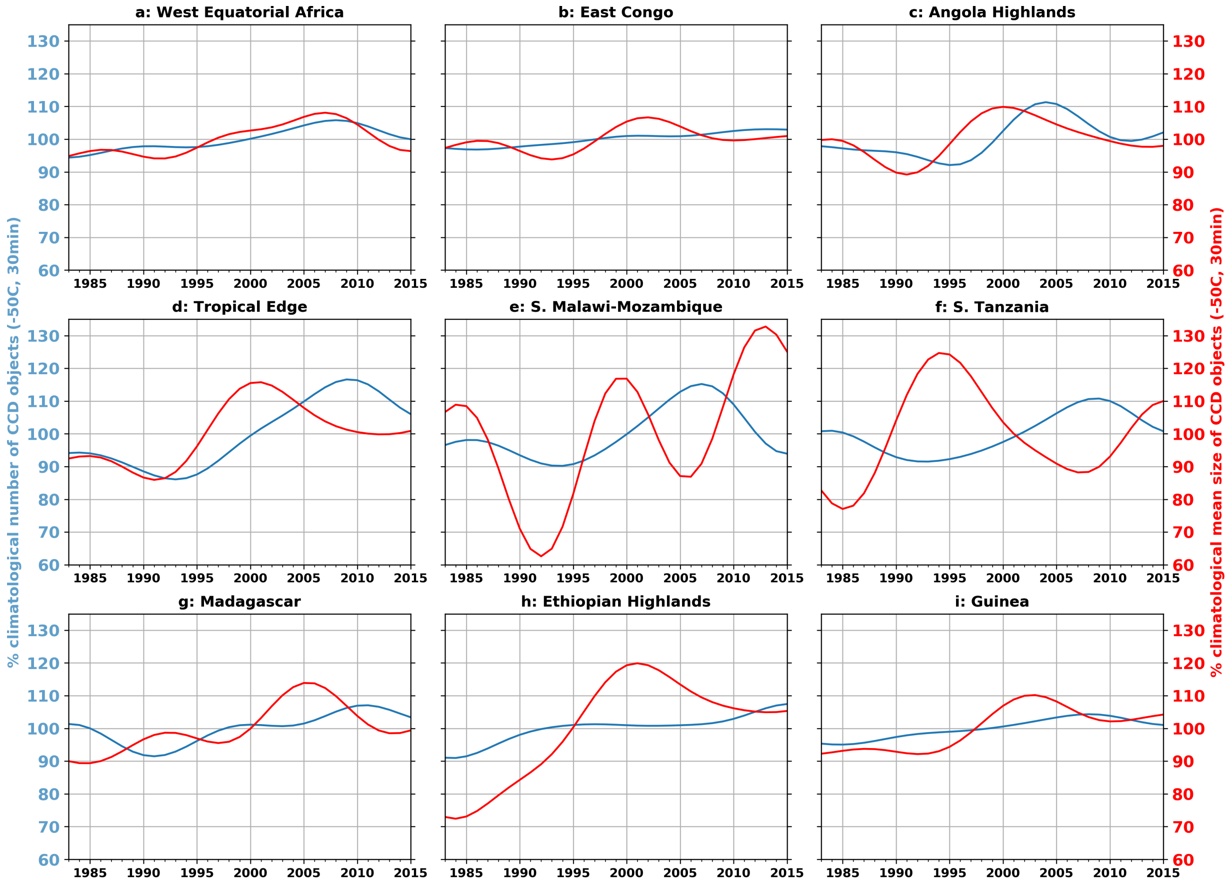

FIG. 13. Separation of ccratio trends presented in Fig. 12 into frequency versus spatial extent of convective actvitity. Annual mean total number of CCD convective objects (blue line) and the mean areal extent of objects (red line), represented by % long-term mean, for convection hotspots (locations in Fig. 8). Each time series has smoothed with a low-pass (>6 years) Butterworth filter to highlight long-term variability.

Hamada et al. 2015; Raghavendra et al. 2018). However, in regions at the tropical edge of the rainbelt such as the Angolan Highlands, more convection does appear associated with more rainfall and increased groundwater recharge rates (eg. Rodell et al. 2018). Similar increases have been observed for most of the hotspots for convection across the continent. These results complement work on rainfall changes in the African monsoon systems (for review see Cook and Vizy 2019).

Statistically distinct changes vary by season across the continent. However, the annual mean changes in convective activity are remarkably consistent with the larger contemporary increase in mean surface temperature of the Northern Hemisphere relative to the Southern Hemisphere. This result is consistent with work over West Africa, which has demonstrated the influence of a warming Sahara on severe precipitation in the most intense MCS systems (Taylor et al. 2017, 2018). This study complements these findings by showing that the hemispheric asymmetry in surface warming is concomitant with pan-African increases the *mean* climatology of wide-spread convection too.

7. Conclusions

This study set out to develop an integrated picture of wide-spread convection over the African continent. This approach has allowed important and long overdue results to surface. The first is the recognition that Africa is most convectively active, in a continental sense, during March. This is primarily a result of frequent wide-spread outbreaks in both the East Congo and west equatorial Africa. A secondary peak in pan-African convection is observed in October. Together, these results imply that the tropical forcing of the general circulation by African convection may be greatest in the transition seasons (Silva Dias et al. 1983).

The second result to emerge from this continent-wide study is that southeastern Africa hosts the strongest and largest off-equatorial convective hotspot. This region, including Madagascar, is most active December to February. Such a large off-equatorial heating hotspot is likely to provide an important forcing to extratropical circulation in the Indo-Australian sector of the Southern Hemisphere (Sardeshmukh and Hoskins 1988).

Wide-spread convection in this southeastern African hotspot also exhibits the largest interannual variability of anywhere on the continent. Much of this variability is related to the influence of ENSO, both due to proximity and the maxima in ENSO anomalies in the Pacific being synchronous with peak convective here.

Throughout the continent the well-documented influence of ENSO is detected in convective activity. In particular, convective hotspots at the edges of core tropical rainbelt are prone to less wide-spread convection during El Niño and more convection during La Niña. This response is reflected in the pan-African mean response, which shows less convective activity across Africa during El Niño.

Finally, this continental-wide study has provided an integration of contemporary changes in convection that have been reported across Africa. Previous studies have focused on convective extremes in particular regions (eg. Taylor et al. 2017; Raghavendra et al. 2018) or derived rainfall products (eg. Maidment et al. 2015). We have shown that general increases in *mean* convective activity are observed everywhere. These increases of 10-20% in annual mean wide-spread convection across the continent have closely matched the growing inter-hemispheric asymmetry in warming. This intriguing result warrants speculation that African convection may be more broadly sensitive to inter-hemisphere energy balances, rather than just warming of the Sahara.

Reconciling the observed annual cycle, variability and change of deep convection with climate model simulations and projections over Africa is crucial to current efforts at regionalising global change. The inability of climate simulations to correctly locate Congo rainfall (Creese and Washington 2016, 2018), in contrast to high-confidence results of change in rainfall onset and season length (Dunning et al. 2018) need careful attention in order to inform climate information needs. And while African convection and rainfall does respond to global forcing, the convective hotspots here identified have potential to provide a first-order forcing on regional circulation. Whether convection-parametrized general circulation models represent these local convective forcings needs to be answered. Is this a role best filled by convective-permitting models?

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Supplementary Figures for Deep Convection over Africa: annual cycle, ENSO, and trends in the hotspots

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ABSTRACT

Contemporary changes in African convection when consider with a -60°C CCD threshold. The main manuscript diagnosed wide-spread deep convection using cold cloud duration based on a brightness temperature cooler than -50°C. Results in the main manuscript showed that convection over Africa has increased during the satellite-era record (1983-2015). These supplementary figures show that this increase is greater for more intense convection as diagnosed using the colder cloud threshold of -60°C. The figures replicate Fig. 10 and 12 in the main text, with the difference that the ccratio was computed from CCD$_{\text{-60C}}$ with a duration threshold of at least 20 minutes.

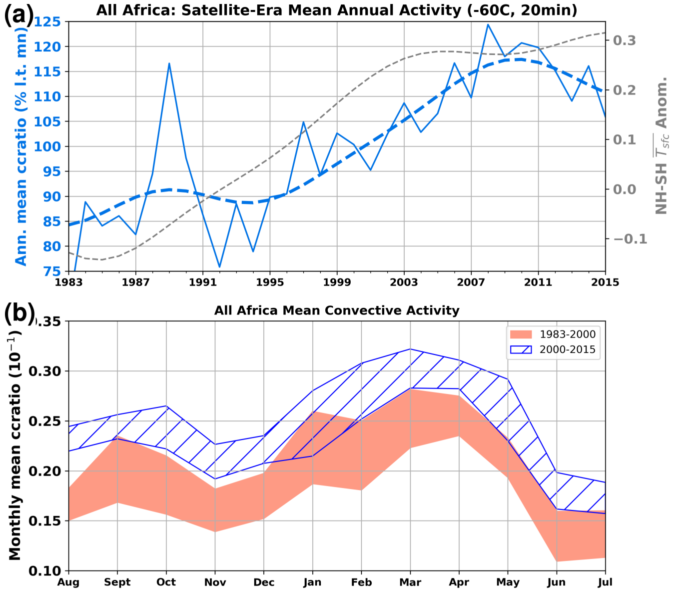

FIG. 1. (a) the annual mean of pan-African convective activity for the geostationary satellite record since 1983 (blue line). A Butterworth filter is applied to only retain the low-frequency variation (>6 years) across the period (blue dashed). The low-pass filtered inter-hemispheric surface temperature difference for the same period is shown in grey line. The distribution of this change across the annual cycle is shown in (b). The interquartile range of monthly mean convective coverage is captured by the width of the curves for the 1983–2000 period (coral shading) and the 2000–2015 period (blue hatching). Median shown in dashed curves.

Adapted from v4.3.2 of the AMS LaTeX template

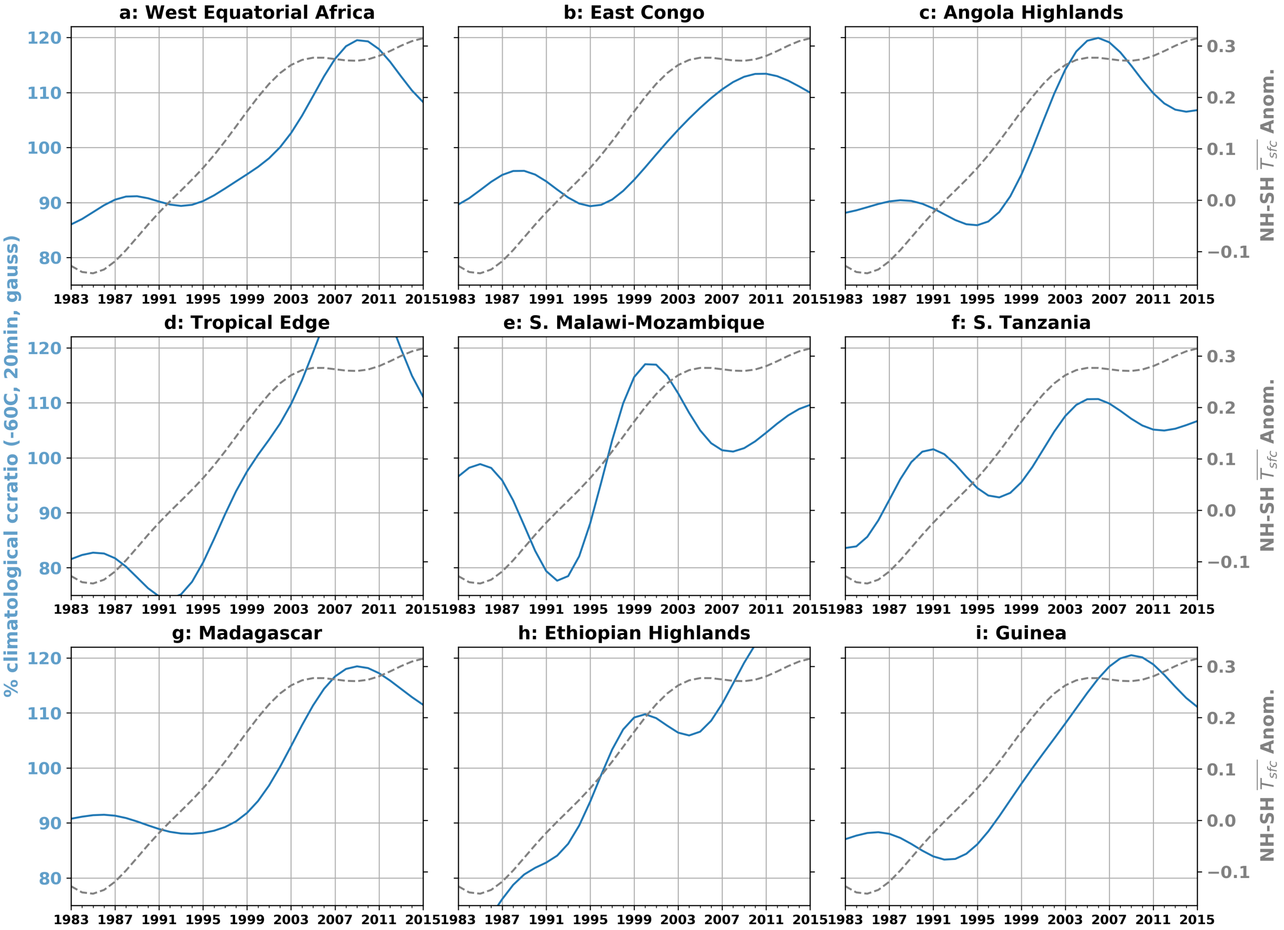

FIG. 2. Low-frequency variation in the annual mean wide-spread convective activity (% long-term mean) for convection hotspots (locations in Fig. 8), as diagnosed from a low-pass (>6 years) Butterworth filter applied to the satellite-era record (blue line). The low-pass filtered hemispheric surface temperature difference for the same period is shown for reference (grey line).