An Observational Examination of Long-Lived Supercells. Part I: Characteristics, Evolution, and Demise

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ABSTRACT

Observations of supercells and their longevity across the central and eastern United States are examined, with the primary focus on understanding the properties of long-lived supercells (defined as supercells lasting ≥4 h). A total of 224 long-lived supercells, occurring in 184 separate events, are investigated. These properties are compared with those of short-lived supercells (lifetimes ≤2 h) to determine the salient differences between the two classifications. A key finding is that long-lived supercells are considerably more isolated and discrete than short-lived supercells; as a result, the demise of a long-lived supercell (i.e., the end of the supercell phase) is often signaled by a weakening of the storm's circulation and/or a rapid dissipation of the thunderstorm. In contrast, short-lived supercells commonly experience a demise linked to storm mergers and convective transitions (e.g., evolution to a bow echo). Also noteworthy, 36% of the long-lived supercell events were associated with strong or violent tornadoes (F2–F5), compared with only 8% for the short-lived supercell events. Evolutionary characteristics of long-lived supercells vary geographically across the United States, with the largest contrasts between the north-central United States and the Southeast. For example, 86% of the long-lived supercells across the north-central United States were isolated for most of their lifetime, whereas only 35% of those in the Southeast displayed this characteristic. Not surprisingly, the convective mode was discrete for 70% of the long-lived supercell events across the north-central United States, compared with 39% for the Southeast.

1. Introduction

a. Importance of long-lived supercells

Supercell thunderstorms, which were originally defined by Browning (1962, 1964), represent the most organized, most severe, and longest-lived form of isolated, deep moist convection. Their updraft cores can be largely undiluted (i.e., conserved equivalent potential temperature from cloud base), with vertical velocities approaching 50 m s^{-1} in the strongest storms (e.g., Musil et al. 1986; see their Fig. 9). Exemplifying their severity, the 5 May 1995 supercell that struck the Dallas–Fort Worth, Texas, area was the single costliest nontornadic thunderstorm in U.S. history, producing large hail, damaging winds, and flash flooding with economiclosses near $2 billion (NOAA 1995; Calianese et al. 2002). Moreover, some of the longest-lived supercells can produce an extensive swath of severe weather, and on occasion they generate a devastating combination of large hail and damaging winds (e.g., Nelson 1987; Klimowski et al. 1998; Glass and Britt 2002). It is also noteworthy that long-lived supercells[1] have been

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[1] Long-lived supercells are hereafter arbitrarily defined as *supercells* that persist in a quasi-steady manner for ≥4 h, moderate-lived supercells are defined as supercells whose lifetime is between 2 and 4 h, and short-lived supercells are defined as supercells with lifetimes ≤2 h. The goal of the present research is to better understand the supercell longevity spectrum, and these definitions were chosen with this in mind. Note that it is possible to have a *long-track* supercell by virtue of its speed, yet it might not meet the above definition of long lived. A temporal definition of supercell longevity was chosen because time is inherent to the definition of a supercell, whereas the distance a supercell travels is not germane to its definition.

observed during many tornado outbreaks in the United States, including the 3 May 1999 outbreak in central Oklahoma (Thompson and Edwards 2000).

Not surprisingly, part of the supercell definition includes persistence, namely, that the storm's midlevel circulation (i.e., mesocyclone or mesoanticyclone) persists at least on the order of tens of minutes (Moller et al. 1994), representing the upper bound of the time it takes for a single thermal to be processed by an updraft (Doswell 2001). Operational experience suggests the typical lifetime of a supercell is 1–2 h, which is consistent with Burgess et al. (1982), who found the average lifetime of single-core mesocyclones to be 90 min. In some cases, a supercell may persist in a quasi-steady manner for several hours, and in even fewer cases, the lifetime of a supercell may extend beyond 4–5 h (e.g., Paul 1973; Browning and Foote 1976; Warner 1976).

b. *Motivation for this study*

Considerable research has been directed toward the understanding of supercell dynamics since the 1940s (Doswell 2001), and much of this effort has focused on tornadic versus nontornadic supercells (e.g., Johns et al. 1993; Brooks et al. 1994a,b; Rasmussen and Blanchard 1998; Markowski et al. 2003; Thompson et al. 2003; among many others). Conversely, comparatively little has been done to elucidate supercell longevity and, ultimately, supercell demise.[2] Most of what has been done to study long-lived supercells involves case studies (e.g., Browning and Foote 1976; Glass and Britt 2002). Indeed, very little information exists on the general properties of long-lived supercells, and a formal definition of long-lived supercells does not exist (i.e., only nebulous definitions appear in the literature).

There are several reasons why it would be advantageous to anticipate long-lived supercell occurrence in an operational setting. First, the duration of severe weather warnings sometimes might be lengthened, beyond what is commonly used, if an operational forecaster could correctly anticipate long-lived supercells (e.g., a 60-min warning versus a 45-min warning). One potential benefit of this is increased lead time for tornado and severe thunderstorm warnings. Second, longevity predictions would be useful when generating short-term forecasts for locations (or counties) downstream of an existing supercell. Third, a forecast of supercell longevity may be a beneficial factor in making operational staffing decisions—both for the number of personnel needed and their duration of duty. Fourth, information about anticipated supercell longevity may assist operational forecasters when determining whether to issue or extend severe weather watches, which typically have a valid time of at least 4 h (corresponding to the long-lived supercell definition). Finally, knowledge of thunderstorm demise mechanisms, which directly affect thunderstorm longevity, may be especially beneficial in an operational setting where several supercells are present, thereby enabling warning forecasters to effectively subdivide warning operations.

Considering the preceding discussion, the general characteristics, evolution, and demise of long-lived supercells across the United States are documented in the current study. Short-lived supercells are also examined to determine how their properties differ from their longer-lived counterparts. After defining supercells, supercell events, and data collection methods (section 2), the results are presented for the long- versus short-lived supercell events, as well as for various geographical regions of the United States (section 3). In section 4 the results are summarized, with a focus on operational forecasting, although a more detailed analysis of long-lived supercell environments is presented in Bunkers et al. (2006, hereafter Part II).

2. Data and methods

a. *Defining and identifying supercells and supercell events*

The feature that distinguishes supercells from other thunderstorms is their persistent, rotating updraft in the midlevels (approximately 2–8 km AGL) of the storm (Browning 1964; Weisman and Klemp 1984; Doswell and Burgess 1993; Moller et al. 1994). Although a multicellular structure can be imposed upon a supercell (e.g., Foote and Wade 1982; Foote and Frank 1983; Nelson 1987; Doswell et al. 1990), a quasi-steady rotating updraft in the midlevels of a thunderstorm, lasting at least on the order of tens of minutes, defines it as a supercell. It is not always easy to classify a thunderstorm as a supercell because of the subjectivity in deciding how "strong and steady" the rotating updraft needs to be (e.g., Browning 1977; Moller et al. 1994); however, supercells become relatively easy to identify given ample operational experience.

Supercells in the present study were identified consistent with the procedures in Thompson (1998) and Klimowski et al. (2003). A combination of radar reflec-

[2] The word "demise" is used throughout this study to indicate the end of the supercell phase (i.e., the end of the midlevel circulation), and not the end of the thunderstorm. Accordingly, a supercell can experience its demise, but via merger and/or evolution to another form (e.g., a bow echo) the remaining nonsupercellular thunderstorm may persist well beyond this time.

tivity characteristics was sufficient to identify most supercells, especially during the middle portions of their lifetimes. The characteristics included hook echoes, midlevel overhang or bounded weak echo regions (BWERs), strong reflectivity gradients on the inflow side of the storm, quasi steadiness of storm reflectivity, and deviant motion (Marwitz 1972; Browning 1977; Lemon 1980; Bunkers et al. 2000). These were chosen because they can be used to infer updraft rotation and strength–persistence, which can be particularly helpful when velocity data are missing (e.g., at relatively far ranges from the Doppler radar). Furthermore, motion transverse to the vertical wind shear is a fundamental property of supercells (Bunkers et al. 2000; Zeitler and Bunkers 2005), which is a direct result of the contribution of updraft rotation to updraft strength (Weisman and Rotunno 2000; see their Fig. 14). Therefore, by definition storm motion must change when an ordinary cell becomes a supercell (and vice versa), at times producing a "reverse S shaped" storm track (Fankhauser 1971; see his Fig. 3); this can be an invaluable tool when identifying supercells.

In cases where supercell identification was not clear based on the reflectivity signatures (e.g., when storms were not isolated), storm-relative velocity data were consulted to verify the existence of mesocyclonic or mesoanticyclonic rotation within the storm. Moreover, storm-relative velocity data were used, when available, during the beginning (ending) stages of a supercell's lifetime to help determine the onset (cessation) of rotation (and also demise); a minimum azimuthal velocity difference of 20 m s^{-1} across a distance of less than 10 km was required (similar to Thompson et al. 2003). If a supercell weakened (i.e., the parent thunderstorm lost its supercell characteristics), and then the same thunderstorm subsequently reacquired supercell status, it was treated as two separate supercells.

As noted in the introduction, a supercell was considered long lived if its individual lifetime, as a supercell, was $\geq$4 h. By way of distinction, a long-lived supercell event was defined as any convective event[3] in which at least one long-lived supercell was observed (this included both right and left movers). Accordingly, this means not all supercells in a long-lived event had to persist for $\geq$4 h. Thus, there were one or more long-lived supercells per event (the average is 1.2; see section 3b below)—along with some shorter-lived supercells at times. When more than one long-lived supercell event occurred on the same day, the events had a separation of at least 185 km (100 n mi), and most often they were in different states with few intervening thunderstorms. Of the 184 long-lived supercell events obtained for the current study, there were two (three) long-lived events per day on 23 (5) separate occasions, and four long-lived events occurred on only one day.

A slightly different approach was taken for defining short-lived supercell events. These were determined by averaging the lifetimes of the supercells for a given convective event, and if the average supercell lifetime was $\leq$2 h (consistent with the definition of a short-lived supercell), then the event was considered to be short lived. Note that some short-lived supercell events included individual supercells with lifetimes $>$2 h, but not $\geq$4 h (in which case it would have been a long-lived event), provided the average supercell lifetime did not exceed 2 h. In addition, a number of short-lived supercell events lasted well over 2 h, but again, the average lifetime of the individual supercells per event was $\leq$2 h. This approach was chosen so as not to bias the moderate-lived supercell events (defined below) with several short-lived supercells. Of the 119 short-lived supercell events obtained for the current study, there were two (three) short-lived events per day on 10 (3) separate occasions.

On days when a large number of supercells occurred across a fairly broad region, it was possible to have a combination of long- and short-lived supercell events. For example, the northern end of a series of convective clusters may have consisted of one or more long-lived supercells, thus classifying it as a long-lived supercell event. Farther south, presumably in a different environment, a short-lived supercell event may have occurred. Accordingly, there were 21 days in which both long- and short-lived supercell events occurred. The average distance between the nearest supercells in the long- and short-lived events in these situations was 740 km (400 n mi), with only three events as close together as 185–278 km (100–150 n mi; refer to footnote 3).

As is typical with such classification-type studies, certain convective events containing supercells were difficult to place in either of the two above categories. For example, there were convective events with supercells displaying average lifetimes between 2 and 4 h, but in which no long-lived supercells occurred. These were subsequently classified as moderate-lived supercell events, with a total of 137 such events acquired. This portion of the database will be used in Part II of this study and is not discussed further here.

[3] Based on operational experience, a convective event is defined as an area of thunderstorms that is separated from any other area of thunderstorms by at least 185 km (100 n mi) at its edges. If areas of thunderstorms were closer together than this, they were considered part of the same event. The duration of the parent mesoscale convective system defined the temporal constraint.

b. Supercell data sources and radar data

Several sources were used to gather supercell data. Initially, a literature search produced 17 long-lived supercell events (Hamilton 1958; Fujita and Grandoso 1968; Fujita et al. 1970; Paul 1973; Browning and Foote 1976; Warner 1976; Fujita 1974; Wade 1982; Curran and Rust 1992; MacGorman and Burgess 1994; NOAA 1994; Pence and Peters 2000; Rasmussen et al. 2000; Thompson and Edwards 2000; Doswell et al. 2002; Knupp et al. 2003). Clear graphical or written evidence of supercells that persisted for ≥4 h was required in these documents. For example, the Lahoma, Oklahoma, supercell (Conway et al. 1996) was only considered a moderate-lived event (a conservative estimate) because it was unclear whether or not the supercell persisted for ≥4 h *before* it evolved into a bow echo. If there was any doubt whether or not a supercell's lifetime was ≥4 h, the case was not considered long lived, even though the supercell may have become a bow echo with a total *thunderstorm* lifetime (supercell plus bow echo) much greater than 4 h.

Bunkers (2002, plus references therein) and Klimowski et al. (2003) provided a significant source of supercell information. These data were reviewed for both long- and short-lived supercell events. To augment these data, and especially to obtain commensurate coverage for the remainder of the United States, radar data were also collected for supercell events observed across the United States from 2001 to 2004. Last, the National Oceanic and Atmospheric Administration (NOAA) *Storm Data* resource was interrogated—using the software of Hart and Janish (2005)—to graphically examine spatial and temporal characteristics of severe storm reports from 1996 to 2000 across the United States. If there was a temporally consistent and quasi-systematic progression of severe storm reports on a given day (indicating the possibility of a long-lived supercell; e.g., Fig. 1), the relevant radar data were acquired. These data were subsequently examined for the presence of long-lived supercells, and some short- and moderate-lived supercells were also discovered via this process.

Radar data consisted of a myriad of Weather Surveillance Radar-1988 Doppler (WSR-88D) sources.

1) When available, WSR-88D level IV data (Crum et al. 1993) from the National Weather Service (NWS) Advanced Weather Interactive Processing System were used. These data were confined mostly to the northern Great Plains.
2) In cases where level IV data were not easily accessible, the NWS's Next Generation Weather Radar (NEXRAD) Information Dissemination Service

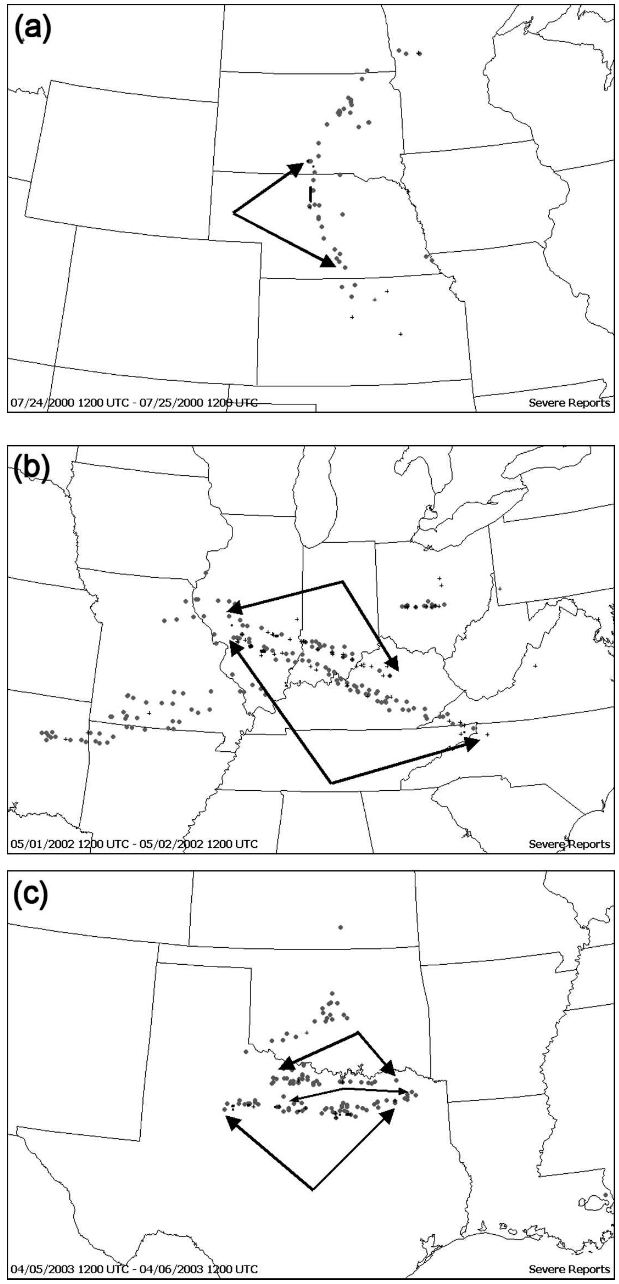

FIG. 1. *Storm Data* reports for the 24-h periods beginning at 1200 UTC on (a) 24 Jul 2000, (b) 1 May 2002, and (c) 5 Apr 2003. Hail reports are indicated with gray circles, wind reports are indicated with dark plus signs, and tornado reports are indicated with black dots or lines. Arrows point to the beginning–ending locations of the long-lived supercells responsible for the storm reports. All images are at the same scale. In (a) 34% (100%) of the total (significant) severe weather reports across the United States originated from this one long-lived supercell, in (b) 60% (91%) of the total (significant) severe weather reports across the United States originated from these two long-lived supercells, and in (c) 77% (100%) of the total (significant) severe weather reports across the United States originated from these three long-lived supercells (two of the tracks overlap).

TABLE 1. Properties recorded for the long- and short-lived supercell events. Refer to section 2c for definitions of these properties.

Long-lived supercell events	Short-lived supercell events
Beginning–ending times and location (including duration and track)	Avg lifetime and location of supercells (per event)
No. of long-lived supercells	—
Obs motion (2-h average) during most steady part of motion	Obs motion (1-h average) during most steady part of motion
Occurrence of tornadoes and other severe weather	Occurrence of tornadoes and other severe weather
Convective mode	Convective mode
Isolated vs nonisolated	Isolated vs nonisolated
Occurrence of storm mergers	Occurrence of storm mergers
Occurrence of supercell cycling	—
Storm demise mechanism	Storm demise mechanism

(NIDS) data were acquired from the Cooperative Program for Operational Meteorology, Education, and Training (COMET) archive. These NIDS data consisted of a 0.5°-elevation mosaic, derived from the WSR-88D sites across the continental United States, and possessed a temporal (spatial) resolution of at least 10 min (2 km).

3) If the NIDS data were not available from COMET, the following Internet resources were examined for archived WSR-88D data:
   (a) http://www.spc.noaa.gov/exper/archive/events/
   (b) http://locust.mmm.ucar.edu/case-selection/
   (c) http://www.rap.ucar.edu/weather/radar/
4) Last, WSR-88D archive level II data (Crum et al. 1993) were obtained from the National Climatic Data Center for the remaining events in which the above radar data could not be obtained.

For most of the events, radar data were available from at least two of the above sources. Using these data and procedures, supercell lifetimes were approximated to the nearest 15 min.

c. Properties recorded for the supercell events

Properties recorded for the supercell events were based on operational experience, and information collected for each of the long-lived supercell events was slightly more detailed than what was collected for the short-lived supercell events (Table 1). For example, the beginning time (when the storm became a supercell), ending time (when the storm ceased being a supercell), and reflectivity-based centroid track of each long-lived supercell were recorded, but only the average supercell lifetime and general location were needed for the short-lived supercell events. Furthermore, the occurrence of supercell cycling (defined below) was noted only for the long-lived supercells, and the observed storm motion was also calculated over a longer duration for the long-lived supercells (versus the short-lived supercells; see Table 1).

Tornado and severe storm reports for the supercell events were obtained from *Storm Data* as described in section 2b (see above). There are several deficiencies within the *Storm Data* database (Doswell and Burgess 1988; Weiss et al. 2002; Brooks et al. 2003), including (i) an underreporting of weak tornadoes (F0 and F1), (ii) an increase in the number of "low end" severe reports [i.e., hail diameter 1.9–2.5 cm (0.75–1.0 in.) and/or measured or estimated wind gusts 26–27 m s^{-1} (58–60 mi h^{-1})] in the last few decades of the 1900s, and (iii) an overall increase in the total number of severe reports since the mid-1900s. However, the reporting of strong and violent tornadoes (F2–F5; also referred to as significant tornadoes) has been more consistent throughout the period of record. As a result, the main items of interest from *Storm Data* are (i) whether F2–F5 tornadoes were reported (versus F0 and F1 tornadoes), (ii) whether any severe hail or wind was reported (as opposed to the total number of reports), and (iii) whether significant severe hail or wind was reported [i.e., hail diameter ≥5.1 cm (2.0 in.) and/or measured or estimated wind gusts ≥33.5 m s^{-1} (75 mi h^{-1}); Hales (1988)]. Other more scarce information about storm reports was derived from the meteorological literature—mostly from the 1940s to 1980s (e.g., as listed in Wade 1982).

The convective mode of each long- and short-lived supercell event was classified into one of three categories: linear, discrete, or mixed. These partitions are consistent with Dial and Racy (2004). In the linear mode, supercells were embedded in, or attached to, one or more line segments (i.e., length to width ratio ≥5 to 1), each contained within a common 35-dB*Z* echo. These were usually manifest in the form of one large squall line, or else a few smaller bowing or linear segments, with <10% discrete convection. Taken by itself, the squall line in the northwestern half of Fig. 2 would be considered a linear convective mode. On the other hand, the discrete convective mode consisted of separate identifiable cells that were distinct from one an-

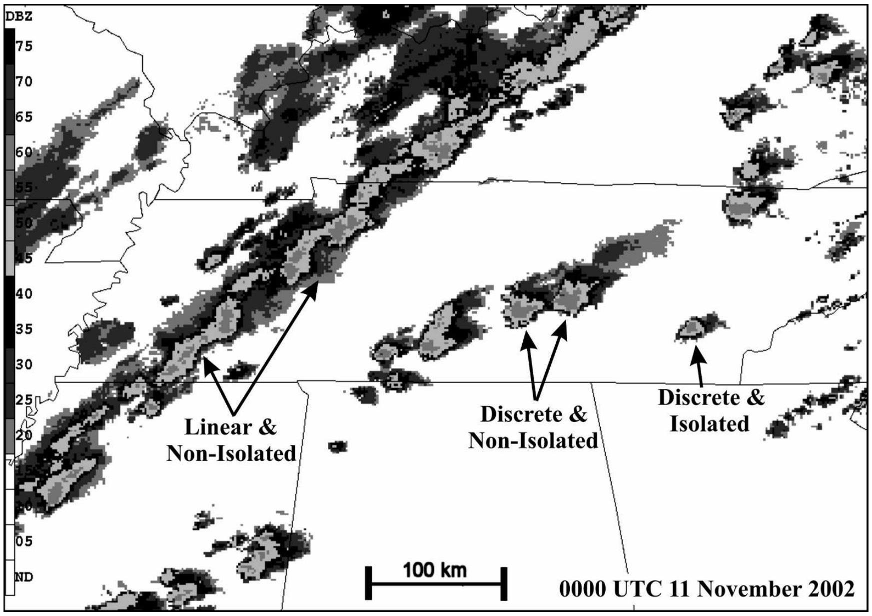

FIG. 2. The 0.5°-elevation mosaic reflectivity image centered on TN at 0000 UTC 11 Nov 2002, illustrating a mixed convective mode. The references to isolated, nonisolated, discrete, and linear storms are discussed in section 2b.

other (e.g., the cells in the southeastern half of Fig. 2). In some cases the discrete mode consisted of supercells occurring along a common line, but the 45-dB*Z* echo of the storms did not overlap, and the cells were clearly identifiable. If a supercell event could not be classified into the linear or discrete convective mode categories, it was considered to be mixed mode. In addition, if discrete supercells occurred ahead of, or close to, a line of thunderstorms, the event was also classified as mixed mode (e.g., Fig. 2). Last, if an event began as discrete supercells (which was common), but then transitioned into a linear mode about halfway through the event, the convective event was also classified as mixed mode.

A supercell was considered isolated if it was separated from nearby cells by at least one storm diameter for $>$75% of its lifetime. This diameter was taken as the average diameter of the 35-dB*Z* echo. For example, the discrete supercells ahead of the line in Fig. 2 (located in central Tennessee) were not considered isolated at that point in time, although the lone storm in southeastern Tennessee was classified as isolated. The primary goal of this classification was to identify supercells whose inflow source regions presumably were not cut off, or affected, by nearby thunderstorms. By way of comparison, Bluestein and Parker (1993) used 100 km (54 n mi) as a threshold separation for defining isolated storms related to severe convective development along the dryline (note the scale on the bottom of Fig. 2). They also defined "companion storms" as cells that stayed "close" to another storm for at least 20 min, but did not merge with it. Beyond this, quantitative definitions of "isolated" in the meteorological literature are generally lacking, with the phrase "relatively isolated" commonly used. As will be seen in section 3b, long-lived supercells can be isolated but still experience mergers, especially when the mergers are nondestructive and relatively brief.

Given the importance of storm mergers in modulating convective evolution, this information was noted for both the long- and short-lived supercell events. These mergers can be either destructive or reinforcing (e.g., Lindsey and Bunkers 2005). To eliminate the smallest "feeder" cells (Browning 1977) from consideration, a merger between a supercell and another storm (i.e., the blending of the storm cores) was only documented if the reflectivity of the second storm was $>$35 dB*Z*.

Supercells often go through a time evolution involving a cyclic process (Burgess et al. 1982; Foote and Frank 1983; Doswell et al. 1990; Adlerman et al. 1999; Dowell and Bluestein 2002). In the present study, supercells that followed a cyclic mesocyclogenesis (or mesoanticyclogenesis) process, such as described in Burgess et al. (1982), were treated as one supercell. However, if a supercell developed separate from an existing supercell, even though in close proximity, it was treated as a new supercell. For example, if the outflow of a supercell surged ahead of the storm and initiated a new storm (i.e., a separate area of reflectivity on radar) that subsequently developed a persistent rotating updraft, then two separate supercells were identified. This process is akin to discrete propagation due to daughter cells (Browning 1977) along a storm's gust front, and can result in a multicell–supercell hybrid as described in Weaver and Nelson (1982) and Foote and Frank (1983). This information on supercell cycling was recorded only for the long-lived supercells.

An important component of supercell longevity is the way in which a supercell reaches its demise. Based on a literature search and operational experience, the most common mechanisms responsible for the *end of the supercell phase* are (i) the supercell travels—spatially or temporally—into an environment that is too stable to support deep moist convection (e.g., Maddox et al. 1980; Doswell et al. 2002); (ii) the supercell travels into a thermodynamically and/or kinematically different environment that favors a transition into another convective mode, such as a bow echo—perhaps related to an enhanced surface gust front (e.g., Johns and Leftwich 1988; Brooks et al. 1993; Conway et al. 1996); (iii) the supercell merges or interacts with other thunderstorms, which can either destroy its circulation or cause it to evolve into another convective mode (e.g., Calianese et al. 2002; Knupp et al. 2003); (iv) the supercell has its supply of buoyant and moist inflow cut off by other storms or by its own downdraft (e.g., Grasso 2000; Doswell et al. 2002); and (v) the supercell interacts destructively with gravity waves, an occurrence that may be quite rare (e.g., Barnes and Nelson 1978; Warner 1976). Although this list is not exhaustive, it is believed to represent most causes of supercell demise. Therefore, to assist in the understanding of supercell longevity, an effort was made to document the basis for demise of both long- and short-lived supercells.

3. Results

a. *Distribution of long-lived supercells*

We emphasize that the present study does not attempt to depict a precise geographical climatology of long-lived supercells. As noted in section 2b, supercell data were obtained from a wide variety of sources, and were not systematically gathered so as to faithfully represent each region of the United States over a continuous time interval. For example, there is a bias of long-lived supercell tracks across the northern high plains and Oklahoma (Fig. 3), which is due, in part, to the availability of data from these areas.

Keeping the above caveat in mind, it is nevertheless apparent that most long-lived supercells occur across the central and eastern United States (Fig. 3). By way of contrast, only one long-lived supercell (which barely reached the 4-h definition) was documented across the western United States—along the Snake River valley of southeastern Idaho. The Teton–Yellowstone F4 tornadic thunderstorm (Fujita 1989) may have been another long-lived supercell in the West, but insufficient evidence precluded classification of the parent thunderstorm. Other than these cases, Tolleson (1996) presented a case of a moderate-lived supercell (~3 h) over the northwestern United States. It is plausible that long-lived supercells are quite rare across the West because of the rugged terrain and relatively limited low-level moisture. Another possibility is that sparse radar and observer coverage over parts of the western United States has prevented the identification and documentation of long-lived supercells in this region.

Other locations where long-lived supercells appear to be relatively infrequent are the far northeastern and southeastern United States (Fig. 3). It is difficult to determine if the reasons for this are meteorological, or if they are an artifact of the data collection process. For example, the frequent lack of strong deep-layer shear across Florida may be a hindrance to the development of long-lived supercells in this region. On the other hand, long-lived supercells may not be documented across Florida and adjacent waters because the radar coverage does not extend far enough to encompass the complete supercell lifetime. At any rate, limited radar coverage near the northern and southern borders of the United States, along with a lack of other documentation for Mexican and Canadian storms, likely reduced the number of long-lived supercell detections in these areas.

In contrast to the aforementioned areas, the frequency of long-lived supercells appears relatively enhanced east of the Front Range of the Rocky Mountains. This is an area where thunderstorms commonly initiate, and subsequently track across the central plains. It is also tempting to view the area from southern Illinois through Kentucky, Tennessee, Virginia, and North Carolina as a region where long-lived supercell occurrence is above average. However, confirmation of this observation awaits a detailed climatology (i.e., continuous observations over a period of many years).

The long-lived supercells tracked mostly toward the northeast, east, or southeast (Fig. 3). There were regional variations, however, with northeastward-moving supercells common in the Southeast, and southeastward-moving supercells relatively more frequent in the Northeast. Additionally, long-lived supercells tended toward a southeast direction east of the Front Range of the Rockies, and some supercells tracked nearly due south across the central United States. The fact that there were at least 10 supercells with a strong south-

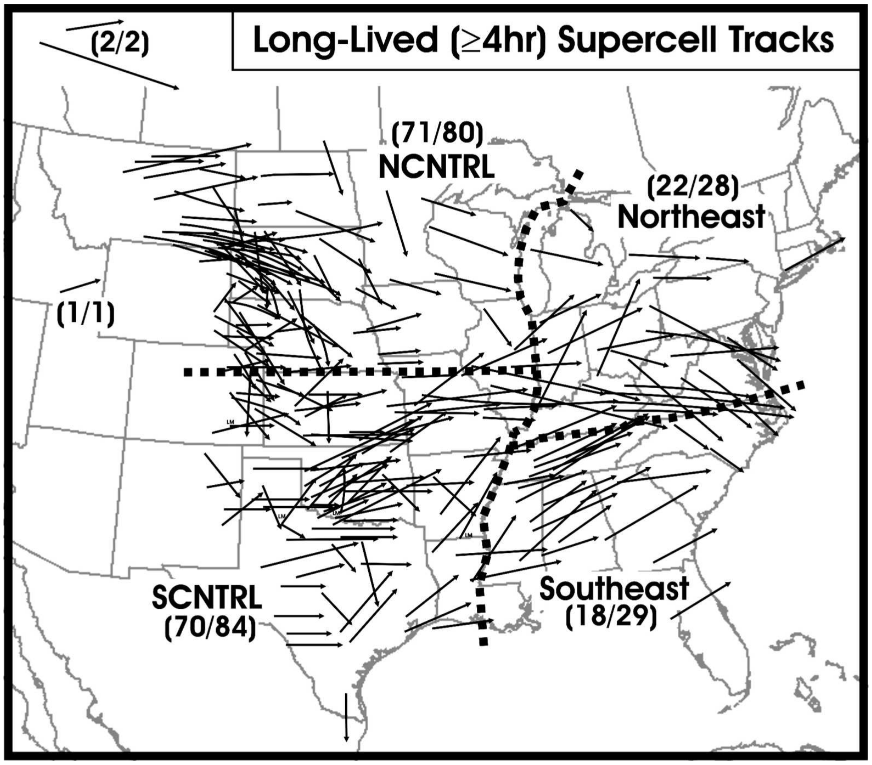

FIG. 3. Tracks of the 224 long-lived supercells in the present study (composing 184 long-lived supercell events). The tips of the arrows indicate where the supercells reached their demise. Four arbitrary regions of the central and eastern United States are delineated with the thick dashed lines (NCNTRL, Northeast, SCNTRL, and Southeast). The first number in parentheses corresponds to the number of long-lived *supercell events* per region, and the second number represents the number of long-lived *supercells* per region. Supercell tracks were assigned to the region that contained the greatest length of the track. Refer to section 2 for a discussion of supercell events.

ward component to their motion (over the central United States), and only a few with a strong northward component (excluding left movers), is intriguing, and perhaps related to the low-level moisture source from the Gulf of Mexico. Rarely did supercells track very far over the ocean after leaving the eastern United States, likely because of the stabilizing effect of the relatively cold ocean surface on the lower atmosphere. Last, the motion of the supercells was generally constant throughout their lifetime, but some gradually curving tracks were observed.

There were only four long-lived left-moving supercells in the dataset; all occurred across the south-central United States (SCNTRL) during April–June, and they also resulted in significant severe hail. Three of the four left movers were isolated, and all were associated with a discrete convective mode. One of the left-moving supercells traveled straight eastward, while the other three had a motion toward the north or northeast; each of the four left movers had a lifetime at or just slightly greater than 4 h. All four of the long-lived left-moving supercells resulted from thunderstorm splits [one of these left movers was elevated as its inflow originated above a surface-based stable layer (Rochette et al. 1999)], and their right-moving counterparts were also long lived. Not surprisingly, three of the hodographs associated with these left-moving supercells displayed unidirectional shear above 1 km AGL, and the fourth hodograph had a shear profile that was unidirectional throughout the lowest 8 km AGL.

Although Fig. 3 cannot be interpreted as a true spatial climatology of long-lived supercells across the United States, a rough temporal climatology can be constructed using the current dataset. Not surprisingly, the diurnal and monthly frequencies of long-lived supercells follow the cycle of daytime heating (Fig. 4a), as well as the typical increase in thunderstorm activity throughout the spring and summer months (Fig. 4b). The peak frequency of occurrence at 0000–0100 UTC is about 25 times the minimum from 1000 to 1600 UTC,

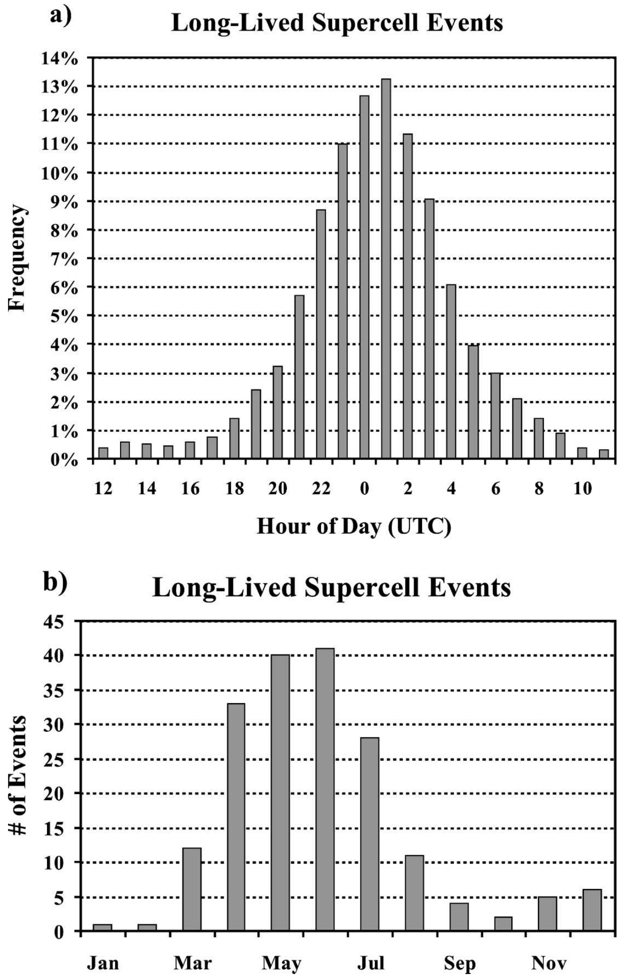

FIG. 4. (a) Hourly and (b) monthly frequencies of occurrence for the long-lived supercell events. In (a), one count is plotted for each hour a long-lived supercell existed.

and furthermore, 95% of the occurrences of individual long-lived supercells fell between 1800 and 0800 UTC (Fig. 4a). (Note, however, that the maximum in Fig. 4a is smoothed slightly because the data were not normalized to local time.) The average initiation time of a long-lived supercell was 2200 UTC, with a mean longevity of 5.5 h.

Even though long-lived supercells were relatively rare in most of the winter and fall seasons, a small secondary peak was noted in November and December (Fig. 4b). One gains a different perspective of this second-order cold-season maximum when inspecting the monthly distribution geographically. Over the north-central United States (NCNTRL), 94% of the long-lived supercell events occurred between May and August, with none recorded in the cold season. Values were similar in the Northeast, with 86% of the events from April through June, and the rest in August and September. Conversely, across the Southeast 56% of the long-lived events were observed from October through March, with none in the summer months. Finally, the SCNTRL was somewhere in between the other regions, with 24% of the events occurring from October through March, and 48% in the summer months.

b. Comparison of properties between long- and short-lived supercell events

Severe weather of some variety [i.e., hail diameter ≥1.9 cm (0.75 in.), measured or estimated wind gusts ≥26 m s^{-1} (58 mi h^{-1}), or wind damage; tornadoes are treated separately below] was observed with all of the long-lived supercell events, and with 92% of the short-lived supercell events (Table 2). This is consistent with previous studies, which report that 90% or greater of supercells are severe (e.g., Burgess and Lemon 1991; Bunkers 2002). Indeed, it was extremely rare for any of the supercell events not to be associated with severe hail; just 1%–2% of the events produced severe wind only. Many of the long-lived supercells produced severe hail along a substantial portion of their path (74% were associated with significant severe hail; Table 2), and particularly damaging storms resulted when this was accompanied by severe wind (e.g., Klimowski et al. 1998; Parker et al. 2005; Segele et al. 2005). In addition, a substantial portion of the severe storm reports on some days was generated by one (e.g., 24 July 2000—34% of total), two (e.g., 1 May 2002—60% of total), or three (e.g., 5 April 2003—77% of total) long-lived supercells (Fig. 1), illustrating the significant forecasting and societal impacts from these storms.

It is important to note that just because a supercell is short lived does not mean the severe weather threat is diminished. In 38% of these short-lived events, the supercells were observed to evolve into a squall line or bow-echo system (Table 2), often producing a swath of severe winds *after* the supercell phase had ended and thus prolonging the convective event (e.g., Tuttle and Carbone 2004; also recall footnote 2). Indeed, significant severe winds were associated with 31% of the long- and short-lived supercell events (Table 2). Additionally, there was a tendency for the short-lived supercells, along with the associated nonsupercells, to be more numerous at any given location over the course of an event (versus the case for the long-lived supercells), thus increasing the local probability of severe storm reports.

The production of tornadoes by the two supercell classes revealed a greater difference than what was observed for the severe hail and wind. For example, the percentage of long-lived supercell events that produced

TABLE 2. Comparison of properties between the long- and short-lived supercell events. Refer to section 3b for a discussion of these variations.

Long-lived supercell events		Short-lived supercell events
	Tornado reports	
36% ≥ F2		8% ≥ F2
34% F0–F1		30% F0–F1
30% nontornadic		62% nontornadic
	Hail/wind reports	
100% severe		92% severe
84% hail and wind		67% hail and wind
15% hail only		23% hail only
1% wind only		2% wind only
24% significant hail and wind		19% significant hail and wind
74% significant hail		42% significant hail
31% significant wind		31% significant wind
	Convective mode	
68% discrete		37% discrete
28% mixed (discrete and linear)		50% mixed (discrete and linear)
4% linear		13% linear
	Supercell demise	
63% weakened or dissipated		38% weakened or dissipated
6% experienced a destructive merger		20% experienced a destructive merger
21% evolved to another mode		21% evolved to another mode
7% merged and then evolved		17% merged and then evolved
3% had inflow source region cut off		4% had inflow source region cut off
	Isolated and mergers	
79% isolated (vs 21% not)		30% isolated (vs 70% not)
47% with mergers (vs 53% without)		74% with mergers (vs 26% without)
35% of the isolated also had mergers		17% of the isolated also had mergers
89% of those not isolated also had mergers		99% of those not isolated also had mergers

strong and violent tornadoes (F2–F5) was over four times the value for short-lived supercell events (36% versus 8%; Table 2). Moreover, only about one-third of the long-lived supercell events did not result in a tornado of any rating, while this increased to nearly two-thirds for the short-lived supercell events. Perhaps this higher percentage of tornado occurrence with the long-lived supercells is due, in part, to the greater likelihood of these storms interacting with a favorable environment—via their longevity. This difference may also be related to the increased probability of receiving a local storm report from the long-lived supercells simply because they persisted for a long time. Indeed, the average lifetime of the long-lived supercell events was 3.9 times that of the short-lived supercell events. Therefore, the fact that about twice as many of the long-lived supercell events were tornadic should not necessarily be surprising.

In contrast to the F0–F1 tornadoes (see Table 2), the production of strong and violent tornadoes by the long-lived supercells does appear noteworthy. For the 184 long-lived supercell events, 66 (or 36%) produced tornadoes of ≥F2 rating, but for the 119 short-lived supercell events, only 9 (or 8%) produced tornadoes of ≥F2 rating. To compare the number of hours of strong and violent tornado production between the long- and short-lived events for equivalent numbers of total storm hours, the ratio of total long-lived supercell lifetime to total short-lived supercell lifetime in the dataset was computed. Because the average lifetime of the supercells per long-lived event was 5.5 h, with 1.2 long-lived supercells per event, there were approximately 1214 h of long-lived supercell lifetime (184 events × 1.2 supercells per event × 5.5 hours per supercell). The average lifetime of the supercells per short-lived event was 1.4 h, with an average of 2–3 short-lived supercells per event; thus, there was a range of 333–500 h of short-lived supercell lifetime (119 events × 2–3 supercells per event × 1.4 hours per supercell). Therefore, the database contains 2.4–3.6 times the number of hours of long-lived supercell occurrence versus short-lived supercell occurrence. Taking this range of values times the number of F2–F5 short-lived events (nine) yields 22–33 per 1214 hours (or one event per 36.8–55.2 hours). The number of F2–F5 long-lived events (66) is 2–3 times this (or one event per 18.4 hours). Therefore, on a normalized basis, the long-lived supercell events produced about 2–3 times the number of strong and violent tornadoes per hour when compared with the short-lived supercell events, suggesting there may be a connection between supercell longevity and the production of F2–F5 tornadoes.

Many of the remaining supercell properties—convective mode, demise, degree of isolation (i.e., the percent isolated), and mergers—appear to be interrelated. Of these, the most discriminating variable between the two supercell classes is the degree of isolation of the supercells; 79% of the long-lived supercell events were classified as involving isolated storms, but only 30% of the short-lived supercell events fell into this category (Table 2). On some occasions there were no other storms within 100–200 km of a long-lived supercell. Furthermore, in a few instances there were two or three distinct long-lived supercells in relatively close proximity (but still defined as isolated) for a majority of their lifetimes (e.g., Fig. 1). When the long-lived supercells were isolated (nonisolated), their average lifetime was 5.6 h (5.1 h). Consistent with the degree of isolation of the supercells, only 47% of the long-lived supercell events displayed storm mergers, versus 74% for the short-lived supercell events. This result may seem counterintuitive since one might expect the longest-lived supercells to have the greatest chance of experiencing mergers, simply because of their longevity. However, this finding is consistent with the above observations that supercells were more numerous in the short-lived events (see previous paragraph), indicating coverage is a nontrivial influence on longevity. Simply put, if a supercell is relatively isolated for most of its lifetime, no matter how long it lives, storm mergers are not likely (refer to the bottom of Table 2).

With this understanding of the degree of isolation for the two supercell classes, it is not surprising that 68% of the long-lived supercell events exhibited a discrete convective mode, in contrast to just 37% for the short-lived supercell events (Table 2). The discrete-mode long-lived supercells had the greatest average lifetime at 5.7 h, compared with 5.4 h for the mixed mode and 4.5 h for the linear mode. The most common convective mode for the short-lived supercell events was mixed (50%), whereby the supercells commonly began in a discrete fashion, but grew upscale into a quasi-linear MCS by about midway through the supercell event. Moreover, only 7% of these mixed-mode short-lived supercell events were classified as involving isolated storms. The linear convective mode was least common for both of the supercell classes, but still over three times as likely for the short-lived supercell events versus the long-lived events. Finally, isolated supercells were not observed within the linear convective mode for either supercell class, whereas 92% (70%) of the long-lived (short lived) supercell events exhibiting a discrete convective mode were isolated.

Supercell demise was partitioned into five categories as described in section 2c [Table 2; 1) weakened or dissipated; 2) destructive merger; 3) evolved to other convective mode; 4) merger, then evolved to other convective mode; and 5) inflow source region cut off]. The results of this partitioning fit together with the findings on the degree of isolation of the supercells, as well as storm mergers. For example, 63% of the long-lived supercell events involved a demise characterized by a weakening of the supercell circulation (but the parent thunderstorm was still present), or else simply by storm dissipation whereby the reflectivity quickly decreased below 35 dBZ (Table 2); isolated storms are most likely to experience such a demise. By way of comparison, only 13% of the long-lived supercell events involved a demise characterized by storm mergers.[4] On the other hand, just 38% of the short-lived supercell events were typified by supercells that weakened or dissipated, while 37% involved a supercell demise distinguished by storm mergers; this is consistent with storms that are relatively numerous.

Another demise mechanism that was equally common between the two supercell classes was evolution to another convective mode [e.g., supercell to bow echo; Johns and Leftwich (1988); Moller et al. (1994)], which subsequently may have persisted for some time after the supercell phase ended. This evolution was sometimes triggered by a storm merger, especially for the short-lived supercells (Table 2; Klimowski et al. 2004). Finally, although the percentage of supercell events identified as having their inflow source region cut off was $<$5% for both classes (an admittedly conservative result), this value may have been higher if more detailed radar data (e.g., 1-km resolution), as well as a denser network of radar data, had been available for all events.

In summary, long-lived supercells, when compared with short-lived supercells, have a much greater tendency to be isolated and discrete, thereby limiting adjacent storm interactions and potentially destructive mergers. Because of this, the production of F2–F5 tornadoes appears to be enhanced for long-lived supercells [although other factors such as low-level shear and cloud-base height are equally or even more important for tornadogenesis; Thompson et al. (2003)]. Consequently, the less isolated supercells are, the greater the likelihood they will experience destructive mergers and

[4] Note that the percentage of supercell events with storm mergers exceeds the percentage of supercell events reaching their demise via storm mergers. This is because not all storm mergers were destructive (i.e., they did not all result in the end of the supercell phase).

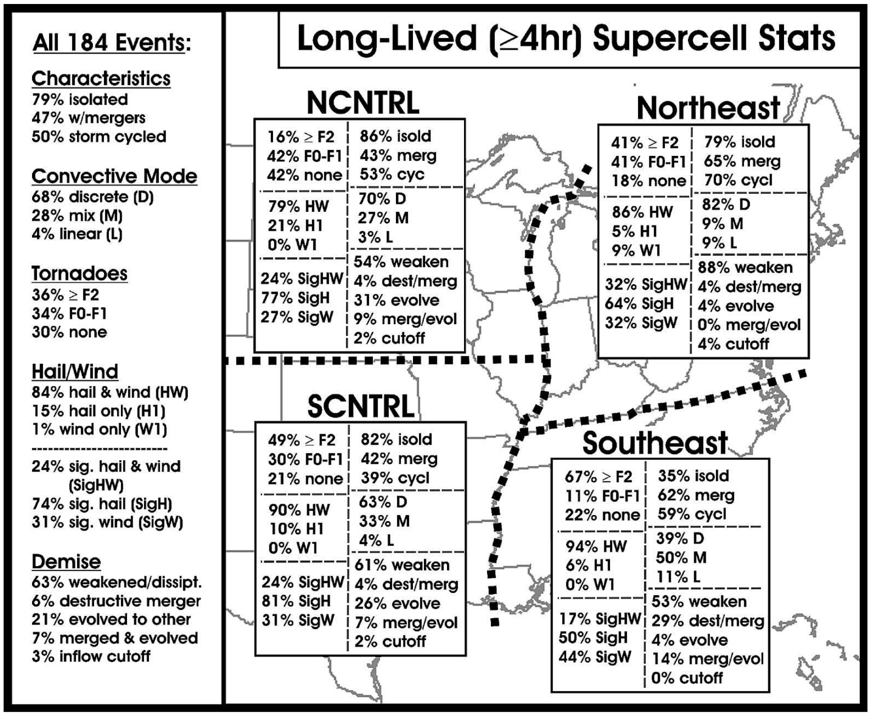

FIG. 5. Properties of all 184 long-lived supercell events (left column), along with the properties of four arbitrarily defined regions of the central and eastern United States. Refer to section 3c for a discussion of these variations.

be short lived, potentially curtailing their production of F2–F5 tornadoes.

c. Regional variations for the long-lived supercells

Several differences were noted between long- and short-lived supercells in section 3b. In the present section, differences in long-lived supercell properties among four regions (see Fig. 3) of the central and eastern United States are discussed. Because of the extremely small sample of long-lived supercell events across the western United States (one), this discussion of regional variations does not include that area.

Considering this somewhat arbitrary geographical division, the largest overall contrast in long-lived supercell properties is evident between the NCNTRL and the Southeast. Most noteworthy are the following: (i) long-lived supercells were more than twice as likely to be isolated in the NCNTRL versus the Southeast; (ii) the convective mode was dominated by discrete supercells over the NCNTRL, versus a mixed mode in the Southeast; (iii) on an event basis, significant severe hail was 1.5 times more common in the NCNTRL and significant severe wind was 1.6 times more common in the Southeast; and (iv) significant tornadoes were four times less likely to occur with supercells in the NCNTRL than in the Southeast (Fig. 5). In fact, the NCNTRL stands out as the only region where the occurrence of tornadoes with long-lived supercell events (58% tornadic) was less than average for the entire long-lived dataset (70% tornadic), whereas the other three regions displayed above average percentages for the tornadic long-lived events (78%–82% tornadic). The long-lived supercells in the NCNTRL were also 2–4 times more likely to be associated with hail reports only—versus hail and wind reports—when compared with the other three regions.

Although the storm environmental conditions will be discussed in Part II, a few things can be said at this point to help explain the above differences. For one, low-level moisture is considerably more abundant in the Southeast versus the NCNTRL. As a result, deep moistconvection should lead to storms that are more closely spaced in the Southeast, and more isolated in the NCNTRL. In turn, this would translate into relatively more destructive mergers and mixed convective modes over the Southeast. Recall from section 3a that most of the long-lived supercell events across the Southeast occurred during the cold season, suggesting a propensity for strong atmospheric forcing, which in turn would favor a mixed or linear convective mode. Other nonmeteorological factors, such as differences in population and tree densities, may partially explain the fewer wind and tornado reports over the NCNTRL (e.g., Klimowski et al. 2003).

Some other regional differences are also of interest. For example, the Southeast is distinguished from the other three regions by way of destructive mergers (29% versus 4% for the other three regions), as well as a greater percentage of mergers that produce an evolution to another convective mode (Fig. 5). This may very well be related to the relatively small percentage of isolated supercells in the Southeast (35% versus 79%–86% for the others), and the fact that 61% of the events in the Southeast consisted of mixed or linear convective modes (versus 18%–37% for the others). Another observation is that just under one-third of the long-lived supercell events over the central United States reached their demise by way of evolution into another convective mode (26%–31%); however, this was quite a rare occurrence over the eastern United States (only 4% of the events). The drier low-level environment over the central United States, compared with the eastern United States, may foster this type of transition via enhancement of evaporatively cooled downdrafts. In support of this, Klimowski et al. (2003) found 29% of the high-wind-producing supercells studied across the northern high plains evolved into a bow echo. It is also noteworthy that mergers were relatively more common over the eastern United States (62%–65%) when compared with the central United States (42%–43%).

Like the NCNTRL, the Northeast appears to have some interesting properties that set it apart from the other three regions, especially from the southern areas. First, discrete-mode long-lived supercells were most common in the Northeast (82%), ranging from 19% to 43% more frequent than the values across the SCNTRL and Southeast, and 12% more than for the NCNTRL (Fig. 5). Second, for 88% of the events, long-lived supercells simply weakened over the Northeast, which is 27%–35% greater than for the other regions. Some of this weakening occurred as the supercells traveled off the coast and over the Atlantic Ocean. Finally, it is difficult to explain why mergers were most common over the Northeast, yet 79% of the long-lived supercell events were still classified as isolated. Apparently mergers are not as destructive in the Northeast when compared with the other regions, which is consistent with the predominantly discrete convective mode (82%). Note that these results for the Northeast and Southeast may possibly be affected by the small sample size (only 22 and 18 events, respectively); care should be used when making use of them.

Last, anywhere from 39% to 70% of the supercells experienced a cycling or regeneration, in which a new mesocyclone developed within the same storm, or the storm experienced some noncontinuous development (Foote and Frank 1983; Browning 1977; Burgess et al. 1982). This appears to be a relatively common feature of these longest-lived storms. Given the difficulty in observing this transition within the present dataset (i.e., some of the radar data were at 2-km resolution), comparisons of storm cycling among the four regions should be made with caution. However, it can be concluded that in general, long-lived supercells are likely multiple-core mesocyclones (or mesoanticyclones).

4. Conclusions and summary

It is proposed that long-lived supercells be defined as supercells that persist in a quasi-steady manner for at least 4 h. Moreover, an upper limit for short-lived supercell lifetime is suggested at 2 h. Using these definitions and a dataset of supercells across mainly the central and eastern United States, the radar-observed properties and severe weather production of long-lived supercells were compared with those of short-lived supercells. In addition, geographical variations of long-lived supercell properties across the United States were also examined. Based on these analyses, the primary conclusions of this study are as follows.

- Long-lived supercells produce notably more F2–F5 tornadoes when compared with short-lived supercells, and a single long-lived supercell can also produce a substantial amount of nontornadic severe weather.
- Long-lived supercells are frequently isolated (which helps them live longer), and therefore experience storm mergers relatively infrequently. Short-lived supercells are not isolated very often and, thus, experience storm mergers more frequently.
- Long-lived supercells are most often observed when there is a discrete convective mode, but short-lived supercells are mostly likely when a mixed convective mode is present.
- Long-lived supercells typically reach their demise (i.e., the end of the supercell phase) when the parent thunderstorm dissipates or its circulation weakens. Short-lived supercells are most likely to experience a destructive (i.e., circulation disrupting) merger or else evolve into another convective mode at their demise.
- Long-lived supercells are rare in the western United States, and long-lived left-moving supercells are rare everywhere in the United States.
- Long-lived supercells have the highest probability of producing F2–F5 tornadoes in the Southeast (>60%)

when compared with the NCNTRL, Northeast, and SCNTRL.

- Long-lived supercells in the Southeast are not isolated as often as in other parts of the United States, and they commonly occur within a mixed convective mode.
- Most of the long-lived supercell events over the NCNTRL occur between May and August, but more than half of the long-lived events over the Southeast occur from October through March (with none in the summer months).

When ruminating on these results, it is important to remember the definitions in section 2a. First, note that long-lived supercell events can, and sometimes do, contain short-lived supercells. Second, some short-lived events have supercells with lifetimes between 2 and 4 h. Therefore, there can be a long-lived supercell event that has predominately short-lived supercells, while at other times a short-lived supercell event may contain a few moderate-lived supercells. Because the goal of this study is to better understand the supercell longevity spectrum, and also given the relatively large dataset, it is believed that these "blurred" boundaries among long-, moderate-, and short-lived supercell events do not pose a serious problem.

With this word of caution as a backdrop, it is clear that a fundamental property of long-lived supercells is their generally isolated nature. Furthermore, if long-lived supercells are going to occur on any given day, then the probability of significant tornadoes is enhanced. Along these lines, a single long-lived supercell may produce a majority of the severe storm reports during a convective event. Therefore, if supercell longevity can be anticipated in an operational setting, one of the potential benefits is improved severe local storm watches and warnings. Short-term (0–12 h) forecasts can also be improved with proper knowledge of long-lived supercell occurrence.

The differences between long- and short-lived supercells appear significant enough to warrant further investigation into the environmental conditions supporting their existence. For example, why are long-lived supercells more isolated and discrete than short-lived supercells? What is the reason why long-lived supercells produce significantly more F2–F5 tornadoes than short-lived supercells? Can regional differences in environmental variables help to explain variations in convective mode and tornado production? We will address these and other questions in Part II of this work.

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