Mesoscale Convective Systems in the Southeast United States during 1994–95: A Survey

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ABSTRACT

A preliminary survey of mesoscale convective systems (MCSs) in the southeastern United States is presented. MCSs are identified and characterized by means of high-resolution, digital, composite radar reflectivity data. Surveys of this kind are needed to give forecasters better guidance in their real-time assessment of MCS evolution, severe weather potential, and quantitative precipitation. The average lifetime and maximum length of the nearly 400 MCSs included in this survey are 9 h and 350 km, respectively. MCSs are more common in the summer months, when small and short-lived MCSs dominate. In winter larger and longer-lived systems occur more frequently. Because cold-season MCSs, which are about half as numerous as warm-season MCSs, are larger in size and duration, the MCS probability at any location is about constant throughout the year. In summer MCSs occur more commonly in the afternoon, approximately in phase with thunderstorm activity, but the amplitude of the diurnal cycle is small compared to that of observed thunderstorms. Some characteristic echo patterns are discussed.

1. Introduction

Little is known about the spectrum of mesoscale convective systems (MCSs) in the southeastern United States or elsewhere. Certainly, the characteristics of organized deep convection have been documented by means of geostationary satellite imagery (e.g., Dirks 1969; Purdom 1976; Farfán and Zehnder 1994), but a description of the precipitation structure and evolution of MCSs has been difficult, on the one hand because satellite infrared imagery does not clearly separate convective from stratiform areas within the storm (e.g., Negri and Adler 1981), and on the other hand because the domain seen by ground-based weather radar data is small compared to the area occupied by a typical MCS during its lifetime (e.g., Houze et al. 1990).

The density of Weather Surveillance Radar-1988 Doppler (WSR-88D) radars supports the display of a mosaic of simultaneous reflectivity observations over most of the contiguous United States. Until a few years ago, composite radar reflectivity imagery was rare and limited to a few field experiments [starting with GARP's Atlantic Tropical Experiment, Houze and Betts (1981)], but since the deployment of the Next-Generation Radar network, it has become widely used in the U.S. media along with animated satellite imagery. Composite reflectivity imagery is also a unique but underutilized tool for research and nowcasting (R. Carbone 1997, personal communication). This paper illustrates the use of this type of imagery to typify the mesoscale organization of deep convection.

Several studies have documented the characteristics of MCSs in the United States Bluestein and Jain (1985) and Bluestein et al. (1987) explore the genesis of springtime convective lines in Oklahoma. They document cases where less organized convection metamorphoses into a squall line. Using the same nondigital single-radar data, Houze et al. (1990) also examine springtime organized convection in Oklahoma. They find that MCSs with a squall line and a trailing stratiform region are predominant. The internal precipitation, kinematic, and dynamic structure of a select few MCSs have been studied in great detail. For instance, many studies have focused on observational and modeling aspects of the 10–11 June 1985 squall line in Oklahoma (e.g., Augustine and Zipser 1987; Johnson and Hamilton 1988; Houze et al. 1989; Biggerstaff and Houze 1991; Zhang 1992). These cases were selected based on criteria such as apparent organization, longevity, and severity, and not because their organization was the most commonly observed mode of convection. Therefore caution is paramount when using these case studies as archetypes of the wide gamut of MCSs observed elsewhere during other seasons.

An MCS can be broadly defined as a mesoscale system of cloud and precipitation that includes at least one thunderstorm cell during its lifetime or part thereof (Zipser 1982). An MCS is one order of magnitude larger

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than a convective-scale event, and includes several convective events, interacting with each other in space and/or time. MCSs occur in a continuous spectrum from small, short-lived systems (e.g., Browning and Hill 1984; Knupp and Cotton 1987; Knupp et al. 1998) to long-lived mesoscale convective complexes (MCCs), which exhibit an average maximum size of $\sim 200 \times 10^3$ km^2 and a lifetime of ~15 h (e.g., Maddox et al. 1982).

Houze (1993) suggests that MCSs have a maximum length scale of at least 100 km; however, any definition of a spatial or temporal threshold of MCSs is specific to the instrument(s) used for identifying MCSs. The larger MCCs are defined and typically described in terms of their cloud-top appearance (i.e., upwelling longwave radiation measured aboard geostationary satellites), while smaller MCSs have been analyzed mainly by means of radar data. Mohr and Zipser (1996a) use 85-GHz ice-scattering signatures recorded by the Special Sensor Microwave/Imager on a polar-orbiting satellite. Microwave radiation wells up from deeper within the cloud system than does infrared radiation. Brightness temperatures not exceeding 250 K and 225 K imply, respectively, precipitation and heavy precipitation at the ground. Mohr and Zipser define an MCS as having an area of at least 2000 km^2 at 250 K or less, and a minimum microwave brightness temperature of at most 225 K.

Undoubtedly the smallest systems occur most frequently, and MCCs are relatively rare, representing only a small fraction of the total MCS population. For instance, Mapes and Houze (1993) estimate that just 1% of the MCSs in the western tropical Pacific attain MCC size. This fraction may be slightly larger in North America (E. Zipser 1997, personal communication). The seasonal and diurnal variation of MCCs has been documented. MCCs are most common in summer in an area ranging from the southern plain states to the Midwest (Velasco and Fritsch 1987). In the southeastern United States (hereafter referred to as the Southeast), they are less common, and they occur mainly in autumn and spring, when baroclinic forcing is more active. In the United States (Cotton et al 1989) and elsewhere (Velasco and Fritsch 1987; Miller and Fritsch 1992; Laing and Fritsch 1993) MCCs typically develop in the late afternoon, attain their maximum anvil size between midnight and sunrise, and have a lifetime (as MCC) of 9–12 h.

The smaller MCSs typically are shorter lived and their diurnal variation appears to be regionally less uniform. Over continental areas with significant baroclinic activity, the diurnal cycle of smaller MCSs is weak and ill defined. Using radar data, Houze et al. (1990) find that in Oklahoma in spring the largest systems are longest lived and attain their peak size around midnight, whereas smaller systems ($13–38 \times 10^3$ km^2) have no clear diurnal preference. Over tropical oceans smaller MCSs may be more common at night (e.g., Churchill and Houze 1984), although the diurnal modulation is weak.

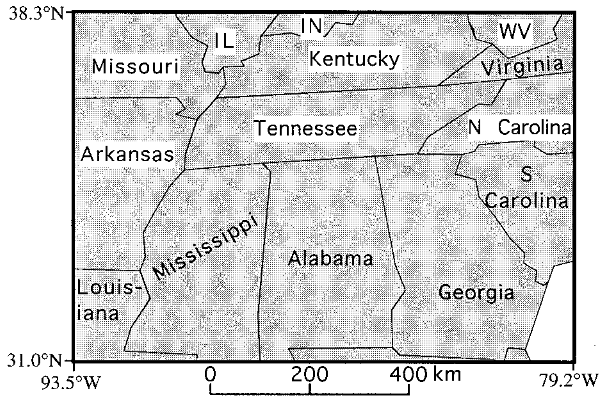

FIG. 1. The area of study.

In low-latitude continental environments, which are essentially barotropic, smaller MCSs are nearly in phase with thunderstorm activity and tend to develop in the afternoon and decay soon after sunset. Mohr and Zipser (1996b) find that over continental areas between 35°N and 35°S, MCSs are 60% more common at sunset than at sunrise. Over the Southeast, the troposphere is essentially barotropic during most of the warm season. The diurnal modulation of small, summertime MCSs in the Southeast, then, can be expected to be very similar to that of thunderstorms in general, which are most frequent in the afternoon (1500–1700 local time) (Rasmusson 1971; Court and Griffiths 1983). A slight phase shift toward the evening is likely because many small, short-lived MCSs in the Southeast in summer form as individual thunderstorm cells, which then coalesce to form one mesoscale stratiform region. If such a region is sufficiently long lived, then it may meet the threshold criteria of an MCS used in this study (see section 2), because convection is present in the initial stage. An example of such an MCS is detailed in Knupp et al. (1998). The cellular reflectivity structure disappeared in all but the southern end of this MCS, and lightning activity was much reduced in the mostly stratiform MCS.

Little attention has been paid to MCSs occuring in fall and winter. In the Southeast, MCSs are fairly common during the transient and cold seasons, and they are usually triggered (and possibly sustained) by baroclinic disturbances. Both prefrontal squall lines and convection embedded within widespread stratiform precipitation occur, and some systems produce severe weather. This study documents the entire seasonal cycle of MCSs in a geographically unique region of the United States. The data source and study methodology are presented next. The survey of MCSs is summarized in section 3 and a discussion follows in section 4.

2. Methodology

This study focuses on the southeastern quadrant of the contiguous United States (Fig. 1). The area of interest includes the southern Appalachian region and parts of the Midwest, and excludes almost all of Florida, so our definition of the Southeast is different from the commonly used one. The gulf coast and most of Florida have been excluded because the coastline leads to a very different spatial organization of convection, especially during the warm season, and the inclusion of these regions would contaminate the climatology of an otherwise fairly homogenous geographical area. To identify MCSs, the digital composite radar reflectivity data is used at a spatial resolution of 2 km $\times$ 2 km, a time resolution of 15 min, and 15 discrete bins of reflectivity values. The composite data are derived mainly from WSR-88D radars, but earlier types of weather radars operated by the National Weather Service are incorporated where necessary. These data have been received in near-real time and archived for the entire continental United States since March 1994 at the Hydrological Cycle Distributed Active Archive Center (DAAC) located at the National Aeronautics and Space Administration (NASA)/Marshall Space Flight Center. This survey is based on a 1-yr period from May 1994 to April 1995. During this period the dataset was nearly complete: reflectivity maps were missing during a cumulative period of just 265 h, together about 11 days or 3% of the survey period. The sampling period is sufficient to depict the annual cycle, yet the reader should be aware that the seasonal variations shown in this paper are based on 1 yr only, which is too short for a climatology.

For the purposes of this study, the working definition of an MCS is as follows: a continuous region of precipitation (defined as the area with reflectivities exceeding 20 dB*Z*), with a long axis of at least 100 km, must exist for at least 4 h, and during the lifetime of the system the maximum reflectivity during at least two consecutive hours must exceed 40 dB*Z*. The dual-reflectivity threshold assures that the precipitation system has both mesoscale dimensions and convective activity. This is in accordance with the dual brightness temperature threshold used by Mohr and Zipser (1996a). Regions recording 20–40 dB*Z* usually receive *stratiform* precipitation (as defined in Houze 1993) while *convective* precipitation occurs in areas with $>$40 dB*Z* (Steiner et al. 1995)

An MCS is labeled ''intense'' when, ceteris paribus, the maximum reflectivity exceeds 50 dB*Z* during at least two consecutive hours. Therefore the label intense does not refer to the severity of the MCS but rather to the intensity of the convection. An example of an intense MCS is shown in Fig. 2. This is a long-lived prefrontal squall line that produced 11 tornadoes in Alabama alone. A trailing stratiform region clearly separated from the squall line yet well ahead of the surface cold front can be seen, mainly in central Alabama.

A total of 398 MCSs occurred within the study area during the 1-yr period. A number of systems affected the border regions of the study area, yet they did not satisfy the MCS criteria within the study area. Therefore these systems are excluded. However, partially sampled systems that did satisfy the MCS criteria within the study domain were included. A rough estimate of the resulting undersampling is given by the ratio of the minimum length of an MCS (100 km) to the typical dimension of the domain (1000 km), that is, 10%.

For each MCS, the time of initiation and dissipation was noted, and through visual inspection the following questions were answered. Is the MCS linear? If so, what is its orientation? What is the average speed and direction of propagation (the average storm motion is based on the centroid locations at the MCS initial and final times)? What is the geographical path of travel of the MCS centroid? Is the MCS intense? Is the convection in the MCS continuous or cellular? Remarkable echo patterns are noted as well, for instance a leading convective line with a trailing stratiform region.

3. Characteristics of MCSs in the Southeast

The seasonal distribution of MCS occurrences is shown in Fig. 3. Only 1 yr of data is included, which explains why the distribution is not smooth. April 1995, for instance, was an anomalously dry month in the Southeast (NCDC 1995). Figure 3 shows that MCSs can occur any time of the year, and are most common in spring and mainly in summer. The amplitude of the annual cycle of MCSs, normalized by the mean monthly frequency, is merely 24%. The normalized amplitude of the annual cycle of thunderstorms (as reported at weather stations) is much larger in the Southeast. The monthly station data presented in Table 2.1 of Court and Griffiths (1983) suggest that this amplitude is about 80% in the Southeast, ranging from 43% to 117%.

In spring, MCSs tend to be shortest lived (6–8 h on average), while in autumn and winter MCSs are longer lived (10–12 h) (Fig. 4). However, there is a wide range of MCS lifetimes. The most common duration is 5 h (Fig. 5a), and the average life span is 9.4 h (Fig. 4). The distribution of MCS lifetimes exceeding the mode decays exponentially, but a significant number of MCSs live longer than the half-period of the diurnal cycle. In particular, there is an anomalously large number of MCSs lasting between 14 and 18 h. In summer many MCSs are short lived (4–6 h), whereas in winter very long lived systems ($>$20 h) occur (Fig. 5b). It is speculated that the long-lived MCSs between October and May are almost all driven by well-defined synoptic disturbances, and the MCSs generally occur at or ahead of a surface cold front. In summer synoptic forcing generally is weak and of little relevance to the MCS longevity.

The maximum length (L_{max}) of an MCS is defined as the maximum size of the long axis of the continuous 20-dB*Z* contour during the lifetime of the MCS. The author realizes that in a study area of limited dimensions the MCS lifetime and length scales tend to be under-

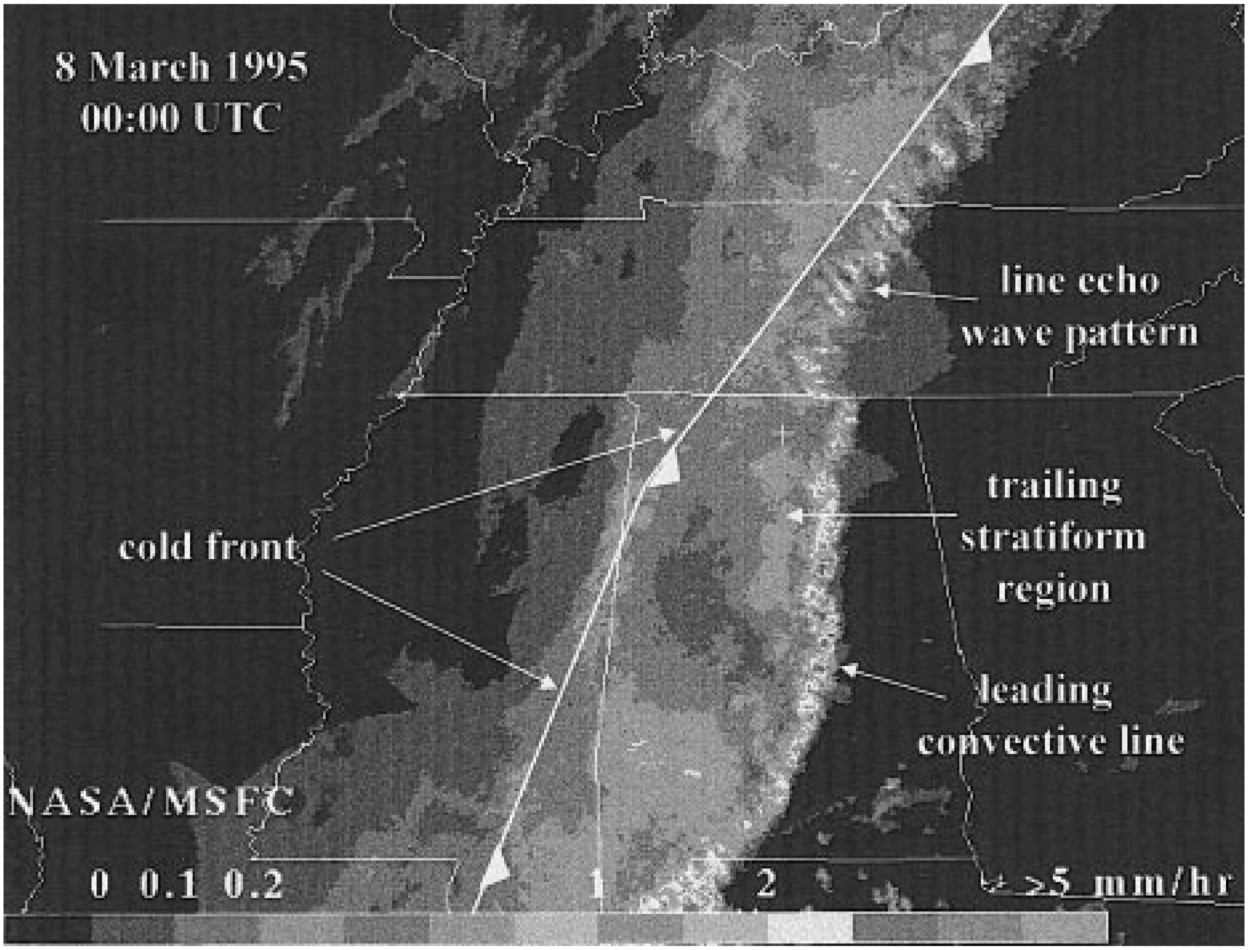

FIG. 2. Composite radar image at 0000 UTC on 8 Mar 1995. The radar reflectivity is converted to a rainfall rate. The approximate position of the surface cold front is shown, as estimated from hourly and 5-min station data, as well as satellite imagery and the composite radar images. The cross in northern Alabama indicates the location of Huntsville.

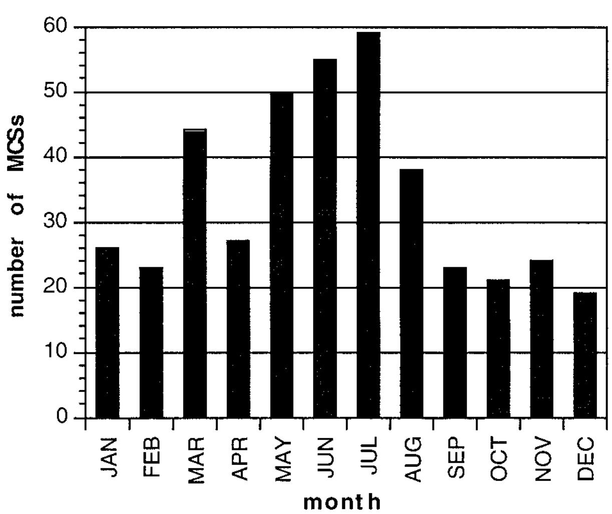

FIG. 3. Estimated seasonal variation of MCS frequencies in the Southeast, based on data from May 1994 to April 1995.

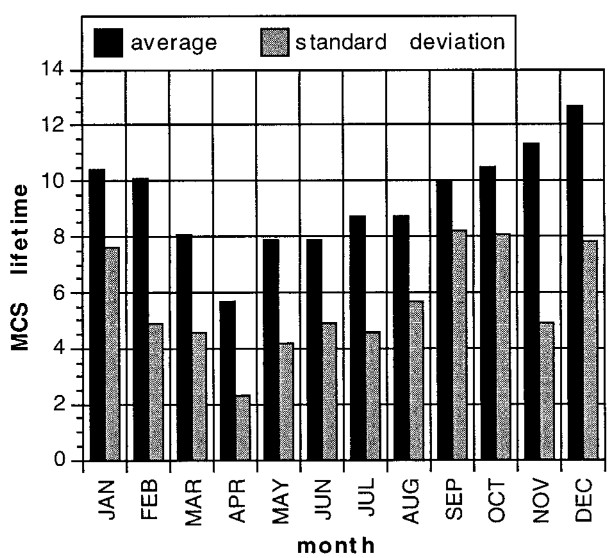

FIG. 4. Seasonal variation of the typical duration of MCSs in the Southeast (h).

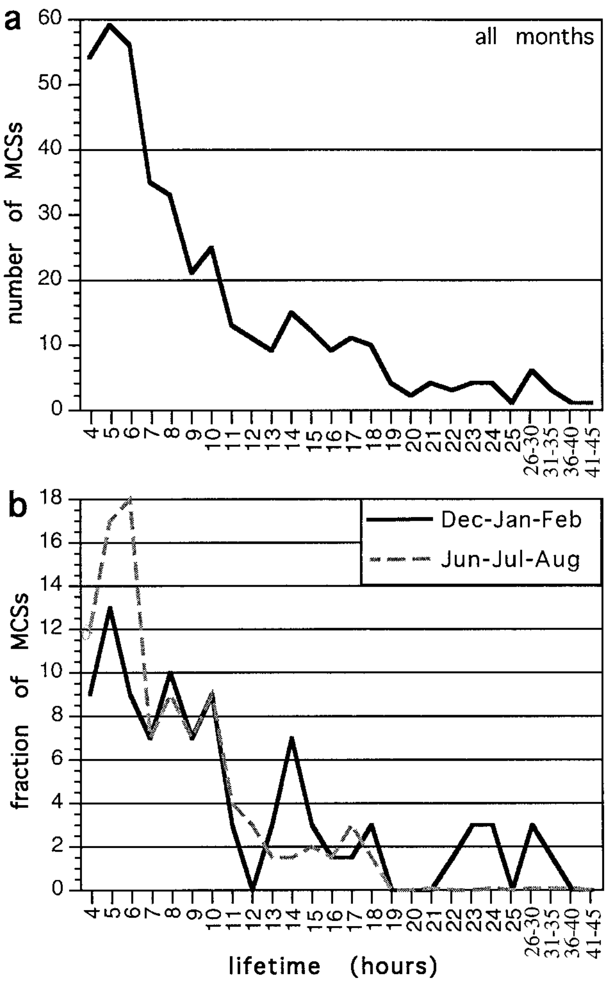

FIG. 5. Distribution of lifetimes of MCSs in the Southeast (a) for all months and (b) for winter and summer only. In (b) the occurrences are expressed as a percentage of the total for either season.

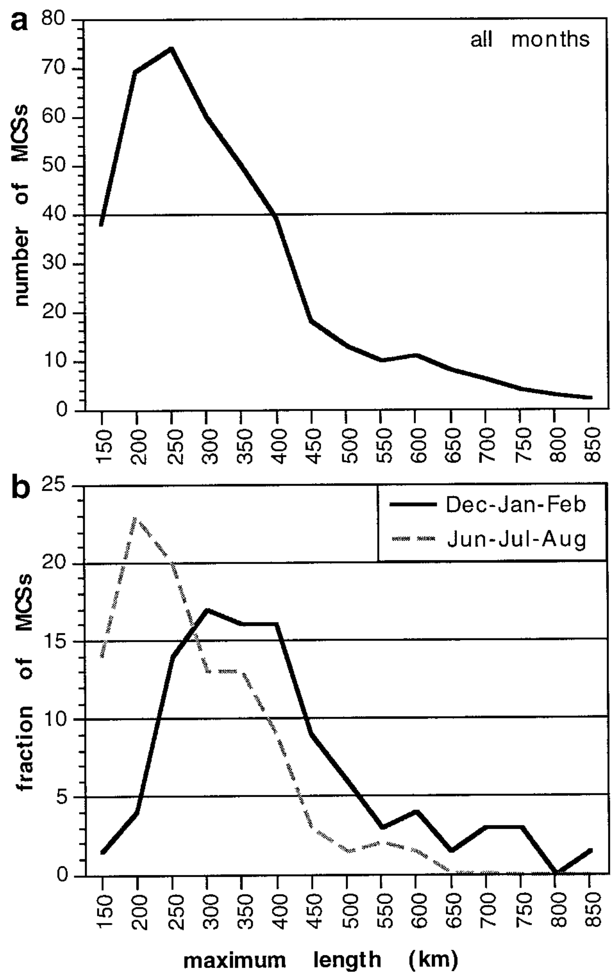

FIG. 6. As Fig. 5 but showing the maximum length of MCSs.

estimated, and an upper threshold is imposed for L_{max}. For instance, the 7 March 1995 squall line extended from the southern to the northern border of the domain (Fig. 2). No attempt was made to correct for this truncation error.

The most common L_{max} of MCSs in the Southeast is 250 km (Fig. 6a), and the average L_{max} is 350 km. In winter MCSs are longer, on average, due to the predominance of large-scale, baroclinic forcing, whereas in summer MCSs are generally small (L_{max} is 400 km or less) (Fig. 6b). This result is corroborated by the Cooperative Huntsville Meteorological Experiment (COHMEX) conducted over northern Alabama and south-central Tennessee during June and July of 1986 (Williams et al. 1987). Sixteen MCSs occurred at least partly within the COHMEX observational network having an area of $\sim 53 \times 10^3$ km^2, yet none of them reached MCC size.

MCSs are 70% more likely at 2300 UTC (about 1700 local time) than the mean (Fig. 7). They are 38% more likely between 2000 and 0000 UTC [1400–1800 central standard time (CST)] and 35% less likely at 1000–1100 UTC (0400–0500 CST). There is a secondary peak just after sunrise (0600–0900). The phase of this diurnal cycle is similar to that of thunderstorms in the Southeast, but the amplitude is surprisingly small. According to Wallace (1975), the amplitude of the first harmonic of hourly observed thunderstorms in the Southeast is about equal to (i.e., 100%) the 24-h mean frequency of thunderstorms. The amplitude of the diurnal cycle of MCSs in the Southeast is just 9% of the mean frequency. The weakness of the diurnal modulation is partly explained by the dilution by wintertime systems, which appear unaffected by the diurnal cycle (Fig. 8). Yet even summertime systems (June–August) are only weakly modulated: the amplitude of the first harmonic is just 25% of the mean hourly frequency.

The warm-season MCSs, which are most modulated by the diurnal cycle, assume their organization most often at 1200–1300 local time, and they dissipate most commonly at 1600–2000 (Fig. 9). Few systems decay between midnight and sunrise. The diurnal variation of

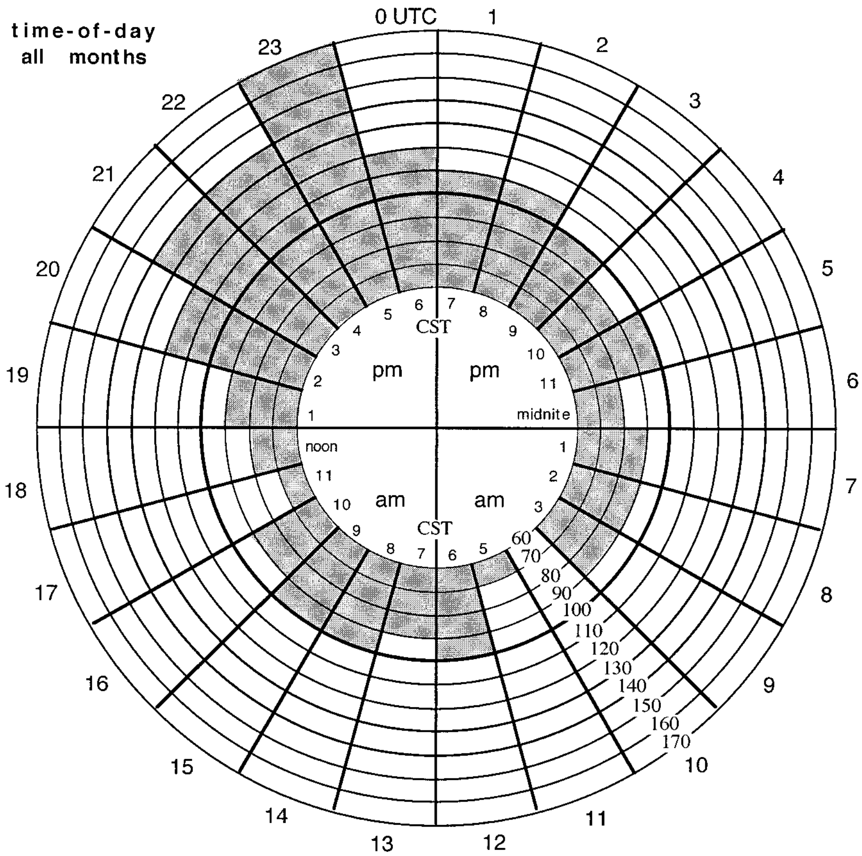

FIG. 7. Time of occurrence of MCSs, plotted on a 24-h clock. The central time between the beginning and ending of an MCS is shown, not the time of maximum size or intensity. The frequency is expressed as a percentage of the mean frequency, i.e., that expected if MCS probability were uniform throughout the diurnal period. Both UTC and CST are shown.

MCSs in the Southeast is distinct from that of MCCs in the United States (see the introduction) and it also differs from that of the springtime mesoscale precipitation systems in Oklahoma (Houze et al. 1990). The phase match of MCSs and thunderstorms (Fig. 7), and the frequent decay of MCSs just before and around sunset (2200–0200 UTC, Fig. 9), suggest that many summertime MCSs do not develop the mesoscale dynamical organization that would sustain a longer lifetime.

By definition, *linear* MCSs have a mean long axis that is at least five times longer than the mean short axis. Nearly half (47%) of all MCSs assume a linear pattern and the remainder is rather amorphous. Baroclinically forced MCSs are generally linear. Yet the fraction of linear MCSs varies little with season, even though baroclinic forcing is absent or very weak in summer. We did not investigate whether the long-lived, linear MCSs in summer occurred in environments in which the wind speed and stability profiles were suitable for long-lived squall lines (Weisman et al. 1988).

The dominant orientation of the convective lines is broadly southwest to northeast (Fig. 10), yet there is no clear preference within the region between 10° and 90° from north. The orientation is most random in summer. There is a second inconspicuous maximum at an orientation of $-60°$ (WNW to ESE). Many of the MCSs aligned in this direction occur at the southern end of the study domain (Fig. 1).

Some squall lines display a clear line echo wave pattern (LEWP) (Nolen 1959). This pattern can be seen in the squall line shown in Fig. 2 across Tennessee: a series of short line elements are rotated about 45° counterclockwise of the line itself. During the cold season (November–April) 8.1% of the MCSs displays an LEWP during at least part of their lifetime, whereas during the warm months (May–October) only 1.7% of the MCSs does. All MCSs with an LEWP are labeled intense (see section 2); in other words, the appearance of an LEWP can be used as an element in the severe storm probability assessment. Knupp et al. (1996) find the LEWP in several vigorous prefrontal squall lines.

Other squall lines tend to bow out and propagate rapidly (Weisman 1993); these are known as bow echoes or derechos (Johns and Hirt 1987). A total of 16 clear cases of bow echoes were noted, 13 of which occur between April and August. Most of these bow echoes

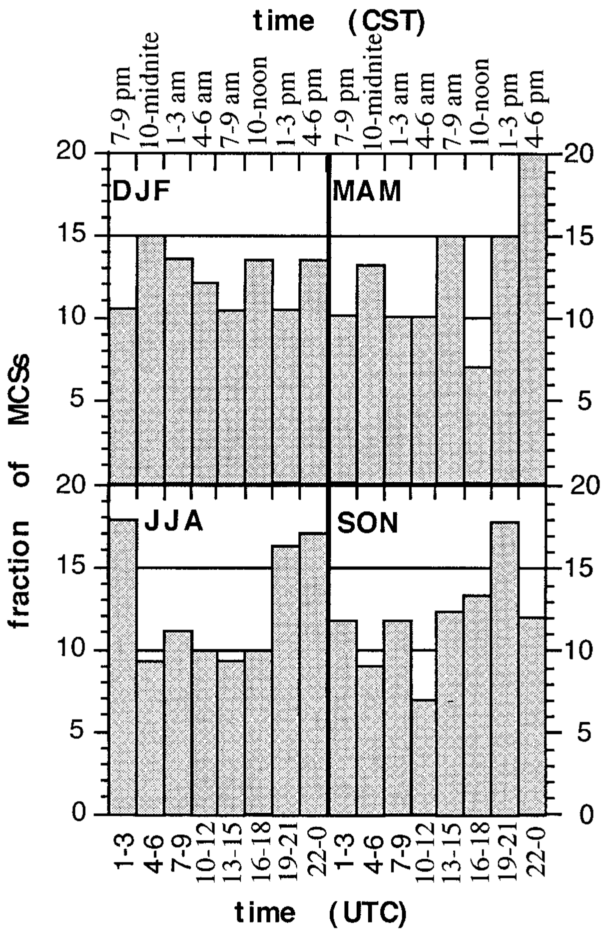

FIG. 8. Seasonal variation of the central time of occurrence of MCSs. DJF (for instance) stands for the months of December, January, and February.

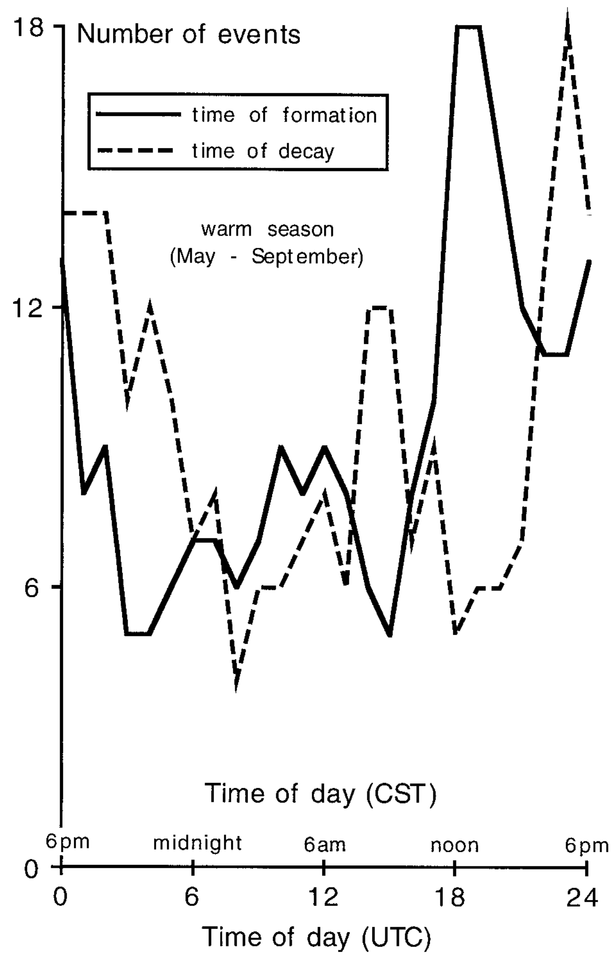

FIG. 9. Time of initiation and dissipation of MCSs during the warm season.

are found in the northern half of the study area. The seasonal occurrence, frequency, and prevailing geographical location of bow echoes correspond well with the climatology by Johns and Hirt (1987).

Convective activity in 41% of the MCSs is intense (as defined in section 2). In summer this fraction increases to about 60% (Fig. 11). Many studies have documented the structure and dynamics of a leading line of convection, a transition region, and a trailing region of stratiform precipitation (e.g., Zipser 1977; Houze 1977; Smull and Houze 1985; Houze 1993). This archetype, known as the ll/ts type (leading line/trailing stratiform) can be either symmetric or asymmetric (Houze et al. 1990). In the Southeast, 15% of the MCSs clearly display the ll/ts structure during at least part of their lifetime. The remaining linear MCSs (32% of all MCSs) resemble the ll/ts structure either weakly or not at all. Sometimes the convective line is trailing, or it intersects the broader belt of stratiform precipitation at a small angle.

The ll/ts type is rare in winter (5% in December–February), and it is most common in summer (26% in June–August). Schiesser et al. (1995), studying severe precipitation systems in Switzerland, find the ll/ts structure in 24% of the cases in June–August, and in very few systems in the winter. Houze et al. (1990), examining mesoscale precipitation systems in Oklahoma in spring (April–June), find that 22% of the systems bear a strong similarity to the ll/ts type. In the present study, 20% of the springtime MCSs bear a strong resemblance to the ll/ts type. Almost all of the MCSs of the ll/ts type are classified as intense in this study. In the Houze et al. (1990) study, severe weather is associated mostly with systems that at least moderately resemble the ll/ts type.

Sometimes a MCS develops when a number of ill-organized thunderstorm cells merge to form a mesoscale stratiform system in the decaying stage of the MCS. The resulting MCS may even assume the ll/ts structure [as in the case study by Knupp et al. (1998)]. One-third of the MCSs in June and July exhibit this two-staged evolution, with a convective growth phase and a stratiform expansion and decay phase. This life cycle is most com-

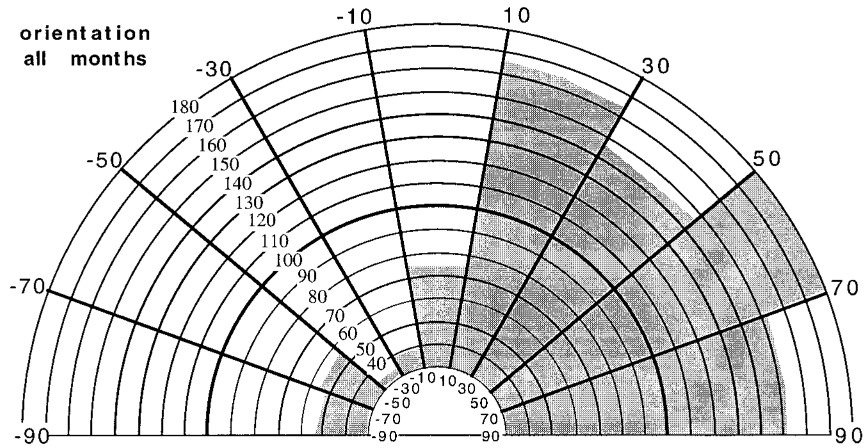

FIG. 10. Orientation of linear MCSs. The orientation is defined as the clockwise angle from north and is grouped in 20° bins. The frequency is plotted as a percentage of the mean frequency.

mon in the warm season and is not observed in any MCS in December or January.

4. Discussion

It should be emphasized that this study covers a period of 1 yr only, so it is not a climatology, and it does not document the interannual variability of MCS frequency and MCS characteristics. However, our results have shown a clear, and impressively coherent, seasonal cycle of MCS frequency and MCS characteristics, which suggests that the 12-month sample used in this study is sufficient for at least a basic description of the MCS climatology. Nevertheless our results should be understood as first-guess estimates only, and they need to be fine-tuned as more years of data become available.

Our working definition of an MCS is that a continuous region of radar reflectivity exceeding 20 dB*Z*, with a long axis of at least 100 km, exists for at least 4 h (i.e., in a continuous series of at least 17 samples), and that its peak reflectivity (at 2-km resolution) during at least two consecutive hours (9 samples) exceeds 40 dB*Z*. This (somewhat arbitrary) definition is essential in the interpretation of the results and the exact criteria are open for discussion. The author is confident that by his definition all archetypical MCSs are included in the database, yet perhaps the criteria allow the inclusion of rather weak or ill-organized systems that, when studied in detail, would not be labeled MCS. In particular, these borderline systems are unlikely to develop the mesoscale circulations that characterize the larger MCSs, and therefore they would not satisfy certain more restrictive definitions of MCSs, for example that of MCCs. On the other hand, the peak reflectivity within rainbands associated with landfalling hurricanes and tropical depressions typically is low, too low for these rainbands to be labeled intense MCSs (see section 2), yet in terms of damaging winds, rainfall rate, and accumulated rainfall these rainbands may rank near the upper end of the severity scale.

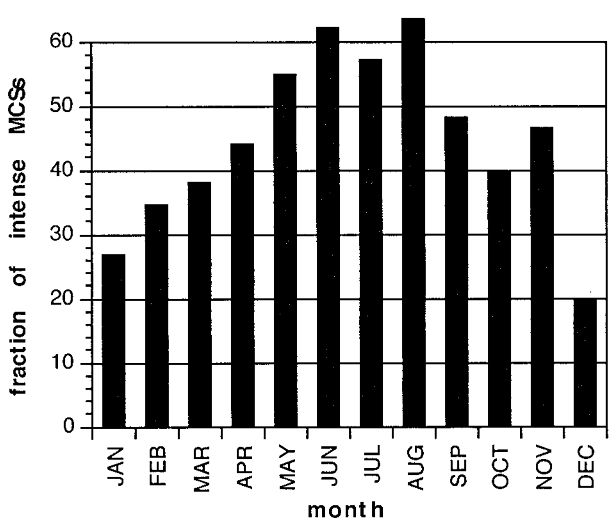

FIG. 11. Seasonal variation of the fraction of MCSs that qualify as "intense" (see text).

The question arises whether changes in the threshold reflectivities would substantially alter our findings. The methodology used in this study does not allow answering this question easily, but the sensitivity to the lower threshold of 20 dB*Z* was checked. A decrease of this threshold to 10 dB*Z*, to include regions partially filled by the radar beam and regions where the precipitation does not reach the ground, added just 11 more MCSs to the database of 398 events. Visual inspection suggests that a slight increase of the lower threshold beyond 20 dB*Z* would rapidly trim the database. Another question is how the set of MCSs in this study would compare to the set of MCSs derived over the same period, in the same area, by means of other data.

5. Conclusions

This survey uses digital composite radar reflectivity data to analyze the entire population of mesoscale convective systems in the southeastern United States (excluding Florida), and to climatologically describe them, in terms of spatial structure, evolution, seasonal and diurnal variation, etc. Such a description is very useful as guidance for forecasters.

This study is based on a 12-month sample only, so it is very preliminary, but the author is confident that the following findings will be confirmed by studies using longer samples.

- MCSs can occur at any time of the year, but are about twice as frequent in summer as in winter.
- The average lifetime and maximum length of MCSs are 9 h and 350 km, respectively. However, these attributes, as well as the MCS frequency, are slightly underestimated because of spatial truncation in a study area of limited size.
- In the summer months small and short-lived MCSs are relatively more common, whereas in winter larger and longer-lived systems occur more frequently. In terms of MCS probability of occurrence at any location in the Southeast, cold-season MCSs, the dynamics and characteristics of which are not well documented, are about equally common as warm-season MCSs, because of their larger size and duration.
- MCSs occur more commonly in the afternoon, but the amplitude of the diurnal cycle is small compared to that of thunderstorms in general.
- A few MCSs display a characteristic line echo wave pattern (mainly in winter), and a few others, mainly in the northern part of the study area, appear as a bow echo (mainly in summer).
- Some MCSs appear either as a squall line with a trailing stratiform region, or else assume a two-staged lifecycle, that is, a convective growth phase and a stratiform expansion and decay phase. Such clear separation of convective and stratiform components occurs in about half of the MCSs during the warm season (May–September).

These findings should be fine-tuned with radar imagery over a period of several years and compared against climatologies based on other observation techniques (e.g., Mohr and Zipser 1996a).

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REFERENCES

Augustine, J. A., and E. J. Zipser, 1987: The use of wind profilers in a mesoscale experiment. *Bull. Amer. Meteor. Soc.,* **68,** 4–17.

Biggerstaff, M. I., and R. A. Houze Jr., 1991: Kinematic and precipitation structure of the 10–11 June 1985 squall line. *Mon. Wea. Rev.,* **119,** 3035–3065.

Bluestein, H. B., and M. H. Jain, 1985: Formation of mesoscale lines of precipitation: Severe squall lines in Oklahoma during the spring. *J. Atmos. Sci.,* **42,** 1711–1732.

——, G. T. Marx, and M. H. Jain, 1987: Formation of mesoscale lines of precipitation: Nonsevere squall lines in Oklahoma during the spring. *Mon. Wea. Rev.,* **115,** 2719–2727.

Browning, K. A., and F. F. Hill, 1984: Structure and evolution of mesoscale convective system near the British Isles. *Quart. J. Roy. Meteor. Soc.,* **110,** 897–913.

Churchill, D. D., and R. A. Houze Jr., 1984: Development and structure of winter monsoon cloud clusters on 10 December 1978. *J. Atmos. Sci.,* **41,** 933–960.

Cotton, W. R., M.-S. Lin, R. L. McAnelly, and C. J. Tremback, 1989: A composite model of mesoscale convective complexes. *Mon. Wea. Rev.,* **117,** 765–783.

Court, A., and J. F. Griffiths, 1983: Thunderstorm climatology. *Thunderstorm Morphology and Dynamics,* 2d ed., E. Kessler, Ed., University of Oklahoma Press, 9–40.

Dirks, R. A., 1969: A climatology of central Great Plains mesoscale convective systems. Final Rep., ESSA Grant E-10-68G, Atmospheric Science Dept., Colorado State University, Fort Collins, CO, 60 pp. [Available from Atmospheric Science Dept., Colorado State University, Fort Collins, CO 80523.]

Farfán, L. M., and J. A. Zehnder, 1994: Moving and stationary mesoscale convective systems over northwest Mexico during the Southwest Area Monsoon Project. *Wea. Forecasting,* **9,** 630–639.

Houze, R. A., Jr., 1977: Structure and dynamics of a tropical squall-line system. *Mon. Wea. Rev.,* **105,** 1540–1567.

——, 1993: *Cloud Dynamics.* Academic Press, 573 pp.

——, and A. K. Betts, 1981: Convection in GATE. *Rev. Geophys. Space Phys.,* **16,** 541–576.

——, S. A. Rutledge, M. I. Biggerstaff, and B. F. Smull, 1989: Interpretation of Doppler weather radar displays of midlatitude mesoscale convective systems. *Bull. Amer. Meteor. Soc.,* **70,** 608–619.

——, B. F. Smull, and P. Dodge, 1990: Mesoscale organization of springtime rainstorms in Oklahoma. *Mon. Wea. Rev.,* **118,** 613–654.

Johns, R. H., and W. D. Hirt, 1987: Derechos: Widespread, convectively induced windstorms. *Wea. Forecasting,* **2,** 32–49.

Johnson, R. H., and P. J. Hamilton, 1988: The relationship of surface pressure features to the precipitation and airflow structure of an intense midlatitude squall line. *Mon. Wea. Rev.,* **116,** 1444–1472.

Knupp, K. R., and W. R. Cotton, 1987: Internal structure of a small mesoscale convective system. *Mon. Wea. Rev.,* **115,** 629–645.

——, R. L. Clymer, and B. Geerts, 1996: Preliminary classification and observational characteristics of tornadic storms over northern Alabama. Preprints, *18th Conf. on Severe Local Storms,* San Francisco, CA, Amer. Meteor. Soc., 447–450.

——, B. Geerts, and S. J. Goodman, 1998: Analysis of a small, vigorous mesoscale convective system in a low-shear environment. Part I: Formation, radar echo structure, and lightning behavior. *Mon. Wea. Rev.,* **126,** 1812–1836.

Laing, A. G., and J. M. Fritsch, 1993: Mesoscale convective complexes over the Indian monsoon region. *J. Climate,* **6,** 911–919.

Maddox, R. A., D. M. Rodgers, and K. M. Howard, 1982: Mesoscale convective complexes over the United States in 1981: Annual summary. *Mon. Wea. Rev.,* **110,** 1501–1514.

Mapes, B. E., and R. A. Houze Jr., 1993: Cloud clusters and superclusters over the oceanic warm pool. *Mon. Wea. Rev.,* **121,** 1398–1415.

Miller, D., and J. M. Fritsch, 1992: Mesoscale convective complexes in the western Pacific region. *Mon. Wea. Rev.,* **120,** 2978–2992.

Mohr, K. I., and E. J. Zipser, 1996a: Defining mesoscale convective systems by their 85-Ghz ice-scattering signatures. *Bull. Amer. Meteor. Soc.,* **77,** 1179–1189.

——, and ——, 1996b: Mesoscale convective systems defined by their 85-Ghz ice-scattering signature: Size and intensity comparison over tropical oceans and continents. *Mon. Wea. Rev.,* **124,** 2417–2437.

NCDC, 1995: *Climate Variations Bulletin.* Historical Climatology Series, Vol. 7, No. 4, National Climatic Data Center, 13 pp.

Negri, A., and R. Adler, 1981: Relation of satellite-based thunderstorm intensity to radar-estimated rainfall. *J. Appl. Meteor.,* **20,** 66–78.

Nolen, R. H., 1959: A radar pattern associated with tornadoes. *Bull. Amer. Meteor. Soc.,* **40,** 277–279.

Purdom, J. F. W., 1976: Some uses of high-resolution GOES imagery in the mesoscale forecasting of convection and its behavior. *Mon. Wea. Rev.,* **104,** 1474–1483.

Rasmusson, E. M., 1971: Diurnal variation of summertime thunderstorm activity over the U.S. U.S. Air Force Tech. Note 71-4, 12 pp. [Available from Air Force Environmental Technical Applications Center, Bldg. 159, Navy Yard Annex, Washington, DC 20333.]

Schiesser, H. H., R. A. Houze Jr., and H. Huntrieser, 1995: The mesoscale structure of severe precipitation systems in Switzerland. *Mon. Wea. Rev.,* **123,** 2070–2097.

Smull, B. F., and R. A. Houze Jr., 1985: A midlatitude squall line with a trailing region of stratiform rain: Radar and satellite observations. *Mon. Wea. Rev.,* **113,** 117–133.

Steiner, M., R. A. Houze Jr., and S. E. Yuter, 1995: Climatological characterization of three-dimensional storm structure from operational radar and rain gauge data. *J. Appl. Meteor.,* **34,** 1978–2007.

Velasco, I., and J. M. Fritsch, 1987: Mesoscale convective compexes in the Americas. *J. Geophys. Res.,* **92** (D8), 9591–9613.

Wallace, J. M., 1975: Diurnal variations in precipitation and thunderstorm frequency over the conterminous United States. *Mon. Wea. Rev.,* **103,** 406–419.

Weisman, M. L., 1993: The genesis of severe, long-lived bow echoes. *J. Atmos. Sci.,* **50,** 645–670.

——, J. B. Klemp, and R. Rotunno, 1988: Structure and evolution of numerically simulated squall lines. *J. Atmos. Sci.,* **45,** 1990–2013.

Williams, S. F., H. M. Goodman, K. R. Knupp, and J. E. Arnold, 1987: Space/COHMEX data inventory document. NASA Tech. Memo. 4006, 476 pp. [Available from NASA Scientific and Technical Information Office, Code NTT-4, Washington, DC 20546-0001.]

Zhang, D.-L., 1992: The formation of a cooling-induced mesovortex in the trailing stratiform region of a midlatitude squall line. *Mon. Wea. Rev.,* **120,** 2763–2785.

Zipser, E. J., 1977: Mesoscale and convective-scale downdrafts as distinct components of squall-line circulation. *Mon. Wea. Rev.,* **105,** 1568–1589.

——, 1982: Use of a conceptual model of the lifecycle of mesoscale convective systems to improve very-short-range forecasts. *Nowcasting,* Academic Press, 191–204.