Eastern Region Technical Attachment
No. 2010-02
October 2010

A SEVERE WEATHER CLIMATOLOGY FOR THE WFO GREENVILLE-SPARTANBURG, SOUTH CAROLINA COUNTY WARNING AREA

Justin D. Lane
NOAA/National Weather Service
Greer, SC

ABSTRACT

This study documents a 13-year climatology of damaging convective wind gusts (DW, defined as an instantaneous wind gust of at least 25 m s^{-1}*)*[1] *and large hail (LH, defined as hail that is at least 1.9 cm [¾ inch] in diameter), and a 58-year climatology of tornadoes (TO) in the Greenville-Spartanburg, South Carolina (GSP) County Warning Area (CWA). The climatology analyzes severe weather occurrence in terms of long-term and seasonal frequency and favored time of day. These analyses reveal distinct differences between the climatology of the mountainous areas and that of the foothills and Piedmont. While DW are the most common form of severe weather over the region, the disparity between DW and LH frequency in the Piedmont is much greater than that of the mountains. Summer is the favored time of year for DW in the Piedmont, but portions of the mountains experience peak DW activity during the spring. TO are most frequent during the spring, suggesting that they are generally associated with large-scale, baroclinic weather systems. Meanwhile, the tendency for DW to peak in summer implies they are most typically associated with convection that develops in response to the diurnal heating cycle. Since LH peaks in the late spring and early summer, it may occur with organized storm systems, or with diurnal convection. It is inferred from the DW climatology that they typically occur in moist, weakly sheared environments, suggesting that localized wet microbursts are the most common form of severe weather event across the GSP CWA. Finally, while the early afternoon is the favored time of day for severe weather across the mountains, middle to late afternoon is more favored over the foothills and Piedmont. This reflects a progression of convection developing over the mountains during the early afternoon and moving downstream into the lower elevations later in the afternoon, a scenario that is often observed during the late spring and summer.*

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[1] Since measurements of convective wind gusts are rare, most National Weather Service offices use local damage criteria to define a DW event. The Weather Forecast Office at Greenville-Spartanburg has traditionally used criteria of at least two trees blown down within 10 miles and 15 minutes of each other to define a DW event.

1. Introduction

The GSP Weather Forecast Office (WFO) has forecast and warning responsibility for 46 counties in the western Carolinas and extreme northeast Georgia (Fig. 1). This region is characterized by diverse geography, encompassing much of the mountainous terrain of western North Carolina, including the highest point east of the Mississippi River (Mount Mitchell, 2037 m), as well as the relatively uniform topography of the western Piedmont, where elevations of 150 m or less are common. The GSP CWA is also proximal to two major sources of atmospheric moisture: the Atlantic Ocean 300 km to the southeast, and the Gulf of Mexico 600 km to the southwest. This unique geography is largely responsible for the diverse climate regime across the region. While most of the Piedmont, foothills, and mountain valleys are characterized by the humid subtropical climate typical of the southeast United States, the higher elevations of the southern Appalachians are more characteristic of a marine west coast climate (Peel et al. 2007). Additionally, due to the two moisture sources and complex terrain, some locations in the mountains of North and South Carolina receive as much as 230 cm of precipitation annually, making these locations the wettest areas of the continental United States outside of the Pacific Northwest (U.S. Department of Commerce 2002).

Largely as a result of these factors, the GSP CWA is prone to a variety of weather-related hazards, one of which is severe thunderstorms. The GSP CWA is the most active in terms of severe thunderstorm occurrence in the National Weather Service's (NWS) Eastern Region, accounting for over 9% of the region's total events since the GSP CWA was expanded to 46 counties on 1 October 1995.

The purpose of this study is to document the occurrence of the three elements of severe thunderstorms (TO, LH, and DW) in the GSP CWA by geographic location, long-term frequency, as well as the time of year and the time of day. In addition, this study will provide forecasters in the area with a climatological basis for evaluating the severe weather potential and specific severe weather threats for a given time of year, time of day, and location. This study is also intended to provide information to operational forecasters in the western Carolinas and northeast Georgia regarding the specific severe weather threats that are most common in the region, so that training efforts can be concentrated in those areas in order to improve warning services.

2. Data analysis and methods

The NCDC Storm Events (NSE) database was accessed to collect all reports of TO, LH, and DW occurring within the GSP CWA between 1950 and 2008[2]. According to the NSE website, June 1993 and July 1993 events are missing from the database, so the Storm Data publication was consulted to fill this gap.

There are myriad problems with the severe weather events database. These issues have been documented and addressed in previous studies (e.g., Doswell and Burgess 1988). Any climatological analysis based upon these reports is beholden to the imperfections of this data set. The quality of the severe weather database depends on a number of non-meteorological factors. Most of these involve the accuracy of the individual making the report (i.e., inaccuracies in hail size/wind speed estimates, imprecise time/location of the event, etc.) It should also be stated that the severe weather record is undoubtedly incomplete. Some severe weather events likely occur without being witnessed by individuals. Other events are likely observed by individuals, but are not reported. For this reason, it is more accurate to describe any climatology based upon this record as a "climatology of severe weather reports," rather than severe weather occurrence.

One of the main deficiencies from a climatological perspective is the large increase in the number of severe weather reports that has occurred over the years, giving the superficial impression that severe weather occurrence has increased dramatically with time. For instance, there are 24 reports of LH from rural Graham County, North Carolina occurring between 1990 and 2008. However, only one report of LH exists in the database between 1955 and 1990. Mecklenburg County, North Carolina, the most populated county in the GSP CWA, has only 55 LH events between 1955 and 1990, yet 104 LH events between 1990 and 2008 (Fig. 2). There is no meteorological explanation for these data trends, but

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[2] LH and DW reports are only available since 1955.

it is rather a reflection of a greater NWS emphasis on collecting reports for forecast verification, improvements in communication systems, storm spotter networks, public awareness, population expansion, and other non-meteorological factors.

Perhaps the most familiar source of error in the severe weather events database is a supposed population bias. Since the database depends upon reports from the field, it stands to reason that more reports would be received from heavily populated areas than in less populous locations. However, previous studies have challenged the validity of this assumption (e.g., King 1997), while Doswell et al. (2005), argue that attempting to adjust the dataset for population bias would have minimal impact on the results. Brooks et al. (2003) state that the most reliable aspect of any historical tornado report is the day on which it occurs and its approximate location. For this reason, their study focuses on "tornado days" rather than "tornado events." This methodology is extended to large hail and damaging winds in Doswell et al. (2005). It is also assumed that this methodology reduces some of the population bias (if it exists), as multiple reports are theoretically more likely to be received when severe thunderstorms affect a heavily populated county, as opposed to a less populous county. The current study will also focus on "severe weather days (SWD)" as opposed to events.

Nevertheless, the author acknowledges that a population bias probably exists in the current study, especially with regard to LH and DW. It is noteworthy that the DW and LH climatology will reveal a relative maximum in occurrence along the heavily populated Interstate-85 corridor, with a general decrease noted in the lesser populated areas of the Piedmont south of this corridor (Fig. 3 and Table 1). Having acknowledged this potential bias, the discussion section of this study will focus strictly on possible meteorological explanations for trends in the climatological analysis.

For TO, the period of study is 1 October 1950 through 30 September 2008. For LH and DW, the period of study is 1 October 1995 through 30 September 2008. The discrepancy in the two study periods is due to the fact that the historical TO record has been the subject of great scrutiny and research efforts (Grazulis 1993), presumably resulting in a more robust data set. To the author's knowledge, historical LH and DW reports have not received the same treatment. Another reason the shorter time period is used for hail and wind is due to the phenomenon of increased reporting of severe weather addressed above. According to Doswell et al. (2005), the number of LH and DW reports has increased much more significantly since 1950 than the number of tornado reports. Choosing a shorter period of study for the LH and DW climatologies removes some of this bias. The beginning of this period is 1 October 1995 to coincide with GSP assuming warning responsibility for the 46 counties covered in this study.

Another issue that arises from the county-based climatological record is differences in the area of the counties. Counties in the GSP CWA range in size from 477 km^2 (Stephens County, Georgia) to 2,122 km^2 (Spartanburg County, SC). The average county area is 1196 km^2, while the median is 1206 km^2. All else being equal, more reports should be received from larger counties than from smaller counties. For the purposes of this study, SWD were normalized based upon the area of each county. Since all but one of the 46 counties is larger than 500 km^2, the climatology is expressed as the number of SWD per 500 km^2. Once these numbers were calculated for each severe weather day in each county, they were plotted at the centroid of each county. An objective analysis of these data were then performed to produce the climatology maps presented in Section 3. The analyses reflect the number of SWD per 500 km^2 during the entire periods of study. The only exception to this was the DW and LH analyses, which reflect the average number of SWD per 500 km^2 over a five-year period.

3. Frequency

a. Tornadoes

The number of days with TO during the 58-year period of study is presented in Figure 4. The map shows that TO are most common across northeast Georgia, into western Upstate South Carolina, extending northeast into the southwest Piedmont of North Carolina. Most locations in the Piedmont, eastern North Carolina foothills, and the South Carolina and Georgia foothills can expect one day with a tornado within 500 km^2 every 7 to 10 years. Meanwhile, TO are extremely rare in the rugged terrain of the mountains and western-most North Carolina foothills.

A possible meteorological explanation for the maximum in TO occurrence is that this area roughly coincides with the typical position of the lee trough, which often acts as a focus for convective initiation and organization during the warm season (Weisman 1990). In addition, this area's proximity to the Southern Appalachians suggests that it is more susceptible to convection that originates over the higher terrain which subsequently organizes as it moves into the Piedmont and foothills. However, this is more of a summer pattern (i.e., occurring in moderate or weakly sheared environments), and may therefore be more relevant to the HW and LH climatology.

Figure 5 represents the number of days in which a significant TO, defined as EF2 (F2) or stronger, occurred within the GSP CWA. Notable similarities exist between Figures 4 and 5, particularly with the paucity of significant tornado occurrence across the mountains, and the relative maximum in the western Piedmont and foothills, presumably due to lee trough activity. On average, locations in these areas experience a significant TO within 500 km^2 once every 20 to 40 years on average (Fig. 5). However, there is a noticeable decrease in significant TO activity across eastern portions of Upstate South Carolina and the northwest Piedmont of North Carolina. This trend in the data is likely "real" (i.e., not a result of data biases), as this area encompasses the relatively densely populated Interstate-77 corridor, and it is unlikely that unreported significant tornadoes have occurred in this area during the period of study. The minimum over the northwest Piedmont may be explained due to the relative frequency of cold air damming (CAD; Bell et al. 1988) during the peak TO season of spring. Since CAD typically develops northeast of the GSP CWA and expands to the southwest, the frequency of CAD events increases from southwest to northeast across the Piedmont and foothills. CAD often occurs in strongly sheared environments during this time of year. However, the cool, statically stable air within the CAD air mass precludes development of strong TO due to the absence of surface-based buoyancy.

The number of days with an EF3 or EF4 tornado during the period of study is presented in Figure 6. There has never been an EF5 tornado documented within the GSP CWA. The EF3 and EF4 map closely mirrors Figure 5. There are two maxima in occurrence: one in the far western Piedmont and foothills, and another across the extreme southern and southeastern tip of the CWA. On average, an EF3 or EF4 tornado occurs within 500 km^2 of any location in these areas every 40 to 60 years. Between these maxima, there is a narrow strip of the Piedmont from which no documented instances of an EF3 or stronger tornado exist. Meanwhile, no reports of an EF3 or stronger tornado were received from any mountain counties during the entire period of study.

b. Large Hail

The average number of days in a five-year period with LH is presented in Figure 7. LH occurrence is somewhat more uniform across the GSP CWA than TO. The most active areas for LH are across the foothills of South Carolina and northeast Georgia, and areas from the eastern mountains of North Carolina through the foothills and into the western Piedmont. Locations in these areas can expect an average of 1 to 2 days per year with LH within 500 km^2. This maximum can be explained by the persistent warm season lee trough, due to its proximity to the higher terrain and associated warm season diurnal convection.

As was the case with TO, LH reports are generally less common across some areas of the mountains than in the Piedmont. While it is to be expected that TO activity across the rugged terrain of far western North Carolina would be much less than that of the Piedmont, this is not necessarily true for LH. This is due to the fact that the mountains are a favored location for development of deep convection during the warm season. The map in Figure 7 indicates relative low frequency of LH along the Tennessee border, with occurrence increasing to the southeast. Frequency of LH across the eastern portion of the North Carolina mountains is comparable to that over the foothills and Piedmont. A possible meteorological explanation for the low frequency of LH reports along the Tennessee border may have some relationship to the frequency of initiation of diurnal warm season convection. A radar study by

Outlaw and Murphy (2000) suggested that areas along the Tennessee border are upstream (assuming a westerly component to the mean flow) of the most favorable areas for initiation of summer convection over the higher terrain of western North Carolina (Fig. 8).

The number of days with hail that is at least 4.5 cm in diameter (i.e., golf ball size) expressed per decade is presented in Figure 9. For the most part, the distribution mirrors that of large hail. However, there is one notable difference in that the maximum in very large hail over northern Upstate South Carolina is displaced farther west.

c. Damaging Winds

Figure 10 depicts the average number of days per 5-year period with DW. The data pattern is similar to that of Figure 7. However, the maximum in DW is a bit farther southeast, with the eastern foothills and the Piedmont being the most favored areas. In general, DW are more common than LH, and much more common than TO. This is mainly true of the foothills and Piedmont, where most locations experience two to three days per year with a DW event within 500 km^2. In the Piedmont, there are about twice the number of days with DW over that of LH. In the foothills, the number of LH event days are about two-thirds the number of DW event days. Over the mountains, DW event days (a total of 396) are only slightly more frequent than days with LH (a total of 327). One exception to this trend over the mountains is the relative maximum in DW occurrence that is seen over the southwest mountains of North Carolina. In these areas, DW are approximately twice as common as LH. This is likely related to the somewhat recurrent phenomenon of organized severe convection moving into the area from the Tennessee Valley, before undergoing rapid weakening, or complete dissipation over the rugged terrain along the crest of the southern Appalachians (Keighton et al. 2007). This area roughly parallels the border between Tennessee and North Carolina. This convection, which generally occurs from late winter through mid-spring, is often in the form of linear mesoscale convective systems (MCS) which tend to produce rather widespread DW and little if any LH.

4. Seasonal Climatology

a. Tornadoes

Seasonal maps of TO occurrence, expressed as the number of event days over the 58-year period of study, are presented in Figure 11. The analyses reveal that the winter months are generally the least active time of year for TO across much of the GSP CWA. Even in areas that are relatively “active” (i.e. northern Upstate South Carolina, northeast Georgia, and the southwest Piedmont of North Carolina), winter tornadoes recur only every 40 to 60 years on average. Over the North Carolina foothills, tornadoes are practically non-existent outside of the spring. Since the coexistence of the lee trough with adequate instability and wind shear for organized deep convection rarely occurs outside of the spring, this trend in the data stands to reason. Additionally, the location of the foothills “downstream” of the rugged terrain of the mountains renders this area somewhat “sheltered” from the possibility of tornadic convection developing upstream. However, this is not true of the South Carolina and Georgia foothills, or the southern Piedmont area of the GSP CWA. These areas are “downstream” of the rather uniform terrain of the Piedmont. In fact, previous studies of tornado-producing convection affecting the area have revealed that at least some of this convection originates from central Georgia (Lane and Moore 2009, Lane 2008b).

There is a dramatic increase in TO occurrence over all of the Piedmont and foothills during the spring, which is the most active time of year. The March through May period represents a two- to three-fold increase in TO activity from the winter. Most locations south and east of the mountains can expect a spring day with at least one TO within 500 km^2 every 10 to 20 years. TO occurrence undergoes an abrupt decline in the summer months. In fact, summer is only slightly more active than winter, despite the frequency of deep convection. This is a consequence of the climatological trend of weakening wind shear over the Southeast United States during the summer. Despite the dry weather and convective inactivity that typically affects the GSP CWA during most of the autumn season, TO activity only decreases slightly during this time, and actually increases in some areas (i.e., northeast Georgia and the southwest Piedmont of North

Carolina). The increase in these areas can be attributed to: (a) periodic tropical cyclone remnants early in the season (Gentry 1983) and (b) an increase in mid-latitude cyclones late in the season that are marked by strongly sheared/weakly buoyant regimes (e.g., McAvoy 2003).

While the seasonal TO climatology over the Piedmont and foothills is typical of a subtropical humid climate, it is interesting to note that there does not appear to be a favored time of year for TO over the mountains. In fact, despite the rarity of TO over the mountains, many mountain counties have reported a tornado in all four seasons. If anything, the data reveals that winter and summer may be slightly more favored than spring over the higher terrain, which is at odds with the trends outside the mountains. However, considering the rarity of TO over the higher terrain, the sample size may be inadequate to draw reasonable conclusions about the seasonal TO climatology. In other words, there is no known meteorological explanation as to why spring would not be a favored time of year for TO over the mountains.

b. Large Hail

As with any humid subtropical climate, the warm season (i.e., March through August) is the favored time of year for severe thunderstorm occurrence across the GSP CWA. Figure 12 displays the seasonal hail climatology for the area, expressed as the number of days per 500 km^2 during the 13-year period of study. The maps depict monthly frequency during the warm season and seasonal frequency for winter (December, January, February) and autumn (September, October, November).

Figure 12 indicates that LH is very rare during the typically dry autumn over the western Carolinas and northeast Georgia. In most areas, only one autumn day with LH occurs on average over a 10 to 15-year period. The winter months are slightly less active than autumn. When large hail does occur in the autumn and winter, it is most likely over northeast Georgia and Upstate South Carolina.

LH frequency begins to increase in March, when LH is about as frequent as it is during the entire winter season. Occurrence in April represents as much as a two-fold increase over that of March, while LH frequency in May almost doubles that of April. The warm season increase in LH frequency is somewhat slower over the mountains, likely due to cooler temperatures and a related weakness in instability. The slight increase in LH occurrence in June (Fig 12e) makes this the most active month for LH across most of the CWA. On average, most locations will experience a day in May and June with LH within 500 km^2 every two to three years. This is the time of year that is most likely for sufficient instability (to support vigorous convective updrafts conducive to large hail production) and relatively low freezing levels (to allow hail to reach the surface without undergoing substantial melting) to coexist.

In June and July (Figs. 12e and 12f), LH is almost as frequent over some mountainous locations, especially eastern portions of the North Carolina mountains, as it is over the foothills and Piedmont. This is not surprising, considering the increase in diurnal convective activity that occurs over the higher terrain during the late spring and summer in the warm, humid, quiescent atmospheric conditions that typically exist.

LH frequency begins a decreasing trend in July (Fig. 12f). In fact, some areas of the foothills and Piedmont experience half the number of days with LH from what is observed in June. This diminishing trend occurs despite any appreciable decrease in diurnal convective activity. In fact, July is climatologically a relatively “wet” month over the GSP CWA (U.S. Department of Commerce 2002). The decrease in LH frequency is actually due to a very warm atmosphere resulting in high freezing levels that typically exceed 4500 m above mean sea level (MSL). Although sufficient instability typically exists to allow for development of very vigorous updrafts, the high freezing levels often preclude LH from reaching the surface.

LH frequency continues a diminishing trend in August (Fig. 12g). In fact, LH becomes as infrequent during August as it is during the early spring months, despite the fact that diurnal convection remains fairly common, especially early in the month. This decrease is due to persistent high freezing levels. As diurnal instability begins to wane during the late summer and early autumn, convective activity diminishes sharply across the area. There is also a relative paucity of organized storm systems during this time. Therefore, LH occurrence falls off rapidly in September (Fig. 12h) and remains infrequent until spring.

c. Damaging Wind

The seasonal climatology maps for DW are presented in Figure 13. The maps reveal that DW are possible during any time of year, although they are most rare in the winter (Fig. 13a) and autumn (Fig. 13h) months. DW occurrence begins to increase gradually in March (Fig. 13b) and April (Fig. 13c). DW frequency during each of these months is comparable to that of the winter season, occurring on one day every 10 to 15 years on average. Frequency begins to increase more sharply in May (Fig. 13d), when the number of event days doubles that of March and April in many locations. May coincides with the period of time in which strong wind shear and at least moderate levels of instability are most likely to overlap in the GSP CWA. It can therefore be inferred that the significant increase in DW that occurs during May is likely associated with an increase in the frequency of organized convective systems. This is reflected in the relative maximum in occurrence over the southwest mountains of North Carolina. As previously stated, this maximum appears to be related to weakening MCS activity moving out of the Tennessee Valley.

In most areas, the peak months for DW are June (Fig. 13e) and July (Fig. 13f), when many locations across the foothills and Piedmont can expect around one day per month with a DW event within 500 km^2. Since incidence of highly organized convection begins to diminish in June, and becomes quite rare by July, the data suggests that most DW events in the GSP CWA are the result of localized microbursts that occur in environments characterized by moderate to high instability, high moisture content, and weak wind shear. The tendency for DW to be much more common over the western and upper Piedmont (as opposed to the mountains or lower and eastern portions of the Piedmont) during the summer can be attributed to two phenomena. Convective scenarios that are commonly observed during this time of year are: (a) The lee trough providing a focus for initiation and/or (b) the tendency for diurnal convection to initiate across the rugged terrain of the southern and eastern North Carolina mountains during the early or mid-afternoon, which then moves into the lower elevations and intensifies (and in some instances organizes along convective cold pools) as it encounters a more unstable air mass. Finally, considering the annual frequency of DW compared to LH (Fig. 12) and TO (Fig. 11), it can be reasonably stated that localized wet microbursts represent the most common form of severe weather over most of the GSP CWA.

5. Time of Day

a. Tornadoes

Figure 14 displays the diurnal distribution of each TO day within each of the 46 counties. The graphs are divided into the following geographical regions: a.) Mountains, b.) Foothills, and c.) Piedmont (Table 1). Since these graphs represent “Event Days” and not “events,” for days on which multiple events occurred within a county group, the time range chosen for the graphical displays represents the time range in which the majority of events occurred on a given day.

The charts show that TO are possible at any time of day in the GSP CWA. In general, the most common time of day for TO is in the early-to-middle afternoon (1200 to 1600 LST) over the mountains. Half of the total TO days falls within this range of time. Over the foothills, about 40% of TO days fall in the late afternoon and early evening (1600 to 2000 LST), while about 30% are during the early afternoon. The numbers for the Piedmont are similar to the foothills, albeit slightly higher for both the 1200 to 1600 LST and 1600 to 2000 LST time periods. The least likely time of day for TO over the mountains is the late night hours (0000 to 0400 LST, 3% of the event days), while TO are least frequent during the early morning hours (0400 to 0800 LST) over the Piedmont and foothills (4% for the Piedmont and 6% for the foothills).

b. Large Hail

Figure 15 shows a series of graphs displaying the diurnal climatology of LH across the GSP CWA. As is the case with TO, the peak time of day for LH across the mountains is early afternoon, which encompasses around 46% of the event days (about 34% of the event days fall between 1600 and 2000). In the foothills, the favored time of day is evenly split between the early afternoon and late afternoon/early evening, with both categories containing around 40% of the event days. The diurnal climatology observed in the Piedmont is almost opposite that of the mountains, with late afternoon/early evening being a peak time for LH (49% of the event days), with early afternoon being less favored (31%). This trend in the data is at least partially influenced by the tendency for late spring and summer convection to initiate over the mountains during the early afternoon and spread east or southeast into the Piedmont during the late afternoon and early evening (Parker and Ahijevych 2007). Early morning (0400 to 0800) is generally the least active time of day, with only 2% to 4% of event days falling in this range.

c. Damaging Winds

The diurnal climatology of DW in the GSP CWA is presented in the graphs in Figure 16. Over the mountains, the afternoon and early evening hours are not as dominant for DW occurrence as they are for LH. While 80% of mountain LH events occur between 1200 and 2000 LST, only 65% of DW events occur during this time. (Over the foothills and Piedmont, the percentages are around 80% for both LH and DW). This could be an indication that DW events over the mountains are not as closely tied to the late spring and summer diurnal convective cycle as they are over the foothills and Piedmont. Early afternoon is slightly more favored over the mountains than late afternoon (36% vs. 30%). Outside the mountains, the diurnal climatology is similar to that of LH, in that there is a tendency for DW occurrence to peak later in the day the as distance from the mountains increases. Over the foothills, the favored time of day is late afternoon (45% of the event days), followed by early afternoon (35%). This disparity between late and early afternoon is much larger over the Piedmont (53% vs. 27%). DW are least frequent during the early morning and mid/late morning across the mountains (5% for both categories). Across the foothills and Piedmont, only 2% to 3% of the days with DW are early morning episodes.

6. Summary

The unique geography of the western Carolinas and northeast Georgia, with its proximity to two major sources of water vapor, and containing the largest variation of terrain in the Eastern United States results in the GSP CWA being one of the most active in terms of severe weather occurrence in the Eastern Region of the NWS. Although tornadoes are rare across the area, large hail is much less rare, while damaging thunderstorm wind gusts are relatively common. Spring is the favored time of year for TO over the Piedmont and foothills, indicating that they are often associated with the periodic occurrence of organized storm systems. These storm systems are typically marked by strong wind shear and weak or moderate buoyancy. The paucity of tornadoes over the GSP CWA has been tied to the rarity of the juxtaposition of these necessary atmospheric ingredients (Lane 2008a). Weakening wind shear during the summer months results in a sharp decline in TO occurrence. However, TO activity increases slightly in some areas during the autumn, owing to occasional passage of tropical cyclone remnants early in the season and organized subtropical storm systems later in the season.

As instability increases later in the spring and into the early summer, convection becomes common on a daily basis across the GSP CWA. While the concurrent reduction in wind shear reduces the TO threat, there is an increase in LH occurrence. The lee trough is a regular phenomenon during the warm season across the GSP CWA, often serving as a focus for convective initiation. This feature provides much of the explanation for maxima in severe weather occurrence over the western and upper Piedmont and the foothills of South Carolina and Georgia. However, it can also be attributed to this region’s susceptibility to convection moving off the higher terrain from late spring through summer. Convection often develops across the eastern and southern mountains during the early-to-mid afternoon, producing isolated to scattered LH and DW. As this convection moves east and southeast into the foothills and Piedmont, it may encounter a more unstable air mass, resulting in intensification. The convection may also become somewhat organized along convective cold pools. This often results in severe weather (LH and especially DW) becoming more widespread east of the mountains during the mid-to-late afternoon and early evening. This cycle appears to be reflected in the diurnal severe weather climatology, as DW and LH tend to peak in the early afternoon over the mountains, while maximizing in the late afternoon and early evening over the Piedmont. Both time periods are almost equally favored over the foothills, thus suggesting a natural diurnal progression from mountains to foothills to Piedmont.

Although this semi-regular convective cycle (and the lee trough) often persists into July and early August, LH becomes much less common across the area than DW during this time of year. This is due to the very warm nature of the atmosphere (high freezing levels). However, the threat for DW remains high throughout July and much of August, especially outside the mountains. In fact, this time of year represents the most active period for DW. This time of year is typically characterized by moderate to high levels of instability, high atmospheric moisture, and weak wind shear, indicating that most of the DW events during this time are likely the result of localized wet microbursts and are not associated with highly organized convection. Since DW are the most common form of severe weather across the Piedmont and foothills, it is reasonable to conclude that wet microbursts are the most common form of severe weather event across the GSP CWA.

The severe weather climatology over the mountainous areas of the GSP CWA is somewhat different than that of the foothills and Piedmont. Although spring may be slightly more favored for TO than other seasons, the data seems to suggest that winter and summer are almost as “active.” Autumn, which represents a secondary “peak” in TO occurrence across portions of the Piedmont and foothills, is actually the least favored time of year over the higher terrain. However, tornadoes are so rare over these areas that the data sample may be inadequate to draw appropriate conclusions about seasonal trends.

While DW are twice as frequent as LH over the Piedmont, this is not the case over the higher terrain, where DW is only slightly more frequent than LH. (The number of LH event days is more than three-fourths the number of days with DW over the mountains). It is hypothesized that since June and July are generally the most active months for DW, this trend in the data is at least partially explained by the tendency for convection to remain scattered and disorganized as it develops over the mountains during the afternoon before spreading into the foothills and Piedmont. In these scenarios, severe weather is often localized over the mountains. An exception to the trend of DW being only slightly more common than LH over the mountains is across the southwest mountains of North Carolina, where DW is twice as common as LH. This trend is likely associated with the recurrent phenomenon of organized severe convection moving out of the Tennessee Valley that weakens or dissipates over the southern Appalachians.

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Acknowledgments

The author is indebted to Dave Radell of NWS Eastern Region Headquarters' (ERH) Scientific Services Division and Larry Lee, Science and Operations Officer at WFO GSP for their insightful comments and suggestions. Two anonymous reviewers from ERH also contributed helpful comments.

The estimated population density map in Figure 3 was provided by Greg Dobson of the University of North Carolina - Asheville's National Environmental Modeling and Analysis Center.

All climatology maps were created using spatial analysis tools within the ArcGIS software. References to trade names or commercial products in this document do not constitute an endorsement or recommendation by the Department of Commerce/National Oceanic and Atmospheric Administration/National Weather Service.

7. Tables

Table 1. Counties used in the analysis. Population data are from the 2000 census.

Counties categorized by geographic area	Total Land Area (km^2)	Population	Population Density (people/km^2)
Mountain Counties	**14,081**	**578,511**	**41.08**
Rabun, GA	976	16,087	16.48
Avery, NC	640	17,641	27.56
Buncombe, NC	1,709	218,876	128.07
Graham, NC	781	8,085	10.35
Haywood, NC	1,436	56,482	39.33
Henderson, NC	971	97,217	100.12
Jackson, NC	1,281	35,368	27.61
Macon, NC	1,345	32,148	23.90
Madison, NC	1,170	20,256	17.31
Mitchell, NC	575	15,784	27.45
Swain, NC	1,400	13,167	9.4
Transylvania, NC	986	29,626	30.05
Yancey, NC	811	17,774	21.92
Foothills Counties	**16,697**	**1,425,357**	**85.37**
Franklin, GA	690	21,590	31.29
Habersham, GA	723	39,603	54.78
Stephens, GA	477	25,060	52.54
Greenville, SC	2,059	407,383	197.85
Oconee, SC	1,745	69,577	39.87
Pickens, SC	1,326	113,575	85.65
Spartanburg, SC	2,122	266,809	125.73
Alexander, NC	682	35,492	52.04
Burke, NC	1,334	89,399	67.02
Caldwell, NC	1,228	79,122	64.43
Catawba, NC	1071	151,641	141.59
McDowell, NC	1,156	43,201	37.37
Polk, NC	618	19,134	30.97
Rutherford, NC	1,466	63,771	43.5
Piedmont Counties	**23,296**	**2,329,198**	**99.98**
Elbert, GA	970	20,799	21.44
Hart, GA	664	24,036	36.20
Abbeville, SC	1,324	26,133	19.74
Anderson, SC	1,962	175,514	89.46
Cherokee, SC	1,029	53,844	52.33
Chester, SC	1,518	33,228	21.89
Greenwood, SC	1,199	67,979	56.70
Laurens, SC	1,875	70,293	37.49
Union, SC	1,336	28,539	21.36
York, SC	1,802	190,097	105.49
Cleveland, NC	1,214	98,288	80.96
Davie, NC	691	39,136	56.64
Gaston, NC	942	196,137	208.21
Iredell, NC	1,546	140,924	91.15
Lincoln, NC	795	69,851	87.86
Mecklenburg, NC	1,415	79,6372	562.81
Rowan, NC	1,357	135,099	99.56
Union, NC	1,657	162,929	98.33

8. Figures

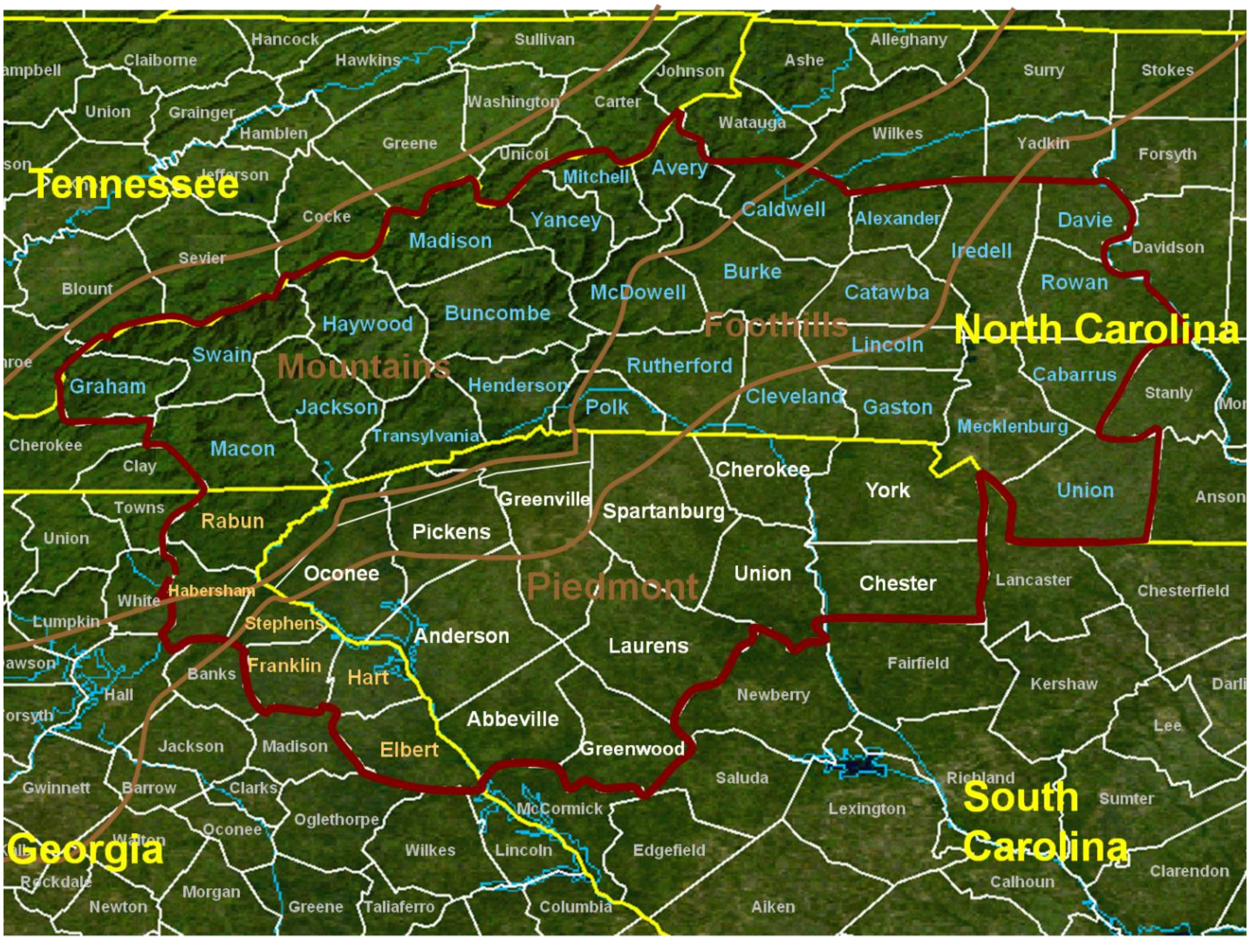


Figure 1. Topographic map of the Greenville-Spartanburg, SC (GSP) County Warning Area (CWA). Yellow lines indicate state boundaries, white lines county borders, red lines the CWA. Brown lines represent the approximate geographic boundaries between the mountains, foothills, and Piedmont. Counties within the GSP CWA are labeled in blue (for North Carolina), white (for South Carolina), and light brown (for Georgia).

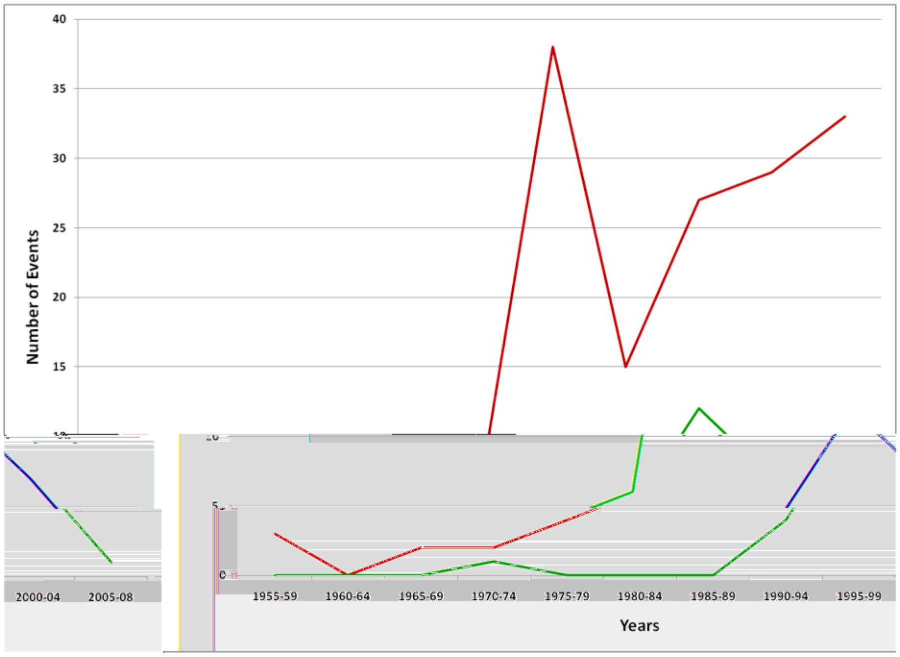


Figure 2. Number of large hail reports received from Mecklenburg County, North Carolina (red) and Graham County, North Carolina (green) in 5-year increments from 1 October 1955 through 30 September 2008.

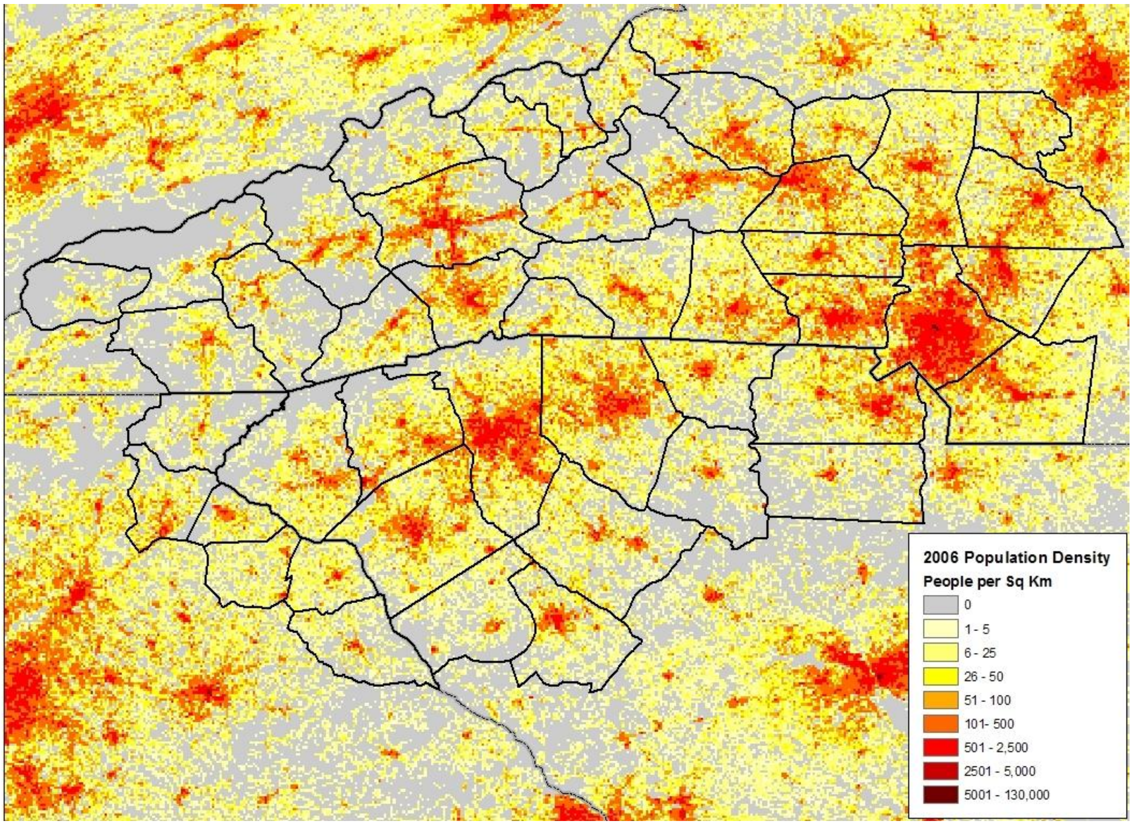


Figure 3. A 2006 estimate of population density in the GSP CWA. Data provided by the Oak Ridge National Laboratory LandScan program. Image provided by Greg Dobson, UNCA – NEMAC.

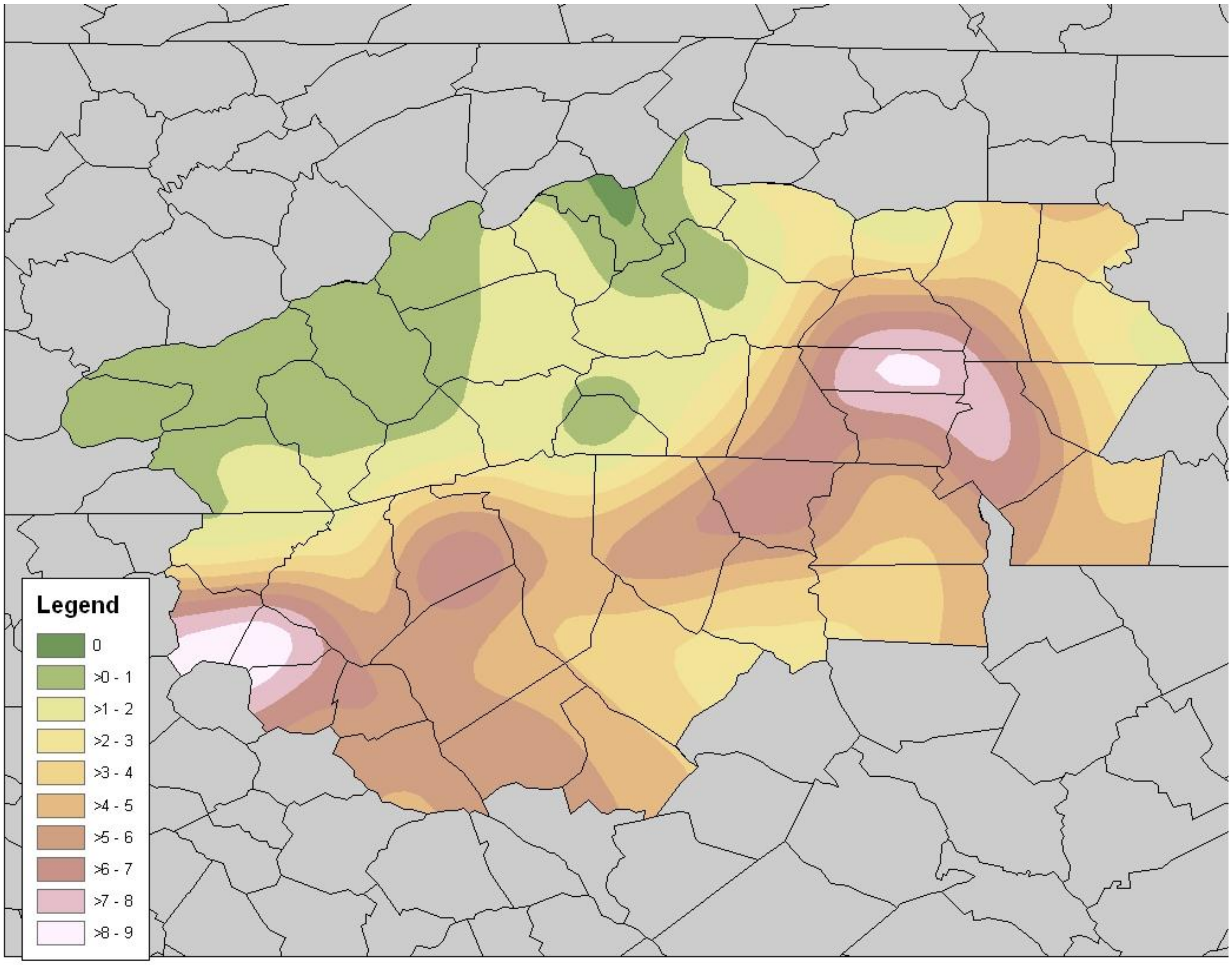


Figure 4. The number of days during the 1950 to 2008 period with a tornado within 500 km^2 of any point.

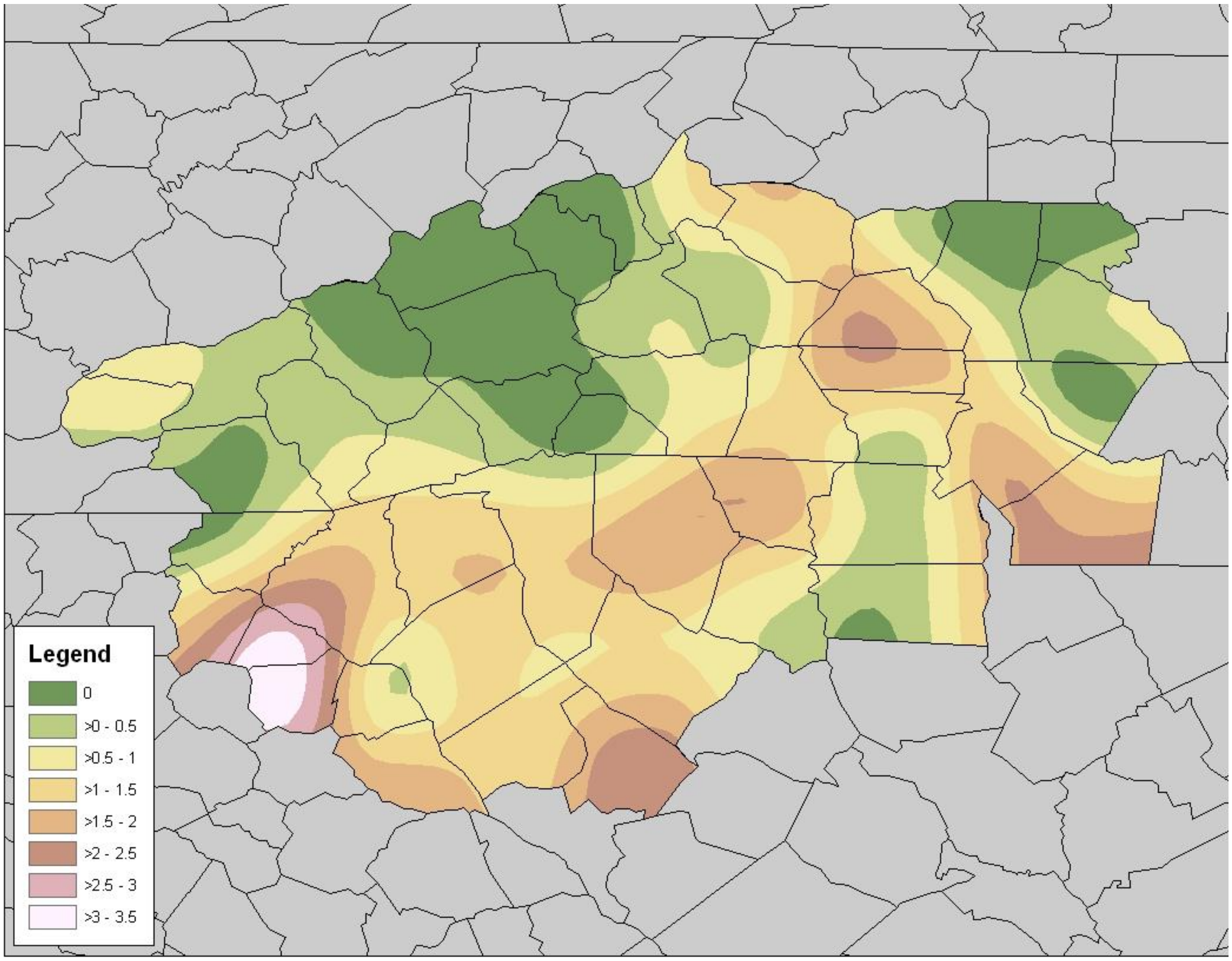


Figure 5. Same as in Figure 3, except for significant tornadoes**.**

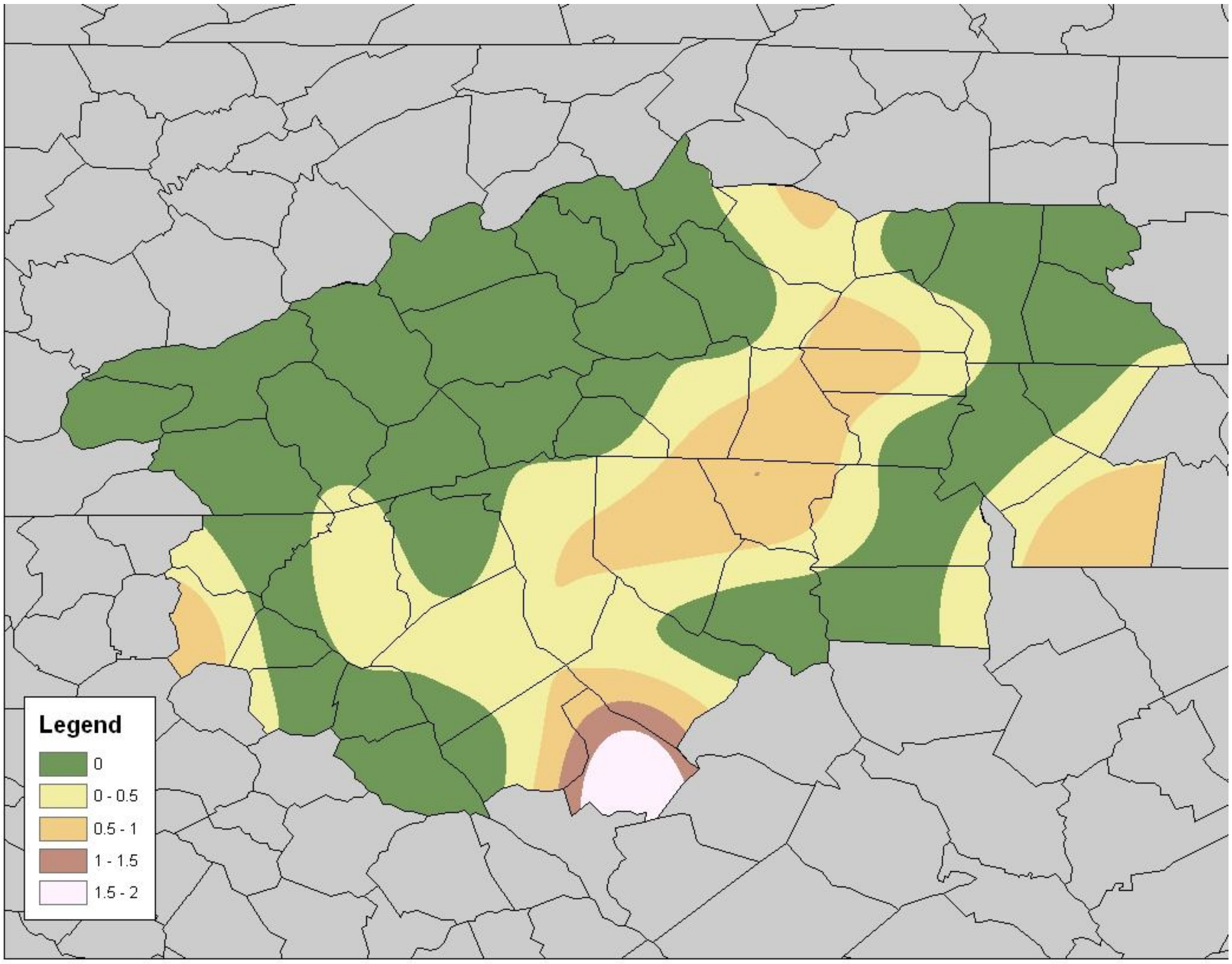


Figure 6. Same as in Figure 3, except for EF3 and EF4 tornadoes.

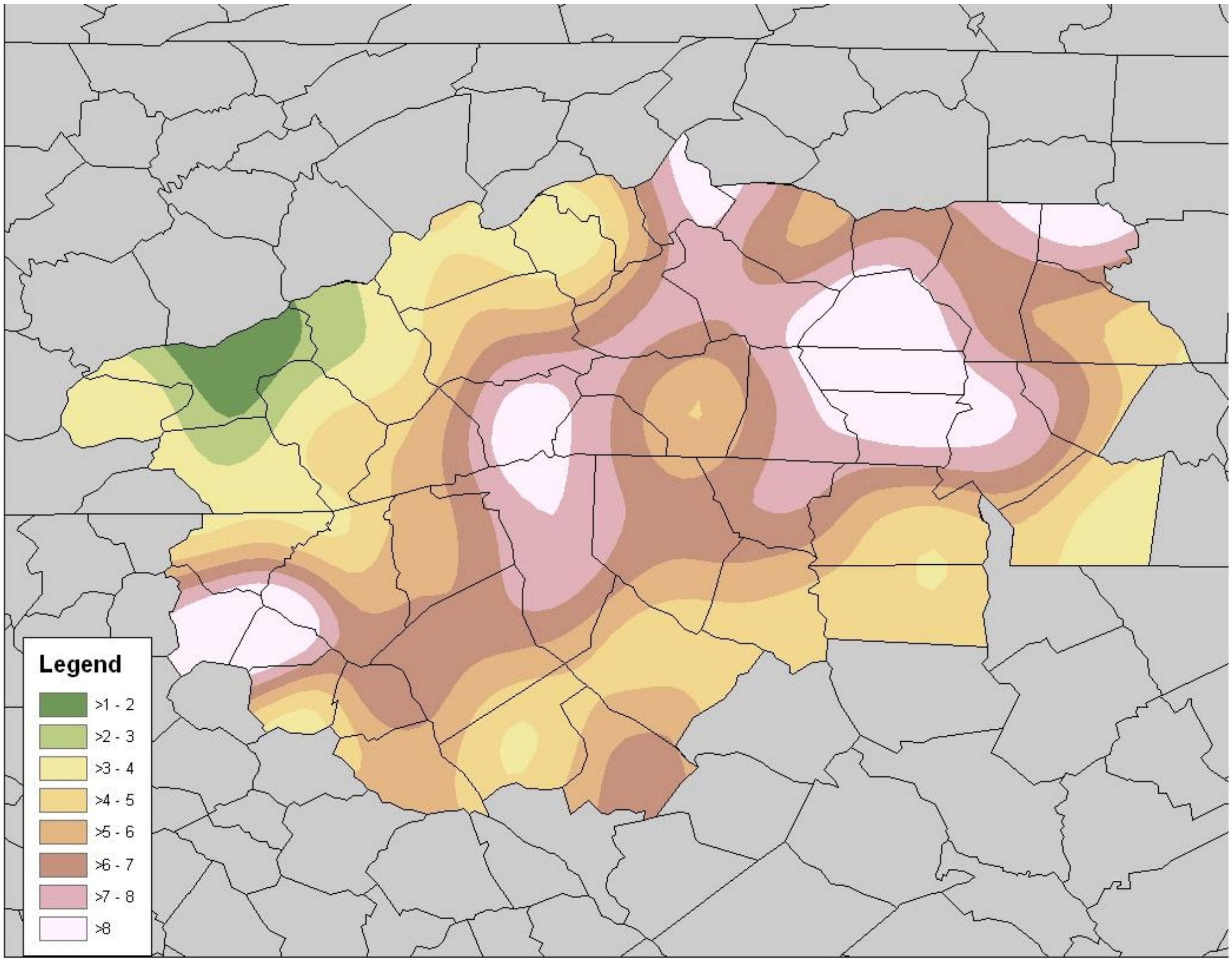


Figure 7. Average number of days per five-year period from 1995-2008 with large hail (0.75 inch) within 500 km^2 of any point.

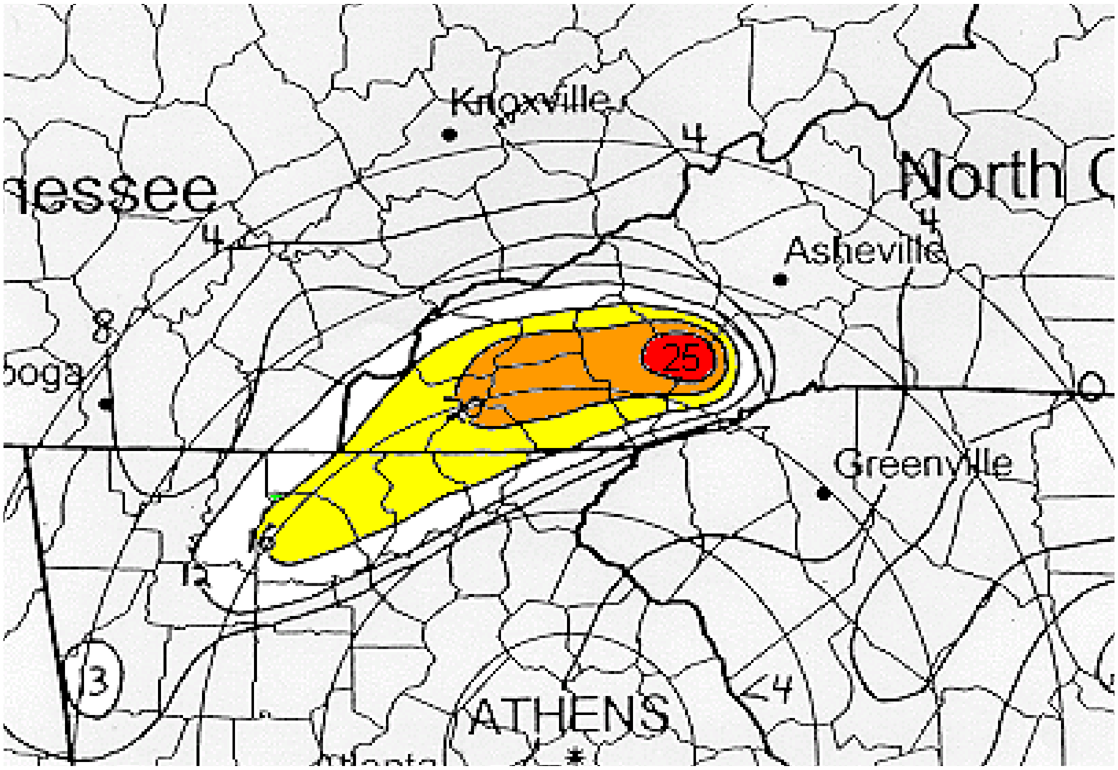


Figure 8. Number of July convective initiations over the western Carolinas and North Georgia over the 10-year period from 1985 to 1994. From Outlaw and Murphy (2000).

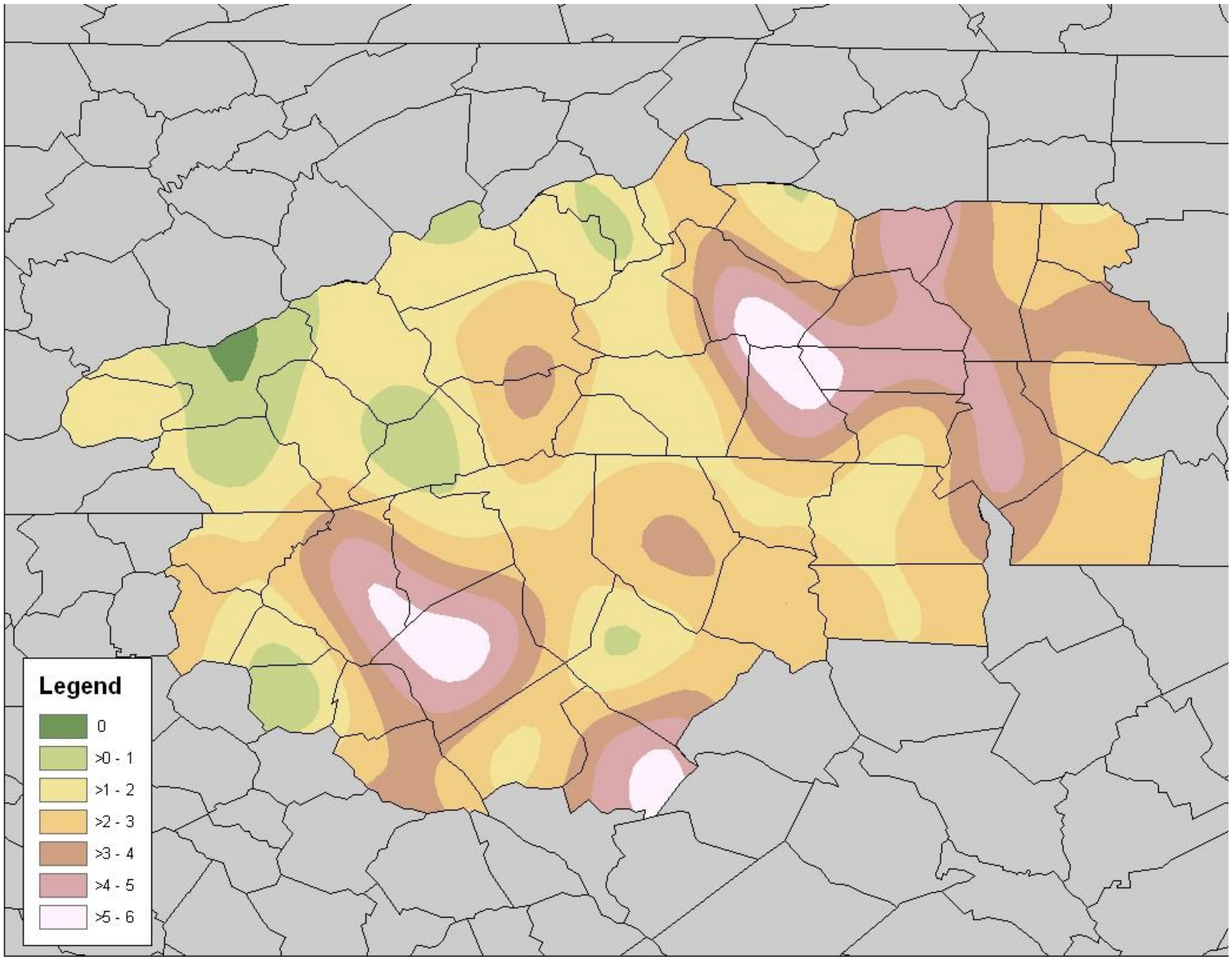


Figure 9. Number of days from 1995 to 2008 with very large hail (4.5 cm diameter or greater) within 500 km^2 of any point.

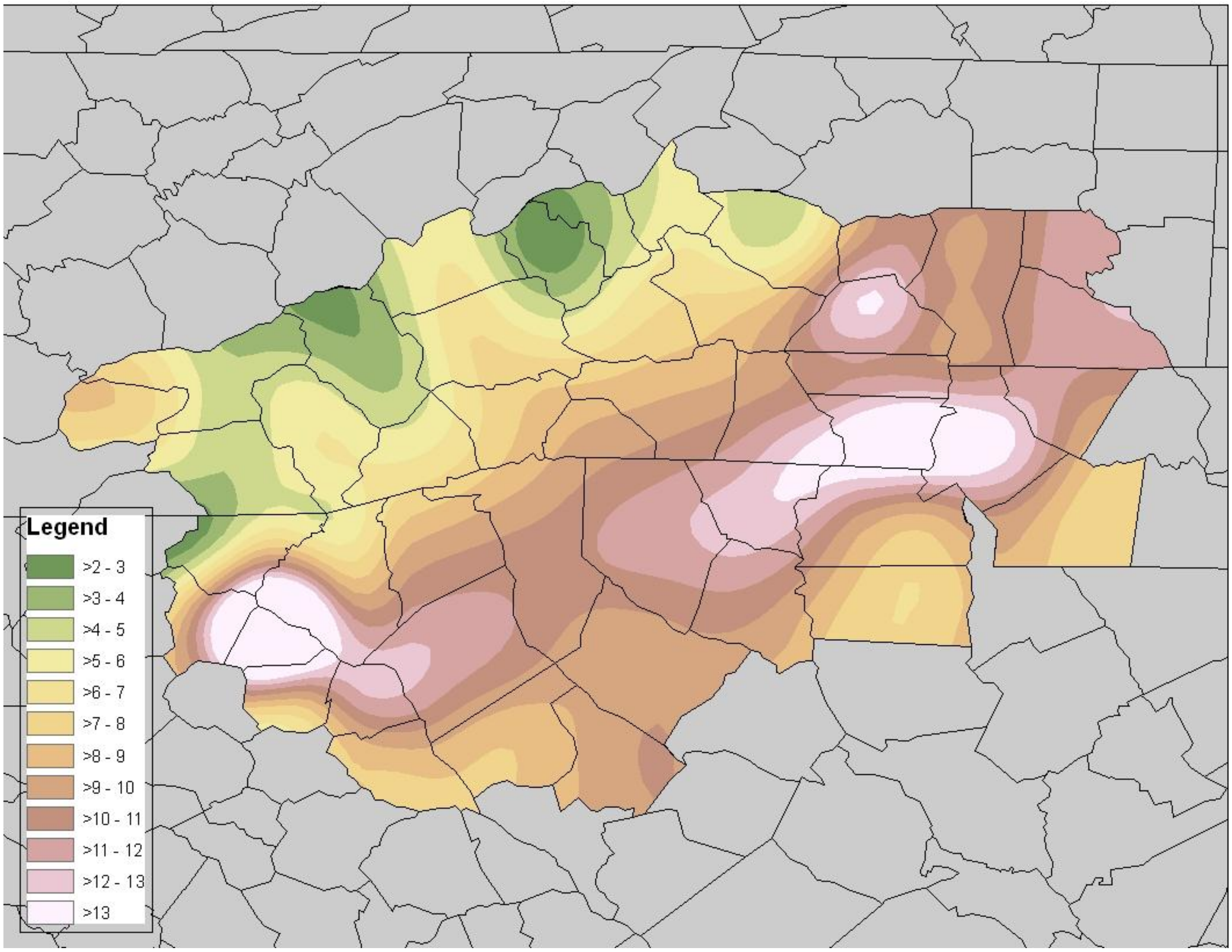


Figure 10. Same as in Figure 7, except for damaging convective wind gusts.

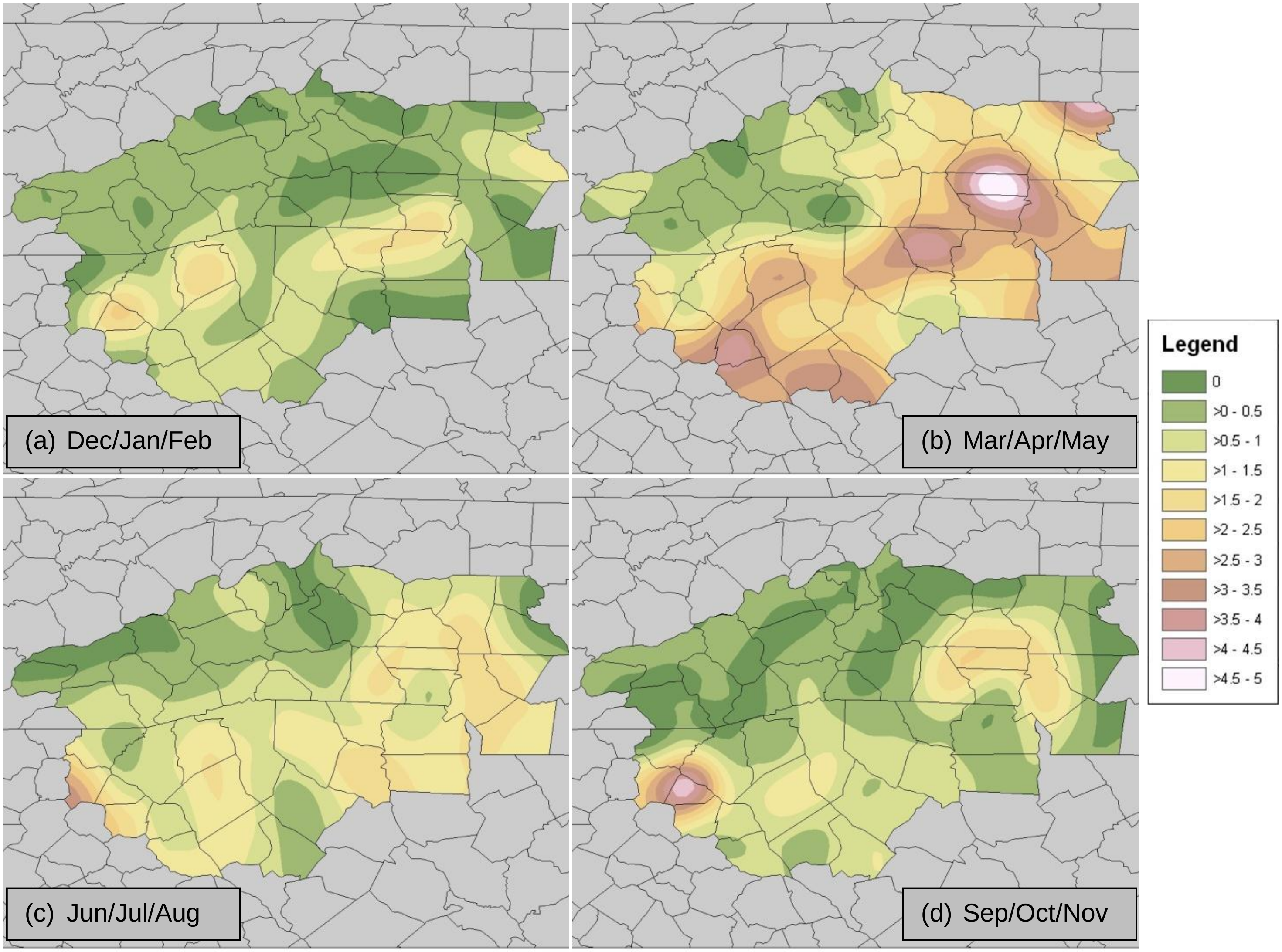
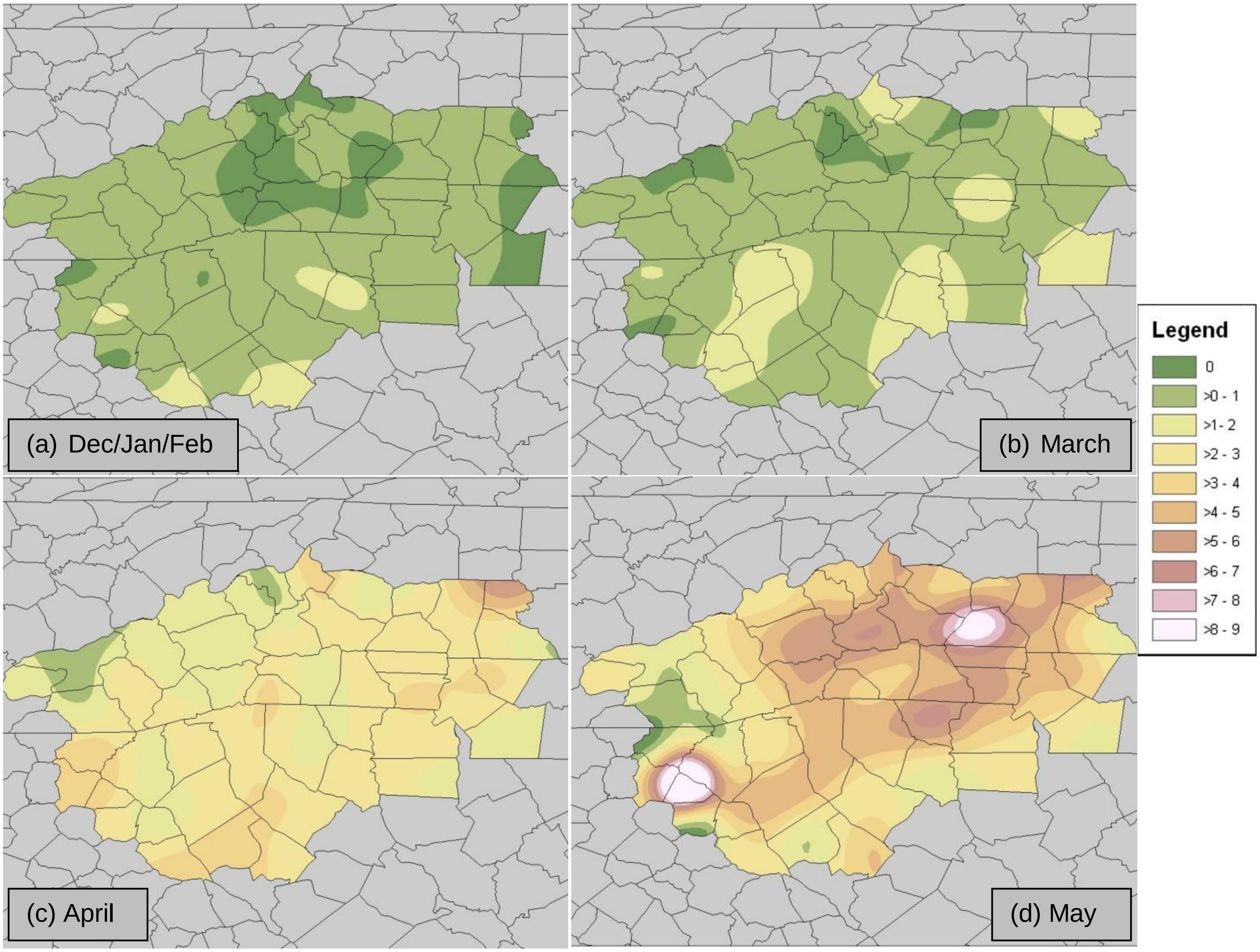


Figure 11. The number of days during the 58-year period of study (1950-2008) with a tornado within 500 km^2 of any point in (a) winter (December, January, and February), (b) spring (March, April, and May), (c) summer (June, July, and August), and (d) autumn (September, October, and November).


(a) Dec/Jan/Feb
(b) March
(c) April
(d) May
Legend
0
>0 - 1
>1- 2
>2 - 3
>3 - 4
>4 - 5
>5 - 6
>6 - 7
>7 - 8
>8 - 9

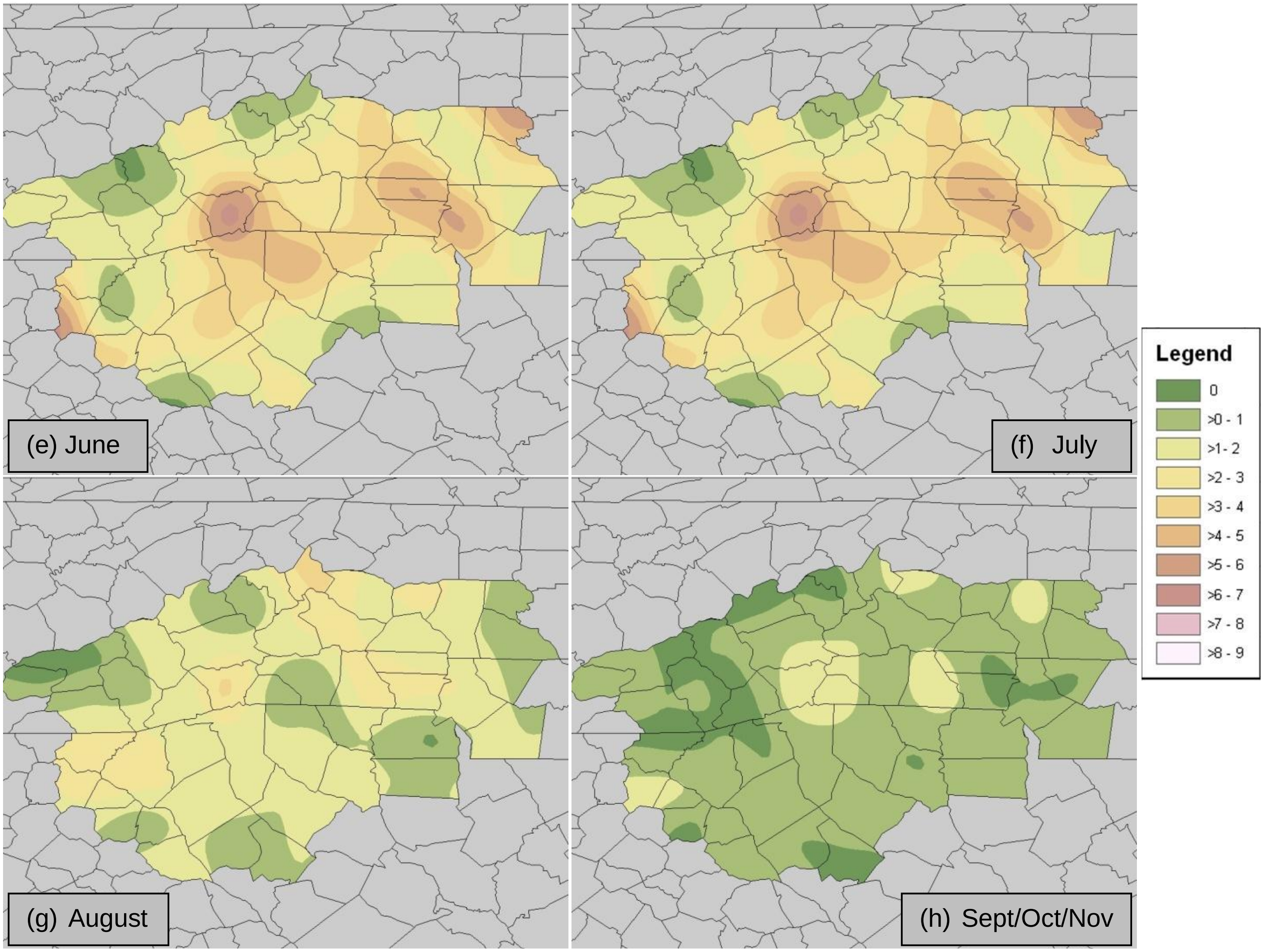
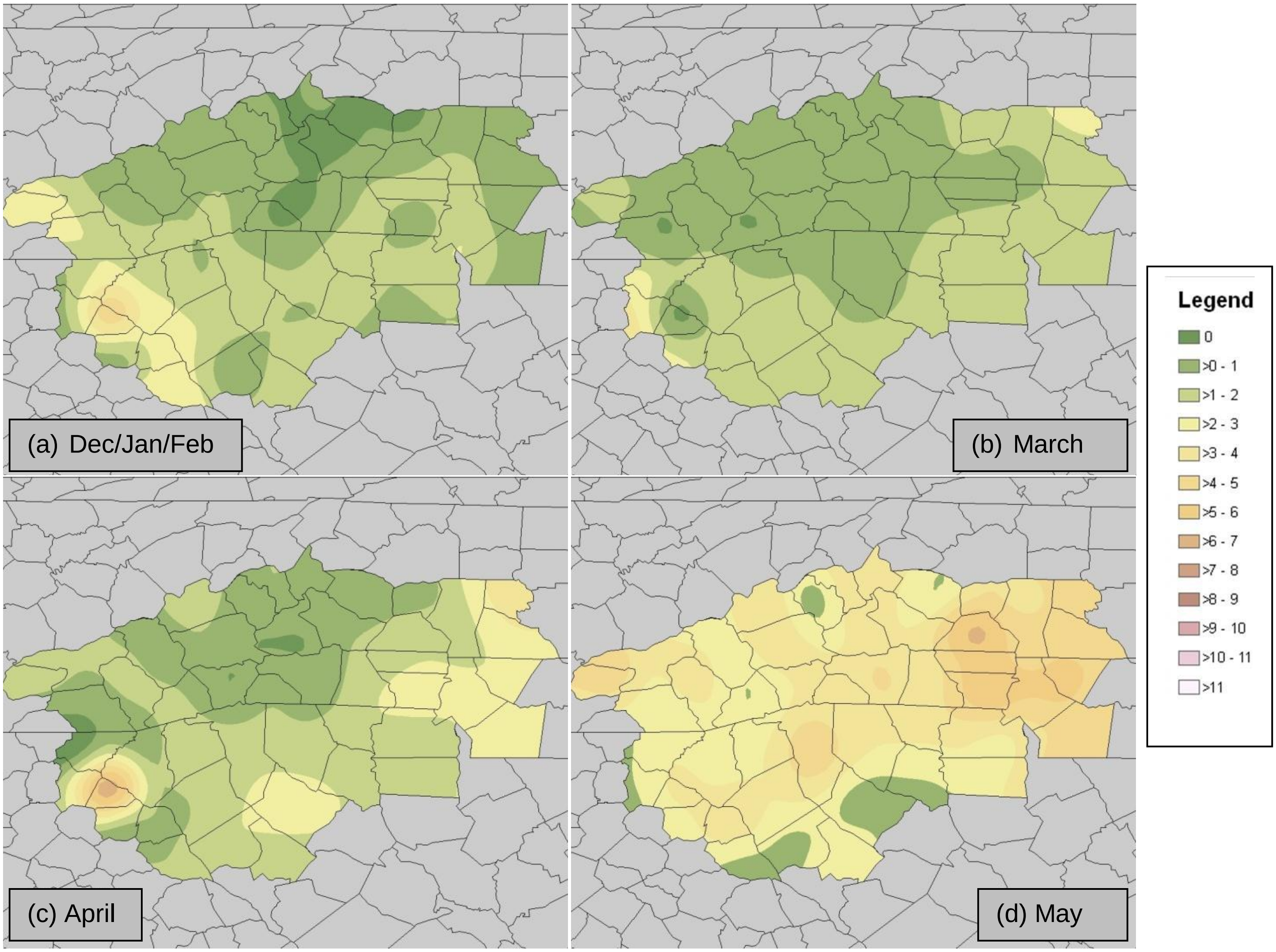


Figure 12. The number of days during the 13-year period of study with large hail within 500 km^2 of any point in (a) December/January/February, (b) March (c) April, (d) May, (e) June, (f) July, (g) August, and (h) September/October/November.


(a) Dec/Jan/Feb
(b) March
(c) April
(d) May
Legend
0
>0 - 1
>1 - 2
>2 - 3
>3 - 4
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>8 - 9
>9 - 10
>10 - 11
>11

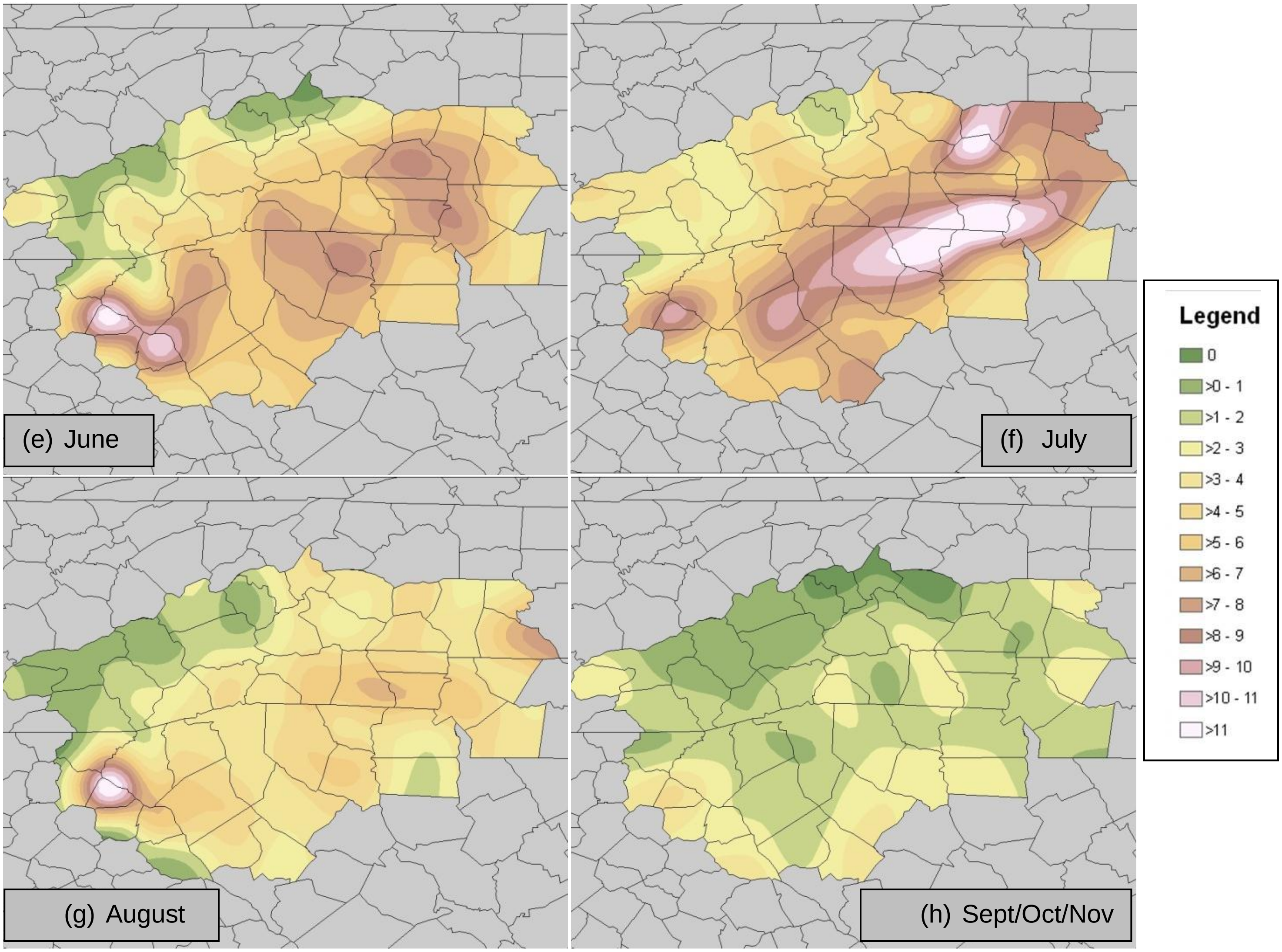
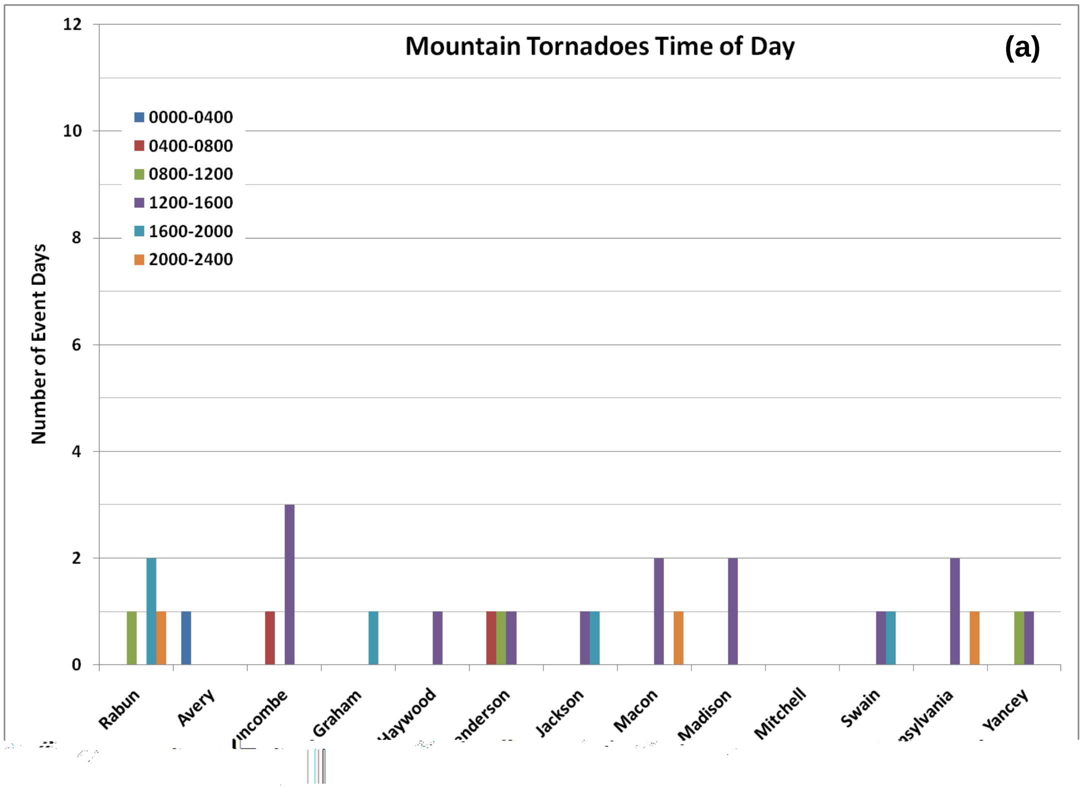
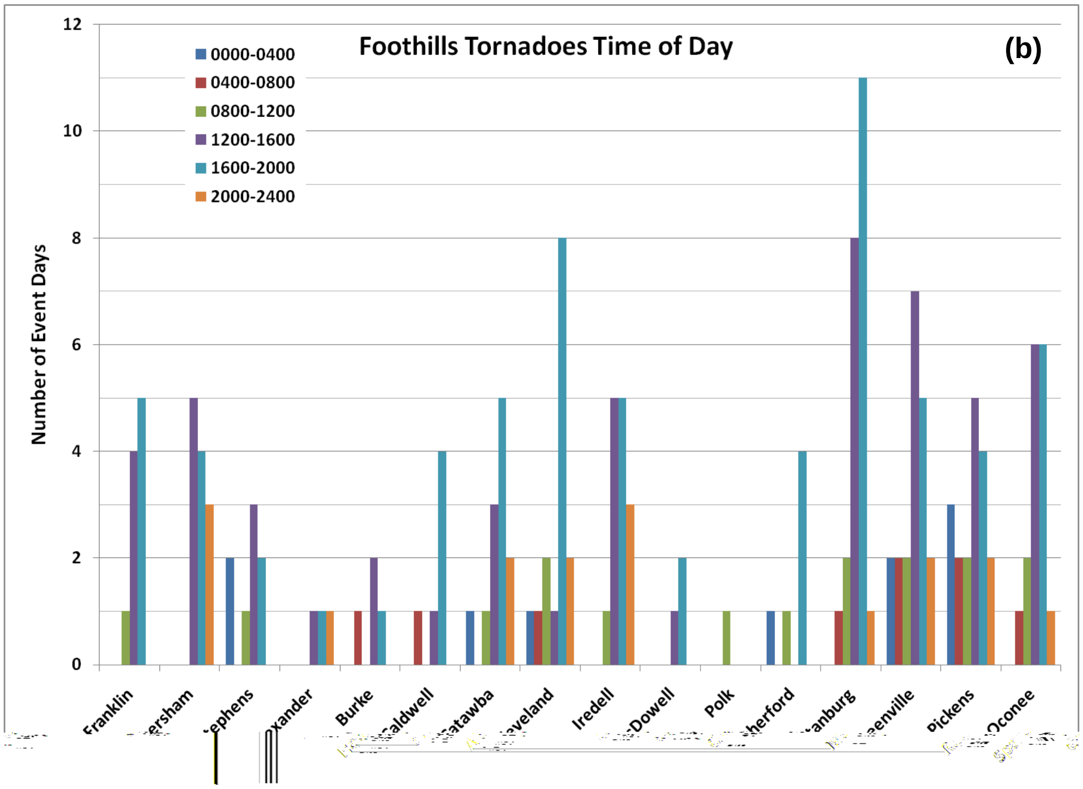


Figure 13. Same as in Figure 11, except for damaging convective wind gusts.


Mountain Tornadoes Time of Day
(a)
0000-0400
0400-0800
0800-1200
1200-1600
1600-2000
2000-2400
Number of Event Days
0
2
4
6
8
10
12
Rabun
Avery
ncombe
Graham
aywood
nderson
Jackson
Macon
Madison
Mitchell
Swain
nsylvania
Yancey


Foothills Tornadoes Time of Day
(b)
0000-0400
0400-0800
0800-1200
1200-1600
1600-2000
2000-2400
Number of Event Days
0
2
4
6
8
10
12
Franklin
ersham
ephens
xander
Burke
aldwell
atawba
eveland
Iredell
Dowell
Polk
herford
anburg
eenville
Pickens
Oconee

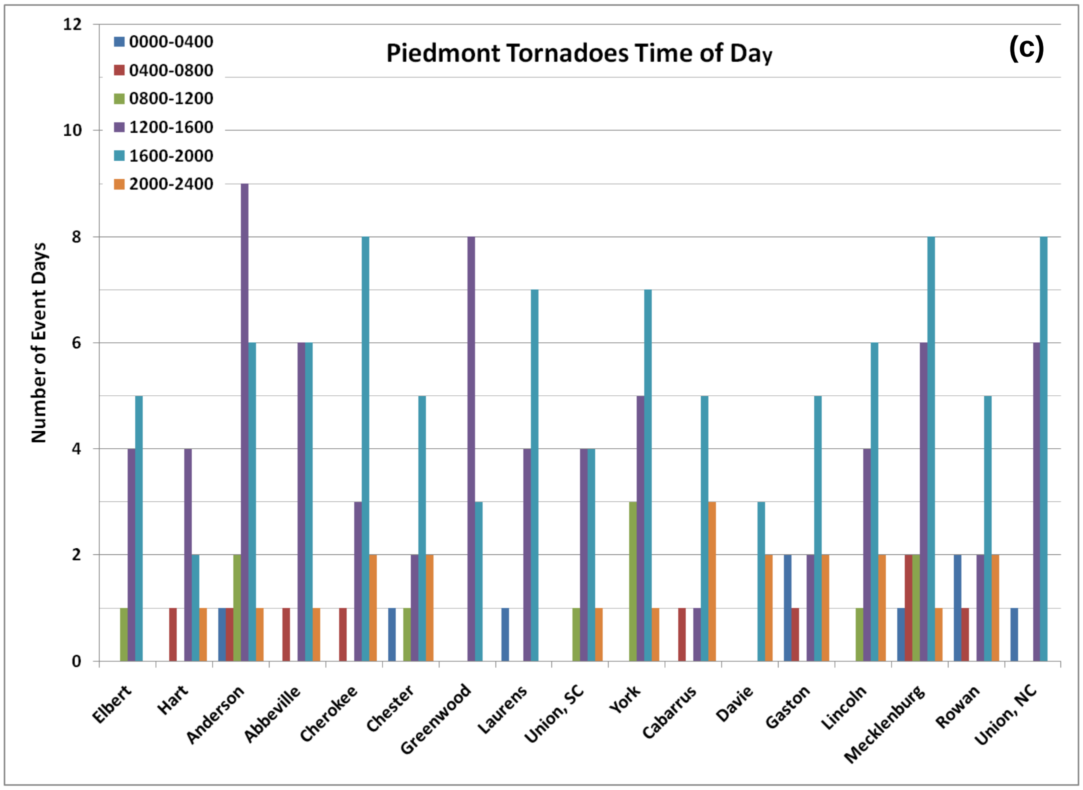
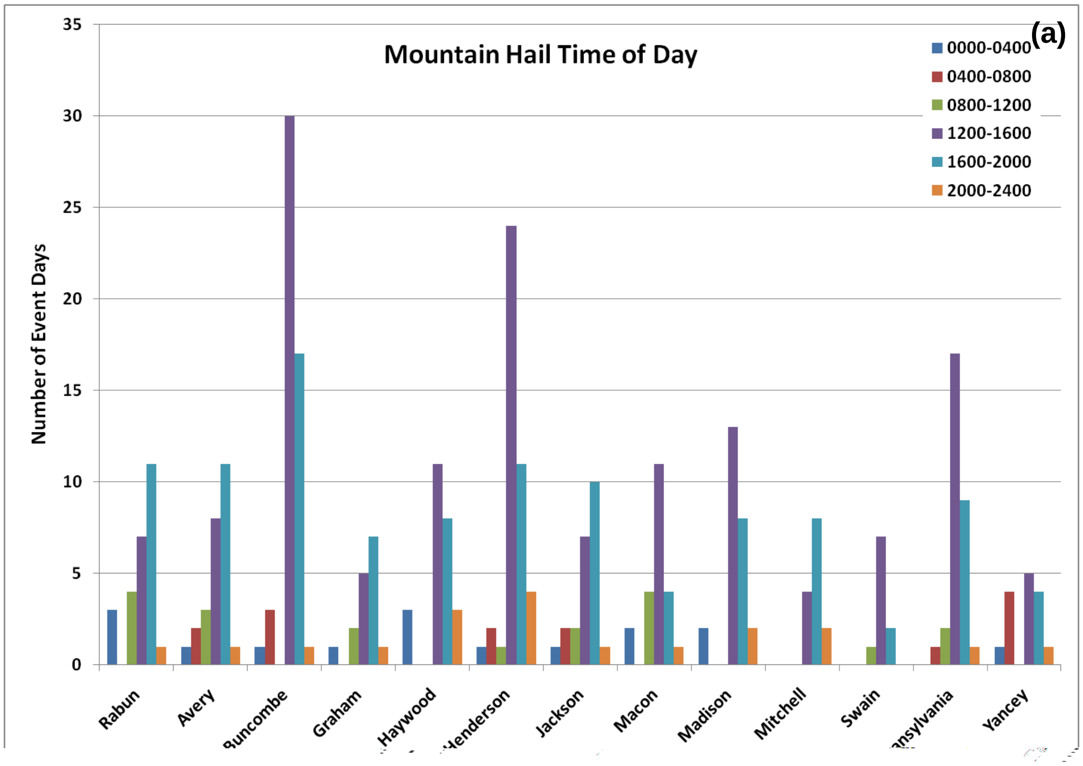
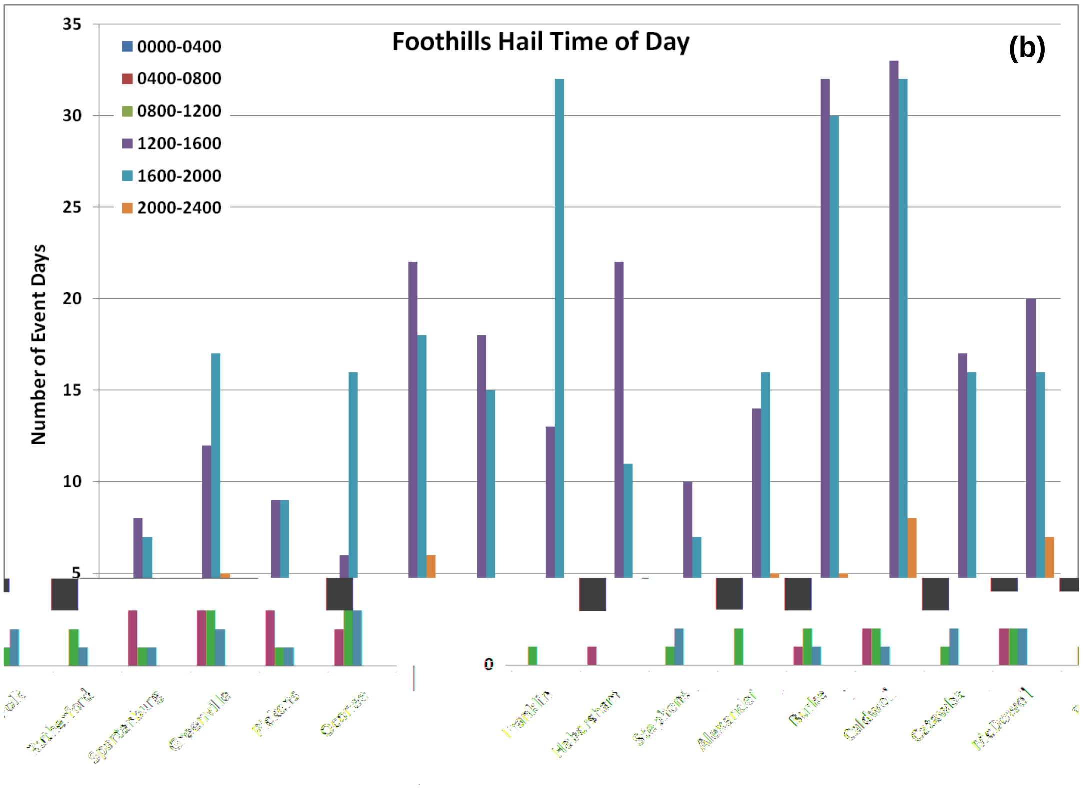


Figure 14. The number of tornado event days since 1 October 1950 categorized by time of day for (a) the mountain counties, (b) foothills counties, and (c) Piedmont counties. Times ranges are in LST.


Mountain Hail Time of Day
(a)
0000-0400
0400-0800
0800-1200
1200-1600
1600-2000
2000-2400
Number of Event Days
35
30
25
20
15
10
5
0
Rabun
Avery
Buncombe
Graham
Haywood
Henderson
Jackson
Macon
Madison
Mitchell
Swain
Transylvania
Yancey


Foothills Hail Time of Day
(b)
0000-0400
0400-0800
0800-1200
1200-1600
1600-2000
2000-2400
Number of Event Days
35
30
25
20
15
10
5
0
Rutherford
Spartanburg
Greenville
Pickens
Oconee
Franklin
Habersham
Stephens
Alexander
Burke
Caldwell
Catawba
McDowell

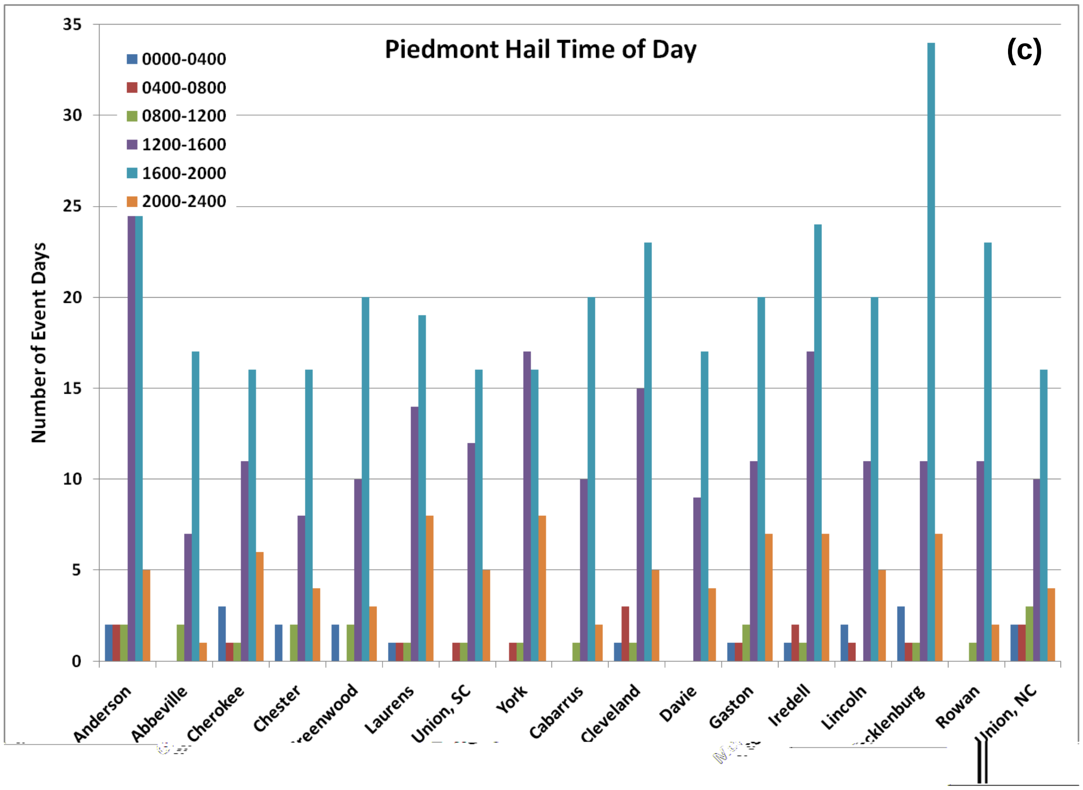
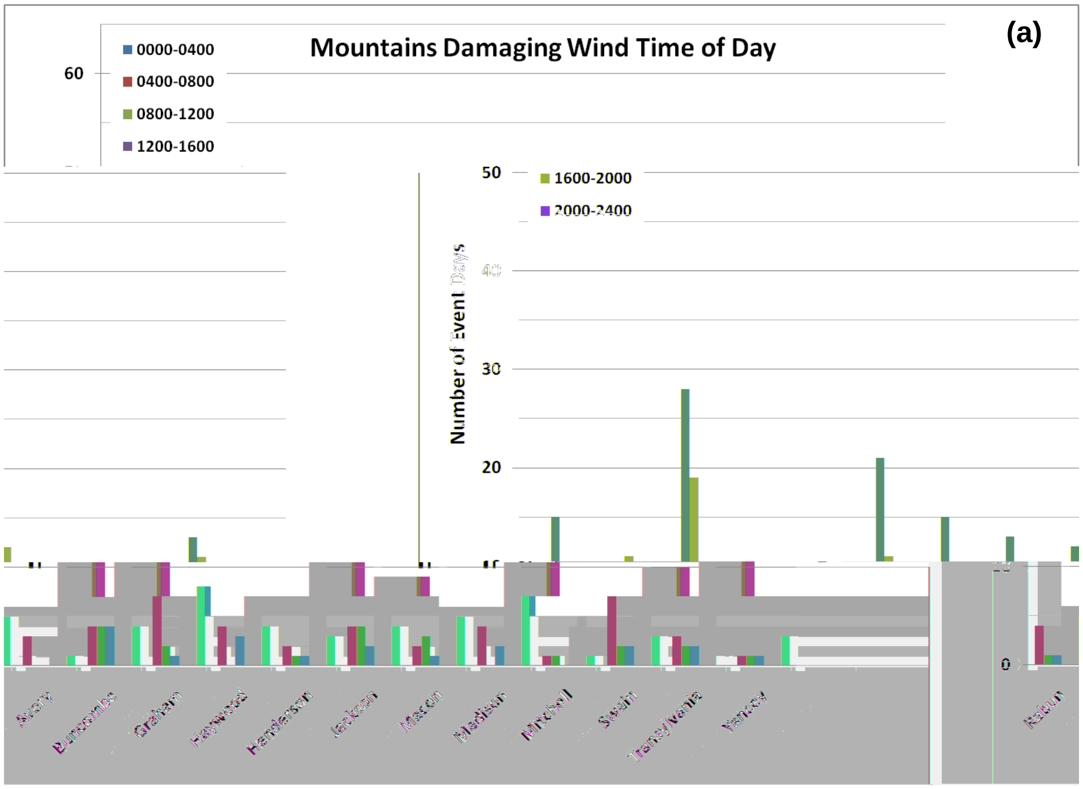
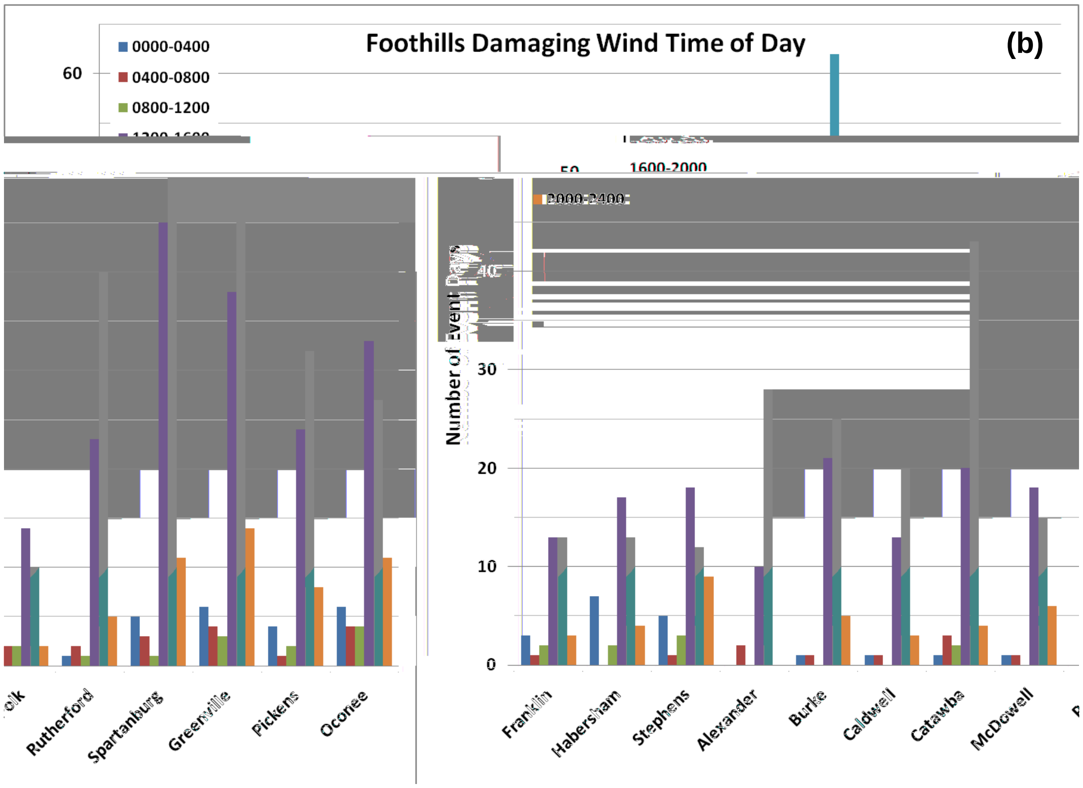


Figure 15. The number of large hail event days since 1 October 1995 categorized by time of day for (a) the mountain counties, (b) foothills counties, and (c) Piedmont counties. Times ranges are in LST.


(a)
Mountains Damaging Wind Time of Day
0000-0400
0400-0800
0800-1200
1200-1600
1600-2000
2000-2400
Number of Event Days
60
50
40
30
20
10
0
Avery
Buncombe
Graham
Haywood
Henderson
Jackson
Macon
Madison
Mitchell
Swain
Transylvania
Yancey
Rabun


(b)
Foothills Damaging Wind Time of Day
0000-0400
0400-0800
0800-1200
1200-1600
1600-2000
2000-2400
Number of Event Days
60
50
40
30
20
10
0
Rutherford
Spartanburg
Greenville
Pickens
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Franklin
Habersham
Stephens
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Burke
Caldwell
Catawba
McDowell

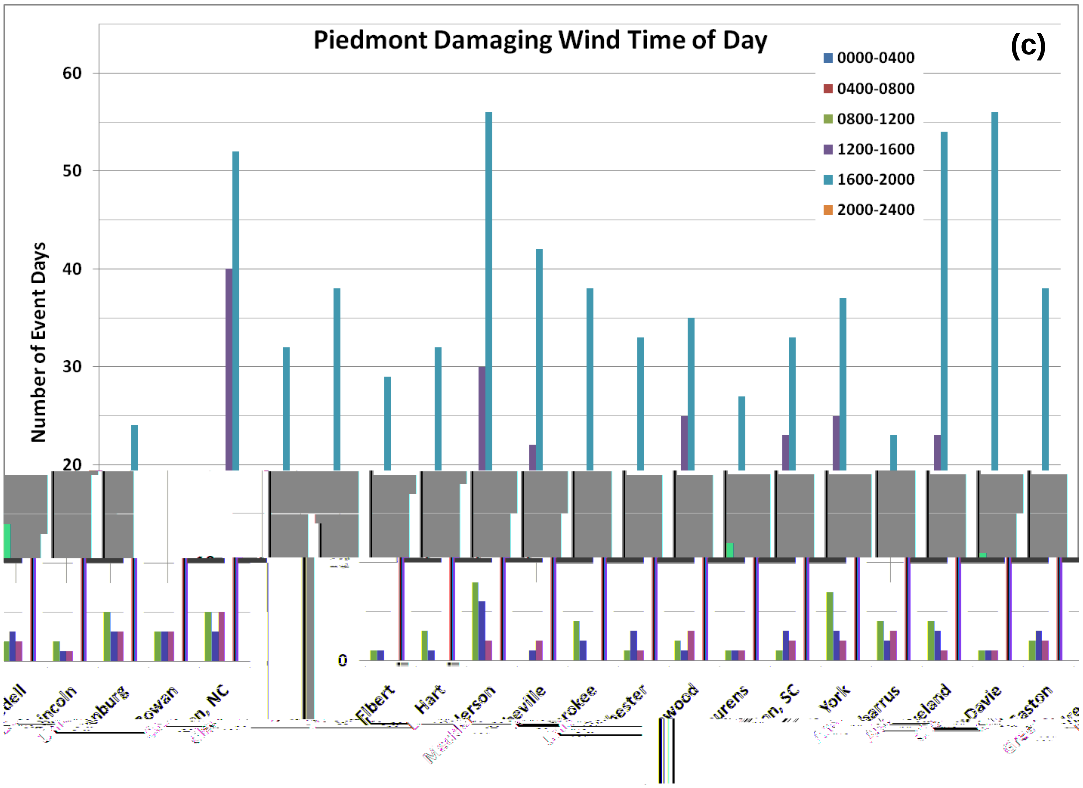

Figure 16. Same as in Figure 14, except for damaging thunderstorm winds.