

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

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### 1. Introduction

Cloud-to-ground lightning has a major impact on a wide variety of activities and industries. The spectrum of impacts ranges from individual and organized recreation, to power utility and communications operations, forestry, aviation, defense, mining, and numerous other outdoor leisure and workplace situations. On the national scale, annual maps of cloud-to-ground lightning have been produced since the National Lightning Detection Network (NLDN) first monitored the contiguous 48 states in 1989. Such maps for one or more years have been published by Orville (1991, 1994, 2001), Orville and Silver (1997), Huffines and Orville (1999), Orville and Huffines (1999), Orville et al. (2002, 2011), Zajac and Rutledge (2001), and Orville (2008). Cloud-to-ground lightning concentrates along the coasts of large water bodies and near large mountains; is often associated with excessive precipitation, severe, isolated, and winter storms; and affects geophysical properties such as  $\text{NO}_x$  production.

In addition to these existing annual maps, knowledge of hourly and monthly lightning distributions assists in planning the time of lightning-sensitive outdoor activities. Such information is useful for anticipating the threat of lightning that can lead to power and manufacturing disruptions, as well as vulnerable outdoor public, military, aviation, and personal situations (Holle et al. 1999).

A recent companion study to the present paper showed the monthly distribution of cloud-to-ground lightning over the lower 48 United States (Holle and Cummins 2010; Holle et al. 2011). The results showed a dominance of lightning in June, July, and August. Exceptions were almost no June flashes in the southwestern monsoon states, minimum activity in the southern Plains in July, and late summer to autumn maxima in some west coast regions. With that background of monthly distributions, the variability within individual days will now be examined.

While the previously-mentioned studies showed annual and monthly flash distributions, national diurnal lightning maps have not been compiled. Previously published diurnal lightning

results have consisted of time series for an entire region, occasionally by flow regime, and sometimes a map was shown for one or two time periods. The most complete prior U.S. diurnal lightning study was by Zajac and Rutledge (2001), who included a normalized amplitude map of summer diurnal lightning distributions across the U.S. at several cities, a map of the phase of the diurnal cycle of lightning frequency, and 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 satellite data.

Prior to the existence of lightning networks, maps of thunderstorm hours and days were based on human observers reporting the presence of thunderstorms, typically at airports. Such an observation based mainly on audible thunder is not an especially good indicator of lightning frequency. A map of human observations of thunderstorm hours by Easterling and Robinson (1985) used harmonic analyses to map four seasonal patterns of diurnal lightning variations.

In the present paper, accurately-measured NLDN lightning flashes were utilized to prepare lightning flash density maps at local overhead time, and these lightning distributions were related to meteorological factors as they arise during the course of daily variations.

### 2. NLDN data and analysis methods

The NLDN detects cloud-to-ground lightning flashes and strokes, as well as a portion of cloud impulses (Cummins et al. 1998; Cummins and Murphy 2009). The present paper deals only with cloud-to-ground flashes, although NLDN stroke data have been available since 1995 (Cummins and Murphy 2009). There are three to four cloud-to-ground strokes per cloud-to-ground flash, and 1.4 to 1.5 ground strike locations per flash (Cummins and Murphy 2009). Network Improvements have included upgrades in 1995 (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.

In order to develop reasonably stable lightning maps, several years of lightning data are needed, since convective events tends to be distributed in a nonlinear fashion. Olascoaga (1950) and Riehl (1954) showed that about 50% of rainfall in Argentina occurred on 10% of the days, and 90% of the rainfall fell on 50% of the days. The same relationships apply to smaller areas and shorter time periods of rainfall records. Additionally, lightning is more clustered than indicated by the Olascoaga rainfall data. López and Holle (1986) showed that lightning flashes are concentrated sufficiently in short time and small space intervals that individual storms can dominate a lightning sample that is compiled for one or two years.

As a result of these considerations, a quality longer-term database is desirable, preferably for several years or more; 2006 through 2010 is used here. For the spatial analysis, data are accumulated into 20 by 20 km grids of cloud-to-ground flashes across the contiguous 48 states and adjacent areas.

For the diurnal analyses, flash data are grouped into two-hour time periods by five-degree longitude segments. This approach provides results in local mean time (LMT) that proved to be adequate in identifying hourly lightning patterns without identifiable boundaries between longitude segments. The spatial boundaries are:

- North - 250 km into Canada from the U.S. border.
- South - 600 km to the south from the U.S. land area into Mexico and the Gulf of Mexico, as far south as 23.2° N.
- West - 600 km to the west from the U.S. land area into the Pacific, as far west as 125.8° W.
- East - 600 km to the east from the U.S. land area into the Atlantic, as far east as 65.85° W.

### 3. Annual U.S. flash density

The NLDN flash density map in Figure 1 has data for all hours and months combined. The range of annual flash density is on the order of two orders of magnitude, from over 14 flashes/km<sup>2</sup>/year in three areas of Florida, to less than 0.1 flashes/km<sup>2</sup>/year along the west coast.

Much of the atmospheric moisture over the U.S. has its origin in warm oceans adjacent to the south and east of the U.S. Cloud-to-ground flash densities are highest over Florida and along the Gulf Coast, due to the very warm adjacent ocean waters that provide deep moisture for strong updrafts to altitudes colder than freezing over strongly heated land areas. Low flash densities

along the west coast in Figure 1 occur where cold water and sinking motion inhibit 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. Many of these variations are related to diurnal influences that will be described in the present paper.

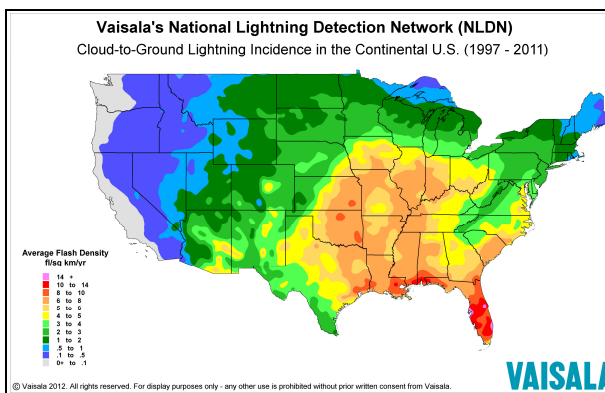


FIGURE 1. Cloud-to-ground lightning flash density per square kilometer per year for the U.S. from 1997 to 2011. Scale is on left side of map.

### 4. Two-hourly flash density maps

Figure 2 shows the measured two-hourly average number of flashes per year in local mean time over the contiguous U.S. and adjacent land and ocean areas. These values are not corrected for detection efficiency. Cloud-to-ground lightning in Figure 2 from thunderstorms driven by daytime heating have a minimum at 1000 LMT (local mean time), as shown by Zajac and Rutledge (2001).

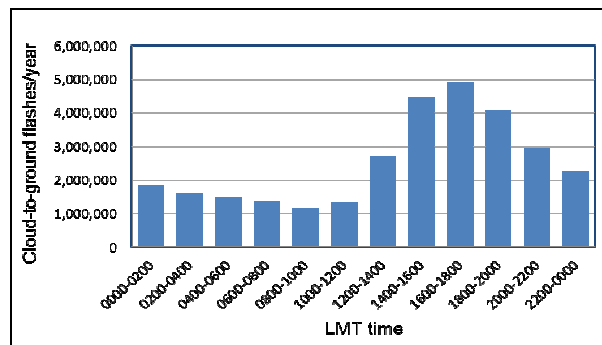


FIGURE 2. Cloud-to-ground flashes in two-hour periods from 2006 though 2010 for the U.S. and adjacent areas from the National Lightning Detection Network.

### a. 1000 to 1200 LMT

The 1000 LMT lightning minimum is used as the starting time for the following series of maps. The diurnal cycle of lightning over the United States will be presented in two-hour increments, through the day, evening, and nighttime hours until the 1000 LMT minimum is reached again.

The first map from 1000 to noon is in Figure 3. Notable features are:

- The highest lightning frequency is just inland along the Gulf Coast and immediately offshore.
- Frequent lightning is occurring on the plains to the Mississippi Valley that is mainly remnants from the previous night's convection.
- Lightning maxima coincide with high mountains in the Four Corners states of Arizona, Utah, New Mexico, and Colorado.

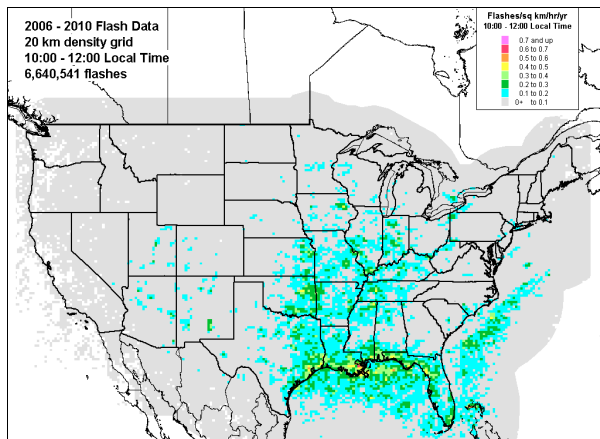


FIGURE 3. Map of cloud-to-ground lightning flash density per square kilometer from 1000 to noon LMT for the U.S. from 2006 through 2010. Scale is in upper right portion of map.

Curran et al. (2000) indicate that lightning casualties begin to increase in the late morning, toward the much larger afternoon maximum. Late morning is when activities such as morning mountain hikes and beach visits are sometimes vulnerable to lightning. An early flash resulting in a Colorado mountain fatality is described in Hodanish and Zajac (2002).

The Florida peninsula has late-morning flashes in Figure 3 that are also apparent in distributions in Maier et al. (1984), López and Holle (1986), Reap (1994), Lericos et al. (2002), and Shafer and Fuelberg (2006, 2008). Most studies subdivided lightning climatologies by time of day with respect to flow regimes during the summer, and show this late-morning start to daily

lightning activity. Similarly, Figure 3 also identifies a late morning flash concentration along the Gulf of Mexico and Atlantic coasts (Camp et al. 1998; Smith et al. 2005) and near Houston and southern Louisiana (Steiger et al. 2002).

Colorado has several small high-mountain maxima before noon in Figure 3. The state has strong local forcing due to large topographic gradients that result in well-defined lightning patterns (Cummins 2012; López and Holle 1986; Hodanish and Wolyn 2012).

Arizona lightning occurs mainly during the summer monsoon months of July and August, and distributions are well defined due to major topographic gradients (Figure 3). Diurnal Arizona flash variations in true solar time studied by King and Balling (1984) showed flash activity beginning at the higher sloping terrain (Figure 3) and moving toward Phoenix in the evening. The timing was also studied by Watson et al. (1994) with comparisons to precipitation data by hour.

New Mexico lightning in the late morning also occurs over higher elevations and slopes (Figure 3). Fosdick and Watson (1995) showed selected hourly maps similar to Watson et al. (1994) for Arizona. For New Mexico extending into west Texas, regime-flow lightning patterns, especially with respect to first flashes of the day, were compiled by Wagner and Fuelberg (2006).

### b. 1200 to 1400 LMT

Figure 4 shows substantial growth in all areas compared with the period two hours earlier. As shown in the studies by region mentioned for the 1000 to 1200 map in Figure 3, Florida and the Gulf Coast have frequent lightning, and areas in the southeastern states also have increased flash activity. The two sea breezes in peninsular Florida

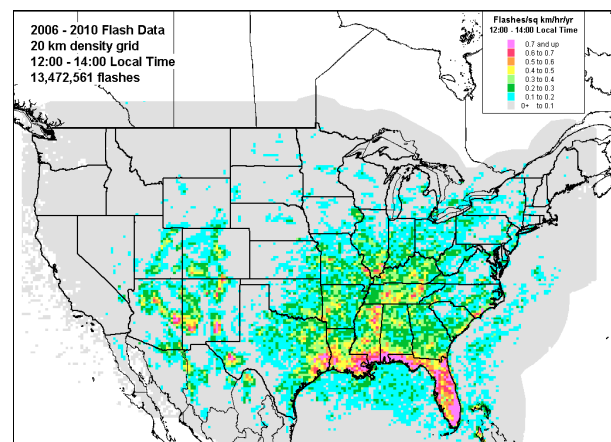


FIGURE 4. Same as Figure 3, except 1200 to 1400 LMT.

are apparent in Figure 4. Also of interest is the increase in flashes at higher elevations of the Four Corners states. This early afternoon period has much of the day's lightning in this region, and indicates an important time to exclude outdoor activities on days when any lightning is forecast or occurring.

#### c. 1400 to 1600 LMT

During the time of maximum heating between 1400 and 1600 LMT (Figure 5), all areas with frequent lightning two hours earlier have increased in lightning frequency. There are no new large areas of lightning. Activity increases across Florida, along and inland from the Gulf of Mexico, in Mexico south of Arizona, in a north-south line over the mountains of New Mexico, across Arkansas, northeast Texas and eastern Oklahoma, as well as expansion and intensification in other locations. This maximum coincides with an afternoon concentration of lightning at the Nevada Test Site (Randerson and Saunders 2002).

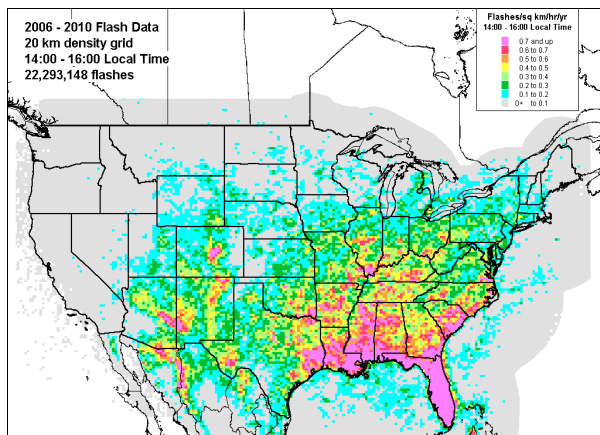


FIGURE 5. Same as Figure 3, except 1400 to 1600 LMT.

#### d. 1600 to 1800 LMT

This two-hour period has the most cloud-to-ground lightning of the diurnal cycle for the continental U.S. as a whole (Figure 2). Figure 6 shows enhanced frequencies in many regions, especially in the southeastern third of the U.S., compared with two hours earlier in Figure 5. Most areas to the west of the Continental Divide begin to show a decrease since two hours earlier.

The 1996 Atlanta Olympics prompted lightning climatologies by Watson and Holle (1996) and Livingston et al. (1996). These emphasized the

afternoon to early evening lightning occurrence in Atlanta and surrounding regions that are evident in Figures 5 and 6. A flash climatology for northern Georgia and western North Carolina by Murphy and Konrad (2005) showed the late afternoon to evening maximum to depend partially on storm size and organization.

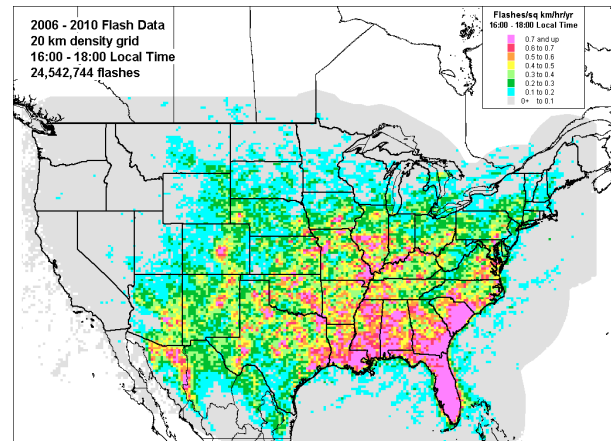


FIGURE 6. Same as Figure 3, except 1600 to 1800 LMT.

#### e. 2000 to 2200 LMT

Moving ahead four hours, Figure 7 shows a strong decline in lightning near and after sunset in the summer, when the most lightning occurs in many regions of the country (Holle and Cummins 2010; Holle et al. 2011). Lightning now has much lower flash densities where it is diurnally forced on the southeastern coast and over the western mountains. Lightning in the central states remains the same or is somewhat enhanced compared with that shown in Figure 6 four hours earlier due to storms propagating from the west.

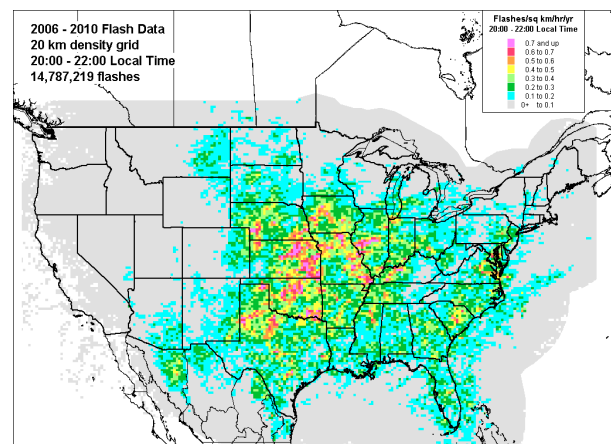


FIGURE 7. Same as Figure 3, except 2000 to 2200 LMT.



A significant portion of the evening and nighttime enhancement of plains lightning is due to mesoscale convective systems in the spring and summer. The well-known MCS, and its largest version the mesoscale convective complex (MCC), were first described by Maddox (1983). MCCs and MCSs are prolific lightning producers during the night as shown by Holle et al. (1994), Nielsen et al. (1994), and many subsequent studies that show various features of lightning in MCSs.

Derechos are also a source of frequent evening and nighttime lightning in the region from the Great Lakes to the east coast in summer. The prevalence for derechos to originate in late afternoon to evening in the southern Great Lakes is emphasized by Johns and Hirt (1987) and Bentley and Mote (1998). A lightning map in a derecho has not been published for its lifecycle. Figure 8 shows frequent flashes during the destructive June 2012 derecho (Figure 8) that traversed a broad region near or after sunset. While this derecho occurred farther east than usual, it is a significant producer of lightning in the late afternoon, evening, and at night.

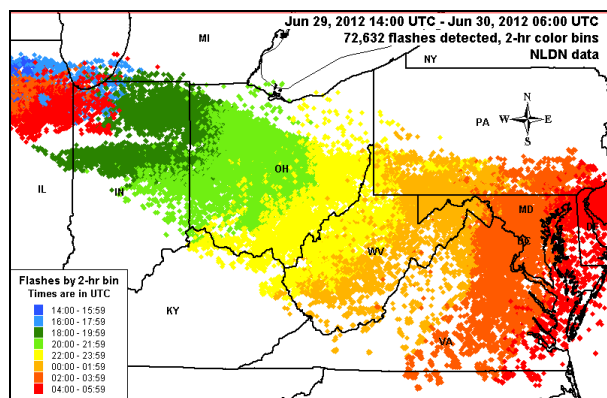


FIGURE 8. Map of NLDN strokes during a large derecho for 14 hours starting at 1400 UTC 29 June 2012. A total of 72,632 flashes are mapped during this period. Colors indicate time in two-hour increments.

#### g. 0000 to 0200 LMT

Moving forward four more hours, Figure 9 shows a large maximum on the plains, where storms from the previous day continue to move east. Storms are actually more frequent here at this time than during the day. MCSs and derechos continue on the plains and Midwestern states on some summer nights at this time. During these hours, the exposure of people to cloud-to-ground lightning is minimal except for camping and similar unprotected activities (Curran et al 2000).

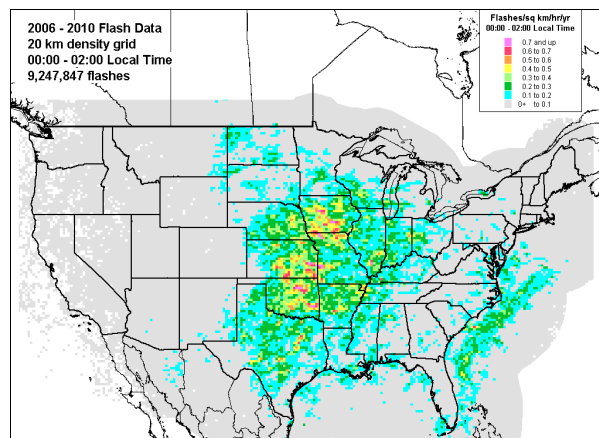


FIGURE 9. Same as Figure 3, except from midnight to 0200 LMT.

#### f. 0400 to 0600 LMT

Four hours later, Figure 10 shows that most lightning has continued to decrease since midnight. However, two areas have significant activity. One is from Oklahoma to Iowa, where the activity continues to move from west to east. The other is an enhancement offshore of the southeast coast over the Gulf Stream.

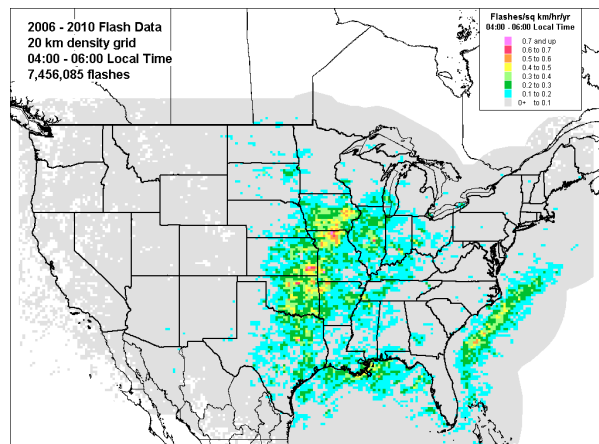


FIGURE 10. Same as Figure 3, except 0400 to 0600 LMT.

#### h. 0800 to 1000 LMT

The final two-hour map of the diurnal lightning cycle is four hours later in Figure 11. Flash activity is weaker than in any two-hour time period (Figure 2). The new day's convection begins with the map from 1000 to 1200 (Figure 3), when the cycle of thunderstorms develops again along coastlines, over mountains, and in the center of the country due to lingering activity from the previous night.

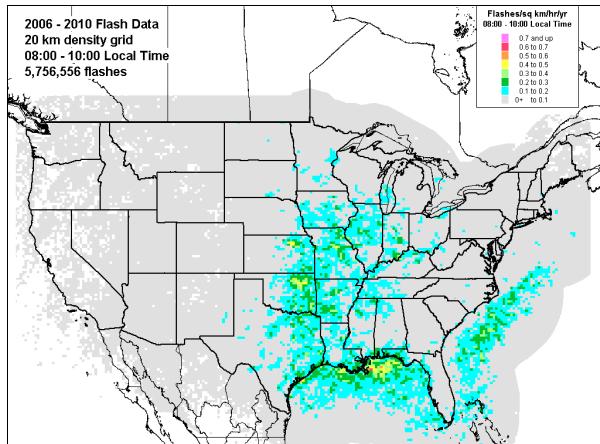
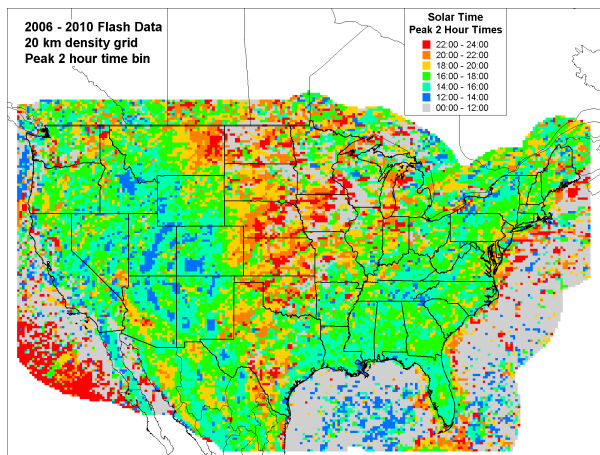


FIGURE 11. Same as Figure 3, except from 0800 to 1000 LMT.



## 5. Combined diurnal maps

Results from the 12 two-hour NLDN datasets are now combined in Figures 12. The left map is for the more active time of day for lightning from noon to midnight, and the right panel is for the less active period from midnight to noon.

### a. Noon to midnight

The left panel of Figure 12 shows that most land areas have their peak lightning activity during the 12 hours starting at noon. Blue grid squares have lightning most often from 1200 to 1400 local time. The two green shades are during the next four hours in mid-afternoon. Yellow grids are loca-

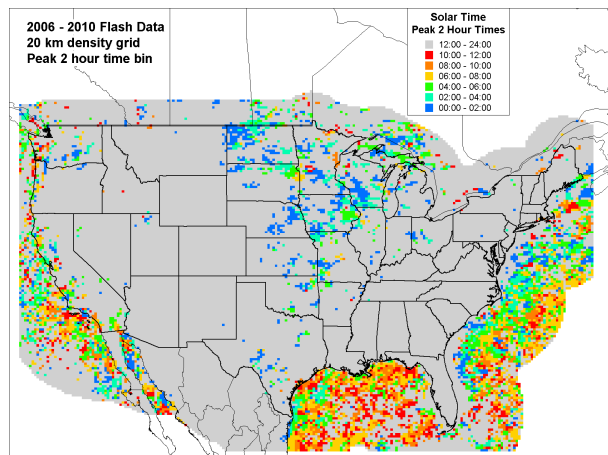


FIGURE 12. Time of maximum cloud-to-ground lightning flash density from 1200 to 2400 LMT (left) and 0000 to 1200 LMT (right) for the U.S. from 2006 through 2010. Scale is in upper right portion of map.

tions with maxima from 1800 to 2000 LST, which is often near sunset during summer. The orange, then red areas have maxima during the hours leading up to midnight. Gray areas in the left panel are for maxima between midnight and noon that are color coded in the right panel.

The most common noon-to-midnight time is shown by two shades of green for a maximum frequency between 1400 and 1800 LMT. This period is often when much of the routine outdoor activities are engaged by people. Florida grid squares (in green) are all during mid-afternoon, as well as most southeastern states. Over Arizona, Utah, Colorado, and New Mexico, flashes begin over high terrain in the early afternoon (blue), then progress outward to lower elevations in the evening and nighttime (yellow then red) to the east or southwest. The central Plains maxima progress

at later and later times toward midnight as storms move eastward off the higher terrain to the west.

### b. Midnight to noon

The right panel of Figure 12 plots in color the grids where lightning has a maximum between midnight and noon. Gray squares are color coded between noon and midnight in the left panel.

In many 20 by 20 km grid squares of the Upper Midwest and Northern Plains, the most frequent lightning is after midnight. More than a third of the squares in Iowa have peak lightning between 0000 and 0400 LMT, which coincides with this area's nighttime maximum in mesoscale convective systems. An NLDN flash climatology in the upper Mississippi Valley also showed a 2100 to 2200 CST maximum (Cook et al. 1999).

Most grid squares in the Atlantic and Pacific Oceans, Gulf of Mexico, and Gulf of California have maxima between midnight and noon. The much lower flash densities over the water result in less organized times of the maxima due to small sample sizes in many grid squares. Near Florida, Georgia, and South Carolina, the ocean close to land had maxima before midnight (Figure 12) associated with daytime thunderstorms moving offshore in the evening. Figure 13 shows some eastward storm motion after midnight into the adjacent Atlantic. A lightning enhancement over the Gulf Stream relative to land in North Carolina during a winter field program was identified by Biswas and Hobbs (1990), Orville (1990), and Dodge and Burpee (1993). In contrast the monthly NLDN study (Holle and Cummins 2010; Holle et al. 2011) showed the Figure 13 maximum to occur mostly in summer, and the present study shows it to be at night

## 6. Conclusions

The first complete survey of lightning density over the United States divided by local time of day was compiled. The source was data from Vaisala's National Lightning Detection Network. Flashes were combined during two-hour periods into five-degree longitude strips that resulted in seamless views of the diurnal variation of lightning at the same overhead sun time. Patterns were related to meteorological factors that occur regularly over the United States during the course of the diurnal cycle.

The minimum time of lightning over the U.S. is between 0800 and 1000 LMT. First flashes of the daily cycle due to solar heating of the land occurred between 1000 and 1200 LMT along the Florida and Gulf of Mexico beaches, and over high mountains of the southwestern states. During the following six hours, lightning increased greatly in frequency in these same places, as well as spreading to new locations in southeastern states after noon. The most common time of maximum lightning was between 1400 and 1800 LMT. A notable maximum in the evening began on the High Plains to the lee of the Rocky Mountains and moved eastward through the night. These storms resulted in nighttime maxima as late as 0200 to 0400 in some Upper Midwest locations. Oceanic lightning tended to be during the night and morning hours, although the times of these maxima are variable due to small sample sizes.

The results of the present study agree substantially with aspects shown by Zajac and

Rutledge (2001), especially the general phase of the diurnal lightning maximum in their Figure 10b. The present study includes maps at individual two-hour time periods, and has more spatial resolution than that prior study. Other partial diurnal maps and time series were referenced in the course of the current study also agree with prior regional and local studies on which the new maps provide a more complete context of the diurnal lightning cycle over the United States than has been compiled prior to this time.

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