AN EXAMINATION OF THE RELATIONSHIP BETWEEN COOL SEASON TORNADOES AND CLOUD-TO-GROUND LIGHTNING FLASHES

A Thesis

by

DOUGLAS ALLEN BUTTS, JR.

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2006

Major Subject: Meteorology

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Approved by:

Chair of Committee,	Larry Carey
Committee Members,	Gerald North
	Benjamin Giese
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ABSTRACT

An Examination of the Relationship Between Cool Season

Tornadoes and Cloud-to-Ground Lightning Flashes. (December 2006)

Douglas Allen Butts, Jr., B.S., University of South Alabama

Chair of Advisory Committee: Dr. Larry D. Carey

The southeast United States is prone to severe weather throughout the year. Despite technological advances, some severe weather events occasionally remain unwarned in this part of the country. Past studies examined the relationship between cloud-to-ground (CG) lightning and warm season severe weather episodes. The present study examined the relationship between cool season tornadoes and CG lightning, with a focus over the southeastern United States, where most cool season tornadoes occur. Data from the Storm Prediction Center and National Lightning Detection Network (NLDN) were used to investigate CG lightning properties within 50 km and one hour before tornado touchdown. This was completed over a period of 13 cool seasons from October 1989 through March 2002.

Of 3325 tornado events, 2358 contained at least one NLDN-detectable flash. CG lightning attributes of peak current, multiplicity, and flash density compared well with those of prior warm season lightning research. Overall event frequency appeared to be lower than in the warm season. Almost all Central Plains events were accompanied by at least one NLDN-detectable flash. Up to 70% of tornado events near the Gulf of Mexico and Atlantic coasts contained no NLDN-detectable lightning. Although it is not

known why this trend was observed, it is speculated that NLDN detection efficiency and/or storm structure differences may play a role in these observations.

Warm season studies have correlated tornadoes with predominantly positive (>50% positive CG lightning), or PPCG storms. Gridded maps showed the greatest percentage and highest frequency of cool season PPCG storms across Kansas and Nebraska, with up to 70% of events associated with PPCG lightning. A secondary, albeit lower, frequency maximum extended 1° to 2° inland across Louisiana into North Carolina. This study also subjectively defined a storm with "enhanced" positive cloud-to-ground (EPCG) lightning as one containing >25% positive cloud-to-ground lightning, which corresponds to approximately the 75th percentile of all cool season tornadoes. This has lead to speculation that EPCG criterion may be a better indicator of the possibility of severe weather than the traditional PPCG criterion.

This manuscript is dedicated to

my parents Douglas (Sr.) and Janice,

brother Dennis,

and grandmother Lucille

for your enduring love and support throughout my life.

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There are many people who have helped me in this long, sometimes strange journey of educational attainment. I am sure there are many more I am forgetting. For that, I apologize.

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Throughout this endeavor, I have had the privilege of working with many fine friends and colleagues at several National Weather Service Offices. A special thank you goes to Meteorologist-in-Charge Alan Gerard and the staff at the Jackson, MS office for their encouragement. This project stemmed, at least in part, from observations made during my four-year tenure as a General Forecaster at this office. Now, when asked, "Finished your thesis yet?!" I can respond, "Yes."

I would also like to thank my many friends (too numerous to name here) across the country who have provided support, encouragement, or advice in one way or the other. Whether it was opinions directly related to the thesis, the occasional road trip, meal, or reminder of why I enjoy the field of meteorology, it was greatly appreciated. You know who you are. Thank you.

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CHAPTER I

INTRODUCTION AND MOTIVATION

The National Weather Service defines a severe thunderstorm as one which produces a tornado, wind speeds of 25 m s^{-1} or higher, or hailstones with a diameter of 1.9 cm or larger (Brooks et al. 2003). From previous studies documenting severe thunderstorm occurrence, it can be seen that severe weather phenomena impact many people across the United States each year. Boruff et al. (2003) documented more than 9000 fatalities, 73 000 injuries, and $300 billion in damage due to weather-related hazards since the mid-1970s.

Much has been written about the United States' tornado alley, a region of the country possessing the greatest frequency of severe weather during the April through September warm season. However, as indicated in Table 1, severe weather is also possible during the cool season of the year. From the table, it can easily be seen that the severe weather risk, including the possibility of damaging tornadoes, is especially great over the Southeast United States (Brooks et al. 2003). In fact, Boruff et al. (2003) noted that parts of the Southeast United States have shown an increase in "hazard frequency" since the 1950s. That is, an increase in population across areas susceptible to tornadoes has resulted in a greater tornado hazard.

These hazards appear to have been mitigated somewhat upon modernization of National Weather Service offices across the United States. Boruff et al. (2003) and Simmons and Sutter (2005) point out technological and training advances completed in

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This thesis follows the style of *Monthly Weather Review*.

TABLE 1. A sample of cool season tornado events and the areas affected.

Date	States/Areas Affected
18 March 1925	Illinois, Indiana, Missouri (Tri-State Tornado Outbreak)
21-22 March 1952	Arkansas, Tennessee (First Tornado Watch issued)
21 February 1971	Arklamiss Region
21-23 November 1992	Alabama, Georgia, Indiana, Kentucky, Maryland, Mississippi, North Carolina, Ohio, South Carolina, Tennessee, Texas, Virginia
27 March 1994	Alabama, Georgia, North Carolina, South Carolina (Palm Sunday II Tornado Outbreak)
21-22 January 1999	Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, Tennessee
13-14 February 2000	Georgia
10 November 2002	Alabama, Georgia, Indiana, Kentucky, Louisiana, Mississippi, Ohio, Pennsylvania, South Carolina, Tennessee, Virginia, West Virginia
18 October 2004	Alabama, Arkansas, Missouri, Tennessee
15 November 2005	Alabama, Arkansas, Illinois, Indiana, Kentucky, Missouri, Tennessee

the late 1990s, including the WSR-88D Doppler radar, have resulted in increased lead times, lower false alarm ratios, and improved probability of detection scores for tornado warnings. Real-time cloud-to-ground lightning data from the National Lightning Detection Network were also incorporated into National Weather Service computer systems as part of modernization efforts. Despite these advances, tornadoes (as well as other severe weather phenomena) occasionally go unwarned. The detection of severe weather can be difficult for any operational meteorologist. This is especially true in the Southeast United States, where environmental conditions may result in climatological trends and organizational modes of tornadic thunderstorms which differ, sometimes significantly, from that which is typically observed in the Plains region.

These cool season tornado events will be the focus for this study. The relationship between these events and cloud-to-ground lightning will be examined, with the hope that this effort may provide useful information to operational meteorologists responsible for the interrogation and forewarning of severe convective events.

The remainder of this chapter will provide useful information concerning the development and organization of thunderstorms and tornadoes. Chapter II will briefly address thunderstorm electrification processes and climatological trends, then conclude with prior research and a complete statement of objectives for this study. Data and research methods used will be described in Chapter III, with results provided in Chapter IV. A synthesis of this study's results and previous research will be stated in Chapter V, with special attention given to two "companion" warm season studies. Finally, conclusions will be provided in Chapter VI.

1. Thunderstorm organization and development

As pointed out by Holton (1992), convection may organize on many spatial scales in the atmosphere. These scales may vary from isolated thunderstorms to large clusters of thunderstorms spanning hundreds of kilometers. Outside of these mesoscale convective systems, it is widely accepted that thunderstorms can broadly be classified into three groups: single cell, multicell, or supercell. While the amount of available instability may aid in determining whether thunderstorm development may occur, the amount of low-level wind shear largely decides how thunderstorms organize.

a. Single cell thunderstorms

Single cell thunderstorms are the most favored method of organization when vertical wind shear in the lowest 4 km is less than 10 m s^{-1} (Holton 1992). These are rather short-lived thunderstorms, with a typical life span of approximately 30 minutes. While short life span and weak wind shear precludes most severe weather in this mode, the single cell thunderstorm provides the ideal method in which to study the three stages in a thunderstorm's life cycle, which are depicted in Figure 1 (Rogers and Yau 1989; Browning 1992; Bluestein 1993; Ahrens 1994).

Initially, only updrafts are possessed by the developing cell in the first, or cumulus stage (Fig. 1a). Upward vertical velocities up to 10 m s^{-1} contained within the updraft are responsible for the vertical transport of moisture in an unstable environment.

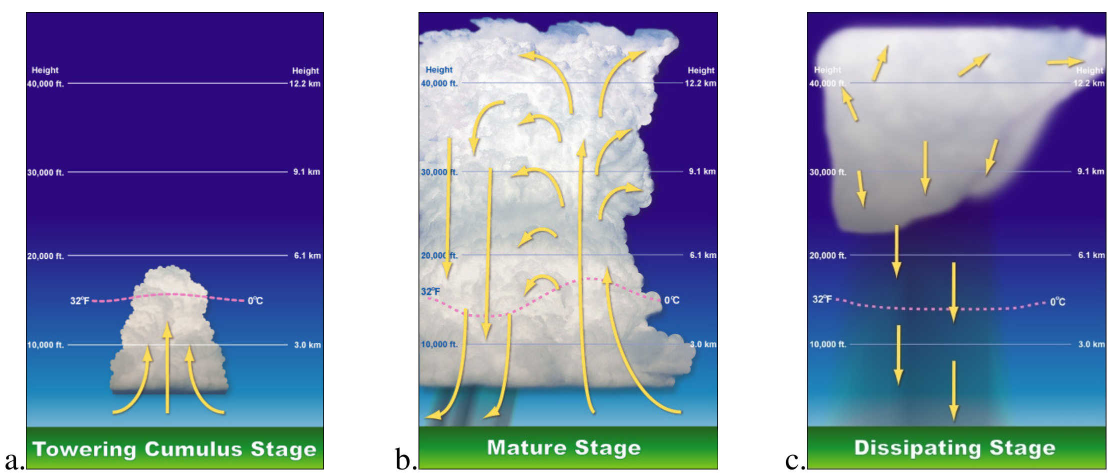

FIG. 1. Illustrations depicting the life cycle of a single cell thunderstorm through the (a) cumulus, (b) mature, and (c) dissipating stages. (NOAA 2006)

Increasing amounts of air are gradually entrained into the updraft as the cell continues to grow. Precipitation particles begin to grow when condensation commences. Even in this mode of convection, updraft velocities are typically strong enough to result in some moisture being contained in the mixed-phase region, which is important in lightning development.

Eventually, precipitation will initiate a downdraft as it falls through the cloud. This, the existence of both an updraft and downdraft, signals the beginning of the mature stage of a thunderstorm's life cycle (Fig. 1b). Colder, rain-cooled air will gradually be pulled toward the ground as the precipitation falls. With weak or no vertical wind shear, the downdraft will destroy the thunderstorm's updraft region and reduce the amount of available buoyancy for additional convective development. Upon reaching the ground, low-level wind fields are modified by the downdraft as it spreads isotropically across the earth's surface. The leading edge of this colder, denser air is known as a gust front.

Once this occurs, the storm has reached the dissipating stage (Fig. 1c). Since its source of inflow has all but been eliminated, the storm can no longer sustain itself. An anvil and a relatively stable airmass is all that remains during this stage as precipitation associated with the storm diminishes. As previously stated, the single cell thunderstorm may undergo these stages in less than an hour.

b. Multicell thunderstorms

Thunderstorm organization changes with an increased low-level vertical wind shear of 10 to 20 m s^{-1} (Holton 1992). Under these circumstances, multicell thunderstorms are the more favored mode of convective development. In this convective mode, gust fronts from individual single cell thunderstorms merge, producing a single large gust front, or outflow boundary. The increased vertical wind shear now results in any additional convective development propagating downshear, parallel with the mean wind in the lowest 5 to 7 km. Convective development is enhanced in this downshear region of the gust front, due to increased amounts of storm-relative inflow and low-level convergence in a favorable thermodynamic environment. Once new storms develop, the convective process may then continue for several hours. Convective growth will eventually cease after some time as the outflow boundary becomes increasingly shallow with greater distance from the initial thunderstorm development (Weisman and Klemp 1986; Bluestein 1993).

In addition to the development of thunderstorm clusters, as described above, multicell storms may also form into lines. Even though some uncertainty may remain as to the precise factors which determine the mode in which convective development occurs, Hane (1986) pointed out that low-level wind shear again plays a major role in determining the convective mode of the multicellular environment. According to Bluestein (1993) and Houze (1993), multicell thunderstorms organize into lines (e.g., squall lines) when additional storm development takes place in voids between pre-existing thunderstorm clusters ahead of such features as a cold front, surface low-pressure trough, or dryline. Most multicellular line convection is characterized by an initial convective precipitation line with a relatively large trailing stratiform region, although instances in which stratiform precipitation occurred parallel to or ahead of the convective precipitation region have been documented (Parker and Johnson 2000; Parker et al. 2001).

Regardless of the convective mode, the various stages of thunderstorm development, as described in preceding paragraphs, are frequently seen within multicellular storms. The "newer" thunderstorms are seen to contain only updrafts, while thunderstorms in later stages of development possess both updrafts and downdrafts or only downdrafts (Houze 1993). With the presence of increased vertical wind shear, severe weather and flash flooding are greater possibilities with multicell thunderstorms (Weisman and Klemp 1986). In addition, Moller et al. (1994) states that, in organized[1] multicell storms, severe weather events are episodic in nature. This is in contrast to storms forming in more weakly sheared environments, where any severe weather occurs as a "quick burst" prior to dissipation.

c. Supercell thunderstorms

The term "supercell" may broadly be used to refer to any long-lived (usually severe) thunderstorm which possesses a persistent mesocyclone several kilometers in diameter (Klemp and Rotunno 1983; Weisman and Klemp 1986; Keighton et al. 1991; MacGorman and Bugess 1994; Moller et al. 1994; Rasmussen and Straka 1998; Davies-Jones et al. 2001). Most supercell thunderstorms have other operationally recognizable characteristics. These include an almost steady-state updraft, possible deviate motion to the right or left of the mean winds, and a bounded weak echo region[2] (indicative of a very strong updraft region). Because of the uniqueness of the environment in which they form, supercell thunderstorms (hereinafter supercells) are rare. Despite this, they are

[1] By statements made in preceding paragraphs, any storm which is *organized* is one which developed in an environment with higher amounts of low-level vertical wind shear. Likewise, *unorganized* storms develop in an environment with lower amounts of low-level vertical wind shear.
[2] A bounded weak echo region (BWER) is a radar-detected signature in which the weak echo region is encompassed by higher reflectivity values on each side (Browning 1964; Browning 1965).

responsible for producing much of the large hail and strong/violent tornadoes which produce damage and casualties each year (Houze 1993; MacGorman and Burgess 1994; Moller et al. 1994).

The development of a prototypical supercell is qualitatively described by Klemp and Rotunno (1983), Weisman and Klemp (1986); Houze (1993), and Moller et al. (1994). Most supercells begin by evolving similarly to the single cell or an individual storm in a multicell cluster of storms. Unlike the single cell or multicell cluster of storms, though, the supercell develops in an environment which has greater instability and/or stronger low-level wind shear. Because of these two factors (primarily the vertical wind shear), a tilted updraft will likely develop which will allow hydrometeors to fall away from the main updraft.

As Bluestein (1993) points out, it is not this updraft tilting which sustains the supercell's updraft. Wind shear is not only responsible for updraft development and maintenance, but also necessary for thunderstorm rotation. Bluestein continues illustrating that in an environment where the updraft is weak (due to a marginally unstable atmosphere), hydrometeors will tend to fall into the storm's inflow region. Increased wind shear will provide sufficient tilt in the downshear direction, using the available energy more efficiently. If a strong updraft is present, Bluestein states the addition of vertical wind shear will "enhance the intensity and increase the longevity of the storm" through the development of dynamic and buoyancy pressure forces as wind shear interacts with the storm's updraft. However, Moller et al. (1994) are quick to note that even if high amounts of instability are not present, damaging supercells can still occur.

1) TYPES OF SUPERCELLS

Many different types of environments lead to the development of supercells. As such, storms exhibit many different types of observational traits when viewed in the field or by radar. It is generally accepted that there are three broad classes of supercell thunderstorms, based upon the spatial distribution of precipitation with respect to the updraft: 1) classic, 2) low-precipitation, and 3) high-precipitation (MacGorman and Burgess 1994; Moller et al. 1994; Rasmussen and Straka 1998).

(i) Classic supercells

Most of the prior discussion regarding supercell development was largely based upon the structure of the classic supercell, which traditionally presents the greatest risk of significant tornado production. According to Moller et al. (1994), classic supercells represent the classification closest to the traditional conceptual models of supercell storms. The classic supercell normally develops in an environment with strong values of low- and mid-level vertical wind shear and moderate to high amounts of low-level moisture. Visually, there is a highly visible rain-free updraft tower, with falling precipitation downshear of the rotating updraft tower. "Traditional" supercell features such as a hook echoes and BWERs are likely to be seen when observing the storm using radar (Moller et al. 1994; Rasmussen and Straka 1998).

(ii) Low-precipitation supercells

With the lowest risk of significant tornado production, low-precipitation (LP) supercells are usually found in the dryline environment of the High Plains as well as western parts of the Great Plains. These storms develop in an environment that has weaker low- and mid-level vertical wind shear than the classic supercell (Rasmussen and Straka 1998) and smaller amounts of low-level moisture when compared to the classic supercell (Moller et al. 1994). Because of the circumstances under which they form, LP supercells produce no downdrafts induced by falling hydrometers and only minimal amounts of rain (Bluestein 1993; Rasmussen and Straka 1998). When seen in the field, the updraft tower associated with LP supercells is normally bell-shaped and highly striated[3], with anvil clouds upshear and downshear from the storm. Many of the radar-observed features associated with "traditional" supercell thunderstorms are not found with LP supercells, due to a lack of hydrometeors falling in vicinity of the mesocyclone. In fact, LP supercells may appear rather innocuous when viewed from weather radar.

(iii) High-precipitation supercells

On the opposite end of the spectrum are high-precipitation (HP) supercells, which have been called the most common supercell form, especially east of the Mississippi River (Doswell et al. 1990). Despite its commonality, it usually poses a lower risk for significant tornado development than classic supercell thunderstorms. Environmental conditions conducive for HP supercell development are similar to that of a classic supercell, with the exception of a weaker mid-level storm-relative wind field

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[3] The striations seen in the updraft tower are a visible sign of thunderstorm rotation.

(Rasmussen and Straka 1998). As such, the mesocyclone remains enshrouded in rain for much of the storm's life cycle, making the visual detection of storm-scale rotation and severe weather phenomena such as tornadoes difficult at best. A greater variety of radar-observed features is also seen with HP supercells, including echoes with bowing and kidney bean shapes (MacGorman and Burgess 1994).

2) DEVELOPMENT OF ROTATION IN SUPERCELLS

Mid-level mesocyclone development in supercells is discussed both quantitatively and qualitatively by Bluestein (1993) and Houze (1993). Simply put, supercell rotation develops in response to the conversion of horizontal vorticity in the environment to vertical vorticity in the cloud. Assuming the wind profile is unidirectional, the vertical tilting of the horizontal vorticity by the storm's updraft region results in a pair of counter-rotating vortices and two perturbation pressure areas in the mid-levels of the storm.

Upward vertical velocity then diminishes as precipitation loading aids in the development of an upper-level downdraft. Termed the "central downdraft", the resultant cold pool of downdraft air eventually reaches the ground. As Klemp (1987) points out, increased wind shear associated with supercell thunderstorms produces two results. First, storm-relative inflow prohibits the cold pool from outrunning the thunderstorm. Second, non-linear upward-directed pressure gradients also aid in new updraft growth on the southern and northern periphery of the (now) original updraft. These dynamically-generated upward-directed pressure gradients are crucial to storm splitting and occur regardless of whether or not a central downdraft develops.

According to Klemp (1987) and Bluestein (1993), the non-linear perturbation pressure aids in updraft growth on the northern and southern peripheries of the original updraft by inducing strong mid-level rotation on the flank of the updraft. Horizontal buoyancy gradients on the flanks of the updraft enhance the *x*- and *y*-components of vorticity and aid in lowering the pressure on the flanks of the mid-level updraft. Klemp (1987) points out that "strong rotation about the vertical axis appears to be the special feature that promotes the splitting within evolving supercell thunderstorms."

The storm splitting eventually results in two vortex-pair circulations on the northern and southern peripheries of the original updraft, with an updraft moving transverse to the mean wind shear (Klemp 1987). As this occurs, the storm-relative inflow changes such that the storm's inflow now contains both a streamwise and crosswise component of the horizontal vorticity. Several studies (as documented in Klemp 1987) have demonstrated the importance of the streamwise component of horizontal vorticity in contributing to the rotation noted in supercell thunderstorms.

According to Bluestein (1993), this process yields two results. First, with the repeated updraft regeneration, it allows the storm to persist for longer periods of time than other modes of storm organization. Second, this ultimately results in the storm splitting, which, in an environment with unidirectional vertical wind shear, yields two "mirror image" rotating storms (Houze 1993); the "left mover"[4] possesses anticyclonic rotation, while the "right mover" possesses cyclonic rotation. This is not typically the setup as the supercell which propagates to the right of the mean wind is usually favored

[4] The terms "left mover" and "right mover" refer to storms which deviate to the left and right of the mean wind, respectively.

in the Northern Hemisphere, since the wind shear vector usually veers with increasing height.

2. Tornadoes

a. Development

The development of tornadoes from rotating thunderstorms has been described by many authors (including Bluestein 1993; Houze 1993; Davies-Jones et al. 2001). Prior to tornadogenesis, a downdraft develops on the forward side of the storm, downshear of the updraft. This results in the development of a buoyancy gradient on the leading edge of the downdraft and an additional source of horizontal vorticity. As air parcels interact with this, the forward flank downdraft, they are pushed toward the mesocyclone. The result is stretching and an amplification of the low-level vorticity as the air parcels are pulled into the updraft. With increased rotation, a downward-directed pressure perturbation pressure gradient is induced by the low-level mesocyclone which then spreads rearward of the storm. This is the rear-flank downdraft (RFD). The RFD then propagates toward the updraft region of the storm, with possible tornado development taking place between the RFD and updraft region of the storm. Ironically, the RFD will result in colder air being ingesting into the updraft upon intersecting the downdraft on the forward flank. While this will likely result in the demise of the tornado, subsequent tornadogenesis may occur as new updrafts, mesocyclones, forward-flank, and rear-flank downdrafts develop. In addition, studies have shown that the presence of low-level thermal and moisture boundaries likely aid in the initiation and maintenance of the tornado potential of severe thunderstorms (Maddox et al. 1980;

Goodman and Knupp, 1993; Davies-Jones et al. 2001). It should be noted that tornado development remains an active area of scientific research. The theory presented here is only one of those theories.

b. Non-mesocyclone tornadoes

Weaker tornadoes have been documented outside of supercell thunderstorms (Wakimoto and Wilson 1989; Bluestein 1993; Houze 1993). Tornadoes that form in this manner are usually due to boundary layer processes. Under these circumstances, tornadogenesis typically occurs when a developing convective cloud interacts with a region of heightened localized vertical vorticity. Landspouts typically form in this nature.

It should be noted that in reality, most storms, both severe and non-severe, do not neatly fit into one of the previously mentioned classifications. Even though tornadoes may be more likely when the atmosphere is conducive for supercell development, tornadoes have occurred with all types of storm organization. Thunderstorms often transition between different methods of organization depending on the incipient atmospheric conditions (Keighton et al. 1991; MacGorman and Burgess 1994; Butts and Blackwell 1997; Pfost and Gerard 1997). Using the present dataset (described in Chapter III), there is no ability to know the preferred method of storm organization or tornadogenesis at the time of tornado occurrence.

c. Fujita scale

A Fujita scale (or F-scale) number has been assigned to all reported tornadoes by the National Weather Service since 1971 through a subjective inspection of tornado damage (McDonald 2001). Developed by Dr. Ted Fujita, it assigned a number, 0 through 12, to a category of wind speeds which connected wind speeds with a Beaufort force of 12 to speeds at Mach 1 using a smooth curve. F-scale ratings of F6 or higher were deemed inconceivable based upon engineering studies, which showed that most of the intense tornado damage was likely caused by wind speeds under 160 m s^{-1}. As such, values between F0 and F5, as shown in Table 2, are used to describe tornado intensity. In addition, tornadoes are commonly termed "weak", "strong", or "violent" based upon F-scale ratings and are also shown in Table 2. In addition to the ratings of F0 through F5, these qualitative groupings will be used in this study as well.

TABLE 2. Fujita scale rating system and brief damage descriptions. Commonly used descriptive "categories" and the mean annual percentage of tornadoes are also provided. Modified from McDonald (2001).

F-scale Rating	Wind Speed [m s^{-1}]	Damage Description	"Grouping"	Mean Percentage
F0	18-32	Light Damage	"Weak"	74%
F1	33-50	Moderate Damage		
F2	51-70	Considerable Damage	"Moderate"	25%
F3	71-92	Severe Damage		
F4	93-116	Devastating Damage	"Strong"	1%
F5	117-142	Incredible Damage		

CHAPTER II

BACKGROUND INFORMATION

1. Thunderstorm electrification

All clouds contain some amount of electrical charge (Wallace and Hobbs 1977). However, the process by which the electrical charge develops and subsequently separates has been the focus of many years of research. Wilson (1929) was one of the first to suggest an inductive charging mechanism. This process uses an existing vertical electric field to result in polarization of cloud and precipitation particles. When smaller particles collide with larger particles during rebounding collisions, charge separation occurs and the electric field would be strengthened as negatively charged particles fall against the storm's updraft. However, as Saunders (1993) points out, this process relies on "glancing collisions" between graupel and ice crystals. Because of the relatively short contact time, the inductive process has largely been discounted as a primary means of developing an electrical charge within a thunderstorm. This process may play a larger role when mostly warm cloud processes are involved and when the local electric field has increased later in thunderstorm development (Saunders et al. 1991).

Non-inductive processes, though, could play a bigger role in cloud electrification (Saunders 1993; Wiens et al. 2005; Carey and Buffalo 2006). In this process, electrical charges are transferred independent of the strength of the local electric field during particle collision. Many studies have been conducted (e.g., Takahashi 1978; Jayaratne 1993; Carey and Rutledge 1996) in order to look at the resultant charge of either the involved graupel or ice crystals. Most researchers agree, though, that liquid water content and temperature largely determine the resultant charge of each particle (Takahashi 1978). One theory, states that the particle that is either evaporating faster or growing through a riming process will typically gain the negative charge (Saunders 1991). The positive charge will be acquired by the other particle. In order for this to occur, it is important that non-inductive processes occur in the presence of supercooled water in the mixed layer of the cloud.

Yet another electrification process was described by Williams (1989), Saunders (1993), and Stolzenburg et al. (1998b). Known as the convective charging mechanism, the updraft process brings positive charges from the surrounding atmosphere into the growing cumulus cloud. These charges then attach themselves to the cloud particles, only to be distributed through convective processes.

From the discussion above, it should be obvious that none of the processes described above could singly account for cloud electrification observed in thunderstorms. Saunders et al. (1991) as well as Stolzenburg et al. (1998b) both suggest that at least two of the charging mechanisms are working concurrently to produce an electrical charge in the thunderstorm. It is likely that, at least initially, non-inductive processes dominate as a thunderstorm develops, with inductive processes having a greater influence once the electrical field is established. As mentioned before, though, the extent to which a process dominates will likely be determined by the cloud's liquid water content and temperature within the mixed layer.

Early twentieth century attempts to describe a generalized charge distribution within thunderstorms usually involved what is now known as the positive dipole model

(Wilson 1929). In this model, cloud electrification processes result in the upper-levels of the thunderstorm becoming positively charged, while the lower-levels are negatively charged.

Through recent studies (Williams 1989; Stolzenburg et al. 1998b; Rust and MacGorman 2002), it has been shown that thunderstorm charge distribution is more complicated than the positive dipole model would suggest. Through the use of balloon-borne observation platforms in field campaigns (Stolzenburg et al. 1998a; Rust and MacGorman 2002; Wiens et al. 2005), the generalized charge distribution of thunderstorms has been shown to at least follow that of a tripole model, with a principal region of negative charge located between two areas of positive charge. However, depending on the convective organization, Stolzeburg et al. (1998b) has shown as many as five main charge layers could be present in the vertical. Since a negative charge dominates near the base of the thunderstorm, the preceding explanations of charge distributions could describe the development of negative cloud-to-ground lightning flashes[5] (NCG) with a minimal amount of effort.

Increasing amounts of research, though, are focusing attention toward the phenomena of positive cloud-to-ground lightning (PCG), partly because of their association with many types of severe weather (e.g., Reap and MacGorman 1989; Seimon 1993; Knapp 1994; MacGorman and Burgess 1994; Stolzenburg 1994). Analogous to its negative counterpart, PCGs lower a positive charge to the earth's

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[5] Negative cloud-to-ground lightning flashes are those lightning flashes which lower a negative charge to the ground. Most cloud-to-ground lightning in the continental United States is of this type (Orville 1994; Orville and Huffines 1999; Orville and Huffines 2001).

surface. However, this phenomenon cannot easily be explained with conventional charge distribution theories as described above. In order to do this, Williams (2001), as well as Lang and Rutledge (2002) provided several hypotheses under which a PCG could occur.

Using the tilted dipole mechanism, strong upper-level winds shift the upper positive charge in the thunderstorm. Because of this lateral movement, the positive charge is exposed such that it could be directly transferred to the ground. Note that this explanation could be used to explain PCGs seen in stratiform precipitation or emanating from the thunderstorm anvil. Engholm et al. (1990) stated that this mechanism cannot explain the occasional "predominance of positive events" observed in several studies or PCGs observed in "foul" weather. In conducting research for their own study, Gilmore and Wicker (2002) concluded that this mechanism alone is not sufficient for the generation and subsequent prediction of PCGs.

Supported by most of the recent studies, the inverted polarity mechanism was offered as an alternative to provide an explanation of PCG occurrence. With this mechanism, charge dominance within the thunderstorm shifts toward the lower positive charge. In its simplest form, the charge structure would resemble a negative dipole, with a negative upper-level charge overlaying a positive lower-level charge. It more likely resembles a modified (inverted) tripole structure, through which non-inductive charging processes and storm-scale motions interact to separate positively charged graupel and negatively charged ice crystals. The result is a positive mid-level charge between two negative charges (Rust and MacGorman 2002; Wiens et al. 2005).

Finally, Carey and Rutledge (1998) offered the precipitation-unshielding mechanism as another possible explanation on PCG generation. Utilizing this mechanism, the mass flux of precipitation becomes so large in intense storms such that the negative charge center is either removed or greatly reduced by the fallout of precipitation. Admittedly PCG flash rates could increase through this method, through increased "exposure" of the upper positive charge region. In addition, this explanation appears to be consistent with the scarcity of NCGs observed in storms which are PCG-dominated (PSD) or produce low numbers of cloud-to-ground lightning flashes.

2. Climatology

a. Thunderstorms

The distribution of thunderstorms across the continental United States (Fig. 2) has been described in studies conducted by Changnon (1988a, 1988b) as well as Court and Griffiths (1992). These studies show that most of the thunderstorms across the United States occur over the central and southern part of the country on an annual basis. An annual maximum is noted along the central Gulf Coast and Florida Peninsula, primarily due to summertime seabreeze effects. The amount and duration of thunderstorms diminishes as one heads north and east of this area, to a minimum across the Mid-Atlantic States. It is interesting to also note that most of the central and southern United States also experiences a nocturnal maximum in thunderstorms. The exception to this region is the Southeast Atlantic coast and Florida Peninsula, a daytime maximum is noted due to convection along the seabreeze.

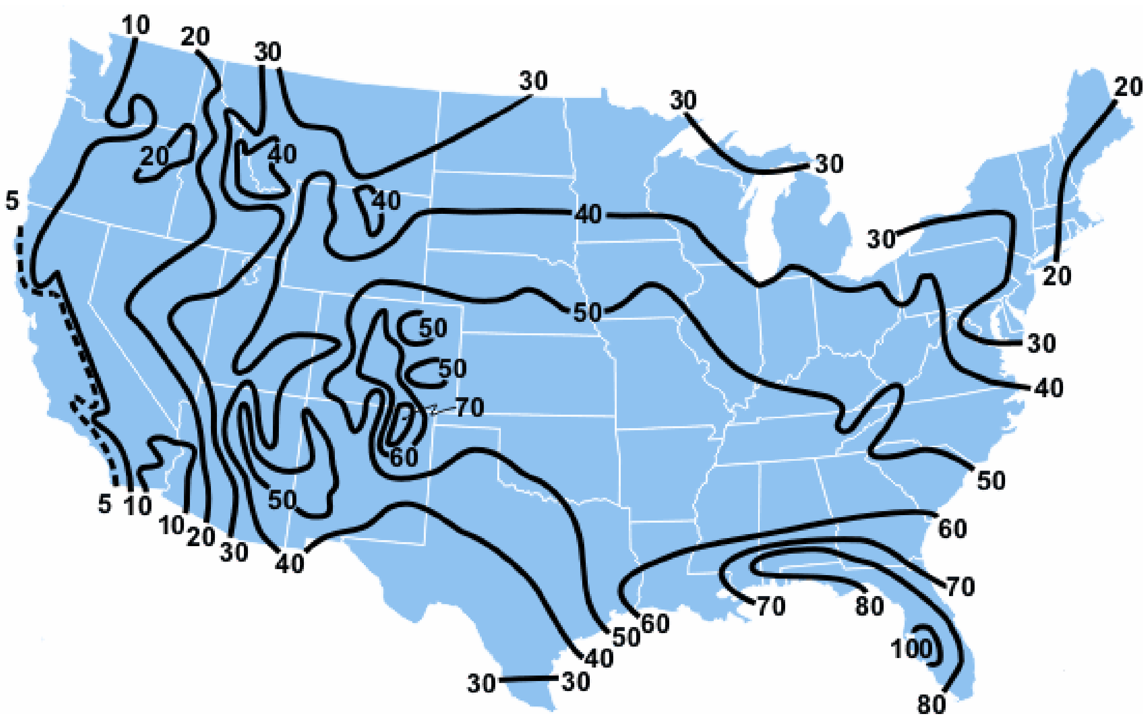

FIG. 2. Distribution of thunderstorms across the continental United States (NOAA 2006).

A relative maximum in thunderstorms remains near the Central United States throughout the year. However, the maximum shifts southeast into the Lower Mississippi River Valley during the cool season of the year (October through March). As suggested by Changnon (1988b), the shift appears to be closely aligned with the mean storm tracks that progress through the region.

Most climatological thunderstorm studies since the middle twentieth century have used the unit of a thunderstorm day[6], rather than individual thunderstorms. This

[6] Using the World Meteorological Organization definition stated in Court and Griffiths (1992), a thunderstorm day is "a local calendar day on which thunder is heard, … regardless of the actual number of thunderstorms."

was primarily because of the difficulty weather observers would have in discerning which storm (or group of storms) is responsible for producing the "rain, hail, lightning, and thunder" reported in a weather observation (Court and Griffiths 1992). However, several problems have been noted with this method (Changnon 1988a, 1993; Reap and Orville 1990; Court and Griffiths 1992; Huffines and Orville 1999;). First, because of the subjective nature of weather observations, reports of thunder may or may not coincide with the true beginning and ending of the storm. While thunder can be heard up to 20 km from the observation site, the actual distance at which thunder may be heard is dependent on many factors, including station noise level and atmospheric conditions. Other responsibilities held by the observer may also affect the time at which thunder is reported in a weather observation. Second, a thunderstorm occurring at midnight results in a report being attributed to two days. This practice may affect the number of nocturnal thunderstorms across parts of the United States. Instead of the thunderstorm day, Changnon (1988a, 1988b) used thunder reports in his studies, which were obtained from weather observations. Unfortunately, this method also suffered from the limitations stated above.

b. Lightning

Reap and Orville (1990) utilized what was to evolve into the National Lightning Detection Network (NLDN)[7] to conduct early research on the relationship between thunder reports in surface observations and cloud-to-ground lightning flashes. Expanding to cover the Continental United States, subsequent papers by Huffines and

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[7] Details on the NLDN are given in Chapter III.

Orville (1999), Orville and Huffines (1999, 2001), Zajac and Rutledge (2001), and Orville et al. (2002) investigated such parameters as flash density, peak current, multiplicity, and the percent of PCG lightning flashes.

Results from these studies (Fig. 3) indicate relatively high flash densities (> 4 flashes km^{-1}) stretch across much of the Central, eastern, and southern United States. The highest flash density, with more than 9 flashes km^{-1}, extends from the Florida Peninsula northward to and extends across the Central Gulf Coast. However, cloud-to-ground lightning flashes in this region appear to be characterized by lower values of negative peak current, with widespread values of 15 to 20 kA noted. Cloud-to-ground lightning flashes in the region extending from the Colorado/Kansas border region, northward into eastern South Dakota and northwestern Minnesota possess lower flash densities, with values ranging from 0.1 to 3 flashes km^{-1}. Despite this, NLDN data indicates this region has the highest percentage of PCG lightning flashes in the country (Fig. 4), as well as the greatest values of median positive peak current, with values of 40 kA or larger. The highest values of NCG lightning stroke multiplicity (more than 2.5 strokes) extended from the Upper Midwest into Southwest Texas and over the Florida Peninsula, northward to the South Carolina Coast. Meanwhile, PCG lightning stroke multiplicity showed the greatest values, 1.3 flashes or more, over the Upper Midwest. Also, studies by Huffines and Orville (1999), Orville and Huffines (1999, 2001), Zajac and Rutledge (2001), and Orville et al. (2002) showed that the percentage of PCG lightning flashes increased in thunderstorms during the cool season.

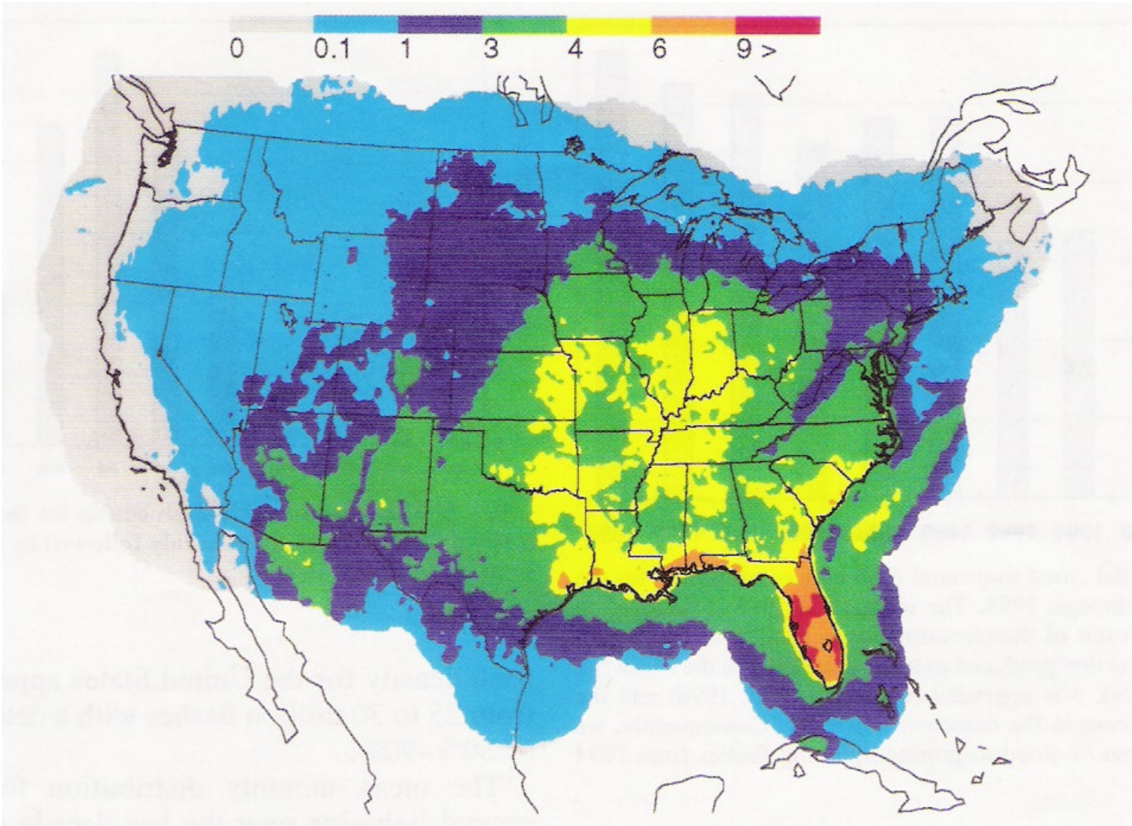

FIG. 3. The mean annual flash density for the continental United States from 1989-1998 from Orville and Huffines (2001).

It is worthy to note that, when comparing the annual occurrence of thunderstorms across the United States, trends noted in studies utilizing NLDN data compared favorably to previous research, which used either thunderstorm days or the report of thunder in a weather observation. As pointed out by Huffines and Orville (1999), NLDN data have the potential to "provide more comprehensive coverage of the United States than previous first-order thunder allowed."

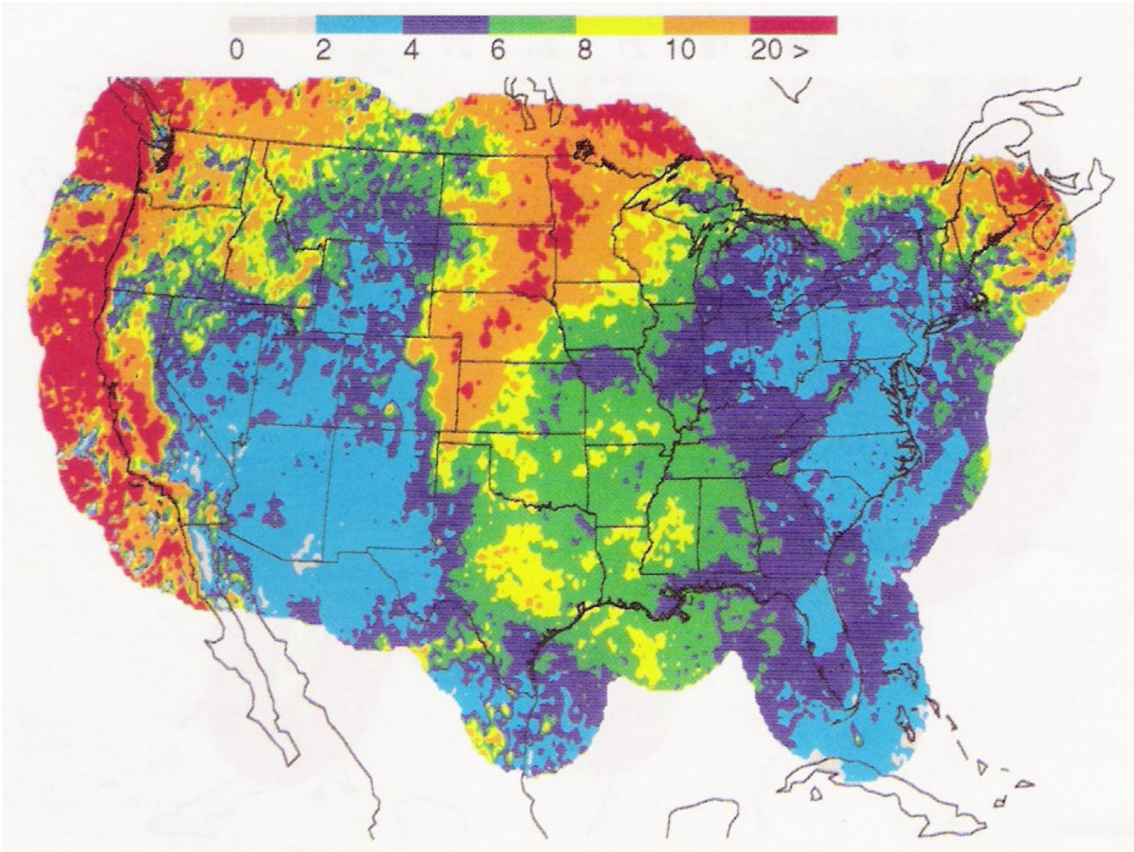

FIG. 4. The percentage of positive cloud-to-ground lightning strkes across the continental United States. Image from Orville and Huffines (2001).

c. Tornadoes

The climatological distribution of tornadoes is equally important to this study. Many of the tornadoes across the United States are traditionally described as occurring in a region known as Tornado Alley, which encompasses much of the Central and southern Plains (Bluestein 1993). Research by Kelly et al. (1978) and Brooks (2003) have shown that tornadoes are most frequent in an area extending south and west from East Kansas, encompassing much of Oklahoma, into North Texas. Tornadoes in this region frequently occur during the late afternoon and early evening, coincident with a maximum in instability, mainly from early May to mid June.

Concannon et al. (2000) looked at the mean number of tornado days[8] (Fig. 5) for strong and violent tornadoes (those with Fujita Scale ratings of F2 or greater). They discovered that a majority of these tornadoes occurred in a band from Southwest Iowa to Central Oklahoma across to extreme West-Central Alabama. The authors also looked at the annual tornado threat cycle, comparing locations in the southern Plains (e.g., Oklahoma City and Dallas/Ft. Worth) to locations in the Southeast (Northwest Alabama and East Mississippi). Their research indicated that when compared to Oklahoma, Northwest Alabama had a less consistent maximum probability of strong and violent tornado occurrence during the spring. However, Northwest Alabama had a more consistent maximum probability of strong and violent tornado occurrence in the fall. When looking at the annual cycle, the study showed the dates in which the peak threat of strong and violent tornadoes occurring had much greater variability in East Mississippi than the Dallas/Ft. Worth Metroplex. Information such as this indicates the risk of seeing strong and violent tornadoes across the Southeast United States is much more equally distributed throughout the year.

For the cool season[9], tornado probability plots from Brooks (2003), shown in Fig. 6, indicate the greatest risk of tornadoes across the Arklatex region, east across the Lower Mississippi and Tennessee River Valleys. Within this area, the greatest risk of

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[8] The tornado day is similar in concept to a thunderstorm day. According to the authors, this method was used primarily because it has been more consistent through time.

[9] Defined here as the period of time from 1 October to 31 March.

seeing strong or violent tornadoes is greatest from South-Central Arkansas into North Alabama. This region has come to be known as Dixie Alley.

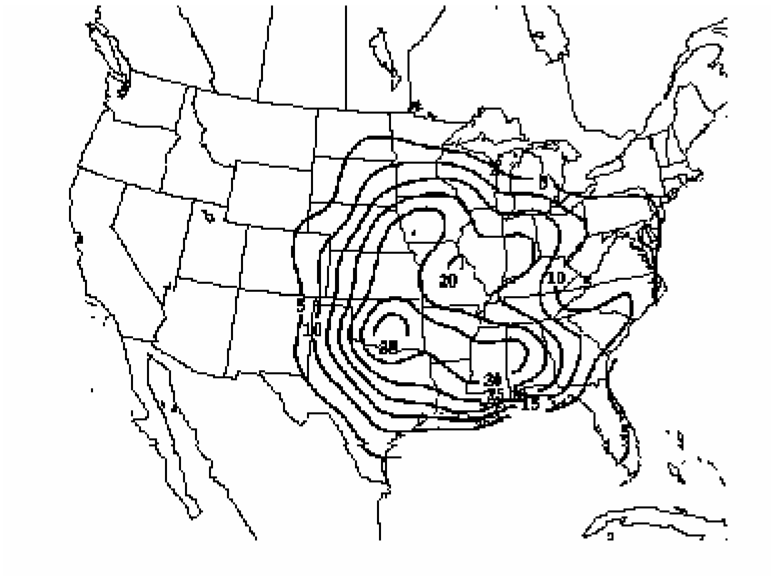

FIG. 5. Mean number of days per century with at least one strong or violent tornado touchdown. Image from Concannon et al. (2000).

Using Storm Prediction Center data, Gerard[10] (2006, personal communication) recently compared statistics between Dixie Alley and the traditional Tornado Alley. Their research broadly agrees with the information presented in prior research (Concannon et al. 2000; Brooks 2003) in showing a greater frequency of strong and violent tornadoes between October and March. Unlike Tornado Alley, though, it appears there is a greater risk for fatalities associated with strong and violent tornadoes

[10] Mr. Alan Gerard is the Meteorologist-in-Charge of the National Weather Service Forecast Office in Jackson, MS. The recent informal tornado research was conducted by A. Gerard, J.P. Gagan, and J.D. Gordon. Results are available upon request.

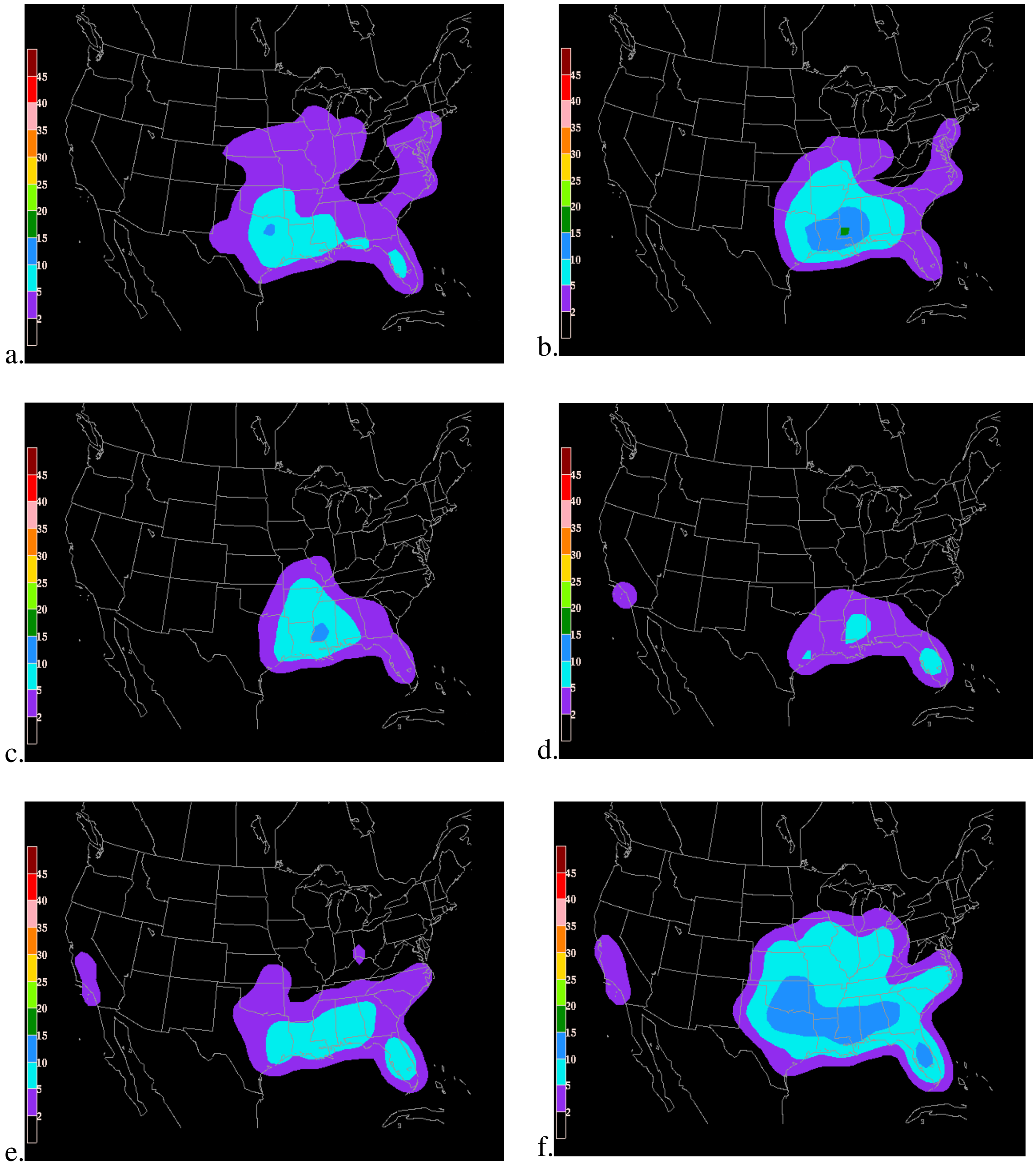

FIG. 6. Probability of seeing a tornado within 25 miles of a point during a given month during (a) October, (b) November, (c) December, (d) January, (e) February, and (f) March. Images are from 1980 to 1994 and from Brooks (2003).

across Dixie Alley. While the diurnal distribution of tornadoes is similar to Tornado Alley, it appears there is a greater loss of life associated with tornadoes which occur between 0600 and 1200 UTC. Gerard and collaborators also noted that while more tornadoes occurred overall in Tornado Alley, Dixie Alley possessed about 1.5 times as many strong tornadoes when compared to Tornado Alley. With nine days in which ten or more strong tornadoes occurred, Dixie Alley also had more outbreaks of strong tornadoes than the traditional Tornado Alley. Hence, it is important to have effective tornado forecasting tools available to warning forecasters, especially those in the Southeast United States, during the cool season.

3. Previous research

Understanding the relationship between tornadoes and lightning has been an active area of research. Many studies dealing with this topic have been finished, especially since the completion of the NLDN in 1989. A large majority of these projects have dealt with warm season convection, with topics broadly falling in one of two areas: 1) environmental trends, and 2) cloud-to-ground lightning trends and tornado evolution. The remaining subsections will better describe each of these areas.

a. Environmental trends

Smith et al. (2000) as well as Gilmore and Wicker (2002) have investigated the possible relationship between polarity changes, thunderstorm structure, and low-level environmental conditions. Smith et al. used NLDN, radar, surface, and satellite data in order to correlate changes in the cloud-to-ground lightning field associated with tornadic storms to surface θ_e fields. In the study, the authors noted that most of the predominately negative tornadic storms developed in a weak θ_e gradient and downstream of a maximum in θ_e (i.e., to the right of a θ_e ridge axis), then subsequently moved into a region with lower values of θ_e. Predominately positive tornadic storms generally developed in strong θ_e gradients, upstream of a maximum in θ_e (i.e., to the north and west of a θ_e ridge axis). The predominantly positive group of thunderstorms can then be organized into two groups. One group will remain in the strong θ_e gradient, essentially moving parallel to the θ_e ridge axis. As another group of thunderstorms moved across the θ_e ridge axis, surface moisture began to decrease and the dominant polarity of the tornadic thunderstorms changed. It was also reiterated that changes in updraft strength may be reflected in the electrical structure of the associated thunderstorm.

Gilmore and Wicker utilized NLDN and mobile mesonet data, radar information, and proximity soundings to document any changes in thunderstorm behavior to the mesoscale environment. They found that, given a pre-existing boundary, cloud-to-ground lightning characteristics would be determined by the location in which the storm developed and the movement of the severe storm. If the thunderstorm crossed the boundary, the thunderstorm usually became dominated by PCG lightning flashes within an hour of boundary crossing. On the other hand, if the thunderstorm developed either on the warm side of the boundary, or on the boundary and moved toward the cooler conditions, NCG lightning flashes were noted.

b. Cloud-to-ground lightning trends and tornado evolution

NLDN data have been widely used in order to discern what signal, if any, could be used in order to improve meteorologists' detection of severe weather, more specifically tornadoes, within the operational environment. Studies such as MacGorman and Burgess (1994), Bluestein and MacGorman (1998), and Carey et al. (2003b) have used PCG lightning in an attempt to infer a relationship between lightning field trends and tornadogenesis. Bluestein and MacGorman, as well as MacGorman and Burgess mention that the most damaging tornado occurs after a peak in PCG lightning flash rates, whenever flash rates exceed 1.5 min^{-1}. This was clearly not the case with the violent Spencer, South Dakota tornado, in which Carey et al. showed a dramatic increase in PCG lightning flash rates associated with tornadogenesis and, more importantly, around the commencement of F4-rated damage.

Still others investigated possible signals utilizing both both positive and negative cloud-to-ground lightning flashes. Seimon (1993), Knapp (1994), and Perez et al. (1997) noted that cloud-to-ground lightning flash rates were greatest as much as 15 to 20 minutes prior to tornadogenesis. After a precipitous drop in cloud-to-ground flash rates, the authors indicate tornado development is usually observed, generally coincident with a descent of a radar-observed reflectivity core. Knapp adds this "pulsing"[11] signature was stronger in tornadic storms dominated by PCG lightning flashes, generally agreeing with both MacGorman and Burgess (1994) and Bluestein and MacGorman (1998).

Changes in the predominant cloud-to-ground lightning polarity of tornadic storms have also been noted by several authors (Seimon 1993; Bluestein and MacGorman 1998; McCaul et al. 2002). In each of the cases researched by these authors, the dominant cloud-to-ground lightning polarity switched from positive to

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[11] This is Knapp's term for the "peak-lull-peak" trend observed in cloud-to-ground lightning flash rates.

negative around the time of tornado development. Considering the study described earlier by Smith et al. (2000), the polarity switch was probably indicative of dynamical changes occurring within the tornadic storm incipient of tornado production.

Obviously, these relationships are rather preliminary in nature, as the conditions under which tornadoes develop and subsequently move vary greatly. As Carey et al. (2003b) noted, for utility in an operational environment, any type of signal must consistently be seen to precede the onset of severe weather. Still, though, Perez et al. (1997) states that these trends may provide some utility in determining severe weather risk, especially if they are used in conjunction with Doppler radar and other observational data.

4. A ten-year look at the CG lightning and severe thunderstorm relationship

Carey et al. (2003a) used data from the NLDN, Storm Prediction Center, and National Centers for Environmental Prediction (NCEP) to examine many of the parameters discussed in the above section. Defining a severe thunderstorm as one which contained a tornado or hail larger than 1.9 cm in diameter, their goal was to look at severe thunderstorm events across the continental United States over a span of ten warm seasons. In particular, they wished to examine the mean monthly frequency of severe thunderstorm events dominated by both positive and negative cloud-to-ground lightning flashes. Using a computer program, the percentage and flash density were calculated for both positive and negative cloud-to-ground lightning flashes observed within "50 km and 0.5 h of each large hail report and 1 km prior to and within 50 km of an initial tornado report."

The resulting data were then sorted into three groups based on the behavior of nearby cloud-to-ground lightning flashes: 1) predominately negative cloud-to-ground lightning (PNCG), which contains more than 90% negative flashes, 2) predominately positive cloud-to-ground lightning (PPCG), which contains more than 50% positive flashes, and 3) high flash density (HFD) PPCG lightning, which meets the criterion of having 0.01 flashes $km^{-2}\ h^{-1}$ or more. The percentage and frequency (normalized to an area of 10 000 km^2 per warm season) of severe thunderstorm reports meeting these criteria were then calculated and gridded on a $1° \times 1°$ grid.

During this ten season period, gridded maps showed most of the severe thunderstorm reports occurred across the Central and southern Plains, consistent with trends shown in previous tornado and hail climatologies. A similar geographical pattern was observed when investigating the frequency of PNCG lightning events. However, when looking at the frequency of PPCG lightning events, it is evident that most of the severe thunderstorm reports associated with this criterion occur between the Rocky Mountains and the Mississippi River, with the greatest frequency noted across the High Plains of western Kansas, eastern Colorado, and the Nebraska Panhandle, which compared favorably to the results presented in Knapp (1994). The location of HFD PPCG severe thunderstorms were highly correlated with the location of PPCG thunderstorms, with the greatest frequency noted in western Kansas, the Nebraska Panhandle, and eastern South Dakota. Because of the low percentage of PPCG thunderstorms over the eastern United States, it appeared as if the occurrence of PPCG severe thunderstorms were highly dependent upon latitude and longitude.

Histograms were also devised for the flash density and percentage of positive cloud-to-ground lightning per severe storm report. Nationally, it was discovered that PPCG lightning was associated with 15% of the severe thunderstorm reports. Additionally, only 10% of the severe thunderstorms met HFD criterion of PCG lightning. Half of this population met HFD PPCG criteria. According to the authors' findings, low flash densities (<0.002 km^{-2} h^{-1}) of PCG lightning were associated with 58% of severe thunderstorm reports.

The mean monthly 0000 UTC θ_e plots were derived from the gridded NCEP reanalysis data fields of temperature, humidity, and pressure at the 0.995 sigma level. These data were restricted to include information only from HFD PPCG lightning days. Findings correlated well with Smith et al. (2000). Research showed that the monthly θ_e ridge axis migrated northwestward during the warm season, which matched the migration of PPCG- and PNCG-related reports. Severe thunderstorms classified as PPCG were found to develop in the strong gradient west through north of the θ_e ridge axis. Meanwhile, storms classified as PNCG developed toward areas with greater mean moisture content. In addition, the authors noted that storm microphysics, kinematics, and lightning behavior were at least indirectly controlled by the near-surface θ_e pattern.

Finally, Carey et al. (2003a) investigated a possible relationship between storm severity and cloud-to-ground lightning polarity. In general, a direct relationship between hail size and percentage of PCG lightning flashes was noted. The relationship between tornado damage intensity and percentage of PCG lightning flashes was not as intuitive. As tornadoes increased from F2 to F3 on the Fujita scale, there was a strong correlation with the percentage of PCG lightning. It was hypothesized that this was the result of a bimodal distribution in the percentage of PCG lightning flashes that was a strong function of geographic location. Measurements of tornadoes at other damage intensities did not show such a trend.

5. Objectives

Even though there is a large volume of work examining severe weather, tornado events, and cloud-to-ground lightning, the vast majority of studies utilize warm season cases. Several studies (Concannon et al. 2000; Brooks 2003; Gerard 2006, personal communication) indicate a greater frequency of tornadoes rated F2 or greater across the southern part of the United States, especially during the cool season. Because of this, it is hypothesized that, when compared to the warm season, the percentage and frequency of tornadoes associated with PPCG lightning over the southeastern United States is significantly higher in the cool season. In addition, this study will document and examine the relationship between cool season tornadoes and cloud-to-ground lightning, effectively extending the warm season results of Carey et al. (2003a). Specific questions to be addressed are as follows:

1. Is there a relationship between cloud-to-ground (especially PCG) lightning and cool season tornadoes?
2. What is the distribution of cool season PPCG storms across the Southeast United States?
3. How does the occurrence of cool season tornadoes and cloud-to-ground lightning compare with that of the warm season?

4. What are the characteristics of cloud-to-ground flashes in cool season tornadoes, especially over the Southeast United States?
5. What is the operational utility of cloud-to-ground polarity for forecasting tornadoes?

CHAPTER III

DATA AND RESEARCH METHODS

1. National Lightning Detection Network (NLDN)

a. Network development

Use of lightning data in an operational environment began in the mid-1970s with the Bureau of Land Management's development of a lightning detection in the western United States for use in forest fire management (Krider et al. 1980). Research networks expanded the system into Oklahoma and New York during the late 1970s and early 1980s. As regional networks continued to grow, lightning detection systems eventually covered the continental United States. While the NLDN formally began in 1987, when data from these regional networks were consolidated, real-time operations were not seen until 1989. Commercial data services for the NLDN were eventually consolidated under Global Atmospherics in the early 1990s (Orville 1991; Cummins et al. 1998a).

Currently, the NLDN operates over 100 sensors across the United States (Fig. 7), utilizing both magnetic direction finder (MDF) and time of arrival (TOA) capability in order to determine the location of cloud-to-ground lightning flashes (Orville 1991; Cummins et al. 1998a). MDF sensors use two or more crossed-loop antennas to investigate the waveform of the return stroke, which is essentially the vertical component of the electrical field (Wacker and Orville 1999a). The amplitude of the waveform's crest is then used to determine the azimuth of the flash by repeatedly moving it's location around a model oblate spheroid until a minimum gradient in error is found. Error sources such as non-vertical lightning channels, background noise, and

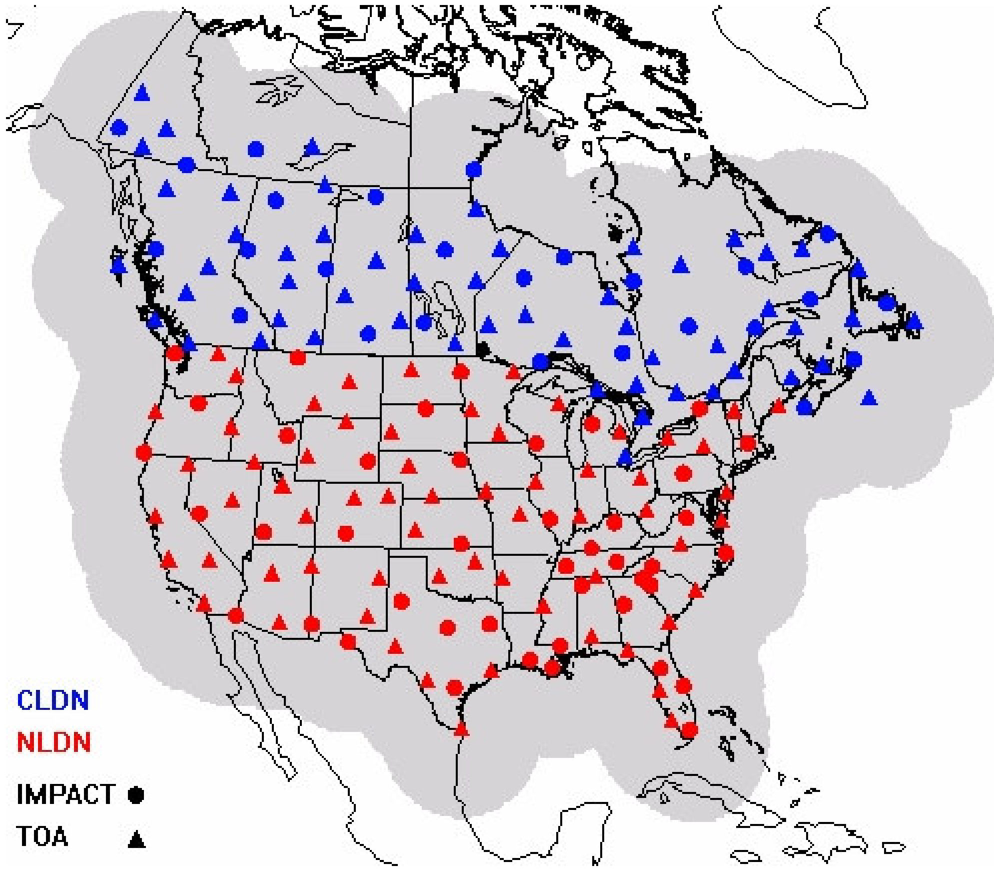


FIG. 7. Location of sensors in the NLDN during the late 1990s (Orville and Huffines 2001; their Fig. 1.)

misaligned antennas could result in the indicated flash azimuth to be different from the true azimuth (Mach et al. 1986). TOA systems, known as LPATS[12] in the NLDN, use at least three antennas to locate flashes by calculating the difference in arrival times for electromagnetic waves associated with cloud-to-ground lightning flashes (Petersen et al. 1996). Other sensors have been part of the NLDN since 1992, which utilize both TOA and MDF technology in order to accurately determine the location of cloud-to-ground

[12] LPATS is an acronym for Lightning Positioning and Tracking System (Cummins et al. 1998).

lightning flashes (Cummins et al. 1998a). These are IMPACT sensors, which is an acronym for Improved Accuracy from Combined Technology.

Cummins et al. (1998a) describe the communications structure and principal error sources in the NLDN. After the sensors acquire data, it is transmitted via satellite to the company's Network Control Center for processing. Here, in under a minute, the information is processed to extract pertinent information on the location, time, and peak current of each cloud-to-ground lightning stroke. The resultant data are then transmitted via satellite and made available for customers. Inherently, two principal error sources exist in NLDN data. Sensor calibration problems primarily arise when the NLDN is undergoing changes which incorporate the relocation or installation of equipment. This could result in errors in the MDF system or in the calibration of peak amplitude. Communication delays tend to be seen only during periods of high data transfer or rain fade.

A single cloud-to-ground lightning flash is comprised of several strokes, which discharge the leader channel. Collectively, the number of strokes contained by a single flash is called its multiplicity. Flash multiplicity, as well as the location, polarity, and peak magnetic radiation field of the first return stroke are measured provided by the NLDN (Orville 1994).

Cummins et al. (1998a, 1998b) describe the flash algorithm in detail. Prior to 1995, all strokes which occurred within one second and 2.5° of the first stroke were counted. This tended to overestimate the true multiplicity, since, relative to the sensors, one or more sensors could detect concurrent flashes at similar azimuths. The current configuration similarly adds strokes to a flash for a period of one second after the first stroke. However, additional strokes must be within 10 km and 500 ms of the first stroke. If the stroke could be assigned to more than one flash, then it will be assigned to the flash with the closest return stroke. In addition, if a stroke is between 10 km and 50 km from the initial stroke and not clearly separated from the flash, the stroke is included in the flash. The maximum multiplicity of any NLDN-detected flash is 15, with additional strokes associated with a different flash. Also, the assigned flash location and polarity is the same as that of the initial return stroke.

NLDN performance is primarily measured through its detection efficiency and accuracy in locating cloud-to-ground lightning flashes. Detection efficiency is simply a ratio of the number of cloud-to-ground lightning flashes recorded to the number of flashes that actually occurred (Orville 1994). The individual detection efficiencies of the sensors, number of sensors detecting cloud-to-ground lightning flashes, and peak current distribution all determine the NLDN's detection efficiency (Cummins et al. 1998a).

b. NLDN upgrades

Several aspects of the NLDN were upgraded during the mid-1990s, as described by Cummins et al. (1998a) and Wacker and Orville (1999). While some of the primary goals of the upgrade were to improve location accuracy and detection efficiency (especially of weak flashes), other goals included improvement of the network's long-term reliability and data delivery infrastructure. Since the IMPACT method provides superior location accuracy over MDF technology alone, MDF sensors, which were part of the original Bureau of Land Management network, were replaced across the western United States in the spring of 1993.

Subsequent improvements to the network were completed in the summer of 1994. In order to allow all MDF sensors to meet IMPACT criteria, sensor gains were increased, pulse width recognition time for return strokes was reduced, and the field overshoot tolerance was increased. These modifications resulted in a greater detection of weak flashes at greater distances. TOA sensors were also modified, primarily to filter the measurement of cloud flashes. The result of these changes was two groups of sensors which detected cloud-to-ground flashes with similar sensitivity.

After the 1994 upgrade, it was estimated that 80 to 90 percent of cloud-to-ground lightning flashes were being detected within a median value of 500 m of its actual location[13]. While this is a great improvement, it produced an increase in the number of detected weak NCG and PCG flashes. This was especially true with PCG flashes, where a substantial increase was noted in those flashes with peak current values between 5 and 15 kA. As Cummins et al. (1998a) points out, at least part of this increase was probably due to an increased detection of in-cloud lightning flashes. As such, they recommended that "the subset of small positive discharges with peak currents less than 10 kA be regarded as cloud discharges unless they are verified to be cloud-to-ground." This procedure has since become common practice in subsequent studies utilizing the NLDN data set.

[13] Prior to 1994, flash detection efficiency ranged between 65 and 80 percent. Location accuracy decreased from as much as 16 km prior to 1992 to 2-4 km prior to the 1994 upgrade.

The most recent large-scale upgrade of the NLDN, as described in Cummins et al. (2006) and Murphy et al. (2006), occurred in 2002. After the inception of the Canadian Lightning Detection Network in 1998 (as described in Orville et al. 2002), location accuracy and detection efficiency improved across the northern border of the United States. However, these problems continued to plague the coastal and southern United States. In addition, an increase in sensor dependability, a reduction in maintenance cost, and the ability to detect some cloud discharges were desired. In order to accomplish these goals, a uniform sensor type was deployed nationwide. The new IMPACT-ESP sensors have resulted in greater sensitivity and improved flash detection efficiency (90 to 95 percent). As such, flashes can be located with as few as two NLDN sensors, meeting the requirement of cloud discharge detection. The result has been a greater number of misclassified in-cloud flashes than what was seen prior to the upgrade, despite improved lightning discharge algorithms.

This presents a problem. Field campaigns indicate around 90% of "positive events" with a peak current less than 10 kA are actually cloud discharges, while approximately 90% of "positive events" with a peak current greater than 20 kA are likely cloud-to-ground lightning flashes. Similarly, further research has indicated that a most of the negative charges seen in PSD storms with a peak current less than 10 kA could also be cloud discharges.

2. Research methodology

As stated in Chapter I, the purpose of this study was to examine cloud-to-ground lightning characteristics in the vicinity of cool season tornado events. To that end, mean monthly cool season tornado probability data from Brooks (2003), presented in Chapter II, were studied in order to determine the study domain. After careful examination of monthly tornado probabilities, areas south of 42° north and east of 102° west (Fig. 8) were included in the study's spatial domain.

This study's period of research included thirteen cool seasons[14] from 1989 to 2002, limited by other data sources used in the study. Since NLDN data are not available prior to 1989 (Orville 1991; Cummins et al. 1998a), this made an ideal starting point for research. At the time this study was initiated, tornado data were only available through the end of 2003. However, in consideration of issues and uncertainty related to the 2002 NLDN upgrade, described in Section 1 of this chapter, it was decided to end research on 31 March 2002.

Reports of tornadoes were obtained in a comma-delimited format from the Storm Prediction Center (SPC). The information presented in their ONETOR database is a subset of local storm report information contained in NOAA's *Storm Data* publication. Information such as the latitude and longitude of touchdown, path length and width, number of injuries and/or fatalities, F-scale rating, and of course, date and time of

[14] Here, an individual cool season is defined by the period between 1 October and 31 March, inclusive. For instance, the "1990 Season" includes the period from 1 October 1989 through 31 March 1990.

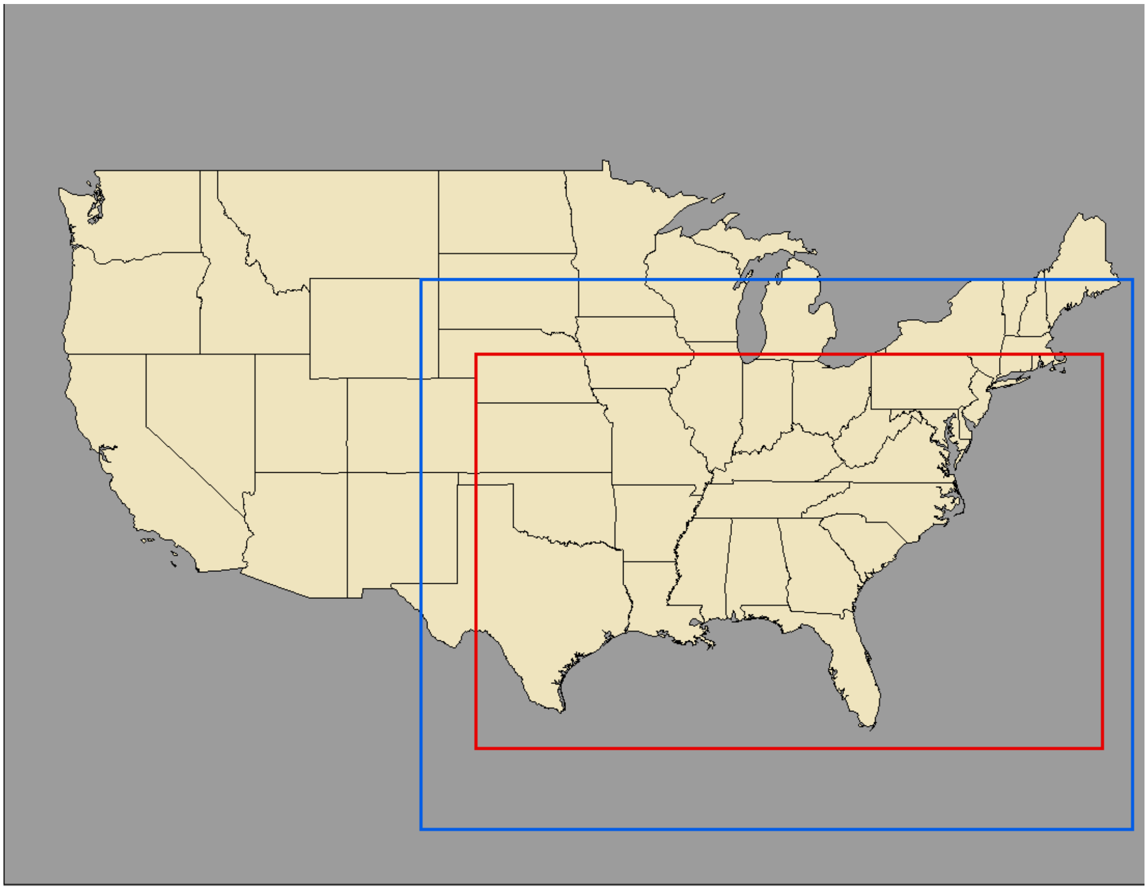


FIG. 8. Approximate location of regions used in this study. The area outlined in blue encompasses the “extraction region” described in the text, generally south of 45°N and east of 105°W. The area outlined in red is the investigation region for this study, generally south of 42°N and east of 102°W.

occurrence are included in the ONETOR database. In order to allow the tornado reports to be easily compared with NLDN data, a series of perl scripts were written by the author in order to properly format the dataset. Data parsing functions were also completed by the scripts, resulting in data extraction based upon specified latitude and longitude criteria. Due to the correlation criteria, anomalously high values of flash density, multiplicity, frequency, and percentage may be seen near the border of the study domain, the extraction region encompassed tornado reports which occurred south of 45° north and east of 105° west (Fig. 8).

NLDN data for the period of study were obtained from the Vaisala Corporation through an agreement with Texas A&M University. A series of IDL scripts were used to isolate data falling in the "expanded domain" specified above. Once this was completed, NLDN lightning events and tornado reports were correlated using a FORTRAN program written for use in the study conducted by Carey et al. (2003a). As specified in the program's documentation, the program uses tornado reports to determine, within a specified temporal and spatial scale, the total number of PCG and NCG lightning flashes, the percent of PCG lightning flashes, flash density for PCG and NCG lightning flashes, the F-scale, and the multiplicity, mean, and standard deviation of peak PCG and NCG peak currents. Pursuant to Carey et al. (2003a), only cloud-to-ground lightning flashes occurring 1 km prior to and within 50 km of the initial latitude and longitude of the tornado was used in this study. The program was executed twice. Initially, it was executed to remove PCG flashes with peak currents under 10 kA (e.g., Cummins et al. 1998a; Wacker and Orville 1999a, 1999b; Carey et al. 2003a) beginning in January 1995 because of the likelihood of misidentified cloud discharges. Second, in order to explore the effect of a 10 kA filter, the program was executed without the 10 kA peak current correction. Using this program, three broad groups of correlated data were obtained for each "tornado day": 1) PCG flash information, 2) NCG flash information, and 3) a large file containing both PCG and NCG flash information.

Once the correlation of cloud-to-ground lightning and tornado reports was completed, individual "tornado days" were concatenated for grouping by annual seasons and the study period. Awk scripts were then utilized to further group data based on cloud-to-ground flash behavior similar to Carey et al. (2003a). Groups included tornadoes associated with: 1) PPCG lightning, 2) a high flash density (HFD; ≥ 0.01 km^{-2} h^{-1}) of cloud-to-ground flashes, 3) "Anomalous" low flash density PCG lightning ($\geq 25\%$ PCG and < 0.01 km^{-2} h^{-1} flash density), 4) at least 1 NLDN-detectable cloud-to-ground lightning flash, and 5) no NLDN-detectable cloud-to-ground lightning flashes. An additional subset of data was also grouped, which included tornadoes associated with storms possessing $\geq 25\%$ PCG lightning flashes. This grouping was largely based on work presented in Knapp (1994), but also completed as part of the Carey et al. (2003a) study. A copy of the resulting files was imported into the PC-based application, Microsoft Excel, in order to facilitate the derivation of frequency histograms and basic statistical parameters.

In order to further investigate cloud-to-ground lighting trends associated with cool season tornadoes, additional work was performed on the files described in the preceding paragraph. Another FORTRAN program utilized in the Carey et al. (2003a) study was modified by the author in order to incorporate the present range of study and generate gridded files in netCDF format. Gridded plots of frequency and percentage were made on a $2° \times 2°$ resolution using the application pltgks.

CHAPTER IV

RESULTS

The specific results of the procedures in Chapter III are described here. However, prior to the discussion of the relationship between cool season tornadoes and cloud-to-ground lightning, it is useful to begin with a description of the dataset in further detail. Subsequent sections of this chapter will explore characteristics of the relationship between cool season tornadoes and cloud-to-ground lightning, especially those flashes which lower net positive charge to the ground. Finally, this chapter will conclude with a section examining PPCG storms.

1. Description of tornado and NLDN datasets

a. Correlated tornado events

Correlation of cloud-to-ground lightning and tornado events provided a dataset of 3325 tornado events available for use in this study (2358 tornado events possessing at least 1 cloud-to-ground flash), with an average number of approximately 181 tornado events per season (Fig. 9). The number of tornado events in a given cool season showed great variation through the study period. Numbers of these events ranged from 93 in the 1992 season to 345 in 1999. The greatest frequency of tornado events, as indicated by Fig. 10, was found in a broad region stretching from South-Central Texas into far West Georgia, where more than 1 tornado per 10 000 km^2 per cool season was indicated. Within this region, up to 2.5 tornadoes per 10 000 km^2 per cool season were noted in localized areas from interior Southeast Texas, northeast into Central Mississippi. Another localized maxima in tornado event frequency was located across Central

Florida, between Tampa and Orlando, with up to 2.5 tornadoes per 10 000 km^2 per cool season noted. Minima, as expected, were located north of this region, most notably over the Appalachians in western Pennsylvania and West Virginia, as well as northern Missouri. These regions exhibited frequencies less than 0.2 tornadoes per 10 000 km^2 per cool season. Keep in mind that this dataset does not provide any indication as to the reason why maxima and minima are shown in these locations and is considered beyond the scope of this study.

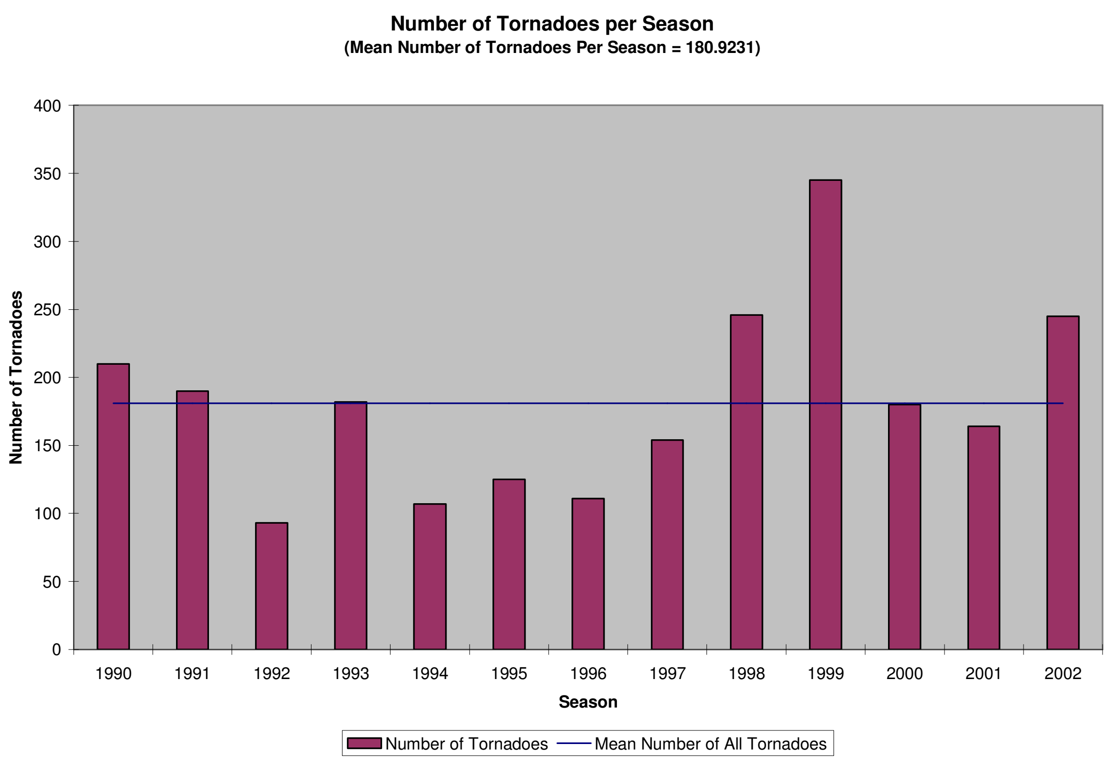


FIG. 9. Frequency histogram indicating the number of tornadoes per cool season. The blue line represents the mean number of tornadoes per cool season during the study period.

Stratification of these tornado events by F-scale is shown in Fig. 11. Fig. 11 indicates that the distribution of cool season tornadoes in the study area is skewed toward weaker (F0, F1) events. Even though the data are distributed similarly to the mean distribution of F-scale groupings ("weak", "strong", or "violent", as described in Chapter I), cool season tornadoes in this region have a slightly higher percentage of weak tornadoes (approximately 78%) when compared to the mean F-scale distribution.

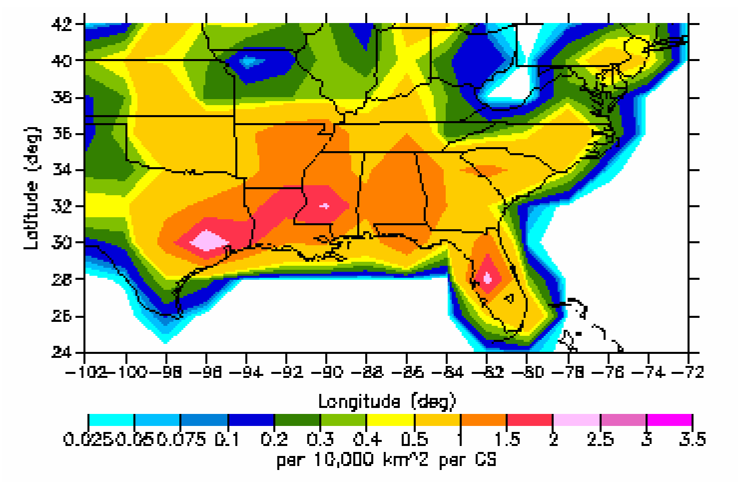


FIG. 10. Gridded map showing the frequency of correlated cloud-to-ground lightning flashes and cool season tornado reports from 1 October 1989 to 31 March 2002. Frequency is normalized to 10 000 km^2 per cool season.

b. Lightning characteristics of correlated tornado events

1) MULTIPLICITY

The mean cloud-to-ground lightning multiplicity for tornado events is shown in

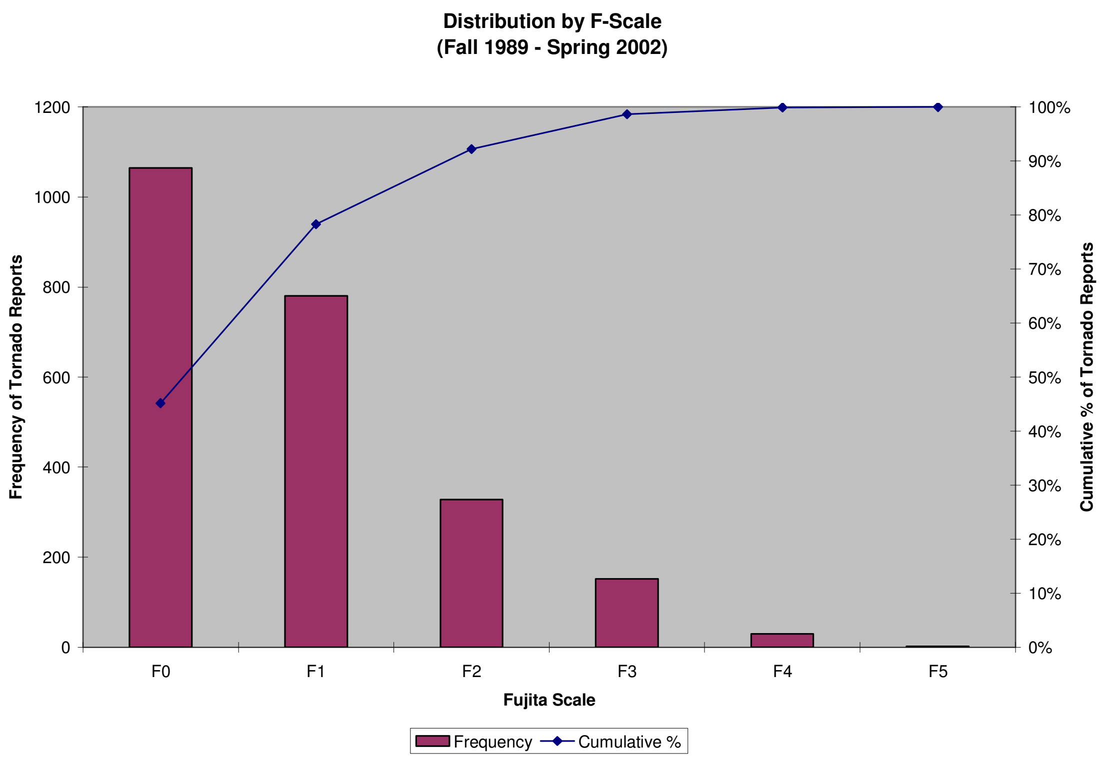


FIG. 11. Histogram showing the distribution of cool season tornado events by F-scale.

Fig. 12 for PCG flashes and Fig. 13 for NCG flashes. On average, these charts show that the multiplicity of NCG lightning flashes is two to three times that of PCG flashes. In fact, roughly 97% of PCG lightning around cool season tornadoes have, on average, 1 to 2 return strokes. On the other hand, almost 62% of NCG lightning flashes have a multiplicity between 2 and 3 strokes, with approximately 90% of the NCG lightning flashes around tornadoes possessing a return stroke multiplicity of 3 or less. This behavior is consistent with other studies documenting the multiplicity of cloud-to-ground lightning (e.g., Orville and Huffines 2001).

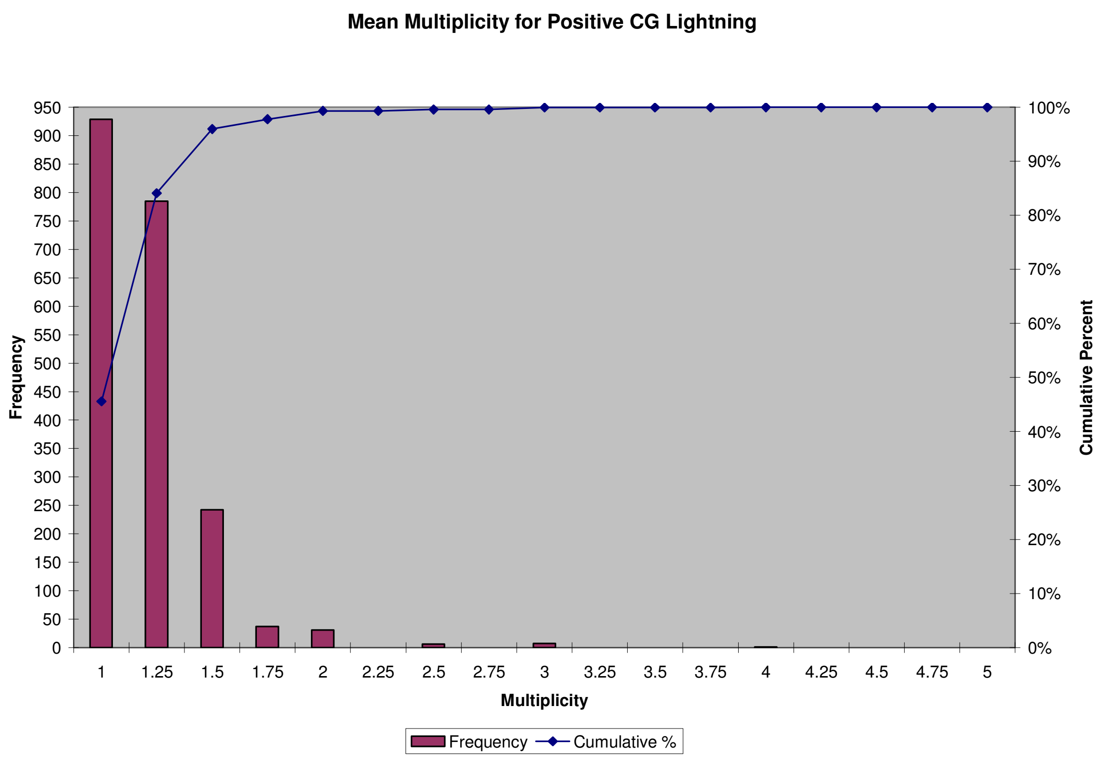


FIG. 12. Histogram showing the mean multiplicity for positive cloud-to-ground lightning flashes associated with cool season tornado events from the Fall 1989 to Spring 2002 cool seasons. Data were binned every 0.25 multiplicity. Values represent the upper extreme of each bin.

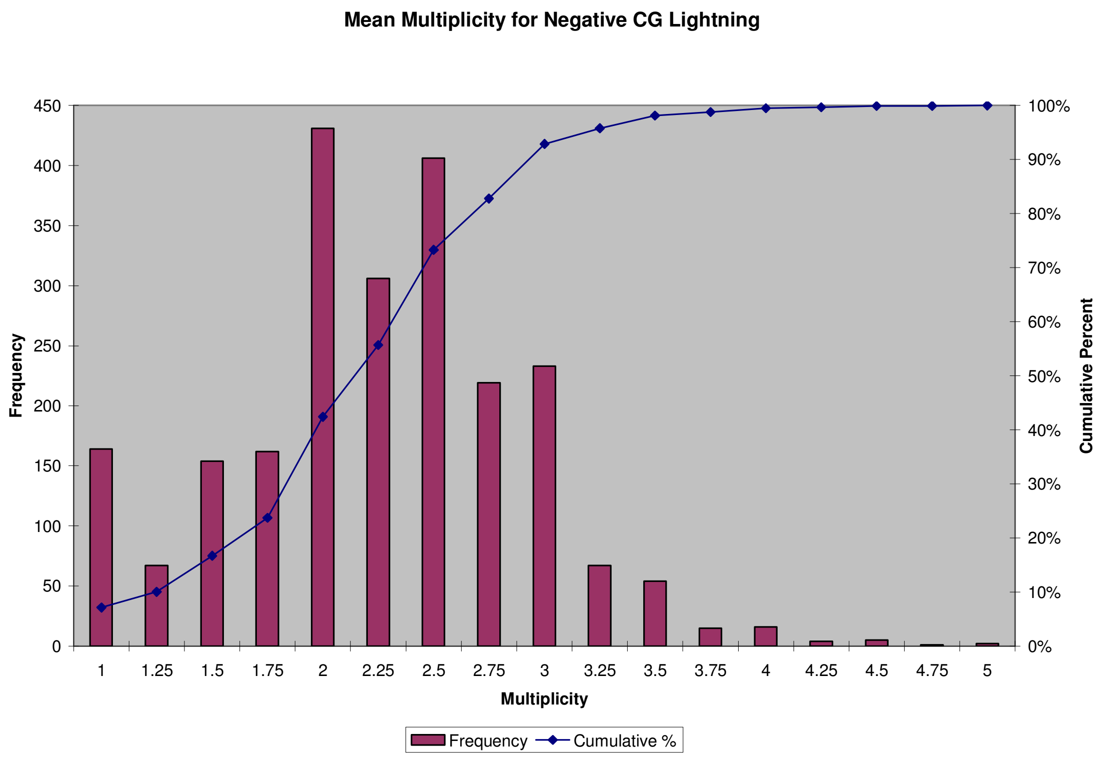


FIG. 13. Same as Fig. 12, except for negative cloud-to-ground lightning flashes.

2) PEAK CURRENT

Histograms showing mean peak current distributions for PCG and NCG lightning associated with tornado events are shown in Figs. 14 and 15, respectively. These charts indicate that most NCG flashes associated with tornado events possess a peak current between 10 and 15 kA, with approximately 71% of NCG lightning flashes indicating a mean peak current less than 30 kA. In comparison, the mean peak current of PCG lightning for most tornado events fall into the slightly more narrow range of 15 to 20 kA, with roughly 75% of PCGs showing a mean peak current less than 40 kA in the vicinity

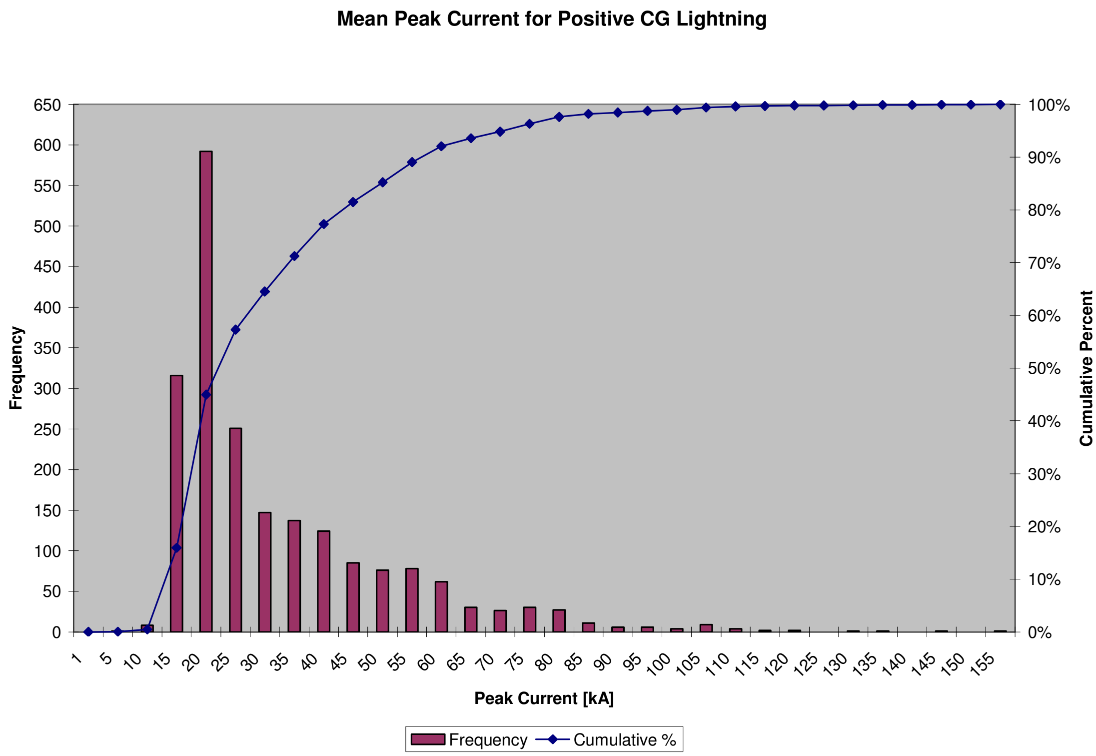


FIG. 14. Frequency histogram of mean PCG peak current in cloud-to-ground lightning flashes associated with cool season tornado events during the cool seasons of 1989 to 2002. Data were binned every 5 kA. Values represent the upper extreme of each bin.

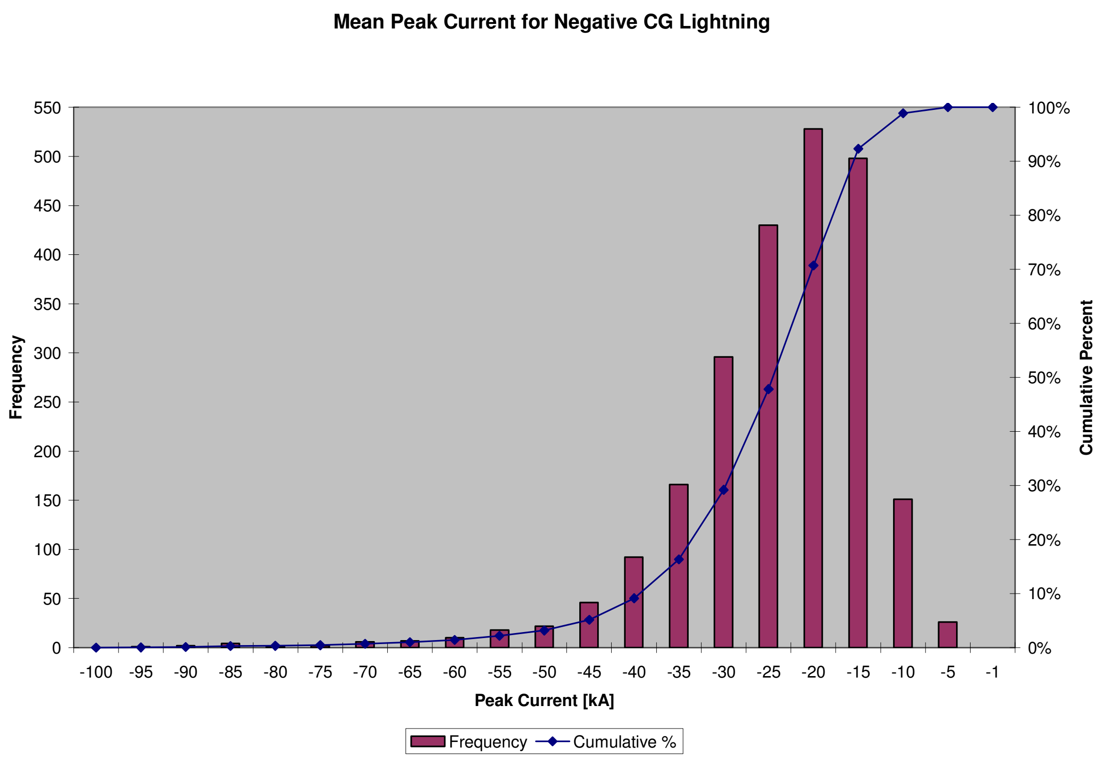


FIG. 15. Same as Fig. 14, except for NCG lightning flashes.

of tornadoes. Almost 90% of tornado events are characterized by a mean peak current less than 55 kA.

3) FLASH DENSITY

Histograms showing the frequency distribution of mean flash density for PCG and NCG lightning (not shown) indicate that cloud-to-ground lightning flashes associated with tornado events are skewed toward lower values of flash density (flashes km^{-2} h^{-1}). Approximately 72% of tornado events have a PCG flash density of 0.0042 km^{-2} h^{-1} or less, with roughly 91% of events indicating a flash density less than 0.0104

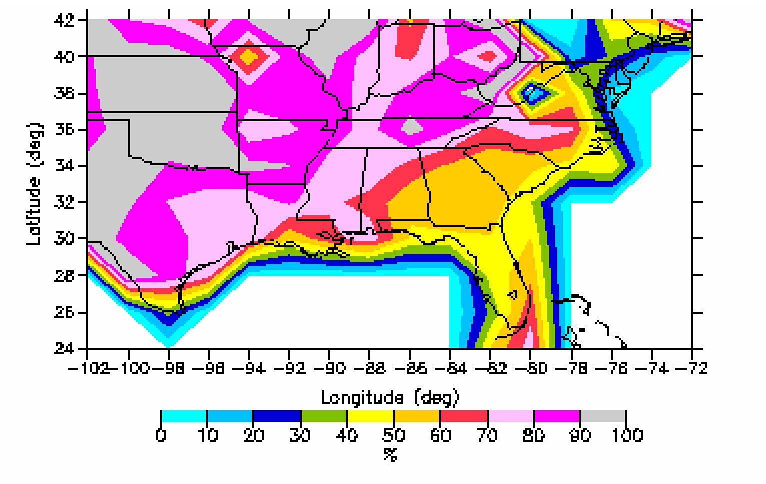
km^{-2} h^{-1}. In general, tornadoes possessed a greater NCG flash density. About three-fourths of tornado events had a flash density of 0.0276 km^{-2} h^{-1}, with 90% of tornado events holding an NCG flash density of 0.0551 km^{-2} h^{-1} or less. It should also be noted that the percentage of tornado events falling under the category of "very low" PCG flash density ($\leq$ 0.001 km^{-2} h^{-1}) is 2.5 times that of very low NCG flash density events.

2. The relationship between cloud-to-ground lightning and tornadoes

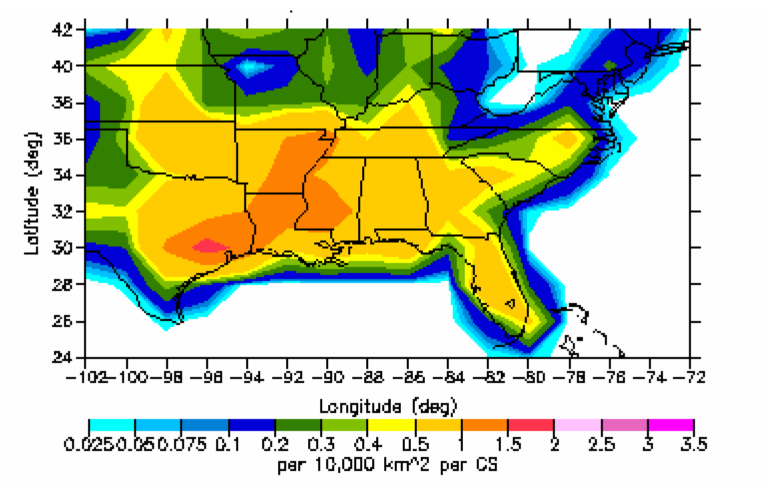
a. Correlated events with at least one NLDN-detectable flash

In general, the percentage of correlated tornado events containing at least one NLDN-detectable lightning flash increases heading inland across the study domain (Fig. 16a). Percentages approach 100% from West Texas into and across most of Oklahoma and Kansas, then fall to as low as 40% along much of the immediate Gulf Coast region and Florida Peninsula. The lowest percentages are seen across the Mid-Atlantic region and the Appalachian Mountains (along the Virginia/West Virginia border), where 10% or less of the tornado reports may be accompanied by lightning flashes detectable by the NLDN. It is interesting to note the localized maxima over the Cumberland Plateau, just west of the Appalachian Mountains. Cloud-to-ground lightning percentages in this region are as high as many locations in the Central and southern Plains.

The frequency of correlated tornado events with at least one NLDN-detectable lightning flash is shown in Fig. 16b. Exhibiting a pattern similar to Fig. 10, a broad regional maximum of at least 1 per 10 000 km^2 per cool season extends from South-Central Texas northeast toward the Missouri Bootheel and Central Mississippi. When combined with Fig. 16a, several inferences can be drawn. In the region of greatest



a.



b.

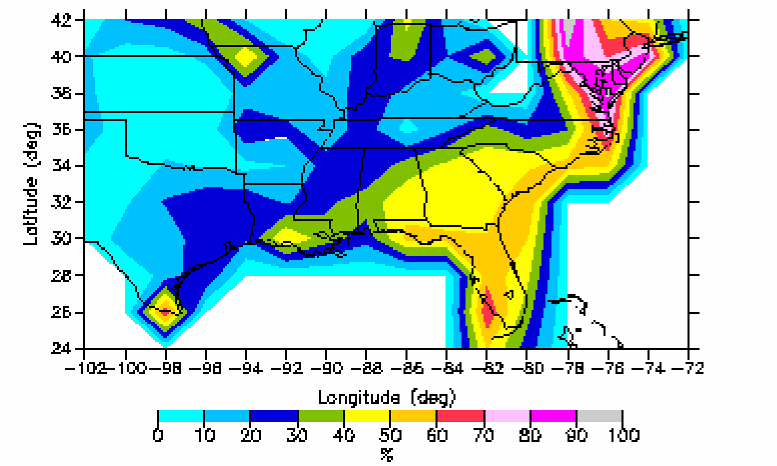
FIG. 16. Gridded maps of cool season tornado events containing at least 1 NLDN-detectable flash. (a) Percentage. (b) Frequency normalized to 10 000 km^2 per cool season.

tornado event frequency (e.g., Fig. 10), generally 70 to 80 percent of the correlated tornado events contain at least one cloud-to-ground lightning flash. While a lower frequency of events is generally found north and west of the region of maximum frequency, a greater percentage of correlated events exist with NLDN-detectable flashes. The exceptions to this trend were found from the Southeast coast toward the Mid-Atlantic region, as well as northern Missouri. In these areas, there appeared to be a direct relationship between event frequency and correlated events, with at least one NLDN-detectable lightning flash observed.

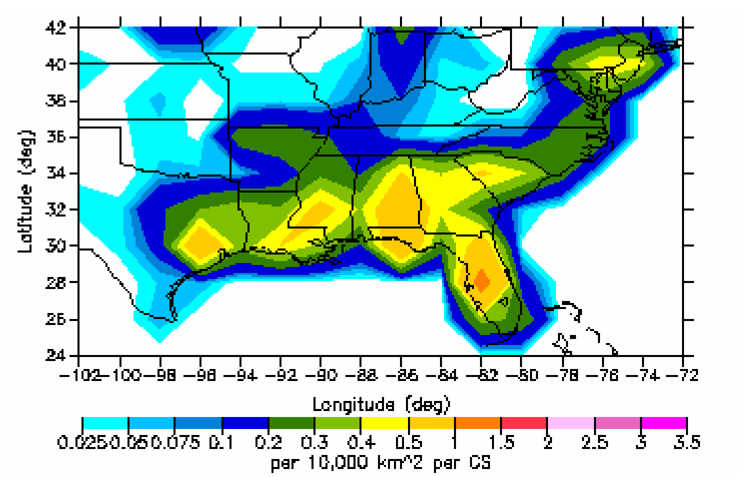
b. Correlated events with no NLDN-detectable flash

Figure 17a shows the percentage of correlated tornado events with no detectable NLDN lightning flashes. The most interesting observation here is that 40% or more of the tornado events do not possess any NLDN-detectable flashes from the Northwest Florida coast into the Mid-Atlantic States. From Maryland northward into Pennsylvania, greater than 60% of the events fall into this category. Other localized maxima were noted across Northwest Missouri, Southwest Florida, and Deep South Texas. In general, areas with less than 30% of correlated events having no NLDN-detectable lightning correspond well with the areas of greatest percentage seen in Fig. 16a.

Most of the events with little or no NLDN-detectable lightning are located near the Mid-Atlantic region. However, they occur with the greatest frequency over Central Florida (Fig. 17b), where up to 1.5 per 10 000 km^2 per cool season occur. Localized maxima in the percentage of tornadoes with no NLDN-detectable lightning occurred across Northwest Missouri and Deep South Texas in Fig. 17a and correspond with a



a.



b.

FIG. 17. Gridded maps of cool season tornado events containing no NLDN-detectable flash. (a) Percentage. (b) Frequency normalized to 10 000 km^2 per cool season.

rather low event frequency (< 0.075 per 10 000 km^2 per cool season) seen in Figure 17b. This indicates that while cool season tornado events meeting this criterion may not occur often in these locations, a relatively high percentage of the tornado events which occur may have no lightning flashes which are detectable by the NLDN. Another interesting observation noted upon comparison of Figs. 17a and b is the relatively high frequency and percentage of tornado events with no detectable NLDN lightning across South Louisiana. Upon consideration of the spatial distribution of NLDN sensors across the Central Gulf Coast (Fig. 7), there does not appear to be a sampling problem with the NLDN in this region. This at least suggests the possibility that something meteorologically different may be occurring here.

3. PCG lightning and tornado events

As referenced in previous chapters, the relationship between PCG lightning and severe weather phenomena has been the subject of significant past research. This section will look at this relationship more closely during the cool season. In order to facilitate this, histograms of PCG lightning percentage (Fig. 18) and flash density (Fig. 19) associated with each tornado event were developed.

As indicated in Fig. 18, approximately 77% of cool season tornado events have a PCG lightning percentage less than 28%. In fact, roughly 13.5% of all cool season tornado events contain no PCG lightning at all. The distribution of events is heavily skewed toward lower percentages, with roughly 86% of events having a PCG percentage less than 40%. With percentages greater than this, the distribution is rather flat, except

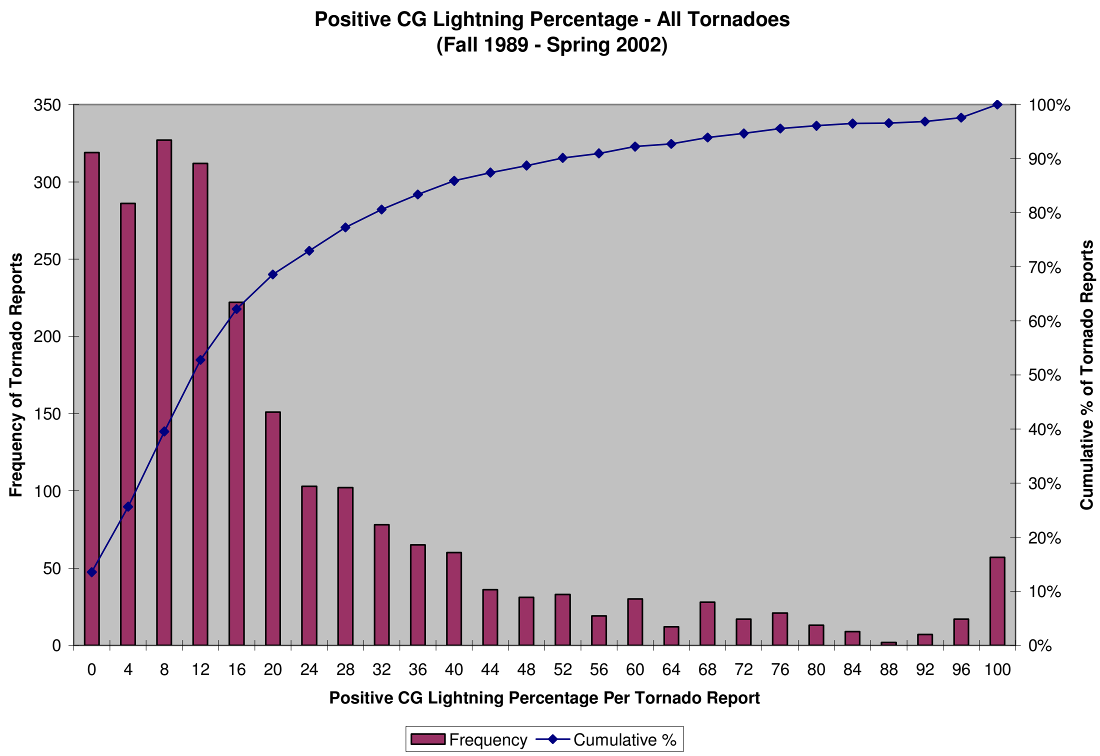


FIG. 18. Histogram showing the frequency and cumulative percentage of PCG lightning percentage associated with cool season tornadoes. With the exception of the first bin, data were binned every 4%. The first bin represents 0% PCG lightning percentage, with values of each successive bin representing the upper extreme.

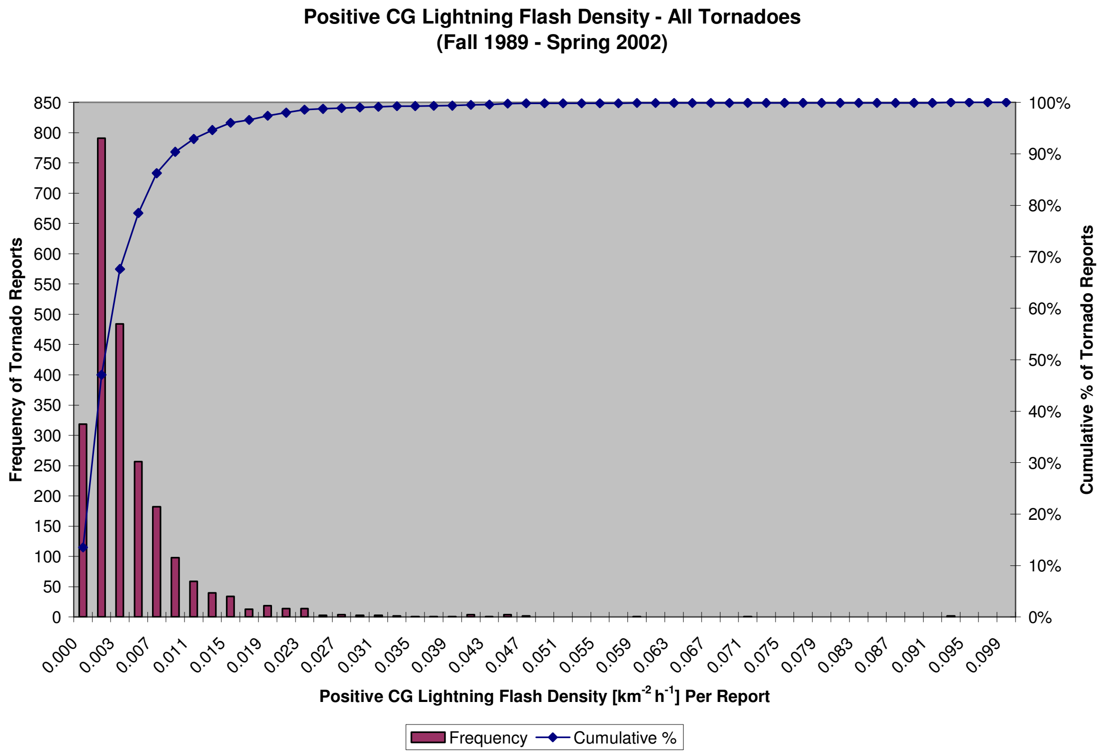
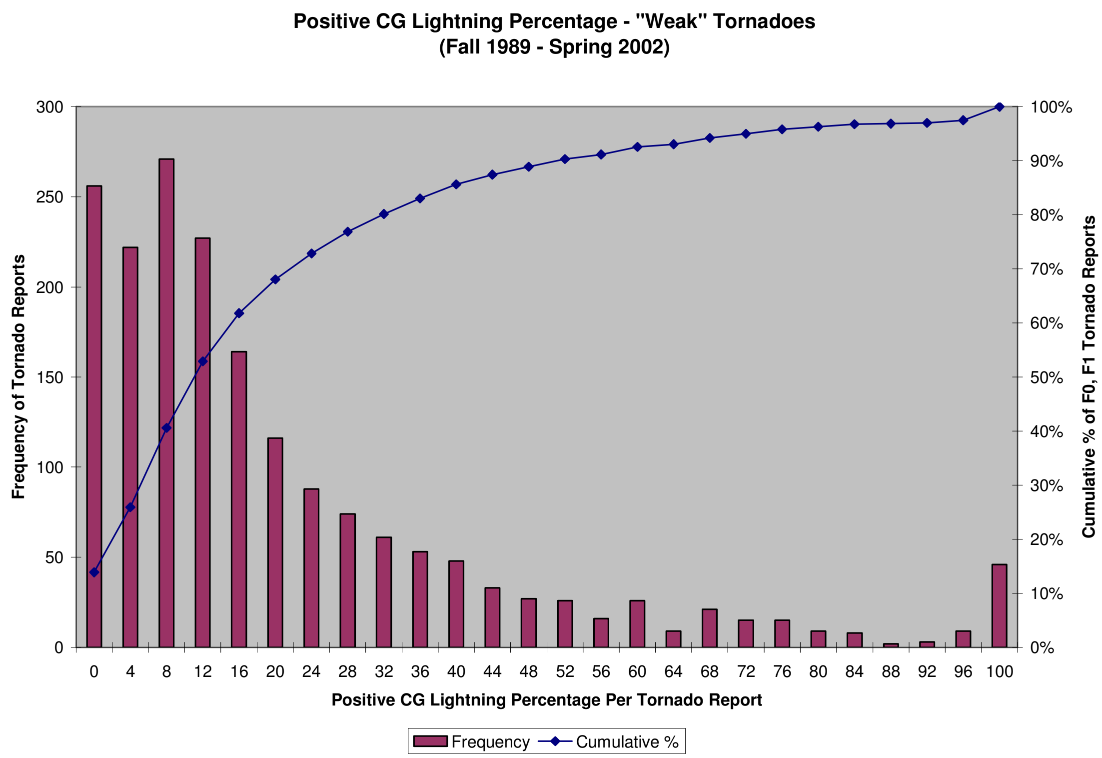


FIG. 19. Histogram showing the frequency and cumulative percentage of PCG lightning flash density [km^{-2} h^{-1}] associated with cool season tornadoes. With the exception of the first bin, data were binned every 0.004 km^{-2} h^{-1}. The first bin represents a flash density of 0 km^{-2} h^{-1} PCG lightning, which is comparative to the 0% bin in Fig. 18. Values of each successive bin represent the upper extreme.

when PCG lightning percentage is 90% or more. The reasoning behind this increase is not known at this time.

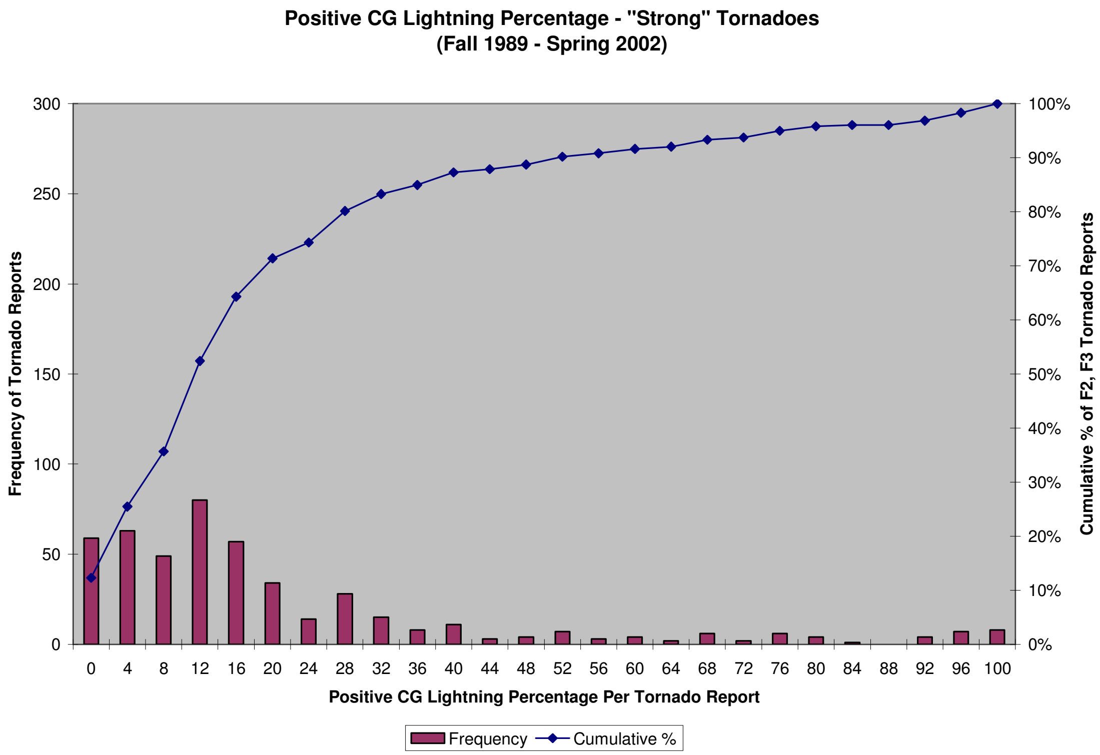
The flash density of PCG lightning flashes associated with cool season tornadoes is shown in Fig. 19. Comparing favorably to Carey et al. (2003a; their Fig. 2b), it shows that almost 68% of the events have a low flash density (< 0.003 km^{-2} h^{-1}). Only 9.6% of events had a flash density which met HFD criterion ($\geq$ 0.01 km^{-2} h^{-1}).

Histograms were used to further investigate PCG lightning percentage and flash density in the “weak”, “strong”, and “violent” data subsets (Figs. 20a-c and 21a-c). As expected, because of their number, trends observed in the correlated cool season dataset are heavily influenced by weak tornado events. These charts reiterate that, at least for tornadoes rated “weak” or “strong” on the F-scale, cool season events generally possess low values of flash density and PCG lightning percentage, regardless of F-scale damage intensity. Because of the infrequency of tornadoes rated F4 or F5, no clear determination could be made as to whether or not this trend is consistent for violent tornadoes. However, it appears as if there is a continued trend toward lower flash densities, with less of a trend observed in the percentage of PCG lightning flashes. Attention was again turned toward the events in which PCG lightning comprised 90% or more of the total cloud-to-ground field. When investigating data falling into the “weak”, “strong”, or “violent” groupings, it was discovered that 3.14%, 3.97%, and 12.90% of the tornado events, respectively met this criterion. Due to the small sample size, it is difficult to determine whether or not the percentage of “violent” tornadoes meeting the 90% PCG lightning criterion is statistically significant. However, if the “strong” and “violent” groupings are combined into a new group containing all tornado events rated F2 or greater (so-called “significant tornadoes”), approximately 4.5% of the events contain 90% or more PCG lightning flashes. After conducting a *t*-test utilizing this dataset, it was determined that this value was not statistically significant at the 95% confidence interval.



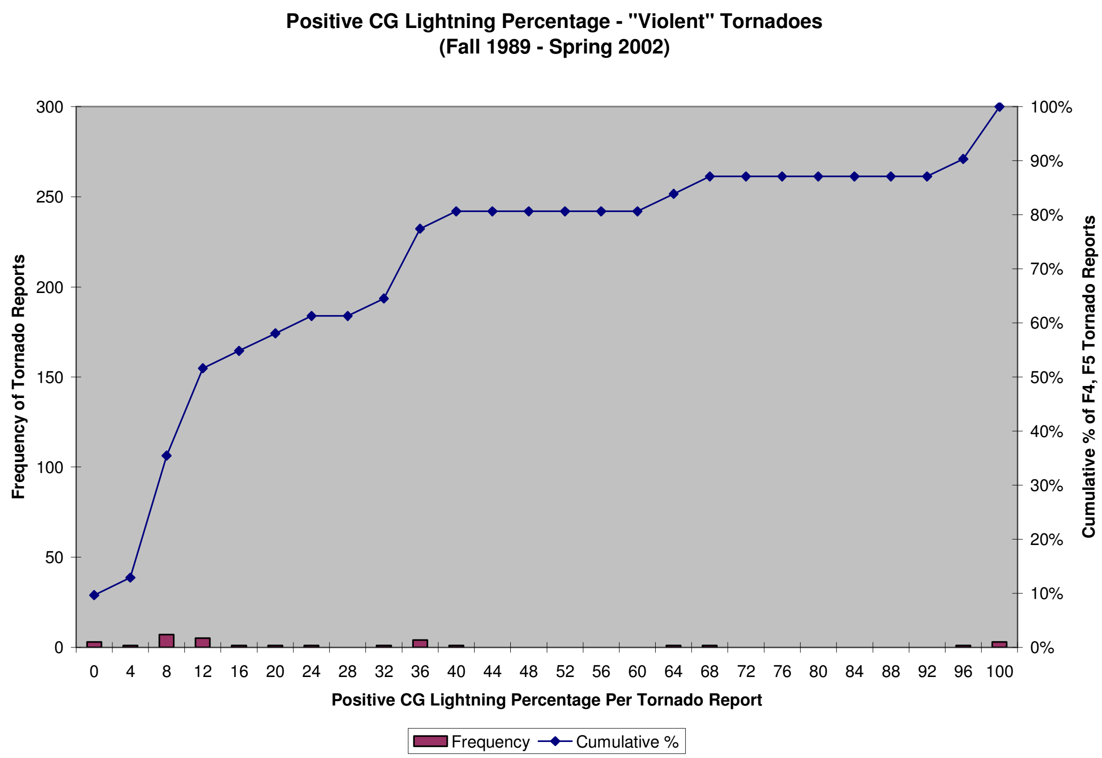
a.

FIG. 20. Histogram showing the frequency and cumulative percentage of PCG lightning percentage associated with cool season tornadoes rated with different damage intensities (a) "Weak", (b) "Strong", and (c) "Violent". With the exception of the first bin, data were binned every 4%. The first bin represents 0% PCG lightning percentage, with values of each successive bin representing the upper extreme.



b.

FIG. 20. *(Continued)*



c.

FIG. 20. *(Continued)*

a.

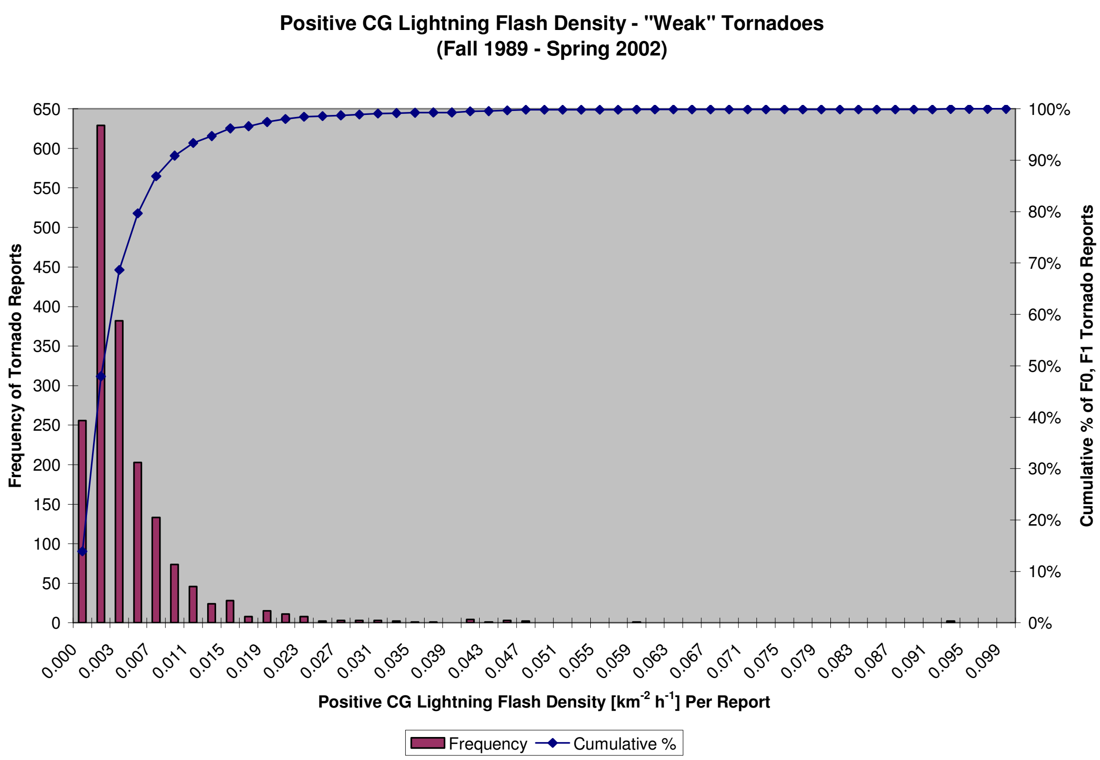


FIG. 21. Histogram showing the frequency and cumulative percentage of PCG lightning flash density [km^{-2} h^{-1}] associated with cool season tornadoes rated with different damage intensities (a) "Weak", (b) "Strong", and (c) "Violent". With the exception of the first bin, data were binned every 0.004 km^{-2} h^{-1}. The first bin represents a flash density of 0 km^{-2} h^{-1} PCG lightning. Values of each successive bin represent the upper extreme.

b.

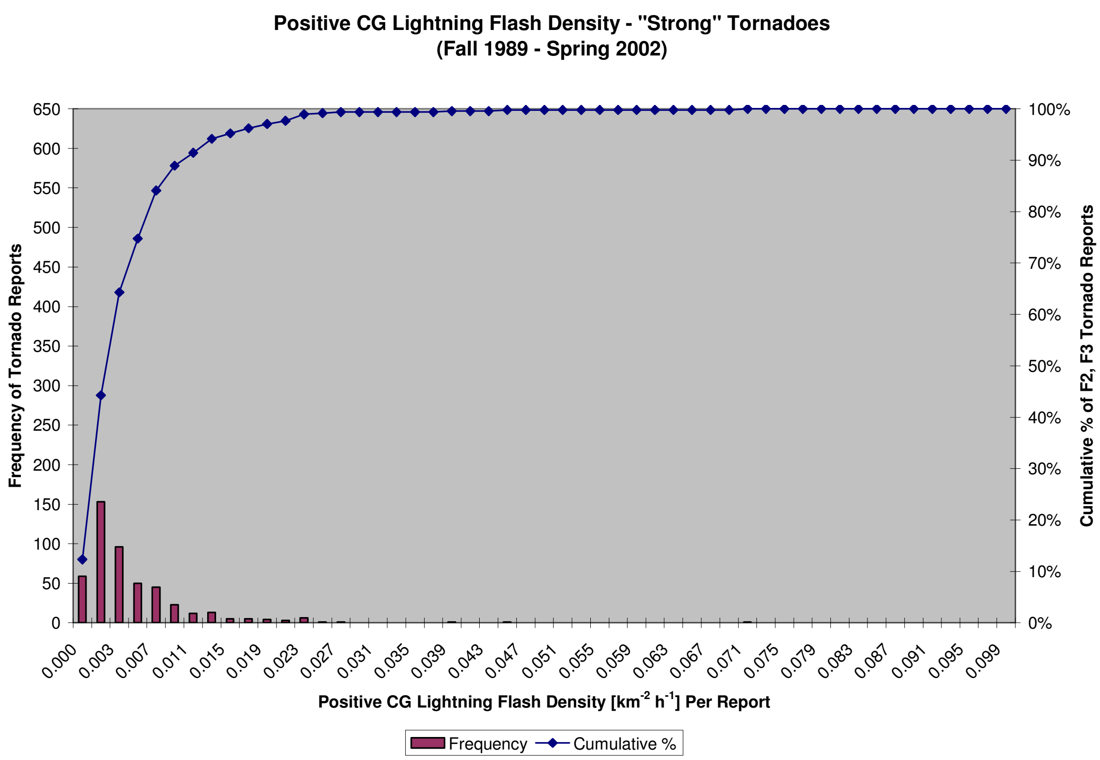


FIG. 21. *(Continued)*

c.

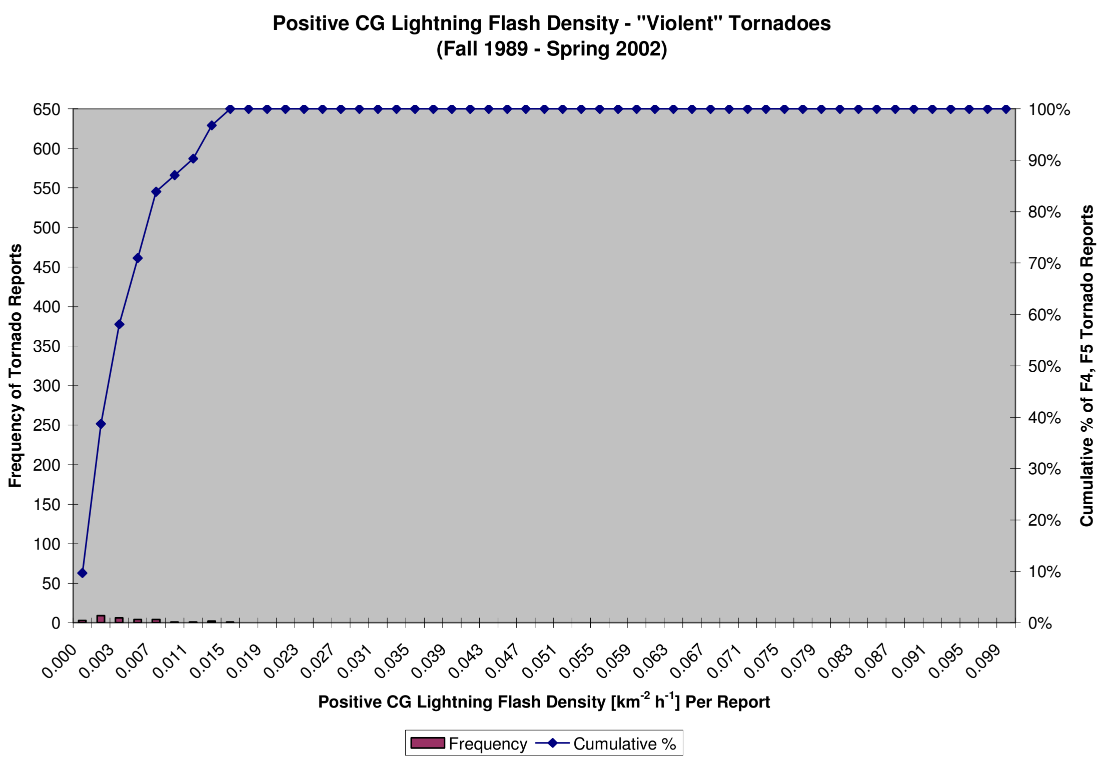


FIG. 21. *(Continued)*

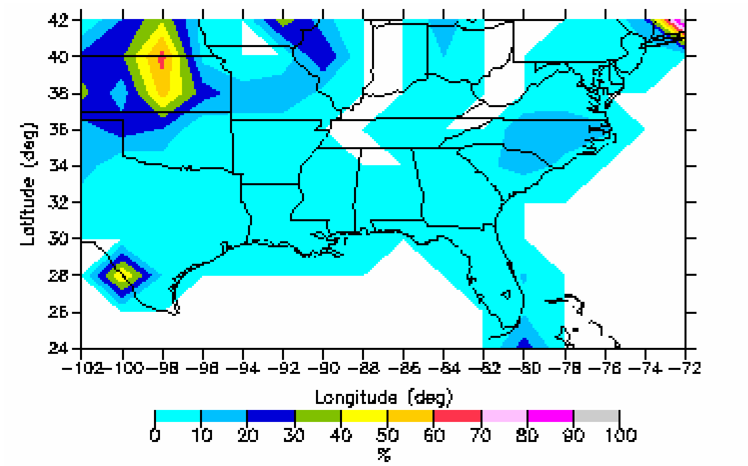
4. Anomalous PCG storms

a. Tornadic storms with more than 50% PCG lightning flashes

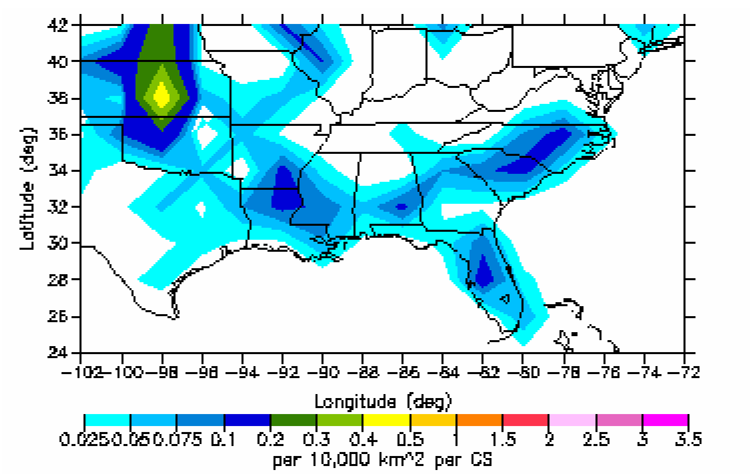
Most prior research, especially for warm season storms, has defined PPCG storms as those storms in which PCG lightning flashes comprise 50% or more of the total cloud-to-ground lightning sample (see Chapter II). This criterion has also been used here in order to investigate cool season tornado events across the study domain. Gridded images (Figs. 22a and b) have been developed to aid in this investigation.

The percentage of cool season tornadoes which met the PPCG criterion was generally low over the study domain. In most places, percentages around 10% or less were noted. Low event frequencies were seen as well across a similar region, with most places reporting less than 0.1 per 10 000 km^2 per cool season. Slightly higher frequencies of 0.1 to 0.2 per 10 000 km^2 per cool season were also noted from Southeast Arkansas into Northeast Louisiana, Northeast South Carolina through East North Carolina, and in Central Florida.

Looking at frequency and percentage maps, the highest values occurred over the Central Plains, from Central Kansas into Central Nebraska. PPCG storms accompanied up to 70% of the tornado events in this region. Frequency values were noticeably lower than those observed in Carey et al. (2003a), with maximum values of up to 0.5 per 10 000 km^2 per cool season. Meanwhile, cool season PPCG storm percentage was comparable to those observed in the Carey et al. (2003a) warm season study. In general, though, observed frequency and percentage trends in this study were geographically similar to those noted in Carey et al. (2003a).



a.



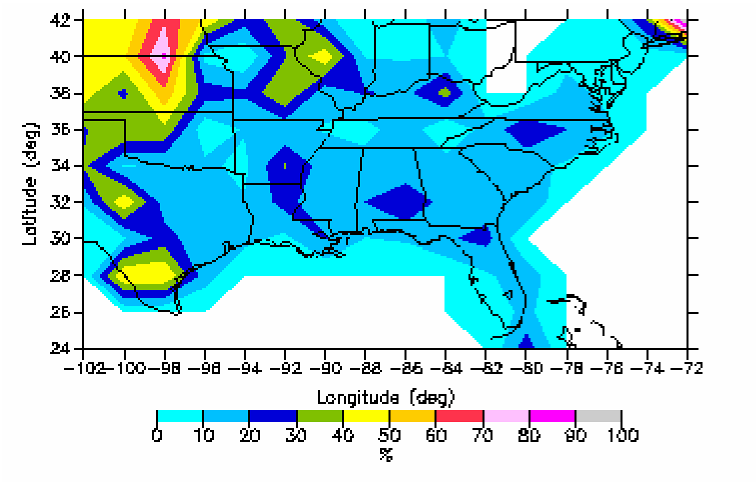
b.

FIG. 22. Gridded maps of cool season tornado events whose total cloud-to-ground lightning met traditional PPCG criterion (> 50% PCG lightning) during the 1990-2002 cool seasons. (a) Percentage. (b) Frequency normalized to 10 000 km^2 per cool season.

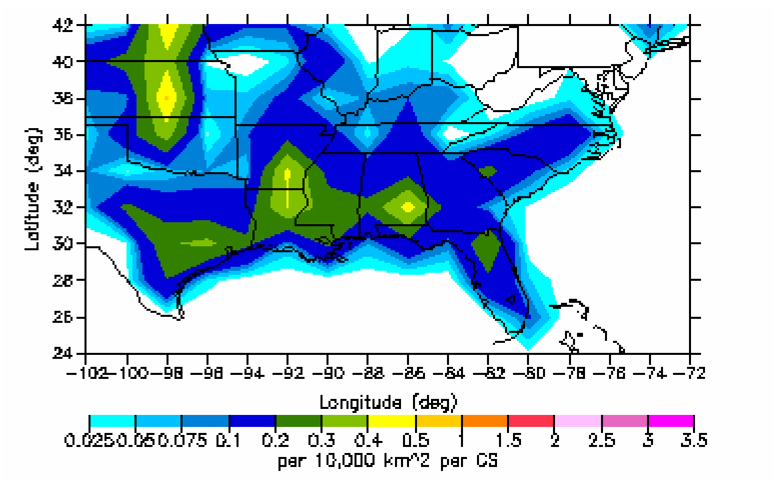
b. Tornadic storms with more than 25% PCG lightning flashes

Because of the low occurrence of cool season tornado events meeting the traditional PPCG criterion, gridded maps showing the percentage and frequency of tornado events containing 25% or more PCG lightning were also developed ("enhanced" PCG storms). These maps, which approximately represent the upper quartile of PCG lightning events, are shown in Figs. 23a and b, respectively. Data distribution broadly resembles what was seen in Figs. 22a and b; the greatest percentage of tornado reports containing cloud-to-ground lightning comprised of 25% or more PCG lightning remained over (mainly) the Central Plains. However, the region containing this maximum was expanded, with as much as 90% of the events meeting the criterion for "enhanced" PCG storms northward from the Texas Panhandle through Central Oklahoma. Other localized maxima were also enhanced, most notably across parts of Central and South Texas, as well as East Missouri and West Illinois. Additionally, several "enhancements" were now observed over the Southeast United States. "Enhanced" PCG lightning flashes accompanied cool season tornadic storms up to 30% of the time in several areas. Some of these areas included: Southeast Arkansas into Southeast Louisiana, South Alabama, North Kentucky, Central North Carolina, and Northeast Florida.

Figure 23b shows the frequency of cool season tornado reports accompanied by "enhanced" PCG lightning. Somewhat unexpectedly, frequencies in the maximum region in the Central and southern Plains were very similar to those in the PPCG frequency plot. Values continued to range from 0.2 to 0.5 per 10 000 km^2 per cool



a.



b.

FIG. 23. Gridded maps of cool season tornado events whose total cloud-to-ground lightning met "enhanced" PPCG criterion (> 25% PCG lightning) during the 1990-2002 cool seasons. (a) Percentage. (b) Frequency normalized to 10 000 km^2 per cool season.

season in this region. An increase in frequencies was noted across the Southeast United States, where a broad maximum of 0.2 to 0.4 per 10 000 km^2 per cool season existed from Central Texas east into South Alabama. Within this area, localized maxima, sometimes with values as high as those seen in the Plains, were seen from South Arkansas into North Louisiana, as well as in Southeast Alabama.

CHAPTER V

DISCUSSION

1. Comparison to past results

Much of the prior research correlating tornado events and cloud-to-ground lightning flashes has utilized episodes which occurred in the warm season of the year (April through September). Using tornado events which occurred between 1 October and 31 March, this study was different. Over a span of 13 seasons, 3325 tornado events were correlated with data from the NLDN according to procedures described in Chapter III. Of these events, 2358 tornado events possessed at least one NLDN-detectable lightning flash.

Cool season tornado events tended to be more concentrated in the Southeast United States when compared to Carey et al. (2003a). The greatest observed frequencies, with values between 1.0 to 2.5 per 10 000 km^2 per cool season, were closely aligned with the definition of Dixie Alley used by Gerard (2006, personal communication), which showed a greater frequency of tornado events rated “strong” or “violent” on the F-scale during the cool season. This region also closely resembles cool season tornado probability charts shown in Brooks et al. (2003). They showed the greatest probabilities near Natchez, Mississippi early in the cool season, which then expanded to encompass much of the domain used in the present study by the start of the warm season (1 April).

Results from the present study show a lower frequency of events than in the warm season. However, this is believed to be due to a lower sample size. Many similar previous studies encompassed other types of severe weather phenomena. Because tornadoes are infrequent events (when compared to large hail or damaging wind events), the lower frequency makes sense.

The localized frequency maximum on the Florida Peninsula, between Tampa and Orlando, is a persistent feature in many studies involving severe weather events and cloud-to-ground lightning. This study was no exception. Many studies, such as Brooks et al. (2003), have attributed this maximum to either waterspout activity or non-supercellular tornado events. While this reasoning might account for many warm season events, the explanation may not totally account for all cool season events. Both waterspouts and non-supercell tornadoes are primarily boundary layer phenomena, many times developing at mesoscale boundary intersections under growing cumulus clouds. Climatologically, seabreeze convergence and other mesoscale processes drive warm season conditions over the Florida Peninsula. Meanwhile, Florida tends to be affected by weather systems on a more synoptic scale during the cool season, driven by stronger dynamical support. These systems possess increased wind shear, which leads to increased storm scale organization and possibly the occurrence of supercellular tornadoes. Without the use of climatological maps documenting surface and upper-atmospheric patterns, the full reasoning behind the persistent frequency maxima will not truly be known.

Histograms illustrating the PCG lightning percentage associated with both cool and warm season tornado events were compared. In both cases, PCG lightning percentages were skewed toward lower values. Most tornado events were accompanied by a PCG lightning percentage between 0 and 4 percent. These events comprised a slightly lower percentage of events during the cool season, encompassing approximately 25% of tornado reports. Values reported in Carey et al. (2003a) were some 10 to 15 percent higher for comparable cool season percentages. The percentage of PCG lightning associated with cool season tornado reports also appeared to taper more slowly than in the warm season, indicating a slightly higher percentage of tornado events with a greater percentage of PCG lightning. This finding is similar to results in Orville and Huffines (2001), which states move positive flashes are found during the cool season.

Interestingly, the sizable increase in the number of cool season reports associated with a PCG lightning percentage greater than 90% is also evident in the Carey et al. (2003a) warm season study. However, the small increase noted in warm season data appears to encompass a smaller fraction of the dataset. Regardless, as mentioned in Chapter IV, the reason why this increase was observed is not known at this time.

Results of a comparison of PCG lightning flash density histograms between cool and warm season tornado events were remarkably similar. In both cases, values showed a similar distribution, with most PCG lightning possessing a flash density less than 0.003 $km^{-2}\ h^{-1}$ per report regardless of season. Similar to the cool season histograms of PCG lightning percentage per report, cool season tornado events appeared to taper less quickly than its warm season counterpart (Carey et al. 2003a), indicating a greater frequency of tornado reports accompanied by PCG lightning with a higher flash density. Despite this finding, the occurrence of HFD PCG lightning ($\geq 0.01\ km^{-2}\ h^{-1}$) associated with cool season tornado events remains very low and, similar to Carey et al. (2003a), confined to the High Plains region of the United States.

One of the primary goals of this study was to examine the occurrence of PPCG lightning associated with cool season tornado events. The spatial distribution of cool season tornado events closely matched the results found in Carey et al. (2003a), who examined the relationship between cloud-to-ground lightning flashes and warm season tornado/hail events. In general, the greatest frequency and highest percentage of PPCG tornado events were located over the Central Plains. These regions are juxtaposed south and east (as much as 5° of latitude) of their warm season counterparts, probably due to the more southerly track of mid-latitude storm systems. Interestingly, there are several localized regions of higher frequency noted in the Southeast United States which are not as evident in the warm season[15]. The occurrence of PPCG tornado events in the Southeast United States appears to be an infrequent occurrence regardless of the time of year, with less than 10% of events meeting PPCG criterion.

Knapp (1994) used a lower, subjectively defined threshold to define a PPCG storm. In his one year study of warm season tornado events, a storm was predominately positive when it contained at least 30% PCG lightning in at least eight of the fifteen minute periods he defined. In this spirit, the occurrence of EPCG storms were examined, utilizing a PCG lightning percentage of 25% or greater. This value roughly matches the upper quartile of the PCG percentage for cool season tornado events. Similar to the PPCG distribution, EPCG storms occurred most frequently over the

[15] The exception to this is eastern North Carolina (east of the Appalachians), where slightly greater percentages of 10 to 20 percent were observed.

Central Plains. However, as mentioned in Chapter IV, a secondary region of higher frequencies, some as high as those in the Plains, were observed in an area from South-Central Texas into Southeast Alabama. As indicated in Fig. 23a, up to 30% of the events meet EPCG criterion in parts of this region. These results are not consistent with those presented in the Knapp study, as all but one of the tornadic storms in his paper occurred west of the Mississippi River.

The similarities noted between frequency values associated with cool season PPCG and EPCG storms (Figs. 22b and 23b) suggest little geographic sensitivity between the definitions of EPCG and PPCG storms across the Central Plains, as found by Carey et al. (2003a) for the warm season. Across the Southeast United States, though, this may not be the case. The frequency of EPCG storms was twice as great in several spots across this region. This indicates that the occurrence of EPCG storms may be a more useful indicator of storm severity in this region during the cool season. Future studies will hopefully investigate this further.

In addition to examining the relationship and distribution of cool season tornadoes and cloud-to-ground lightning, individual aspects of cloud-to-ground lightning flashes associated with cool season tornadoes were examined in context of annual "climatological" studies such as Orville and Huffines (2001). In this study, peak current and multiplicity are examined.

Orville and Huffines (2001) stated that, with values between 15 and 25 kA, the Southeast United States annually had the lowest median PCG lightning current values across the country. Figure 14 shows the peak current for 75% of PCG lightning associated with cool season tornado reports is less than 40 kA. Peak current values showed the greatest frequency between 15 and 20 kA, with a median value of 21.6 kA across the study domain. This is well within the values given in their study, which focused on annual means.

In contrast, the Orville and Huffines study found the Southeast United States had the highest median NCG peak current values. The highest values encompassed the immediate Gulf Coast region, from the Upper Texas Coast eastward, with common values between 27 and 30 kA. Peak current values for NCG lightning associated with cool season tornadoes, however, compared more favorably to those presented for PCG lightning. As shown in Fig. 15, 71% of NCG lightning flashes possessed a peak current less than 30 kA. Most peak current values ranged from 10 to 25 kA, with a median value across the study domain of 24.6 kA. Even though this value is outside the peak values observed along the Gulf Coast in the Orville and Huffines study, it is suspected that the median value is within the regional median peak current values for NCG lightning flashes.

Cloud-to-ground multiplicity values associated with cool season tornadoes compared remarkably well with annual results presented in Orville and Huffines (2001). Approximately 85% of PCG lightning had a multiplicity of 1.25 or less, consistent with their mean values of 1.2 to 1.3. Even though NCG lightning multiplicity values in their study were lowest during the cool season of the year, values approximately ranged from 2.0 to 2.25. Multiplicity values for NCG lightning in this study were again in remarkable agreement, with most values between 2.0 and 2.5.

2. Utility in an operational environment

a. Background of the NLDN in National Weather Service operations

The National Weather Service (NWS) is a Federal agency charged with the protection of life and property across the United States. This is accomplished through issuing severe weather watches and warnings by national, regional, and local offices. To this end, NWS meteorologists utilize all available information to make the best decision possible.

One piece of available information is flash data from the NLDN. The modern use of NLDN flash information by NWS meteorologists is closely tied to the nationwide deployment of the Advanced Weather Information Processing System, or AWIPS. AWIPS provides the means by which most daily NWS operations are accomplished. Most NLDN data available to NWS meteorologists are overlaid on a plan view map of interest, simply indicating the number of PCG and NCG flashes. Data are available at a temporal resolution which shows flashes that occurred in the last one-, five-, or fifteen-minutes. PCG flashes are indicated by a "+", while NCG flashes are denoted by a "-". Software developed for use with the WSR-88D Doppler radar provides additional NLDN information for each radar-identified storm, such as the percentage of PCG flashes.

b. Concerns

Despite the increase in information and training available to NWS meteorologists, this author has several concerns based upon the results of this study. First, are the NLDN data used by the NWS filtered to remove low peak current PCG flashes (i.e., those with peak currents between 5 and 15 kA)? As documented in Chapter III of this study, there was a substantial increase in low peak current PCGs after the 1994 upgrade. Cummins et al. (1998) attributed at least part of this increase to an increased detection of misidentified in-cloud lightning flashes. Since this time, it has been common practice in the research community to remove all PCG flashes with a peak current of less than 10 kA. As will be seen in the Appendix of this study, many PCG flashes in the Southeast United States fall into this category. If operational meteorologists are attempting to incorporate prior research (which attempted to link an anomalous percentage PCG flashes with tornado development) into severe weather warning operations, this might have a large impact in the warning decision making process.

Second, do NWS employees know about the "common practice" mentioned in the previous paragraph? Unless the operational meteorologist is involved in local lightning research that utilizes NLDN data, knowledge of removing PCG flashes with a peak current less than 10 kA is not likely. During a severe weather event, operational meteorologists incorporate many types of remotely sensed data into the warning decision making process, especially information available from Doppler radars around the meteorologist's region of responsibility. In most cases, these data sources are taken "at face value" with very little additional quality control by the user (outside of automated pre-processing). However, this may not be the best practice in NLDN data usage, especially when information in the preceding paragraph is considered.

Finally, there are concerns with data usage across the NWS. NLDN data are not used in a consistent manner within the forecasters of a local warning and forecast office (WFO), much less from office-to-office or across the agency. This severely limits the utility of real-time cloud-to-ground flash data in an operational environment.

c. Discussion on use

Previous studies, as described in Chapter II, have attempted to discern relationships between anomalous percentages of PCG lightning and severe weather phenomena in various regions of the United States. Indeed, this study, supported by a prior investigation of warm season severe weather events, indicates a broad signal in anomalous PCG percentage values. Results indicate that EPCG criterion could be more indicative of cool season severe weather phenomena, when compared to the traditional PPCG criterion. As noted earlier in this chapter, this assertion is based upon slightly higher values of frequency and percentage over the Southeast United States when compared to the traditional PPCG criterion, while maintaining comparable values across the Plains.

CHAPTER VI

CONCLUSIONS

Data from the Storm Prediction Center and NLDN were used to examine the relationship between cool season tornadoes and cloud-to-ground lightning flashes. This study focused on the months of October through March, encompassing 13 seasons from 1989 to 2002. Lightning and tornado data were correlated and sorted using a series of computer programs and scripting languages, then analyzed using a combination of PC-based applications and gridded data plots. The resultant dataset compared very well to research which was broader in scope (e.g., Brooks et al. 2003; Orville and Huffines 2001).

Even though cool season tornado events tended to have a higher frequency in the Southeast United States, the findings of this study were generally consistent with previous warm season studies of severe weather phenomena and cloud-to-ground lightning. The highest percentage of storms containing at least one NLDN-detectable flash was found across much of the Central and southern Plains, where percentages were greater than 70%.

One of the more interesting findings of this study was the location and frequency of tornado events in which no NLDN lightning flashes were detected. Most of these events were confined to the coastal regions of the Gulf of Mexico and (especially) over the Atlantic Ocean, with well over 70% of the events falling into the category in the Mid-Atlantic region. Due to the relative dense spatial distribution of sensors in these regions and a detection efficiency of 80 to 90 percent, this occurrence is not thought to be a detection problem. As such, it is thought that atmospheric conditions which lead to the development of tornadoes in these areas are different than those in the Plains.

Again, similar to previous warm season research, the percentage and flash density of PCG lightning associated with cool season tornadoes was relatively low. Most PCG lightning percentages were generally less than 10%, while flash density values averaged less than 0.003 km^{-2} h^{-1} per report. This trend was also evident when the dataset was separated by F-scale groupings, at least for those rated “weak” or “strong”. The small number of samples contained in the “violent” category prohibited any substantial inference from being made. However, utilizing data from “weak” and “strong” events (almost 99% of the dataset), there appeared to be no relationship between F-scale groupings and the percentage or flash density of PCG lightning associated with the parent thunderstorm.

Much discussion has already been provided on the occurrence of cool season PPCG storms across the study domain. The percentage and frequency of tornado events in this study were consistent with results presented in previous warm season severe weather and cloud-to-ground lightning research. Simply put, most PPCG storms seemed to occur in the Plains region of the United States and this author’s hypothesis was not supported. While this trend continued in EPCG storms, up to 30% of the events also met this criterion across some limited portions of the Southeast United States.

So what then is an anomalous PCG storm? The frequency and percentage enhancement noted across the Southeast United States has lead to speculation by the author that the occurrence of 25% or greater PCG lightning (EPCG criterion) would be a better definition of anomalous PCG storms, especially in this region since it approximately represents the upper quartile of PCG flashes.

It is likely too early to use NLDN data as a forecast or nowcast tool for tornado events and, in fact, should not be used as the only tool in the investigation of intense convection. As pointed out by Carey et al. (2003b), a cloud-to-ground lightning signal must consistently be observed prior to severe weather occurrence. No study (past or present) has shown consistent flash trends prior to the onset of severe weather between storms or regions. Despite this, NLDN flash information could provide useful information on storm trends if incorporated into the arsenal of tools at the operational meteorologist's disposal during potentially severe weather events.

A possible relationship between severe weather and anomalous PCG storms has been documented in prior research. Hopefully, in order to assist meteorologists in the interrogation of intense convection in an operational environment, future studies will better isolate the definition of anomalous PCG storms across this severe weather prone region of the southeastern United States.

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APPENDIX

INCLUSION OF LOW PEAK CURRENT PCG FLASHES

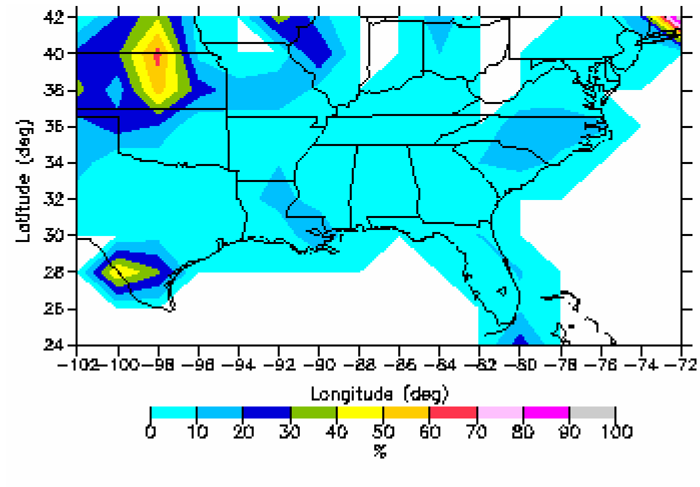
The results presented in this study utilized data in which low peak current PCG flashes (those PCG flashes with peak current values < 10 kA) were removed from the dataset. As discussed earlier in Chapter III, as well as in Cummins et al. (1998), Wacker and Orville (1999a, 1999b), and Carey et al. (2003a), this method of data quality control has become a common practice within studies using NLDN flash data because of the likelihood of misidentified in-cloud flashes.

In order to examine the effects of the "10 kA filter" and the occurrence of low peak current PCG flashes across the Southeast United States, gridded maps and frequency histograms were also derived from data that incorporated low peak current PCG flashes. These maps and histograms were developed using the same scripts, programs, and techniques described in Chapter III. The maps which deal with anomalous PCG storms will be presented here.

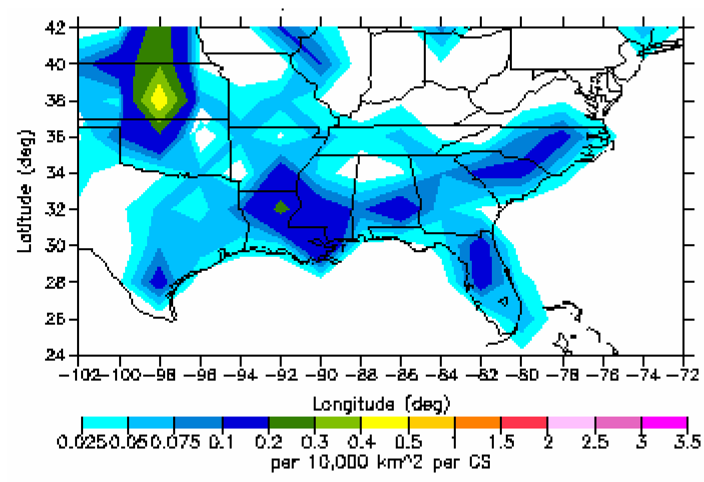
Gridded maps that illustrate the percentage and frequency of tornadic storms which meet traditional PPCG criterion are shown in Figs. A1a, b. When compared to Figs. 22a, b, little overall difference in frequency or percentage is noted across the Plains. A higher frequency of tornado events associated with PPCG storms is noted in the unfiltered maps (Figs. A1a, b) across much of the Southeast United States, especially from the Lower Mississippi River Valley through the coastal regions of the Gulf of Mexico and Atlantic Ocean. Here, frequency values as great as 0.3 tornado events per 10 000 km^2 per cool season were observed, especially over Northeast Louisiana. Only a slight increase in PCG percentage was noted over the Southeast, with the greatest increase observed in the Lower Mississippi River Valley, just west of the Mississippi River.

The percentage and frequency of tornadic storms meeting EPCG criterion are shown on the maps in Figs. A2a, b. Similar to the PPCG tornado events discussed above, little difference is noted across the Plains when compared to Figs. 23a, b. The increase in the percentage and frequency of low peak current PCG flashes in the unfiltered data (Figs. A2a, b) is very noticeable across the Southeast United States, especially in areas near the Gulf coast and Cumberland Plateau. This influence of low peak current PCG flashes is most dramatic near the Cumberland Plateau, where up to 60% of cool season tornado events now meet EPCG criterion. The addition of low peak current PCG flashes resulted in the greatest frequency increase from Southeast Arkansas through Northeast Louisiana, where up to 1 tornado event per 10 000 km^2 per cool season was noted. This frequency is approximately twice as great as shown earlier in the filtered results (Figs. 23a, b).

As indicated in Figs. A1 and A2, a large number of PCG flashes possess a low peak current over the Southeast United States, consistent with past results (e.g., Zajac and Rutledge 2001; Orville and Huffines 2001). It is apparent that removing low peak current PCG flashes, as described in prior research, has a great effect on the number of NLDN-indicated PCG flashes over the Southeast United States and increases this author's concerns about use in an operational environment (see Chapter V).

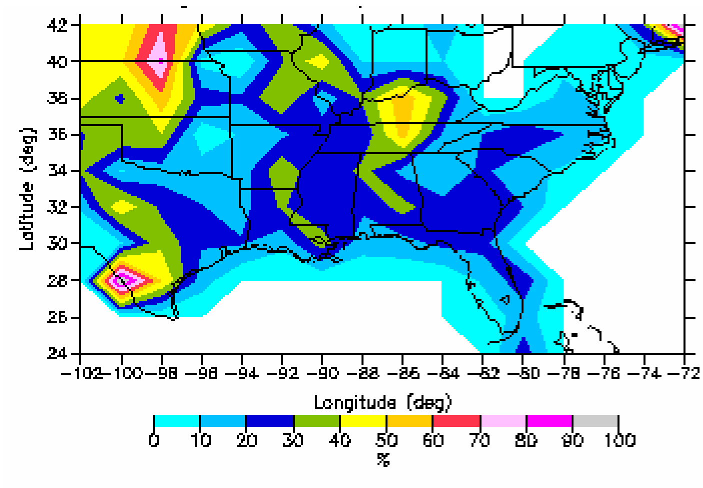


a.

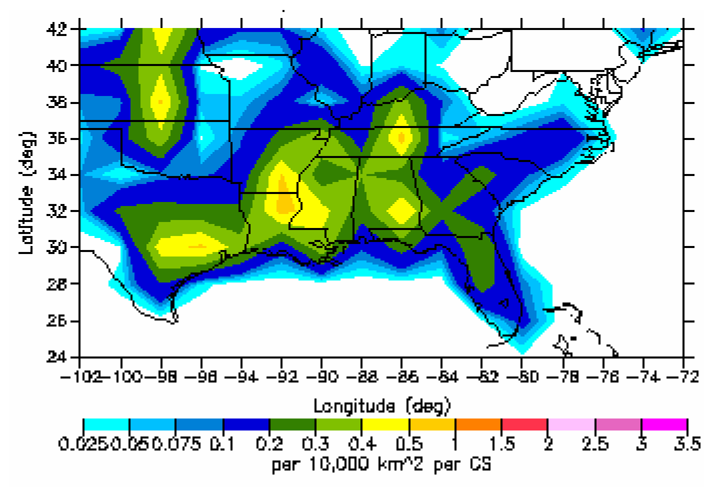


b.

FIG. A1. Gridded maps of cool season tornado events whose total cloud-to-ground lightning met traditional PPCG criterion (> 50% PCG lightning) during the 1990-2002 cool seasons. Data presented on these maps includes low peak current PCG flashes. (a) Percentage. (b) Frequency normalized to 10 000 km^2 per cool season.



a.



b.

FIG. A2. Gridded maps of cool season tornado events whose total cloud-to-ground lightning met "enhanced" PPCG criterion (> 25% PCG lightning) during the 1990-2002 cool seasons. Data presented on these maps includes low peak current PCG flashes. (a) Percentage. (b) Frequency normalized to 10 000 km^2 per cool season.

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"Low-Topped Supercell Event in Coastal Alabama". Southeast Severe Storms Symposium, 2002 (D. Butts, D. Cramer)

"Effective Hazardous Weather Communication Between NWS Offices and Broadcast Media: A NWS Southern Region Initiative", AMS Broadcasters' Conference, 2004. (D. Butts, B. Goldsmith)

"Breathing New Life Into Weather Radio: WFO Jackson, MS Initiatives", NWS Southern Region Headquarters, 2004. (D. Butts)

"The Relationship Between Tornado Reports and Cloud-to-Ground Lightning Polarity in the Southeastern United States During the Cool Season From 1989 to 2002", AGU Fall Meeting, 2006. (L. Carey, D. Butts)