OBSERVATIONS OF THE FORMATION AND EARLY EVOLUTION OF BOW ECHOES

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1. INTRODUCTION

For over 20 years, the bow echo (Fujita 1978) has been recognized as a distinct and destructive severe wind-producing convective structure. Bow echoes have been observed to occur in a wide variety of sizes and shapes, and evolve from a diverse set of morphologies (Fujita 1978; Johns and Hirt 1987; Lee et al. 1992; Przybylinski 1995). The geographic extent of their occurrence includes the tropics as well as the mid-latitudes (Alfonso and Naranjo 1996; Businger et al. 1998; Jorgensen et al. 1997). Even though bow echoes have been studied extensively and numerically simulated, the issue of how they evolve within various initial convective structures has not been comprehensively addressed. It is the purpose of this paper to identify preferred evolutionary pathways that lead to the development of bow echoes and associated damaging downburst winds, and to give insight on the mechanisms controlling their formation within these modes of convection. Radar data from 110 bow echo cases were accumulated and analyzed to achieve this goal.

2. BOW ECHO CLASSIFICATION

Fujita (1978) first introduced the term *bow echo* when referring to "bow or crescent"-shaped radar echoes associated with downbursts. As downbursts cannot be verified for all bowing structures observed on radar, a somewhat broader definition must be adopted here. A bow echo, therefore, is defined as a bow or crescent-shaped radar echo with a tight reflectivity gradient on the convex (leading) edge, the evolution and horizontal structure of which is consistent with outflow-dominated systems. That is, the bowing echo should demonstrate an increasing radius with time, be associated with very strong winds, and/or exhibit a persistent arc which deviates significantly (in direction or magnitude) from the mean tropospheric wind. Other radar features such as rear inflow notches or strong rear inflow jets may give insight into the severity of bow echoes, but are not required for them to be defined as such.

In order to adequately describe the varied nature and horizontal scale of bow echoes, several classifications are recognized here. The terms *Cell Bow Echo* (CBE) and *Squall Line Bow Echo* (SLBE) are adopted from the work of Lee et al. (1992), and are used to describe bows which occur on small scales (10 - 25 km - CBE), or as a part of larger-scale linear systems (SLBE). The general term *Bow Echo* (BE) is used (in addition to the generic definition) to describe those bows larger than CBEs, not associated with a larger linear complex, which are mostly isolated from other organized convection. The term *Bow Echo Complex* (BEC) describes those Mesoscale Convective Systems of which the bow echo is a primary, but not the only, significant organized convective structure. Derechos are frequently of the BEC type - several examples are given in Przybylinski and DeCaire (1985), Johns and Hirt (1987), and Moller et al. (1990).

3. NATURE OF THE DATA SET

Radar reflectivity data were mostly derived from Archive II WSR-88D sources with a temporal resolution of 10 minutes or better. Data for fifty-seven bow echo cases came from a COMET Cooperative research project on convective high wind events over the Northern High Plains (Klimowski and Hjelmfelt 1999). Nineteen cases over the Mid-Mississippi Valley were acquired from similar COMET Cooperative research currently being performed between the NWSFO St. Louis and the St. Louis University. Perusal of the meteorological literature yielded an additional 15 cases where the evolution of the bow echo could be discerned. Most recently, analyses of radar data early in the year 2000 allowed for the acquisition of 19 additional cases. In all, radar and other meteorological observations encompassing the early evolution of 110 bow echoes were accumulated for this project.

4. OBSERVED BOW ECHO EVOLUTION

The 'classic' evolution of a bow echo given in Fujita (1978) illustrates the oft-referenced transition from a "strong tall" echo, to "bow" echo, and finally into a "comma" echo. One of the goals of this research is to expand this conceptual model to include bow echoes which evolve over a wider range of scales and from a variety of convective forms. There is much predictive value in the identification of structures and surface features which are associated with the initiation and early evolution of bow echoes and related downbursts. It is important to note that the bow echo itself is the result of downburst activity (Fujita 1978; Lee et al. 1992) and therefore is an *indicator* that severe weather is occurring, rather than a *predictor.*

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Figure 1 illustrates the evolutionary paths favored by the 110 bow echoes studied. Three primary initial modes of convection were identified from which the bow echoes developed: (i) isolated (initially non-interacting) cells, or groups or storms; (ii) squall lines; and (iii) supercells. The resultant bow echoes formed over a wide variety of time scales, and were virtually all associated with severe surface winds. Though large hail was not common with these bows, some of those which evolved from supercells exhibited the dangerous combination of both severe winds *and* large hail. The primary evolutionary paths are described below.

4.1 *Isolated, or Groups of Cells - Bow Echo Evolution* —

Forty-seven of the observed bow echoes evolved from isolated cells, or groups of cells. These initial groups were typically composed of 4-10 unorganized members. The deviant motion of one or more of the cells would initiate mergers, from which the bow echo would form. A brief convective line might form prior to the bow initiation, but is treated here as a transitional feature (not a discrete initial mode) if the line persisted for less than 20 minutes. A typical example of this type of evolution is shown in Figure 2a. In this case, a storm moving rapidly to the northeast (furthest south in the figure) merged with a group of slower, eastward-moving cells. The bow echo which resulted produced severe winds for more than two hours. Interestingly, the majority (70%) of bow echoes observed to evolve from isolated or groups of storms occurred immediately after some type of convective merger. As was the case in this example, bow echoes which form concomitant with storm mergers can develop very quickly (5-10 minutes). The resulting bow echo most frequently moved in the direction (and close to the speed) of the fastest (and often the strongest) cell.

Occasionally, a small scale bow echo (CBE) will develop from an isolated cell without any apparent external interaction, perhaps developing dynamically as described in Lee et al. (1992). CBEs which form in this way (shown by the lower 'Groups of Cells' evolutionary path) typically are short lived, often dissipating within an hour of initiation. As a result of the small spatial and temporal scale of CBEs along this evolutionary path, severe winds are not frequently measured with their occurrence, and their identification can be quite difficult.

In just over half of the total cases observed in this initial mode, the bow echo formed near, and moved

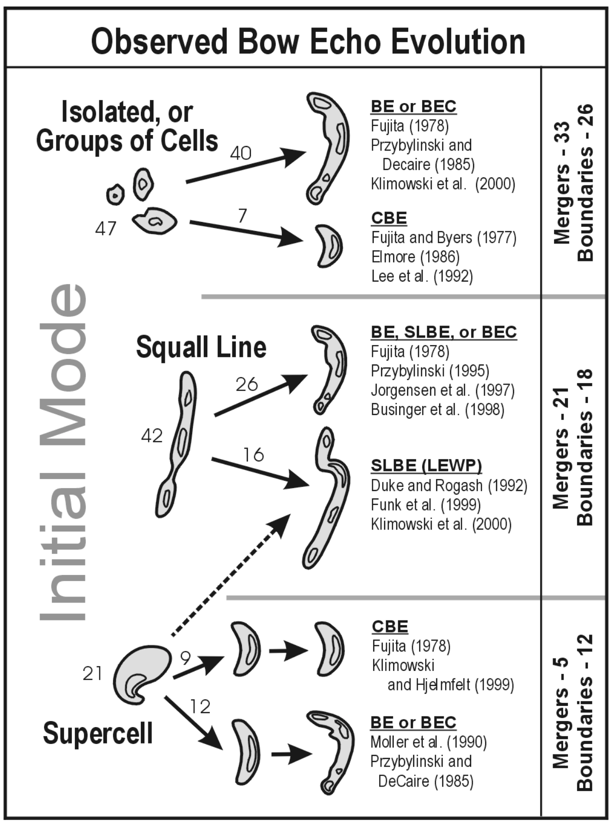

Figure 1. *Illustration of the primary evolutionary pathways for bow echoes observed in this study. The number of cases following each path is indicated above the arrows. References for representative bow echo cases are given. Number of bows preceded by merging storms, and / or which occurred in the immediate vicinity of external boundaries is given at right. See text for explanation of the acronyms BE, CBE, SLBE, and BEC.*

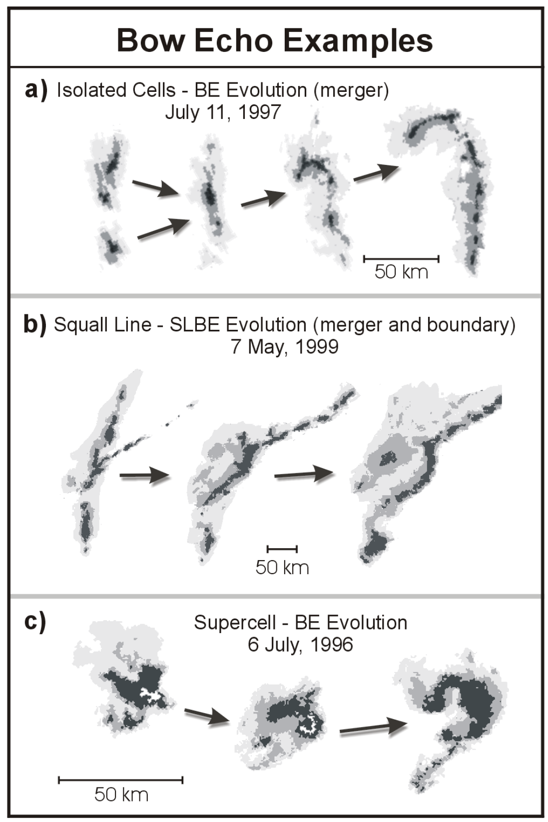

Figure 2. *Examples of observed bow echoes which developed from the three primary initial modes illustrated in Figure 1: a) isolated, or groups of cells initial mode; b) squall line initial mode; c) supercell initial mode. Note the different horizontal scales for each of the cases. Shading represents increasing radar reflectivity.*

roughly parallel to a pre-existing surface boundary. This boundary could be a stationary front, very slowly moving cold (Pacific) front, or outflow from previous convection. The existence of such a feature can also help to explain the frequency of mergers in these cases, as cells are frequently observed to be anchored to a boundary, while surrounding storms exhibit significant motion.

Bows which developed from isolated cells or groups of cells generally formed in environments similar to the 'warm season' type of bow echo synoptic pattern as identified in Johns (1993), with the organization of the storms associated with the passage of weak short wave troughs moving through the mean flow. Preliminary research indicates that the formation of these bow echoes is very dependant on the vertical wind shear at the lowest levels (0-3 km), with most severe bow echoes developing with greater than 13 m s^{-1} of total wind shear in this layer. Isolated downbursts and short-lived bows tend to dominate in environments with less shear.

4.2 *Squall line - Bow Echo Evolution*

Of the bow echoes observed, 42 evolved from pre-existing squall lines, or linearly-oriented storms which shared a common gust front or leading edge. The bows of this type either evolved into a moderate-to-large solitary bow echo (the top squall line evolution path in Figure 1), or become a part of a larger-scale linear convective structure, such as a LEWP (Nolen 1959). Evolutionary paths for each of these types are shown in Figure 1.

An example of squall line - bow evolution is shown in Figure 2b, and illustrates several of the features frequently observed in this mode of bow echo evolution. In this illustration, a broken line of convection oriented north-south (and moving eastward) intersected a quasi-stationary boundary, made visible by weak cells developing along, and anchored to it. The bow echo formed south of this boundary as the squall line merged into these slow moving, or stationary cells. Similar behavior has been observed in several damaging bow echoes studied over the Mid-Mississippi Valley (Przybylinski et al. 2000).

Some bow echoes were also observed to form as a result of a more gradual transition from a squall line (without any external factors), similar to the numerical simulations of long-lived bow echoes by Weisman (1992). In the modeled scenario, the bow echo forms as an elevated rear inflow and bookend vortices strengthen within a highly unstable and sheared atmospheric regime. In this type of evolution, bow echoes develop two to four hours into the lifetime of the convective system. Observations demonstrate that pre-existing boundaries (as described above) or cells merging into the line can significantly accelerate the production of bow echoes within squall lines, or can act as the catalyst which aids in the transition of the storm into a damaging wind-producing event.

Over the Northern High Plains, the bows which evolve from squall lines typically form within the 'warm seaon' type of synoptic environment (Johns 1993). Across the Midwest and eastern part of the United States these storms frequently form within the 'dynamic' synoptic pattern, associated with progressive surface fronts, occasionally forming 'serial' derecho-type events (Johns and Hirt 1987).

4.3 *Supercell - Bow Echo Evolution*

The evolution of bow echoes from supercells was first elucidated in the high precipitation (HP) supercell conceptual models of Moller et al. (1990), and has been documented by several others (Przybylinski et al. 1993; Klimowski et al. 1998). As was noted in Moller et al. (1990), this evolution is quite common, and indeed, the present research supports this. Twenty-one cases of supercell to bow echo evolution were identified, and in most cases, the parent supercell was classified as an HP. In a few cases, rotation of the suspected supercell could not be verified with Doppler 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 2c 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 bow echo which occurs as a result of mergers, the HP to BE transition is typically a more gradual (predictable) transition. Most frequently, the parent supercells are already producing severe winds prior to the production of the bow echo, and the evolution to the bow echo state may not necessarily indicate an intensification of the winds (Klimowski et al. 1998). Bow echoes of this evolutionary mode were observed to be isolated, imbedded within squall lines, or as a part of BECs, and showed some preference for developing and moving along surface boundaries.

In 9 out of the 21 observed cases of supercell to bow echo evolution, the resultant bow persisted as a quasi-steady, small-scale (<30 km), and very intense bowing structure. Unlike the other types of bow echoes investigated here, these bows were associated with both severe winds *and* very large hail. 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. A separate evolutionary path is shown for this type of event in Figure 1, and are referred here as CBEs because of their characteristic and distinct small-scale steady-state appearance. An example of this type of storm is shown in Fujita (1978). These bows do not typically demonstrate the HP to bow echo evolution as characterized by Moller et al. (1990).

5. *On the Influence of Storm Mergers and External Boundaries*

A striking feature of most of the bow echoes observed was that their formation was preceded by the merging of convective cells very near (in time and space) the point of initiation of the bow. Almost 70% of the bow echoes that initiated from isolated or groups cells were preceded by a visible merger. Nearly 50% of bows evolving from squall lines also had merging cells identified prior to bow development. It is important to note that bow echoes which develop in association with cell mergers can form very quickly, even on the order of minutes. The merging of storms appears to accelerate the processes responsible for bow echo formation.

Similar to the observations of Johns (1992) and Johns and Hirt (1987), the surface meteorological data associated with the observed bow echoes herein illustrate that their formation was closely associated with external surface boundaries. The term ‘external’ is used here to describe fronts or thunderstorm outflow not associated with the development of the initial mode, but with the initiation and motion of the bow echo. Most frequently these external boundaries took the form of east-west oriented stationary fronts, though over the Northern High Plains, slow-moving Pacific fronts often served as the focus for clusters of cells or squall lines to evolve into bow echoes. An important factor in this association with surface boundaries appears to be the presence of quasi-stationary cells anchored to them, which may act as the focus of storm mergers. Fifty-one percent of the bow echoes identified were initiated near (within 50 km of) a surface boundary, and in most cases, the bow moved roughly parallel to it.

6. SUMMARY AND CONCLUSIONS

The characteristic evolution of 110 bow echoes have been documented and characterized through the analysis of radar and surface meteorological data. It was found that bow echoes develop from three primary initial modes: isolated, or groups of cells, squall lines, and supercells. Most frequently, bow echoes were observed to develop from unorganized groups of storms, with little prior linear organization. Severe winds were associated with the great majority of bows observed.

The initiation and early evolution of bow echoes were found to be very closely tied to the occurrence of storm mergers and the position of external surface boundaries. Bow echoes were often observed to rapidly develop soon after storm mergers if the ambient environment was conducive for the development of downbursts and severe outflow-dominated storms. Bow echoes are an indicator of severe winds, and not a predictor. As such, the purpose of this paper was to identify observable radar features associated with the initiation of bow echoes, so that their formation could be anticipated.

Ongoing and future research will further utilize the surface, upper-air, and model data collected for each of the 110 cases studied here in an attempt to determine the threshold parameters which could be used by forecasters to determine the future development and severity of bow echoes and related severe wind-producing convective events.

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