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ORIGINAL PAPER

A winter-season lightning climatology for the contiguous United States

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Abstract
This research characterizes the spatial and temporal distribution of cloud-to-ground lightning occurring during the winter season (December through February) by utilizing 14 years (2002–2015) of data from the National Lightning Detection Network. Additionally, a Spatial Synoptic Classification system was utilized to examine flash patterns associated with a variety of weather types. The spatial and temporal analysis was conducted by incorporating these datasets into a geographic information system to determine the winter season distribution and associated lightning characteristics across the contiguous US as well as within weather types. The Southeast US and adjacent Oceanic regions, as well as California and Nevada were examined at a higher spatial resolution to further discern flash patterns. The results provide visualization of the lightning flash distribution utilizing flash density and lightning day metrics by weather type and for the winter months; a season under-represented in previous lightning investigations.

1 Background

The National Lightning Detection Network (NLDN) began recording occurrences of cloud-to-ground lightning strikes in 1989. Subsequent research utilizing the NLDN dataset has yielded significant insights into lightning distributions and characteristics at a variety of scales, from local to national (Stallins et al. 2006; Orville 1991). Contiguous US cloud-to-ground (CG) lightning climatologies using the NLDN data commenced in 1989 and continued in various yearly intervals thereafter, with some expanding to North America (Orville 1991; Orville and Silver 1997; Zajac and Rutledge 2001; Rudlosky and Fuelberg 2010; Orville et al. 2011). Diurnal variations in flash densities across the US have been more recently investigated (Holle 2014; Koshak et al. 2015). Improvements in the NLDN detection efficiency have led to increases in flash densities since 1989.

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Although annual NLDN flash distributions across the contiguous US have been investigated, winter season studies have been infrequent (Trapp et al. 2001; Holle and Watson 1996). The majority of lightning climatologies have focused on warm season patterns and associated convective phenomena when lightning is most prevalent. Winter lightning occurrence outside of the Southeast US is relatively uncommon, with only 1.3% of cool season thunder reports from surface observing stations associated with snow (Curran and Pearson 1971). During winter, diurnal heating is normally weak and moisture limited; however, eddy available potential energy is elevated due to strong meridional temperature gradients (Carlson 1991). Using this energy, vigorous low pressure develops that produces strong synoptic forcing and promotes an environment more conducive for convection and associated lightning.

Although the perceived threat of lightning is less during the winter, with less than one percent of injuries and deaths occurring in December, January and February; winter storms present favorable conditions for the initiation of upward lightning flashes from tall structures and also higher percentages of positively charged flashes (Holle et al. 1997; Montanyà et al. 2016). Positively charged flashes are thought to increase the likelihood of initiating a forest fire (Latham and Williams 2001). Additionally, the greatest recorded lightning currents and the largest charge transfers to the ground are thought to be associated with positive flashes (Rakov 2003). Greater wind shear and smaller warm cloud depth, typical of the winter, enhance the relative frequency of positive flashes (Engholm et al. 1990). Winter storms are also capable of producing frequent lightning events and significant damage (Yokoyama et al. 2014). Lightning research in winter precipitation has been primarily focused in Japan, underlining the importance of orography and air–sea interactions (Brook et al. 1982; Michimoto 1993).

Summer and cool season lightning distributions across several US cities have been examined along with diurnal characteristics that include the winter months (Zajac and Rutledge 2001; Holle 2014; Holle et al. 2016). Additionally, several regional investigations have focused on flash characteristics associated with winter precipitation and thunder snow (Hunter et al. 2001; Market et al. 2002; Pettegrew et al. 2009). However, an investigation of the spatial and temporal distribution of winter lightning across the contiguous U.S. utilizing the NLDN has not been conducted.

This investigation develops a winter lightning climatology and associates flashes with eight weather types obtained from the Spatial Synoptic Classification system (SSC; Sheridan 2002). Weather type analysis of the flash distribution yields insights into synoptic conditions and air mass characteristics associated with convection and lightning. There have been several investigations that have utilized the SSC to identify and analyze synoptic weather types associated with convection and lightning (Bentley et al. 2012; Stallins et al. 2013).

An examination of flash density and lightning days stratified by the SSC system was conducted to examine flash patterns and associated weather types. The SSC allows for the identification of resident weather types utilizing hundreds of weather stations and is a hybrid classification scheme, based on manual and automated processes (Kalkstein et al. 1996). The SSC system permits inter-comparison of daily weather types across the US which allows for the evaluation of lightning characteristics for and among individual air masses (Kalkstein et al. 1996). Since the SSC allows for migratory air mass modification, it is especially useful in studies that cover large geographical regions where the spatial cohesion of weather types is important. The SSC was initially developed using data from the winter months but has expanded both seasonally and globally in more recent iterations (Kalkstein et al. 1996; Sheridan 2002). Surface weather observations of temperature, dew point, wind, pressure and cloud cover are incorporated into the statistical model four times a day and then compared to “seed days” to create the most accurate classification (Sheridan 2002).

2 Data and methods

Two primary data sources were utilized to perform the analyses:

- Cloud-to-ground flashes and associated metrics were acquired from the National Lightning Detection Network (NLDN) owned and maintained by *Vaisala*, *inc*. The NLDN data were archived from 2002 to 2015 for the contiguous United States and obtained from the Unidata Internet Data Distribution (IDD). Detection efficiencies have improved during the period increasing from 90 to 95% from 2002 to 2012 to greater than 95% from 2013 onwards (Cummins et al. 2006; Cummins and Murphy 2009; Murphy and Nag 2015). To eliminate the potential of non-CG flash contamination, flashes with peak currents less than 15 kA have been excluded from this study (Koshak et al. 2015; Nag et al. 2015).
- Spatial Synoptic Classification (SSC) polygons of the eight weather types (dry polar, dry tropical, dry moderate, moist polar, moist tropical, moist moderate, moist tropical plus, transitional) for each day of the study were obtained from Jim Detwiler at Penn State University. The daily SSC is based on surface weather conditions observed four times per day at over 400 stations across the US, Canada and Europe (Sheridan 2002).

2.1 NLDN data characteristics and joining with the SSC polygons

The NLDN dataset spanned the period from December 2002 through February 2015. Winter months (December, January and February) were extracted from the dataset for analyses. An examination of the acquired flash data archived from Unidata’s Internet Data Distribution (IDD) revealed several months where flashes contained errors in peak current estimates. Since this prevented the determination and subsequent elimination of flashes of less than 15 kA, data for these months were removed from the investigation. The data for the months removed were December (2010, 2011, 2014), January (2011, 2012, 2013) and February (2011). Thirty-five months remained for analyses including 11 Decembers, 11 Januaries and 13 Februaries.

Flashes occurring outside of the contiguous US were also removed from the analysis. The total number of flashes identified over the 14-year period across the contiguous US were 6,179,313. February contained the most flashes (3,283,948; 252,611 flashes month^{-1}), followed by December (1,789,149; 162,650 flashes month^{-1}) and January (1,081,616; 98,329 flashes month^{-1}). Diurnal trends in flash activity were also assessed by summing flashes into 5-min intervals and adjusting the counts based on local standard time. ESRI shapefiles containing polygons of the eight SSC weather types were spatially joined to the flashes (i.e., point data) for each day of the study period. Flash counts and days were determined by weather type to assess the spatial and temporal distribution of lightning with respect to surface weather conditions.

2.2 Gridding the joined SSC and NLDN data

To visualize the spatial distribution of flashes across the contiguous US and remain consistent with previous national-scale lightning analyses, a 20-km grid was created and populated with the flash counts which were summed over the 14-year period and spatially joined to the SSC polygons (Orville 1991; Orville and Silver 1997; Zajac and Rutledge 2001; Rudlosky and Fuelberg 2010; Orville et al. 2011). The Southeastern US and West Coast were identified for further analyses of the flash distribution using an 8-km grid resolution to examine regional flash patterns. Additionally, flash days that were spatially joined to the SSC polygons were summed into grid cells and compared to the flash count distribution. A flash day is defined as any day in a grid cell when at least one flash is identified as occurring in a particular weather type. The flash day metric is useful in assessing whether a small number of days with very high flash rates is impacting the flash density.

3 Results

The spatial distribution of winter lightning is heavily concentrated in the Southeastern US, with maxima in flash counts as well as lightning days focused from eastern Texas through southern Alabama (Fig. 1). Flash densities of over 13 flashes km^{-2} and 108 lightning days occurred in the southwestern corner of Mississippi along the border of Louisiana (Fig. 1). The location and magnitude of flash densities in this region is similar to previous research that also indicated maxima in Louisiana and southern Mississippi (Holle et al. 2016). There is also a noticeable reduction in flash densities along the Appalachians, especially in North Carolina, Virginia, West Virginia and Pennsylvania (Fig. 1). This minimum in lightning activity over the Appalachians is evident in annual flash climatologies (Holle 2014; Orville et al. 2011). When flash activity is combined with precipitation, the Appalachian minimum appears to be associated with the predominance of non-convective forcing in the region (Virts et al. 2015). Lake effect bands are evident when examining the lightning day distribution in comparison to flash densities (Fig. 1). Increased CG lightning days on the eastern (downwind) side of Lakes Erie and Ontario are indicative of a higher frequency of lightning activity. However, the flash densities do not show a similar pattern; therefore, these events are characterized by many days of low frequency lightning and are most likely associated with lake effect snow bands (Fig. 1; Market et al. 2002; Steiger et al. 2009). The lightning day distribution also illustrates similar types of flash events (many days of low frequency lightning) occurring within the mountains of Arizona, Utah, California (especially the Central Valley) and along the Oregon and Washington coasts (Fig. 1). Similar patterns during winter, spring and autumn were found in California and the Pacific Northwest (Holle et al. 2016). Winter-season maximum flash densities and lightning days in Florida are located in the panhandle, contrasting with the location of the annual maximum in central and southern Florida (Fig. 1; Orville et al. 2011; Holle et al. 2016).

Winter intraday lightning frequencies exhibit diurnal patterns similar to those in previous annual investigations (Fig. 2; Zajac and Rutledge 2001; Holle 2014). Although the overall lull in activity between 0900 and 1200 and increase in afternoon flash activity occurs, there exists considerably less diurnal variability in the winter than other seasons, especially during the months of December and January (Fig. 2). Additionally, the actual winter peak in CG flash activity occurs shortly before 0300 local standard time, indicative of the lessened importance of insolation in modulating lightning activity (Fig. 2).

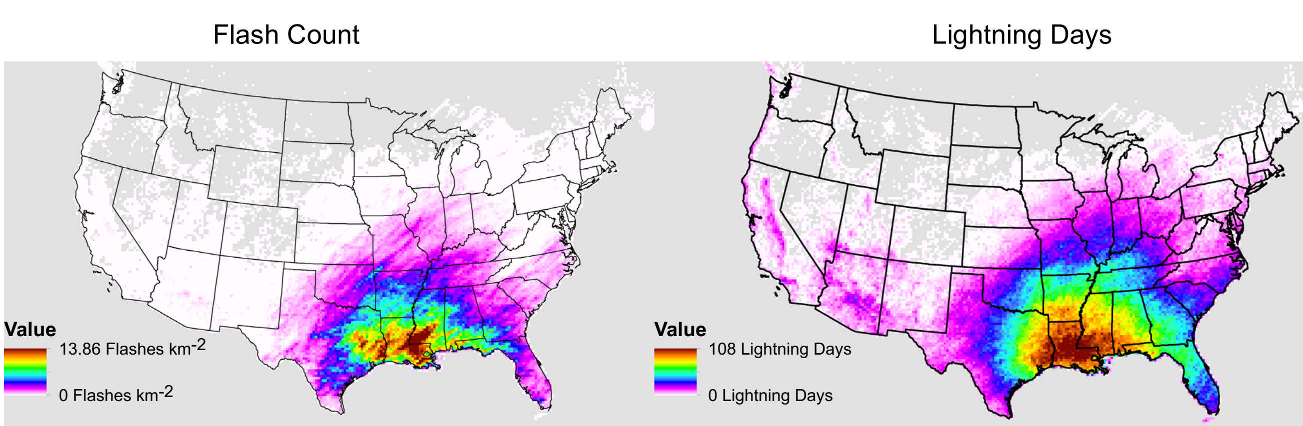


Fig. 1 CG lightning flash density and lightning days for all winter seasons, 2002–2014. Flash density and days are classified per 20 km^2 grid cells

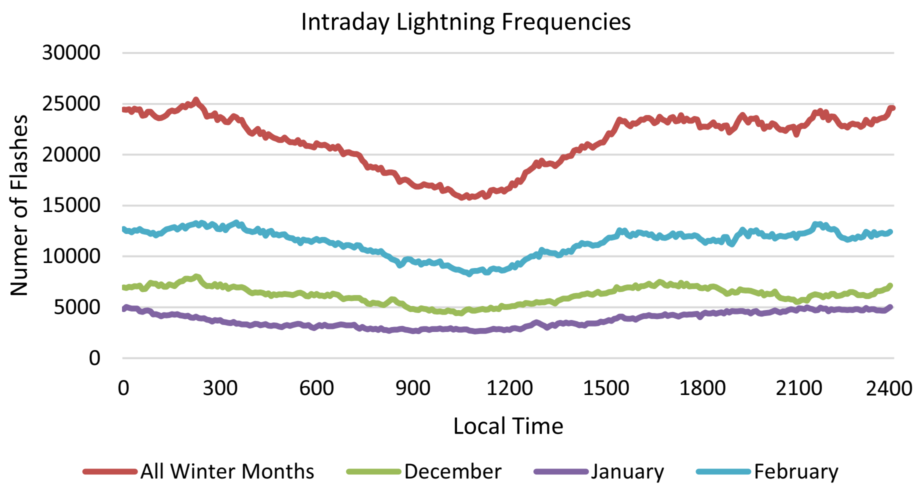


Fig. 2 Intraday flash frequencies (local standard time) for winter and December, January, February, 2002–2014

3.1 Weather type analysis

The spatial domains of seven weather types and transitional regions were examined with respect to daily lightning activity (presented from low flash activity to high): dry polar, dry tropical, dry moderate, moist polar, moist tropical, moist tropical plus, moist moderate, and transitional.

3.1.1 Dry polar

This weather type is synonymous with continental polar. It is the coldest, driest weather type and is characterized by predominantly northerly winds (Kalkstein et al. 1996; Sheridan 2002). This weather type is sourced from northern Canada and Alaska and is advected into the US by cold core anticyclones (Sheridan 2002). As expected in such a cold airmass, there were only 25,895 flashes identified within dry polar during the entire period of record (Fig. 3). However, approximately 19.4% of the recorded flashes were of positive polarity which is slightly higher than the 16–18% average found during the winter in the U.S. (Fig. 3; Orville and Huffines 2001). Given the low frequency of flash activity, the only relative maxima occur through southern Arkansas (over 0.3 flashes km^{-2} and 8 lightning days) as well as lightning day maxima in the lake effect snow belt regions immediately downwind of Lakes Erie and Ontario (Fig. 4a). The localized areas of elevated lightning days downwind of Lakes Erie and Ontario are likely a result of dry polar air advecting over a non-frozen lake which, as evidence suggests, leads to low-level sensible and latent heating produced vertical motions that can offset the lack of lower tropospheric moisture and produce lake enhanced, convective snow squalls (Schultz 1999). Examining an active flash day from the dry polar dataset illustrates the propensity for lake effect snow bands to produce lightning through the combination of orographic lift (Tug Hill Plateau), low-level sensible and latent heating produced vertical motions and possibly wind turbine locations (Fig. 5; Schultz 1999; Kristovich et al. 2016).

3.1.2 Dry tropical

The dry tropical weather type originates in the Desert Southwest or northern Mexico and is associated with warm and dry conditions that often reach into the Midwest (Kalkstein et al. 1996). This weather type can also be produced by strong downsloping winds such as the Chinook and Santa Ana (Sheridan 2002). There were 143,889 flashes, 19.8% of positive polarity, within the dry tropical weather type with a focus of activity found along the Gulf Coast where dry tropical air would likely be somewhat modified by proximity to the Gulf of Mexico (Figs. 3 and 4b). Maximum flash counts occurred in Mississippi (more than 2.5 flashes km^{-2}) with lightning day maxima along the Texas—Louisiana border (5 lightning days; Fig. 4b).

3.1.3 Dry moderate

Also known as a dry temperate weather type, this is normally an adiabatically warmed Pacific air mass that has descended the lee side of the Rockies (Kalkstein et al. 1996). This weather type has no source region as it can consist of significantly modified air of differing origins (Sheridan 2002). There were 337,313 flashes, 16.6% of positive polarity that occurred within the dry moderate classification (Fig. 3). Flash density and lightning day maxima are located in Louisiana and Texas with frequencies in southeast Texas near Houston of more than 1.4 flashes km^{-2} along with 17 lightning days (Fig. 4c). The spatially concentrated distribution of lightning days northeast of Houston appears to be created from frequent instances of weak convection circulating onshore and ahead of low pressure moving across Texas during winter (Fig. 6; note low radar reflectivity). Higher flash count and lightning day frequencies are also found

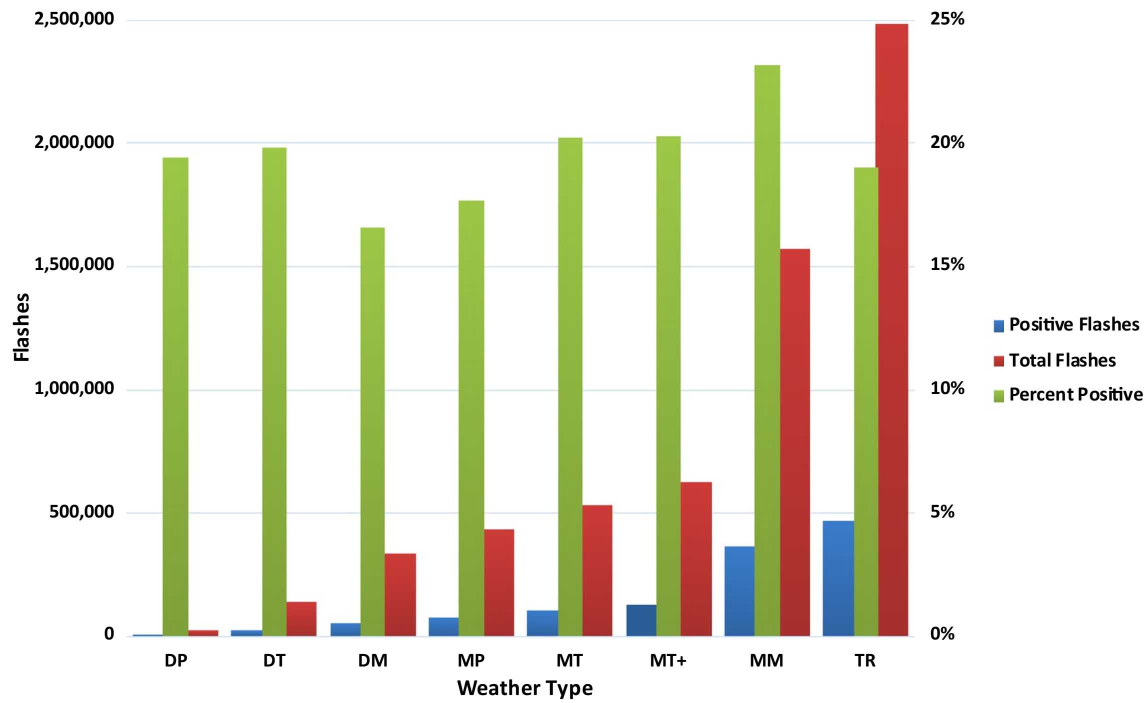


Fig. 3 Positive polarity flashes, percent positive polarity flashes and total flashes by weather type for the winter seasons, 2002–2014

in Arizona as well as minor flash increases in the Wasatch Range of Utah (Fig. 4c).

3.1.4 Moist polar

Moist polar air is synonymous with maritime polar and consists of cool, humid conditions (Kalkstein et al. 1996). In the eastern US, this weather type is frequently associated with easterly winds found around the northern flank of mid-latitude cyclones or advected inland from the North Pacific in the western US (Sheridan 2002). Moist polar is also associated with overrunning conditions around a slow moving front or through acquiring moisture from a cool water body (Kalkstein et al. 1996; Sheridan 2002). There were 437,366 flashes, 17.7% of positive polarity, associated with this weather type (Fig. 3). The flash distribution surrounding moist polar is similar in many ways to moist moderate except shifted northward and slightly westward with much lower flash densities and lightning days (Fig. 4d). There are two southwest to northeast oriented flash density maxima with much larger flash densities and lightning days in northeast Texas and Arkansas (1.8 flashes km^{-2}) that are not directly located with the maxima of lightning days (Fig. 4d). Evidence suggests that the events producing linear shaped flash density corridors are likely individual events that produced high flash densities over a relatively small number of lightning days. The lightning day maxima are more diffused and clustered throughout Arkansas (18 lightning days), Oklahoma and northeastern Texas (Fig. 4d). There also exist higher lightning day frequencies along the Oregon coast, but very little activity along the California and Washington coastlines (Fig. 4d).

3.1.5 Moist tropical

This weather type is synonymous with maritime tropical and represents warm humid conditions typically found within the warm sector of a mid-latitude cyclone or the western flank of a subtropical anticyclone (Kalkstein et al. 1996). Convective precipitation is common with this weather type and exemplified by the 531,138 flashes, 20.2% of positive polarity, within the moist tropical weather type (Fig. 3). When combined, moist tropical and moist tropical plus (a subset of moist tropical) weather types contained 1,154,863 flashes making it the second most lightning active weather type during the winter (Fig. 3). The higher percentages of positive polarity flashes for moist tropical and moist tropical plus weather types are likely associated with the geographical locations of the flash maxima. During the cool season in the Southeastern US, greater wind shear and shallower cloud depths associated with mid-latitude synoptic patterns, combined with more frequent cold frontal passages and mesoscale convective systems combine to create an environment more supportive of positive polarity flashes (Zajac and Rutledge 2001). The moist tropical maxima for

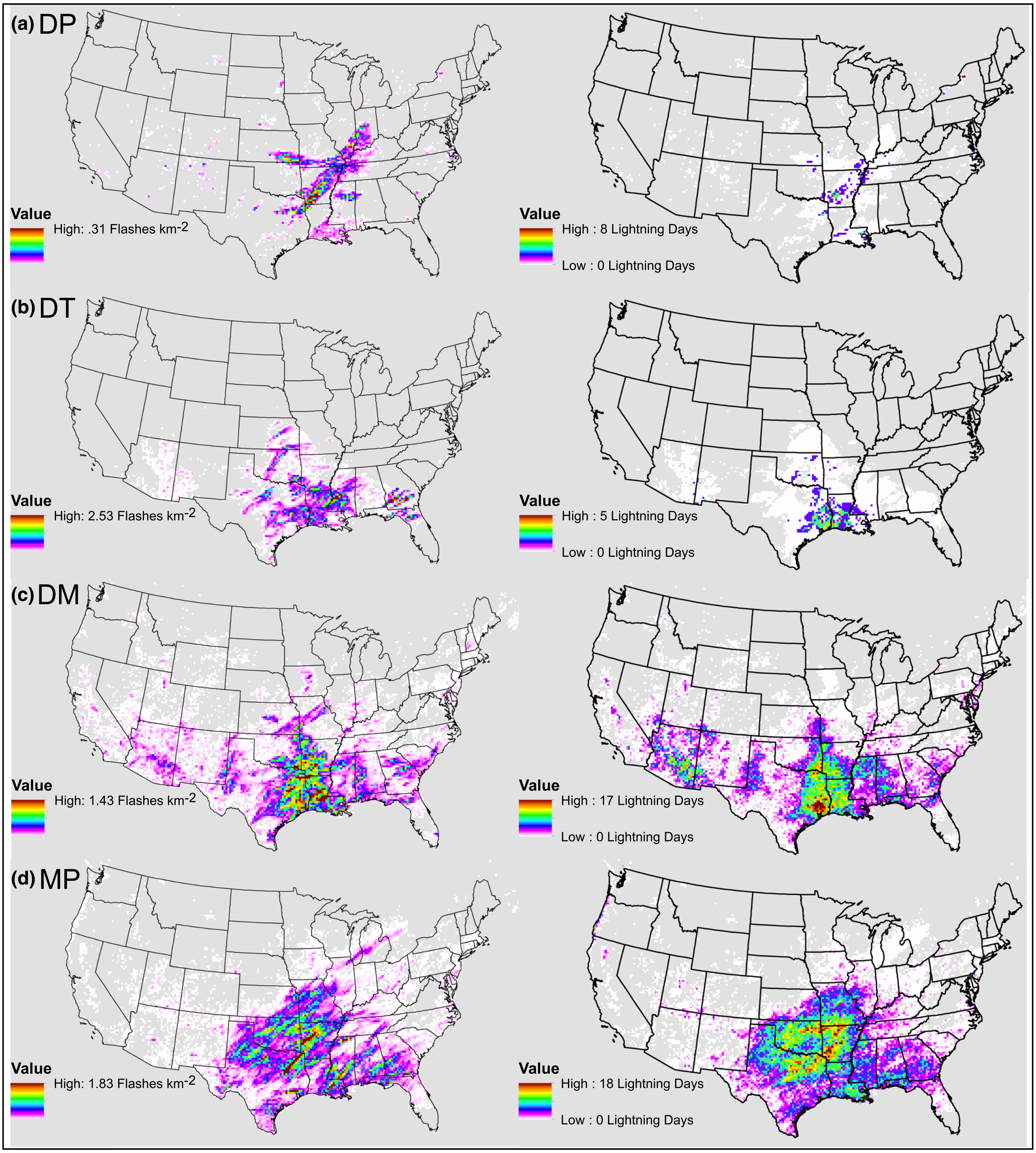


Fig. 4 CG lightning flash density and lightning days for the winter seasons, 2002–2014. Flash density and days are classified per 20 km^2 grid cells. **a** Flashes stratified by the dry polar (DP) classification. **b** Flashes stratified by the dry tropical (DT) classification. **c** Flashes stratified by the dry moderate (DM) classification. **d** Flashes stratified by the moist polar (MP) classification

flash density (2.65 flashes km^{-2}) and lightning days (20 lightning days) occur in Louisiana (Fig. 7a). There exist high lightning day frequencies northward through the Mississippi Valley and into western Tennessee (Fig. 7a). There also exist lowered but evident maxima in flash density and lightning days in the Central Valley just west of the Sierra Nevada Mountains and in Arizona near Tucson (Fig. 7a).

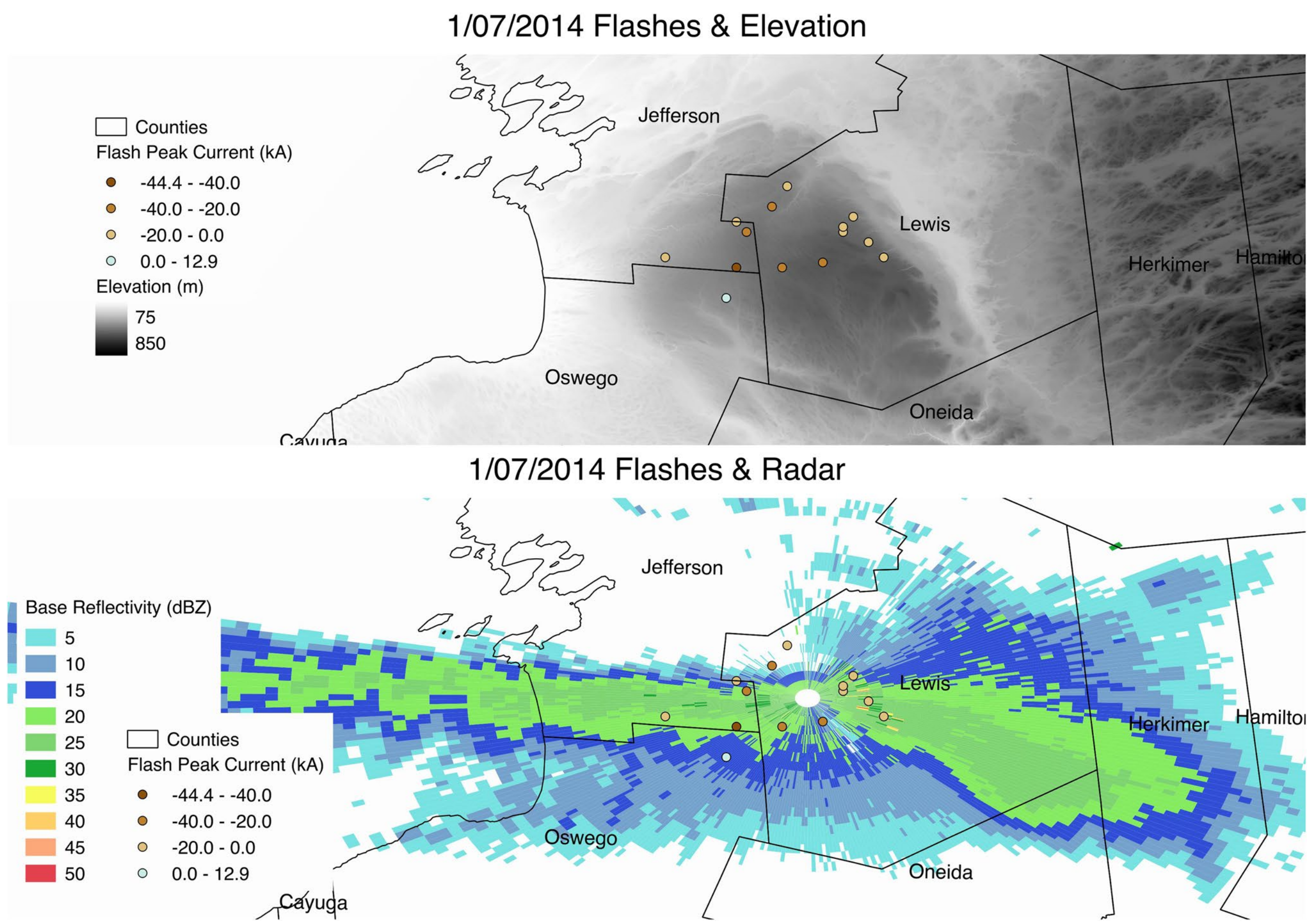


Fig. 5 Elevation, flashes and WSR-88D (KRMX) base reflectivity for 7 January 2014

3.1.6 Moist tropical plus

This is a subset of the moist tropical weather types where both morning and afternoon apparent temperatures are above "seed day" means (Sheridan 2002). This weather type captures the most warm and humid subset of maritime tropical days in the warm subtropics and is especially conducive to convective activity. There were 623,725 flashes, 20.3% of positive polarity, associated with moist tropical plus over land (Figs. 3 and 7b). There were many more flashes associated with this weather type over the Gulf of Mexico. Three distinct flash density maxima were found; east-central Texas (near Dallas-Fort Worth), the Louisiana–Mississippi border (2.5 flashes km^{-2}), and near the borders of Alabama, Georgia, and Florida (Fig. 7b). The lightning day maximum is located in northern Florida, suggesting the flash density maxima are likely produced by high activity events (19 lightning days). This is also evident in central Illinois where areas of higher flash counts exist with little representation in the lightning day distribution (Fig. 7b). The region of enhanced flash activity in Illinois is located within a region of greatest average number of days with freezing rain and sleet (Changnon 2003). Illinois is also ranked in the top ten for winter lightning casualties (Curran et al. 2000). As expected, Florida's most active winter flash days and densities are associated with the moist tropical plus weather type.

3.1.7 Moist moderate

Moist moderate (aka moist temperate) is associated with overcast and humid conditions with higher temperatures and dew points (Kalkstein et al. 1996). This weather type can stagnate and persist if frontal movement slows as it typically forms from modified maritime polar air or southward of maritime polar air near a warm front (Sheridan 2002). Given the warm and humid characteristics, there were 1,572,465 flashes, 23.2% of positive polarity, associated with moist moderate making this weather type the most productive in the percentage of positive polarity winter flash activity (Fig. 3). The percentage of positive polarity flashes is considerably higher than the 16–20% range found in previous investigations of winter lightning (Orville and Huffines 2001; Zajac and Rutledge 2001). The relatively high percentage of positive polarity flashes

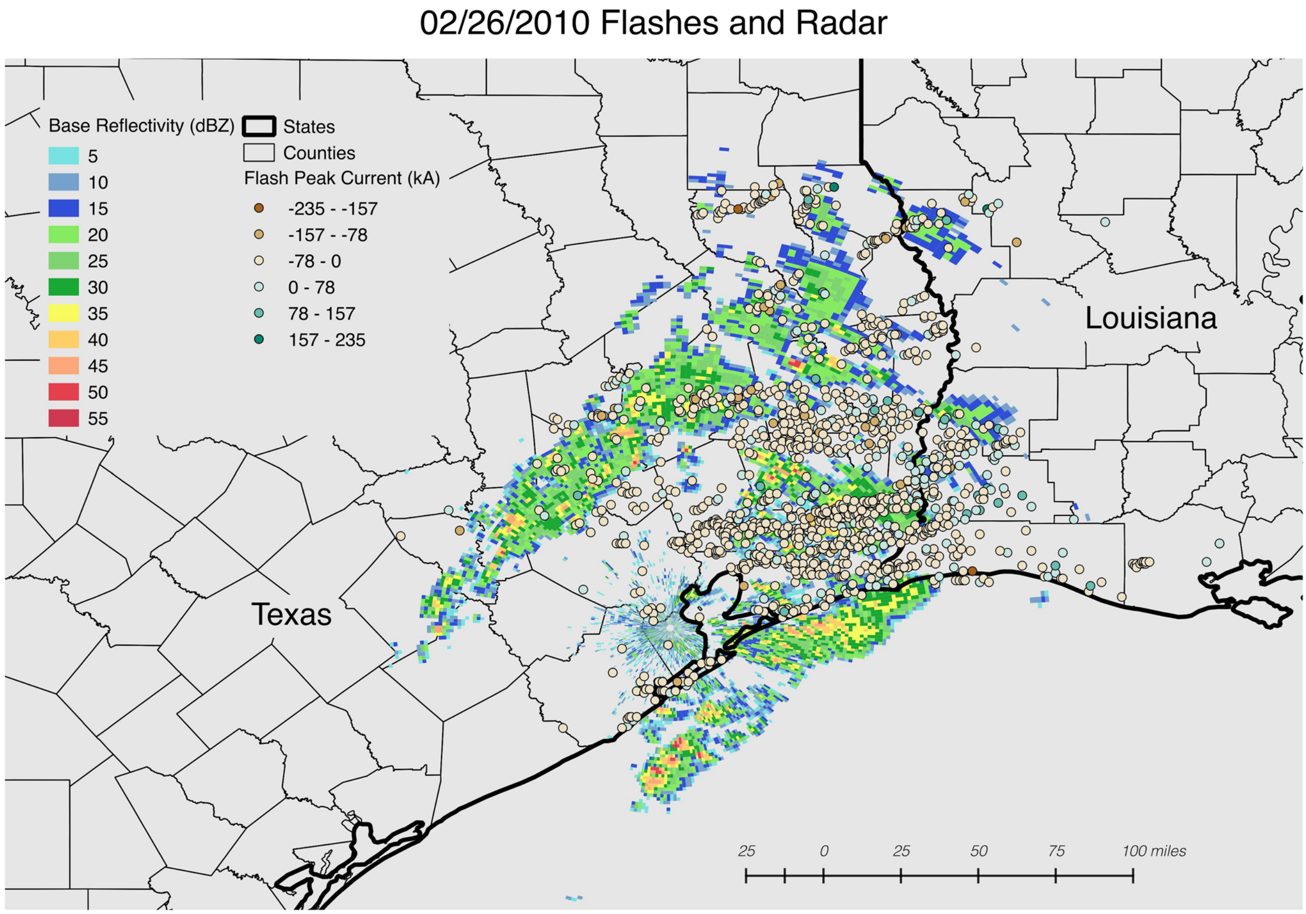


Fig. 6 Same as Fig. 5, except for WSR-88D (KHGX) on 26 February 2010

in this weather type highlights an environment conducive for the development of shallow convection and stratiform rain regions, both supportive of increased positive polarity as well as intra-cloud flashes which evidenced suggests are correlated (Engholm et al. 1990; Rakov 2003; Medici et al. 2017). Evidence suggests that flash activity is more closely associated with individual high flash events given the differences found between flash density and lightning days (Fig. 7c). The highest flash densities occur in southwestern Mississippi (6.5 flashes km^{-2}) versus lightning day activity maximized in southern Louisiana, Mississippi, and Alabama (Fig. 7c; 26 lightning days). The frequent winter occurrence of stationary frontal boundaries along the Gulf Coast likely leads to the higher flash counts and lightning days in this area under moist moderate conditions (Fig. 7c; Henry 1979). In contrast, there also exist elevated lightning days along the Sierra Nevada Mountains, the Angeles and San Bernardino Forests, Pacific Coast north of San Francisco, and near Las Vegas that appear to consist of several low-magnitude flash density events (Fig. 7c).

3.1.8 Transitional

This nomenclature is used to represent a day in which one weather type yields to another (Sheridan 2002). Given that the winter-season is typically the most active with respect to mid-latitude cyclone frequency, it was expected that transitional days would consist of the largest counts of flash density and lightning days (Carlson 1991). There were 2,482,922 flashes, 19% of positive polarity that occurred within transitional situations (Figs. 3 and 7d). In areas of the Southeast US, transitional days account for more than half of all flashes and lightning days. Frequent frontal boundary occurrence in the Southeast US leads to both changes in weather type as well as an environment conducive to convection (Henry 1979). Overall, the distribution of flashes and lightning days most closely approximates the overall distribution during the winter with highest flash densities (6.9 flashes km^{-2}) as well as lightning days (46 lightning days) located in Louisiana (Fig. 7d).

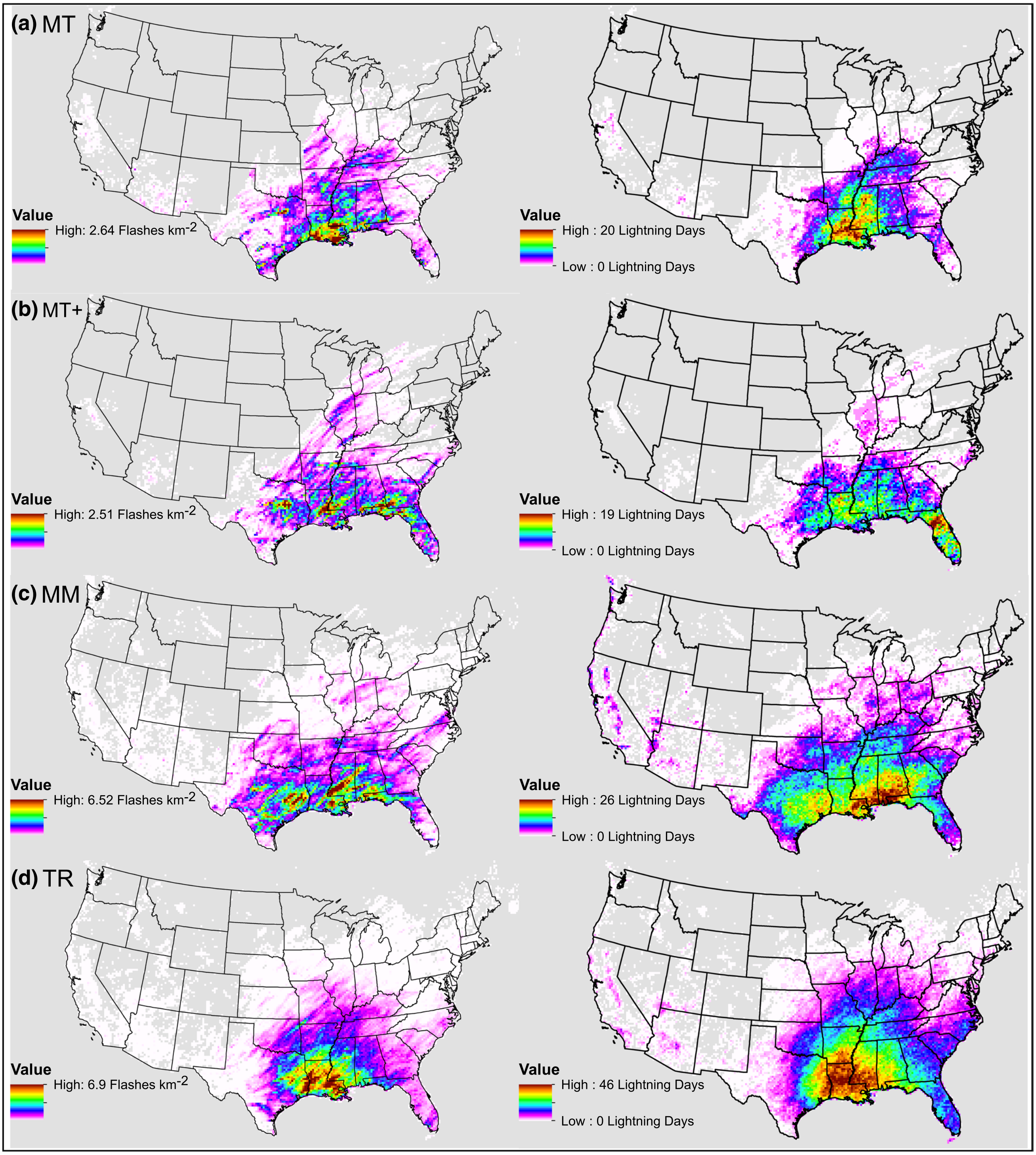


Fig. 7 CG lightning flash density and lightning days for the winter seasons, 2002–2014. Flash density and days are classified per 20 km^2 grid cells. **a** Flashes stratified by the moist tropical (MT) classification. **b** Flashes stratified by the moist tropical plus (MT+) classification. **c** Flashes stratified by the moist moderate (MM) classification. **d** Flashes stratified by the transitional (TR) classification

3.2 Regional distribution

To investigate smaller scale patterns in the flash distribution, two regions were identified to grid and visualize at 8 km spatial resolution. The two regions, the Southeast US (including Gulf of Mexico) and California/Nevada, were chosen since one (Southeast) contained the majority of winter flash activity and the other (CA/NV) contained spatial patterns that are more visible at higher resolutions.

3.2.1 Southeast US

Given the importance of warm, moist low-level air in promoting convection, it was expected that the Southeast US would be the dominant region in winter-season lightning activity. Prior investigations also illustrated the propensity for lightning to occur here during the winter (Holle et al. 2016). The spatial bounds of the lightning data were not constrained to the coast in this analysis, but mapped 600 km into the Gulf of Mexico and Atlantic to visualize the impact of moist tropical plus air emanating over the Gulf of Mexico and the Gulf Stream (Atlantic; Fig. 8). The maximum number of winter lightning days occurs along the Louisiana/Mississippi border with a region of enhanced activity extending into the Gulf of Mexico, west of Florida (Fig. 8). There is a significant decrease in lightning activity over Florida with lightning activity more frequent in northern Florida and the panhandle (Fig. 8). Evidence suggests this is associated with more unstable air advecting northward in advance of developing mid-latitude cyclones (Hodanish et al. 1997). Additionally, as mid-latitude cyclones progress eastward across the continental US, their associated cold fronts will cross the Florida panhandle, and at times, stall, promoting an environment supportive of convection (Hodanish et al. 1997). There is also an increase in winter lightning activity in the Atlantic Ocean over the Gulf Stream (Fig. 8). This pattern is consistent with previous findings and supports the presence of lightning associated with the development and progression of East Coast mid-latitude cyclones (Virts et al. 2015). Furthermore, diurnal variability in lightning activity also appears controlled more by synoptic weather systems than insolation (Fig. 9; Virts et al. 2015).

3.2.2 California and Nevada

The flash distribution contains relatively high flash densities just west of the Sierra Nevada Mountains in the Central Valley, areas north of Las Vegas, Nevada and in the mountains of southern California (Fig. 10). A local flash density maximum is located near the northern California coast (Fig. 10; 1.81 flashes km^{-2}). The flash density maximum west of the central Sierra Nevada Mountains in the Central Valley occurs at relatively low elevations (900–1500 m; Fig. 10). Orographic processes appear to be shaping the distribution as flashes cluster along and proximal to favorable upslope flow out of the Central Valley (Fig. 11). The winter concentration of lighting in the Central Valley has been noted in previous monthly climatologies (Holle and Cummins 2010). Orographic influences on flash density become less defined outside of the Central Valley/Sierra Nevada Mountains, especially in Southern California (Fig. 10).

The diurnal cycle in lightning activity is markedly different in California/Nevada than the Southeast US (Fig. 12). There exists a strong afternoon peak in flashes with frequencies nearly an order of magnitude greater than

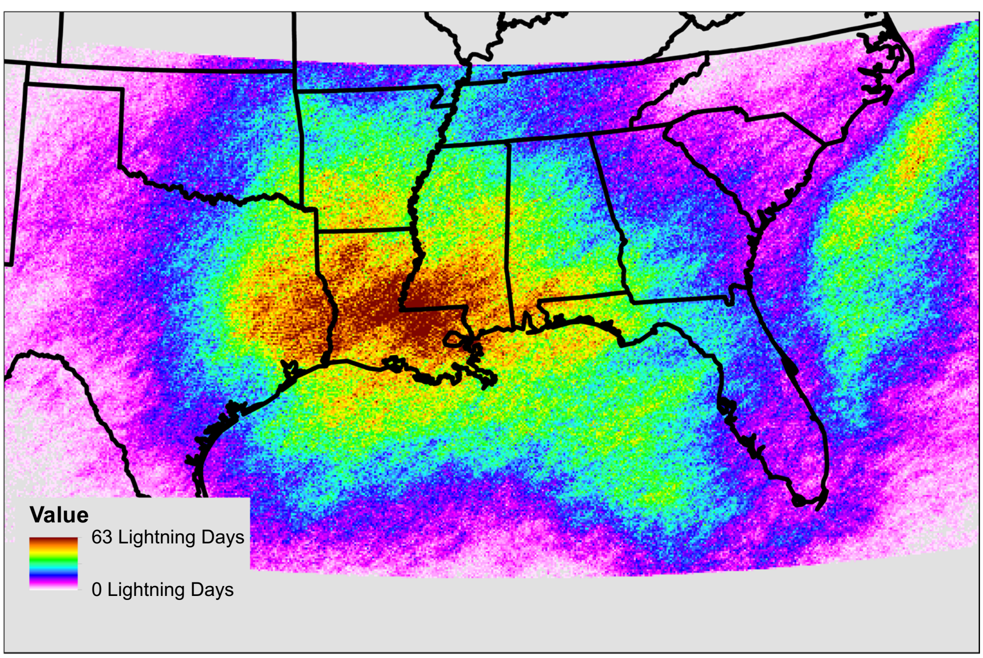


Fig. 8 CG lightning flash density and lightning days focused on the Southeastern US and adjacent Oceanic regions for the winter season, 2002–2014. Flash density and days are classified per 8 km^2 grid cells

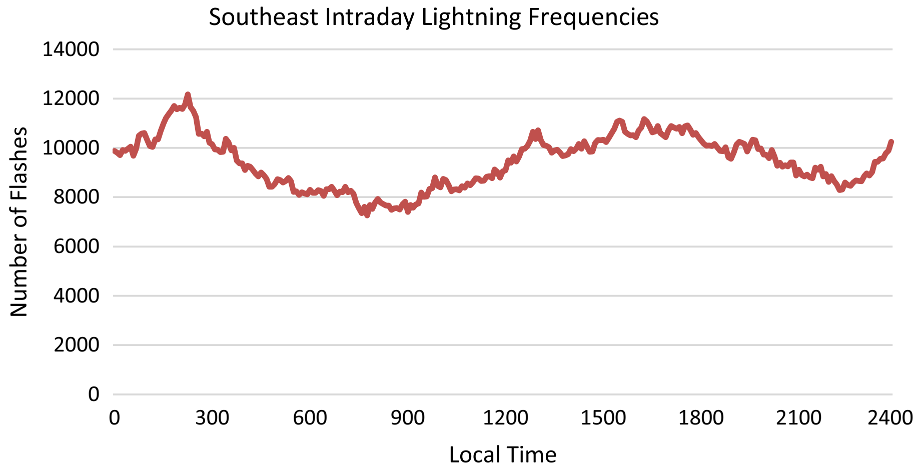


Fig. 9 Intraday flash frequencies (local standard time) focused on the Southeastern US and adjacent Oceanic regions for winter and December, January, February, 2002–2014

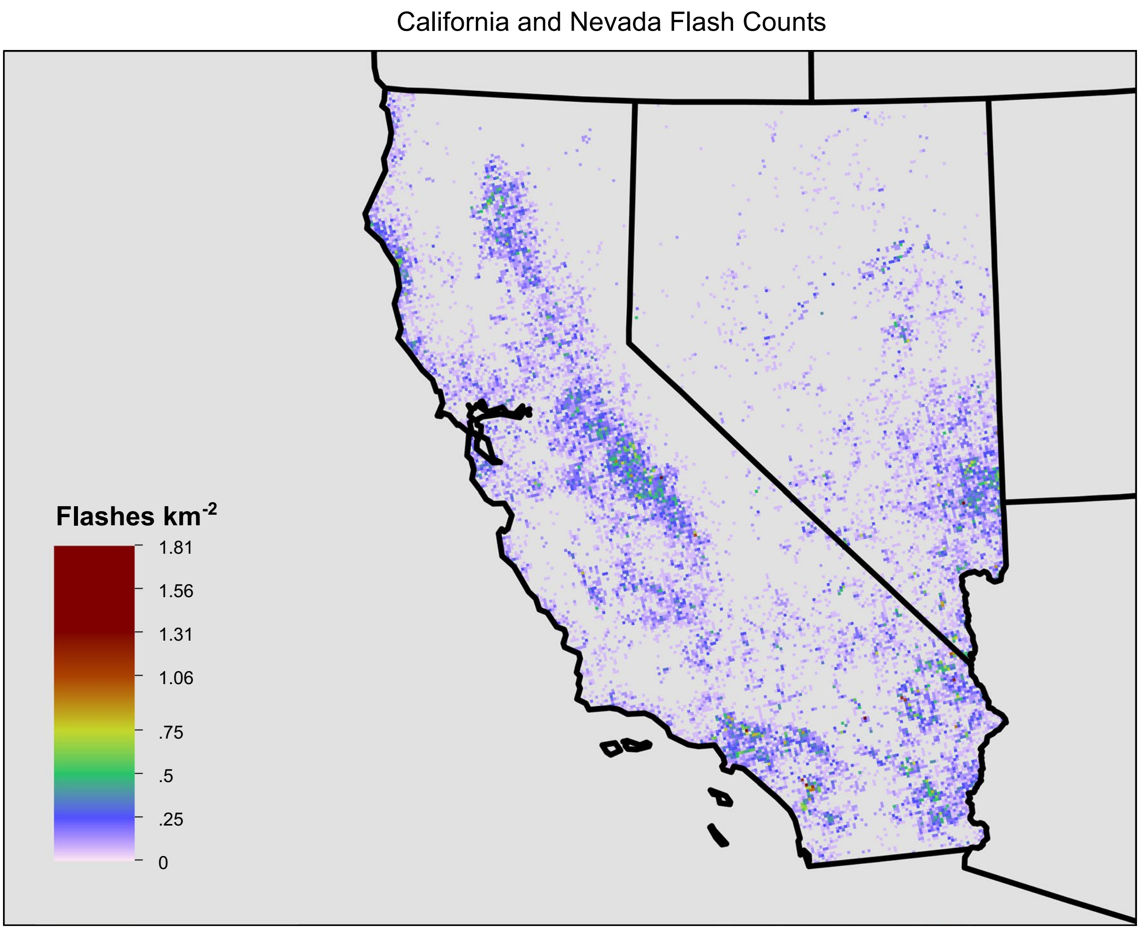


Fig. 10 Same as Fig. 8, except for focused on California and Nevada

those in the early morning (Fig. 12). Additionally, over 20% of flashes in the region occurred during a single storm in late February, 2005. The intraday distribution of flashes during this event closely matched the overall distribution for the region, suggesting that similar high magnitude flash days are likely responsible for the majority of flashes in the region.

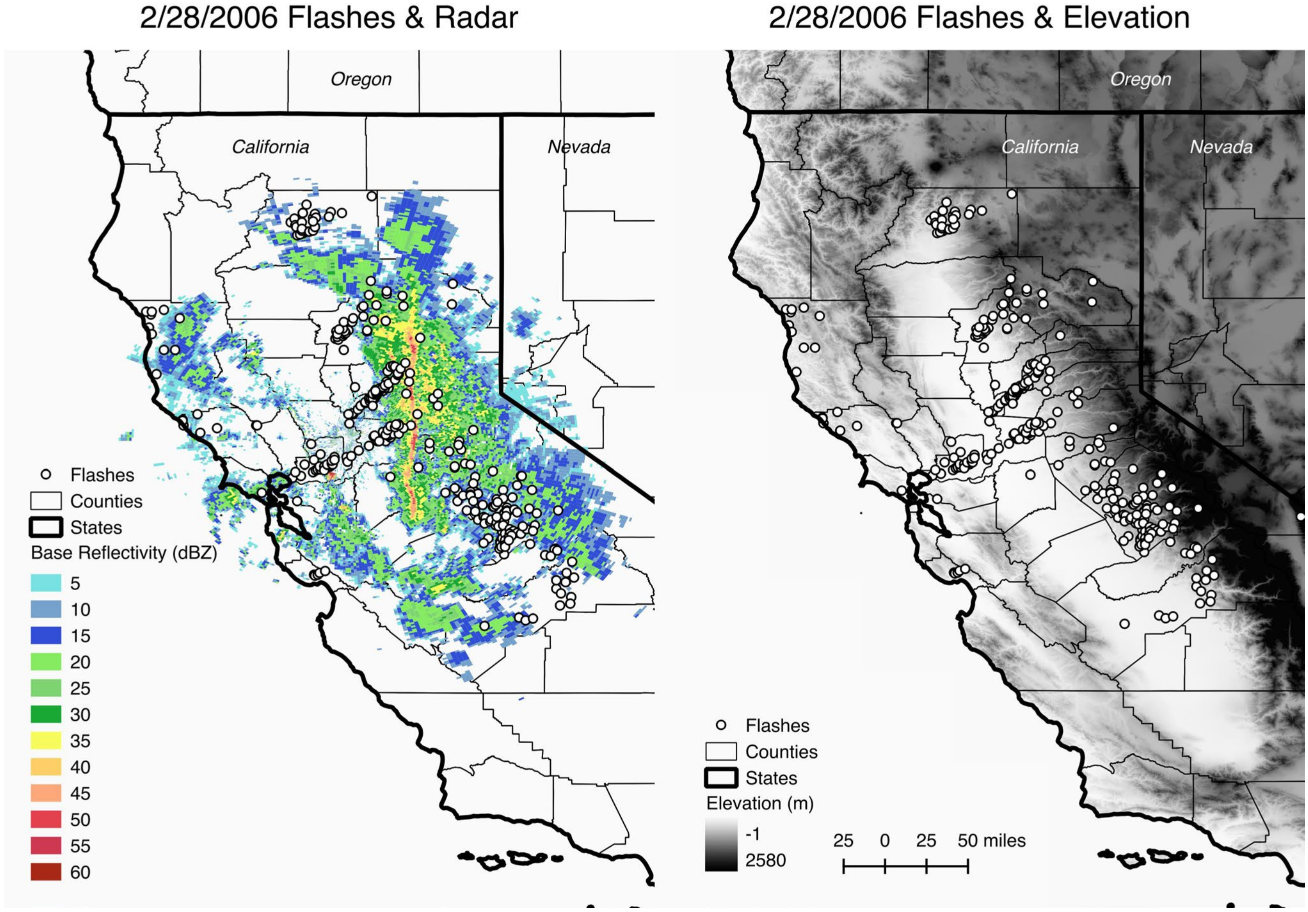
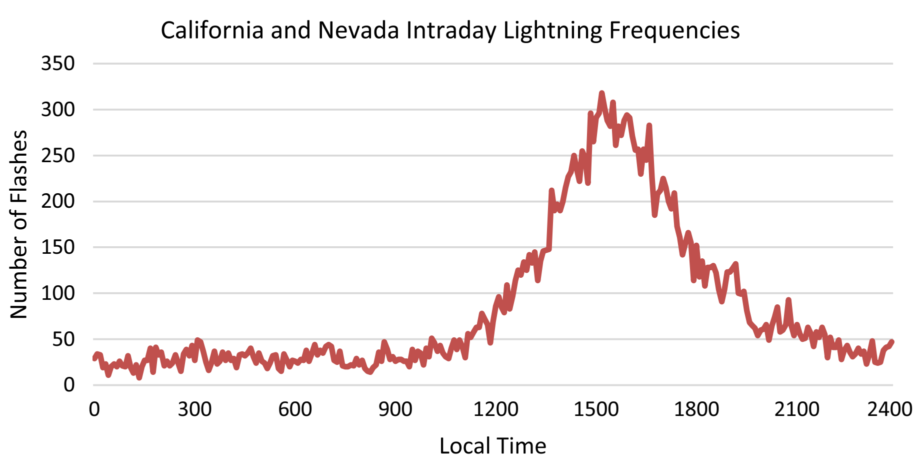


Fig. 11 Same as Fig. 5, except for WSR-88D (KDAX) on 28 February 2006

Fig. 12 Same as Fig. 9, except for focused on California and Nevada



4 Conclusions

This investigation, which visualized the temporal and spatial distributions of over 6 million flashes occurring during December, January and February, yielded several notable patterns. Diurnally, winter CG lightning exhibits a relatively flat distribution with little temporal variability. The peak in flash activity occurs slightly before 0300 LST further highlighting the lessened importance of insolation in promoting winter lightning.

When stratifying the CG lightning dataset by the SSC system, several patterns emerge. These include:

1. The existence of flash enhancement downwind of Lakes Erie and Ontario within the dry polar weather type;
2. The moist moderate, moist tropical plus and moist tropical weather types exhibit flash distributions with considerably higher percentages of positive polarity flashes (> 20%);
3. Greater flash counts in the moist tropical plus weather type can occur as far north as central Illinois and are oriented similar to areas experiencing more frequent freezing rain and sleet events;
4. The moist moderate weather type is associated with the highest flash density and lightning days over land with a distribution focused in parts of Texas, Louisiana, Mississippi and Alabama, but with elevated activity also located in the Western US; and
5. More than half of all winter flash activity occurs during transitional periods, when weather types are changing.

When examining oceanic lightning occurrence, the northern Gulf of Mexico and Gulf Stream (Atlantic) exhibits enhanced flash activity. Overall winter flash distribution maxima are concentrated in eastern Texas, Louisiana, southern Mississippi, Alabama and the Gulf of Mexico; however, the distribution of lightning days also exhibits relative maxima in areas of California, the Pacific Northwest and downwind of the Great Lakes.

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