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DIURNAL VARIATIONS OF NLDN CLOUD-TO-GROUND LIGHTNING IN THE UNITED STATES

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1. INTRODUCTION

National maps of cloud-to-ground lightning flash density for the entire year have been produced since the National Lightning Detection Network (NLDN) was first deployed across the contiguous 48 states in 1989. Multi-year national maps have been published by Orville (1991, 2001), Orville and Silver (1997), Huffines and Orville (1999), Orville and Huffines (1999), Orville et al. (2002), Zajac and Rutledge (2001), and Orville (2008). Monthly maps of NLDN cloud-to-ground lightning were shown in Holle and Cummins (2010) and Holle et al. (2011).

While these publications showed the annual flash distributions from the NLDN, national diurnal maps of cloud-to-ground lightning have not been compiled. Previous diurnal lightning data were in the form of a time series for an entire region, occasionally by flow regime, and sometimes a map was shown for one or two time periods.

Zajac and Rutledge (2001) showed a normalized amplitude map of summer diurnal lightning distributions across the U.S. and at several cities, as well as a review of previous thunderstorm climatologies prior to the deployment of lightning networks. Cecil et al. (2011) indicated a broad evening maximum over the central U.S. with LIS data. In the present paper, NLDN maps for the U.S. by two-hourly intervals will be shown.

2. NLDN DATA AND ANALYSIS METHODS

The National Lightning Detection Network (NLDN) detects could-to-ground lightning flashes and strokes, as well as a small percentage of cloud events (Cummins et al. 1998; Orville 2008; Cummins and Murphy 2009). The present paper will deal only with cloud-to-ground flashes, although stroke data have been available since 2006 (Cummins and Murphy 2009). Improvements to the network have included upgrades in 1998 (Cummins et al. 1998) and 2003 (Cummins et al. 2006). The estimated flash detection efficiency for the contiguous 48 states is 90 to 95%. No polarity separation is made in the present study.

Data were accumulated into 20 by 20 km square grids of cloud-to-ground flash density across the contiguous 48 states. The time period from 2006 through 2010 includes data since the recent NLDN upgrade.

Flash data are assigned to two-hour time periods in five-degree longitude segments. This approach proved to be adequate at identifying patterns of hourly lightning without identifiable boundaries between longitude segments. The spatial boundaries are:

- North - 250 km into Canada.
- South - 600 km to the south into Mexico and the Gulf of Mexico, but no farther south than 23.2° N.
- West - 600 km to the west into the Pacific, but no farther west than 125.8° W.
- East - 600 km to the east into the Atlantic, but no farther east than 65.85° W.

3. ANNUAL FLASH DENSITY

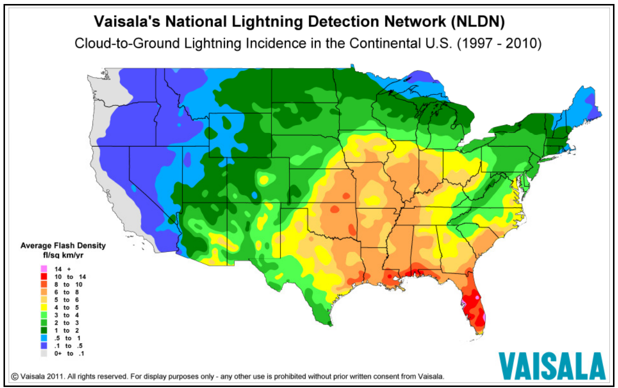

FIGURE 1. Cloud-to-ground lightning flash density per square kilometer per year for the U.S. from 1997 to 2010. Scale is on left side of map.

The range of flash density is very large, from over 14 flashes/km^2/year in three areas of Florida, to less than 0.1 flashes/km^2/year along the west coast. Densities are highest in Florida and along the Gulf Coast where very warm adjacent ocean waters provide deep moisture for strong updrafts. Low west coast densities are where cold offshore water inhibits deep convection. A general decrease from south to north, and east to west, occurs on a national scale. However, there are important variations over and east of the Rocky Mountains, and over the interior western states.

4. TWO-HOURLY FLASH DENSITY MAPS

Two-hourly U.S. maps of NLDN cloud-to-ground flash density were developed at selected times. An average of 27 million cloud-to-ground flashes was detected by the NLDN over the land area of the contiguous U.S during each year, when corrected for detection efficiency. Table 1 shows measured (not corrected by detection efficiency) two-hourly average and total flashes over the contiguous U.S., and adjacent land and ocean areas defined in section 2. Lightning is most common during the afternoon, and two thirds occur in June, July, and August (Holle and Cummins 2010; Holle et al. 2011). The afternoon maximum, especially in the southeastern states, is mostly due to heating of the lower and middle levels of the atmosphere. An additional important ingredient is the large amount of moisture in lower and middle levels of the atmosphere that provides fuel for the daily thunderstorm cycle; much of that atmospheric moisture has its origin in adjacent warm oceans to the south and east of the U.S.

TABLE 1. Average annual, and total cloud-to-ground flashes in selected four-hour periods from 2006 though 2010 for the U.S. and adjacent areas from the National Lightning Detection Network.

Time (LMT)	2006-10 average	2006-10 total
0000-0200	1,849,569	9,247,847
0600-0800	1,351,876	6,759,381
0800-1000	1,151,311	5,756,556
1000-1200	1,328,108	6,640,541
1200-1400	2,694,512	13,472,561
1400-1600	4,458,630	22,293,148

4.1. 1000 to noon LMT

Zajac and Rutledge (2001) and others have shown that thunderstorms driven by daytime heating have a minimum near 1000 LMT (local mean time). Starting at 1000 to noon, Figure 2 shows the first two hours of the convective day. Some grid squares in the southwest, and many in the eastern half of the country had moderate lightning during these hours. Notable features are:

- Higher elevation regions are found in western states that represent a distinct threat to outdoor recreation vulnerable to lightning.
- The highest late morning lightning frequency is just inland along the Gulf Coast and immediately offshore.
- Additional frequent lightning during these hours is found in the plains to the Mississippi valley, which is mainly a remnant from the previous night's convection.

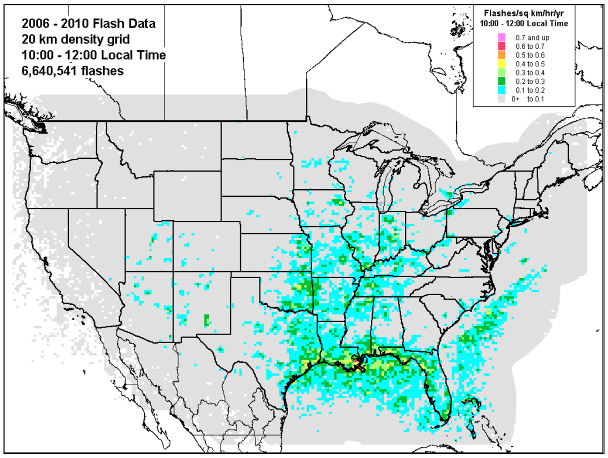

FIGURE 2. Map of cloud-to-ground lightning flash density per square kilometer from 1000 to noon LMT for the U.S. from 2006 through 2010. Scale is in upper right portion of map.

4.2. Noon to 1400 LMT

The map two hours later (Figure 3) has 13,472,561 flashes during the five years, at an average of 2,694,512 per year (Table 1). This represents a substantial growth in all areas where half as much lightning was present in the two hours before noon. Florida and the Gulf Coast have frequent lightning, and such areas in the southeastern states also have grown. The two sea breezes in peninsular Florida are apparent.

Particularly interesting is the growth of cloud-to-ground flashes at the higher elevations of the Four Corners states of Arizona, Colorado, New Mexico, and Utah. This early afternoon period has much of the day's lightning and indicates an important time to exclude outdoor activities on days when any lightning is forecast or occurring.

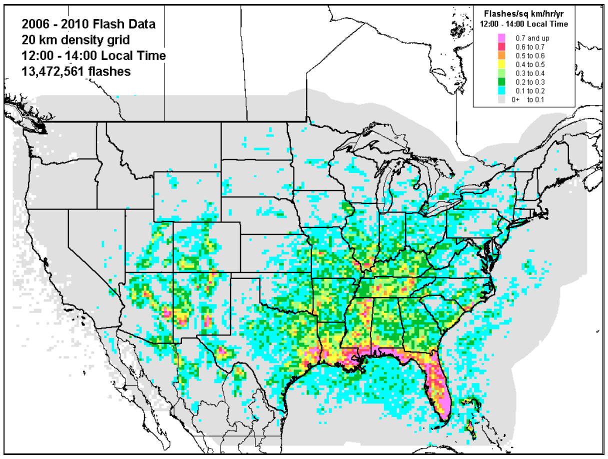

FIGURE 3. Same as Figure 2, except from noon to 1400 LMT.

4.3. 1400 to 1600 LMT

During the time of maximum heating between 1400 and 1600 LMT (Figure 4), flashes in all areas with frequent lightning two hours earlier have increased in frequency. In general, there are no large new areas of lightning activity, but an overall increase, since thunderstorms have expanded and become more frequent in the same areas as two hours earlier.

The frequency has increased across all of Florida, along the Gulf of Mexico coast and inland from there, in Mexico south of Arizona, and in a north-south line over the mountains of New Mexico, as well as expansion and intensification in other locations.

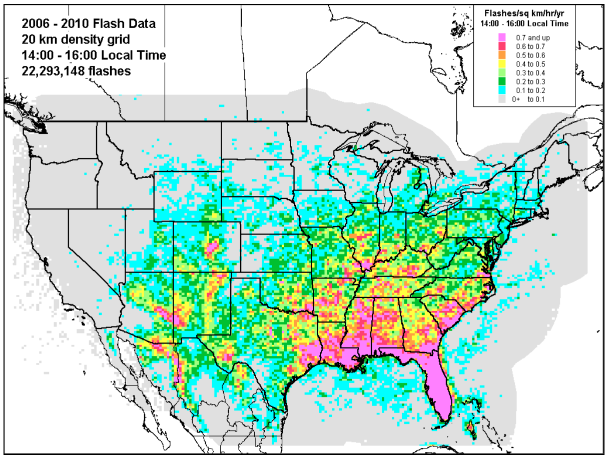

FIGURE 4. Same as Figure 2, except from 1400 to 1600 LMT.

4.4. 0000 to 0200 LMT

Moving forward ten hours past the time of the afternoon maximum, Figure 5 shows the map for two hours starting at midnight when much less lightning occurred. The strong lightning occurrence along the Florida and Gulf Coasts has almost entirely disappeared, and offshore lightning is apparent. Similarly, the maxima over the southwest mountain states have disappeared.

Instead, a large and strong maximum is located from Oklahoma north and east to Iowa, where thunderstorms from the previous day have moved eastward. At this time, storms are much more frequent in these regions than they were during the time of daytime heating.

Mesoscale convective systems and derechos occur on the plains and Midwestern states on some nights in the summer, and these systems can have frequent lightning. In terms of lightning safety, the danger is somewhat lessened in these locations because of the late hour for outdoor activity exposure to lightning.

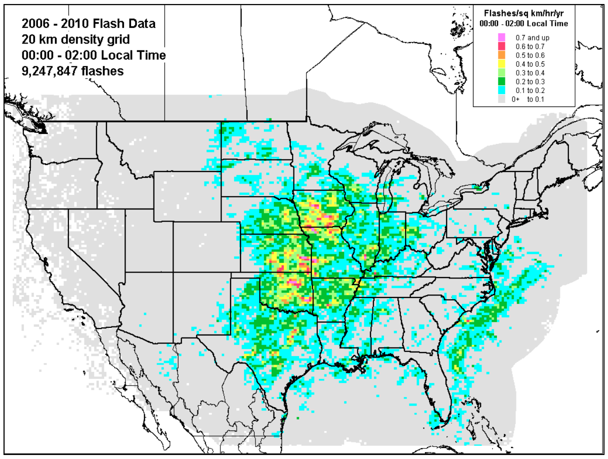

FIGURE 5. Same as Figure 2, except from midnight to 0200 LMT.

4.5. 0600 to 0800 LMT

Six hours later, Figure 7 shows 6,759,381 flashes during the five years for a continued but lessened frequency of lightning over the interior of the contiguous states, and located somewhat farther east. These storms continue to be partially due to development to the west during the previous day, as well as nocturnal events such as mesoscale convective systems and derechos.

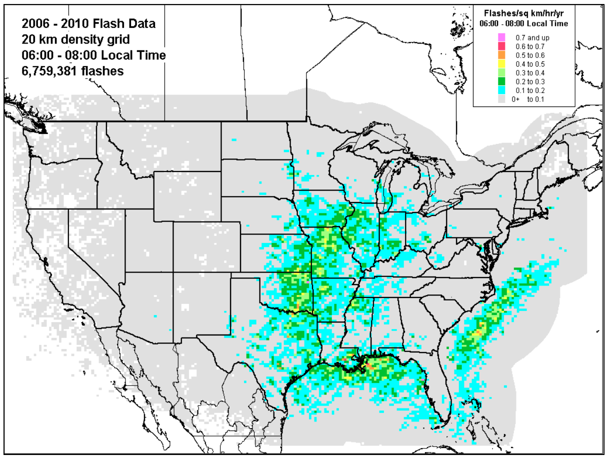

FIGURE 6. Same as Figure 2, except from 0600 to 0800 LMT.

4.6. 0800 to 1000 LMT

Two hours later, Figure 7 shows flashes for a continued but lessened frequency of lightning over the interior of the contiguous states, although somewhat farther east. The activity is not yet responding to the development of new convection over land from daytime heating, and corresponds to the frequently-observed 1000 LMT minimum in convective studies.

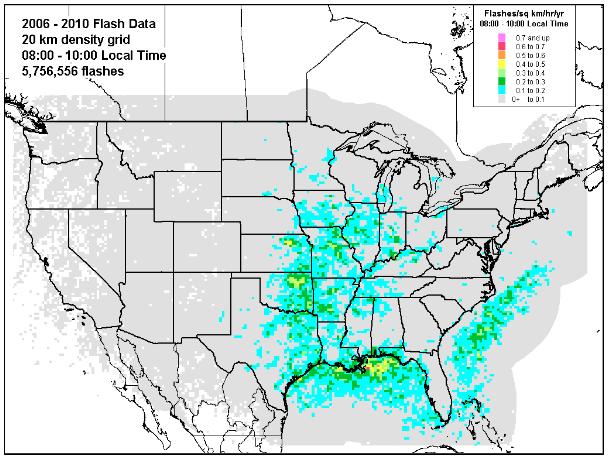

FIGURE 7. Same as Figure 2, except from 0800 to 1000 LMT.

4.7. Transition

Flash activity from 0800 to 1000 LMT in Figure 7 has weakened somewhat from the previous day's activity, and is the lowest of any analyzed two-hour time period during the daily cycle (Table 1). The new day's convection begins with the map from 1000 to noon (Figure 2). Later, by noon, a new series of storms develops along the Florida and Gulf of Mexico coasts, over the southwestern mountains, and in the center of the country where activity lingers from the previous night. Additional maps are planned to be prepared to document the features between the hours shown in the present paper.

5. REGIONAL FEATURES WITH DIURNAL EMPHASES

5.1. Peninsular Florida

The Florida peninsula has a concentrated period of flashes from late morning to early evening. There have been many studies of the spatial and diurnal lightning distributions during summer across the peninsula. Among the Florida studies, the diurnal pattern is specifically shown by Maier et al. (1984), López and Holle (1986), Reap (1994), Lericos et al. (2002), Shafer and Fuelberg (2006, 2008), and Bauman et al. (2008). These papers often subdivide lightning climatologies by time of day with respect to flow regimes during the summer.

5.2. Gulf of Mexico coast

The present paper identifies an afternoon concentration of flashes along the Gulf of Mexico and Atlantic coasts. Previous summertime studies in the northern Gulf coast from the panhandle of Florida to Texas (Camp et al. 1998; Smith et al. 2005) used similar approaches to those described for Florida. The repeatability of summertime lightning patterns based on low-level flow led to methods to forecast patterns and timing of lightning across the northern Gulf (Stroupe et al. 2004).

The summertime maxima and their timing near Houston and southern Louisiana were studied by McEver and Orville (1995). A later focus on the relative importance of coastal effects and anthropogenic impacts included diurnal effects (Steiger et al. 2002).

5.3. Georgia and southeastern states

The Atlanta Olympics of 1996 prompted lightning climatologies by Watson and Holle (1996) and Livingston et al. (1996). These emphasized the afternoon into evening occurrence of lightning in Atlanta and surrounding regions. Additional studies have included diurnal effects in the exploration of the potential for urban lightning enhancement around Atlanta (Bentley and Stallins 2005). A flash climatology at the higher elevations of northern Georgia and to the northeast by Murphy and Konrad (2005) included diurnal factors by location and storm life cycle.

5.4. Colorado

Colorado has strong local forcing due to large topographic gradients that result in well-defined lightning patterns. Colorado summer lightning distributions by López and Holle (1986) for the eastern slopes of the Front Range emphasized the strong maximum from late morning to early evening, as shown in the present paper. Hodanish and Wolyn (2004) also emphasized the strong diurnal nature of lightning in the state. In another mountainous region, Austria, Prinz et al. (2011) showed the altitude of the afternoon lightning maximum to be between 1500 and 1800 UTC with a maximum between 1 and 2 km.

5.5. Arizona and New Mexico

Diurnal lightning changes in Arizona were studied by King and Balling (1984). The timing of the summer monsoon-season lightning over Arizona was studied by Watson et al. (1994) with maps and comparisons with precipitation data by hour.

A lightning climatology developed for New Mexico by Fosdick and Watson (1995) shows selected hourly maps similar to Watson et al. (1994). Regime-flow lightning patterns, especially with respect to first flashes of the day, were compiled by Wagner and Fuelberg (2006) for New Mexico extending into west Texas.

5.6. Other climatologies

Other NLDN cloud-to-ground lightning climatologies showing diurnal variations are:

- **Central Plains:** A climatology of NLDN flashes in the upper Mississippi River Valley (Cook et al. 1999) showed time variations by summer month.
- **Derechos:** The prevalence for the origination of derechos, that can produce large amounts of lightning, to begin in late afternoon to evening in the southern Great Lakes is emphasized by Johns and Hirt (1987) and Bentley and Mote (1998).
- **Nevada:** A series of lightning studies around the Nevada Test Site showed detailed diurnal variations in this region (Randerson 1999; Randerson and Saunders 2002).

6. LIGHTNING SAFETY ASPECTS

The time of day of lightning is found in this study to vary across the country. For example, most Florida, Gulf Coast, and high-elevation western mountains regions have lightning concentrated during the period from mid-morning to early evening. The early start along the coastal beaches, and over the mountains of the Four Corner states of Arizona, Colorado, New Mexico, and Utah is a critical issue for lightning safety since storms begin earlier than may be expected, or a daily outdoor schedule may accommodate easily.

On the plains and into the middle Mississippi Valley and Great Lakes regions, thunderstorms move steadily across the country from west to east and reach those areas from midnight to as late as sunrise the next morning. In such a situation, the exposure of people to cloud-to-ground lightning is minimal except for camping and similar unprotected activities (Curran et al 2000).

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