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Spatial patterns of diurnal lightning activity in southern Africa during austral summer

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ABSTRACT

In the present study we used harmonic analysis to investigate the spatial distribution of diurnal patterns of hourly lightning flash activity during the months of January and February from 1998 to 2013 in southern Africa. The data were obtained from the Tropical Rainfall Measuring Mission dataset collected through a lightning imaging sensor. The spatial distribution of lightning activity during the austral summer season was mostly concentrated over land, with the highest total lightning activity observed over the Congo and Zambezi river basins. The strength of the diurnal cycle was mainly determined by the presence of warm and cold ocean currents along the coastal areas, and the presence of the St. Helena high pressure cell, along with local level processes including land sea breeze convergence, local topography, and surface heating processes. The strength of the diurnal cycle was relatively weaker in the interior of the study area across the Kalahari Desert and Democratic Republic of Congo. The peak lightning activity across most of the study area occurred in the afternoon hours, while a nocturnal peak was observed in the case of the limited maritime activity in the Atlantic Ocean.

1. Introduction

The dominance of the diurnal cycle in weather processes in the tropics is widely acknowledged; the strong diurnal cycles are mainly driven by continentality (distance from large water bodies such as oceans and large lakes), topography, and cloudiness (McGregor and Nieuwolt, 1998). Variations in temperature during day and night lead to diurnal wind patterns triggered by differential heating of land and water and differences in highlands and lowlands. The general absence of fronts and strong depressions favors the development of diurnal wind systems in the tropics. Additionally, relatively small pressure gradients and low wind velocities lead to reduced large-scale turbulence allowing for the formation of local pressure differences (McGregor and Nieuwolt, 1998). As a result, significant diurnal patterns have been observed in convection-related rainfall regimes in the tropics. Majority of the earlier studies examining diurnal patterns of weather phenomena focused on the Western Hemisphere due to the existence of long term data in those regions. Some of these studies include diurnal variations in precipitation patterns at various spatial scales across the North American continent (Balling and Brazel, 1987; Winkler et al., 1988).

However, with the availability of high temporal resolution satellite data from the recently launched TRMM (Tropical Rainfall Measuring Mission) satellite, it is possible to examine diurnal processes in less explored regions of the world including continental Africa. This is particularly relevant for lightning related processes, because of the relatively sparse availability of high resolution data at the global scale before 1998. In the recent years, lightning data from the lightning imaging sensor (LIS) aboard the TRMM satellite have been extensively used to examine lighting related processes across the tropics. For instance, Ushio et al. (2001) found

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an exponential increase in lightning flash rate with increase in storm heights. This was later revised by Boccippio (2002) who connected the lightning flash rate to dynamic and geometric properties of thunderstorms. A subsequent study by Yoshida et al. (2009) found lightning flash rates proportionate to the fifth power of the cloud depth independent of regional dependencies. Furthermore, Albrecht et al. (2011) found a decrease in the highest total lightning flash rates in the tropics, with no systematic trends in median to lower-end of the lightning flash rate distributions.

At a spatial scale, the analysis of global lightning activity by Ávila et al. (2010) revealed an average of 20% greater daily lightning activity in the Southern Hemisphere than the Northern Hemisphere, which was attributed to a larger fractional cover by deep convective clouds in the Southern Hemisphere. In another study, Zipser et al. (2006) revealed the dominance of some of the more severe thunderstorms near the Equator extending southwards into the Congo Basin in continental Africa. Recently, Blakeslee et al. (2012) revealed the highest annual flash rate over the African continent at the global scale. In this context, the analysis of lightning flash density in the Congo River Basin by Williams and Satori (2004) showed the distinct role of surface characteristics including temperature, diurnal temperature range, insolation, Bowen ratio, response to semiannual forcing, inundation fraction, boundary layer relative humidity, and associated cloud base height on the concentration of lightning activity in this region. The Congo Basin is widely referred to as a lightning hot spot in recently published literature (Boccippio et al., 2000; Christian et al., 2003). Collier et al. (2006) also revealed the concentration of lightning incidence close to the Equator with maximum concentrations located over Madagascar (32.1 km^{-2} $year^{-1}$) and South Africa (26.4 km^{-2} $year^{-1}$) during December to February. Their study also indicated a clear diurnal pattern in lightning activity with peak in the afternoon hours, but the spatial variations in the diurnal patterns were not analyzed. A similar pattern of diurnal variation in lightning activity in the form of a late afternoon peak was also observed over the Tibetan Plateau (Qie et al., 2003). Some of the main factors that determine the diurnal variations in lightning activity include the role of orography in Southeastern Brazil (de Souza et al., 2009), and surface temperature conditions modulating the resulting convective processes at the regional scale in India (Siingh et al., 2014). Furthermore, more lightning activity was observed in the tropical and extra-tropical land regions during warm, El Niño episodes, particularly in Southeast Asia (Sátori et al., 2009). Therefore, given the distinct role of surface conditions on convection related processes, recently published studies have indicated substantial variations in the spatial distribution of diurnal patterns of lightning activity in the tropics (Sen Roy and Balling, 2013a, 2013b, 2013c). Additionally, Geerts and Dejene (2005) mentioned the significant presence of a diurnal cycle in the development of convective processes during both boreal and austral summers in tropical Africa, with the occurrence of the deepest storms in the late afternoon, and weaker shallow storms around noon along with substantial regional variations. Similarly, Liu and Zipser (2005) also found the formation of extreme convective systems penetrating the tropopause over central Africa, with substantial diurnal variations. Therefore, in the present study we have analyzed the spatial variations in the diurnal patterns of summer lightning activity in southern Africa during the period 1998 to 2013.

2. Data and methods

Lightning flash activity data for the months of January and February from 1998 to 2013 were assembled from the data collected by the LIS instruments aboard the polar-orbiting TRMM satellite. The design of the LIS instrument lenses decreases its view time rapidly from the nadir to its borders, with decreasing flash counts at the borders. Additionally, when there are very high flash incidence the sensor saturates and both flash counts and view times are decreased (Albrecht et al., 2011). The LIS instrument itself consists of a 128 × 128 charge coupled device (CCD) pixel array, with individual pixel resolutions from 3 to 6 km across, a total field of view of 550 × 550 km^2, and 90–95% detection efficiency. As a result of the sensitivity and dynamic range of the sensor, it can identify lightning despite the presence of bright, sunlit clouds (Christian et al., 1999). The detection efficiency of LIS is 90% of the lightning in the Northern Hemisphere, and 98.6% in the Southern Hemisphere. This accuracy varies seasonally with maximum missed by the LIS sensor at 28% in the Northern Hemisphere in July, 3% in the Southern Hemisphere in January, and the minimum missed by LIS is 1% in both hemispheres (Blakeslee et al., 2012). Furthermore, the detection proficiency of LIS sensor ranges between 73 ± 11% (daytime) and greater than 93 ± 4% (nighttime) with the storm scale location accuracy at 4 km with limited regional bias (Boccippio et al., 2002). As a result of the TRMM satellite's movement in an "x-forward" or "x-reverse" attitude (orientation), the LIS sensor array does not rotate leading to all geographic locations observed by LIS during a given orbit for about 90 s and high spatial accuracy. Additionally, the 100-day averaging window is adequate to remove aliases of the diurnal lightning cycle from climatological LIS data (Boccippio et al., 1998). Additional detailed information about TRMM lightning data may be obtained from the recently published study by Cecil et al. (2012). In this study we have analyzed the lightning activity during the two convectively active months of January and February in most of the tropics of the Southern Hemisphere, when lightning activity is at a maximum.

The TRMM lightning data are recorded in an hdf format, with the lightning data stored in various groupings of lightning optical pulses, which match with physical features including thunderstorms, flashes, and strokes. We obtained the lightning flash activity from the area files, which are defined as distinct regions of the Earth that have one or more flashes in a given orbit (see Boccippio et al., 1998). These files had records for number of flashes in specific locations, along with the time and period of the observations. There were 16 orbits per day, with lightning flash times and locations stored at about a 5 km resolution.

Next, we developed a matrix with one row for each observation including the critical location measurement of the latitude, longitude, and the time of the lightning flash recorded in International Standard Atomic Time (TAI93). We converted the atomic time values to month, day, year, and true solar time at the location of the lightning flash ranging from 0.00 to 24.00. As seen in Fig. 1, there were 163,906 recorded flashes in January and February during 1998 to 2013 with considerable inter-annual variations