Radar Observations of the Early Evolution of Bow Echoes

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ABSTRACT

The evolution of 273 bow echoes that occurred over the United States from 1996 to 2002 was examined, especially with regard to the radar reflectivity characteristics during the prebowing stage. It was found that bow echoes develop from the following three primary initial modes: (i) weakly organized (initially noninteracting) cells, (ii) squall lines, and (iii) supercells. Forty-five percent of the observed bow echoes evolved from weakly organized cells, 40% from squall lines, while 15% of the bow echoes were observed to evolve from supercells. Thunderstorm mergers were associated with the formation of bow echoes 50%–55% of the time, with the development of the bow echo proceeding quite rapidly after the merger in these cases. Similarly, it was found that bow echoes formed near, and moved generally along, synoptic-scale or mesoscale boundaries in about half of the cases (where data were available).

The observed bow-echo evolutions demonstrated considerable regional variability, with squall line-to-bow-echo transitions most frequent over the eastern United States. Conversely, bow echoes typically developed from a group of weakly organized storms over the central United States. Bow-echo life spans were also longest, on average, over the southern plains; however, the modal life span was longest over the eastern United States. Finally, the supercell-to-bow-echo evolution was most common across the northern plains, but the data sample is too small for this result to be considered significant.

1. Introduction

Klimowski et al. (2003) found that bow echoes[1] account for nearly one-third of the convectively generated severe wind reports over the northern High Plains of the United States. Furthermore, 86% of the bow echoes that they studied produced severe winds, with severe wind reports being 3 times as frequent as severe hail reports. Klimowski et al. (2000, 2003) also observed that bow echoes were preceded by thunderstorm mergers roughly 40%–50% of the time, which in turn led to bow-echo configurations and lifetimes of widely varying spatial and temporal scales. Because the radar appearance of a bow echo is an *indicator* of severe winds (not a *predictor*), it is important to understand the early evolution of bow echoes to better anticipate the production of the downbursts responsible for these bowing storms. Specifically, it is the purpose of this paper to identify (i) the convective structures preceding bow-echo development, and (ii) the varying morphologies and lifetimes of the resulting bow echoes. It should be noted that the dataset in the present study has been significantly expanded upon from Klimowski et al. (2003) to include cases over the majority of the United States (primarily regions east of the Rocky Mountains).

Fujita (1978, 1979) was the first to define the typical evolutionary characteristics of the bow echo. According to Fujita (1979), the bow echo commonly evolves from either a single convective cell or a line of cells into a comma-shaped echo with a dominant cyclonic vortex on its poleward side. Weisman (1993, 2001) further illustrated the importance of bookend vortices and the

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[1] A bow echo is defined as a *nontransient* bow- or crescent-shaped radar signature with a tight reflectivity gradient on the convex (leading) edge, the evolution and horizontal structure of which is consistent with storms that propagate along a strong outflow. Note that this definition is not specific in the size, duration, or evolution of the storm, only its shape and association with strong winds (also see Fujita 1978; Przybylinski 1995; Weisman 2001; and Klimowski et al. 2003).

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rear-inflow jet (RIJ) in sustaining and/or strengthening a bow echo. Bow echoes have been observed to occur over a wide range of sizes (e.g., 10–150 km), while evolving from a diverse set of morphologies (e.g., Przybylinski and DeCaire 1985; Johns and Hirt 1987; Moller et al. 1990; Lee et al. 1992).

Even though bow echoes have been studied extensively through observational studies (Przybylinski and Gery 1983; Burgess and Smull 1990; Smith 1990; Przybylinski 1995; Funk et al. 1999, just to name a few) and numerical simulations (Weisman 1993, 2002; Finley et al. 2001), how they evolve from various initial convective structures has not been comprehensively documented. For example, there are a few studies illustrating that storm mergers sometimes occur prior to bow-echo formation (e.g., Przybylinski and DeCaire 1985; Smith 1990; Finley et al. 2001), but they do not provide any information on how frequently this occurs. Other studies have documented supercell-to-bow-echo transitions (e.g., Moller et al. 1990; Conway et al. 1996; Klimowski et al. 1998), but, again, the frequency of this type of evolution is not well known. Rear-inflow notches (RINs), a manifestation of the RIJ, may also be present (on radar) before noticeable bowing occurs (e.g., Przybylinski and Gery 1983; Burgess and Smull 1990; Przybylinski 1995), but this signature may not provide much warning *before* severe surface winds occur; it may only be an indicator that severe winds are imminent or occurring. Finally, most of these bow-echo studies involve individual cases, which prevents broader conclusions from being drawn.

Some of the more comprehensive bow-echo studies have shed some light on their early evolution. Przybylinski and Gery (1983) examined radar reflectivity structures from over 30 bow echoes. They found that strong low-level reflectivity gradients and maximum storm tops often occurred near the leading edge of the bow echo in the early stages of development; however, the radar characteristics leading up to this stage were not presented. More recently, Schmocker et al. (1996) used the midaltitude radial velocity convergence (MARC) signature to identify thunderstorms that would likely produce downbursts and eventual bow echoes. Although Schmocker et al. focused on the early stages of bow-echo development, it is not clearly understood what convective structures typically precede these MARC signatures. Nevertheless, the MARC signature has proven useful as warning guidance for the onset of severe surface winds (e.g., Funk et al. 1998). In yet another regional study, Przybylinski et al. (2000) found that initial bow echoes frequently developed near the intersection of a convective line and external boundary. The overarching goal of all of these studies has been to provide better warning guidance for the early stages of these windstorms. Therefore, in the present paper, we are especially interested in the chain of events that initiate the downbursts that eventually produce the bow-echo structure.

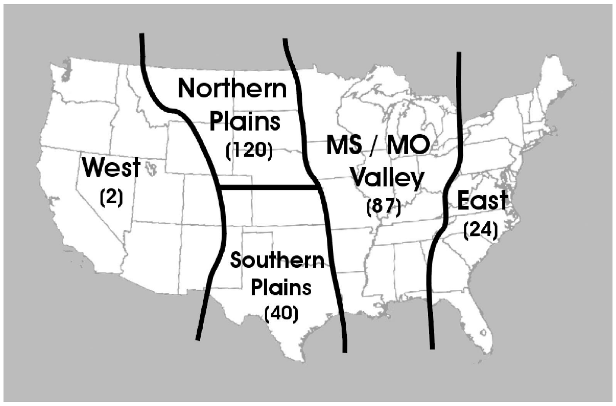

FIG. 1. The regional divisions used in the categorization of the bow echoes. The total number of bow echoes initiated within each region is given in parentheses.

2. Nature of the dataset

The identification of bow echoes was performed using radar reflectivity and velocity data derived from a variety of Weather Surveillance Radar-1988 Doppler (WSR-88D) sources.[2] WSR-88D archive level II data were used for the majority of the cases from 1996 through 1999. Where needed, these data were supplemented with the National Weather Service's Next Generation Weather Radar (NEXRAD) Information Dissemination Service (NIDS) data. With the availability of the higher-resolution NIDS data after 1999, the majority of the radar data for the cases from 2000 to 2002 were acquired from single-site and mosaic NIDS data. For all cases, the temporal (spatial) resolution of the radar data were at least 10 min (1–2 km).

Data for 65 bow-echo cases came from a Cooperative Program for Operational Meteorology, Education, and Training (COMET) research project on convective high wind events over the northern High Plains from 1996 to 1999 (Klimowski et al. 2003). In order to acquire as many bow-echo cases as possible, in addition to the Klimowski et al. (2003) dataset, several methods of identification were employed. Most directly, regional and national radar mosaics were perused daily to visually identify potential bow echoes. In the event that the review of available radar data were not possible, archived severe wind reports were scrutinized for patterns that might infer an organized high wind event (three or more severe wind reports grouped together). Radar data associated with the high wind reports were then acquired and analyzed for potential bow echoes. Analyses of radar data in this way (primarily from the years 2000 to 2002 and some earlier data) allowed for

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[2] The identification of a bow echo was subjectively based on the definition of bow echo given in the introduction. The initiation of the bow echo was determined from the first radar scan in which incipient bowing was present. The demise of the bow echo was that time at which the definition of a bow echo could no longer be satisfied.

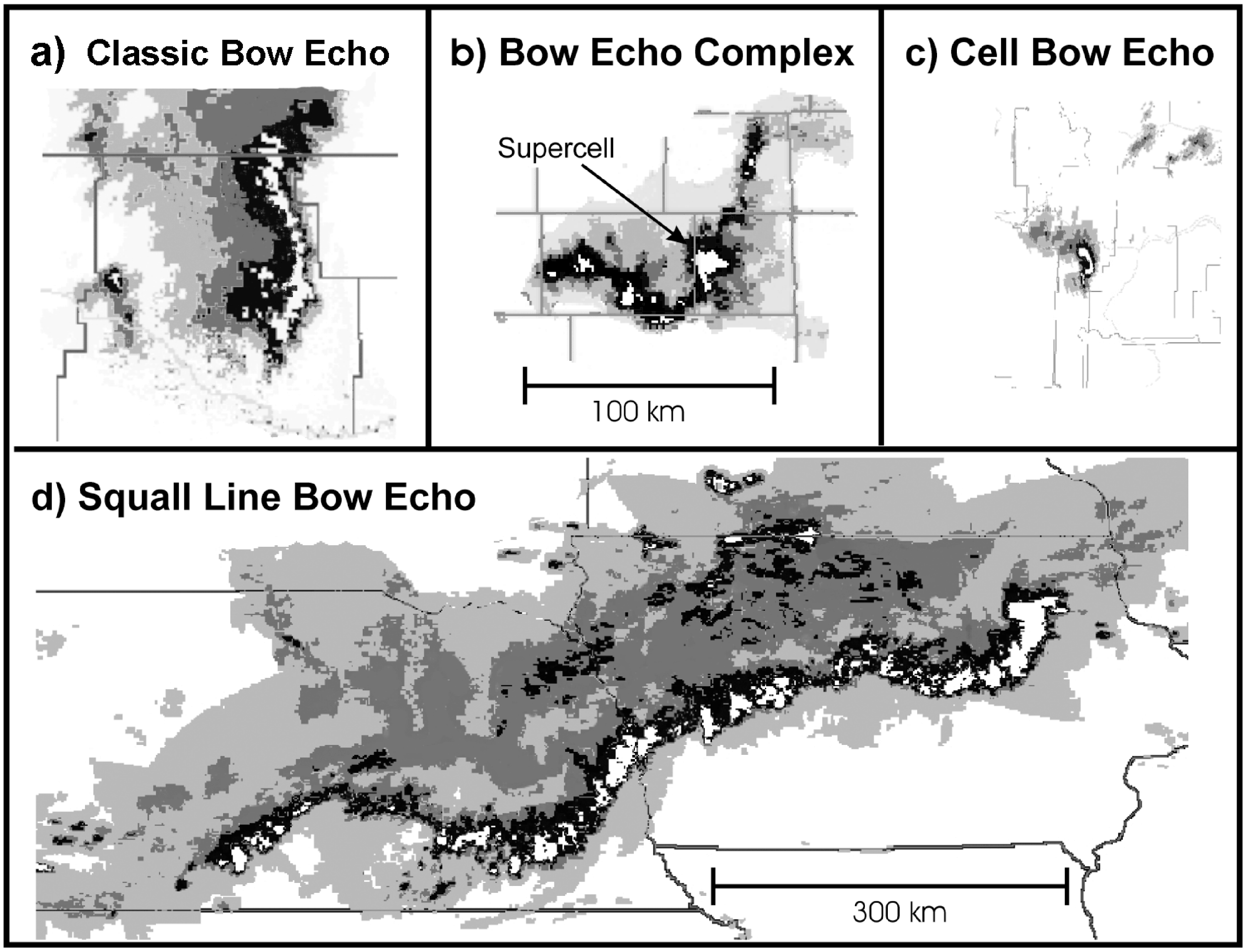

FIG. 2. The four general types of bow echoes described in the text: (a) BE, (b) BEC, (c) CBE, and (d) SLBE. The BE, BEC, and CBE are all relative to the scale as given in (b). Reflectivity shaded every 10 dBZ. Refer to section 3 for a description of these four classifications.

the acquisition of 208 additional cases (with much of the radar data for these cases also provided by COMET). In all, radar and other meteorological observations (mostly surface) encompassing the early evolution of 273 bow echoes were accumulated for this research.

There is a bias of the number of cases toward the northern plains [due to the fact that this research is based on the earlier work of Klimowski et al. (2003)], with only two cases from the western United States (Fig. 1). It should also be noted that this is not a comprehensive bow-echo climatology, but rather, the bow-echo cases were gathered in an opportunistic fashion in both real time and during the perusal of radar data archives and severe-weather reports, and is likely biased toward the larger and longer-lived bowing convective systems.

3. Proposed bow-echo classifications

Several classes of bow-echo structures are proposed here (as in Klimowski et al. 2000) in order to adequately describe the varied nature and spatial scale of bow echoes. The term *classic bow echo* (BE; as in the classic definition of Fujita 1978) is used to describe those bow echoes (i) larger than a single thunderstorm, (ii) not associated with a large linear complex, and (iii) which are mostly isolated from other organized convection (e.g., Fig. 2a). The term *bow-echo complex* (BEC) describes those mesoscale convective systems (MCSs) in which the bow echo is the primary, but not the only, organized convective structure; supercell thunderstorms are frequently a component of a BEC (e.g., Fig. 2b). Przybylinski and DeCaire (1985; their type-II and -III events), Johns and Hirt (1987), and Moller et al. (1994) describe examples of BECs that were also associated with derechos. The category of *cell bow echo* (CBE) is adopted from the work of Lee et al. (1992), and is used to describe bow echoes that occur on very small scales (i.e., 10–25 km), which are not associated with any larger organized convective system (e.g., Fig. 2c; also see Knupp 1996). Last, the category of *squall line bow echo* (SLBE) is adopted from the work of both Lee et al. (1992) and Przybylinski and DeCaire (1985; their type-I event), which describes those bow echoes that are part of a large-scale, elongated (quasi linear) con-

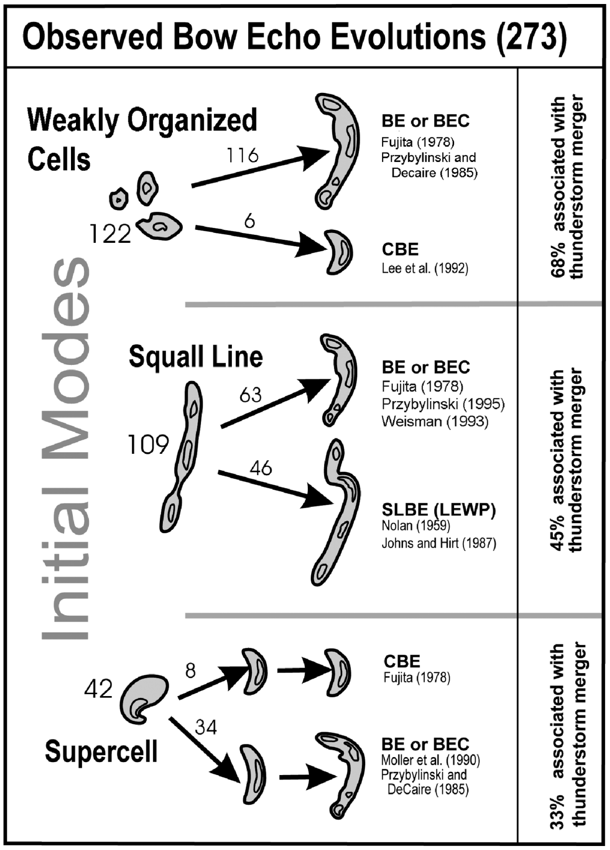

FIG. 3. Illustration of the primary evolutionary pathways for bow echoes observed in this study. The number of cases identified following each path is indicated above the arrows. References for representative bow-echo cases are given. The percentage of bow echoes preceded by merging storms is given at right. Refer to section 3 for an explanation of BE, BEC, CBE, and SLBE.

vective system (e.g., Fig. 2d) and is similar to Nolen's (1959) line echo wave pattern (LEWP). Serial derechos (Johns and Hirt 1987) frequently contain SLBEs.

4. Initial modes of bow-echo evolution

As stated in the introduction, a primary goal of this research is to identify and describe the convective structures preceding bow-echo development, in order to facilitate the predictability of the severe weather associated with these storms. Accordingly, from the 273 bow-echo cases analyzed, three primary modes of convective organization were identified from which the bow echoes formed (hereafter referred to as the *initial modes*):

- weakly organized cells (WO),
- squall lines (SL), and
- supercells (SC).

These initial modes of bow-echo development are symbolically illustrated in Fig. 3. The resultant bow echoes developed and persisted over a wide range of temporal scales, and virtually all of them were associated with severe surface winds. Even though large hail was a rare occurrence with these bow echoes, a few of those that evolved from supercells exhibited the dangerous combination of both severe winds ($>$25 m s^{-1}) and large hail ($>$1.9 cm). The primary evolutionary paths are described in detail below.

a. Weakly organized cell initial mode bow-echo evolution

In the most common scenario, 122 (45%) of the observed bow echoes evolved from initially noninteracting cells, or groups of weakly organized thunderstorms (hereafter referred to as the WO initial mode; Fig. 3, top panel). These initial groups were most often composed of 3–10 members. Typically, the deviant motion of one or more of the cells would initiate the merging of cells, from which the bow echo would form. Alternately, the group of cells might organize behind (but along) a common gust front, briefly forming a convective line prior to evolving into a bow. Any such linear organization prior to bow-echo formation that lasted for more than 20 min was classified as a squall line case (see below).

A typical example of this type of bow-echo evolution is shown in Fig. 4a, in which a BE evolved. In this case, a storm moving rapidly to the northeast (farthest south in the figure) merged with a group of slower, eastward-moving cells. The bow echo that resulted was associated with severe winds for over 2 h. Interestingly, the majority (68%) of bow echoes observed to evolve from the WO initial mode occurred immediately after the some type of convective merger. These data also indicate that bow echoes that form concomitant with storm mergers can evolve very quickly after the merger (i.e., in as little as 15–30 min). Further, it was observed that bow echoes resulting from mergers tend to move in the direction (and close to the speed) of the fastest (and often the strongest) initial cell (this behavior has been observed in greater than 50% of the cases analyzed).

In 32% of the WO initial mode cases, mergers were not identified prior to the formation of the bow echo. These cases generally exhibited a brief linear organization that immediately evolved into a bow echo. Alternatively, the cell bow echoes that formed occurred without any larger-scale organization or external interaction.

In 47 cases where adequate surface data were obtained (out of 122), it was found that 57% of the bow echoes formed and moved roughly parallel to, or along, a preexisting surface boundary. This boundary could be a stationary front, a very slowly moving cold front, or outflow from previous convection. The existence of the boundary may help to explain the frequency of mergers observed in these cases (65% of the bow echoes that moved along boundaries experienced a radar-observed merger), because some cells are frequently observed to be ''anchored'' to the boundary (e.g., Przybylinski et

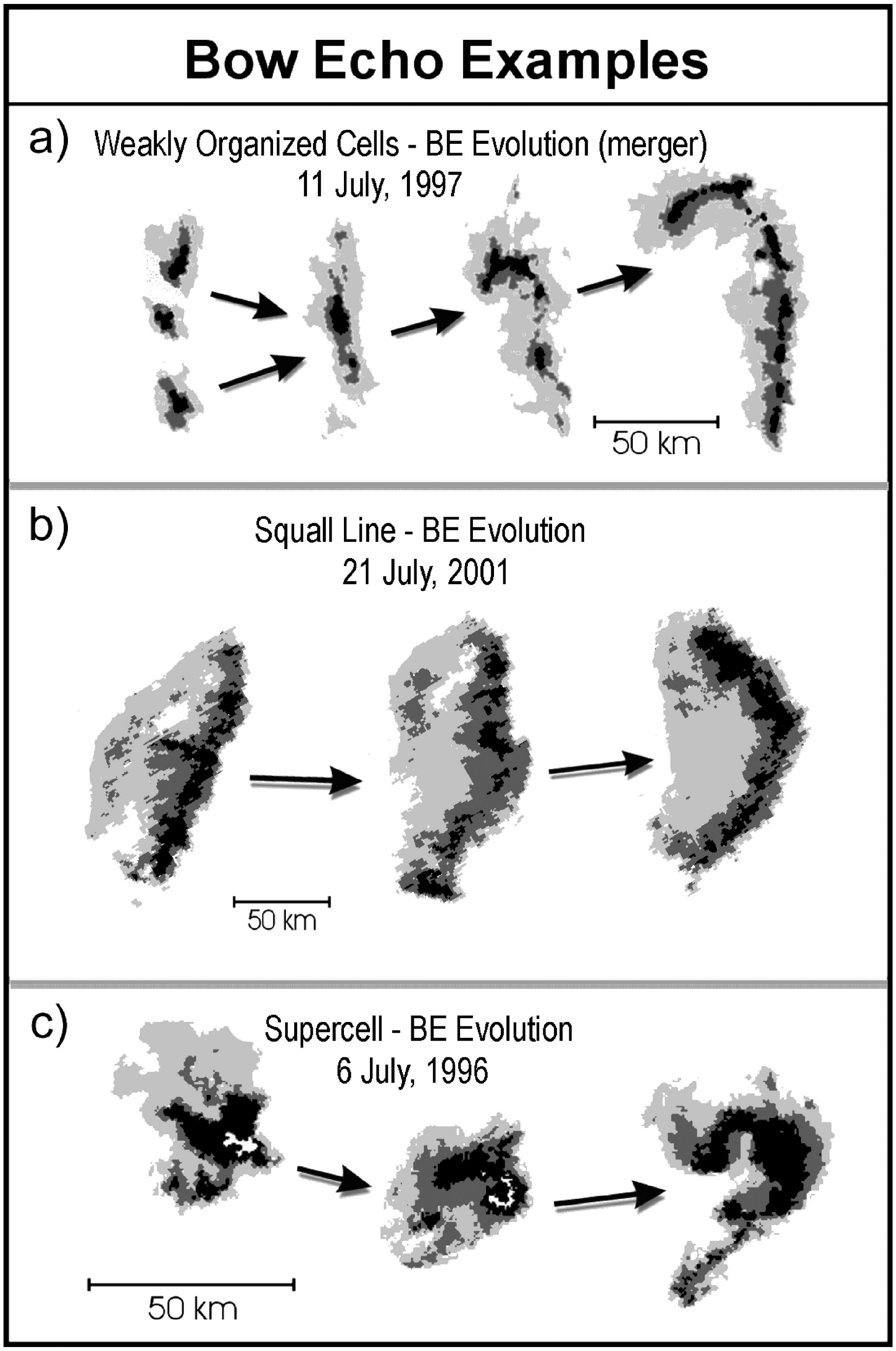

FIG. 4. Examples of observed bow echoes that developed from the three primary initial modes illustrated in Fig. 3: (a) WO initial mode, (b) SL initial mode, and (c) SC initial mode. Note the different horizontal scales for each of the cases. Shading represents increasing radar reflectivity.

al. 2000), while surrounding storms exhibit a different motion relative to the boundary. It is clear, however, from the wide variety of motions observed in the weakly organized convection that many processes may be responsible for the ‘‘deviant’’ motions observed (such as the depth to which cells become ‘‘rooted’’ in the boundary layer, differing steering influences due to varying height of the storms, influence of topographic features, etc.).

Occasionally, a CBE will develop from an isolated cell without any apparent outside interaction, perhaps developing dynamically as described in Lee et al. (1992) and Knupp (1996). CBEs that form in this way are typically short lived, often dissipating within 1 h of initiation. As a result of the small spatial and temporal scale of CBEs along this evolutionary path, severe winds are not frequently reported with their occurrence (perhaps a sampling issue), and their identification can be quite difficult.

b. Squall line initial mode bow-echo evolution

Of the bow echoes observed, 109 (40%) evolved from preexisting squall lines (i.e., the squall lines persisted for at least 30 min prior to bow-echo formation) or linearly oriented storms that shared a common gust front or leading edge (Fig. 3, middle panel). Over half (58%) of the bow echoes that developed from squall lines evolved into a relatively isolated (generally smaller) bow-echo structure (i.e., either a BE or BEC). In the remaining cases, the primary squall line persisted and the bow echo formed as a part of the larger linear structure (i.e., SLBE). In these cases, it was common to observe more than one bow echo form along the line (e.g., Funk et al. 1999), producing a wavelike pattern similar to that of a LEWP (Nolen 1959).

An example of the squall line–to-BEC evolution is shown in Fig. 4b, which illustrates the gradual transition from a quasi-two-dimensional squall line into a bow echo. In this example, a solid line of convection, moving generally eastward, developed a ‘‘bulge’’ at the midpoint of the line, which eventually accelerated to the east. There was no apparent interaction with external features—such as boundaries or other cells—in this case. Similar behavior has been observed in numerical model simulations by Weisman (1993).

The bow echoes modeled by Weisman (1993) form as an elevated RIJ and bookend vortices strengthen within a highly unstable and sheared atmospheric regime. In this type of evolution, bow echoes develop 2–4 h into the lifetime of the convective system. Observations in the present study demonstrate that preexisting boundaries or cells merging into the line can significantly accelerate the production of bow echoes within squall lines, effectively acting as a catalyst that aids in the transition of the storm into a damaging wind-producing event. Without these external influences, the evolution of squall lines into SLBEs apparently follows a cycle similar to that proposed by Weisman. In 45% of the squall line–bow-echo evolutions observed, the formation of the bow was preceded by some type of convective merger near the location of the eventual bowing.

Bow echoes that formed from squall lines exhibited the longest average life spans[3] of any of the observed initial modes, with a mean life span of 3.4 h (as compared to 3.2 h for bow echoes that evolved from the WO initial mode, or 2.9 h for bow echoes that evolved from supercells). Though the differences in these mean life spans are relatively small, the results are consistent with the hypothesis that when a bow echo evolves from a squall line, the environment is already conducive for linear convective development (hence, the presence of the squall line), and, thus, the bow echo forms within a supportive environment that aids in its longevity.

c. Supercell initial mode bow-echo evolution

The development of bow echoes from supercells was first elucidated in the high-precipitation (HP) supercell conceptual model of Moller et al. (1990), and has been documented by several others since then (Conway et al. 1996; Klimowski et al. 1998; Finley et al. 2001). As was noted in Moller et al. (1990), this evolution is not uncommon, and, indeed, the present research supports this (Fig. 3, bottom panel). Forty-two cases of supercell-to-bow-echo evolution were identified (15% of the total), and in most cases, the parent supercell was classified as being HP. In a few cases, rotation of the suspected supercell could not be verified due to the lack of WSR-88D velocity data. However, if the storm exhibited an echo pattern and deviant motion consistent with that of a supercell (Moller et al. 1994; Bunkers et al. 2000), the storm was assumed to be a supercell.

Figure 4c illustrates a typical example of this type of evolution, which closely resembles the HP supercell composite life cycle in Moller et al. (1990). As opposed to the more rapid transition to a bow echo that occurs as a result of mergers, the HP-to-bow-echo transition is typically a more deliberate (predictable) transition (as compared to the WO initial mode). Most frequently, the parent supercells are already producing severe winds prior to the production of the bow echo (as in Fujita 1979), and the evolution to the bow-echo stage may not necessarily indicate an intensification of the winds (Klimowski et al. 1998). Bow echoes of this evolutionary mode were most frequently observed to be either classic (BE), or else part of BEC, and showed some preference for developing and moving along surface boundaries. Interestingly, the life span of bow echoes that evolve from supercells was, on average, the shortest of the three initial modes (2.9 h).

In 8 out of the 42 observed cases of supercell-to-bow-echo evolution, the resultant bow echo persisted as a quasi-steady, small-scale ($<$30 km), and very intense CBE structure, in contrast to the weaker CBEs in the WO initial mode. Unlike the other types of bow echoes investigated here, these storms were associated with both severe winds *and* very large hail (perhaps due to their supercell characteristics). It was also noted that these storms frequently developed in a series of two or three similar storms, with the latter storms moving along the outflow of previous storms. An example of this type of storm is shown in Fujita (1978, his Fig. 5.9).

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[3] Herein, the life span is defined as that period of time beginning with the onset of echo curvature, to the demise of the bow echo (when it can not be subjectively recognized).

TABLE 1. Percentages of bow echoes that evolved from each initial mode (WO, SL, SC; see section 4); percentages of bow echoes in each final mode (BE, BEC, CBE, SLBE; see section 3); percentage of bow echoes preceded by mergers for each region; and average life span of bow echoes for each region. Refer to Fig. 1 for delineations of each region.

	Initial mode (%)			Final mode (%)					
	WO	SL	SC	BE	BEC	CBE	SLBE	Mergers (%)	Average life span (h)
Northern plains	44	31	25	75	4	7	14	49	3.0
Southern plains	51	33	16	80	—	5	15	53	3.8
Mississippi–Missouri valley	47	47	6	73	1	2	24	55	3.3
Eastern United States	28	72	0	46	—	8	46	54	3.1

5. Regional characteristics of bow-echo evolution

For the purpose of identifying regional differences in bow-echo evolution, the United States east of the Rocky Mountains was divided into four arbitrary regions (refer back to Fig. 1). Table 1 summarizes the characteristics of the observed bow-echo evolutions within each of these regions.

There is an increasingly high percentage of bow echoes evolving from squall lines as one goes east from the Rocky Mountains to the eastern seaboard (Table 1). Over the northern and southern plains, approximately 32% of the bow echoes were observed to evolve from squall lines. This number increases to 47% over the Mississippi–Missouri valley region, and to over 72% across the eastern United States. A similar result is noted for the resultant bow-echo type. While only 14% of bow echoes over the northern plains evolved into SLBEs, 24% of those over the Mississippi–Missouri valley region, and 46% of those over the eastern United States, ended up as SLBEs (Table 1). From these data there appears to be a clear preference for linear structures as initial and final modes of bow-echo evolution as one goes from west to east across the United States. Conversely, it appears that the supercell initial mode is much more frequent over the northern and southern plains, as opposed to locations further to the east. Ninety-four percent of the observed supercell-to-bow-echo evolutions were observed over the northern or southern plains, with only 6% observed over the Mississippi valley region, and none over the eastern United States (but, this is clearly affected by the smaller sampling period over these eastern areas).

The frequency of observed mergers associated with bow-echo initiation was very constant across the four regions, with all values near 50% (Table 1). This suggests that the processes associated with thunderstorm mergers might be an important part of the processes in the initiation of bow echoes. In contrast to the mergers, the life span of bow echoes across the four regions did demonstrate some noteworthy differences (Table 1), with those bow echoes forming over the northern plains having the shortest life spans (3.0 h), and those developing over the southern plains exhibiting the longest (3.8 h). Interestingly, the modal life span of bow echoes in the eastern United States was the longest, and fell in the range of 3–4 h (36% of the bow echoes exhibited life spans in this range), while in the other three regions the mode was 1–2 h (with 24%–33% of the bow-echo life spans falling in this range). This suggests that a few relatively long-lived bow echoes dominated the average life span over the southern plains.

6. Summary and conclusions

The evolution of 273 bow echoes have been documented and characterized through the analysis of radar reflectivity data with the goal of better understanding their early formation and life cycles. The main conclusions of this study are as follows:

- Three primary initial modes of bow-echo formation are (i) weakly organized cells, (ii) squall lines, and (iii) supercells. The weakly organized cells initial mode was the most common in the central United States, but the squall line initial mode was most common in the eastern United States.
- Thunderstorm mergers were associated with the formation of bow echoes 50%–55% of the time, with the development of the bow echo proceeding rapidly after the merger in these cases. For the WO initial mode of formation, 68% of the bow-echo cases were associated with mergers. In many of the merger cases, the resulting bow echo tended to move with the speed and direction of the cell initiating the merger.
- Bow echoes formed near synoptic-scale or mesoscale boundaries in about half of the cases.
- Squall line bow echoes were the longest-lived bow echoes on average, and supercell-to-bow-echo transitions were the shortest lived.

These results suggest that understanding the merger process and deviant motion of the merger cell appears crucial in improving the forecastability of some bow echoes. Those not evolving from cell mergers often appear to develop without any apparent outside influence, suggesting that the primary evolution process might be internal. With this information, it is hoped that the forecasting of bow-echo development and associated damaging winds can be improved over the United States. Additional information on the environments of the initial modes of bow-echo formation will also potentially assist in the forecasting of their occurrence.

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