Lightning in the North American Monsoon: An Exploratory Climatology

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ABSTRACT

Temporal and spatial distributions of the North American monsoon have been studied previously with rainfall and satellite data. In the current study, the monsoon is examined with lightning data from Vaisala’s Global Lightning Dataset (GLD360). GLD360 has been operating for over three years and provides sufficient data to develop an exploratory climatology with minimal spatial variation in detection efficiency and location accuracy across the North American monsoon region. About 80% of strokes detected by GLD360 are cloud to ground. This paper focuses on seasonal, monthly, and diurnal features of lightning occurrence during the monsoon season from Mazatlán north-northwest to northern Arizona and New Mexico. The goal is to describe thunderstorm frequency with a dataset that provides uniform spatial coverage at a resolution of 2–5 km and uniform temporal coverage with individual lightning events resolved to the millisecond, compared with prior studies that used hourly point rainfall or satellite data with a resolution of several kilometers. The monthly lightning stroke density over northwestern Mexico increases between May and June, as thunderstorms begin over the high terrain east of the Gulf of California. The monthly lightning stroke density over the entire region increases dramatically to a maximum in July and August. The highest stroke densities observed in Mexico approach those observed by GLD360 in subtropical and tropical regions in Africa, Central and South America, and Southeast Asia. The diurnal cycle of lightning exhibits a maximum over the highest terrain near noon, associated with daytime solar heating, a maximum near midnight along the southern coast of the Gulf, and a gradual decay toward sunrise.

1. Introduction

Convection in the North American monsoon has been studied with incomplete spatial and temporal coverage because of the rugged terrain that makes direct measurements difficult to obtain. To date, convection in this region has been mostly inferred from relatively low-resolution or sparse data. For example, Douglas et al. (1993, their Fig. 7) illustrated a broad maximum in convection that peaks during July and August over the western portion of Mexico using infrared cloud-top temperatures that detect the upper cirrus extent of large thunderstorms, but not the convective elements beneath them. That publication also used rainfall stations to delineate a narrower band of heavy precipitation than indicated by satellite between the coast of the Gulf of California and the Sierra Madre Occidental mountain range. Similarly, Adams and Comrie (1997) showed a rainfall maximum in the same area that peaks in July and August using a limited number of point measurements over Mexico. Denser networks of rain gauges, pilot balloons, and radars have been deployed in the region during specific field campaigns such as the 1990 Southwest Area Monsoon Project (SWAMP; Douglas 1995) and the 2004 North American Monsoon Experiment (NAME; Higgins et al. 2006), but the limited temporal coverage precludes any long-term climatological study. Lightning detection systems offer both continuous, long-term, uniform areal coverage and sufficient spatial accuracy to permit detailed climatological studies. The purpose of this paper is to use the new capability of Vaisala’s Global Lightning Dataset (GLD360) to examine the convective frequency,
location, and timing over the North American monsoon region with greater spatiotemporal coverage than an intensive experiment like NAME, greater spatial resolution than satellite, and greater areal coverage than radar, especially over Mexico. We specifically study the seasonal, monthly, and hourly features of lightning occurrence over this area.

2. Background

Prior lightning studies of the North American monsoon were limited to areas covered by the U.S. National Lightning Detection Network (NLDN; Cummins and Murphy 2009) or its predecessors. These studies covered primarily the U.S. states of New Mexico (Fosdick and Watson 1995) and Arizona (Watson et al. 1994a,b; King and Balling 1994). These studies found an afternoon to evening maximum in hourly lightning frequency and flash density with a dominant peak during July and August. However, the extent of the maximum lightning density into Mexico could not be examined. Watson et al. (1994a) and Mullen et al. (1998) examined the bursts (wet periods) and breaks (dry periods) that result in significant variability in thunderstorm location and timing within the summer monsoon period over Arizona. Bieda et al. (2009) used NLDN data to identify the structure of inverted troughs during the North American monsoon across Mexico. They extended the lightning analysis to 27.5°N latitude (about 400 km south of the U.S.–Mexico border) and showed significant lightning frequencies in northwestern Mexico. However, they also noted that they were unable to cover the full “tier 1” region of the 2004 NAME, which extended to 20°N latitude, because of NLDN coverage constraints. Murphy and Holle (2005) made an effort to quantify the magnitude of the maximum in lightning density over Mexico, but that study did not extend much beyond 600 km from the U.S. border because of the reduced detection efficiency.

During the last few years, Vaisala’s GLD360 network has been developed and deployed. GLD360 detects lightning continuously across the globe. About 80% of GLD360 detections are estimated to be cloud to ground (CG). Early validations of GLD360 showed CG stroke detection efficiency of around 60% in North America (Said et al. 2013) and parts of Europe (Poelman et al. 2013; Pohjola and Mäkelä 2013), a CG flash detection efficiency of about 90%, and a location accuracy of 2–5 km. The use of GLD360 in the present study eliminates the range effect of NLDN, so that an analysis of the temporal and spatial details of lightning occurrence over the entire North American monsoon region during multiple years can now be prepared.

3. Global and continental lightning detection

A global view of GLD360 lightning density from October 2011 to September 2014 in Fig. 1 shows that most lightning is over land. The observed stroke density exceeds 32 strokes km$^{-2}$ yr$^{-1}$, averaged over 20 km by 20 km grid squares, in only a few areas in the world, including northwest Mexico, the northwest corner of
South America, Cuba, east-central Africa, and portions of Southeast Asia and northern Australia. Figure 2 shows the terrain and selected cities within our region of analysis, which is also bounded by the black outline in later figures (e.g., Fig. 3).

Figure 3a shows the density map comprising 45,640,820 strokes detected by GLD360 within the region in Fig. 2 during the same 3-yr period as in Fig. 1. The maximum exceeds 48 strokes km$^{-2}$ yr$^{-1}$ in several 5 km by 5 km grid squares. Note the separation of this lightning density maximum in the North American monsoon from another region of high stroke density farther south that begins at the southern border in Fig. 2.

The corresponding NLDN CG stroke map is in Fig. 3b. GLD360 replicates the primary maxima and minima over the U.S. land area where the NLDN has a location accuracy of $\sim 0.25$ km compared with GLD360 location accuracy of 2–5 km (Nag et al. 2014). The NLDN maximum values are somewhat higher than those of GLD360 because its CG stroke detection efficiency exceeds 70% while it is somewhat lower with GLD360. Of particular interest is the GLD360 coverage to the south where the NLDN stroke detection efficiency drops off rapidly. Because the GLD360 patterns over the United States are substantially similar to those shown by the more accurate NLDN, we infer that GLD360 accurately depicts lightning over the entire region.

The well-defined maximum in lightning stroke density in Fig. 3a lies between the west side of the Sierra Madre Occidental and the Gulf of California. Lightning densities exceeding 32 strokes km$^{-2}$ yr$^{-1}$ are found over the southern half of the domain, and the values drop off to about 8 strokes km$^{-2}$ yr$^{-1}$ at the U.S.–Mexico border. The falloff to the north is due in part to a decrease in the

![Figure 2. Topography of the region of analysis and selected cities of northwest Mexico and the southwestern United States. Shading shows the terrain altitude in meters.](image-url)
number of thunderstorm hours and in part to a decrease in the highest numbers of strokes per thunderstorm hour. In this analysis, a thunderstorm hour is defined as any hour of UTC time in which one or more strokes is observed within a 40 km by 40 km box. For example, if two strokes are observed at 0159 and 0201 UTC, within a single 40 km by 40 km box, then two thunderstorm hours are counted in that box. We have counted the number of thunderstorm hours centered on the cities of Mazatlán and Hermosillo, Mexico, and Tucson, two strokes are observed at 0159 and 0201 UTC, within a single 40 km by 40 km box, then two thunderstorm hours are counted in that box. We have counted the number of thunderstorm hours centered on the cities of Mazatlán and Hermosillo, Mexico, and Tucson,

![Fig. 3. Lightning stroke density (km$^{-2}$ yr$^{-1}$) over the area of the North America monsoon detected by (a) GLD360 and (b) NLDN. The scale is on bottom left of each map. A grid size of 5 km by 5 km is being used to plot the 45 640 820 strokes detected in the area from October 2011 to September 2014. On the GLD360 map, Mazatlán is at the plus sign on the Mexican coast, the plus sign to the west is Cabo San Lucas, and the third plus sign is halfway between the other two.](image)

![Fig. 4. The distribution of the number of strokes per thunderstorm hour on a base-2 logarithmic scale in three cities whose locations are identified in Fig. 2: Mazatlán, Hermosillo, and Tucson.](image)
Arizona. This analysis shows that Hermosillo and Tucson had 507 and 519 thunderstorm hours over the 3-yr period of the study, while Mazatlán experienced 1223 h. Fewer thunderstorm hours are expected in the northern portion of the North American monsoon region because that area is more strongly influenced by variations in the position of the dominant midlevel anticyclone and associated variations in the position of the moisture boundary in the middle troposphere (Heinselman and Schultz 2006).

Despite the nearly identical number of thunderstorm hours in Hermosillo and Tucson, the total number of strokes in Hermosillo was about 3.5 times greater than in Tucson, and that was due to significant differences in the number of strokes per thunderstorm hour in the most active hours. Figure 4 shows the distribution of the number of strokes per thunderstorm hour in each of the three selected locations on a base-2 logarithmic scale. In Tucson, no thunderstorm hours are observed to have 1028 strokes or more, whereas in both Hermosillo and Mazatlán, a few percent of thunderstorm hours have 2048 strokes or more. The high-rate tail of these distributions is especially noticeable in the top 20 thunderstorm hours with the highest stroke counts: in Hermosillo, those top 20 h have between 741 and 5602 strokes, while in Tucson, the top 20 h have only 171–753 strokes. The reduced lightning production during the highest-rate periods in Tucson relative to both Hermosillo and Mazatlán will be the subject of future research.

4. Monthly variations

The North American monsoon has a highly concentrated maximum in time as well as space. Figure 5 divides the data in Fig. 3 into monthly maps. Lightning is much less frequent in April and May along the coast of
the Gulf of California. Both peak monthly stroke density and areal coverage build rapidly in June and reach a maximum in July and August, then slowly weaken. The most rapid growth occurs during the weeks from the middle of June to early July. In southern Arizona, for example, there is almost no lightning until late June, but then the maximum in Mexico overspreads Arizona very quickly from the south and east.

5. Diurnal variability

Two-hourly maps were developed (Fig. 6) for the same North American monsoon area as in preceding figures. Over the whole region, the maximum lightning stroke density occurs between 0000 and 0200 UTC, or 1700 to 1900 local solar time (LST), but there is significant variability as a function of location. The diurnal cycle shows that lightning occurs primarily over the highest terrain of the Sierra Madre Occidental and the Mogollon Rim and White Mountains of Arizona near local noon (1100–1300 LST; 1800–2000 UTC). As the afternoon progresses, lightning spreads toward the west slope of the Sierra Madre Occidental and increases in both areal coverage and intensity leading up to the overall peak between 0000 and 0200 UTC. As the evening progresses, the peak lightning density persists only along the coast in the southern part of the region, near Mazatlán. In fact, Fig. 7 shows that peak lightning density at Mazatlán occurs between 0600 and 0800 UTC (2300–0100 LST). Alongshore and just offshore from northwest of Mazatlán to Puerto Vallarta, Mexico, lightning persists throughout the night. However, Fig. 7
shows that the area of enhanced nighttime lightning density does not extend to the middle of the Gulf. Lang et al. (2007) showed that nocturnal thunderstorms in this region often move parallel to the coast, consistent with a southeasterly component to the midlevel flow, but somewhat faster, implying additional propagation by way of shallow outflow. More specifically, there may be an issue of low-level convergence near the intersection between the nocturnal land breeze and the outflow boundary produced by the thunderstorms themselves, keeping the nocturnal thunderstorms focused along the coastline. The diurnal cycle seen in Figs. 6–7 is consistent with frequencies of cold cloud tops (Vera et al. 2006; Nesbitt et al. 2008) and precipitation and radar observations taken during NAME (Lang et al. 2007; Nesbitt et al. 2008).

### 6. Conclusions

The first description of the spatial and temporal distributions of lightning across the North American monsoon region has been developed using data from Vaisala’s GLD360, which provides full global coverage, including all of Mexico. Three full years of data beginning in 2011 were used to develop this exploratory climatology. We find that the lightning stroke density maximum in northwest Mexico approaches those observed in only a few other regions of the world, including northwest South America, east-central Africa, and large equatorial islands of Southeast Asia, as shown in Fig. 1. The most frequent lightning is found in a narrow band between the Sierra Madre Occidental and the Gulf of California, with a sharp peak during July and August. During the course of the day, lightning begins over the highest terrain in early afternoon, reaches its peak frequency in the early evening, and moves alongshore during the night near Mazatlán. In future studies, the continuous spatiotemporal coverage of GLD360 observations can be utilized, together with a suitable lightning–rainfall relationship, to provide precipitation estimates in data-sparse areas within the North American monsoon such as the Sierra Madre.

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