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Seasonal Lightning Distributions over North America

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***Abstract*—Annual maps of cloud-to-ground (CG) lightning flash density for the United States have been published since deployment of the National Lightning Detection Network (NLDN). However, a summary of seasonal lightning across the contiguous United States has not been developed. CG flash variability by season is addressed on a 20 x 20 km grid with 1) NLDN flash data from 2005 through 2014 for the 48 states and adjacent regions, and 2) GLD360 stroke data from 2012 through 2014 from northern Canada to the tropics. Flash density and percentage of each season's portion of annual totals are compiled. CG lightning is not uniformly distributed through the year in time, space, or frequency and the meteorological conditions that affect seasonal changes in the spatial distribution of lightning in North America are discussed. This seasonal overview complements a prior review of diurnal CG flash variations over the same region using NLDN data.**

Keywords—seasonal flashes; North American lightning; NLDN flashes; GLD360 strokes.

I. Introduction

National maps of cloud-to-ground (CG) lightning flash density for entire years have been produced since the National Lightning Detection Network (NLDN) was first deployed across the contiguous 48 United States in 1989. The first publication showing flash density for this region was for the year 1989 [Orville, 1991], then individual years were summarized from 1992 to 1995 by Orville and Silver [1997]. United States flash density from 1995-1999 was summarized using the NLDN [Zajac and Rutledge, 2001], followed by an extension of United States coverage into Canada during 1998-2000 [Orville et al., 2002]. A history of the NLDN was provided by Orville [2008] that included 1998-2000 North American flash densities. Comparisons of NLDN characteristics across the United States between the periods of 1996-2001 and 2004-2009 were made to evaluate NLDN upgrade impacts by Rudlosky and Fuelberg [2010]. Next was the depiction of annual and combined North American maps from 2001-2009 [Orville et al., 2011]. Diurnal variations in United States NLDN flash density were recently examined from 2005-2012 [Holle, 2014)], and in a ten-year climatology from 2003-2012 [Koshak et al., 2015]. This body of literature included flash density climatologies, as well as polarity, signal strength, and multiplicity. Reported flash densities in these publications increase through the years due to improvements in NLDN detection efficiency (DE).

These publications showed annual NLDN flash distributions, but relatively few included NLDN data for selected months or seasons. Among the publications with periods shorter than the annual cycle, Zajac and Rutledge [2001] showed summer and cold season lightning distributions, as well as monthly cycles at several United States cities. Monthly CG time series with one total per month for the entire country were shown by Orville and Silver [1997], Orville and Huffines [1999], and Orville [2001, 2008)]. Other recent papers have examined annual or seasonal variations in positive flashes, multiplicity, or mean peak current; these topics are not considered here.

The present paper complements a summary of diurnal NLDN-measured variations in CGs over the same region [Holle, 2014]. Meteorological seasons are considered here; spring is March, April, and May and so on through the year. NLDN seasonal maps of CG flash density are complemented by seasonal stroke density maps from Vaisala's Global Lightning Dataset (GLD360). The GLD360 depictions of lightning extend beyond the range of the NLDN to include much of Canada and Mexico, and a portion of the western Caribbean.

II. Lightning Data

A. NLDN

NLDN data are CG flashes; the estimated NLDN CG flash DE for the contiguous 48 United States was 90 to 95% during the period of 2003 through 2012 [Cummins et al., 2006; Cummins and Murphy, 2009]. Recent assessment by Murphy and Nag [2015] indicate 95% or higher CG flash

DE following a network wide upgrade in 2013. No polarity separation was made in this study, and NLDN reports with positive peak currents <15 kA have been excluded. The same flash data were used in the NLDN diurnal flash study by Holle [2014]. Note that the NLDN also reports CG flashes and CG strokes, as well as a fraction of cloud pulses in both CG flashes and cloud flashes (those without return strokes). Prior to 2013, the NLDN reported cloud pulses in 15-25% of cloud flashes. Following the 2013 upgrade, detection increased to about 50% [Nag et al., 2014; Murphy and Nag, 2015]. More details about the temporal evolution of NLDN performance before 2012 are provided in Koshak et al. [2015]. Definitions and context for these lightning performance measures are in Nag et al. [2015].

NLDN flash counts were accumulated into 20 x 20 km grid squares and then converted into annual density across the contiguous 48 United States and adjacent regions from 2005 through 2014. The spatial boundaries of the NLDN data in this study are identical to those for the diurnal study in Holle [2014]:

- 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° S.
- 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.

B. *GLD360*

At distances of more than about 150 km into Mexico and the coastal waters, the NLDN fails to report low-current discharges [Cummins and Murphy, 2009, Fig. 11]. This reduces the stroke and flash DE values which in turn provides an incorrect representation of flash density in these regions. To provide an appropriate representation of lightning incidence in these regions, and well as into northern Canada, we have included data produced by GLD360.

GLD360 is the first ground-based lightning detection network providing worldwide coverage with substantially uniform high DE [Mallick et al., 2014; Poelman et al., 2013; Pohjola and Mäkelä, 2013; Said and Nag, 2012; Said et al., 2013]. GLD360's flash DE and stroke location accuracy (LA) have been validated over Florida [Mallick et al., 2014]. The validation showed a GLD360 CG flash DE (relative to the NLDN) of 67%, CG stroke DE of 37%, and CG stroke median LA of 2.0 km. The performance of GLD360 over North America is estimated to be a CG flash DE of 70% and median CG stroke LA of 2 to 5 km. GLD360 stroke densities in the second portion of this study are in 20 x 20 km grid squares within geographical boundaries extending beyond the NLDN region. No separation is made with regard to polarity, and it is estimated that overall, a significant fraction of the GLD360 reports are cloud pulses. Limits employed for the GLD360 seasonal maps are:

- Latitude - 6° to 51° N.
- Longitude - 50° to 127° W.

III. ANNUAL NLDN FLASH AND STROKE DENSITY

The annual CG flash and stroke densities from 2005 through 2014 across the contiguous United States and adjacent regions are in Fig. 1. An average of 31 million CG flashes and 74 million CG strokes per year were reported by the NLDN over this region, without applying DE corrections. The range of flash density is very large (Fig. 1a). The largest flash density in a 20 x 20-km grid square is 12.75 flashes km^{-2} yr^{-1} over Florida just north of Orlando. Flash densities exceeding 8 flashes km^{-2} yr^{-1} are frequent over other parts of Florida, along the Gulf of Mexico coast, and in the central United States. The least flash density is 0.0025 flashes km^{-2} yr^{-1} in central California.

Strokes have greater densities than flashes (Fig. 1b). Note the extended scale for strokes to account for larger stroke densities in the central and southeast states. Stroke densities have a similarly large range from a few locations over 32 strokes km^{-2} yr^{-1} along the Florida and Gulf coasts to very small values on the west coast.

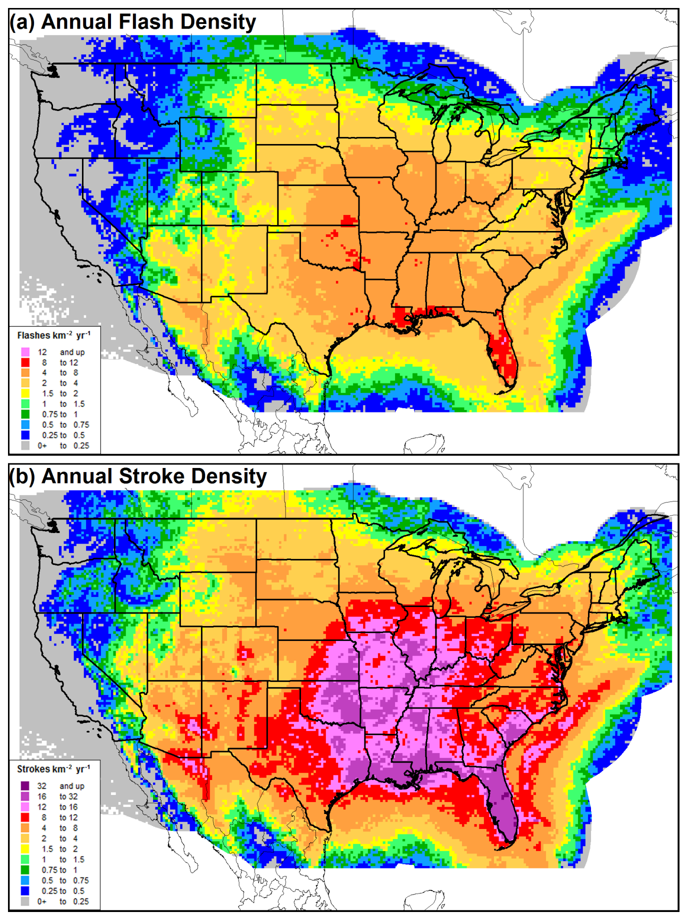

Fig. 1. Annual CG lightning (a) flashes km^{-2} yr^{-1} and (b) strokes km^{-2} yr^{-1} over the United States and adjacent areas based on 310,162,364 CG flashes and 735,630,060 CG strokes from the NLDN from 2005 through 2014. Scales are in lower left portion of maps. Flashes and strokes with positive peak currents <15 kA have been deleted.

Flash and stroke densities are largest over Florida and along the Gulf Coast where the adjacent warm ocean provides deep moisture for strong updrafts in coastal sea breezes. Low densities along the west coast are adjacent to cold offshore water inhibiting deep convective updrafts; this area is also dominated by widespread subsidence aloft during the summer. On the national scale, there is a general decrease from south to north, as well as east to west. However, there are large local variations over and east of the Rocky Mountains, as well as over the interior western states.

Seasonal counts of flashes are plotted in Fig. 2. Lightning is most common during summer - 64% of the year's CG flashes occur in June, July, and August.

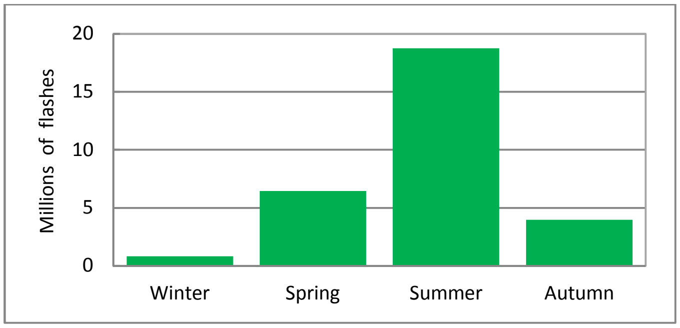

Fig. 2. NLDN cloud-to-ground flashes by season from 2005 through 2014 for the United States and adjacent areas.

IV. NLDN CG Flash Density by Season

A. Spring

During meteorological spring, all areas of the United States with flash densities greater than 0.25 flashes km^{-2} yr^{-1} are located east of the Continental Divide (Fig. 3a). The largest densities are in eastern Oklahoma and adjacent states. In terms of percentages, over 50% of the annual total occurs during spring in southern Texas (Fig. 3b). Other notable areas with a large proportion of spring flashes are the Central Valley of California, northern Nevada into Oregon, and adjacent states. The highest spring percentages are off the west coast of central Baja California.

B. Summer

The pattern and flash density for meteorological summer (Fig. 4a) are similar to the annual map (Fig. 1a). The similarity is to be expected since summer accounts for more than half of the year's lightning (Fig. 2). The widespread dominance of summer lightning is shown by areas exceeding 50% over much of the percentage map in Fig. 4b. Over Arizona and adjacent portions of Mexico, the percentage of the annual lightning during summer is very large (Fig. 4b). In the northern United States, summer is also the dominant contributor to annual lightning frequency. In contrast, the southeast half of Texas and Oklahoma has less than 40% of the year's lightning during the summer due to the persistent summer high-pressure ridge prevailing over the region.

Tropical cyclones and hurricanes occasionally produce lightning in bands or clusters along the coast of Florida, the Gulf Coast, and southeastern states during summer into autumn [DeMaria et al., 2012]. However such tropical systems do not occur in the same location or time, so they have no effect on the long-term climatology.

The following are specific features whose impacts are mainly confined to the summer climatology of CG flashes:

a) Florida: Summer flash density is greatest over Florida in three locations – northeast of Orlando, northeast of Tampa Bay, and west of Palm Beach (Fig. 4a). More than 60% of the year's lightning over the Florida peninsula is during summer (Fig. 4b). Three-month peninsular lightning maps similar to those shown here have been prepared previously [Hodanish et al., 1997; Fieux et al., 2006]. The widely understood Florida lightning features occurring mostly during summer are due to low-level flow regimes that control the frequency and location of lightning over the peninsula [Shafer and Fuelberg, 2008].

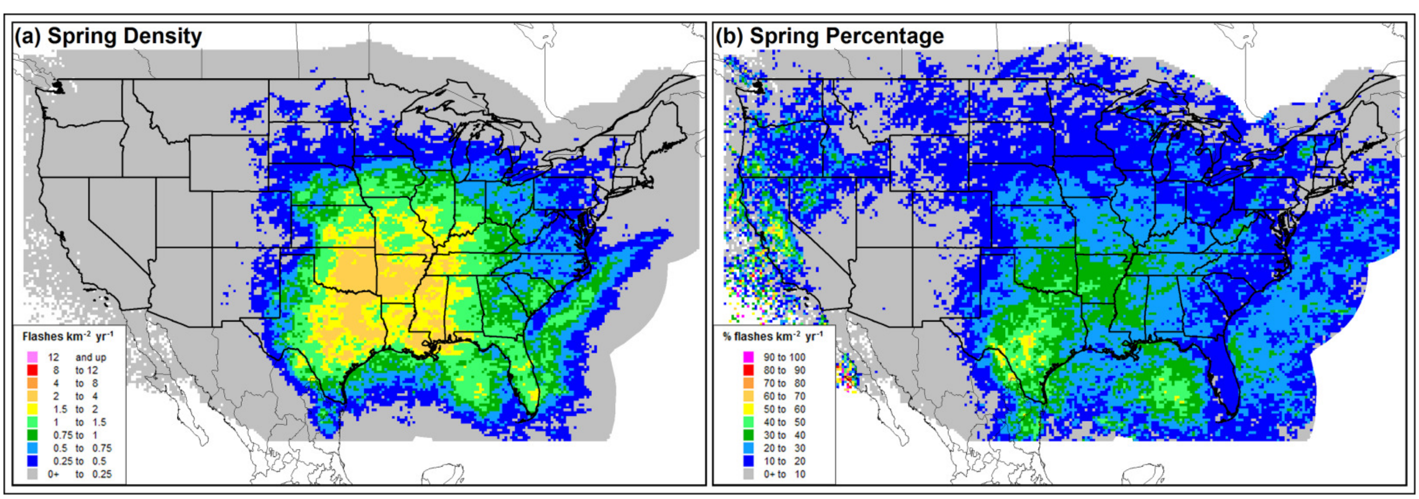

Fig. 3. As in Fig. 1 for (a) spring flash density and (b) spring flash percentage of annual total.

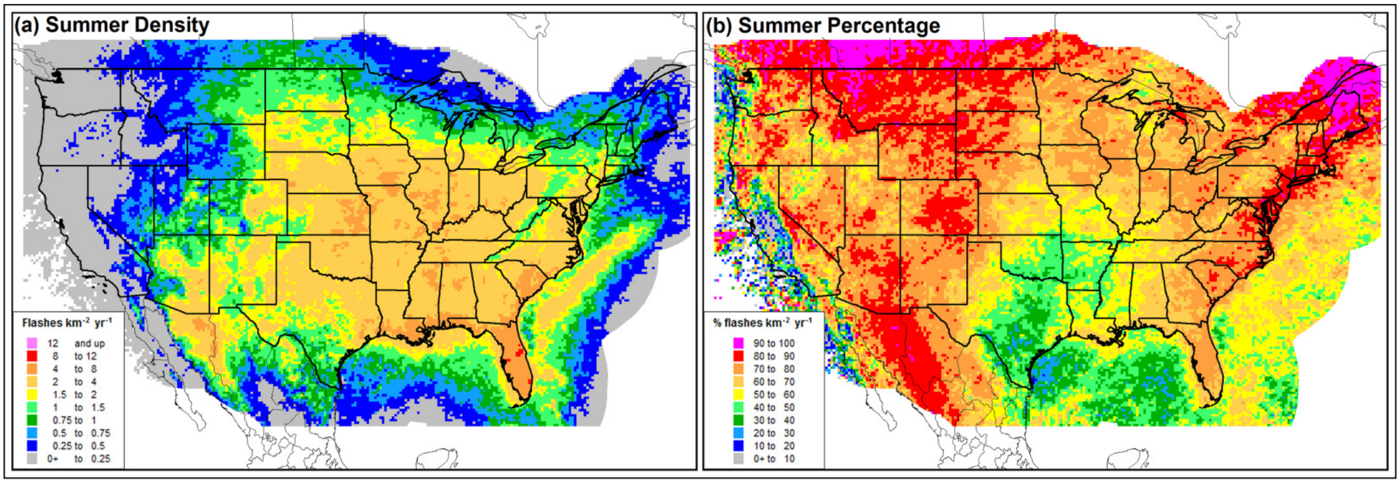

Fig. 4. As in Fig. 1 for (a) summer flash density and (b) summer flash percentage of annual total.

b) Gulf/Atlantic Coasts: A concentration of flashes is present during summer along coasts of the Gulf of Mexico and southeast Atlantic states (Fig. 4a). Previous studies of summer lightning in the northern Gulf coast from the panhandle of Florida to Texas used similar low-level flow regime composite approaches to those for Florida [Camp et al., 1998; Smith et al., 2005].

c) Colorado: Another location with strong local forcing resulting in well-defined lightning patterns is the well-studied summer lightning distribution over Colorado. Summer lightning on the eastern slopes of the Front Range [López and Holle, 1986] indicates a large amount of lightning on the Palmer Lake Divide (Fig. 4a). The dependence of lightning occurrence on altitude over Colorado mountains is shown in annual distributions that are dominated by the summer period [Cummins, 2012; Vogt and Hodanish, 2014].

d) Gulf Stream: Lightning over the Gulf Stream was originally identified as a winter feature due to convective rainbands [Biswas and Hobbs, 1990]. However the summer map (Fig. 4a) shows flash density to be quite strong in that location [Virts et al., 2015]. About half of the NLDN flashes over the Gulf Stream occur during summer (Fig. 4b).

e) Mesoscale Convective Systems: Large CG flash densities are observed from Kansas northeastward to Iowa and surrounding states (Fig. 4a). A portion of this incidence can be attributed to prolific lightning production in mesoscale convective systems during summer [Dotzek et al., 2005 and subsequent studies].

f) Convective SIGMETS: NOAA's Aviation Weather Center defines lines and areas of thunderstorms hazardous to aviation [Slemmer and Silberberg, 2004]. The two areas with the most frequent SIGMETS are the Gulf Coast and Florida during June into September, and over Arizona, New Mexico and Colorado during July and August.

g) Southeast States: July and August lightning climatologies for the 1996 Atlanta Olympics [Watson and López, 1996; Livingston et al., 1996] and a full-summer flash climatology over northern Georgia [Murphy and Konrad. 2005] agree with the large lightning incidence in Fig 4a. Southern Georgia shares a common lightning incidence pattern with the Gulf States, while northern Georgia has a pattern similar to the adjacent southeastern states.

C. Autumn

The CG flash counts in meteorological autumn are sharply reduced compared with summer. Highest flash densities are in eastern Kansas and Oklahoma, as well as over the Florida peninsula (Fig. 5a). In terms of percentages, the highest values are in southern and coastal California into Baja California of Mexico (Fig. 5b). This maximum is due to tropical systems and late monsoon moisture arriving from the south through east, most often in September [Adams and Comrie. 1997; Holle and Murphy, 2015]. Other regional autumn maxima in flash density are in Utah and the northern Great Lakes.

D. Winter

During the winter, most of the southern and southeastern United States had some lightning from 2005 through 2014 (gray shading in Fig. 6a). Almost no CG flashes were reported in the northern Rocky Mountain and northern Plains states. The largest winter flash densities are in Louisiana and Mississippi (Fig. 6a), and the only flash densities exceeding 0.25 flashes km^{-2} yr^{-1} are within a few hundred km of those states. In terms of percentages, the only regions over land exceeding 20% are over the central coast of California (Fig. 6b). Larger percentages are located offshore due to winter storms. Although ten years of data are summarized, winter lightning density maps show banded structures oriented southwest to northeast (Fig. 6b). In some cases, these bands are accompanied by snowfall. Such events have been documented in the central states [Market and Becker, 2009; Warner et al., 2014], southeastern states [Hunter et al., 2001], and south Texas [Dolif Neta et al., 2009)].

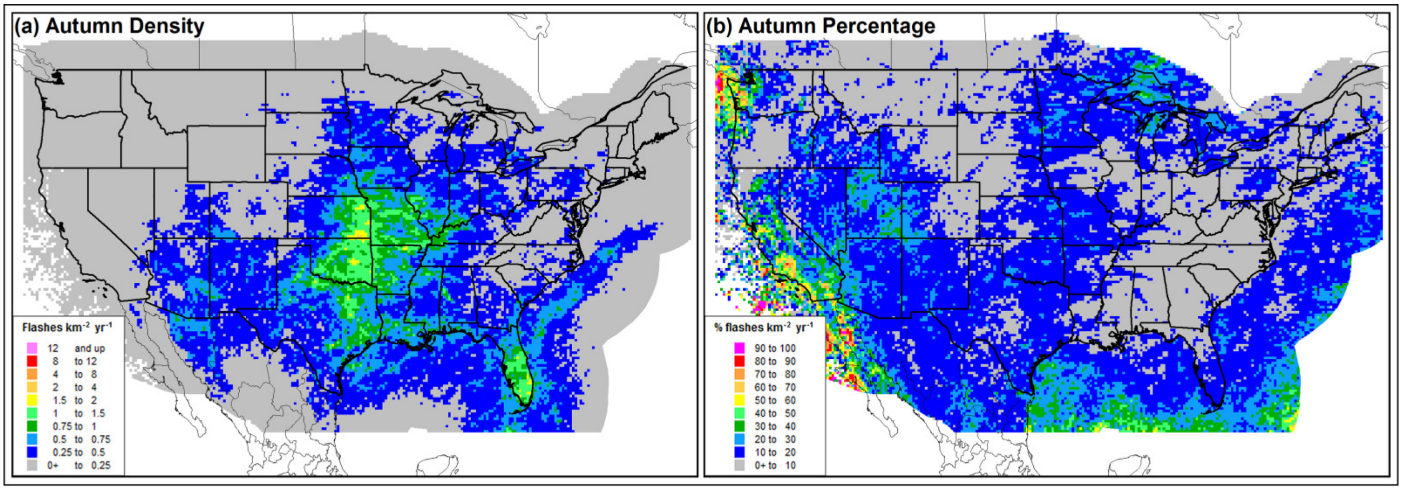

Fig. 5. As in Fig. 1 for (a) autumn flash density and (b) autumn flash percentage of annual total.

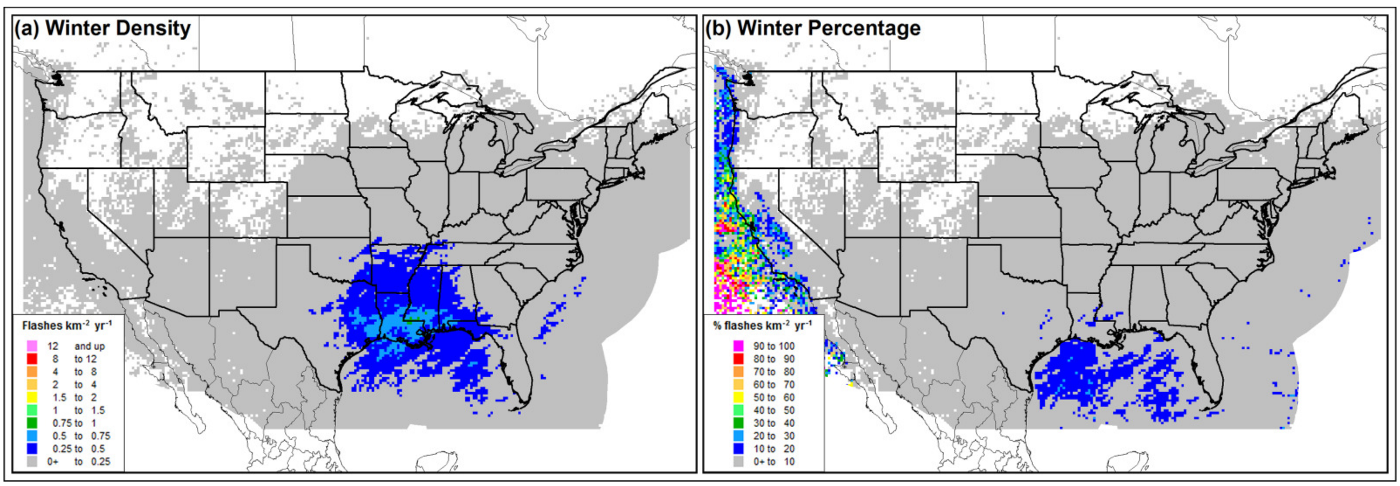

Fig. 6. As in Fig. 1 for (a) winter flash density and (b) winter flash percentage of annual total.

V. GLD360 Stroke Density by Season

GLD360 maps extend the detection range beyond the NLDN in a seamless manner. Over a much larger area than the NLDN maps, GLD360 data will now be used to depict the seasonal distributions of stroke density and the percentage of annual lightning over much of Mexico and Canada, and the surrounding oceans. GLD360 data are cloud-to-ground strokes and cloud pulses, so the GLD360 stroke densities are larger in many areas than shown by NLDN flashes. The meteorological seasons are now described with GLD360 in the same sequence as for the NLDN using a color scale adjusted to facilitate comparisons with NLDN maps.

A. *Spring*

GLD360 strokes during spring (Fig. 7a) show the same general features over the contiguous United States as the NLDN (Fig. 3a). Lightning is detected in spring almost everywhere over the United States, southern Canada, and mainland Mexico (Fig. 7a). Largest densities are over eastern Texas southeastward into coastal Mexico and the Gulf of Mexico. The large stroke density found in the south-central states extends through the northern half of the Gulf of Mexico, across Florida, and eastward over the Atlantic, including a swath generally following the Gulf Stream extending to the northeast over the Atlantic Ocean. Other active lightning locations are Cuba and the Yucatan peninsula. Little to no lightning is reported over northern Canada and much of the Pacific Ocean.

In terms of percentage, most areas had under 20% of their annual total in spring, except in Texas northeast onto the Plains, and southeast into the Gulf, where percentages are as high as 50% (Fig. 7b). These findings supplement our understanding of storms impacting the Gulf of Mexico coast by showing the continuation of lightning beyond the United States land area. Off the California coast, some areas have nearly all of the annual lightning during spring, although densities are very small.

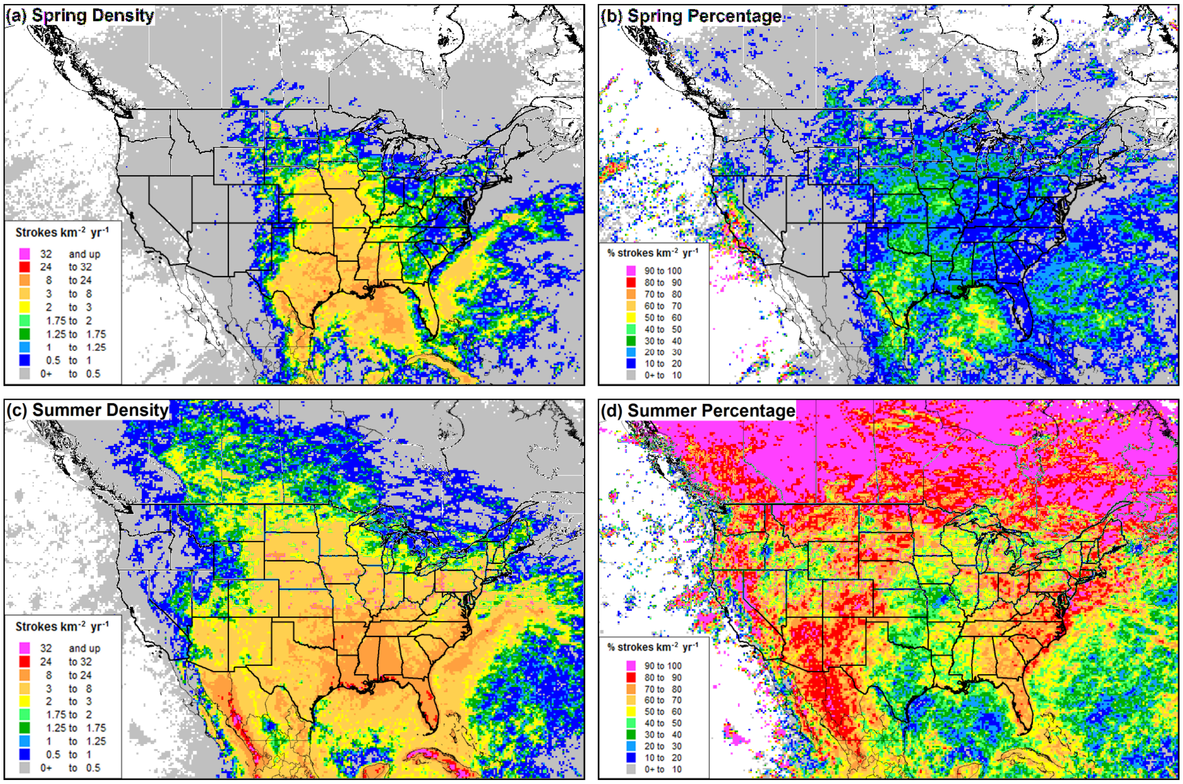

Fig. 7. GLD360-detected lightning over the United States and adjacent countries and oceans based on 401,673,209 strokes during all of 2012 through 2014. (a) Spring stroke density, (b) spring percentage of year's total, (c) summer stroke density, and (d) summer percentage of year's total. Scales are in lower left portion of maps.

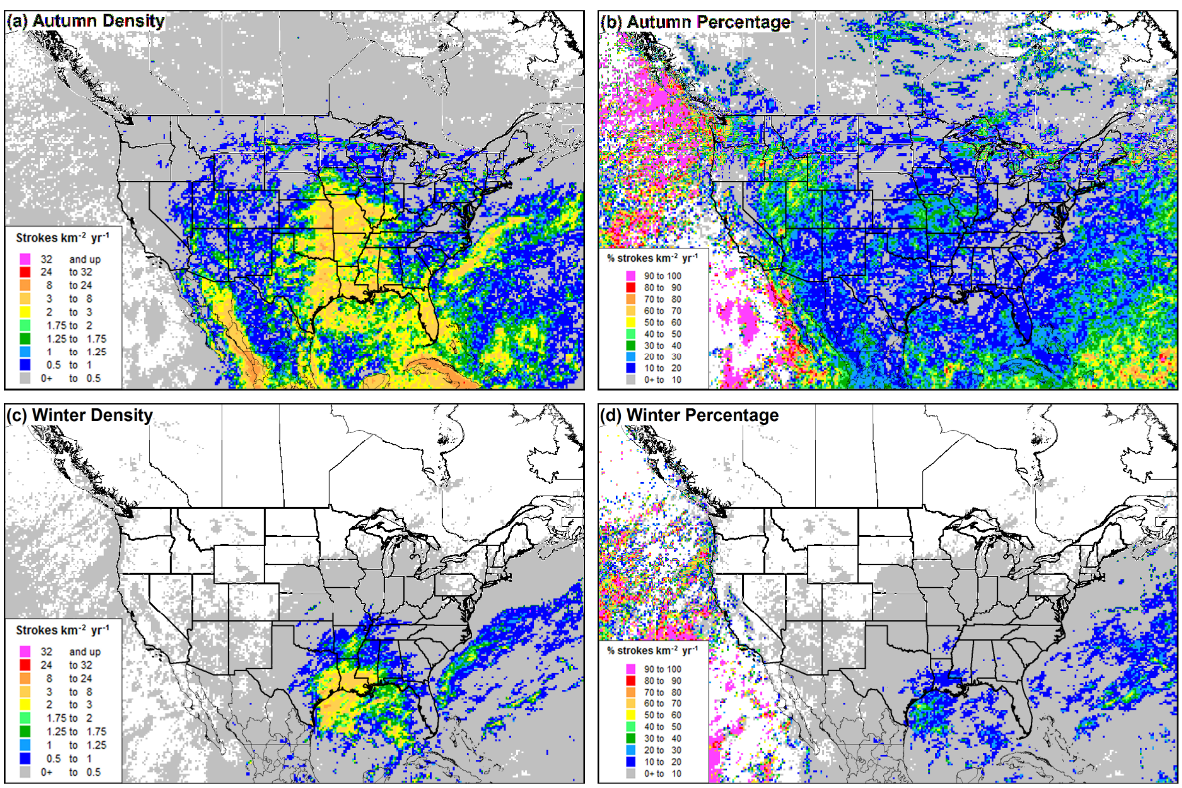

Fig. 8. Same as Fig. 7 for (a) autumn stroke density, (b) autumn percentage of year's total, (c) winter stroke density, and (d) winter percentage of year's total.

B. Summer

Largest stroke densities are in Florida, the southern Plains, the Gulf and south Atlantic Coast, Cuba, as well as Yucatan and Northwest Mexico (Fig. 7c). Frequent lightning reaches into Canada on the east side of the Rocky Mountains. No lightning is reported over much of the area of the Pacific Ocean in summer. The greatest GLD360 stroke densities in northwest Mexico are in a line from northwest to southeast farther south into Mexico than shown by the NLDN on the coastal side of the Sierra Madre Occidental, and exceed those in Arizona and New Mexico. A minimum north and west of the Yucatan peninsula over the Gulf of Mexico is attributable to compensating subsidence due to the adjacent strongly heated land mass during the day, in an area downwind from the land under easterly low-level flow. A potentially similar effect appears in spring west of Florida (Fig. 3a); this topic has not been examined with lightning data. Also note the strong minimum over Torreon in central Mexico (Fig. 7c) that may be analogous with the minimum in flash density over southern Colorado's San Luis Valley (Fig. 4a).

Summer percentages are very large, over 90%, across most of Canada (Fig 7d). Other areas exceeding 80% are in the northwest Mexico monsoon region extending from Arizona southward along the coast of the mainland of Mexico [Adams and Comrie, 1997; Holle and Murphy, 2015], western Oregon and the Nevada-California border, and the central Atlantic coast. The lowest percentages are over Texas and the Central Plains, and south into the Gulf of Mexico where high spring percentages prevail (Fig. 7b).

C. Autumn

Largest stroke densities continue over Cuba, Yucatan, and the west coast of Mexico (Fig. 8a). The frequency of lightning has otherwise quickly diminished from summer into autumn over nearly all of Canada, while most of the Gulf of Mexico northward into the Plains states continues to be quite active. The Gulf Stream maintains frequent lightning offshore into the Atlantic Ocean. Differences between GLD360 and NLDN stroke densities are attributable to partial detection by GLD360 of cloud pulses, higher GLD360 DE outside the 48 states than the NLDN, and differing data collection periods.

The high percentage of autumn lightning along the west coasts of United States, Canada, and Mexico is quite apparent with both networks (Figs. 5b, 8b). Offshore from Mexico, lightning is typically due to tropical storms and hurricanes or their remnants. Farther north over the Pacific, lightning occurrence is due to autumn storms arriving from the west or southwest as winter approaches.

D. Winter

The GLD360 maps in Fig. 8 have similar patterns as NLDN in Fig. 6, however stroke density from GLD360 is much larger over the northern and central Gulf of Mexico, and especially over the Gulf Stream. South Texas, Louisiana, and the adjacent Gulf of Mexico have the highest observed stroke densities over North America during winter (Fig. 8c). The Gulf Stream extending northeast far into the Atlantic is well depicted by GLD360 in winter. Minimal lightning is over Cuba and Mexico in winter after substantial lightning frequencies occurred in autumn. Nearly all of Canada is lightning-free, as well as the northwest third of the contiguous United States. In terms of percentage, the winter portion of the year's lightning is quite small over most of North America except over the Pacific Ocean, Texas Gulf Coast, and isolated locations over the Atlantic Ocean (Fig. 8d).

VI. CONCLUSIONS

Cloud-to-ground flash densities over the United States and adjacent areas are shown on seasonal time scales using NLDN data. Additionally, stroke data for most of North America are presented using GLD360 data. Lightning is concentrated within a few months in most areas of North America. For example, most Florida lightning is during the three summer months, and Arizona and adjacent states have nearly all of their flashes in summer. In the Central Valley of California, lightning occurs mainly in winter. In most of Canada, New England, Montana, and the Dakotas, lightning rarely happens outside of summer. The lightning incidence in Mexico and the Gulf of Mexico is much greater than indicated by the NLDN.

This seasonal summary of lightning over the United States is a complement to the study of the diurnal variations of CG flashes over the United States and adjacent regions by Holle [2014]. The combination of these two publications makes it possible to identify when and where lightning occurs over the United States and North America by season in order to better specify the lightning threat for the public and for specific lightning-vulnerable activities.

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