NOTES AND CORRESPONDENCE

Meteorological Conditions Associated with Bow Echo Development in Convective Storms

ROBERT H. JOHNS

National Severe Storms Forecast Center, Kansas City, Missouri

5 October 1992 and 27 January 1993

ABSTRACT

Most observational and numerical modeling investigations into the meteorological factors affecting bow echo development in the United States have concerned long-lived events occurring during the late spring and summer. As a result, the meteorological patterns and parameter values (conceptual models) typically associated with bow echo development are biased toward the larger-scale warm season events. This note discusses the spectrum of meteorological conditions observed with bow echo development and extends the classification of associated meteorological patterns to cool season cases.

1. Introduction

In the late 1970s, the bow echo (Fujita 1978) was identified as a type of convective storm structure (as observed in radar reflectivity data) associated with intense damaging winds or downbursts (Fig. 1) (Fujita and Caracena 1977). Subsequent observations suggest that bow echoes vary considerably in scale (from less than 15 km to more than 150 km in length) and may be associated with larger-scale convective systems [e.g., see Fig. 8 in Johns and Doswell (1992)]. Further, it appears that bow echo–induced downbursts account for a large majority of the casualties and damage resulting from convectively induced nontornadic winds in the United States (Johns and Hirt 1987).

Bow echo development can be related to a variety of meteorological conditions. Johns and Hirt (1987) observed that vigorous bow echo development associated with widespread damaging winds (derechos) can occur either with strong, migrating low pressure systems or with rather stagnant weather patterns exhibiting relatively weak synoptic-scale features. In the United States, bow echo events associated with the former pattern (hereafter known as the "dynamic" pattern) have been observed in all seasons, while events associated with the latter pattern (hereafter known as the "warm season" pattern) are almost entirely confined to late spring and summer. Since bow echo activity occurring in the weaker weather regimes is particularly difficult to forecast, most observational studies (e.g., Johns and Hirt 1987; Johns et al. 1990) have focused primarily on warm season pattern cases.[1] The purpose of this note is to briefly review what is known about the range of meteorological conditions associated with bow echo damaging winds and to discuss and contrast the two synoptic patterns described by Johns and Hirt (1987).

2. Warm season pattern

The warm season synoptic pattern is usually associated with "progressive" swaths of wind damage associated with either an isolated bow echo or a short squall line with multiple bow echoes (Johns and Hirt 1987). The bow echo(es) travel(s) along a quasi-stationary low-level thermal boundary oriented nearly parallel to the mean tropospheric flow (Fig. 2a). The mid- and upper-level flow is often westerly to northwesterly and may be anticyclonic (Fig. 3). Midlevel wind speeds are usually moderately strong for late spring and summer [averaging 18–21 m s^{-1} (35–40 kt) at 500 mb] [see Johns and Hirt (1987) and Johns et al. (1990) for other warm season pattern composite parameter values and characteristics].

The numerical modeling work of Rotunno et al. (1988) and Weisman et al. (1988) suggests that in typical warm season thermodynamic conditions, the strongest and most long-lived bow echo systems occur when there is moderate to strong vertical wind shear in the lowest 2.5 km above ground level (AGL) (ranging from 17.5 to 25 s^{-1}), with generally constant winds above (through the middle layers). Examination of the low- and midlevel conditions with a few warm season pattern cases indicates that these model results may have operational applications (Weisman 1990). Nu-

[1] Note that the Johns and Hirt (1987) dataset contains a few dynamic pattern cases. However, because the scope of the study was limited to the warmer months of the year (May–August), most of the cases necessarily fit the warm season pattern. Therefore, the checklist values they present do not apply when diagnosing the potential for dynamic pattern bow echo events.

Corresponding author address: Robert H. Johns, National Severe Storms Forecast Center, Room 1728 Federal Building, 601 E. 12th Street, Kansas City, MO 64106-2877.

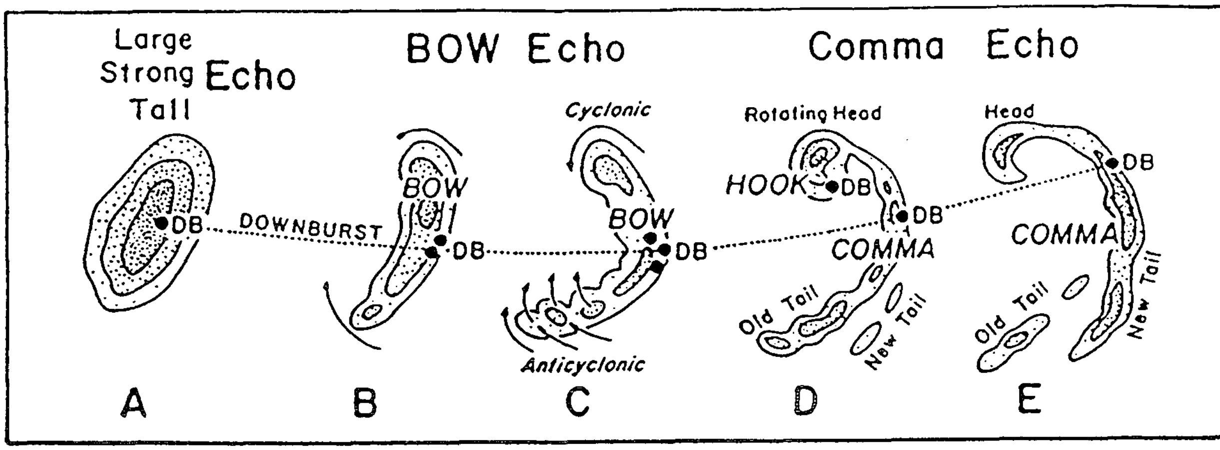

FIG. 1. Idealized morphology of an isolated bow echo associated with strong and extensive downbursts (after Fujita 1978).

merical simulations of a long-lived bow echo convective system by Schmidt et al. (1990) implies that the nature of the upper-level shear and static stability may also play a role in sustaining bow echo development. However, observational studies examining upper-tropospheric conditions associated with bow echo development are limited presently.

Midlevel relative humidities associated with the Johns and Hirt (1987) dataset are not extremely low. However, they are also rarely near saturation. Johns and Hirt (1987) found that average midlevel relative humidities (estimated by averaging 700 and 500 mb values) associated with 59 derecho-producing bow echo cases occurring during the months from May through August ranged from around 25% to over 80%.

The associated thunderstorm activity almost always is initiated in an area of low-level warm advection a few hours before bow echo formation commences. The air along the thermal boundary is usually very unstable, in part the result of very high values of low-level moisture in the convergence zone near the boundary. Johns and Hirt (1987) found that warm season cases associated with weak upper troughs almost always exhibit lifted index values [as defined by Galway (1956)] of −8 or less. Further, the long-lived warm season pattern cases studied by Johns et al. (1990) exhibited an av-

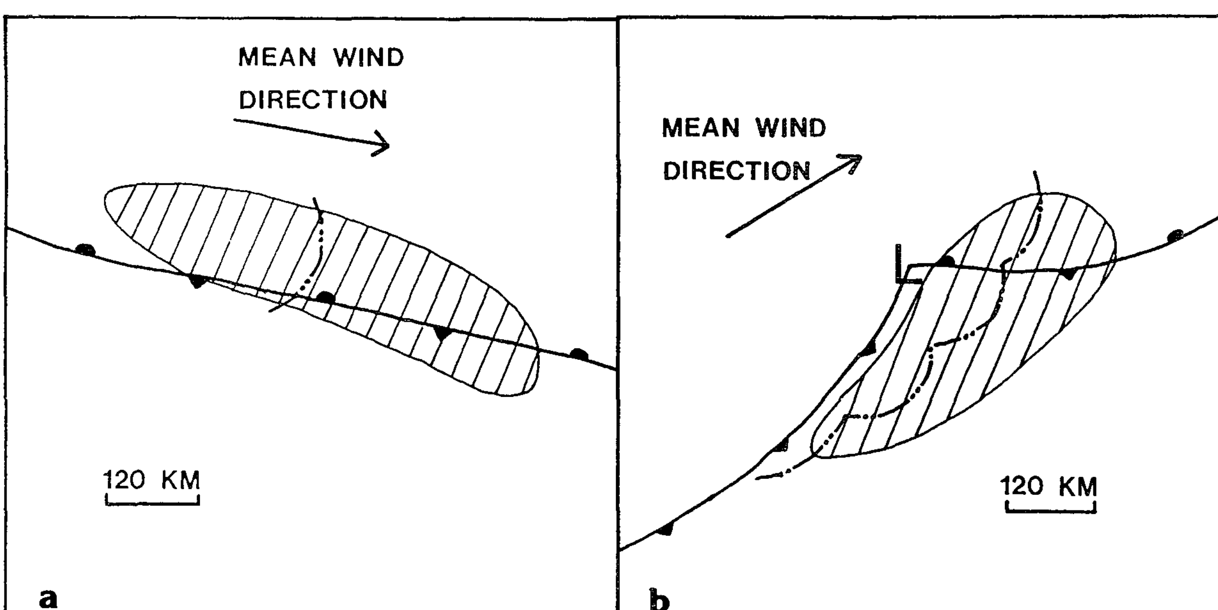

FIG. 2. (a) Schematic representation of features associated with a warm season synoptic pattern. Total area affected by widespread wind damage indicated by hatching. Convective complex comprised of one or more bow echoes indicated by squall line symbols. Frontal symbols are conventional. (b) As in (a) except for schematic representation of features associated with a dynamic synoptic pattern (after Johns and Hirt 1987).

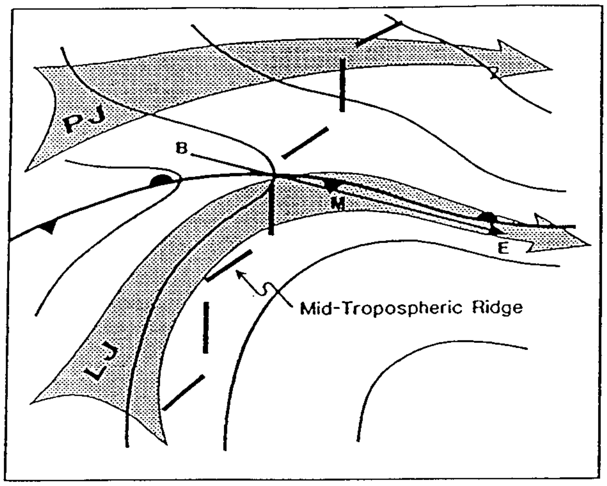

FIG. 3. Idealized sketch of a midlatitude warm season synoptic-scale situation especially favorable for development of long-lived progressive bow echo complexes producing extensive swaths of damaging winds. The line B–M–E represents the track of the bow echo complex. Thin lines denote sea level isobars in the vicinity of a quasi-stationary frontal boundary. Broad arrows represent low-level jet stream (LJ) and polar jet (PJ) in the upper troposphere (after Johns et al. 1990).

erage maximum convective available potential energy (CAPE) value of 4500 J kg^{-1}. The strong instability appears to play a part in maintenance of bow echoes in conditions of weak forcing (Weisman 1990).

In many cases, moisture values in the convergence zone are higher than in the surrounding region. Recent observations (e.g., Segal et al. 1989) and numerical simulations (Chang and Wetzel 1991) suggest that this "pooling" of higher moisture values in the convergence zone is greatly affected by transpiration from vegetation (e.g., trees and fields of corn) and evaporation from moist ground. This may be a primary reason that pooling of moisture along low-level convergence boundaries appears to be most pronounced in late spring and summer (the primary growing season), with surface dewpoints occasionally reaching or exceeding 27°C (80°F) (e.g., see Fig. 4). Further, in years when drought affects the corn belt (which is coincident with the axis of maximum warm season bow echo activity), moisture pooling along any convergence boundaries that do develop in the region appears to be diminished. This was particularly noticeable to Severe Local Storms Unit (SELS) forecasters during the summer of 1988, which was very dry across much of the corn belt.

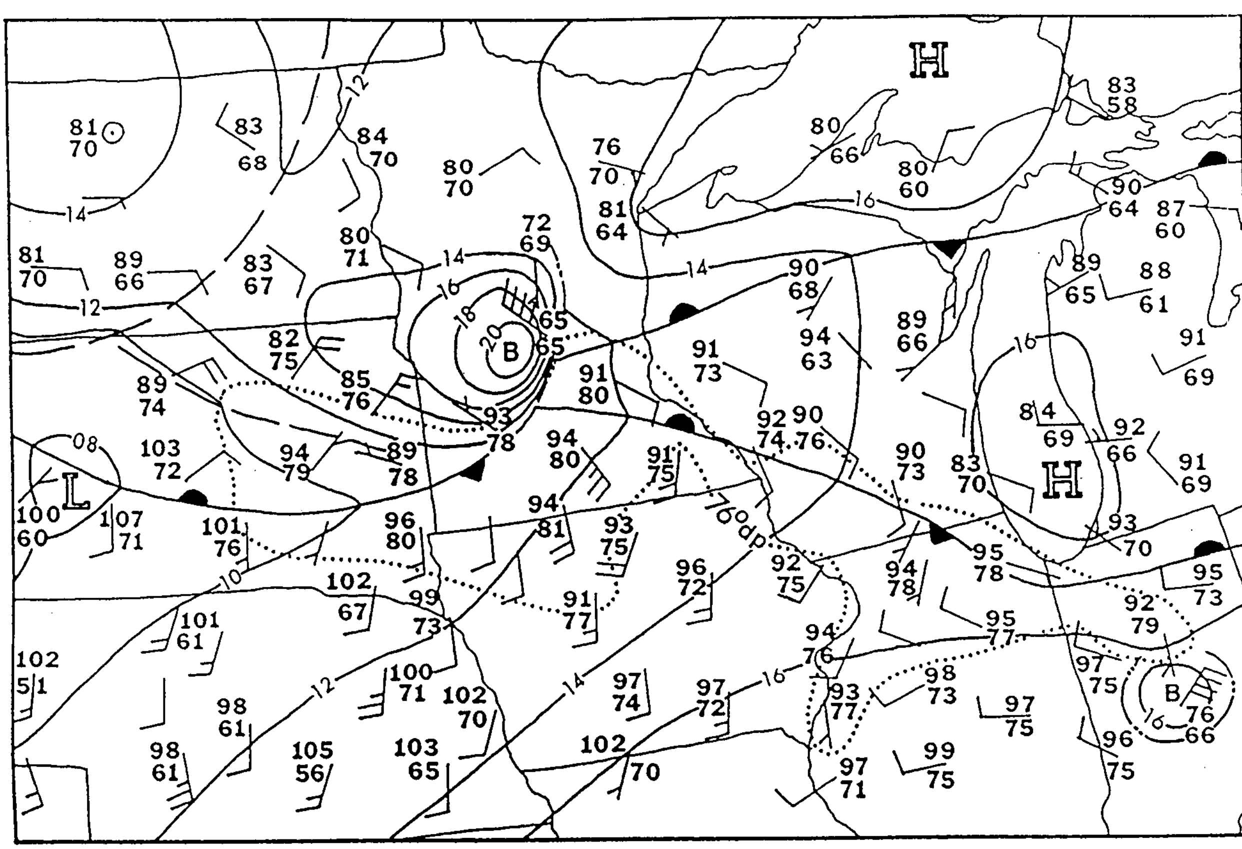

FIG. 4. Surface analysis for 2100 UTC 19 July 1983. A long-lived bow echo convective system over central Minnesota is producing a derecho. Temperatures (top) and dewpoints (bottom) are in degrees Fahrenheit (degrees Celsius × 1.8 + 32). Isodrosotherm for 76°F (24.4°C) (dotted) encloses an area of pooled low-level moisture. Wind barbs (gusts are plotted where available) are 5 m s^{-1} (10 kt) for a full barb and 2.5 m s^{-1} for a half barb. Isobars (solid) are in millibars with the first two numerals (10) omitted. Here "B" denotes a mesoscale high pressure center (after Johns and Hirt 1985).

Tornadoes occasionally are associated with bow echoes occurring in the warm season pattern. Many of these may be shear induced rather than associated with a mesocyclone (e.g., Forbes and Wakimoto 1983). However, in several documented cases, tornado development appears to be associated with mesocyclones near either end of the bow echo (e.g., Moller et al. 1990; Smith 1990), and these tornadoes can reach strong (F2–F3, Fujita 1971) intensity.

3. Dynamic pattern

The other basic synoptic pattern associated with bow echo development is the "dynamic" pattern. This pattern is typically associated with a strong, migrating low pressure system and has many characteristics of the "classic" Great Plains tornado outbreak pattern (Fig. 5a). However, operational experience and case studies (e.g., Duke and Rogash 1992) suggest that in the dynamic pattern the low-level jet is usually more parallel to the mid- and upper-level jets (Fig. 5b). Although this pattern may occur at any time of year, SELS forecasters have noticed that in the cooler months of the year it occurs most often in the lower Mississippi valley and southeastern states, with the maximum frequency of occurrence shifting northward to the north-central and northeastern states during the summer.

Usually, an extensive squall line develops along or ahead of a cold front, and bow echo activity is embedded within this line (Fig. 2b). Typically, a series of line echo wave patterns (LEWPs, Nolen 1959) move along the line as it progresses. If the downburst activity is sufficiently widespread, a serial derecho may result (Johns and Hirt 1987). When the parameters that promote mesocyclone-induced tornadoes are sufficiently strong (see Weisman 1990; Johns and Doswell 1992), tornadoes may accompany the damaging winds in a dynamic pattern. These tornadoes sometimes attain strong or violent intensity (F2–F5, Fujita 1971) and may comprise a tornado outbreak (Galway 1977). The cases of 10 March 1986 (Przybylinski 1988) and 3 July 1983 (see *STORM DATA* and Johns and Hirt 1987) are examples of dynamic pattern events that resulted in both a serial derecho and a tornado outbreak.

Operational experience suggests that tornadoes occurring with the dynamic pattern are often associated with a portion of the bow echo structure [e.g., see Figs. 15a and 15c in Johns and Doswell (1992) and Fig. 5 in Smith and Partacz (1985)]. Tornadoes may also be associated with an isolated supercell that is in the vicinity of or is merging with the bow echo [Przybylinski and DeCaire's (1985) type II convective scenario; see also Fig. 3 in Goodman and Knupp (1990)].

Generally, the environmental midlevel winds associated with the dynamic synoptic pattern are stronger than those with the warm season pattern, particularly from late fall into early spring. In some cool season cases, 500-mb wind speeds exceeding 38.6 m s^{-1} (75 kt) have been observed. For example, the convective windstorm affecting portions of the Ohio valley on 13 January 1976 and a similar event affecting portions of the middle Atlantic region on 21 March 1976 were accompanied by 500-mb wind speeds of 43.8 m s^{-1} (85 kt) and 41.2 m s^{-1} (80 kt), respectively, in the general area where damaging surface winds occurred (Johns 1982). This suggests that transfer of horizontal momentum by downdrafts may be an important con-

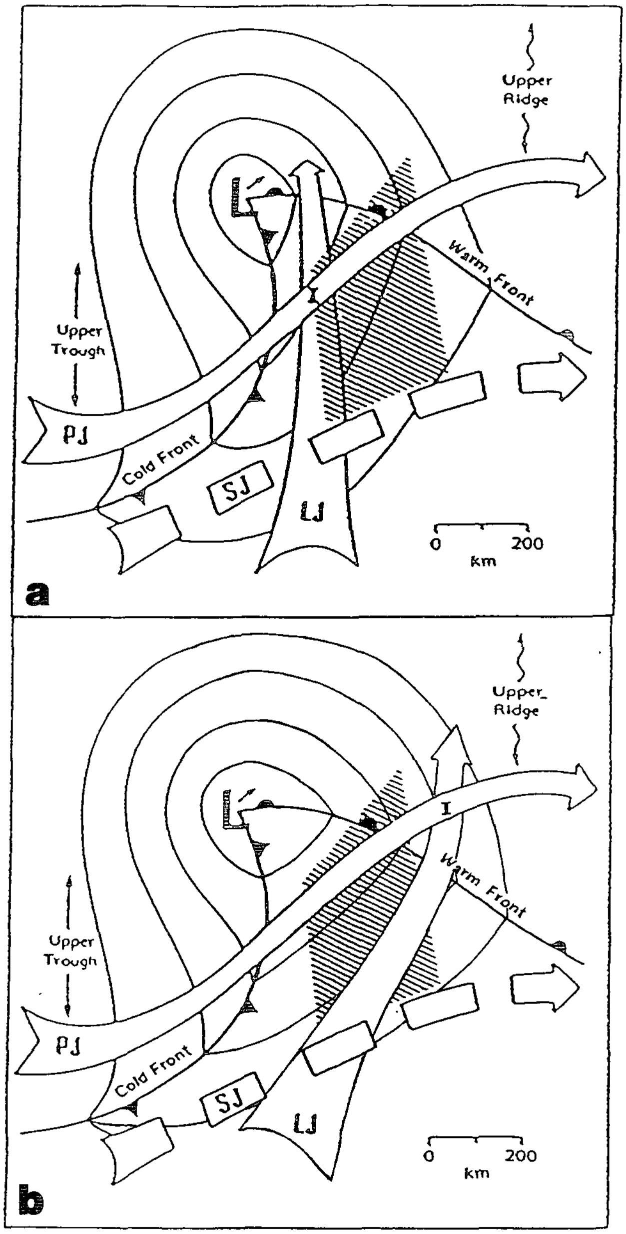

FIG. 5. (a) Idealized sketch of a midlatitude synoptic-scale situation favorable for development of severe thunderstorms, including supercell-induced tornadoes. Thin lines denote sea level isobars around a low pressure center with cold and warm fronts. Broad arrows represent low-level jet (LJ), upper-level polar jet (PJ), and upper-level subtropical jet (SJ) (after Barnes and Newton 1986). (b) As in (a) except for situations favorable for the development of squall lines with extensive bow echo–induced damaging winds.

tributor to outflow wind speeds in the cooler months of the year.

Instability can vary widely with the dynamic pattern, ranging from extremely unstable in the late spring and summer to marginally unstable in the cooler months. The case of 10 March 1986 (Przybylinski 1988) illustrates a situation in which bow echoes produced multiple downbursts in air that was only marginally unstable [Showalter (1953) index of −1 in the initiation region]. Further, the cool season derecho cases cited by Johns (1982) also occurred in air that exhibited marginal instability (Showalter indexes of 2.6 and −0.9 for the January and March 1976 cases, respectively). SELS forecasters have noted that reflectivity values associated with bow echoes in weak instability situations are often relatively low [video integrator and processor (VIP) value levels of 4 or less] and appear to have little correlation with the strength of the outflow winds. Therefore, methods of assessing severe weather potential based on reflectivity (e.g., Lemon 1980; Devore 1983) *are not likely to be very effective* for anticipating bow echo–induced damaging winds in weak instability situations.

Although the thermodynamic profiles associated with the dynamic pattern vary considerably, a common feature is a layer of dry, potentially cold air in the downdraft entrainment region (between 3–7 km AGL). Soundings in the warm sector ahead of the squall line may or may not indicate any dry air in the downdraft entrainment layer. However, in those cases where no antecedent dry air is indicated, a dry air intrusion typically impinges on the squall line from the upstream side. The forecaster may be able to anticipate the development of a dry air intrusion by examining upstream soundings, monitoring changes in satellite-observed water vapor imagery (Petersen et al. 1984; Beckman 1987), and noting changes in the National Meteorological Center (NMC) model-forecast mean relative humidity gradient (Weiss 1988).

4. Discussion

Observational studies of environmental conditions associated with the development and maintenance of bow echo–induced damaging winds have focused on parameters related to storm outflow and updraft strengths. Specifically, wind speeds and relative humidity values in the midlevels (related to outflow strength) and instability (related to updraft strength) have been examined. The results indicate that these parameters exhibit a wide range of values when considering all bow echo situations in which damaging winds are reported. Further, combinations of wind speeds in the midlevels and instability tend to vary with the season and the synoptic situation. For example, when very strong winds are present in the midlevels, bow echo development has been observed in air that is only marginally unstable. Conversely, in conditions of extreme instability, bow echo development has been observed in areas where the midlevel wind speeds are relatively weak [e.g., 25 to 35 kt (13 to 18 m s^{-1}) at 500 mb; see Johns and Hirt (1987)]. Bow echo events associated with the very strong wind–marginal instability combination typically occur with strong, rapidly moving low pressure systems ("dynamic" synoptic pattern) in the cooler months of the year. On the other hand, events associated with the relatively weak wind–extreme instability combination typically occur along a quasi-stationary thermal boundary in rather stagnant weather regimes ("warm season" synoptic pattern) in the late spring or summer. Of course, many bow echo wind events are associated with wind–instability combinations that are between the extremes, and some of these events are associated with synoptic patterns that do not quite match either prototypical pattern. For example, it is not unusual to have a situation that is basically a warm season pattern but exhibits an upper-flow synoptic pattern that is weakly cyclonic and includes an associated well-defined but low-amplitude short-wave trough. Such cases may also exhibit less instability along the quasi-stationary boundary than is suggested in the prototypical warm season model.

Numerical simulations of bow echo development in "warm season pattern" conditions (e.g., Weisman et al. 1988; Schmidt et al. 1990) suggest that the vertical distribution of wind shear is an important factor in bow echo development and maintenance. In particular, the simulations of Rotunno et al. (1988) and Weisman et al. (1988) suggest that optimum wind conditions for bow echo maintenance consist of strong vertical wind shear in the lowest 2.5 km AGL with generally constant winds above, through the midlevels. Although observational studies indicate that moderate to strong environmental wind shear through the midlevels is associated with development and maintenance of bow echo activity (Johns and Doswell 1992), there has not been a thorough investigation into the nature of hodographs associated with bow echo situations. Given the results of the foregoing numerical simulations, it appears that a comprehensive investigation of the hodographs associated with bow echo situations could lead to improved forecasting techniques.

Numerical simulations of bow echoes in "warm season" environments suggest that the very unstable air typical of these situations facilitates the continued regeneration of convection along the gust front, helping to maintain the bow echo system. It is not clear how bow echoes are maintained in those "dynamic" pattern situations where instability is weak. Additional observational and numerical modeling research concerning low-instability bow echo situations may help identify parameters important for bow echo development and maintenance in such conditions.

Finally, it is important to note that SELS forecasters have occasionally observed accelerating, rapidly moving bow echoes [21 m s^{-1} (40 kt) or greater] that apparently do not produce any damaging winds at the surface. In some cases the absence of strong surface winds appears to be the result of the bow echo passing over a very stable layer (such as cold, wet air beneath a strong frontal inversion) near the surface. In other cases the reason is not clear. Burgess and Smull (1990) have shown that Doppler radar can be a valuable tool for observing the wind structure associated with bow echo systems. The widespread availability of WSR-88D Doppler radar systems in the near future should allow observational researchers to learn more about the wind structure associated with bow echoes, including those that do not produce damaging winds at the surface.

Acknowledgments. The author especially appreciates the many helpful suggestions offered by Steve Weiss of NSSFC. The author also appreciates the suggestions and technical assistance of John Monteverdi of San Francisco State University, Fred Ostby and Bill Sammler of NSSFC, and Don Johns of Salt Lake City, Utah. The bow echo-induced damaging winds experienced during the afternoon of 11 August 1992 on Long Island, New York, inspired the completion of this manuscript.

REFERENCES

Barnes, S. L., and C. W. Newton, 1986: Thunderstorms in the synoptic setting. *Thunderstorm Morphology and Dynamics.* 2d ed., E. Kessler, Ed., 75–112.

Beckman, S. K., 1987: Operational use of water vapor imagery. NOAA Tech. Memo. NWS CR-87, 15 pp. [Available from the National Weather Service Central Region Office, 601 E. 12th St., Kansas City, MO, 64106.]

Burgess, D. W., and B. F. Smull, 1990: Doppler radar observations of a bow echo associated with a long-track severe windstorm. Preprints, *16th Conf. Severe Local Storms,* Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 203–208.

Chang, J., and P. J. Wetzel, 1991: Effects of spatial variations of soil moisture and vegetation on the evolution of a prestorm environment: A numerical case study. *Mon. Wea. Rev.,* **119,** 1368–1390.

Devore, D. R., 1983: The operational use of digital radar data. Preprints, *13th Conf. Severe Local Storms,* Tulsa, OK, Amer. Meteor. Soc., 21–24.

Duke, J. D., and J. A. Rogash, 1992: Multi-scale review of the development and early evolution of the 9 April 1991 derecho. *Wea. Forecasting,* **7,** 623–635.

Forbes, G. S., and R. M. Wakimoto, 1983: A concentrated outbreak of tornadoes, downbursts, and microbursts, and implications regarding vortex classification. *Mon. Wea. Rev.,* **111,** 220–235.

Fujita, T. T., 1971: Proposed characterization of tornadoes and hurricanes by area and intensity. SMRP Research Paper No. 91, Department of Geophysical Sciences, University of Chicago, 42 pp. [Available from the Department of Geophysical Sciences, University of Chicago, Chicago, IL 60637].

——, 1978: Manual of downburst identification for project NIMROD. Satellite and Mesometeorology Research Paper No. 156, Department of Geophysical Sciences, University of Chicago, 104 pp. [Available from the Department of Geophysical Sciences, University of Chicago, Chicago, IL 60637].

——, and F. Caracena, 1977: An analysis of three weather-related aircraft accidents. *Bull. Amer. Meteor. Soc.,* **58,** 1164–1181.

Galway, J. G., 1956: The lifted index as a predictor of latent instability. *Bull. Amer. Meteor. Soc.,* **37,** 528–529.

——, 1977: Some climatological aspects of tornado outbreaks. *Mon. Wea. Rev.,* **105,** 477–484.

Goodman, S. J., and K. R. Knupp, 1990: Tornadogenesis via squall line and supercell interaction revisited: The November 1989 Huntsville tornado. Preprints, *16th Conf. Severe Local Storms,* Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 566–571.

Johns, R. H., 1982: Severe weather occurring in areas of low surface dew points. Preprints, *12th Conf. Severe Local Storms,* San Antonio, TX, Amer. Meteor. Soc., 143–146.

——, and W. D. Hirt, 1985: The derecho of July 19–20 July 1983 . . . a case study. *Natl. Wea. Digest,* **10**(3), 17–32.

——, and ——, 1987: Derechos: widespread convectively induced windstorms. *Wea. Forecasting,* **2,** 32–49.

——, and C. A. Doswell III, 1992: Severe local storms forecasting. *Wea. Forecasting,* **7,** 588–612.

——, K. W. Howard, and R. A. Maddox, 1990: Conditions associated with long-lived derechos—An examination of the large scale environment. Preprints, *16th Conf. Severe Local Storms,* Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 408–412.

Lemon, L. R., 1980: New severe thunderstorm radar identification techniques and warning criteria. NOAA Tech. Memo. NWS NSSFC-3, 60 pp. [Available from National Severe Storms Forecast Center, 601 E. 12th St., Kansas City, MO, 64106.]

Moller, A. R., C. A. Doswell III, and R. Przybylinski, 1990: High precipitation supercells: A conceptual model and documentation. Preprints, *16th Conf. Severe Local Storms,* Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 52–57.

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

Petersen, R. A., L. W. Uccellini, A. Mostek, and D. A. Keyser, 1984: Delineating mid- and low-level water vapor patterns in preconvective environments using VAS moisture channels. *Mon. Wea. Rev.,* **112,** 2178–2198.

Przybylinski, R. W., 1988: Radar signatures associated with the 10 March 1986 tornado outbreak over central Indiana. Preprints, *15th Conf. Severe Local Storms,* Baltimore, MD, Amer. Meteor. Soc., 253–256.

——, and D. M. DeCaire, 1985: Radar signatures associated with the derecho, a type of mesoscale convective system. Preprints, *14th Conf. Severe Local Storms,* Indianapolis, IN, Amer. Meteor. Soc., 228–231.

Rotunno, R., J. B. Klemp, and M. L. Weisman, 1988: A theory for strong, long-lived squall lines. *J. Atmos. Sci.,* **45,** 463–485.

Schmidt, J. M., C. J. Tremback, and W. R. Cotton, 1990: Numerical simulations of a derecho event: synoptic and mesoscale components. Preprints, *16th Conf. Severe Local Storms,* Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 422–427.

Segal, M., W. E. Schreiber, G. Kallos, J. R. Garratt, A. Rodi, J. Weaver, and R. A. Pielke, 1989: The impact of crop areas in northeast Colorado on midsummer mesoscale thermal circulations. *Mon. Wea. Rev.,* **117,** 809–825.

Showalter, A. K., 1953: A stability index for thunderstorm forecasting. *Bull. Amer. Meteor. Soc.,* **34,** 250–252.

Smith, B. E., 1990: Mesoscale structure of a derecho-producing convective system: the southern Great Plains storms of May 4, 1989. Preprints, *16th Conf. Severe Local Storms,* Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 455–460.

——, and J. W. Partacz, 1985: Bow echo induced tornado at Minneapolis on 26 April 1984. Preprints, *14th Conf. Severe Local Storms,* Indianapolis, IN, Amer. Meteor. Soc., 81–84.

Weisman, M. L., 1990: The genesis of bow echoes: A rear-inflow induced meso-convective structure. Cooperative thesis No. 125, The Pennsylvania State University and National Center for Atmospheric Research. NCAR/CT-125, 149 pp. [Available from the Department of Meteorology, The Pennsylvania State University, University Park, PA 16802].

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

Weiss, S. J., 1988: On the relationship between NGM mean relative humidity and the occurrence of severe local storms. Preprints, *15th Conf. Severe Local Storms,* Baltimore, MD, Amer. Meteor. Soc., J111–J114.