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Lightning and the African ITCZ

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ABSTRACT

The idea that tropical lightning activity follows the motion of the Intertropical Convergence Zone (ITCZ) is based on anecdotal evidence, or at best indirect measurements. Definitive observations of lightning from satellite instruments are used here to demonstrate that the seasonal motion of peak lightning over tropical Africa has the same phase as the migration of the ITCZ but that there is no precise space-time coincidence. It is also shown that over shorter time scales the tropical band of lightning activity does not simply follow the Sun nor does it adhere to the ITCZ. What emerges is a complex pattern of behaviour which, though clearly influenced by solar declination and the ITCZ, is also determined by the underlying terrain and humidity. It is sometimes considered that lightning in the tropics would be a good locator of the ITCZ, it is shown here that this is not the case.

1. Introduction

1.1. ITCZ mechanism

The Intertropical Convergence Zone (ITCZ), or Monsoon Trough, is a band of low pressure encircling the Earth at low latitudes. In the classical model warm, moist air is drawn into the ITCZ as part of the Hadley Cell circulation. The convergence of the northeasterly and southeasterly trade winds, from the northern and southern hemispheres respectively, produces stagnant wind conditions, leading to the term 'Doldrums'. The ITCZ can also be thought of as a 'meteorological equator' (Waliser and Gautier, 1993; Sherwood et al., 2010). The persistence of intense solar insolation combined with high land and Sea Surface Temperatures (SSTs) results in strong convection at low latitudes. As the humid air rises, it expands and cools adiabatically, the accumulated moisture condensing to produce a band of clouds. The resulting warm, dry air diverges near the tropopause and flows to higher latitudes, where it cools and subsides in the subtropics before returning equatorward. This model generally applies rather well in a marine environment, but is less appropriate over the continents where the trade winds are poorly developed (Nicholson, 2009).

The location of the ITCZ varies through the year as the Sun traverses the tropics, resulting in wet and dry seasons as opposed to the warm and cold seasons experienced at higher latitudes. Surface properties determine the dynamics of the ITCZ. Over the continents the ITCZ moves back and forth across the equator in response to the Sun's annual cycle in declination (Waliser and Gautier, 1993). However, the thermal latency of the ocean retards the motion of the maritime ITCZ, which is dictated more by the distribution of SST (Waliser and Gautier, 1993). The intensity of convection within the continental ITCZ also has a pronounced diurnal variation due to the daily cycle of solar heating. This is less apparent over the oceans where thermal inertial damps out the diurnal variation and the daily SST range is small. However, Bain et al. (2010) did find that the extent of the ITCZ over the eastern Pacific Ocean displayed a diurnal cycle, peaking in the afternoon.

Although it is sometimes possible to identify the location of the ITCZ along a given meridian by locating the tropical pressure minimum, this is not always feasible. During the northern hemisphere summer, for example, there is a region of low pressure over East Asia, deeper than the band of low pressure in the tropics, which leads to a consistently decreasing pressure across the equator, so that no tropical minimum exists. It is perhaps due to this problem with obtaining a rigorous location for the ITCZ that it is generally only depicted on schematic maps of the globe. An alternative method for locating the ITCZ uses accumulated dekadal precipitation data. Waliser and Gautier (1993) used a satellite data set indicating tropical large-scale convective systems (rather than simply the presence of clouds) to construct a climatology of the ITCZ. The results showed that the ITCZ exhibits a bias towards the northern hemisphere at most longitudes. This was linked to the fact that warm SSTs also appear to favour the northern hemisphere. It was speculated that the greater land fraction in the northern hemisphere and more extensive ice sheets in the southern hemisphere might also play a role. Chen and Lin (2005) presented a novel technique for estimating the

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mean position of the marine ITCZ based on the distribution of water vapour. This climatology also indicated that the ITCZ remains perennially north of the equator over much of the Earth's oceans.

1.2. *Significance of the ITCZ*

Obtaining global weather observations is problematic due to the fact that measurements in some regions are either sparse, sporadic or completely unavailable. As a consequence, global model reanalyses, which assimilate existing observations with the output of General Circulation Models (GCMs), are often employed. However, these products can be vulnerable to inaccuracies due to limited physics, inadequate parametrisation or scarcity of measurements. Hadley circulation is an important component of all major GCMs and the latitudinal location of the Hadley cell is centred on the ITCZ (Wu et al., 2003). The position of the ITCZ is thus an important factor in modelling the Earth's climate.

Deep convection in the ITCZ produces thunderstorms which result in upper tropospheric water vapour levels becoming more variable. This is more apparent over land than over the adjacent oceans (Price, 2000). The distribution of ozone can also be affected by deep convection (Janicot et al., 2008). Since water vapour and ozone both influence the Earth's radiation budget, it is important to have an understanding of and a means for observing mechanisms which affect their distribution.

Small latitudinal variations in the location of the ITCZ have been linked to changes in solar activity over times scales between decades and millennia (Neff et al., 2001; Wang et al., 2005). Significant effects are seen at locations close to the edge of the ITCZ where latitudinal gradients are large. Over the longer term, changes in the ITCZ may produce sustained drought or flooding.

1.3. *ITCZ and precipitation*

Precipitation has a direct influence on health, water and food resources throughout Africa (Redelsperger et al., 2006). The ITCZ exerts a potent influence on rainfall patterns near the equator, producing abundant precipitation for the greater portion of the year (Xie and Arkin, 1998). A significant portion of tropical precipitation occurs during thunderstorms, which are episodic in nature. The seasonal cycle of precipitation in the tropics and subtropics is primarily dictated by the annual changes in solar insolation. However, the relationship between insolation and precipitation is complex: the Sun's declination varies smoothly throughout the year, yet precipitation and other meteorological parameters respond abruptly, possibly due to different land surface properties (Riddle and Cook, 2008). Using reanalysis data from the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR), Sultan and Janicot (2000) showed that the precipitation over West Africa occupies two quasi-stationary locations, one at 5°N in May and June and the other at 10°N in July and August, with an abrupt transition between these two states.

1.4. *ITCZ and oceans*

The development of tropical convergence over the oceans appears to be associated with large scale SST gradients (Lindzen and Nigam, 1987). Tropical SST must also exceed a critical threshold and be accompanied by convergent winds in order to produce precipitation (Graham and Barnett, 1987). Waliser and Somerville (1994) found that the maritime ITCZ was generally a well defined, narrow band centred from 4° to 10° away from the equator, even when the SST maximum occurred at the equator. This can lead to two peaks in convective precipitation straddling the equator and only results in a steady ITCZ structure when the SST maximum is not located on the equator.

Although the dynamics of the ITCZ over the oceans are principally dictated by SST, they are also constrained by conditions over the adjacent land. As a result, the ITCZ over the Atlantic Ocean and Pacific Ocean exhibits a diversity of structure. Both the topography of the African continent and soil moisture anomalies over tropical Africa have an influence on the location of the Atlantic ITCZ (Hagos and Cook, 2005). In contrast, the South Pacific Convergence Zone (SPCZ), which is an extension of the ITCZ over the western Pacific Ocean, projecting southeast from New Guinea towards French Polynesia (Vincent, 1994), exhibits negligible dependence on adjacent land. The Southeast Pacific Ocean ITCZ, located just south of the equator between 130°W and 90°W (Halpern and Hung, 2001), is active only during March and April and is separated from the ITCZ by a region of divergent winds, low precipitation and low SST caused by upwelling of a tongue of cold water near the equator. It is possible that during El Niño, the absence of upwelling causes the ITCZ to merge with the Southeast Pacific Ocean ITCZ (Halpern and Hung, 2001).

1.5. *ITCZ over Africa*

In contrast to the oceans, the ITCZ over land is often broad and irregular (Waliser and Gautier, 1993). The continental ITCZ is especially apparent over Africa where it exhibits a significant latitudinal range, extending as far south as Zambia and as far north as Burkina Faso. However, the seasonal migration of the African ITCZ varies with longitude (e.g., Nicholson, 2009, Figure 3). During the northern hemisphere summer it is centred around 20°N. In West Africa it is narrow and characterized by a belt of cloud and rain close to the boundary between the humid westerly winds from the Gulf of Guinea and dry air from the Sahel. This band only moves through 15–20° of latitude during the course of the year, and does not extend out over the Gulf of Guinea during the southern hemisphere summer. In East Africa the ITCZ migrates much further south, extending down to approximately 10°S. The motion of the ITCZ over East Africa is thus more symmetrical around the equator, while in West Africa the latitudinal range is limited, remaining entirely in the northern hemisphere. Waliser and Gautier (1993), considering longitudes between 10°E and 40°E, found that the mean latitudinal profile of the ITCZ was centred over the equator and rather symmetric, with only a slight asymmetry introduced by the dry climate of the Sahara north of around 15°N. The shape of the profile was found to remain roughly constant throughout the year, exercising only a seasonal north-south oscillation.

1.6. *ITCZ and lightning*

Vigorous convection within ITCZ clouds results in charge separation and intense thunderstorms (Ávila et al., 2010). Over the entire globe the average lightning flash rate is $44 \pm 5\,\mathrm{s}^{-1}$, and 78% of this is concentrated between 30°S and 30°N (Christian et al., 2003). The intensity and distribution of global lightning changes through the year in a generally deterministic way. Fig. 2 compares the interannual evolution of lightning flash rate density at two locations on the same meridian but on either side of the equator. There is appreciable interannual variability, but a consistent pattern of maxima during respective summers is evident. However, although peak lightning activity appears to occur in the summer hemisphere, it will be shown that it does not simply follow either the ITCZ or the sub-solar point.

Deep convection is especially prevalent over the oceans, producing tall thunderclouds which are not, however, necessarily accompanied by much lightning (Williams et al., 1992; Zipser, 1994;

Ushio et al., 2001). Ortéga and Guignes (2007) using World Wide Lightning Location Network (WWLLN) data, found perennial oceanic lightning over the SPCZ.

Outside the tropics the temporal pattern of lightning usually conforms to a simple sinusoid with a maximum close to the summer solstice, and a minimum around the winter solstice, when thunderstorms essentially disappear (Collier and Hughes, 2011). This annual routine is in accord with the general understanding that lightning is most prevalent at the hottest, most humid time of the year. Maximum temperatures lag the solar declination by a few weeks. Within the tropics the annual cycle departs from this simple pattern and is more appropriately described as the superposition of annual and semi-annual variations, where the phase difference between these two components can vary in a rather complicated way (e.g., Williams, 1994; Williams and Sátori, 2004; Collier and Hughes, 2011). This effect is discernible in Fig. 2 where careful examination reveals that the curves are not strictly monochromatic, having a broader peak (which sometimes exhibits a shoulder) and a narrower trough. Mackerras et al. (1998) found that lightning activity between 5°S and 5°N had a distinct semi-annual component, yielding a bimodal pattern with maxima around the equinoxes. The bimodal pattern is common for most tropical locations where the peaks may be of comparable height or remarkably different. In the latter case this corresponds to the existence of long and short periods of rain (Levinson, 2005). This is apparent, for example, in the pattern of lightning occurrence for Liberia (Collier and Hughes, 2011, Figure 1g). The two maxima coalesce into one as the ITCZ reaches its most northern and southern latitudes, producing a single peak near the solstice. This, for example, is evident in the pattern of occurrence for Mali (Collier and Hughes, 2011, Figure 1b). However, the relative phase of the annual and semi-annual components is not always such as to produce maxima in lightning activity which correspond to the passage of the Sun through the zenith. In addition to the influence of solar heating, large scale atmospheric circulation and surface characteristics play an important role in the seasonal dynamics of tropical lightning.

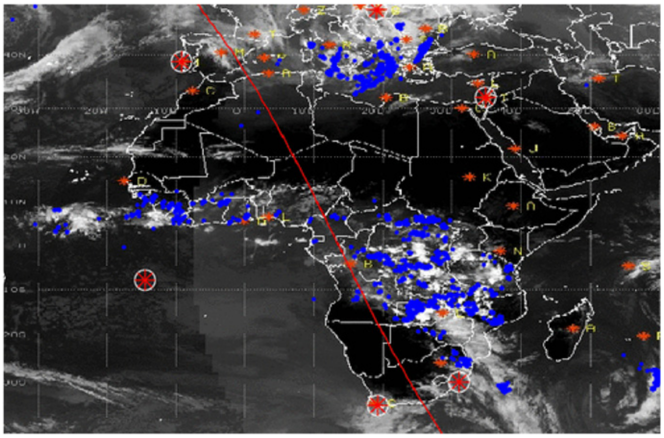

Fig. 1. Lightning activity and cloud cover over Africa between 16:00 and 17:00 UTC on 10 November 2009. WWLLN lightning strokes are indicated by blue dots. Circled red stars show the locations of WWLLN receivers. The red curve gives the location of the day–night terminator. The cloud and lightning lie in an arc which appears to delineate the ITCZ. The cloud image is derived from the 11 μm infrared channel on the 0° Meteosat satellite (http://aviationweather.gov/obs/sat/intl/). Small discrepancies exist between the cloud and lightning locations due to the fact that the cloud image is only updated at 6 h intervals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The possibility of tracking the location of the ITCZ using lightning is attractive as lightning can be continuously located using ground based monitoring systems such as the WWLLN (Rodger et al., 2005; Dowden et al., 2008). With this and similar networks (e.g., Chronis and Anagnostou, 2003), lightning can be located with considerable accuracy from widely spaced stations whereas other methods often require local or regional observations. Lightning maps over Africa, such as Fig. 1, often resemble the generalized schematic diagrams used to illustrate the location of the ITCZ. Here this association is tested using available ground based and satellite lightning data.

2. Data and analysis

WWLLN provides continuous coverage of global lightning activity, facilitating the production of lightning maps with high time resolution. Fig. 3 reflects the relationship between WWLLN lightning activity over Africa and NCEP/NCAR reanalysis sea level pressure for a selection of days in 2009. Fig. 3(d) corresponds to the observations in Fig. 1. In all cases a band of low pressure extends over central Africa, narrowing towards the west but broadening in the east. The pressure distribution is consistent with the qualitative features of the African ITCZ. In each panel the distribution of lightning across Africa lies to the south of the low pressure band and does not provide an accurate indication of its geometry. On a day to day basis this appears generally to be the case and the distribution of lightning does not reflect the location of the ITCZ. This is largely due to the fact that various factors

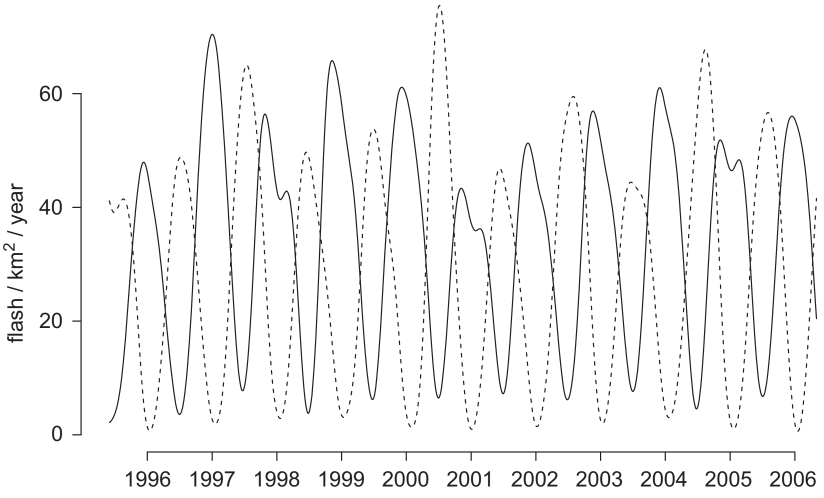

Fig. 2. Lightning flash rate density for two locations centred on the 23.75°E meridian at (solid) 8.75°S and (dashed) 8.75°N.

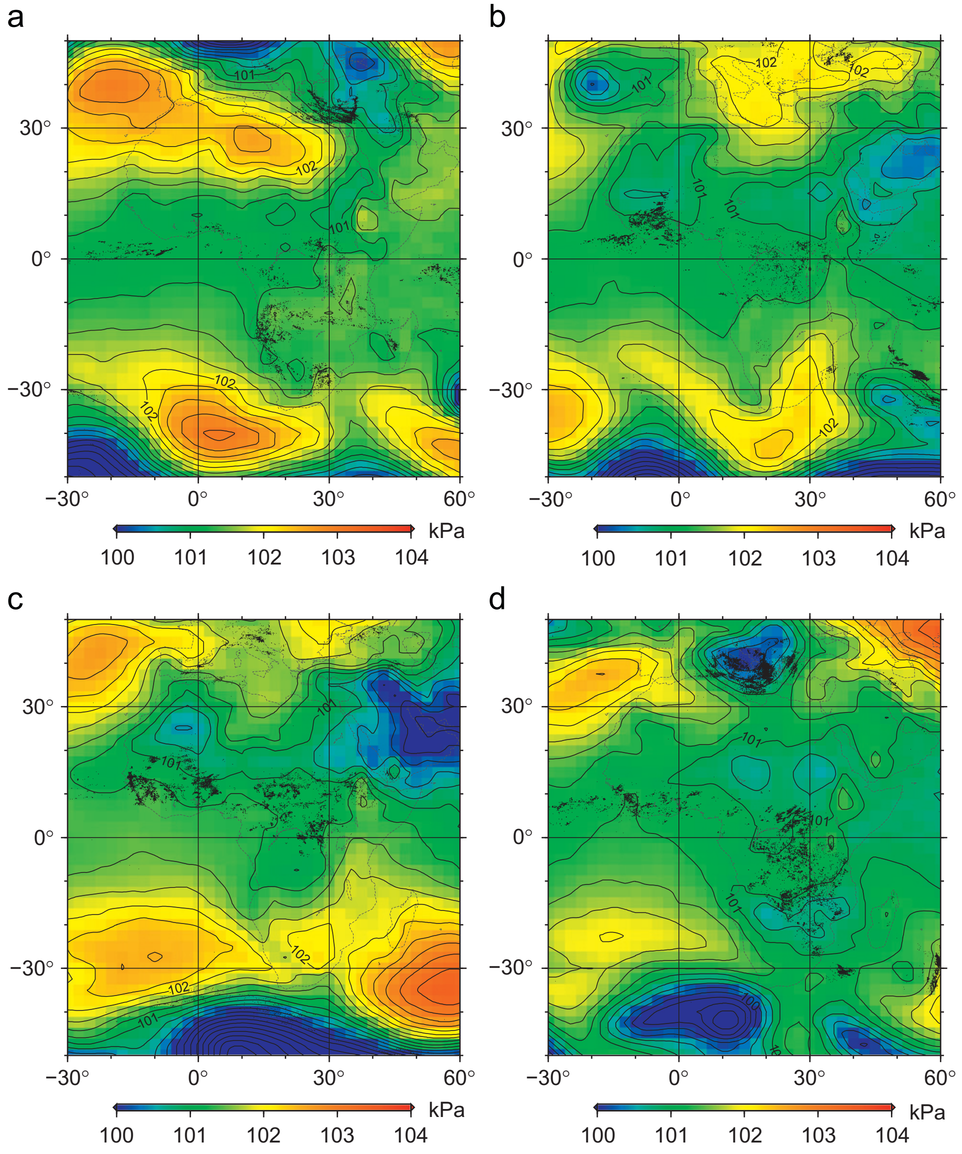

Fig. 3. NCEP/NCAR reanalysis sea level pressure with WWLLN lightning events. (a) 10 February 2009, (b) 10 May 2009, (c) 10 August 2009, (d) 10 November 2009.

besides convergence and convection are instrumental in determining the appropriate conditions for lightning.

The Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS) are two satellite lightning detection systems (Christian et al., 1999; Boccippio et al., 2000, 2002). The Low Resolution Time Series (LRTS) version 2.2 gridded LIS/OTD data used in this analysis are a composite daily time series of total global lightning activity representing a synthesis of the 5 yr OTD (from May 1995 to April 2000) and 8 yr LIS (from January 1998 to December 2005) data sets. The LRTS data have 2.5° spatial and daily temporal resolution, although 7.5° moving average spatial and 110 day temporal low-pass filters were applied to ameliorate the effects of aliasing. The efficiency of LIS/OTD is high relative to that of WWLLN. Although LIS/OTD lack global coverage, the data series extends over a longer period of time.

To study the longer term relationship between tropical lightning and the ITCZ, the LRTS data were partitioned into meridional swathes, each spanning 15° of longitude. Within each swathe the flash rate density was zonally averaged to yield a latitudinal profile. Profiles were generated for each month and consolidated to produce the Hovmøller diagrams in Fig. 4. The annual cycle of lightning activity over tropical Africa is apparent in each of the panels and shows a marked variation across the continent. The slope of the dark band in each panel reflects the meridional speed of the region of maximal lightning activity.

Independent reference locations for the ITCZ were derived from the NCEP/NCAR reanalysis data (Kalnay et al., 1996). Two indicators were employed: the location of the minimum sea level pressure and the peak in the low level convergence determined from the near surface (0.995σ level) winds. Monthly mean sea level pressure and low level convergence were averaged from 1948 to 2009. These data were then zonally averaged to form monthly meridional profiles. The tropical extrema were then located. These represent long term average locations and do not take into account either intra- or interannual variability. As such they indicate the climatological location of the ITCZ and are reflected in Fig. 4 by blue and red lines respectively. It is not possible to construct a reference location for the ITCZ over East Asia and the Pacific Ocean using the first indicator since the low pressure band appears to become bifurcated. Wei et al. (2008) found that an index based on the peak meridional shear of zonal wind speed was a superior indicator of ITCZ location. However, the simple indicators considered here generally provide satisfactory results.

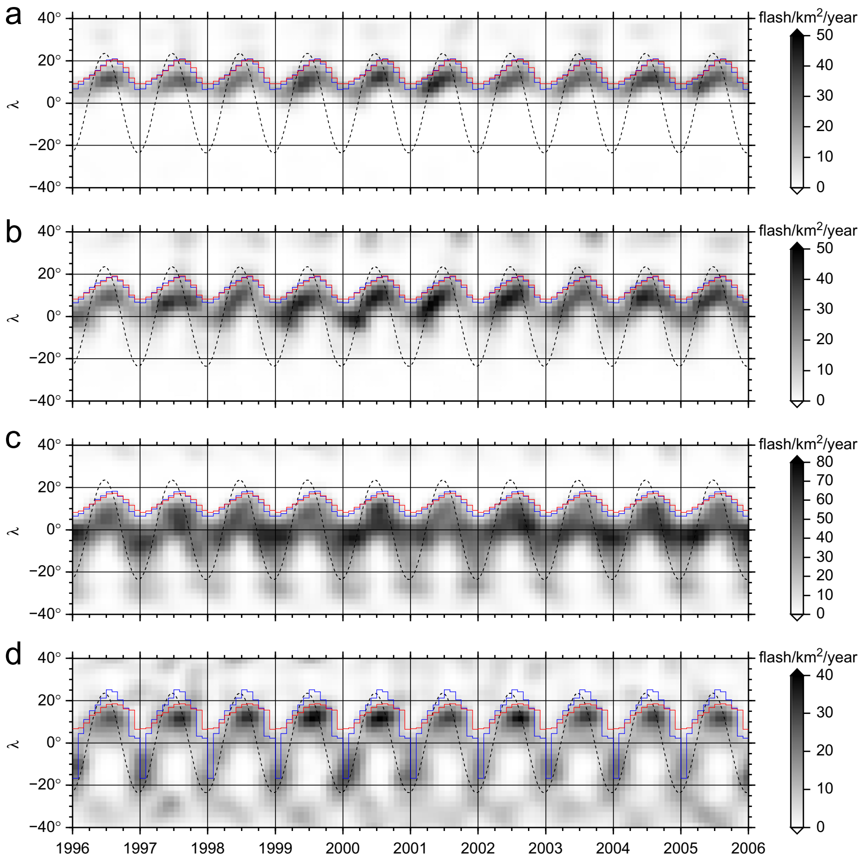

Fig. 4. Hovmøller plot of zonally averaged lightning activity over the African sector for a 10 yr period (1996–2005), reflecting the flash rate density as a function of latitude, λ, and time. The data have been averaged over longitudinal bands of 15° width as follows: (a) from 15°W to 0°E, (b) from 0°E to 15°E, (c) from 15°E to 30°E, and (d) from 30°E to 45°E. The dashed curves indicate the Solar declination, δ. The solid blue and red lines indicate the reference location of the ITCZ inferred from the NCEP/NCAR sea level pressure and wind reanalysis data respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In West Africa (cf. Fig. 4(a), corresponding to the swathe between 15°W and 0°E), lightning occurs mainly in a narrow band with latitudinal width of about 5°, which oscillates about 5° on either side of a mean position of 10°N. Lightning activity increases on its northward migration in the first half of the year. The peak lightning activity and ITCZ are furthest north in July, lagging the maximum solar declination. At this time the lightning maximum is typically 10° south of the ITCZ. The peak in lightning activity is closer to the ITCZ near the equinoxes and is somewhat depressed during the second half of the year. The phase of the lightning motion corresponds to the phase of the ITCZ as measured by the NCEP/NCAR indicators. In this sector neither lightning activity nor the ITCZ extend below the equator, the limit being defined by the coast of the Gulf of Guinea.

Fig. 4(b), representing the range of longitudes from 0°E to 15°E, illustrates behaviour similar to Fig. 4(a) but the lightning band extends further south and has greater latitudinal width. Again the separation of the maximum in lightning activity and the ITCZ is about 10° near the Summer Solstice.

In Fig. 4(c) the band, which is about 15° wide, extends progressively further south during the southern hemisphere summer. Finally, in Fig. 4(d), in addition to the regular latitudinal migration through the tropics, there is lightning throughout the year between 20°S and 35°S, which is due to persistent thunderstorms over the warm Agulhas Current off the east coast of South Africa.

Waliser and Gautier (1993) found that the migration pattern of the ITCZ over Africa was a nearly sinusoidal oscillation between 10°S and 10°N, in close phase with the cycle of solar declination. The intensity of the ITCZ was also found to be roughly constant throughout the cycle. These results are consistent with the data in Fig. 4. The ITCZ over other regions of the Earth was found to vary significantly in intensity, structure and phase during the course of the year (Waliser and Gautier, 1993).

It is important to note that the maximum northern latitude attained by the band of lightning in each of the panels of Fig. 4 is consistently around 10°N, but that the extent of the excursion into the southern hemisphere becomes larger towards the east of the continent. A similar asymmetry is also a characteristic of the ITCZ. The northern limit arises from the transition to arid conditions in North Africa, which are not conducive to thundercloud formation.

A careful examination of the data in Fig. 4 reveals that the intensity of the lightning band varies on both intra- and interannual time scales. In Fig. 4(a) and (b) lightning is consistently more intense while the band is moving northward, and weakens during the southward passage. Further east there is not such a regular pattern. The difference in slope between the northward and southward motion of the lightning band is similar to the ITCZ migration rates, moving gradually northward then more rapidly southward. Across the entire continent there is a clear interannual variation, with some years, for example 1999–2001, being considerably more active than others.

Hu et al. (2007) and Xian and Miller (2008) have documented the abrupt transition of the global zonal-mean ITCZ between hemispheres, noting that it was most apparent over particular tropical domains. Similar rapid changes have been observed in the ITCZ and rainfall patterns over West Africa (Sultan and Janicot, 2000; Riddle and Cook, 2008). Hu et al. (2007) suggested that the transition can occur over a time as short as 10 days. Evidence of

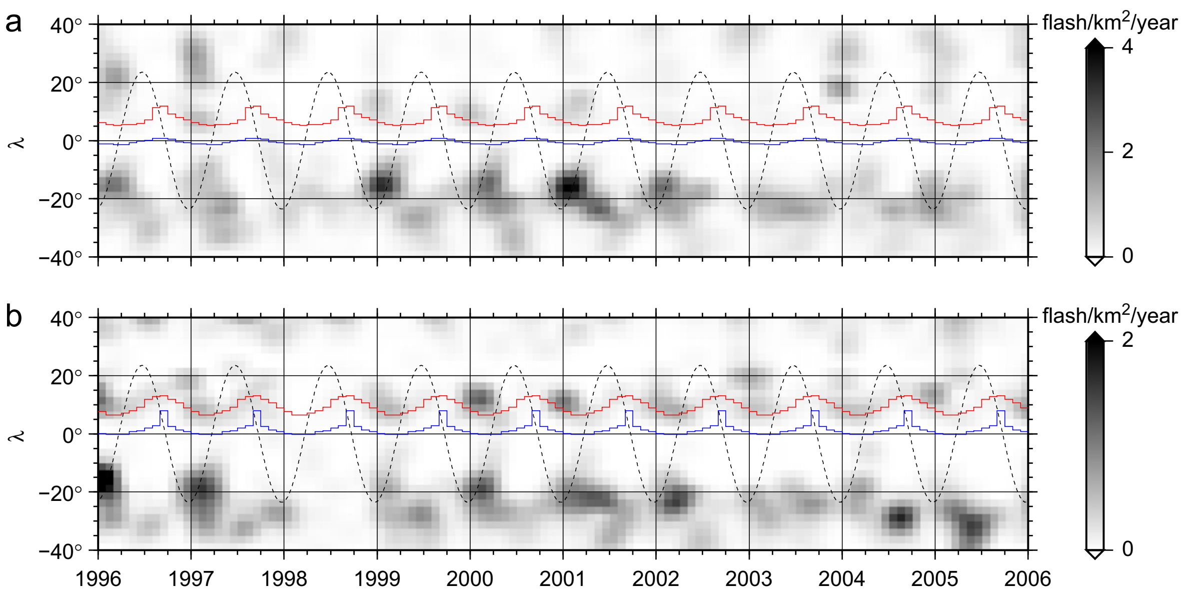

Fig. 5. Hovmøller plot of zonally averaged lightning activity over a portion of the Pacific Ocean. The data have been averaged over longitudinal bands as follows: (a) from 150°W to 135°W and (b) from 135°W to 120°W.

the abrupt transition over the Greater Horn of Africa is apparent in Fig. 4(d), and is consistent with the annual cycle in precipitation, which deviates from the model of a smoothly varying ITCZ (Riddle and Cook, 2008, Figure 9). In East Africa this jump might be associated with a reversal in the sense of the Somali Jet from easterly to westerly.

The intense continental lightning activity over Africa appears to provide a robust indication of the average location of the southern boundary of the ITCZ. By comparison, oceanic lightning activity is relatively mild and not a strong indicator of the ITCZ position. Fig. 5 reflects the latitudinal motion of lightning located over the Pacific Ocean between 150°W and 120°W. The pattern here is not as clear as over Africa, largely due to the lower levels of lightning activity over the oceans. In both panels of Fig. 5 there is evidence of two intermittent bands of lightning located on either side of the equator, although the southern band appears to be more persistent. These bands are not present throughout the year, but display an annual modulation, being elevated during the southern hemisphere summer. There is negligible lightning around the equinoxes.

Whereas interannual fluctuations over Africa are relatively weak, the anomalies over the Pacific Ocean can be quite significant owing to the lower intensity of the ITCZ in this zone. As a result, the variations in Pacific Ocean SST associated with the El Niño Southern Oscillation (ENSO) can have an influence on the location and vigour of the ITCZ over the Pacific Ocean. During La Niña there is often evidence of a double ITCZ over the Pacific Ocean. There is a suggestion of this phenomenon in Fig. 5 where regions of elevated lightning activity are apparent on both sides of the equator with little activity at intermediate latitudes. Elsewhere over the Pacific Ocean the distribution of lightning has a weakly defined pattern similar to that illustrated in Fig. 5.

3. Conclusions

Within the band of latitudes associated with the ITCZ enhanced convective activity, cloudiness, lightning and precipitation may occur over the shorter term without any semblance of systematic structure, and the ITCZ at any instant thus contains a selection of isolated cloud systems. Furthermore, lightning is generated as a result of numerous factors which range from large scale (low level convergence, atmospheric instability and moisture availability), through clouds scale dynamics and finally down to the microphysical. The variability times scales associated with these factors are diverse. However, when averaged over a period which is long compared to the lifetime of individual storm systems, the large scale spatial structure becomes evident.

The results presented here indicate that in the short term there may be only a weak relationship between equatorial lightning activity over Africa and the ITCZ. Over longer periods it becomes apparent that peak lightning activity is generally located on the southern border of the ITCZ. This observation is consistent with the fact that air moving into the ITCZ from the south carries moisture from the Gulf of Guinea and the Congo Basin which, when convected aloft, leads to thundercloud formation. In contrast air moving into the ITCZ from the north originates over the Sahara Desert and thus carries negligible water vapour, inhibiting cloud formation.

Ortéga and Guignes (2007) suggested that lightning activity could be used as a simple proxy for the location of the SPCZ. However, analysis of an extended period of lightning data from LIS/OTD, leads to the conclusion that if tropical lightning were used to locate the ITCZ over Africa it would be consistently placed well to the south of its actual position.

Acknowledgments

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