Cloud-to-Ground Lightning Activity in the Contiguous United States from 1995 to 1999

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ABSTRACT

The spatial and temporal distributions of cloud-to-ground lightning are examined over the contiguous United States from 1995 to 1999 using data from the National Lightning Detection Network. Annual flash density, annual lightning days, cumulative frequency distributions of daily flash counts, and annual and summertime diurnal distributions of lightning are documented. The spatial, annual, and summertime diurnal distributions of positive and negative polarity cloud-to-ground lightning are also documented. Over the same five-year period, the production of positive and negative lightning is examined over two case study areas located in the north-central United States and along the Gulf Coast, centered on Sioux Falls, South Dakota, and Fort Rucker, Alabama, respectively. Case studies include radar–lightning analyses of significant lightning episodes from 1996.

Maximum flash densities and lightning days are found over coastal regions of the southeastern United States. Other prominent maxima are seen over parts of the southern Rocky Mountains and adjacent High Plains. Cumulative frequency distributions indicate that throughout the contiguous United States roughly 10% of the days with lightning accounted for 50% of lightning production. The majority of lightning was produced during summer (June–August) throughout the contiguous United States, except over the south-central United States and along and near the Pacific coast. Summertime lightning activity over the western and eastern United States exhibited a diurnal cycle with maximum frequencies in the afternoon to early evening. Over the central United States, summertime lightning activity was complex with significant longitudinal variations in daily activity and a tendency to occur at night.

Over most of the contiguous United States, a larger fraction of negative lightning was produced during summer than positive lightning, and the diurnal cycle of positive lightning lagged the diurnal cycle of negative lightning by up to two hours during summer. The main exception to these behaviors occurred over an area in the north-central United States extending from the Colorado–Kansas border to western Minnesota. Over this area, positive lightning peaked during midsummer versus late summer for negative lightning, and the diurnal cycle of positive lightning also peaked up to several hours prior to the maximum in the diurnal cycle of negative lightning during summer. In addition, this area was characterized by maxima in the percentage of positive lightning and positive mean peak current. The maximum in the percentage of positive lightning over the north-central United States was caused by a dramatic increase in positive flash density to the east of the Rocky Mountains and a local minimum in negative flash density over the area described above.

Results from the Sioux Falls case study indicate that positive lightning was produced primarily during summer in the hours around sunset by isolated storms and convective lines in various stages of mesoscale convective system (MCS) development. These convective events usually contained one or more storms that were characterized by predominantly positive lightning, high positive flash rate, and large positive peak currents. Negative lightning activity was produced later in the summer and throughout the night by more mature convective systems arranged in lines or clusters. Over Fort Rucker, positive and negative lightning was produced throughout the year, by diurnally forced storms during the warm season and by MCSs with areally extensive stratiform regions during the cold season. Diurnally forced storms (MCSs) were characterized by a low (high) percentage of positive lightning.

1. Introduction

Thunderstorms play an important role in many human societies. Thunderstorms produce beneficial rainfall as well as flooding, tornadoes, hail, strong winds, and lightning. Knowledge of the distribution of these weather phenomena in space and time can be used to 1) infer what physical processes control the occurrence of thunderstorms, 2) predict the beneficial and destructive effects of thunderstorms, and 3) verify output from numerical models that resolve the effects of thunderstorms. Climatologies based on the weather phenomena mentioned above have been developed over the contiguous United States for these and other reasons (Table 1). Collectively, these climatologies document significant spatial, annual, and diurnal variations in thunderstorm activity. However, the annual and diurnal distributions of

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TABLE 1. Studies related to thunderstorm and convective activity in the contiguous United States. List is separated into national studies (phenomena listed) and regional studies of lightning activity (region listed). Methods of documentation are summarized: spatial distributions (S; e.g., map of thunderstorm days), annual or seasonal distributions (A), and diurnal distributions (D). A subscript ''s'' indicates whether temporal distributions are documented over different areas (D_S or A_S). For lightning studies, S_{FD} and S_{LD} indicate that maps of flash density and lightning days are presented, respectively, and P indicates that distinctions are made between positive and negative polarity cloud-to-ground lightning.

National studies		
Precipitation	Wallace (1975)	D_S
	Dai et al. (1999)	D_S
Flash floods	Maddox et al. (1979)	S, A_S, D
Tornadoes	Kelly et al. (1978)	S, A, D_S
Large hail and strong winds	Kelly et al. (1985)	S, A_S, D
Audible thunder	Wallace (1975)	D_S
	Court and Griffiths (1981)	S, A, D_S
	Easterling and Robinson (1985)	D_S
Lightning	Orville (1991)	S_{FD}, A
	Orville (1994)	S_{FD}, P
	Orville and Silver (1997)	S_{FD}, A, P
	Lyons et al. (1998)	S_{FD}, D, P
	Huffines and Orville (1999)	S_{FD}
	Orville and Huffines (1999)	S_{FD}, A, P
	Boccippio et al. (2001)	S_{FD}
Regional studies of lightning activity		
Florida peninsula	Maier et al. (1984)	D_S
Western United States	Reap (1986)	S_{FD}, S_{LD}, D
Colorado and Florida	Lopez and Holle (1986)	S_{FD}, S_{LD}, A_S, D_S
Northeastern United States	Orville et al. (1987)	A, P
Oklahoma and Kansas	Reap and MacGorman (1989)	S_{FD}, D, P
Northeastern United States	Reap and Orville (1990)	S_{FD}, D
Southern Appalachians	Weisman (1990)	S_{FD}, D_S
Gulf Stream	Biswas and Hobbs (1990)	S_{FD}, P
Arizona	King and Balling (1994)	S_{FD}, D_S
Arizona	Watson et al. (1994a,b)	S_{FD}, A, D_S
Florida peninsula	Reap (1994)	S_{FD}, D
New Mexico	Fosdick and Watson (1995)	S_{FD}, S_{LD}, D_S
Southern Great Lakes	Clodman and Chisholm (1996)	S_{FD}, S_{LD}, D_S, P
Southeastern United States	Watson and Holle (1996)	S_{FD}, S_{LD}, D_S
Georgia	Livingston et al. (1996)	S_{FD}, D
Arizona	Lopez et al. (1997)	S_{FD}
Florida	Hodanish et al. (1997)	S_{FD}, A_S
Gulf Coast/Florida Panhandle	Camp et al. (1998)	S_{FD}, D

cloud-to-ground (CG) lightning have not been documented over the contiguous United States in a consistent manner. Therefore, in section 3a, the spatial, annual, and summertime diurnal distributions of CG lightning are examined over the contiguous United States from 1995 to 1999 using data from the National Lightning Detection Network (NLDN). Results from this section complement other climatologies and demonstrate the spatial continuity of NLDN lightning observations.

In section 3b, the spatial, annual, and summertime diurnal distributions of positive and negative polarity CG lightning are examined over the contiguous United States from 1995 to 1999. Documentation of these distributions provides a large-scale context for case studies of thunderstorms and associated positive and negative lightning production. Emphasis is placed on positive lightning due to its anomalous nature. On average, positive lightning accounts for roughly 10% of CG lightning (10.6 million of the 128.9 million flashes detected by the NLDN during 1995–99 were of positive polarity). However, the absolute and/or relative number of positive flashes tends to increase 1) during the dissipating stage of nonsevere storms (Fuquay 1982) and severe storms (Kane 1991), 2) over stratiform regions of mesoscale convective systems (MCSs; Orville et al. 1988; Rutledge and MacGorman 1988; Engholm et al. 1990; Rutledge et al. 1990; Holle et al. 1994; Schuur and Rutledge 2000a,b), 3) during the mature stage of some hailstorms and tornadic storms (MacGorman and Nielsen 1991; Curran and Rust 1992; Branick and Doswell 1992; Seimon 1993; Knapp 1994; MacGorman and Burgess 1994; Stolzenburg 1994; Perez et al. 1997; Carey and Rutledge 1998; Bluestein and MacGorman 1998; Smith et al. 2000), and 4) during the cold season. The tendency for positive lightning to occur during the dissipating stage of nonsevere and severe storms has been tentatively explained using the titled dipole (Brook et al. 1982) and precipitation unshielding mechanisms (Carey and Rutledge 1998), both of which are variations of the dipole charge model (Wilson 1920). Positive lightning production by stratiform regions of MCSs, sometimes referred to as bipolar lightning (Orville et al. 1988), may

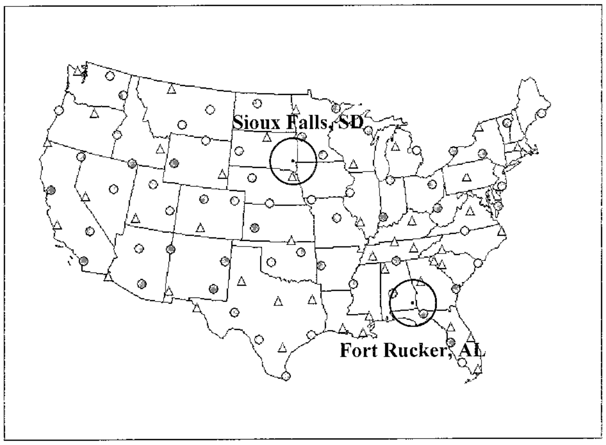

FIG. 1. Locations of the Sioux Falls, SD, and Fort Rucker, AL, case study areas and NLDN sensor types and locations following the 1995 NLDN upgrade. Case study areas are 200-km radius areas centered on WSR-88D radars located in Sioux Falls and Fort Rucker. Triangles and circles show the locations of IMPACT and LPATS sensors, respectively.

result from the advection of positive charge from convective regions (Rutledge and MacGorman 1988) and/or the separation of charge within stratiform regions (in situ charging; see Rutledge et al. 1990; Schuur and Rutledge 2000a,b). Some hailstorms and tornadic storms have exhibited a dominance of positive flashes and positive flash rates comparable to typical negative flash rates (Stolzenburg 1994; Seimon 1993). Tilted dipole, precipitation unshielding, enhanced lower positive charge (MacGorman and Nielsen 1991), and inverted dipole (Seimon 1993) mechanisms have been offered to explain the lightning production by these positive strike dominated (PSD) storms (Knapp 1994). Finally, the percentage of positive lightning increases during the cold season (Orville et al. 1987; Clodman and Chisholm 1996; Orville and Silver 1997; Orville and Huffines 1999). This behavior has been attributed to increased vertical wind shear (i.e., titled dipole) and lower cloud tops during the cold season (Engholm et al. 1990).

In section 4, the production of positive and negative lightning is examined over two 200-km radius areas located in the north-central United States and along the Gulf Coast, centered on Sioux Falls, South Dakota, and Fort Rucker, Alabama, respectively (Fig. 1). Sioux Falls was chosen because it is located within a region characterized by a maximum in the percentage of positive lightning (Orville 1994; Orville and Silver 1997; Orville and Huffines 1999; Boccippio et al. 2001), maximum in the flash density of large peak current positive lightning (greater than 75 kA; Lyons 1996; Lyons et al. 1998; Boccippio et al. 2001), and maximum in positive median peak current (Orville and Huffines 1999). These signals are attributed to PSD storms and stratiform regions of MCSs in the studies just cited (except for Boccippio et al. 2001), since both PSD storms and stratiform regions have been observed to produce large peak current positive lightning at elevated rates (PSD: Seimon 1993; Stolzenburg 1994; stratiform: Lyons 1996). Boccippio et al. (2001) attribute these signals to thunderstorms with strong updrafts, specifically including PSD storms. The production of positive lightning by PSD storms and stratiform regions is examined in the Sioux Falls case study. Fort Rucker was chosen because it is located within a region characterized by diurnally forced convection during the warm season and synoptically forced convection during the cold season (Wallace 1975). Lightning activity is compared between the warm and cold seasons in the Fort Rucker case study. Both case studies include documentation of annual and summertime diurnal distributions of positive and negative lightning from 1995 to 1999, and radar–lightning analyses of significant lightning episodes from 1996. Maps of low-level radar reflectivity and CG strike locations are examined in order to infer information about storm type and associated lightning production.

2. Data and method

a. Lightning data

Cloud-to-ground lightning data analyzed in this study were collected by the NLDN, a lightning location network owned and operated by Global Atmospherics, Inc. (GAI), of Tucson, Arizona. The network comprises 106 lightning sensors (Fig. 1), a satellite communication system, and a central processor. The NLDN records the time, location, polarity, and peak current of the first return stroke, and multiplicity (number of return strokes per flash) of CG flashes occurring over the contiguous United States and adjacent areas (see Cummins et al. 1998 for a thorough discussion). Data from January–December 1995–99 were used for all analyses, except for the analysis of summertime lightning activity, which used data from June–August 1995–99.

The NLDN has undergone a series of upgrades since it became operational in 1989. The most recent upgrade was performed in 1995 to increase the detection efficiency of weak flashes (as low as 5 kA) and to decrease location errors (Cummins et al. 1998). The 1995 NLDN upgrade improved networkwide performance: detection efficiency increased from 65%–80% to 80%–90% and median location error decreased from 2–4 to 0.5–1.0 km (Cummins et al. 1998). Network detection efficiency is greater than 80% over most of the contiguous United States, except toward the national borders, where detection efficiency decreases rapidly (Fig. 2). The installation of GAI lightning sensors in Canada from spring 1997 to fall 1998 has eliminated the strong north-to-south gradient in detection efficiency over the northern tier states (Cummins et al. 1999).

While the 1995 NLDN upgrade improved network performance, it has introduced problems with the detection of positive lightning. Large populations of low peak current positive flashes (less than 10 kA) are now

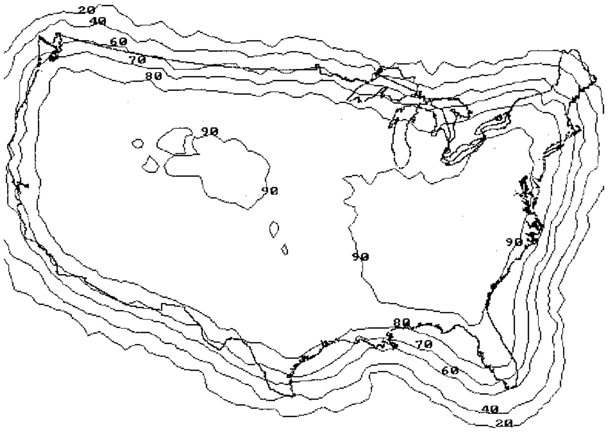

FIG. 2. Model projected NLDN detection efficiency for negative flashes from roughly 1995 to 1997, following the 1995 NLDN upgrade and preceding the installation of lightning sensors in Canada. The addition of sensors in Canada has eliminated the strong south-to-north gradient in detection efficiency over the northern tier states.

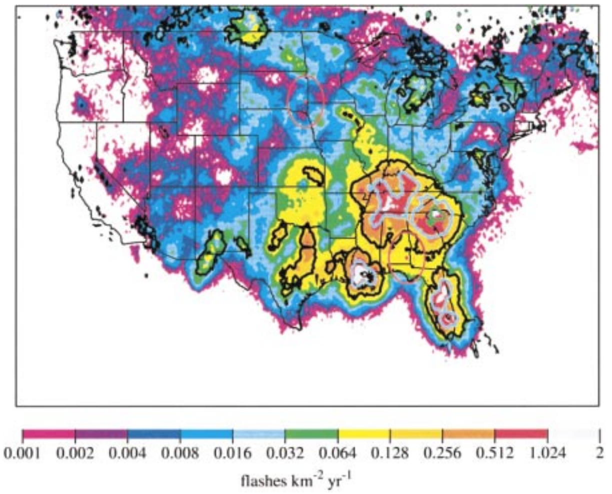

FIG. 3. Low peak current positive flashes (less than 10 kA) from 1995 to 1999. Fill contours show the average annual flash density of low peak current positive flashes. Line contours show the percentage of low peak current positive flashes with respect to all positive lightning detected by the NLDN. Black, blue, and green line contours correspond to 25%, 50%, and 75%, respectively. Locations of the Sioux Falls and Fort Rucker case study areas are shown. Flash densities were not modified in order to account for detection efficiency. Positive flashes with peak current less than 10 kA may be false detections of intracloud lightning and were excluded from all other analyses.

detected over localized areas in the southeastern United States (Fig. 3). These flashes account for greater than 50% of all positive flashes detected over these areas. Low peak current positive flashes may be false detections of intracloud lightning caused by the high density of IMProved Accuracy from Combined Technology (IMPACT) sensors over the southeastern United States (Orville and Huffines 1999; see NLDN sensor map in Fig. 1). GAI and researchers alike recommend discarding positive flashes with peak currents less than 10 kA [see Cummins et al. (1998) and Wacker and Orville (1999a,b), respectively]. With the exception of Fig. 3, positive flashes with peak currents less than 10 kA were not analyzed in this study.

b. *Radar data*

National radar summaries were used to determine the morphology and evolution of thunderstorms occurring over the two case study areas during 1996. Summaries were produced by Weather Services International (WSI) Corporation and are composites of low-level reflectivity scans collected by National Weather Service radars, primarily the 10-cm WSR-88D radar. WSI applied algorithms to remove ground clutter and other spurious reflectivity echoes. Summaries were produced every 15 min and were mapped onto a 8 km × 8 km grid.

c. *Method: National analysis*

The maps and associated plots presented in this study are based on constant latitude–longitude grids covering the contiguous United States and adjacent areas. A 0.2° × 0.2° grid was used in all cases, except for the analysis of summertime diurnal distributions, which used a 1.0° × 1.0° grid. The 0.2° grid was selected to correspond with the audible range of thunder (20 km; Reap and Orville 1990). The 1.0° grid was selected to increase the number of CG flashes sampled per grid element. During the process of gridding lightning data, each flash was assigned to a specific grid element.

Due to the use of a constant latitude–longitude grid, grid element area increases from north to south. For example, grid element area increases by a factor of 1.4 from 49° to 25°N. The calculation of flash density (in flashes per square kilometer) accounts for this latitudinal variation by dividing the number of flashes in a grid element by the grid element area. The calculation of lightning days does not account for the latitudinal variation in grid element area, and a north-to-south gradient in lightning days may be a resulting effect. However, this effect appears to be negligible. Note that the calculation of flash density does not correct for NLDN detection efficiency as is performed in other lightning studies (e.g., Orville 1991, 1994; Livingston et al. 1996; Orville and Silver 1997; Hodanish et al. 1997; Huffines and Orville 1999; Boccippio et al. 2000).

The daily distributions of lightning during summer are summarized using the normalized amplitude and phase of the diurnal cycle of lightning frequency. This method allows a complex time series to be described with two parameters. Lightning data from June–August 1995–99 were first converted from universal time coordinates (UTC) to local mean solar time (LMT). LMT is a function of longitude such that the sun crosses the local meridian at 1200 LMT, eliminating the effects caused by time zones (Kelly et al. 1978). Lightning data were then assigned to a 1.0° × 1.0° grid and filtered into 96 15-min time bins. Time series of 15-min flash density were Fourier decomposed into 72 harmonics. The zeroth harmonic is the daily mean, the first harmonic is the diurnal cycle, the second harmonic is the semidiurnal cycle, etc. The normalized amplitude of the diurnal cycle was calculated by dividing the amplitude of the diurnal cycle by the daily mean and multiplying this value by 100 (Wallace 1975). The phase of the diurnal cycle (i.e., the time of maximum lightning frequency) is resolved to within 30 min or less using a 15-min time series. Normalized amplitude and phase information was calculated for only those 1.0° × 1.0° grid elements with flash densities greater than 0.01 flashes km^{-2} per summer (or approximately 500 flashes). The normalized amplitude and phase of the diurnal cycle was calculated three times, for all CG lightning and for positive and negative lightning.

d. Method: Case studies

The Sioux Falls and Fort Rucker case studies include radar–lightning analyses of significant lightning episodes from 1996. Radar–lightning analyses are based on three 15-min datasets: national radar summaries, maps of CG strike locations over each case study area, and lightning statistics over each case study area. Datasets were examined on a total of 38 days, 19 for each case study. These 38 days were selected for having the greatest positive lightning production. The 19 days selected for the Sioux Falls (Fort Rucker) case study produced 75% (55%) of positive lightning from 1996. Lightning production on these days was usually dominated by one or two episodes of lightning activity. Each episode, or case, was analyzed separately. Using this method, 21 (25) cases were sampled over Sioux Falls (Fort Rucker).

Radar data was used to characterize the morphology and evolution of all 46 cases. Radar reflectivity patterns were subjectively classified into the following six categories, based primarily on the 50-dB*Z* reflectivity contour: isolated cells, cluster of cells (grouped cells with no linear organization), noncontiguous line, contiguous line, linear MCS, and cluster MCS (MCS with no linear organization; Figs. 4a–f). The definition of MCS used in this study follows that given by Cotton and Anthes (1991) with one important qualification. Cotton and Anthes (1991) defined an MCS as

> a deep convective system that is considerably larger than an individual thunderstorm and that is often marked by an extensive middle to upper tropospheric stratiform-anvil cloud of several hundred kilometers in horizontal dimension.

The definition of MCS used in this study requires that an MCS comprise an area of deep convection and an areally extensive, precipitating stratiform region. The requirement of an areally extensive, precipitating stratiform region was used to identify convective systems with well-developed mesoscale updrafts and possible bipolar lightning.

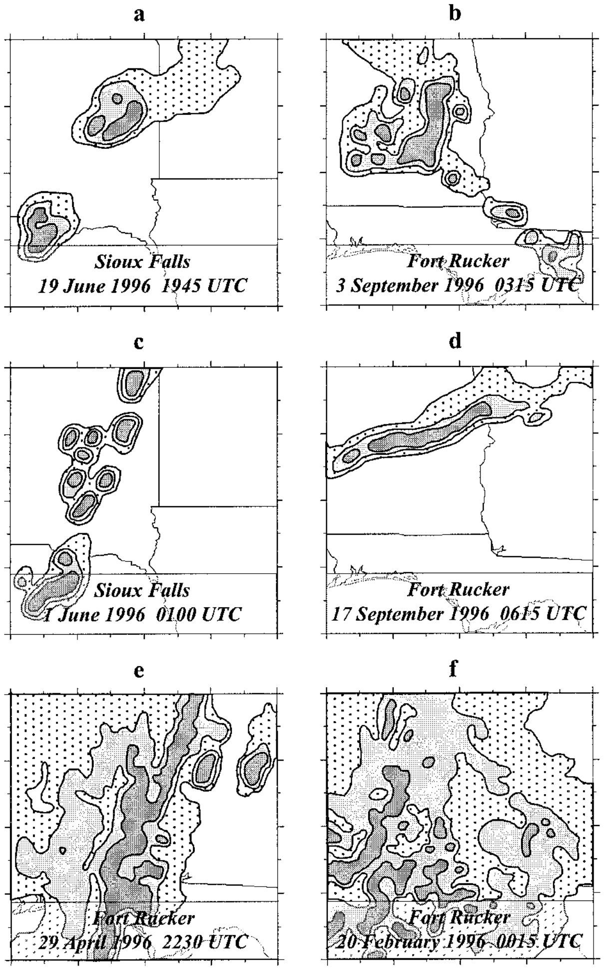

FIG. 4. Radar echo classification scheme. Echoes were classified into the following six categories: (a) isolated cells, (b) cluster of cells, (c) noncontiguous line, (d) contiguous line, (e) linear MCS, and (f) cluster MCS. Panels show 400 km × 400 km areas centered on Sioux Falls or Fort Rucker. Light, medium, and dark shadings correspond to radar reflectivities ranging between 20 and 40, 40 and 50, and 50 and 70 dB*Z*, respectively. Radar scan times are listed and represent the time of maximum positive lightning production for each case. Cloud-to-ground strike locations corresponding to (a) and (e) are shown in Figs. 5a and 5b, respectively.

Radar reflectivity patterns were classified at two times for each case, at maximum positive lightning production and at maximum areal extent. Maximum positive lightning production was determined from time series of 15-min lightning statistics and was defined as the 15-min period of maximum positive lightning production. Maximum areal extent was determined from 15-min radar summaries and was defined as the maximum areal extent for a case based on the 20-dB*Z* reflectivity contour. Maximum areal extent was allowed to occur after the storm or storm system passed over the case study area under analysis. This definition was used to provide informa-

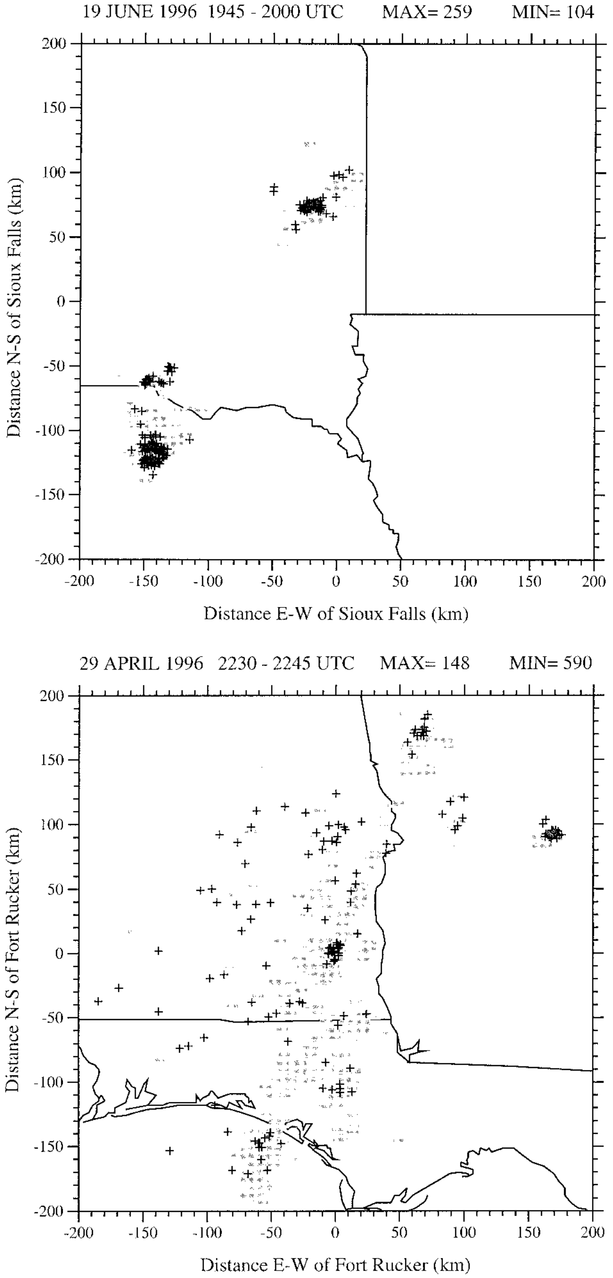

FIG. 5. Cloud-to-ground strike locations for an isolated cells case over Sioux Falls on 19 Jun 1996 from 1945 to 2000 UTC. This time period is the 15-min period of maximum positive lightning production for this case. Pluses (+) and minuses (−) show the strike locations of positive and negative flashes, respectively. MAX and MIN values are the number of positive and negative flashes plotted, respectively. Distances are relative to the WSR-88D radar located in Sioux Falls. Three PSD storms are identified by comparing Figs. 4a and 5a and noting that the storm over the Nebraska–South Dakota border is splitting into a PSD right-mover and a PSD left-mover. Positive mean peak current was 75.0 kA and negative mean multiplicity was 1.0. (b) As in (a), expect for a linear MCS case over Fort Rucker on 29 Apr 1996 from 2230 to 2245 UTC. Distances are relative to the WSR-88D radar located in Fort Rucker. A bipolar lightning pattern is identified by comparing Figs. 4e and 5b and noting the predominantly positive lightning over western extent of system (trailing stratiform region) and the predominantly negative lightning along the eastern edge of the system (leading-line of convection). Positive mean peak current was 22.6 kA and negative mean multiplicity was 2.4.

tion about storm evolution, particularly over Sioux Falls, where storm systems frequently developed upscale as they passed over from west to east.

Two lightning patterns were identified in maps of 15-min CG strike locations. PSD storms (Knapp 1994; e.g., Fig. 5a) and bipolar lightning patterns (Orville et al. 1988; e.g., Fig. 5b) were identified because both have been linked to unique lightning signals observed over the north-central United States. Using the CG strike map from the time of maximum positive lightning production only, PSD storms were subjectively identified as CG clusters containing a greater number of positive flashes than negative flashes. Positive and negative flash counts listed with each CG strike map were useful in estimating the percentage of positive lightning in a cluster. This method differs from that used by Knapp (1994) in the length of time used to identify a PSD storm (15 vs 75 min). Bipolar lightning patterns were identified because they represent the production of predominantly positive (negative) lightning in stratiform (convective) regions of well-developed MCSs. All CG strike maps from a case were examined to find bipolar lightning patterns.

3. National analysis

In this section, the spatial and temporal distributions of cloud-to-ground lightning are examined over the contiguous United States from 1995 to 1999. The distributions of all CG lightning are examined in section 3a, and the distributions of positive and negative lightning are examined in section 3b. Discussion will generally focus on areas within the 80% detection efficiency contour (Fig. 2). Within this contour, NLDN performance is relatively homogeneous and spatial variations in lightning activity can be attributed to natural variations. Toward the continental borders, spatial variations represent a superposition of network performance and natural variations. A topographic map of the contiguous United States is provided (Fig. 6) because features in lightning maps are often collocated with elevated or depressed terrain. Features in lightning maps are attributed to natural variations since the propagation of electromagnetic waves is not affected by topography at the wavelengths detected by NLDN sensors (Lopez and Holle 1986).

a. All cloud-to-ground lightning

1) ANNUAL FLASH DENSITY

Annual flash densities over the contiguous United States ranged from less than 0.01 flashes km^{-2} yr^{-1} along and near the Pacific coast to greater than 5.0 flashes km^{-2} yr^{-1} over coastal regions in the southeastern

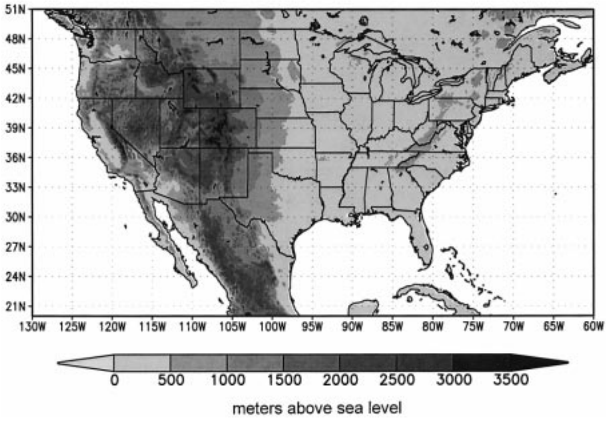

FIG. 6. Topography of the contiguous United States.

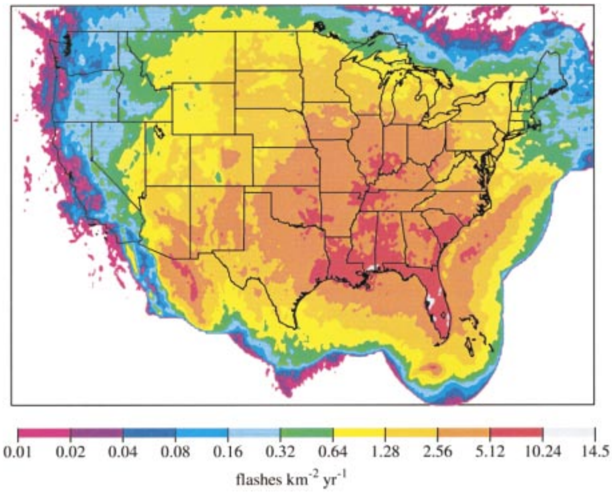

FIG. 7. Average annual flash density from 1995 to 1999. National maximum of 14.5 flashes km^{-2} yr^{-1} occurred near Tampa, FL. Flash densities were not modified in order to account for detection efficiency. This figure and the following figures showing lightning analyses over the contiguous United States are based on a 0.2° × 0.2° grid except for Figs. 10b and 13a, which are based on a 1.0° × 1.0° grid.

United States (Fig. 7). The national maximum of 14.5 flashes km^{-2} yr^{-1} occurred near Tampa, Florida. Other prominent maxima are found over parts of the southern Rocky Mountains and adjacent High Plains and, outside the national borders, over the Gulf Stream, Cuba, and the Sierra Madre in northern Mexico (cf. Figs. 6 and 7). These maxima highlight moisture, instability, and a triggering mechanism as the essential ingredients for thunderstorms (Watson et al. 1994a). The coastlines of the southeastern United States and the elevated terrain of the Rocky Mountains provide a trigger for thunderstorms fueled by moisture from the Gulf of Mexico and Gulf of California. The flash density maximum over the warm Gulf Stream waters shows the importance of instability. Topography can also act to suppress lightning activity, as is seen over the San Luis Valley in south-central Colorado, Snake River Valley in southern Idaho, and Columbia River Basin in eastern Washington. These findings are consistent with results from other studies that present maps of flash density (Table 1).

2) Annual lightning days and cumulative frequency distributions

Annual lightning days varied from less than 10 days along and near the Pacific Coast and over eastern Maine to greater than 70 days over Florida and much of the Gulf Coast (Fig. 8a). The national maximum of 107 days occurred near Fort Lauderdale, Florida. Similar to the map of flash density (Fig. 7), prominent maxima in lightning days are seen over parts of the southern Rocky Mountains and over the Gulf Stream, Cuba, and the Sierra Madre. In fact, the map of lightning days picks out the various mountain ranges and valleys in the Rocky Mountains much more clearly than the map of flash density, which emphasizes the High Plains. In a lightning study over New Mexico, Fosdick and Watson (1995) also note the better correspondence between lightning days and topography than between flash density and topography. Finally, the map of annual lightning days shows reasonable correspondence with the map of annual thunder days published in Court and Griffiths (1986).

Cumulative frequency distributions (CFDs) of daily flash counts indicate that the production of lightning is dominated by a relatively few number of days. Comparison of Fig. 8b, the map of annual number of days to produce 50% of lightning, with Fig. 8a reveals that roughly 10% of the days with lightning accounted for 50% of lightning production throughout the contiguous United States. CFDs from Sioux Falls and Fort Rucker (Fig. 8c) show the consistency of lightning distributions over different climatic regions. Lopez and Holle (1986) report similar results: CFDs of 5-min flash density from northeastern Colorado and central Florida exhibit a similar degree of skewness.

3) Annual distributions

Most studies that have examined annual or seasonal distributions of lightning have shown that the majority of lightning is produced during summer (June–August; Table 1). This result is confirmed here. The percentage of lightning produced during summer was greater than 50% over most of the contiguous United States, except over the south-central United States and along and near the Pacific coast (Fig. 9a). Annual distributions over these two regions, and over the intermountain west, are discussed below.

The percentage of lightning produced during summer shows a strong south-to-north gradient over the central United States. This gradient is a function of proximity to the Gulf of Mexico. Areas closer to the Gulf were more likely to experience thunderstorms throughout the

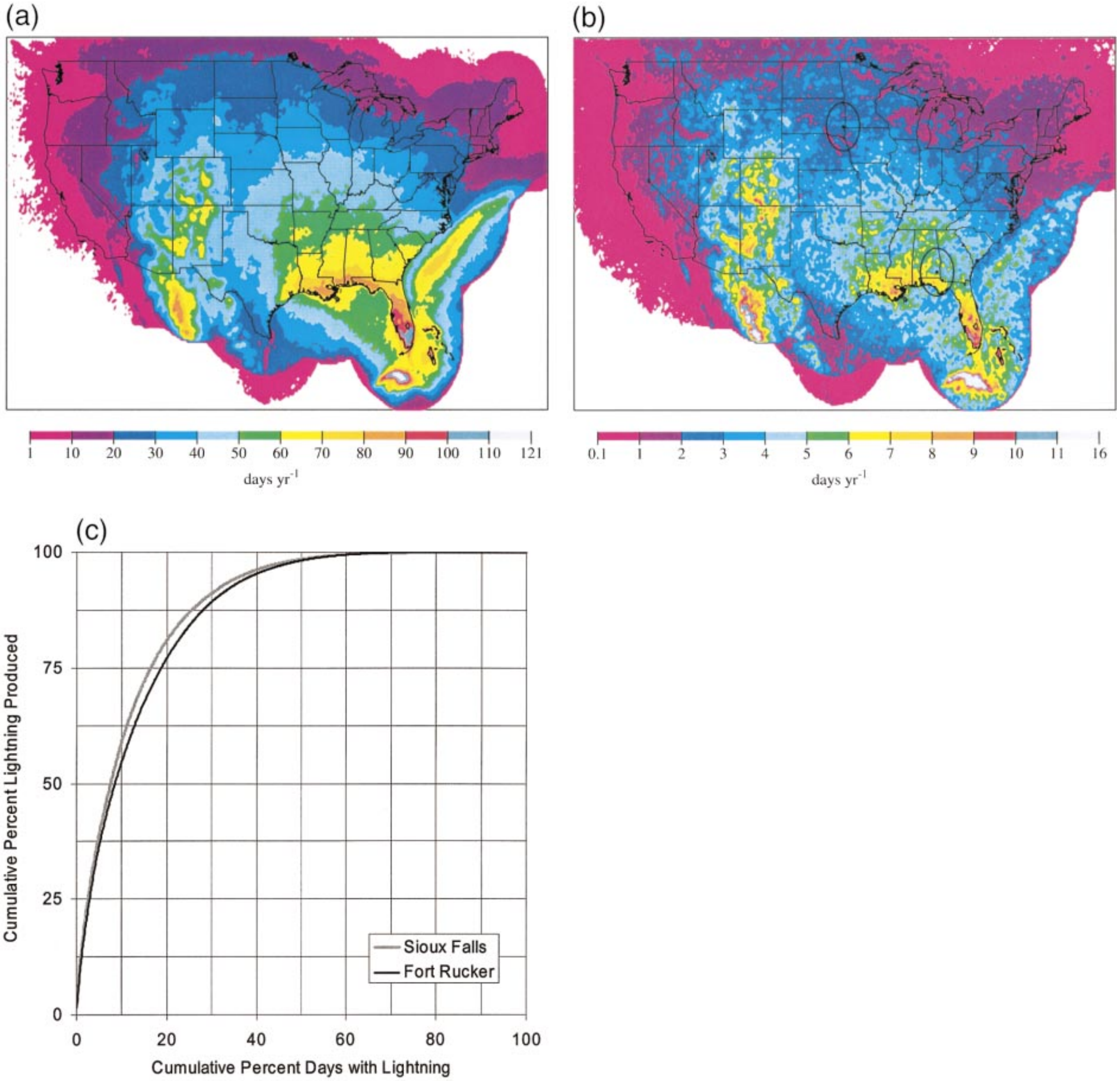

FIG. 8. Cloud-to-ground lightning days and cumulative frequency distributions (CFDs) of daily flash counts from 1995 to 1999. (a) Average annual number of days with one or more cloud-to-ground flashes, or average annual lightning days. National maximum of 107 days occurred near Fort Lauderdale, FL. (b) Average annual number of days to produce 50% of lightning. This analysis is based on CFDs of daily flash counts and shows the minimum number of days needed to produce 50% of lightning. Note that the scales used in (a) and (b) differ by an order of magnitude. (c) CFDs of daily flash counts for the Sioux Falls and Fort Rucker case study areas.

year (Fig. 9b) and had greater cold season flash densities (Fig. 9a). In addition, areas over southern Texas including San Antonio and Brownsville exhibited a relative minimum in lightning activity during summer.

The minimum along the Pacific coast (values less than 10%) reflects the lack of lightning activity during summer and the dominance of lightning activity during the cold season (October–March; monthly plots not shown). The minimum over the intermountain west (values between 40% and 80%) is caused by the significant lightning production during September. July–September were the main months of activity over this region (monthly plots not shown), a finding consistent with results from regional lightning studies (Table 1).

4) SUMMERTIME DIURNAL DISTRIBUTIONS

As is discussed in section 2c, daily distributions of lightning during summer are summarized using a harmonic analysis of the diurnal cycle of lightning fre-

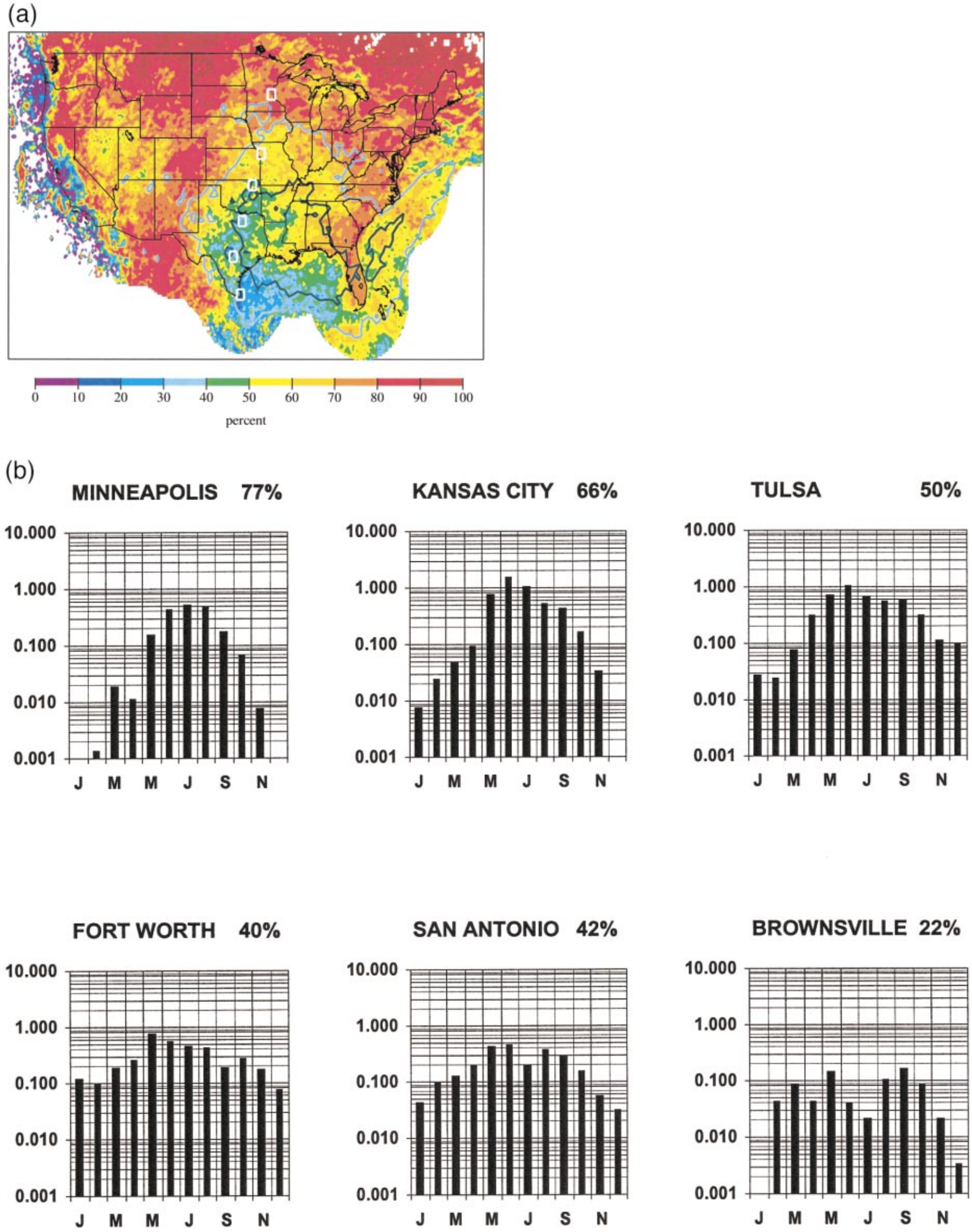

FIG. 9. Annual distributions of cloud-to-ground lightning from 1995 to 1999. (a) Fill contours show the average percentage of lightning produced during summer (Jun–Aug). Line contours show the average cold season (Oct–Mar) flash density. Light and dark gray line contours show flash densities of 0.16 and 0.64 flashes km^{-2} per cold season, respectively. National maximum of 2.0 flashes km^{-2} per cold season occurred in southeastern Oklahoma. Line contours were degraded from a 0.2° grid to a 0.6° grid. Black boxes indicate the areas examined in (b). (b) Average monthly flash density for 1.0° × 1.0° areas containing the city listed. Flash densities are in flashes km^{-2} month^{-1}. The percentage of lightning produced during summer is listed. Note that all areas are within the 80% NLDN detection efficiency contour except for Brownsville (~40%; Fig. 2).

quency. This method allows a complex time series to be described with two parameters: normalized amplitude and phase. The normalized amplitude of the diurnal cycle provides information about the shape of daily distributions. As is stated by Easterling and Robinson (1985),

> a normalized amplitude below 0.5 indicates a lack of a well-defined time of maximum, or a double maximum. Amplitudes between 0.5 and 1.0 suggest a definite diurnal trend with a clear time of maximum, but with storms likely at any hour, while a value over 1.0 represents conditions where there is very well-developed time of maximum activity, with few storms at other times.

Comparison of diurnal cycle curves with the corresponding time series of 15-min flash density in Fig. 10a supports these statements, noting that Easterling and Robinson do not multiply normalized amplitudes by 100 as is done in the present study. The phase of the diurnal cycle provides information about the timing of daily distributions. While the maximum frequency of the diurnal cycle does not always coincide with the peak in the 15-min time series, it is reasonably accurate in most cases. Finally, it is important to recall that lightning activity is not evenly distributed in time [section 3a(2); Figs. 8a–c]. Thus, the diurnal cycle does not indicate lightning activity on any given day. Rather, it emphasizes lightning activity on those days with the greatest lightning production.

Figure 10b shows that normalized amplitudes greater than 100 cover the southeastern United States, the eastern United States in the lee of the Appalachian Mountains, and most of the western United States and adjacent High Plains. The time of maximum lightning frequency over these areas usually occurred between 1500 and 1800 LMT, but occurred as late as 2200 LMT over the High Plains. Normalized amplitude maxima (greater than 140) are found over coastal regions in the southeastern and eastern United States, large parts of the Rocky Mountains and adjacent High Plains, and parts of Nevada and California. These results indicate that summertime lightning activity over much of the western and eastern United States was modulated by the diurnal cycle of solar insolation. Collocation of normalized amplitude maxima with coastal regions and elevated terrain indicates the strong role geographic features play in forcing and suppressing thunderstorm activity.

Summertime lightning activity over the central United States was much more complex with significant longitudinal variations and a tendency to occur at night. Normalized amplitudes decreased from greater than 120 in the lee of the Rocky Mountains to less than 40 over parts of the eastern Great Plains and upper Midwest. The time of maximum frequency was consistently around 1800 LMT in the lee of the Rocky Mountains and occurred progressively later in the evening to the east. The time of maximum frequency over the eastern Great Plains and upper Midwest was variable but generally occurred around 0000 LMT. Over the lower Midwest, normalized amplitudes range between 60 and 100, and the time of maximum frequency occurred between 1600 and 2000 LMT.

The longitudinal variations in summertime lightning activity over the central United States are depicted in detail in Fig. 10a. This figure shows a west-to-east transition from an afternoon regime (Cheyenne), to a nocturnal regime (Omaha), and back to an afternoon regime (Chicago). These longitudinal variations are consistent with the description of thunderstorm activity east of the Rocky Mountains given by McAnelly and Cotton (1989):

> Thunderstorms generally develop in the late afternoon east of the Rockies (or track off of the foothills), then track eastward into the nocturnal period, either decaying or persisting as long-lived MCSs. Further east in the regime (e.g., Iowa), thunderstorms are more variably associated with locally generated, late-afternoon convection, and with MCCs and MCSs at various nocturnal hours and stages of their lifecycle, including some that track all the way from the High Plains through the nocturnal period.

A number of mechanisms have been proposed to explain the occurrence of nocturnal thunderstorms over the central United States, including the development of a nocturnal low-level jet (see Wallace 1975 and Balling 1985 for reviews).

The results from this section are consistent with results from studies that have examined summertime diurnal distributions of lightning, thunder, and precipitation (Table 1). The diurnal cycle of lightning corresponds particularly well with the diurnal cycle of audible thunder (Easterling and Robinson 1985). The reader is referred to Wallace (1975) and McAnelly and Cotton (1989) for detailed discussions about the diurnal cycles of weather phenomena associated with thunderstorms over the central United States (precipitation, audible thunder, severe weather, clouds). Results from this

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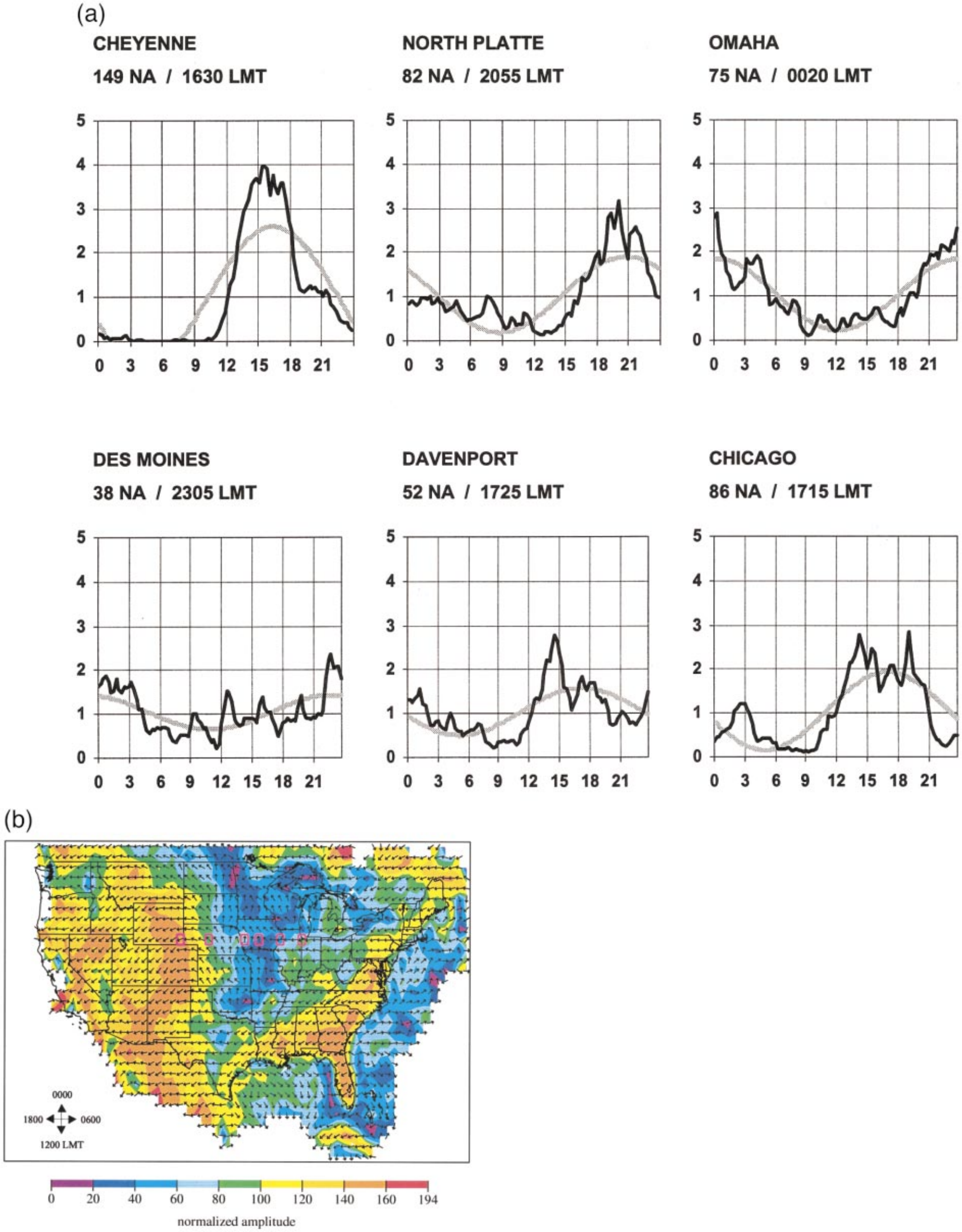
FIG. 10. Summertime diurnal distributions of cloud-to-ground lightning from Jun–Aug 1995–99. (a) Normalized 15-min flash density is shown with black lines for 1.0° × 1.0° areas containing the city listed. Gray lines show the corresponding diurnal cycle with normalized amplitude (NA) and time of maximum frequency (LMT) listed. Locations of 1.0° × 1.0° areas are shown in (b). (b) Normalized amplitude and phase of the diurnal cycle of lightning frequency. Contours show normalized amplitude. Vectors show phase, behave like a 24-h clock, and point to the time of maximum lightning frequency (LMT). A vector pointing to the north indicates a 0000 LMT maximum; a vector pointing to the east indicates a 0600 LMT; etc. This analysis is based on a 1.0° × 1.0° grid and on time series of 15-min flash density as shown in Fig. 10a.


(a)
CHEYENNE
149 NA / 1630 LMT
NORTH PLATTE
82 NA / 2055 LMT
OMAHA
75 NA / 0020 LMT
DES MOINES
38 NA / 2305 LMT
DAVENPORT
52 NA / 1725 LMT
CHICAGO
86 NA / 1715 LMT
0 1 2 3 4 5
0 3 6 9 12 15 18 21
(b)
0000
1800
0600
1200 LMT
0 20 40 60 80 100 120 140 160 194
normalized amplitude

section and the previous section on annual distributions show that lightning activity over the contiguous United States was usually modulated by the annual and diurnal cycles of solar insolation. However, annual distributions exhibited minima during summer along and near the Pacific coast and over southern Texas. Also, summertime diurnal distributions exhibited maxima at night over the eastern Great Plains and upper Midwest, and maxima in the morning over the Gulf of Mexico and Atlantic Ocean (Fig. 10b).

b. Positive and negative cloud-to-ground lightning

1) ANNUAL FLASH DENSITY AND THE PERCENTAGE OF POSITIVE LIGHTNING

Annual positive flash densities varied between 0.001 flashes km^{-2} yr^{-1} along and near the Pacific Coast to greater than 0.5 flashes km^{-2} yr^{-1} over southern Florida, parts of the southeastern United States, and isolated areas in the Great Plains (Fig. 11a). The national maximum of 1.0 flashes km^{-2} yr^{-1} occurred over southern Mississippi. The map of positive flash density is similar to the map of CG flash density (Fig. 7), except that positive flash densities are roughly an order of magnitude smaller. Consequently, the percentage of positive lightning with respect to all CG lightning is roughly 10% over most of the contiguous United States (Fig. 11b). However, the percentage of positive lightning exceeded 20% over the north-central United States and along and near the Pacific coast. Lightning activity over these two areas is discussed below.

The maximum in the percentage of positive lightning over the north-central United States has been observed since 1989 and has been attributed to the elevated production of positive lightning in PSD storms and stratiform regions of MCSs (Orville 1994; Orville and Silver 1997; Orville and Huffines 1999). Examination of positive and negative flash densities over the north-central United States in Fig. 11a reveals that the maximum resulted from a dramatic increase in positive flash density to the east of the Rocky Mountains, as well as a local minimum in negative flash density over the north-central United States. The local minimum in negative flash density over the north-central United States is a new finding and indicates that the maximum in the percentage of positive lightning is caused by more than just elevated positive lightning production. This finding is discussed further in section 5.

The maximum in the percentage of positive lightning along and near the Pacific Coast has also been observed since 1989 (Orville 1994; Orville and Silver 1997; Orville and Huffines 1999). This maximum has been attributed to the decrease in network detection efficiency, coupled with the larger peak currents in positive lightning relative to negative lightning, which results in a larger fraction of positive flashes being detected (Orville 1994; Orville and Silver 1997). Results from this study do not exclude this explanation but suggest that the maximum is caused by the dominance of cold season lightning activity over this region [section 3a(3); Fig. 9a]. As is discussed in the section below, cold season lightning activity is usually characterized by a high percentage of positive lightning.

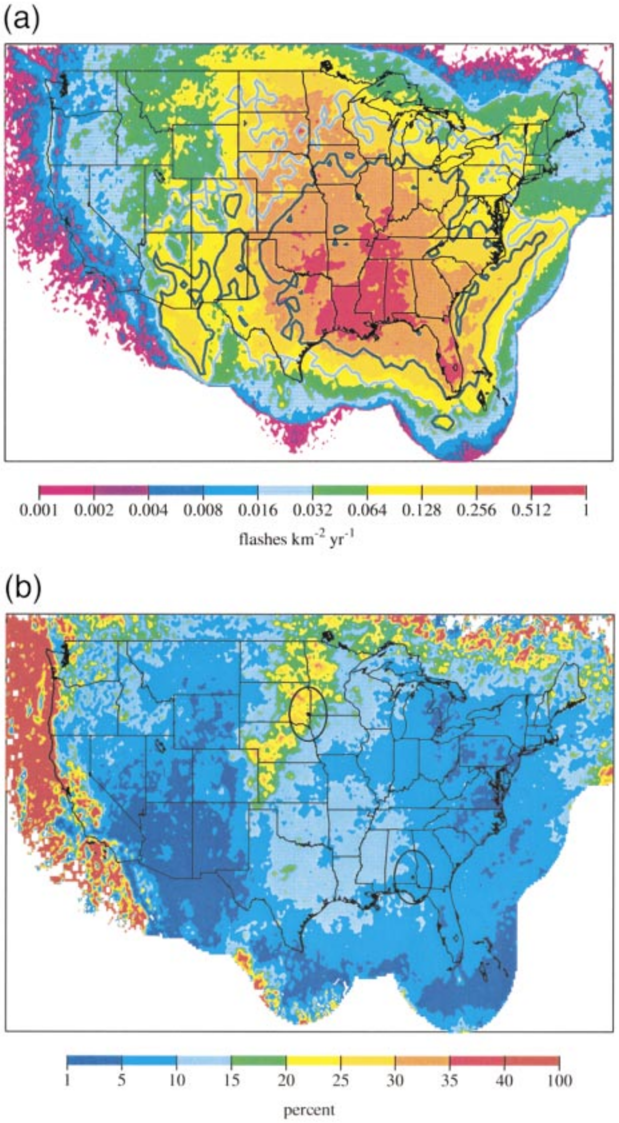


FIG. 11. Positive and negative lightning from 1995 to 1999. (a) Fill contours show average annual positive flash density. National maximum of 1.0 flashes km^{-2} yr^{-1} occurred in southern Mississippi. Line contours show average annual negative flash density. Light and dark gray line contours show flash densities of 1.28 and 2.56 flashes km^{-2} yr^{-1}, respectively. National maximum of 13.9 flashes km^{-2} yr^{-1} occurred near Tampa, FL. Line contours were degraded from a 0.2° grid to a 0.6° grid. Flash densities were not modified in order to account for detection efficiency. (b) Percentage of positive lightning with respect to all CG lightning. Locations of the Sioux Falls and Fort Rucker case study areas are shown. Note that positive flashes with peak current less than 10 kA may be false detections of intracloud lightning and were excluded from these and all other analyses, except for Fig. 3.

2) ANNUAL DISTRIBUTIONS

Most studies that have examined annual or seasonal distributions of lightning by polarity have shown that a larger fraction of negative lightning is produced during summer than positive lightning (Orville et al. 1987; Clodman and Chisholm 1996; Orville and Silver 1997; Orville and Huffines 1999). This result is confirmed here. Over most of the contiguous United States, a larger fraction of negative lightning was produced during summer than positive lightning (Figs. 12a,b). Consequently, the percentage of positive lightning over the entire NLDN varied between 5% in August and 18% in December (Fig. 12c). The percentage of positive lightning varied in a similar manner over Fort Rucker (Fig. 12c) and is examined in section 4b.

Over a contiguous area in the north-central United States and more isolated areas in the western United States, a larger fraction of positive lightning was produced during summer than negative lightning (Fig. 12a). Negative values over the north-central United States were caused by the approximate one-month lag in negative lightning activity (Fig. 12d). More specifically, negative values were caused by dominant production of positive lightning during June–August and significant production of negative lightning during September—as seen over a 1.0° × 1.0° subsection of the Sioux Falls case study area where 77% of positive lightning was produced during June–August compared to 63% for negative lightning and 23% of negative lightning was produced during September compared to 9% for positive lightning (Fig. 12d). The annual distributions of positive and negative lightning over Sioux Falls are examined further in section 4a. The collocation of negative values over the north-central United States in Fig. 12a with a maximum in the percentage of positive lightning in Fig. 11b is discussed in section 5. Negative values over the western United States show no geographical consistency and may reflect the lack of many years of data.

3) SUMMERTIME DIURNAL DISTRIBUTIONS

In this section, the diurnal distributions of positive and negative lightning are examined, first by comparing

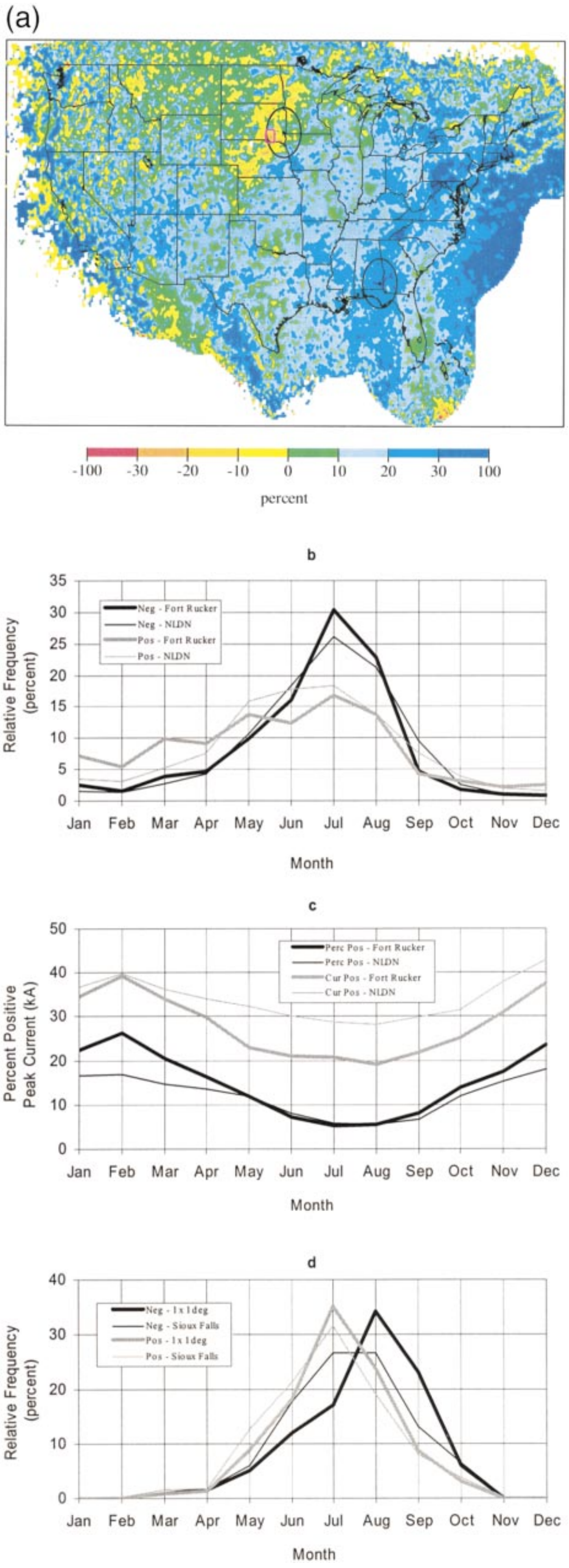


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FIG. 12. Annual distributions of positive and negative lightning from 1995 to 1999. (a) Difference in the percentage of positive and negative lightning produced during summer (Jun–Aug). Positive values indicate that a greater fraction of negative lightning was produced during summer. Locations of the Sioux Falls and Fort Rucker case study areas are shown. The magenta box shows the 1.0° × 1.0° area examined in Fig. 12d. (b) Normalized monthly positive and negative flash density for all flashes detected by the NLDN and for the Fort Rucker case study area. (c) Monthly percentage of positive lightning and mean positive peak current for all flashes detected by the NLDN and for the Fort Rucker case study area. (d) Normalized monthly positive and negative flash density for the Sioux Falls case study area and for the 1.0° × 1.0° area shown in Fig. 12a.

the diurnal cycles of positive and negative lightning over the contiguous United States (Fig. 13a), and then by comparing time series of 15-min positive and negative flash density over the Fort Rucker and Sioux Falls case study areas (Figs. 13b–d). Figure 13a must be interpreted with care because normalized amplitude and phase information is physically significant only if the diurnal cycle accurately describes the time series of 15-min positive and negative flash density. Examination of Figs. 10a,b suggests that normalized amplitude and phase information is reasonably accurate over most of the contiguous United States, with the possible exception of the eastern Great Plains and upper Midwest, where normalized amplitudes are less than 60.

Figure 13a shows that the diurnal cycle of positive lightning lagged the diurnal cycle of negative lightning by up to 2 h over most of the contiguous United States, including the Fort Rucker case study area (Fig. 13b). The tendency for positive lightning activity to peak after negative lightning activity has been observed in nonsevere thunderstorms (Fuquay 1982), severe storms (Kane 1991), and MCSs (Rutledge and MacGorman 1988). This behavior appears to be resolved in this analysis.

The diurnal cycle of positive lightning peaked up to several hours prior to the maximum in the diurnal cycle of negative lightning over an area in the north-central United States extending from the Colorado–Kansas border to western Minnesota (Fig. 13a). The diurnal cycle of positive lightning also exhibits larger normalized amplitudes over this area. Despite the low normalized amplitudes over northern portions of this area (Fig. 10b), these results are physically significant: positive lightning activity over the Sioux Falls case study area peaked several hours before negative lightning activity and exhibited a more pronounced diurnal cycle (Fig. 13c). Differences in the diurnal distributions of positive and negative lightning over Sioux Falls are investigated in section 4a. The collocation of lightning signals over the north-central United States is discussed in section 5.

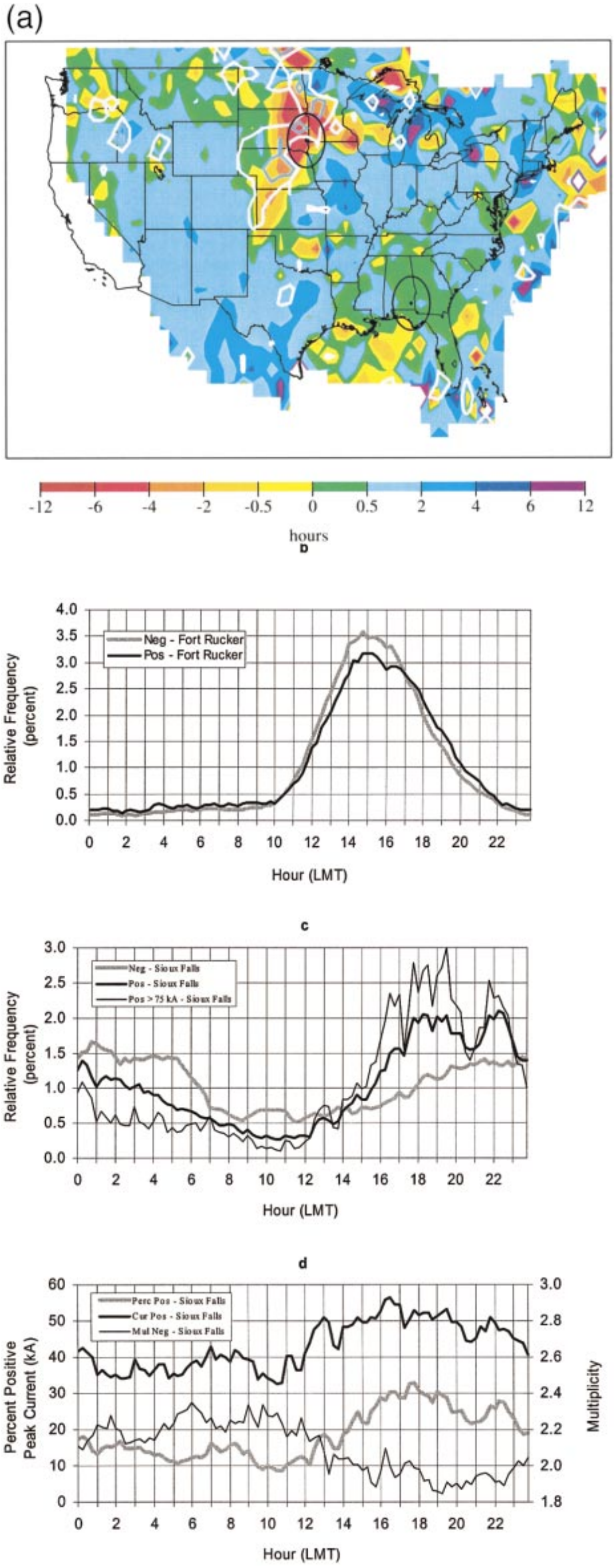

FIG. 13. Summertime diurnal distributions of positive and negative lightning from Jun–Aug 1995–99. (a) Comparison of the diurnal cycles of positive and negative lightning. Fill contours show the temporal lag between the diurnal cycles of positive and negative lightning. Positive values indicate that the time of maximum frequency

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for positive lightning occurred after the time of maximum frequency for negative lightning. Line contours show the difference in the normalized amplitude between the diurnal cycles of positive and negative lightning. Light and dark gray line contours indicate that the normalized amplitude of positive lightning is 20 and 40 greater than the normalized amplitude of negative lightning, respectively. This analysis is based on a 1.0° × 1.0° grid and on time series of 15-min positive and negative flash density. Locations of the Sioux Falls and Fort Rucker case study areas are shown. (b) Normalized hourly positive and negative flash density for the Fort Rucker case study area. (c) Normalized hourly flash density of positive flashes, large peak current positive flashes (greater than 75 kA), and negative flashes for the Sioux Falls case study area. (d) Hourly percentage of positive lightning, mean positive peak current, and mean negative multiplicity for the Sioux Falls case study area.

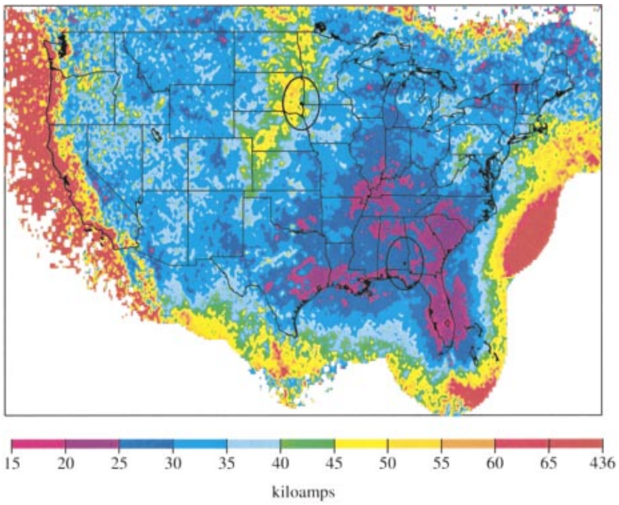

FIG. 14. Positive mean peak current from 1995 to 1999. Locations of the Sioux Falls and Fort Rucker case study areas are shown.

4) ANNUAL POSITIVE MEAN PEAK CURRENT

Annual positive mean peak currents ranged between 15 and 60 kA (Fig. 14) over areas within the 80% detection efficiency contour (Fig. 2). Within this contour, maximum peak currents are found over an area in the north-central United States (values between 40 and 60 kA) and minimum peak currents are found over the southeastern United States (values less than 25 kA). The maximum located over the north-central United States is collocated with a maximum in the percentage of positive lightning in Fig. 11b and with negative values in Figs. 12a and 13a. These signals are discussed in section 5. The low mean peak currents over the southeastern United States are somewhat expected considering the large number of low peak current positive flashes detected over this region (Fig. 3). Despite the removal of positive flashes with peak currents less than 10 kA, peak current distributions for positive lightning are still strongly weighted toward low values. Outside of the 80% detection efficiency contour, mean peak currents generally increase due to fewer low peak current flashes being detected, except along the Pacific coast where elevated values appear to be caused by the dominance of cold season lightning [section 3a(3)]. Cold season lightning is characterized by large positive peak currents (Fig. 12c).

4. Case studies

In this section, the production of positive and negative lightning is examined over the Sioux Falls, South Dakota, and Fort Rucker, Alabama, case study areas (Fig. 1). Annual and summertime diurnal distributions of positive and negative lightning from 1995 to 1999 are described first. Radar–lightning analyses of 46 cases from 1996 are then used to interpret these distributions. These 46 cases are considered to be representative of lightning activity over the two case study areas because 1) the 21 cases over Sioux Falls produced roughly 75% of positive and negative lightning during 1996, 2) the 25 cases over Fort Rucker produced 55% (35%) of positive (negative) lightning during 1996, and 3) annual and summertime diurnal distributions from 1996 (not shown) are similar to those distributions from 1995 to 1999 (Figs. 12b–d and 13b–d).

a. Sioux Falls, South Dakota, case study

In section 3b, a number of lightning signals were found over an area in the north-central United States extending from the Colorado–Kansas border to western Minnesota, which includes the Sioux Falls case study area. These signals are

1) maximum in the percentage of positive lightning (Fig. 11b);
2) negative values in Fig. 12a, indicating the approximate one-month lag in negative lightning activity and significant negative lightning production during September (Fig. 12d);
3) negative values in Fig. 13a, indicating that the maximum of the diurnal cycle of positive lightning preceded that of negative lightning by up to several hours during summer (Fig. 13c);
4) line contours in Fig. 13a, indicating that positive lightning exhibited a more pronounced diurnal cycle than negative lightning (Fig. 13c); and
5) maximum in positive mean peak current (Fig. 14).

Other lightning signals observed over Sioux Falls, not discussed in Sec. 3b, are

6) maxima in the percentage of positive lightning and positive mean peak current during summer in the late afternoon and early evening (Fig. 13d); and
7) minimum in negative mean multiplicity during summer in the evening (Fig. 13d).

Radar–lightning analyses of the 21 cases over Sioux Falls are used to interpret these signals. To investigate the summertime diurnal variations seen in Figs. 13c,d, the 21 cases were partitioned into afternoon–evening cases (12) and nocturnal cases (9) based on the time of maximum positive lightning production. Maximum positive lightning production for afternoon–evening cases occurred between 1100 and 2300 LMT and for nocturnal cases, between 2300 and 1100 LMT.

Lightning production by afternoon–evening and nocturnal cases was substantially different. Afternoon–evening cases produced 53% of positive lightning over the Sioux Falls case study area during 1996 (but only 27% of negative lightning) and were characterized by a high percentage of positive lightning (32%), large positive mean peak current (54 kA), and low negative mean multiplicity (2.04; Table 2). At the time of maximum positive lightning production, afternoon–evening cases were characterized by a higher percentage of positive

TABLE 2. Cloud-to-ground lightning statistics for the Sioux Falls, SD, case study area: annual statistics for 1996, statistics for all 21 cases sampled from 1996, and statistics for afternoon–evening cases (12) and nocturnal cases (9), including statistics for the 15-min period of maximum positive lightning production (MPP). Peak current values are given in kiloamps.

			Positive			Negative		
Event type	Total flash count	Percent positive	Flash count	Mean peak current	Mean multiplicity	Flash count	Mean peak current	Mean multiplicity
1996	234 698	19.1	44 647	43.8	1.12	189 051	24.1	2.19
All 21 cases	173 640	19.8	34 424	44.9	1.12	139 216	23.6	2.23
Aft–evening (12)	73 656	32.2	23 720	53.9	1.14	49 936	23.5	2.04
MPP	3391	63.4	2151	60.5	1.15	1644	18.9	1.47
Nocturnal (9)	99 984	10.7	10 704	25.1	1.09	89 280	23.7	2.33
MPP	3960	16.0	635	24.4	1.10	3325	22.0	2.33

lightning (63%), larger positive mean peak current (61 kA), and lower negative mean multiplicity (1.47). In contrast, nocturnal cases produced 47% of negative lightning (but only 25% of positive lightning) and were characterized by a low percentage of positive lightning (11%), small positive mean peak current (25 kA), and high negative mean multiplicity (2.33). These differences are consistent with the summertime diurnal distributions in Figs. 13c,d and the annual distributions in Fig. 12d, noting that 6 of 12 afternoon–evening cases occurred by the end of June, versus 2 of 9 for nocturnal events (Table 3). Below, occurrences of PSD storms and bipolar lightning patterns in afternoon–evening and nocturnal cases are compared. The morphologies of afternoon–evening and nocturnal cases are also compared.

PSD storms were found in afternoon–evening and nocturnal cases at the time of maximum positive lightning production. However, PSD storms were much more frequent in afternoon–evening cases. PSD storms were identified in 11 of 12 afternoon–evening cases with a total of 38 PSD storms identified (Table 3). In contrast, PSD storms were identified in just 2 of 9 nocturnal cases with a total of 5 PSD storms identified. The lightning characteristics of afternoon–evening cases (high percentage of positive lightning, high positive flash rate, large positive peak current, and low negative multiplicity) are attributed to PSD storms, since lightning production by afternoon–evening cases was dominated by PSD storms at the time of maximum positive lightning production, as is seen in Fig. 5a, for example. PSD storms were also found to be the primary producer of lightning by afternoon–evening cases, especially positive lightning, when all CG maps were examined. The lightning characteristics mentioned above have been observed in other PSD storms (e.g., Seimon 1993; Stolzenburg 1994).

Bipolar lightning patterns were identified in 3 of 9 afternoon–evening MCS cases and in 4 of 6 nocturnal MCS cases (Table 3). A smaller fraction of afternoon–evening MCS cases exhibited bipolar lightning because afternoon–evening MCS cases were usually east of the Sioux Falls case study area when they developed areally extensive stratiform regions. Positive lightning production by bipolar lightning was small relative to positive lightning production by PSD storms because bipolar lightning was observed 7 times versus 43 times for PSD storms (Table 3), and bipolar lightning has low flash densities compared to PSD storms (Stolzenburg 1994; cf. Figs. 5a and 5b).

Afternoon–evening and nocturnal cases both exhibited a broad range of convective structures at the time of maximum positive lightning production (Table 3). However, afternoon–evening cases frequently exhibited isolated convection (i.e., isolated cells and noncontiguous lines) and linear organization. Nocturnal cases, on the other hand, exhibited linear and cluster organization in roughly equal portions and were classified as MCSs more often. From the time of maximum positive light-

TABLE 3. Timing, morphology, and lightning characteristics of the 12 afternoon–evening cases and 9 nocturnal cases sampled over the Sioux Falls case study area from 1996. Morphology was determined at two times for each case, at the time of maximum positive lightning production (MPP) and at the maximum areal extent (MAE).

Timing/characteristics	Afternoon–evening cases (12)	Nocturnal cases (9)
Occurence by month	Mar (1), May (1), Jun (4), Jul (1), Aug (3), Sep (1), Oct (1)	Jun (2), Jul (4), Aug (3), Sep (1)
Morphology at MPP	Isolated cells (2) Noncontiguous line (6) Contiguous line (2) Linear MCS (2)	Noncontiguous line (3) Contiguous line (1) Cluster of cells (2) Linear MCS (1) Cluster MCS (2)
Morphology at MAE	9 of 12 cases classified as MCSs (7 linear MCSs)	6 of 9 cases classified as MCSs (5 cluster MCSs)
Positive strike	11 of 12 cases contained	2 of 9 cases contained
Dominated storms	PSD storms at MPP (38 identified)	PSD storms at MPP (5 identified)
Bipolar lightning	3 of 9 MCSs exhibited bipolar lightning	4 of 6 MCSs exhibited bipolar lightning

TABLE 4. Timing, morphology, and lightning characteristics of the 12 MCS cases and 13 non-MCS cases sampled over the Fort Rucker case study area from 1996. Morphology was determined at two times for each case, at the time of maximum positive lightning production (MPP) and at the maximum areal extent (MAE).

Timing/characteristics	MCS cases (12)	Non-MCS cases (13)
Occurrence by month	All cases occurred between Nov and May	All cases occurred between Apr and Sep
Occurrence by time of day	No preferred timing	Strong diurnal variation (maximum lightning activity at 1500 LMT)
Morphology at MPP	Linear MCS (10) Cluster MCS (2)	Isolated cells (4) Noncontiguous line (5) Cluster of cells (1) Contiguous line (3)
Morphology at MAE	Same as MPP for all cases	Same as MPP for 12 of 13 cases 1 case classified as cluster MCS
Positive strike Dominated storms	0 of 12 case contained PSD storms at MPP	1 of 13 case contained PSD storms at MPP
Bipolar lightning	11 of 12 MCSs exhibited bipolar lightning	1 MCS exhibited bipolar lightning

ning production to the time of maximum areal extent, 7 of 10 afternoon–evening cases and 3 of 6 nocturnal cases developed into MCSs. As at the time of maximum positive lightning production, most afternoon–evening MCS cases exhibited linear organization, while nocturnal MCS cases exhibited linear and cluster organization. These results indicate that positive lightning was produced primarily by isolated storms and convective lines in various stages of MCS development. Negative lightning was produced by more mature convective systems arranged in lines or clusters.

The plot of hourly flash density for large peak current positive lightning (greater than 75 kA; Fig. 13c) is inconsistent with the same plot published in Lyons et al. (1998) as Fig. 5b. Figure 13c shows maximum flash densities around 1900 LMT; Fig. 5b shows maximum flash densities around 0200 central standard time. While these two plots show the same statistic analyzed over different areas (Sioux Falls case study area vs the central United States from 30° to 50°N and from 88° to 110°W), greater agreement is expected since Sioux Falls is located within the central United States maximum for large peak current positive flash density extending from the Colorado–Kansas border to western Minnesota (Fig. 8 in Lyons et al. 1998). This discrepancy is noted because thunderstorm type is strongly controlled by time of day over the central United States. Severe storm activity peaks a few hours prior to sunset (Kelly et al. 1978, 1985), while MCS activity peaks around 0200 LMT (McAnelly and Cotton 1989).

The diurnal variation in negative mean multiplicity seen in Fig. 13d may be related to variations in multiplicity observed during the life cycle of mesoscale convective complexes (MCCs). Goodman and MacGorman (1986) report that mean multiplicity for all CG flashes increases substantially from first storms to MCC maturity. Since Goodman and MacGorman do not distinguish between positive and negative polarity lightning, their result may reflect an increase in negative multiplicity and/or a decrease in the percentage of positive lightning during MCC development (noting that positive flashes usually have only one return stroke; Table 2).

b. *Fort Rucker, Alabama, case study*

The following lightning signals are observed over the Fort Rucker case study area:

1) a larger fraction of negative lightning was produced during summer than positive lightning (Fig. 12b);
2) maxima in the percentage of positive lightning and positive mean peak current during the cold season (Fig. 12c); and
3) positive and negative lightning activity peaked in the afternoon during summer with positive lightning activity lagging negative lightning activity by roughly 30 minutes (Fig. 13b).

Radar–lightning analyses of the 25 cases over Sioux Falls are used to interpret these signals. To investigate the annual variations seen in Figs. 12b,c, the 25 cases were partitioned into those cases classified as MCSs (12) and those cases not classified as MCSs (i.e., non-MCSs; 13) at the time of maximum positive lightning production.

MCS cases and non-MCS cases were substantially different in time of occurrence and lightning production. First, MCS cases occurred between November and May, while non-MCS cases occurred between April and September (Table 4). Second, lightning activity in MCS cases exhibited no significant diurnal variations, while lightning activity in non-MCS cases exhibited a strong diurnal cycle with an afternoon maximum. And third, MCS cases were characterized by a high percentage of positive lightning (23%) and large positive mean peak current (35 kA), while non-MCS cases were characterized by a low percentage of positive lightning (11%) and small positive mean peak current (17 kA; Table 5). These results are consistent with the annual distributions in Figs. 12b,c, and the summertime diurnal distributions in Fig. 13b.

Bipolar lightning patterns were observed in 11 of 12

TABLE 5. Cloud-to-ground lightning statistics for the Fort Rucker, AL, case study area: annual statistics for 1996, statistics for all 25 cases sampled from 1996, and statistics for cases classified as MCSs (12) and cases not classified as MCSs (i.e., non-MCSs; 13). Case classification was determined at the time of maximum positive lightning production. Peak current values are given in kiloamps.

			Positive			Negative		
Event type	Total count ($\times 10^3$)	Percent positive	Flash count ($\times 10^3$)	Mean peak current	Mean multiplicity	Flash count ($\times 10^3$)	Mean peak current	Mean multiplicity
1996	635	10.8	68	25.5	1.11	567	26.9	2.34
All 25 cases	229	16.5	38	28.9	1.11	191	27.1	2.33
MCSs (12)	111	22.5	25	35.2	1.11	86	28.5	2.19
Non-MCSs (13)	119	11.0	13	16.9	1.11	105	25.9	2.44

MCS cases and in the single non-MCS case to develop into an MCS (Table 4). Positive lightning production by stratiform regions was appreciable, since most MCSs were mature and exhibiting bipolar lightning as they moved over the Fort Rucker case study area, generally from west to east. Positive lightning from convective and stratiform regions were not compared, so the source of large peak current positive lightning in the MCSs studied is not known.

Results from this section indicate that positive and negative lightning was produced throughout the year over Fort Rucker, by diurnally forced convection during the warm season and by MCSs with areally extensive stratiform regions during the cold season. These two storm types exhibited significantly different lightning characteristics: diurnally forced storms (MCSs) were characterized by a low (high) percentage positive lightning and small (large) positive mean peak current. Results from the Fort Rucker case study may be applicable to larger areas along the Gulf Coast considering the consistent lightning behavior over this region (Figs. 7; 8a,b; 9a; 10b; 11a,b; 13a; 14). However, caution should be used since differences in positive and negative lightning production are more pronounced over the Fort Rucker case study area than over other areas along the Gulf Coast (Fig. 12a).

5. Conclusions

The spatial and temporal distributions of cloud-to-ground (CG) lightning were examined over the contiguous United States from 1995 to 1999 using data from the National Lightning Detection Network. In addition, the production of positive and negative CG lightning was examined over two case study areas in the north-central United States (Sioux Falls, South Dakota) and along the Gulf Coast (Fort Rucker, Alabama). Case studies include radar–lightning analyses of significant lightning episodes from 1996. The main findings of this study are, in the general order of presentation, as follows.

1) Large populations of positive flashes with low peak currents (less than 10 kA) were detected over localized areas in the southeastern United States. These flashes accounted for more than 50% of all positive flashes detected over these areas. Low peak current positive flashes may be false detections of intracloud lightning and were not analyzed in this study.
2) Maximum flash densities and lightning days occurred over coastal regions in the southeastern United States. Other prominent maximum were seen over the southern Rocky Mountains and adjacent High Plains and, outside the national borders, over the Gulf Stream, Cuba, and the Sierra Madre in northern Mexico.
3) Throughout the contiguous United States, roughly 10% of the days with lightning produced 50% of lightning.
4) The majority of lightning was produced during summer (June–August) throughout the contiguous United States, except over the south-central United States and along and near the Pacific coast. Lightning activity occurred throughout the year over the south-central United States and was limited to the cold season along and near the Pacific coast.
5) Summertime lightning activity over the western and eastern United States exhibited a diurnal cycle with a well-defined maximum in the afternoon to early evening. The diurnal cycle was more pronounced over coastal regions in the southeastern and eastern United States and parts of the mountainous west and adjacent High Plains.
6) Summertime lightning activity over the central United States was complex with significant longitudinal variations in daily activity and a tendency to occur at night. Lightning activity along the eastern slope of the Rocky Mountains and adjacent High Plains exhibited a strong diurnal cycle with maximum frequencies in the afternoon to early evening. Over the eastern Great Plains and upper Midwest, lightning activity was possible throughout the day but was most frequent at night. Over the lower Midwest, summertime lightning activity exhibited a diurnal cycle with an afternoon to early evening maximum but with some activity at night.
7) Throughout the contiguous United States, a larger fraction of negative lightning was produced during summer than positive lightning. The diurnal cycle of positive lightning also lagged the diurnal cycle of negative lightning by up to two hours during summer.

8) The main exception to the above occurred over an area in the north-central United States extending from the Colorado–Kansas border to western Minnesota, which includes the Sioux Falls case study area. Positive lightning activity peaked during midsummer versus late summer for negative lightning activity. In addition, the diurnal cycle of positive lightning peaked up to several hours prior to the maximum in the diurnal cycle of negative lightning, and positive lightning exhibited a more pronounced diurnal cycle. This area was also characterized by maxima in the percentage of positive lightning and positive mean peak current.
9) The maximum in the percentage of positive lightning over the north-central United States was caused by a dramatic increase in positive flash density to the east of the Rocky Mountains and a local minimum in negative flash density over the north-central United States.
10) Over the Sioux Falls case study area, positive lightning tended to be produced during summer in the hours around sunset by isolated storms and convective lines in various stages of mesoscale convective system (MCS) development. These convective events usually contained one or more storms that were positive strike dominated (PSD). PSD storms were characterized by a high percentage of positive lightning, high positive flash rate (the two defining characteristics of PSD storms), large positive mean peak current, and low negative mean multiplicity. PSD storms were found to be the primary producer of lightning, especially positive lightning, in these afternoon and evening convective events. Negative lightning tended to be produced later in the summer and throughout the night by more mature convective systems that were arranged in lines or clusters.
11) Over the Fort Rucker case study area, positive and negative lightning was produced throughout the year by diurnally forced convection during the warm season and by MCSs with areally extensive stratiform regions during the cold season. Diurnally forced storms (MCSs) were characterized by a low (high) percentage of positive lightning and small (large) positive mean peak current.

The most significant findings of this study are the local minimum in negative flash density over the north-central United States, the occurrence of and lightning production by PSD storms over the Sioux Falls case study area, and the distinctly different regimes for positive and negative lightning over the Sioux Falls case study area. These findings can be used to explain the lightning signals seen in Figs. 11b, 12a, 13a, and 14 over an area in the north-central United States extending from the Colorado–Kansas border to western Minnesota.

The local minimum in negative flash density over the north-central United States (Fig. 11a) delineates an area downstream of most topographically forced thunderstorms and upstream from well-developed MCSs. The maximum in negative flash density along the eastern slope of the Rocky Mountains and minimum farther east suggests that most topographically forced storms decay within a few hundred kilometers of their formation zones. The eastern boundary of the negative flash density minimum (2.56 flashes $\mathrm{km}^{-2}\ \mathrm{yr}^{-1}$) corresponds with the centroid of MCC activity and the 15°C surface isodrosotherm during July–August (Velasco and Fritsch 1987). In addition to its role in the upscale development of MCSs, the position of abundant surface moisture is mentioned because the dominant polarity of severe storms over the central United States may be linked to spatial variations in equivalent potential temperature (θ_e). In their examination of three tornadic outbreaks, Smith et al. (2000) found that PSD storms occur in regions of strong surface θ_e gradient and upstream of θ_e maximum, and become negative strike dominated when they move downstream of θ_e maximum.

Maxima in the percentage of positive lightning and positive mean peak current over the north-central United States (Figs. 11b and 14, respectively) can now be seen to delineate an area where negative lightning activity is at a minimum and PSD storms are the primary producer of positive lightning. The lack of topographically forced storms and well-developed MCSs over this area allows for the distinct lightning characteristics of PSD storms to dominate and be easily observed. Boccippio et al. (2001) use similar reasoning to explain the maximum in the ratio of intracloud to cloud-to-ground lightning (IC:CG ratio) located over the north-central United States (ratios between 4 and 10). Since IC:CG ratio is correlated with updraft strength (Boccippio et al. 2001), a maximum in IC:CG ratio can be expected over regions where vigorous and possibly severe storms dominate lightning production.

Negative values over the north-central United States in Figs. 12a and 13a reflect distinct seasonal and diurnal differences in positive and negative lightning production. Positive lightning is produced primarily during summer in the hours around sunset, while negative lightning is produced later in the summer and throughout the night (Figs. 12d and 13c; sunset times over the Sioux Falls case study area range between 1850 and 2130 central standard time during the months of July–August). Considering the elevated production of positive lightning in some severe storms and the elevated production of negative lightning in well-developed MCSs [see Stolzenburg (1994) and Holle et al. (1994), respectively], the seasonal and diurnal differences between positive and negative lightning over the north-central United States are consistent with the tendency for severe storms to occur during late spring and early summer in the late afternoon and early evening (Kelly et al. 1978, 1985) and the tendency for MCSs to occur later in the summer and maturate at night (Velasco and Fritsch 1987). The more pronounced diurnal cycle of positive lightning (Figs. 13a,c) is consistent with the fact that the timing of severe storms is generally constrained to the late afternoon and early evening (Kelly et al. 1978, 1985), while the timing of MCSs is more variably associated with the nocturnal period (McAnelly and Cotton 1989).

More research is needed to substantiate the statements made above, particularly those referring to PSD storms, since radar–lightning analyses over the Sioux Falls case study area encompassed one year only. Lightning budgets should be performed in a more quantitative manner, over longer periods of time, and over other areas to determine if PSD storms are indeed the primary cause for the lightning signals over the north-central United States. The spatial and temporal distributions of PSD storms should be documented since these storms occur throughout the Great Plains and upper Midwest (Knapp 1994; Smith et al. 2000). Finally, the relationship between PSD storms and severe weather should be studied further since PSD storms produce large hail and/or tornadoes in most documented cases. The identification of PSD storms in real time may have utility as a forecast technique for severe weather over parts of the central United States.

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