The Influence of the El Niño–Southern Oscillation on Cloud-to-Ground Lightning Activity along the Gulf Coast. Part I: Lightning Climatology

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ABSTRACT

Cloud-to-ground (CG) lightning flashes from the National Lightning Detection Network are analyzed to determine if the El Niño–Southern Oscillation (ENSO) cycle influences lighting activity along the Gulf Coast region. First, an updated climatology of lightning was developed for the region. Flash density maps are constructed from an 8-yr dataset (1995–2002) and compared with past lightning climatologies. Second, lightning variability is compared with the phases of ENSO. Winter lightning distributions are compared with one published study of ENSO and lightning days in the Southeast.

Flash density patterns are, overall, consistent with past U.S. lightning climatology. However, the peak flash density for the annual mean was less than observed in previous climatologies, which could be due to the disproportionately large percentage of cool ENSO periods compared to previous lightning climatologies.

The highest annual lightning counts were observed in 1997, which consisted of mostly warm ENSO seasons; the 1997–98 El Niño was one of the strongest on record. The lowest lightning counts were observed in 2000, which had mostly cool or neutral phases of ENSO including the lowest Niño-3.4 anomaly of the study period. Analysis of winter season lightning flash densities substantiated the role of the ENSO cycle in winter season lightning fluctuations. Winter lightning activity increased dramatically during the 1997–98 El Niño. The lowest winter flash densities are associated with cool ENSO phases. Although 8 yr is inadequate to establish a long-term pattern, results indicate that ENSO influences lightning and that further study is warranted. As more years of lightning data are acquired, a more complete climatology can be developed.

1. Introduction

Cloud-to-ground lightning is a substantial threat to lives, commercial activity, and personal property (Curran et al. 2000). An improved understanding of lightning distributions and knowledge of the factors that influence convection and subsequent lightning is vital to better prediction and reduction of lightning hazards. Zajac and Weaver (2002) and Zajac et al. (2002) outlined several important “climate controls” that influence lightning distributions including: latitude, continentality, moisture availability, ocean currents, and terrain. The El Niño–Southern Oscillation (ENSO) phenomenon exerts a profound influence on global weather and climate (Philander 1990; Trenberth 1997; McPhaden 2002). In North America, the ENSO extremes lead to a displacement or disruption of the jet stream (Ropelewski and Halpert 1986; Green et al. 1997). For example, during a warm episode (El Niño) winter, the subtropical jet stream shifts southward, displaces storm tracks to the southern United States and enhances moisture flow from the Pacific, and leads to a stormier Gulf Coast.

Although ENSO has been linked to many weather phenomena and hazards, little research has been published on the possible relationship between ENSO and
lightning. Does the ENSO cycle influence lightning through direct or indirect action on the aforementioned climate controls or through other factors? Only one published study is known to specifically examine the ENSO–lightning connection over the Gulf Coast. Goodman et al. (2000) examined winter season [December–February (DJF)] lightning data over the Southeast and found a 100%–200% increases in the frequency of lightning days along the Gulf Coast and adjacent waters during the intense 1997–98 ENSO event. While the study is well constructed, it focuses on lightning or thunderstorm days (based on a 0.5° gridded data), rather than flash density variability. In addition to surface data, Goodman et al. (2000) incorporated intracloud and CG lightning from the Lightning Imaging Sensor (LIS) carried on board the Tropical Rainfall Measuring Mission (TRMM) satellite (Christian et al. 1999). As the satellite is only over the Gulf Coast region 3–4 times day$^{-1}$, its data cannot be used exclusively (Christian et al. 1999). Using data from the TRMM Precipitation Radar and the LIS, Durden et al. (2004) examined the interannual variability of average lightning and radar reflectivity at 6 km. They found that principal component time series of anomalies of lightning or thunderstorm days (based on a 0.5° gridded data), rather than flash density variability. In addition to surface data, Goodman et al. (2000) incorporated intracloud and CG lightning from the Lightning Imaging Sensor (LIS) carried on board the Tropical Rainfall Measuring Mission (TRMM) satellite (Christian et al. 1999). As the satellite is only over the Gulf Coast region 3–4 times day$^{-1}$, its data cannot be used exclusively (Christian et al. 1999). Using data from the TRMM Precipitation Radar and the LIS, Durden et al. (2004) examined the interannual variability of average lightning and radar reflectivity at 6 km. They found that principal component time series of anomalies of lightning and upper-level reflectivity are highly correlated with the Southern Oscillation index (SOI), and hence, El Niño. The time series suggests that El Niño plays a smaller role in lightning anomaly than precipitation anomaly. Their results were based on quarterly averages sampled at 5° grid spacing across the tropics for December 1997–May 2001.

This study documents lightning distribution on a much finer (2.5 km) scale grid at monthly, seasonal, and annual scales and examines how these distributions vary under ENSO extremes. Updating of the lightning climatology is also valuable to forecasters who are using lightning climatologies to initialize daily lightning threat maps (Watson et al. 2005; Lambert et al. 2006).

### a. Lightning climatologies

The National Lightning Detection Network (NLDN), owned and operated by Vaisala, Inc., detects cloud-to-ground (CG) lightning flashes over the contiguous United States and, with decreasing efficiency, over adjacent waters (Cummins et al. 1998). Cloud-to-ground lightning is less frequent but more energetic than intracloud lightning, which is estimated to be 3–9 times more frequent than CG lightning in the contiguous United States (Boccippio et al. 2001). The longest NLDN-based lightning climatologies in the United States have found that the Gulf Coast has the highest flash density with the peak over central Florida (Orville and Silver 1997; Orville and Huffines 1999, 2001; Orville et al. 2002). The 10-yr analysis by Orville and Huffines (2001) was constructed with a spatial grid of 0.2°, approximately 20 km, from which, they determined that greater than 9 flashes km$^{-2}$ yr$^{-1}$ occur across central Florida. Similarly high values occur between Lake Okeechobee and the Atlantic. Relatively high values occur near Houston and New Orleans as well. Zajac and Rutledge (2001), a national climatology with data since the 1995 NLDN upgrade, extends the maximum plotted value to 14.5 flashes km$^{-2}$ yr$^{-1}$. Extending the scale helps pinpoint the locations of high-end CG flash density in Florida and southern Mississippi. However, Zajac and Rutledge’s next-highest category spans from 5.12 to 10.24. This could be misleading because such a broad class masks local variations. This example demonstrates that the selection of classification scheme must be carefully considered.

Warm-season CG lightning distributions over Florida is shaped by prevailing low-level wind velocity, time of day, and coastline complexity, principally because these factors shape sea and land breezes, the primary mechanism for summertime thunderstorms over the state (Lopez and Holle 1987; Reap 1994; Watson and Holle 1996; Hodanish et al. 1997; Lericos et al. 2002; Stroupe 2003). Sea and land breezes generate thunderstorm activity almost daily over Florida during the summer, but their strength and penetration extent depend on prevailing low-level winds. Lericos et al. (2002) found that with large-scale flow from the southeast, the east coast sea breeze and associated lightning are relatively weak while the west coast sea breeze is strong and remains near the coastline, producing more lightning near Tampa. Conversely, with southwesterly large-scale flow, little convection occurs along the west coast, but major lightning activity occurs along the east coast. Stroupe (2003) analyzed lightning data on a 2.5 km × 2.5 km grid over the northern Gulf Coast (from Alabama to east Texas) strong maxima near Biloxi, Mississippi, and large metropolitan areas such as Houston, Texas; Lake Charles and New Orleans, Louisiana; and Mobile, Alabama. Areas of relative maxima are attributed to topographically forced convergence zones, urban heat island effects, and possible impacts from pollution. Steiger et al. (2002) analyzed CG lightning in the Houston metropolitan area from 1989 to 2000 and found 45% more flashes than in the surrounding region. They speculated that this anomaly could be due to the urban heat circulations and heavy pollution. The effect of sea spray from the Gulf of Mexico and sea-breeze enhancements of convection were noted as potential factors. Steiger and Orville (2003) found peak
flash densities over the western side of the Lake Charles area and a heavily industrialized region of eastern Louisiana. These areas are small enough that urban heat is insufficient to alter circulations and the impact of the Gulf is limited; implicating pollution as the likely cause of this lightning anomaly. Smith et al. (2005) examined warm-season lightning over the northern Gulf Coast and found that lightning was closely influenced by the prevailing low-level synoptic flow. Most flashes occurred with southwest flow and the least with northeasterly flow. Wintertime distribution of lightning is less well known than the warm-season distribution. Based on data from 1986–95, Hodanish et al. (1997) found that average winter lightning over Florida was more reduced from the warm season and maxima are aligned in a northeast–southwest-banded pattern across the state. Hunter et al. (2001) examined seven case studies of winter lightning and frozen precipitation between 1994 and 1997. They found two patterns of lightning from what they termed “arctic front” or “migratory cyclones” phases. In the former phase, most CG lightning occurs within or near a subfreezing surface air mass and frozen precipitation that are associated with quasi-stationary arctic fronts. With migratory cyclones, CG flashes occur in the warm sector. Butts (2006) hypothesized that “enhanced” positive CG lightning (>25% positive CG lightning in a storm) indicated the potential for severe weather in cool-season tornadoes. Lightning climatologies have improved substantially in both quality and sophistication with the technological evolution of the NLDN and expansion of the lightning data archive. Satellite-based sensors record lightning of all varieties on a global scale (Christian et al. 1999, 2003). For an extensive, categorized list of lightning climatology studies the reader is referred to Zajac and Rutledge (2001). Additionally, a comprehensive list of lightning studies (both informal and formal) since the 1970s is available online (see Holle 2002).

### b. The ENSO index

The extremes of ENSO, termed El Niño and La Niña, encompass a wide range of climatic conditions (Philander 1990). It is useful to understand the relative strengths of ENSO events so as to compare them with each other and with the neutral state. The ENSO index used for this study is derived from direct SST measurements (Smith and Reynolds 2004). The oceanic Niño index (ONI) was formally defined as the “three-month average of sea surface temperature departures from normal” in the Niño-3.4 region of the Pacific (Department of Commerce 2003). Table 1 depicts warm and cold episodes from 1995 to 2002 based on the ONI. During that period, there were 23 warm episodes, 36 cool episodes, and 37 neutral episodes. Early 1995 was the end of a weak, short-lived El Niño. The winter of 1995–96 was a weak La Niña period. An extended cold anomaly period ran from July 1998 to early 2001. Two major warm episodes occurred, the strong 1997–98 El Niño, and another that began in the spring of 2002. The overall aim of the project is to increase knowledge and understanding concerning the influence of the ENSO cycle on lightning activity along the Gulf Coast. The results presented herein establish an updated pattern of lightning activity in the Gulf Coast region for January 1995–December 2002. A companion paper (Laing et al. 2008), examines the month-by-month correlations between lightning activity over the Gulf Coast and a concurrent 96-month series of sea surface temperature anomaly values from the equatorial Pacific.

### 2. Data and methodology

The study area is the Southeast and near-adjacent waters of the Gulf of Mexico. The region is geographically bounded by 33°–24°N, 79°–99°W (Fig. 1). The primary dataset for this study are CG lightning flash records detected in the study area by the NLDN over
an 8-yr period (January 1995–December 2002). The Air Force Combat Climatology Center acquired the raw NLDN data from Vaisala, Inc.

Records include location, date, time, polarity (positive or negative), signal strength (peak current), multiplicity (number of return strokes), and the number of detectors used to locate each flash. Each lightning record contains several measured attributes to include location, date, and time of individual flashes. Flash records were divided into 96-monthly files. To prepare the raw data for study, each monthly lightning file was imported into ArcMap GIS software [Environmental Systems Research Institute, Inc. (ESRI)] as a point feature layer, saved in ESRI shapefile format, and projected to a custom Albers equal area projection. Albers was selected for the projection because it preserves area, a key property when analyzing flashes per unit area. ESRI shapefiles are composed of a main file, an index file, and a dBase table, which contains feature attributes with one record per feature (Environmental Systems Research, Inc. 1998).

For analysis purposes and usability in ArcMap, flashes were assigned to a fine-resolution grid. This was accomplished by importing the dBase table component of each shape file into the S-Plus statistical package (Insightful Corporation 2003) and running a custom script. The script aggregated and binned individual flashes to a grid of 2.5 km × 2.5 km cells (816 × 418; 314 088 total cells). Each resultant grid box was assigned a corresponding flash count (i.e., for 6 flashes, the flash count value of the box is 6) and written out to 96 monthly ASCII files. Header information specifying the grid corners and geographic extent of the domain was then appended to the files, rendering each readable by ArcMap as monthly raster grids precisely matching the study area.

With this processed data, an updated CG lightning climatology was created for the Gulf Coast region. Using ArcMap, mean CG flash density maps were constructed for the complete period of record, individual months, and the winter (DJF) seasons. With the Albers map, which preserves area, flash density was displayed as flashes per unit area. Maps were compared with past climatologies and the Goodman et al. (2000) ENSO study. The flash densities are analyzed with respect to the phases of ENSO as categorized by the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC). The ENSO indices and SST anomalies were accessed from the CPC Web site (available online at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

**Detection efficiency correction**

Both the sensors and coverage of the NLDN have been incrementally upgraded. The network was upgraded at the end of 1994 (Cummins et al. 1998). This upgrade increased the location accuracy to 500 m and the detection efficiency (DE) to 80%–90% for flashes with peak currents greater than 5 kA, varying some-what by region (Cummins et al. 1998; Wacker and Orville 1999). Between 1995 and 2001, the network consisted of 106 sensors strategically dispersed across the United States (Orville and Huffines 2001). Between 2002 and 2003, existing sensors were replaced by a uni-formed sensor type, the Improved Performance Com-
bined Technology (IMPACT), and six new sensors were added (Jerauld et al. 2005; Cummins et al. 2006). Following the 2002–03 upgrade, location accuracy has remained about the same, but the network is now more sensitive and DE has increased to 90%–95% (Jerauld et al. 2005).

Correction values for relative detection efficiency were obtained from Vaisala, Inc. (K. Cummins 2007, personal communication). The DE values are relative to 1999, to provide compatibility with earlier corrections for 1989–99, and cover the United States. For values between 0.85 and 1.15, DE estimates have a 5% error; for values outside of that range, DE estimates may be in error by 15%–20% (K. Cummins 2007, personal communication). The DE correction values are arranged in a $2^\circ \times 2^\circ$ grid. The Gulf Coast region is subsetted from the national values. The DE correction table is imported to ArcMap and converted to a feature using a Visual Basic script. The DE correction layer is added to ArcMap and reprojected to match the flash density grids (Fig. 2). The cell spacing is set to 2.5 km to match flash density grid boxes. A new flash density map is produced by dividing the current flash density grid by the DE correction grid. Not surprisingly, the greatest differences are in 1995 and 2002 (Fig. 3). The DE differences affected the total count for the domain but had

![Fig. 2. Mean flash density (km$^{-2}$) and detection efficiency values (relative to 1999). Detection efficiency values that are “too low” are darker. Higher values of flash density are darker.](image)
little impact on the spatial distribution of maxima and minima. The correction “darkened” the 1995 map and “lightened” the 2002 map (Fig. 3). Figure 4 shows the difference between the corrected and uncorrected flash density maps all years. For 1995, the DE correction increased the flash density across almost the whole domain; for 2002, clusters of “overdetection” are found mainly over Texas. Histograms of the difference field (not shown) showed that the flash density change was less than 1 flash km\(^{-2}\) for most of the affected cells.

From the new flash density grids, a corrected annual flash total for the full domain is computed by multiplying the mean flash count by the number of cells. Quantitative and qualitative analysis of the annual, seasonal, and monthly mean flash distributions are described in section 3. The large-scale environment is determined from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) global analyses (Kalnay et al. 1996).

3. Results

a. Mean and annual lightning flash density

About 60 million flashes were detected over the Gulf Coast region for the 8-yr period, ranging from a low of 6.76 million flashes in 2000 to a high of 8.12 million flashes in 1997 (Fig. 5). The average for all years is 7.48 million flashes. The annual totals for 1998–2001 are low relative to the mean, while the numbers of flashes in 1995–97 and 2002 are anomalously high (Fig. 5).

About 10 times as many flashes occur in July (the maximum monthly mean) as occur in December (the minimum monthly mean). Flash occurrence is highly variable between October and February when the standard deviation of flash occurrence is nearly equal to the mean (Fig. 6). In contrast, for July–September, the standard deviation is less than one-quarter of the mean.

For the 8-yr mean of CG flash densities (Fig. 7), a maximum flash density of 10.06 km\(^{-2}\) yr\(^{-1}\) occurred near Tampa Bay, Florida. A broad swath with flash densities greater than 9 flashes km\(^{-2}\) yr\(^{-1}\) stretches from the Tampa Bay area eastward through Orlando to the Atlantic coast near Cape Canaveral. A secondary maximum is found in southeast Florida between Lake Okeechobee and West Palm Beach. The maxima correspond with findings from other studies (e.g., Reap 1994; Lericos et al. 2002), and are mostly due to the convergence of the east and west sea-breeze fronts as well as occasional lake breezes. Another maximum exists along the northern Gulf of Mexico, extending from just east of Mobile westward to New Orleans and Baton Rouge. Lightning activity is reduced over Lake Pontchartrain (just north of New Orleans) relative to the immediate surroundings. Along the northwest Gulf Coast, an average, 4–7 flashes km\(^{-2}\) yr\(^{-1}\) was observed in the Lake Charles to Houston area—about half the Florida maximum. The location of secondary maxima in the vicinity of urban areas matches observations by Steiger et al. (2002) with respect to pollution and urban
effects. Flash densities drop off past Houston, progressing southward along the Texas Gulf Coast as observed by Zajac and Rutledge (2001). Over central Georgia, a small local maximum is related to rising terrain, which enhances thermal heating and instability (Bentley and Stallins 2005). Sea-breeze circulations are also responsible for weak maxima (3–5 flash km\(^{-2}\) yr\(^{-1}\)) along the coast of northeast Florida, Georgia, and South Caro-

**FIG. 4.** Difference between corrected and uncorrected annual mean flash density for (a) 1995, (b) 1996, (c) 1997, (d) 1998, (e) 2000, (f) 2001, and (g) 2002.
lina. Along the eastern border of the domain are flash densities of more than 2 flashes km$^{-2}$ yr$^{-1}$, reflecting the instability associated with the warm Gulf Stream. In between the Gulf Stream and the coastal maximum is a band of less than 1 flash km$^{-2}$ yr$^{-1}$ indicating subsidence between to the two areas of instability.

In general, enhanced flash densities are found along the coastline, the result of sea- and land-breeze circulations and their, sometimes, complex interactions, which are influenced by coastline curvature and synoptic conditions. Flash intensity diminishes with distance from the coast as influence from Gulf sea-breeze circulations diminishes and moisture is less available. Lower flash density over the open waters of the Gulf also occurs because convection is less intense over water than land (Zipser et al. 2006) and detection efficiency decreases with distance from the lightning sensors, which are on land (Cummins et al. 1998).

While flash activity appears broadly comparable in geographic distribution from year to year, there are interesting localized variations (Fig. 8). West central Florida (around Tampa Bay) and east central Florida (north of Cape Canaveral) had consistent maxima in flash densities each year. Coastal Mississippi and Alabama had high flash density except during 2001. Spatial distribution in other regions varied from year to year.

During 1995, the pattern is similar to the mean except that a maximum occurred over the central Everglades and few flashes occurred along the southeast Florida coast, an area that had a maximum in flash density during most of the other years (Fig. 8a).

During 1996, the flash density over central Florida increased relative to 1995 (Fig. 8b), remained the same along the Mississippi and Alabama coasts, but decreased along the Louisiana coast and the Florida Panhandle. Maxima in excess of 9 flashes km$^{-2}$ were observed around Houston and over northwestern Louisiana (on the edge of the domain). The latter area of relatively high flash density was observed only in 1996 and 1997. An increase in flash densities occurred along the southeast and northeast Florida coast and the Georgia coast. The flash density maximum over the center of the Florida peninsula had its largest extent during 1996. Small areas of more than 6 flashes km$^{-2}$ were observed offshore the north-central Gulf Coast.

Florida experienced its lowest flash density during 1997 (Fig. 8c). Rather than maxima over central Florida, the flash density diminished to less than 5 flashes km$^{-2}$. Small areas of more than 9 flashes km$^{-2}$ were still present near Tampa, along the southeast Florida coast, and over South Carolina. Near the mouth of the Mississippi flash densities were higher than 1996. A maximum over northwestern Louisiana (on the edge of the domain) was observed only in 1996 and 1997. That year was also unique in that large areas of the northern and central Gulf of Mexico had less than 1 flash km$^{-2}$.

Areas with more than 9 flashes km$^{-2}$ were clustered over the western, south-central, northeastern, and southeastern Florida peninsula during 1998 (Fig. 8d). During late May to early July 1998, Florida experienced...
over 2300 wildfires, the worst season on record. Lightning was the primary cause of the 1998 wildfires, igniting 31% of the total number of fires, which covered 79% of the total acres burned (Laing and Paxton 2002). Following the strong 1997–98 El Niño, which was the wettest November–March since 1895 for northern Florida, there was an abrupt shift to La Niña conditions and rainfall fell to less than 50% of normal (see online at http://www.ncdc.noaa.gov/oa/climate/research/1998/fla/florida.html). High pressure over the Southeastern United States led to subsidence drying and April–June 1998 was the driest and the third warmest on record for northern Florida. Tremendous amounts of lightning were produced by sea-breeze thunderstorms, but precipitation was lower than normal and most lightning occurred on the periphery of the heaviest rain areas (Laing and Paxton 2002). Wildfires in coastal Georgia and South Carolina were also associated with an increase in lightning flashes during 1998. Lightning activity increased over the northern Gulf of Mexico but decreased over Texas and Louisiana.

In 1999, central Florida was marked by high flash rates similar to those of 1996 (Fig. 8e). During the same period, northern Florida had relatively low flash densities. The northeastern Gulf, offshore Alabama, and the Florida Panhandle has moderate-to-high flash density, greater than 7 flashes km⁻², where mostly low flash densities were observed in other years.

The lowest total flashes of the 8-yr period occurred in 2000 (Table 1; Fig. 8f). During 2000, small clusters of high lightning rates were more widespread over northern Florida than in other years, while southeastern Florida had lower flash density than usual. Texas and Louisiana experienced their lowest flash density during 2000.

In 2001 (Fig. 8g), the northern Gulf Coast had its lowest flash density for the 8-yr period with little activity offshore. While coastal activity decreased, flash density of 4–6 flashes km⁻² was spread out over inland regions of Mississippi and western Alabama. Northeastern Florida experienced its highest flash density of the 8 yr—a broad area with greater than 9 flashes km⁻² extended from Cape Canaveral to the Georgia coast. A narrow band of 3–5 flashes km⁻² bordered the Texas coast south of Houston. Low-to-moderate flash density are also scattered over inland areas of Mississippi and western Alabama. A thin band stretches from the Florida Panhandle toward the north-central Gulf. While its intensity is not remarkable, it is a unique feature not seen in other years.

The year 2002 had more lightning activity over coastal Texas and offshore the Mississippi Delta than other years (Fig. 8h). Flash densities exceeded 5 flashes km⁻² offshore the coasts of Louisiana and the Texas border. In contrast, eastern Florida experienced its lowest flash densities during this year.

A few comments can be made about the annual distribution of lightning activity and possible relationship to ENSO. The highest annual flash count was observed in 1997 (Fig. 6), which was the start of one of the strongest El Niño episodes on record (more information is available online at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). The lowest annual flash count was 2000, which had the lowest ONI of the 8-yr period and included 9 months of La Niña and 3 months of neutral conditions.
While the general flash density patterns closely resemble the results of prior studies (e.g., Zajac and Rutledge 2001; Orville and Huffines 2001), the maximum intensity of the annual mean was lower; 10.06 flashes km\(^{-2}\) compared with 14.5 flashes km\(^{-2}\) in Zajac and Rutledge (2001). Areas with greater than 9 flashes km\(^{-2}\) yr\(^{-1}\) observed in Florida and other isolated locations are less extensive in areal coverage than the earlier studies. There are a couple of plausible explanations for the reduced intensity. Since the analysis grid was so fine (2.5 km \(\times\) 2.5 km) subtle, year-to-year shifts in flash distributions can cause high-density grids to be averaged with lower density grids. This explanation is supported by the fact that the maximum flash densities for individual years were consistent with other studies. For instance, multiple grids in some years had 15–17

![Fig. 8. Mean flash density for (a) 1995, (b) 1996, (c) 1997, (d) 1998, (e) 1999, (f) 2000, (g) 2001, and (h) 2002.](image-url)
flashes km$^{-2}$ just north of Tampa, consistent with the maximum calculated by Zajac and Rutledge (2001). Furthermore, examination of the ONI values (Table 1) for individual seasons in the study reveals that this 8-yr period was disproportionately affected by cool ENSO episodes compared to periods studied by Orville and Huffines (2001). For this study, 23 periods were classified as warm episodes (24%) with 36 cool episodes (37%) and 37 neutral episodes (39%). The 1989–98 period examined by Orville and Huffines (2001) incorporated 43 warm seasons (36%), 59 neutral periods (49%), and just 18 cool periods (15%).

b. Synoptic influences on interannual variations

The interannual variation in the spatial distribution of lightning is related to the prevailing synoptic environment. Figure 9 shows the mean synoptic environment for the 8-yr period and the environment for years
during which the expected maxima did not occur. The mean pattern (Fig. 9a) shows the subtropical ridge extending across central Florida into the northwestern Gulf Coast states with a high pressure center over the Mississippi Delta. A weak low pressure is centered to the east, strong southeasterly winds blow across the Gulf of Mexico over Georgia and Alabama, and strong southerly winds blow over western Louisiana and Texas. The northeastern half of the domain has weak pressure gradients and calm to light winds. With weak synoptic flow, topographically forced convection, such as sea-breeze circulations are strengthened, which leads to the predominance of lightning along those boundaries.

Central Florida experienced a marked reduction in lightning activity during 1997 (Fig. 8c). During that period, the subtropical ridge extended across the central part of the peninsula and northwesterly flow brought drier, continental air to north-central Florida (Fig. 9b).

During 2001, coastal Mississippi and Alabama experienced a minimum in flash density (Fig. 8g) and there was little activity over the northeastern Gulf. Winds were mainly southerly and a weak inverted trough occurred over Alabama (Fig. 9c). The trough enhanced instability inland and thunderstorms were pushed northward.

c. Winter

For comparison with the Goodman et al. (2000) study, average flash density maps were prepared for all DJF periods during the study (Fig. 10). Overall, year-to-year lightning distributions were relatively equivalent, and findings largely validate those of Goodman et al. (2000). The two study periods overlapped for four winters (1995–96, 1996–97, 1997–98, and 1998–99), with one common DJF period (1997–98) classified as a strong warm event according to ONI (Table 1).

Lightning activity during this one, shared warm season was considerably more intense and extensive than in any other study year. Enhanced flash values are ob-
Fig. 9. Mean geopotential height of 1000 hPa for (a) 1995–2002, (b) 1997, and (c) 2001.
served surging across much of the northern Gulf of Mexico region, comparable to Goodman et al. (2000) but more detailed features are revealed in this new analysis. Figure 10c shows an envelope of peak lightning from northeastern Texas to the eastern Gulf of Mexico. Within that envelope, streaks of lightning are aligned along northeast to southwest lines. The larger envelope is indicative of a southerly shift in the mid-latitude cyclone track.

Four DJF periods in this study (1995–96, 1998–99, 1999–2000, and 2000–01) were ONI-classified cool events. Lightning was less extensive during the 1995–96 (Fig. 10a), 1998–99 (Fig. 10d), and 1999–2000 (Fig. 10e) DJF periods. The most dramatic decrease in overall

**Fig. 10. DJF mean flash density for (a) 1995–96, (b) 1996–97, (c) 1997–98, (d) 1998–99, (e) 1999–2000, (f) 2000–01, and (g) 2001–02.**
winter lightning activity was observed during 2000–01 (Fig. 10f). For this period, the total number of flashes decreased to 36% of the DJF mean value. The 2000–01 DJF season exhibited the lowest flash densities of any in the study (Fig. 10f). That period had the least amount of oceanic flashes and very few flashes over Florida.

The 2001–02 DJF season marked a return to neutral ENSO conditions, with a slight increase in lightning activity over the previous DJF (Fig. 10g). Notable for this period was that the lightning was primarily concentrated in the western half of the study area, with few flashes over the eastern Gulf States. For the two extremes of the winter seasons, the synoptic environments were markedly different (Fig. 11). For the strong El Niño winter of 1997–98, the Gulf Coast region was under the influence of troughs, lows, and strong southeasterly winds (Fig. 11a). Strong dynamical forcing for convection was provided by a trough that extended across Florida, low pressure centered over Mississippi and Alabama, and another low centered over the southern Gulf of Mexico. Strong southeasterly winds brought warm, moist air into the region, leading to enhanced instability. In contrast, during the 2000–01 winter, high pressure over the northern Gulf Coast, a broad ridge, and light winds were the dominant features. Convection was limited by subsidence. The eastern Gulf experienced cooler, drier northerly and northeasterly winds, which increased stability and reduced convection. Therefore, lightning occurred mostly over the western and central parts of the domain.

d. Summer

Summer is the period of maximum flash density over the Gulf Coast. On average, very high flash densities occurred over Florida during the month of June but only moderate flash densities were observed across the northern and western Gulf Coast (Fig. 12a). Those regions had strong pressure gradient and south-southwesterly flow across the western Gulf (not shown).

July has, on average, the maximum number of lightning flashes (Fig. 5) and the highest flash density maximum across Florida (Fig. 12b). Maxima of greater than
14 flashes km\(^{-2}\) month\(^{-1}\) extend well inland on the northern Gulf Coast as well, with additional, more localized areas of enhanced lighting scattered throughout most of the eastern two-thirds of the study area. Lowest flash density was observed in eastern Texas, past Houston, and extending southward along the coast. The maximum flash density over Florida during July is not strongly influenced by large-scale circulation but rather modulated by local sea- and land-breeze effects.

Cloud-to-ground flash densities remained high overall during the month of August (Fig. 12c). A barely perceptible decrease can be seen over the northern Gulf Coast and oceanic areas, but interestingly, Florida flash densities increased, particularly in the southern half of the state. This increase from average is likely a simple year-to-year variation, as climatologically, 8 yr is not enough to establish a long-term pattern. However, accurate lighting data does not extend much farther back in time, so it is assumed some of these variations will be smoothed as more lighting data is added to the climatologies.

4. Summary and concluding remarks

An 8-yr dataset (1995–2002) of cloud-to-ground lightning flashes was analyzed to determine if the ENSO cycle has an influence on lightning activity along the Gulf Coast region of the United States. First, the study provides new annual, seasonal, and monthly climatologies for the entire region. Previous climatologies documented continental-scale activity up to 1999 and subregional activity up to 2002, with the primary focus on the warm season.

Although the period of record is short, ENSO seems to have an impact on lightning activity in the Gulf Coast region. The highest lightning anomaly was in 1997, during which the highest ONI occurred and the lowest lightning anomaly occurred in 2000, which was coincident with the lowest ONI of the 8-yr period. Between 1998 and 2001, the number of flashes across the domain was less than the mean, which may be related to the long period of cool ENSO anomalies.

The annual mean flash density distribution was
broadly comparable with the studies cited from the literature; however, for 1995–2002, the peak flash density was less than observed in previous national climatologies. One explanation is the increased variability at higher resolution so that year-to-year shifts in the location of flash density maxima can lead to high-density grids being averaged with lower density grids. This explanation seems plausible because the maximum flash densities for individual years were consistent with other studies. In addition, the relatively lower intensity could be due to the differences in the synoptic climatology of the study periods, with this climatology having a disproportionately large number of cool ENSO periods compared to the other climatologies.

Variations were observed in spatial distributions and flash intensities in the seasonal and annual averages. For example, the center of the Florida peninsula, which is noted for having moderate to high flash rates, experienced much lower than average flash rates in 1997, which was related to an increase in northwesterly flow across northern Florida. The coasts of Mississippi and Alabama had consistently high flash density except during 2001 when the density decreased to about half the value of the other years. The large-scale flow was southerly and a weak trough enhanced instability over the interior.

Results from the analysis of winter season lightning data validated the findings of Goodman et al. (2000). Both studies substantiate the role of the ENSO cycle in winter season lightning fluctuations. This is especially evident for the one common warm event winter (1997–98) between the two studies where a dramatic increase in lightning activity was clearly evident. However, this study revealed detailed features such as the banded mesoscale maxima that are associated with fronts. Enhanced CG flash regions and patterns are indicative of the southerly shift in the midlatitude storm track that is known to be influenced by ENSO. A decrease in lightning was observed during cool ENSO phase winters. The striking disparity between two extremes for the

FIG. 11. Same as in Fig. 9, but for DJF (a) 1997–98 and (b) 2000–01.
study period, the winters of 1997–98 and 2000–01, were indicative of the differences in their synoptic environments. The finding of a relationship with ENSO is not surprising since precipitation variability in this region correlates strongly with ENSO. However, a relationship was not guaranteed as Zipser et al. (2006) found that the global maxima in intense thunderstorms (i.e., those with the strongest updrafts, ice scattering, and lightning), were not always coincident with precipitation maxima. In the case of the Gulf Coast, thunder-
storms associated with midlatitude cyclones produce most of the precipitation and lightning.

Summer months experience much less variability in the lightning flash density. The primary mechanisms for summertime thunderstorm activity in the Gulf region are airmaass thunderstorms and thunderstorms triggered by mesoscale processes such as sea-breeze and land-breeze circulations. Frontal activity is virtually nonexistent at these latitudes during summer months. Lightning distribution is modulated by the position of the subtropical high.

Lightning is hazardous for individuals and society as a whole. ENSO is known to alter climate and weather patterns across the globe; as such, the phenomenon is a hazard in its own right. Comparisons with past studies and analysis of new data in this study furnish evidence that the ENSO cycle impacts lightning activity through its influence on the storm tracks, particularly during the winter. Knowledge of the spatial and temporal distribution of lightning and the influence of ENSO on that distribution is valuable to forecasters in Gulf Coast States, where lightning climatologies are being used to initialize lightning threat maps.

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