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# A comparison of the fine-scale structure of the diurnal cycle of tropical rain and lightning

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ABSTRACT

In this study, the fine-scale structure of the diurnal variability of ground-based lightning is systematically compared with satellite-based rain. At the outset, it is shown that tropical variability of lightning exhibits a prominent diurnal mode, much like rain. A comparison of the geographical distribution of the timing of the diurnal maximum shows that there is very good agreement between the two observables over continental and coastal regions throughout the tropics. Following this global tropical comparison, we focus on two regions, Borneo and equatorial South America, both of which show the interplay between oceanward and landward propagations of the phase of the diurnal maximum. Over Borneo, both rain and lightning clearly show a climatological cycle of "breathing in" (afternoon to early morning) and "breathing out" (morning to early afternoon). Over the equatorial east coast of South America, landward propagation is noticed in rain and lightning from early afternoon to early morning. Along the Pacific coast of South America, both rain and lightning show oceanward propagation. Though qualitatively consistent, over both regions the propagation is seen to extend further in rainfall. Additionally, given that lightning highlights vigorous convection, the timing of its diurnal maximum often precedes that of rainfall in the convective life cycle.

## 1. Introduction

Tropical climate exhibits variability over a range of space and time scales. From a temporal viewpoint, a rough catalog consists of interannual phenomena (such as El Niño/Southern Oscillation), seasonal cycles, intraseasonal modes (such as the Madden Julian Oscillation), synoptic systems (such as convectively coupled equatorial waves) and the diurnal cycle. Much of this variability (and its geographic distribution) manifests itself in moist variables, such as rain, with the diurnal cycle being one of the more dominant modes.

Early work on diurnal variability of rainfall was limited to regional analysis using ground-based observations (Wallace, 1975; Kousky, 1980; Pathan, 1994); these studies showed that over continental regions, there is a strong preference for late afternoon/early evening rain. Studies based on proxies (Hendon and Woodberry, 1993; Chen and Houze, 1997) suggested that rainfall over the ocean typically tends to occur in the early morning hours; however, some studies (Gray and Jacobson, 1977; McGarry and Reed, 1978; Shin et al., 1990) reported an afternoon maximum in oceanic rain, at least in some regions. One of the earliest global studies of the diurnal cycle, based on station observations, was by Dai (2001). Using 3-hourly weather reports, he found that drizzle tends to occur around the early morning hours over land, versus around midnight over oceans. On the other hand, showery precipitation and thunderstorms tend to occur in the late afternoon hours over land regions.

More recent studies have explored the diurnal cycle using satellite rainfall data (Zuidema, 2003; Barros et al., 2004; Nesbitt and Zipser, 2003; Liu et al., 2007; Hirose et al., 2008; Yang and Smith, 2008; Kikuchi and Wang, 2008; Biasutti et al., 2012; Prat and Nelson, 2014). In addition to verifying results from station data and proxies, a common finding was that the diurnal cycle over land is stronger than over ocean, and is stronger in summer than during winter. Another prominent feature of the diurnal cycle in rainfall is its phase propagation in coastal regions, e.g., along the western coast of central Africa (McGarry and Reed, 1978; Liang et al., 2008), the Bay of Bengal (Yang and Slingo, 2001; Gambheer and Bhat, 2001; Zuidema, 2003), the coast of Sumatra (Mori et al., 2004) and the northwestern coast of South America (Mapes et al., 2003a,b).

The recent availability of global lightning datasets, especially at very fine space and time scales, provides us an avenue to analyze the occurrence of the most intense convection and compare its variability with that of precipitation. Seasonal variations in global lightning occurrence have been documented by Christian et al. (2003) and Blakeslee et al. (2014), based on data from the Optical Transient Detector (OTD).

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Analysis of tropical- and regional-mean diurnal lightning from the Lightning Imaging Sensor (LIS; Christian et al., 1999) has indicated an evening peak in lightning over land areas and an early morning peak over oceanic areas (e.g., see Liu and Zipser, 2008; Sen Roy and Balling, 2013). However, the infrequent sampling from the satellite-borne OTD and LIS has mostly limited the analysis of the geographic distribution of diurnal lightning variability. Virts et al. (2013a) demonstrated the ability of ground-based lightning networks to capture known features of the diurnal variability of convection near coastlines and topography in select tropical regions.

No comprehensive documentation of diurnal regimes of lightning, or comparison with those of rainfall, has been attempted to date. In this short note, we systematically document the fine-scale structure of tropical diurnal variability of lightning, and compare it with that of rainfall. Specifically, we begin with a global perspective, i.e., establish the dominance of the diurnal mode of lightning variability, and make a comparison of the geographical distribution of its phase with that of rainfall. As a more stringent test of the ability of lightning to capture convection, we then focus on two regions, the island of Borneo and the equatorial Pacific and Atlantic South American coasts, where the coastal propagation is unconventional.

## 2. Data and methods

Our study uses 15 years (1998–2012) of Tropical Rainfall Measurement Mission (TRMM 3B42) data covering the global tropics (30S–30N), and 4 years (2008–2011) of lightning data from the World Wide Lightning Location Network (WWLLN). A detailed description of the rainfall data can be found at http://trmm.gsfc.nasa.gov/3b42.html (see also Simpson et al., 1996; Huffman et al., 2007). The rainfall product has a temporal and spatial resolution of 3 h, and $0.25° \times 0.25°$, respectively. Several validation studies of TRMM 3B42 rainfall data have been performed with ground-based observations and the rainfall estimates are generally considered reliable (Nicholson et al., 2003; Rahman et al., 2009; Shin et al., 2011; Mantas et al., 2015). It is worth noting here that we analyze the new and improved TRMM 3B42 product (V7) (e.g., see Liu, 2015), while many previous studies on the fine-scale structure of precipitation have used V6 data.

Documentation of the ground-based lightning data used in this study can be found at http://wwlln.net (Dowden et al., 2002). The WWLLN network consisted of $\approx$70 stations at the end of 2011 (station locations are shown in Fig. 1 of Virts et al., 2013b) and locates lightning to within $\approx$5 km and $<$10 μs (Abarca et al., 2010). Its global detection efficiency of $\approx$10% (Rodger et al., 2009; Abarca et al., 2010; Hutchins et al., 2012; Rudlosky and Shea, 2013) enables it to detect nearly all lightning-producing storms (Jacobson et al., 2006). WWLLN detects proportionately more lightning over ocean and less over land compared to optical lightning sensors (Rudlosky and Shea, 2013; Hutchins et al., 2013). For the purposes of this study, WWLLN lightning observations were assigned to a spatial grid matching that of the TRMM 3B42 dataset. Hourly maps of lightning frequency were generated based on the number of flashes observed in each grid box, which are then cumulated in time to obtain a 3-hourly lightning dataset.

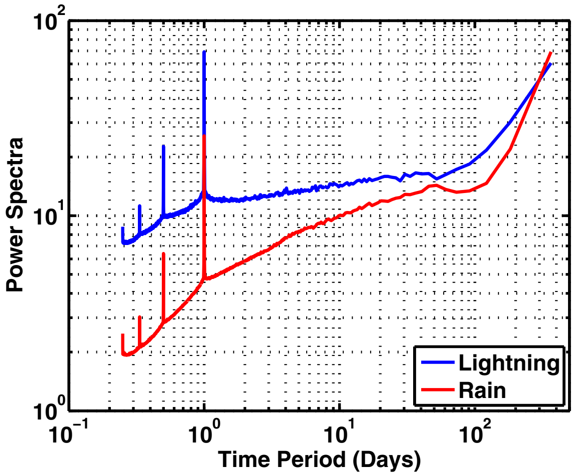

**Fig. 1.** Climatological power spectrum of lightning (blue; 2008–2011; WWLLN) and rain (red; 1998–2012; TRMM 3B42V7) based on 0.25-degree, 3-hourly observations. The climatology shown is the spatial average of the spectrum estimated at each grid point.

We follow different approaches to estimate the time of day when maximum rainfall/lightning is observed. For the TRMM 3-hourly data, for which a longer period of record (1998–2012) is available, we estimate the time of day when maximum rainfall is observed, using harmonic analysis. Specifically, we first compute the Fourier transform of the 3-hourly rainfall at each grid point for every year. (The number of samples per grid point per year is $365 \times 8 = 2920$.) Following this, a time series of rainfall anomalies is constructed by removing (zeroing) all Fourier coefficients corresponding to time-scales greater than 1 day. This filtering procedure is mainly aimed at isolating diurnal characteristics (equivalently, removing the influence of longer time-scales). In other words, the reconstructed time series, referred to from here on as the diurnal anomaly, only contains diurnal (and subdiurnal) variations. From this diurnal anomalies time series, we identify a 3-hour period (peak octet) in which the anomaly is a positive maximum for each day for 15 years. The mode of the frequency distribution of the peak octet is estimated and used to characterize the time of maximum rainfall. For more details on the filtering as well as the possible pitfalls in using the climatology of 3-hourly rainfall for identifying the time of maximum rainfall, we refer to Sahany et al. (2010). For the WWLLN 3-hourly data, we construct the diurnal anomalies by removing the daily mean climatology (2008–2012). Finally, the phase of the diurnal maximum is the 3-hour period with the highest number of lightning strokes.

## 3. Results

### 3.1. Global tropical features: rain vs. lightning

A defining feature of rainfall is that regions with high mean also exhibit large variability (for instance, monsoon hotspots and intertropical convergence zones; see Gershunov and Michaelsen, 1996; Chattopadhyay, 2012). This is also true of lightning (figure not shown). In order to assess the distribution of variability across different timescales, we estimate a point-wise power spectrum; specifically, the spectra of lightning strokes and rainfall at each grid point are computed and then climatological spatial averages constructed (Fig. 1). Besides the considerably “reddish” character of rain compared to lightning, it is quite clear from the spectra that seasonal and diurnal cycles are the most dominant timescales in both the observables. Note that this method of estimating the spectrum is a local point of view and, by construction, suppresses longer timescale variability, as seen by the relatively flat nature of the spectrum between 2 and 100 days.[1]

Having established the dominance of the diurnal cycle of rainfall and lightning, we now focus on the diurnal phase (3-hour period) of maximum rainfall/lightning. Fig. 2 shows the climatology of this phase for rainfall (left column) and lightning (right column). The well-documented preference for an evening maximum over continental land is clearly evident from the figure, as is the more complex behavior near mountain ranges such as the Himalayas and Andes. In addition, in coastal regions, an oceanward propagation of the phase of the diurnal maximum, as noted by several previous studies, is observed. Examples

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[1] A comparison of the ratio of the variance of diurnal anomalies (time scales $\leq$ 1 day) to the total annual variance of rain (e.g., Ruane and Roads, 2007) and lightning shows a better match over continental regions than over open oceans.