Seasonal, Monthly, and Weekly Distributions of NLDN and GLD360 Cloud-to-Ground Lightning

RONALD L. HOLLE

Vaisala Inc., Tucson, Arizona

KENNETH L. CUMMINS

Department of Atmospheric Sciences, The University of Arizona, Tucson, Arizona

WILLIAM A. BROOKS

Vaisala Inc., Tucson, Arizona

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ABSTRACT

Annual maps of cloud-to-ground lightning flash density have been produced since the deployment of the National Lightning Detection Network (NLDN). However, a comprehensive national summary of seasonal, monthly, and weekly lightning across the contiguous United States has not been developed. Cloud-to-ground lightning is not uniformly distributed in time, space, or frequency. Knowledge of these variations is useful for understanding meteorological processes responsible for lightning occurrence, planning outdoor events, anticipating impacts of lightning on power reliability, and relating to severe weather. To address this gap in documentation of lightning occurrence, the variability on seasonal, monthly, and weekly scales is first addressed with NLDN flash data from 2005 to 2014 for the 48 states and adjacent regions. Flash density and the percentage of each season's portion of the annual total are compiled. In spring, thunderstorms occur most often over southeastern states. Lightning spreads north and west until by June, most areas have lightning. New England, the northern Rockies, most of Canada, and the Florida Peninsula have a small percentage of lightning outside of summer. Arizona and portions of adjacent states have the highest incidence in July and August. Flash densities reduce in September in most regions. This seasonal, monthly, and weekly overview complements a recent study of diurnal variations of flashes to document when and where lightning occurs over the United States. NLDN seasonal maps indicate a summer lightning dominance in the northern and western United States that extends into Canada using data compiled from GLD360 network observations. GLD360 also extends NLDN seasonal maps and percentages into Mexico, the Caribbean, and offshore regions.

1. Introduction

National maps of cloud-to-ground (CG) lightning flash density for whole years have been produced since the National Lightning Detection Network (NLDN) was first deployed across the contiguous 48 United States (CONUS) in 1989 (Table 1). The first publication showing flash density for the CONUS was for 1989 (Orville 1991), then individual years were summarized from 1992 to 1995 by Orville and Silver (1997). The U.S. flash density from 1995 to 1999 was summarized using the NLDN (Zajac and Rutledge 2001), followed by an extension of CONUS coverage into Canada during 1998–2000 (Orville et al. 2002). A history of the NLDN was provided by Orville (2008) that also showed 1998–2000 North American flash densities. Comparisons of NLDN characteristics across the CONUS between the periods of 1996–2001 with 2004–09 were made to evaluate NLDN upgrade impacts (Rudlosky and Fuelberg 2010). Next in the time sequence of NLDN CG flash density maps was the depiction of annual and combined North American maps from 2001 to 2009 that includes

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Corresponding author address: Ronald L. Holle, Vaisala Inc., 2705 E. Medina Rd., Tucson, AZ 85756.
E-mail: ron.holle@vaisala.com

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TABLE 1. Summary of selected prior U.S. NLDN climatologies.

References	Data period	Area	Description
Orville (1991)	1989	CONUS	First CONUS map
Orville and Silver (1997)	1992–95	CONUS	First multiyear CONUS map
Zajac and Rutledge (2001)	1995–99	CONUS	Updated multiyear CONUS map
Orville et al. (2002)	1998–2000	CONUS and Canada	Added Canada to CONUS
Orville (2008)	1998–2000	CONUS	History of NLDN in CONUS
Rudlosky and Fuelberg (2010)	1996–2001 vs 2004–09	CONUS	NLDN upgrade impacts
Orville et al. (2011)	2001–09	CONUS and Canada	Annual and multiyear maps
Holle (2014)	2005–12	CONUS	Diurnal variations
Koshak et al. (2015)	2003–12	CONUS	10-yr climatology

coverage into Canada (Orville et al. 2011). Diurnal variations in CONUS NLDN flash density were recently examined from 2005 to 2012 (Holle 2014), followed by a 10-yr climatology from 2003 to 2012 (Koshak et al. 2015). This body of literature included flash density climatologies, as well as the parameters of 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. None address the entire country for every season, month, or week. 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 U.S. 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). The diurnal variability of the signal strength of CG flashes has been recently examined over the same region with NLDN data (Chronis et al. 2015). Other recent papers have examined annual or seasonal variations in positive flashes, multiplicity, or mean peak current; however, these topics are not considered here.

The present paper is the first to show multiyear lightning occurrence over most of North America with the high-resolution GLD360 network whose DE varies slowly over long distances. NLDN seasonal maps of CG flash density are expanded by seasonal stroke density maps from Vaisala's Global Lightning Dataset (GLD360) that extend beyond the NLDN coverage and maps lightning over most of Canada, Mexico, Central America, and the western Caribbean (see full description in section 2b). It is the first of an expected series of GLD360 climatology papers with longer datasets and a better understanding of the capabilities of the GLD360 network performance, similar to the history of NDLN climatologies in Table 1. This GLD360 depiction is also a bridge from the detailed NLDN view that is limited to the CONUS area to an extension that is now possible over the globe, and extends our understanding of the seasonal patterns of lightning incidence at and beyond the edges of NDLN coverage.

This study complements the summary of diurnal NLDN-measured variations in CGs over the same region (Holle 2014). The goal of this study is to address the gap in documentation of lightning occurrence across seasonal, monthly, and weekly time scales to complement the diurnal study. Meteorological seasons are considered here; spring is March, April, and May, and so on through the year.

The order of presentation is as follows. First, NLDN-measured CG flash distributions from 2005 to 2014 are accumulated for seasonal, monthly, and selected weekly time periods, as well as seasonal percentages of the annual total over the CONUS and adjacent regions. Then GLD360-measured stroke distributions accumulated from 2012 to 2014 are presented by season, together with their seasonal percentage of the annual totals over most of North America.

2. Lightning and severe weather data

a. NLDN data

NLDN data presented here are primarily CG flashes. The estimated NLDN CG flash DE for the CONUS was 90%–95% during the period 2003–12 (Cummins et al. 2006; Cummins and Murphy 2009). Recent assessment by Murphy and Nag (2015) indicates 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 due to their tendency to be cloud pulses (Cummins and Murphy 2009). Flash data were also shown in the diurnal NLDN study by Holle (2014). A cloud-to-ground flash has one or more return strokes, and the NLDN reports both CG flashes and CG strokes, as well as some fraction of cloud pulses within both CG flashes and cloud flashes (those without return strokes).

Prior to 2013, the NLDN had a cloud pulse DE of 15%–25%. Following the upgrade in 2013, this DE increased to about 50% (Nag et al. 2014; Murphy and Nag 2015). Koshak et al. (2015) provided more details about the time evolution of NLDN performance before 2012. Definitions and context for these lightning performance measures are provided in Nag et al. (2015).

NLDN flash counts for the first portion of this study were accumulated into 20 km by 20 km grid squares and then converted into annual flash density across the CONUS and adjacent regions from 2005 to 2014. The spatial boundaries of the NLDN data in this study are identical to those for the diurnal study in Holle (2014) (and are apparent in the maps of Figs. 1, and 3–6, and also apply to Fig. 2):

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.

b. GLD360 data

At distances of more than about 150 km into Mexico and the coastal waters, the NLDN fails to report low-current discharges [Fig. 11 in Cummins and Murphy (2009)]. This reduces the stroke and flash DE values, which in turn provides an incorrect representation of the flash density in these regions. To provide an appropriate representation of lightning incidence in these locations, as 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 high DE that is slowly varying over long distances (Mallick et al. 2014; Poelman et al. 2013; Pohjola and Mäkelä 2013; Said and Nag 2012; Said et al. 2013). The GLD360 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 in Florida) of 67%, a CG stroke DE of 37%, and a 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 a median CG stroke LA of 2–5 km. GLD360 stroke densities in the second portion of this study are also in 20 km by 20 km grid squares within geographical boundaries extending beyond the NLDN region. For this study all GLD360-reported strokes are included, no separation is made with regard to polarity, and it is known that some fraction of the GLD360 reports are cloud pulses. Inclusion of all GLD360 reports will impact the magnitude of the annual lightning incidence but should have very little effect on the spatial patterns of lightning, which are the focus of this study. (Spatial limits employed for GLD360 data for the seasonal comparisons are apparent in Figs. 7 and 8.) The latitude range is from 6° to 51°N and the longitude range is from 50° to 127°W.

c. Severe weather probabilities

Lightning distributions are also compared with severe weather probabilities from the Storm Prediction Center (SPC) of NOAA's National Weather Service. SPC probabilities include tornadoes, damaging thunderstorm winds [as indicated by winds 50 kt (25.7 m s^{-1}) or stronger or the occurrence of damage], and large hail [1 in. (2.54 cm) in diameter or more] within 25 mi (40.2 km) of a location in the United States. (Maps are available by week of the year in a temporally and spatially smoothed format at http://www.spc.noaa.gov/new/SVRclimo/climo.php?parm=anySvr.) For comparisons with this SPC dataset, a weekly animation of NLDN flashes is included as an online supplement to this paper.

3. Annual NLDN flash and stroke density distributions

Figure 1 illustrates the annual CG flash and stroke densities from 2005 to 2014 across the CONUS and adjacent regions. The NLDN reported an average of 31 million CG flashes and 74 million CG strokes per year over this region (without applying any DE corrections). The range of flash density is very large (Fig. 1a). The highest flash density in a 20 km × 20 km grid square is 12.75 flashes km^{-2} yr^{-1} just north of Orlando, Florida. Flash densities exceeding 8 flashes km^{-2} yr^{-1} frequently occur over other parts of Florida, along the Gulf of Mexico coast, and over some locations in eastern Oklahoma and southeast Kansas. The smallest flash density of 0.0025 flashes km^{-2} yr^{-1} in central California is due to only one flash per year in a grid box. Other very small values are in West Coast states but all land locations have at least one flash in the dataset in a grid box. Stroke densities (Fig. 1b) 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.

In general, densities are highest in Florida and along the Gulf Coast where the adjacent warm ocean provides deep moisture for strong coastal updrafts in sea breezes. Small densities along the West Coast are located adjacent to cold offshore water inhibiting deep

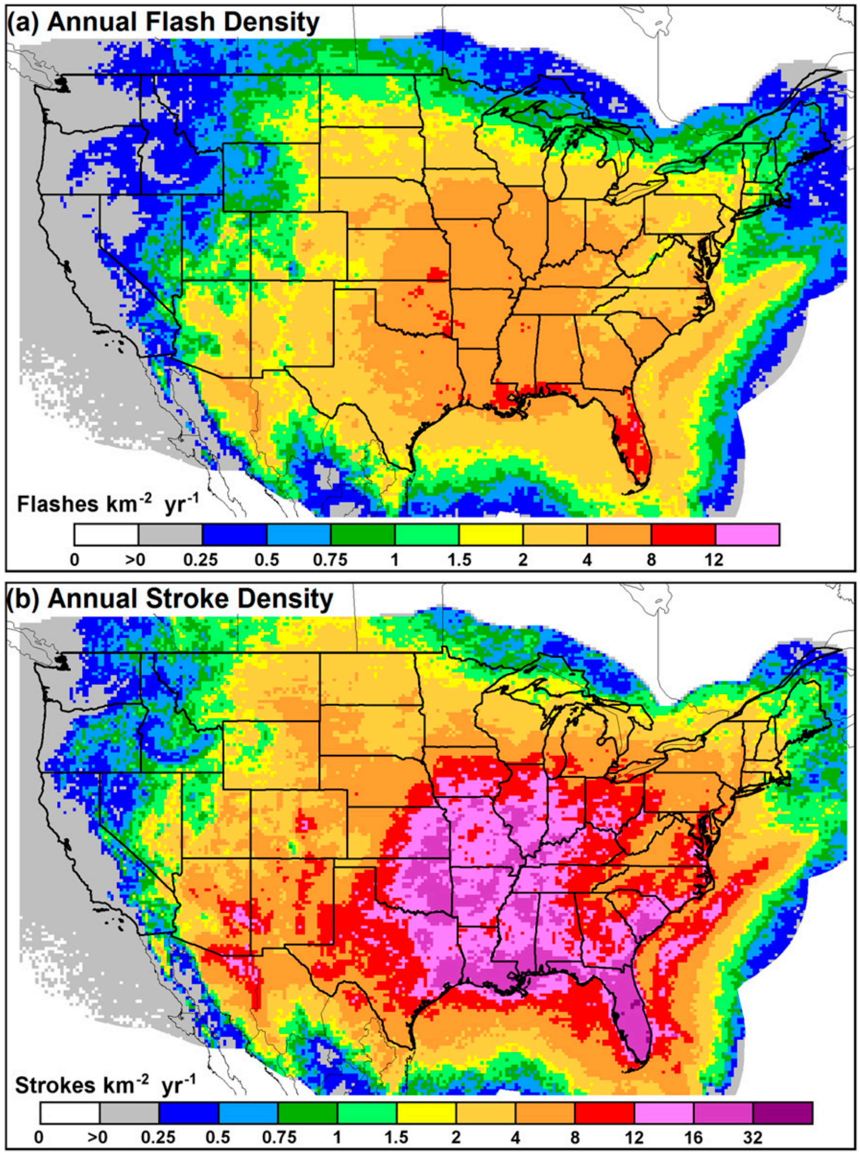

FIG. 1. Annual CG lightning densities of (a) flashes km^{-2} yr^{-1} and (b) strokes km^{-2} yr^{-1} over the CONUS and adjacent areas based on 310 162 364 CG flashes and 735 630 060 CG strokes from the National Lightning Detection Network from 2005 to 2014. Scales are across the bottom of the maps. Flashes and strokes with weak positive estimated peak currents (i.e., <15 kA) are omitted from these maps.

convective updrafts; this area is also dominated by widespread subsidence aloft during the summer (Wood 2012). 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.

Cloud-to-ground strokes have much higher densities than cloud-to-ground flashes (Figs. 1a and 1b). Note that the scale for strokes is extended to account for higher stroke densities in the central and southeast states. There is usually more than one stroke per flash, averaging three to four strokes per flash although the ratio varies by location, time, and storm. Recall that positive cloud-to-ground flashes and strokes with peak currents <15 kA have been excluded.

Figure 2 plots the seasonal, monthly, and weekly counts of flashes. Lightning is by far most common during summer—64% of the annual total of CG flashes occurs in June, July, and August (Fig. 2a). The

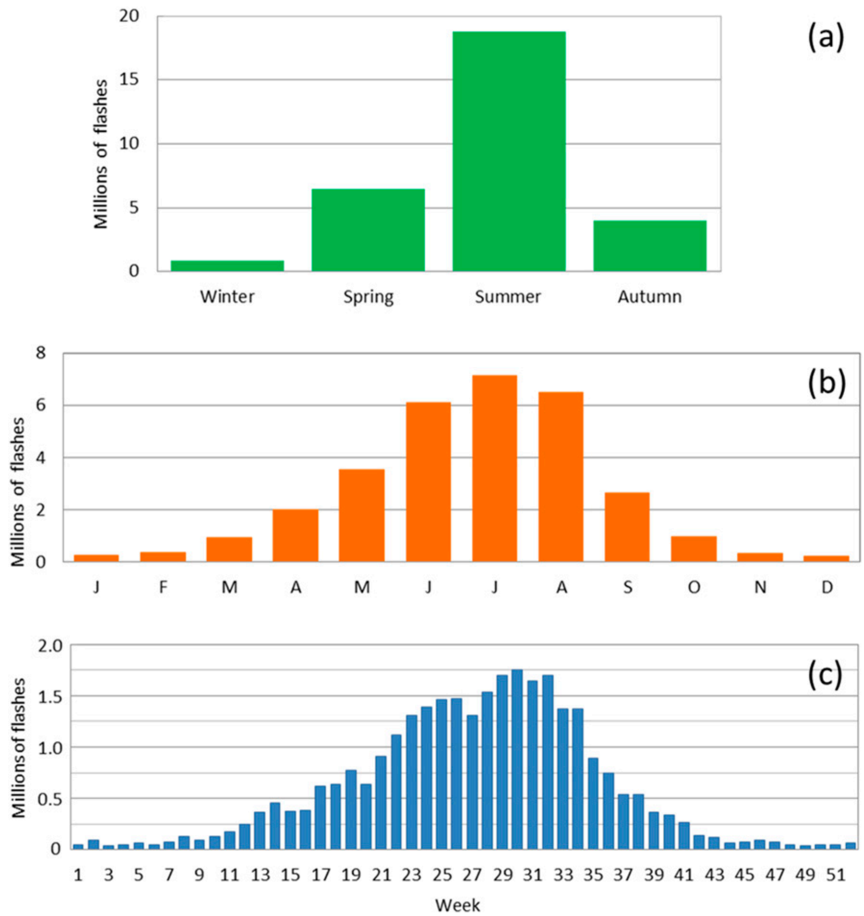

FIG. 2. Cloud-to-ground flashes by (a) season, (b) month, and (c) week from 2005 to 2014 for the United States and adjacent areas shown in Fig. 1 from the National Lightning Detection Network.

increase in monthly CG flashes during the spring months is more gradual than the decay at the end of the summer (Fig. 2b). Weekly CG flashes also show a more gradual growth in frequency at the start of the summer and a more rapid decline at the end (Fig. 2c). The following sections describe the spatial locations where flashes increase and decrease during the course of the year.

4. Spring NLDN CG flash density maps

a. Spring summary

During meteorological spring, all areas of the CONUS with flash densities above 0.25 flashes $km^{-2} yr^{-1}$ occur east of the Continental Divide (Fig. 3a). The highest densities are in eastern Oklahoma and adjacent states. In terms of percentages, southern Texas has its largest portion of the annual total of CGs (>50%, Fig. 3b). Large proportions of lightning during spring also occur in the Central Valley of California, and northern Nevada into Oregon and Idaho. The highest spring percentages are in some locations off the west coast of central Baja California.

b. March

The CG flashes in March are concentrated in the south-central region of the United States (Fig. 3c). A few areas along the Gulf of Mexico coast and over the ocean exceed 0.75 flashes $km^{-2} yr^{-1}$. A small amount of lightning occurs over the Gulf Stream. For the middle week of the month centered on 18 March, the highest SPC severe weather probabilities are centered over Arkansas and nearby states to the east and west. During the course of March, the area of highest probability of severe weather moves westward to southeast Oklahoma while lower severe weather occurrence also starts to appear through the southeastern third of the United States as do the March flash

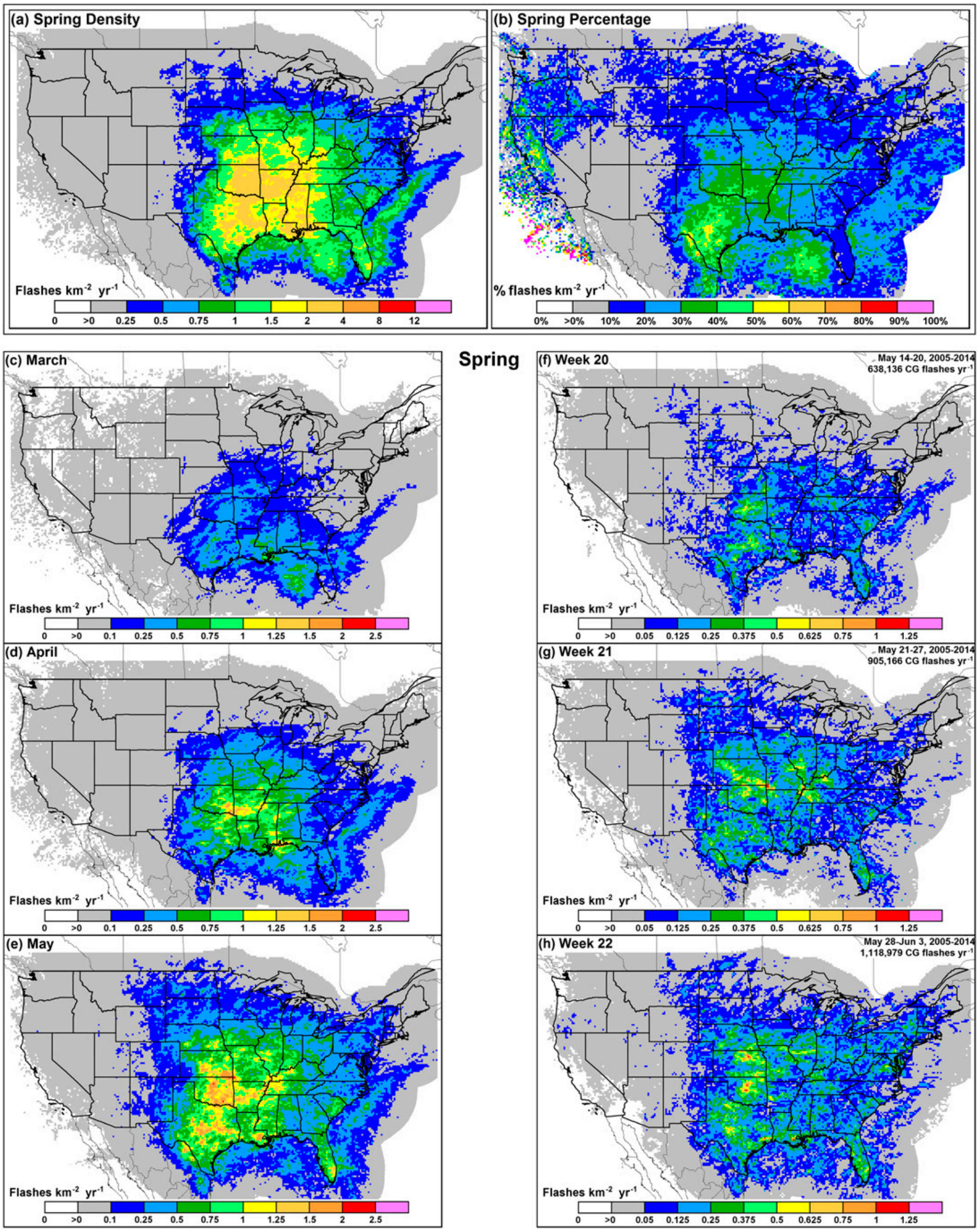

FIG. 3. As in Fig. 1, but for (a) spring flash density, (b) spring flash percentage of annual total, and flash densities for (c) March, (d) April, (e) May, (f) week 20, (g) week 21, and (h) week 22.

densities shown in the weekly maps in the online supplemental material.

c. April

There is an increase in flash density in April and to a lesser extent, areal coverage since March (Fig. 3d). There has been an expansion of the area with 0.75 flashes km^{-2} yr^{-1} as far northward as Indiana and Nebraska. There are also new areas exceeding 1.0 and sometimes 1.5 flashes km^{-2} yr^{-1} along the Gulf Coast and eastern Oklahoma. Increased incidence of lightning occurs offshore of the Carolinas over the Gulf Stream. Peninsular Florida shows some increase in flash density in April compared with March but values are still quite small. During the course of April peak counts of both CG flashes (Fig. 3d) and severe weather probabilities (see weekly SPC maps) are in eastern to central Oklahoma.

d. May

A widespread expansion of CG flashes occurs in May (Fig. 3e). The progression of this transition from mid-May to early June is shown in weekly maps (Figs. 3f–h). Flashes are reported nearly everywhere in the CONUS at some point during May between 2005 and 2014 (gray shading), and nearly all areas east of the Continental Divide have more than 0.25 flashes $km^{-2} yr^{-1}$. No flashes are detected in a few locations along the West Coast. The highest 1-month incidence now exceeds 2.0 flashes $km^{-2} yr^{-1}$ in Oklahoma. Note the start of the summer lightning season in south Florida. Severe weather probabilities in mid-May are centered in Oklahoma, as are CG flashes. However, a secondary severe weather area has developed along the interior North Carolina–South Carolina border that is not apparent in CG density (Fig. 3e). The flash density in this region is not very high during May, but tornado and wind reports are frequent so that storms that form are often severe.

e. Transition from spring to summer

The doubling of lightning flash incidence is apparent in three consecutive weekly maps during this period from mid-May to early June (Figs. 3f–h). The increase is especially notable in the areal extent of greater lightning density over the central Great Plains and eastward. There is also a steady trend toward higher flash densities over the Florida Peninsula and along the Gulf of Mexico coast with the establishment of the strong diurnal cycle that prevails in these locations during the time of greatest heating of the earth's surface during the year (Holle 2014). SPC severe weather probabilities, however, do not increase nearly as much over Florida and the Gulf Coast during this period as do the flash densities due to much weaker vertical shear in wind velocity and direction, a lack of large-scale fronts, troughs, and other surface boundaries, as well as other factors that are responsible for more organized convection resulting in severe weather.

5. Summer NLDN CG flash density maps

a. Summer summary

The pattern and flash density for meteorological summer (Fig. 4a) are similar to the annual map (Fig. 1). The similarity is to be expected since summer accounts for more than half of the annual amount of lightning (Fig. 2a). 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 high (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 have less than 40% of the annual 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 shown here.

b. June

In June (Fig. 4c), there is a significant expansion of the area of high lightning incidence since May. Most notable is the development from May to June of the major lightning maxima over Florida and the upper Great Plains (Fig. 3e). Flash densities exceed 2.5 flashes $km^{-2} yr^{-1}$ across portions of the Florida Peninsula due to the influence of the two coastal sea breezes. An additional sea-breeze influence is apparent across the Florida Panhandle to east Texas. There is a strong severe weather maximum over the eastern plains of Colorado that is not reflected well in the CG flash map (Fig. 4a). Thunderstorms from eastern Colorado to the northeast in the lee of the Rocky Mountains differ from those elsewhere in the United States due to a complex interplay of topography, low-level moisture, and vertical electric fields (Carey and Buffalo 2007).

c. July

In July, two notable lightning maxima have developed over Arizona extending into Mexico that did not exist in June (Fig. 4d) as the Southwest monsoon begins (Holle and Murphy 2015). The week-by-week progression of this rapid development from late June to mid-July (Figs. 4f–h and online supplemental weekly maps) illustrates the development of the east-central Arizona CG flash maximum over the Mogollon Rim (López et al. 1997) and the extension into northwest Mexico over the Sierra Madre Occidental (Holle and Murphy 2015). Severe weather is scant in these regions despite the enhanced CG flash frequencies.

Flash density that increases greatly from June to July over Colorado and New Mexico is also a result of the development of monsoonal moisture flow during this

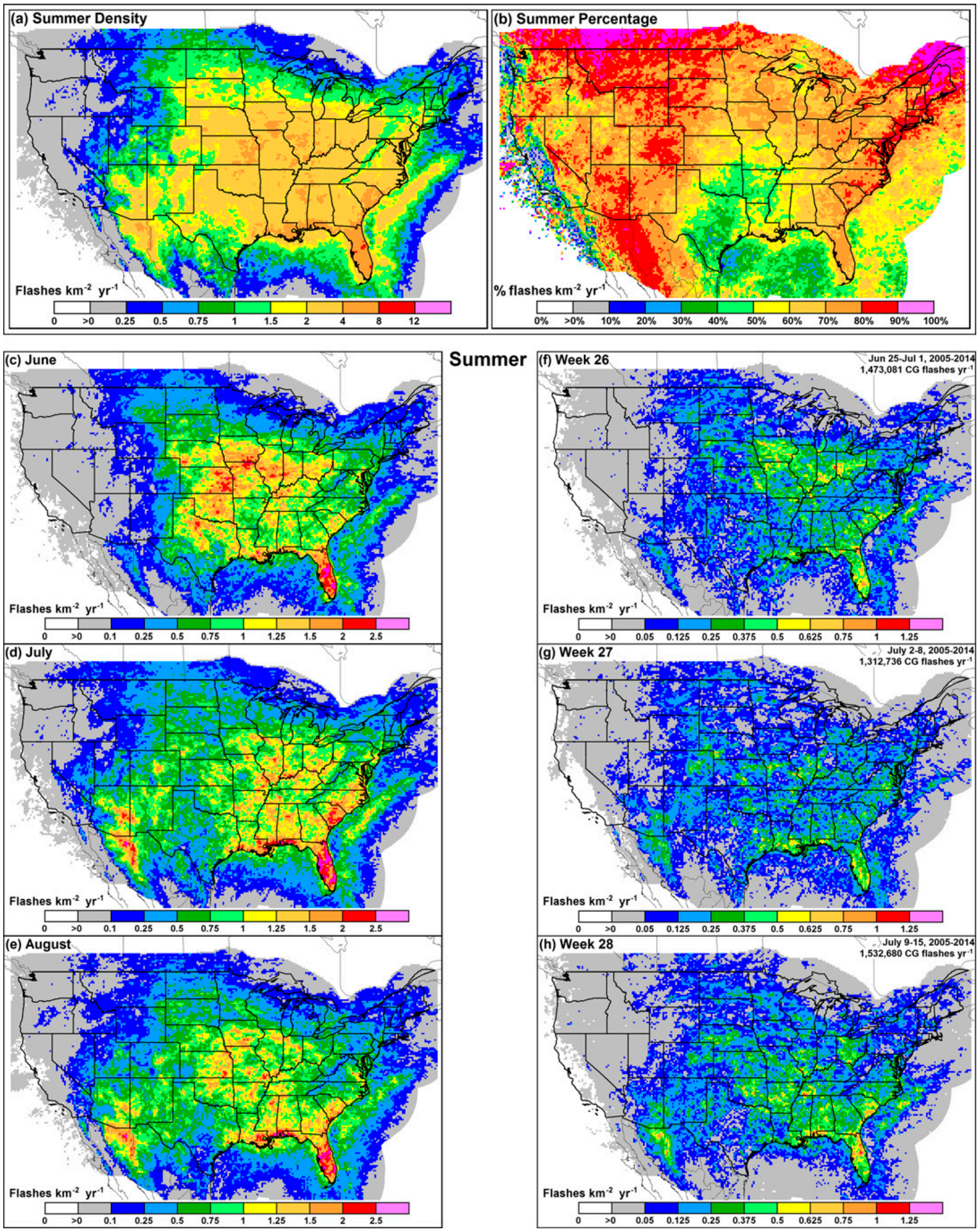

FIG. 4. As in Fig. 1, but for (a) summer flash density, (b) summer flash percentage of annual total, and flash densities for (c) June, (d) July, (e) August, (f) week 26, (g) week 27, and (h) week 28.

transition period in Figs. 4f–h. Lightning occurrence has reduced sharply over much of Texas and Oklahoma compared with June (Fig. 4c). Densities exceeding 2 flashes km^{-2} yr^{-1} over the Great Plains have shifted eastward to central and southern Illinois from their June position over eastern Kansas and locations to the north and south. Over Florida, flash density in July exceeds 2.5 flashes km^{-2} yr^{-1} over three areas of the peninsula (Fig. 4d). The southeast United States coastal region now has widespread moderate-to-large flash densities greater than 2 flashes km^{-2} yr^{-1} that are not much weaker than over Florida coastlines. Flash density continues to be enhanced over the Gulf Stream relative to the surrounding ocean.

d. August

In August, a modest decrease since July in lightning incidence occurs over Arizona, Florida, the southeast coast, and offshore Gulf Stream regions, but patterns are mostly the same (Fig. 4e). The region from northern Georgia northward to the Great Lakes has diminished lightning frequency in nearly all locations, and the reduction since July is greater to the north. A similar dwindling of severe weather occurs through the month across the country during August.

e. Specific regional summer features

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

1) 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 annual lightning over the Florida Peninsula occurs during the three summer months (Fig. 4b). Monthly and three-month peninsular lightning maps similar to those shown here have been prepared (Hodanish et al. 1997; Fieux et al. 2006). The widely understood 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). However, the probability of severe weather remains moderate to low throughout the summer over the peninsula.
2) Gulf/Atlantic coasts: A concentration of flashes persists during summer along the 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). As over Florida, the probability of severe weather is moderate in summer along the coast and does not match the high coastal CG flash densities in these regions.
3) 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 flash density between 4 and 8 flashes $\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$ 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).
4) 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 greater than regions on either side in that location (Virts et al. 2015). About half of the NLDN flashes over the Gulf Stream occur during summer (Fig. 4b), and they are most frequent during the night to morning hours (Holle 2014).
5) Mesoscale convective systems: Large CG flash densities are observed from Kansas northeastward to Iowa and the surrounding states (Fig. 4a). A portion of this increased regional incidence can be attributed to prolific lightning production in summertime mesoscale convective systems, consisting of frequent negative CGs in convective portions and predominantly positive CGs in the stratiform regions (e.g., Dotzek et al. 2005; Makowski et al. 2013). The accompanying severe weather from these systems is indicated by SPC weekly maps that are included as an online supplement to this article.
6) Convective SIGMETS: NOAA's Aviation Weather Center defines lines and areas of thunderstorms hazardous to aviation in real time with the Significant Meteorological Information (SIGMET) product as discussed by 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. While these regions have frequent lightning, none of these regions have especially notable SPC severe weather frequencies. As a result, the existence of lightning is a useful indictor of aviation threats from thunderstorms despite the lack of accompanying severe weather.
7) 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 high 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.

f. Transition from summer to autumn

The August flash density map indicates a decrease in lightning occurring into September. This transition is shown by weekly maps (Figs. 5f–h and online supplemental files). The midsummer maxima over the Florida Peninsula and Gulf of Mexico coast begin to decrease during the week starting 20 August, which continues steadily after that week. The monsoon-related lightning

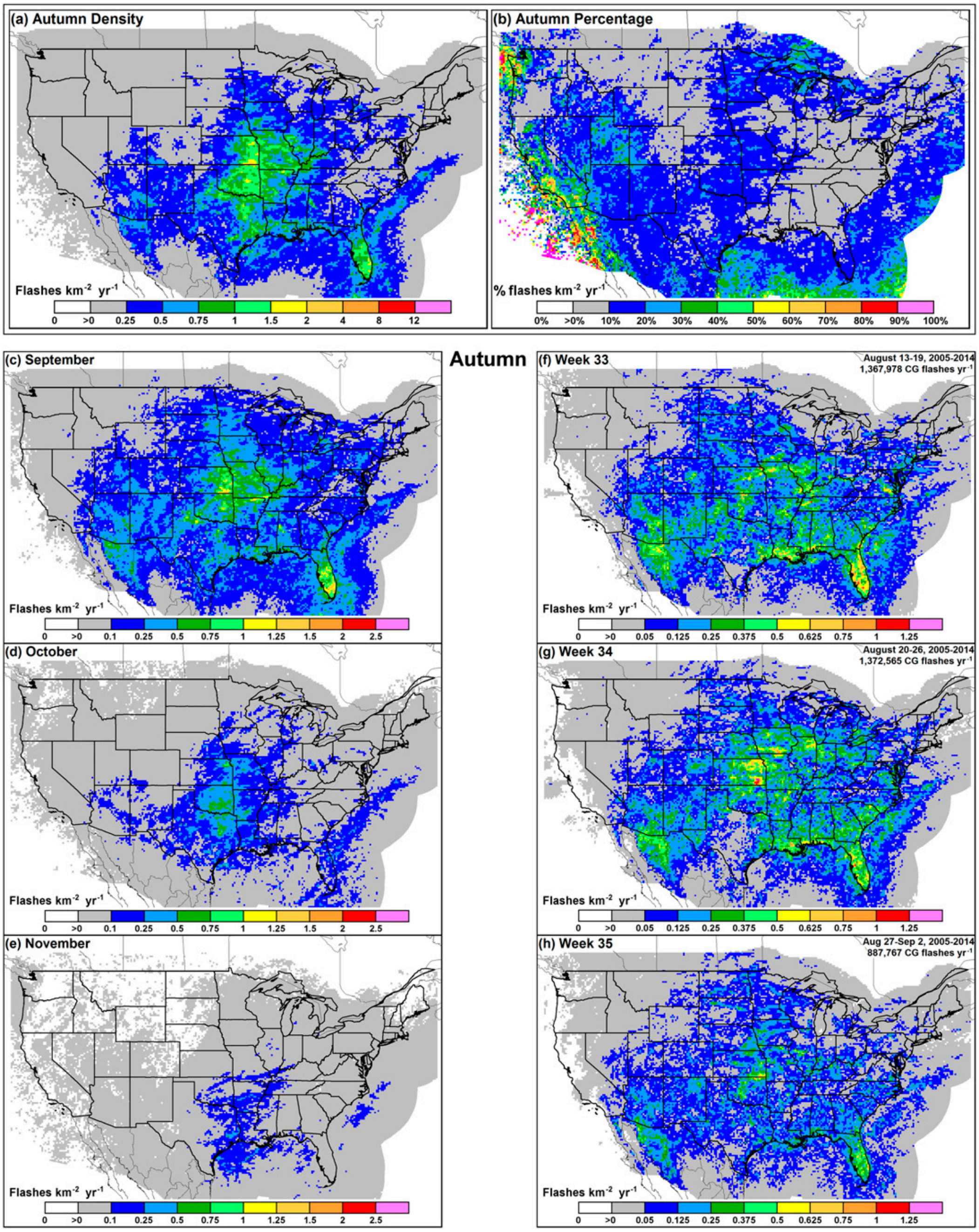

FIG. 5. As in Fig. 1, but for (a) autumn flash density, (b) autumn flash percentage of annual total, and flash densities for (c) September, (d) October, (e) November, (f) week 33, (g) week 34, and (h) week 35.

in the southwest states weakens more gradually from week to week than in the Florida–Gulf region.

6. Autumn NLDN CG flash density maps

a. Autumn summary

The CG flash counts in meteorological autumn are sharply reduced compared with summer (Fig. 2). The greatest flash densities are in eastern Kansas and Oklahoma, as well as over the Florida Peninsula (Fig. 5a). In terms of percentages, the largest values are in Southern and coastal California into the Mexican state of Baja California (Fig. 5b). This maximum is due to occasional tropical systems and late monsoon moisture arriving from the south through the east, most often in September (Adams and Comrie 1997; Holle and

Murphy 2015). Another notable region is Utah, where more than 40% of the annual amount of lightning is measured in autumn in some areas, as well as in the northern Great Lakes. The high percentage over the Lake Superior region may be due to mild to warm water being overrun by cold temperatures aloft during autumn storms resulting in low-topped convection, although there are no studies to date of this possibility.

b. September

There is a large decrease in flash occurrence across the CONUS from August to September (Figs. 4e and 5c). Substantial reductions occur in Florida, Arizona, the plains, and the Midwest, except the trend is less apparent over the Gulf Stream and adjacent East Coast of the United States. The area of the most CG flashes is coincident with the highest SPC severe weather probabilities that are located over Kansas and adjacent states. However, there is an overlap of the diminishing lightning season with the start of high school and college football and soccer activities, resulting in delays and postponements of such sporting events (Walsh et al. 2013). The major decrease from August to September indicates that the lightning flash densities began to trend downward at some time during August. This transition from mid-August to early September can be seen by a broad reduction in flash density over many regions of the CONUS in Figs. 5f–h and the online supplemental weekly NLDN maps.

c. October

A continued widespread decrease in lightning incidence occurs in October (Fig. 5d). As a result, sporting event cancellations are greatly reduced by October. Regions of greater flash densities are scattered across Texas northward to Kansas, coincident with a modest maximum of severe weather in the same location. Only intermittent lightning is now located in parts of Washington and Oregon, Montana, and coastal Northern California.

d. November

Lightning is rare over much of the northwest third of the country and the far northeast states during November (Fig. 5e). Regions with somewhat more CG flashes are in eastern Texas and Louisiana, and nearby regions to the north. These locations coincide with the only area of severe weather in the CONUS indicated by SPC at this time.

7. Winter NLDN CG flash density maps

During the winter, most of the southern and southeastern United States have some lightning from 2005 to 2014 (gray shading in Fig. 6a). Almost no CG flashes are reported in the northern Rocky Mountain and western 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 located within a few hundred kilometers of those states. These are the same regions with a modest number of winter severe weather reports from SPC. In terms of percentages, the only regions over land exceeding 20% are over the central coast of California. Larger percentages are located offshore due to winter storms arriving from the west and southwest (Fig. 6b). Although 10 years of data are summarized, the winter lightning density maps by month show individual storms with banded structures oriented southwest to northeast (Fig. 6d). In some cases, these bands are accompanied by snowfall. While these storms typically do not have large CG flash densities, they occur in seasons with overall small flash density. 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). Although weak, the area above 0.1 flashes $km^{-2} yr^{-1}$ in February (Fig. 6e) is about double that of January.

8. GLD360 seasonal North America maps

GLD360 maps seamlessly extend the detection range beyond the NLDN, thereby providing insight into the spatial pattern of lightning incidence at and beyond the limits of the NLDN. GLD360 data will now be used to depict the seasonal distributions of stroke density and the percentage of annual lightning over the CONUS, as well as Mexico, Canada, and the surrounding oceans. GLD360 data are from 2012 to 2014 only; NLDN data are from 2005 to 2014. An additional difference is that GLD360 data are cloud-to-ground strokes and cloud pulses, so the GLD360 stroke densities are greater in many areas than shown by NLDN flashes. The meteorological seasons are now described with GLD360 in the same sequence as shown for the NLDN using a color scale adjusted to facilitate comparisons with NLDN maps.

a. Spring

GLD360 stroke data (Fig. 7a) for spring show the same general features over the CONUS as the NLDN (Fig. 3a). Lightning is detected in spring almost everywhere over the CONUS, southern Canada, and mainland Mexico (Fig. 7a). The greatest densities are over eastern Texas southeastward into coastal Mexico and the Gulf of Mexico. The large lightning density found in the south-central states extends through the northern half of the Gulf of Mexico, across Florida, and eastward

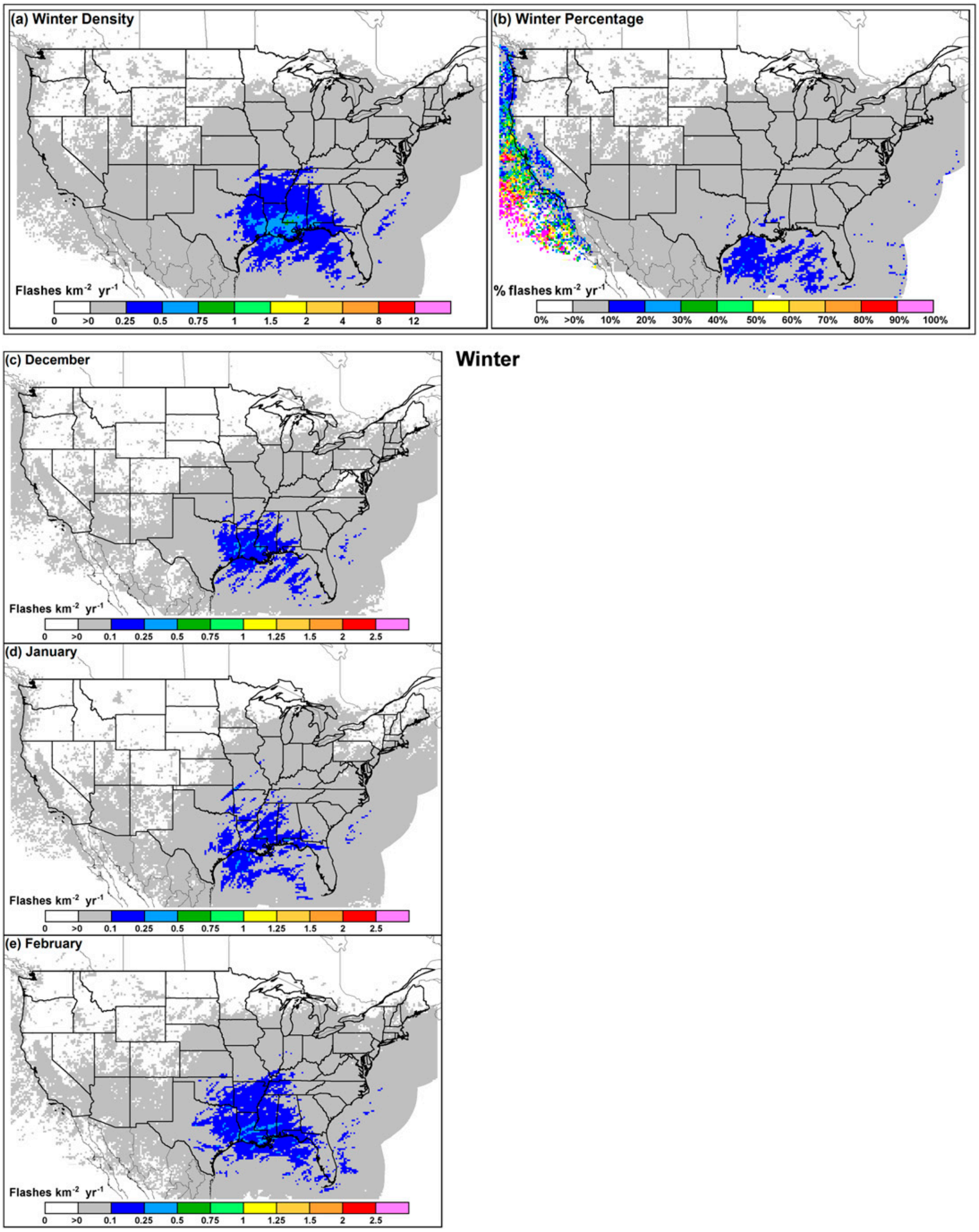

FIG. 6. As in Fig. 1, but for (a) winter flash density, (b) winter flash percentage of annual total, and flash densities for (c) December, (d) January, and (e) February.

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 springtime lightning is reported over northern Canada and much of the Pacific Ocean.

In terms of percentage, most areas have 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 CONUS land area. Off the California coast, some areas have over 80% of the annual lightning during spring, although densities are very low and may indicate very few storms.

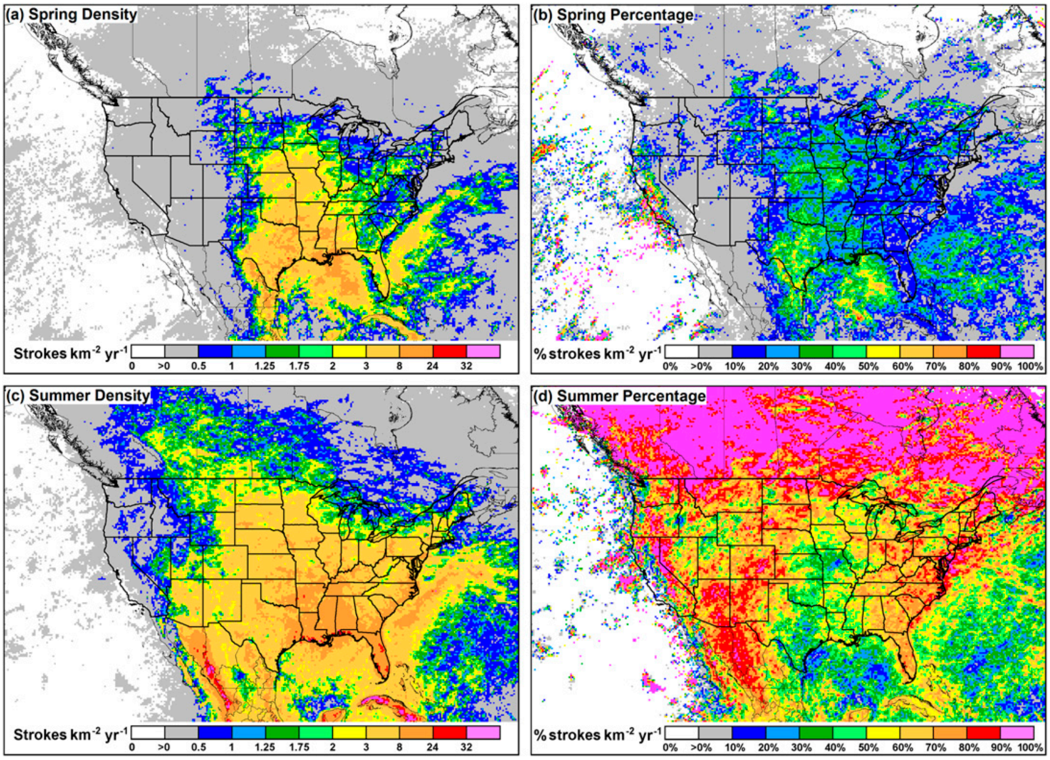

FIG. 7. GLD360-detected lightning over the United States and adjacent countries and oceans based on 401 673 209 strokes during 2012–14. (a) Spring stroke density, (b) spring percentage of annual total, (c) summer stroke density, and (d) summer percentage of annual total. Scales are across the lower portion of the maps.

b. Summer

During summer, the greatest stroke densities occur in Florida, the southern plains, the Gulf and South Atlantic coast, Cuba, as well as the Yucatan Peninsula and northwestern Mexico (Fig. 7c). Frequent lightning reaches into Canada on the east side of the Rocky Mountains in a pattern that is similar to the entire year shown by Orville et al. (2011). No lightning is reported over much of the Pacific Ocean in summer. The largest GLD360 stroke densities in northwestern Mexico are in a line from northwest to southeast much 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); however, this topic has not been examined with lightning data. Also note the distinct 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 high, 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 in Texas and the central plains, and south into the Gulf of Mexico where high spring percentages prevail (Fig. 7b).

c. Autumn

Large stroke densities continue over Cuba, the Yucatan Peninsula, and the west coast of Mexico that are greater than over Florida (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 continues to have frequent lightning that extends offshore into the Atlantic Ocean. Differences between GLD360 and

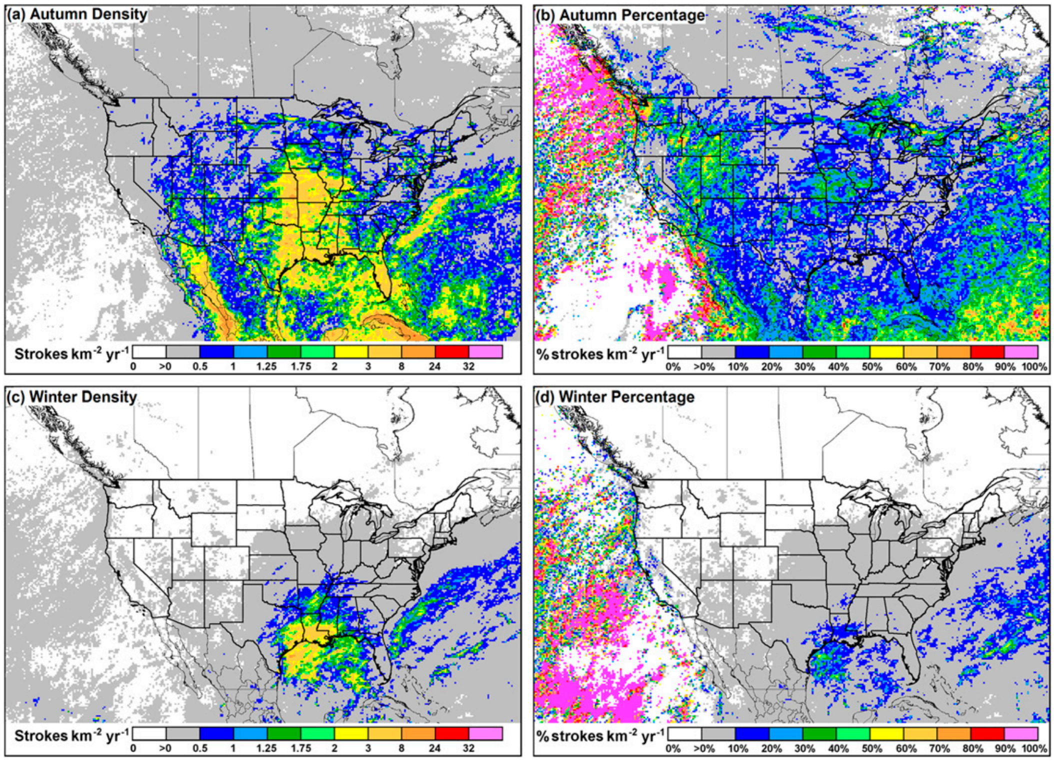

FIG. 8. As in Fig. 7, but for (a) autumn stroke density, (b) autumn percentage of annual total, (c) winter stroke density, and (d) winter percentage of annual total.

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 the United States, Canada, and Mexico is quite apparent with both networks (Figs. 5b and 8b). Offshore from Mexico, lightning is typically associated with 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. Coastal south Texas, Louisiana, and the adjacent Gulf of Mexico have the greatest observed stroke densities over North America during winter (Fig. 8c) whereas the NLDN observations led to the inference of the largest density being over southern Louisiana. The Gulf Stream extending northeast far into the Atlantic is sharply depicted by GLD360 in winter. Minimal lightning is over Cuba and Mexico in winter after substantial lightning frequencies in autumn. Nearly all of Canada is lightning free, as well as the northwest third of the CONUS. In terms of percentage, the winter portion of the lightning through the year is quite low over most of North America except over the Pacific Ocean, the Texas Gulf Coast, and isolated locations in the Atlantic (Fig. 8d).

9. Conclusions

Cloud-to-ground flash densities over the CONUS and adjacent areas are shown on seasonal and monthly 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 of Florida's lightning is during the three summer months, while Arizona and adjacent states have nearly all of their flashes in July and August. In the Central Valley of California, lightning occurs mainly in the winter months. In most of Canada, New England, Montana, the Dakotas, lightning rarely happens outside summer. The lightning incidence in Mexico and the Gulf of Mexico are much greater than depicted by the NLDN. Since the lightning threat is usually concentrated in a few months at a specific location, most lightning impacts can be anticipated at those times. For example, knowledge of the seasonal and monthly lightning distributions allows comparison of impacts of lightning on power reliability at various locations across the country.

Severe weather probability maps from SPC are also compared at various locations through the year. In the central states, CG flashes and severe weather tend to be coincident in time and space. Over the Carolinas, an enhanced area of severe weather occurs in spring and early summer that is not coincident with especially high lightning incidence; the nature of this difference is a topic for future examination. However, large CG flash densities often occur without notable severe weather over Florida, the Gulf of Mexico, the Atlantic, the Southwest, and the Rocky Mountain states.

This seasonal and monthly summary of lightning over the CONUS complements the study of the diurnal variations of CG flashes over the CONUS by Holle (2014). The combination of these two publications makes it possible to identify when and where lightning occurs over the CONUS and adjacent regions by season, month, week, and time of day. It also demonstrates lightning occurrence over nearly all of 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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