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LIGHTNING IN THE NORTH AMERICAN MONSOON: AN EXPLORATORY CLIMATOLOGY

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1. INTRODUCTION

The North American Monsoon has been studied by a variety of means. However, to date, its convection has mostly been inferred from relatively low resolution or sparse data. For example, Douglas et al. (1993, Fig. 7) illustrate a broad maximum 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 by month with limited data 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 areal coverage and sufficient spatial accuracy to permit detailed climatological studies. The purpose of this paper is to use the new capability of the Global Lightning Dataset GLD360 to examine the convective activity over the North American Monsoon region with greater spatio-temporal coverage than an intensive experiment like NAME, greater resolution of spatial detail than satellite, and greater areal coverage than radar, especially over Mexico. We specifically study the lightning activity on seasonal, monthly, and hourly bases.

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 lightning maximum with a dominant peak during July and August. However, the extent of the lightning maximum into Mexico could not be examined. Watson et al. (1994a) and Mullen et al. (1998) examined the bursts (wet periods) and breaks (dry) that result in significant variability in thunderstorm activity 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 and showed significant lightning frequencies in the state of Sonora, 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, due to NLDN coverage constraints. Murphy and Holle (2005) made an effort to quantify the magnitude of the lightning maximum over Mexico, but that study did not extend much beyond 600 km from the U.S. border due to the reduced detection efficiency.

During the last few years, Vaisala's Global Lightning Dataset 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. Early validations of GLD360 show 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), with CG flash detection efficiency of about 90%. 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 activity over the entire North American Monsoon region over multiple years can now be prepared.

3. GLOBAL AND CONTINENTAL LIGHTNING DETECTION

A global view of GLD360 lightning density from October 2011 – September 2014 in Fig. 1 shows that most lightning is over land. Only a few areas have stroke density exceeding 32 strokes/km^2/yr, averaged over 20 X 20 km grid squares, and one of these is located in northwest Mexico.

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).

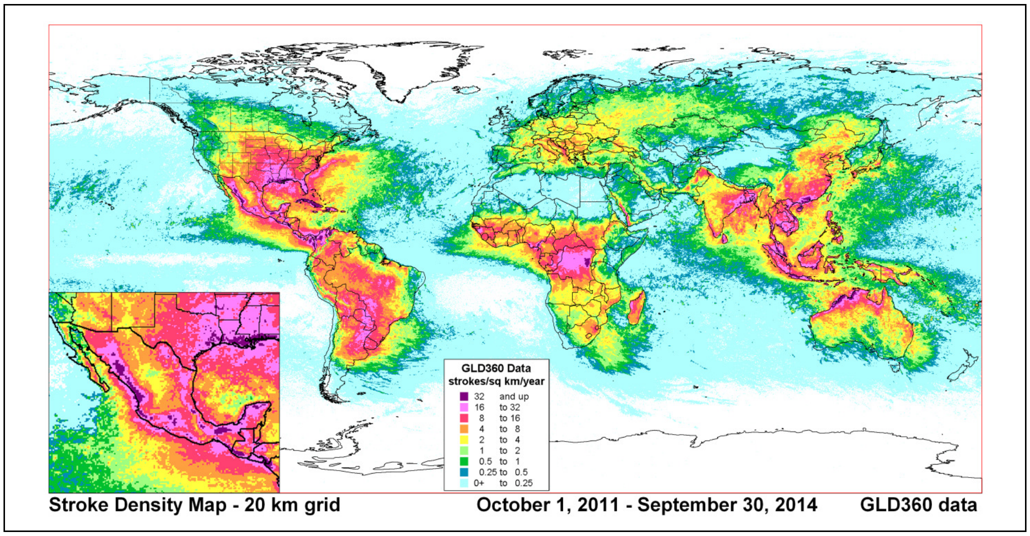

FIG. 1. Lightning stroke density per square kilometer per year from GLD360 for the globe from October 2011 through September 2014. A total of 2,312,246,169 strokes is plotted during these three years. Scale is at lower center of map. The grid size is 20 by 20 km. Inset in lower left shows expansion of the same data over Mexico.

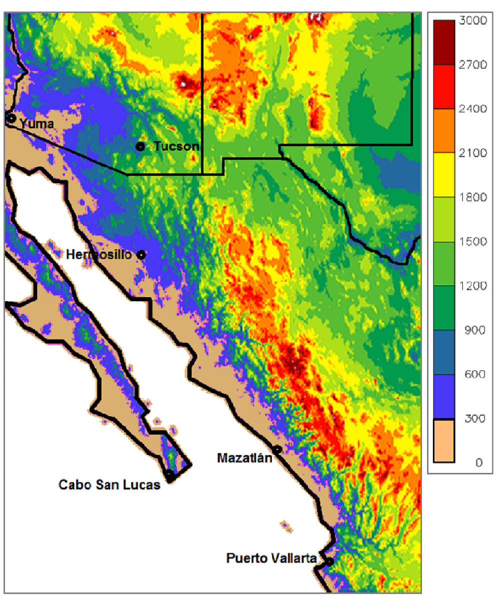

FIG. 2. Topography of the region of analysis and selected cites of northwest Mexico and the southwest United States. Shading shows terrain altitude in meters.

Fig. 3, left side, shows the density map comprised of 45,640,820 strokes detected by GLD360 within the region of Fig. 2 during the same three-year period as Figure 1. The maximum exceeds 48 strokes/km^2/yr in several 5 by 5 km grid squares. Note the separation of this monsoon lightning maximum from another region of high stroke frequency farther south that begins at the southern border of Fig. 2.

The corresponding NLDN cloud-to-ground (CG) stroke map is on the right in Fig. 3. GLD360 replicates the primary maxima and minima over the U.S. land area where the NLDN has a location accuracy of ~0.25 km compared with GLD360 location accuracy of 2 to 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 U.S. are substantially similar to those shown by the more accurate NLDN, we infer that GLD360 accurately depicts lightning over the entire region.

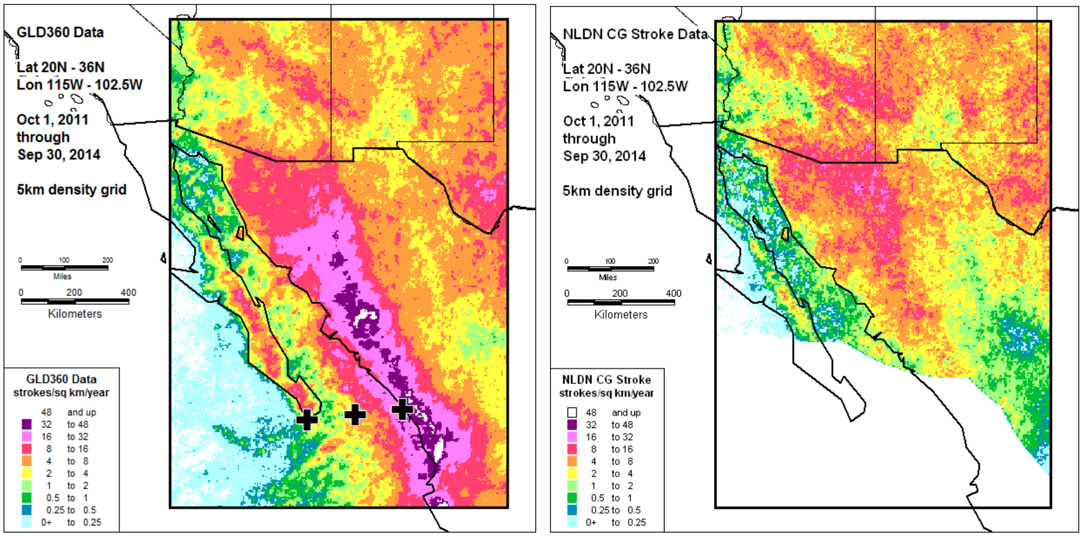

FIG. 3. Lightning stroke density per square kilometer per year over the area of the North America monsoon detected by GLD360 (left) and NLDN (right). Scale is on right side of map. A grid size of 5 by 5 km is being used to plot the 45,640,820 strokes detected in the area from October 2011 through September 2014. On the GLD360 map, Mazatlán is at plus sign on Mexican coast, plus to west is Cabo San Lucas, and third plus sign is halfway between the other two.

The well-defined lightning maximum lies between the west side of the Sierra Madre Occidental and the Gulf of California (Sea of Cortez). Lightning densities exceeding 32 strokes/km^2/yr are found over the southern half of the domain, and the values drop off to about 8 strokes/km^2/yr at the U.S.-Mexico border. The fall-off to the north is due in part to a decrease in the number of thunderstorm hours and in part to a decrease in the highest numbers of strokes per thunderstorm hour. To illustrate these effects, we have counted the number of hours having at least one stroke in a 40 by 40 km box centered on the cities of Mazatlán, Hermosillo, and Tucson. This analysis shows that Hermosillo and Tucson had 507 and 519 such “thunderstorm hours” over the 3-year period of the study, while Mazatlán experienced 1223 hours. Lower numbers of thunderstorm episodes 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 mid-level 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

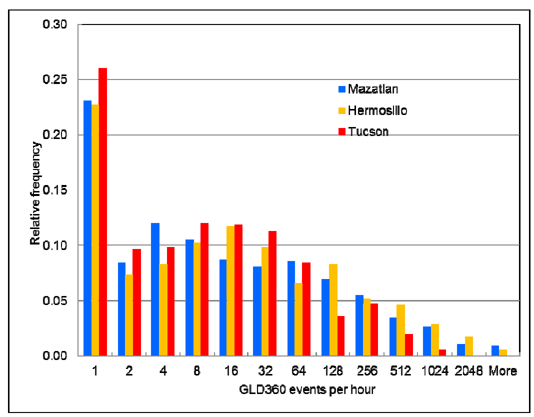

FIG. 4. Distribution of the number of strokes per thunderstorm hour on a base-2 logarithmic scale in three cities whose locations are identified in Figure 2, Mazatlán, Hermosillo, and Tucson.

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 hours have between 741 and 5602 strokes, while in Tucson, the top 20 hours have only 171 to 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 frequency is limited in April and May along the coast of the Gulf of California. Thunderstorm activity, as represented both by peak monthly stroke density and areal coverage, rapidly builds in June and reaches a maximum in July and August, then slowly weakens. The most rapid growth occurs during the weeks from the middle of June to early July. In southern Arizona, for example, there is essentially no lightning until late June, but then the maximum in Mexico overspreads the state very quickly from the south and east.

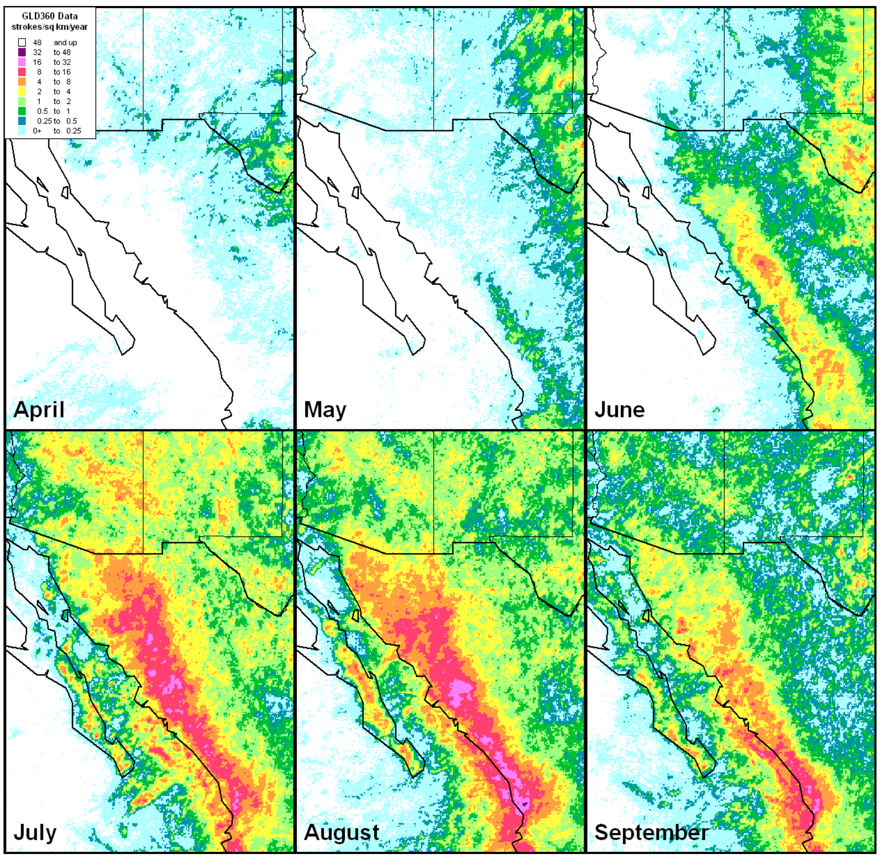

FIG. 5. Monthly maps from April through September of lightning frequency over the monsoon area of Fig. 2.

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 (1800-2000 UTC, 1100-1300 LST). 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 0000-0200 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 at Mazatlán occurs between 0600 and 0800 UTC/2300 to 0100 LST. Along shore and just offshore from northwest of Mazatlán to Puerto Vallarta, 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. (2008) showed that nocturnal thunderstorms in this region often propagate parallel to the coast, consistent with a southeasterly component to the mid-level flow, but somewhat faster, implying additional propagation by way of shallow outflow. More specifically, that 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).

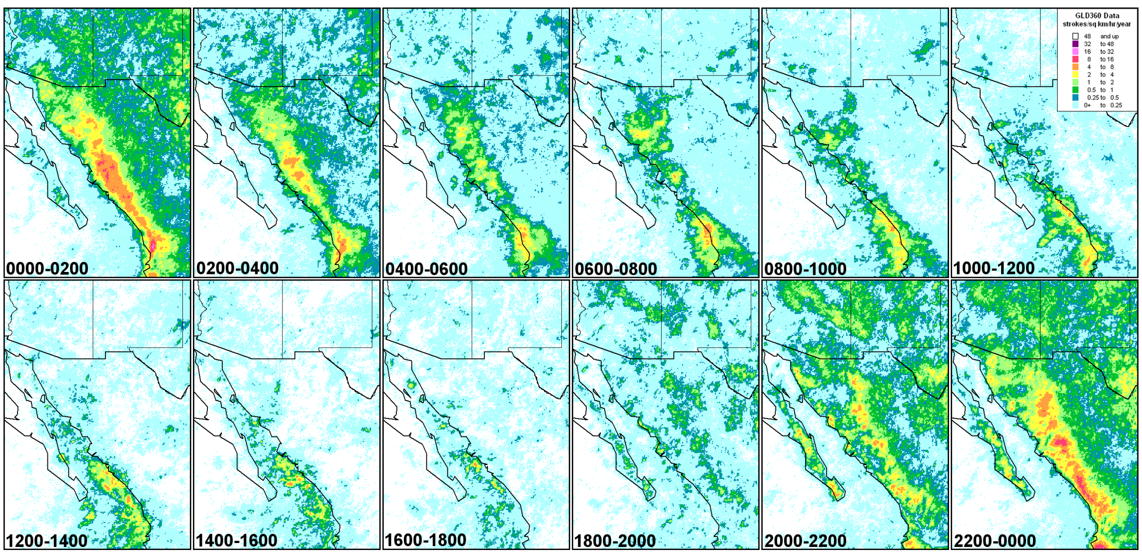

FIG. 6. Two-hour maps of lightning frequency over the monsoon area of Fig. 2. Time is in UTC.

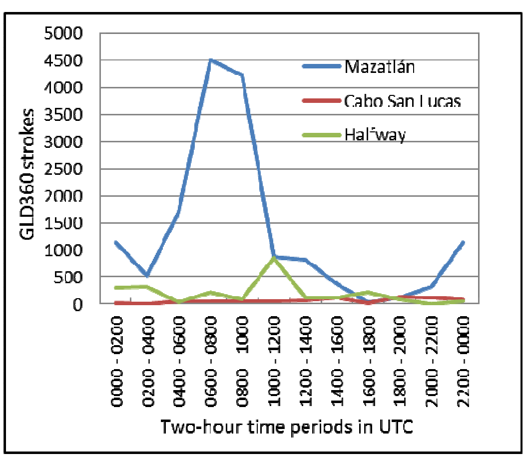

FIG. 7. Diurnal variation of GLD360 strokes at Mazatlán, Cabo San Lucas, and in the Gulf of California halfway between those two cities.

6. CONCLUSIONS

The first comprehensive description of lightning in the North American Monsoon has been developed using data from the 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. 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 along shore during the night near Mazatlán. In future studies, the continuous spatio-temporal 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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