13.2 THE STRUCTURE OF A TORNADIC BOW ECHO IN IDAHO

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1. INTRODUCTION

A climatologically rare severe cold-frontal squall line occurred on 14 February 2000 in southern Idaho and northern Utah during the Intermountain Precipitation Experiment (IPEX, Schultz et al. 2002). This squall line was unusual in that five tornadoes were reported around Pocatello, ID, three of them F1 in strength with path lengths greater than 8 km. No February tornadoes have been previously reported in Idaho (Schultz et al. 2002).

The environment in which this squall line occurred can be characterized as one with very high 0-6 km shear (25 m/s) and relatively low Surface-Based Convective Available Potential Energy (SBCAPE ~ 500 J/kg) yielding a representative Bulk Richardson Number (BRN) less than 10. A BRN number this low suggests the instability is too low to support an updraft in shear of this magnitude (Weisman and Klemp, 1982). However, strong, upright convection developed along a line and managed to produce embedded supercell structures complete with Bounded Weak Echo Regions (BWERs) within 30 minutes of the first reported tornado. This squall line exhibited both trailing stratiform and leading stratiform characteristics as defined by Parker and Johnson (2000).

How this squall line managed to produce a structure with a leading and trailing stratiform region, an erect updraft feature with BWERs (Fig. 1) in the face of such weak instability and strong shear is one of the main questions to be answered in this study.

2. THE SQUALL LINE ORIGINS

The squall line developed in association with a strong Pacific cold front ahead an intense, mobile upper-tropospheric shortwave trough. Figure 2 shows the positions of the leading edge of the squall line from 2015 to 2315 UTC as determined by GOES-10 satellite and a radar mosaic from the Boise, ID, Elko, NV, Pocatello, ID and Salt Lake City, UT WSR-88Ds.

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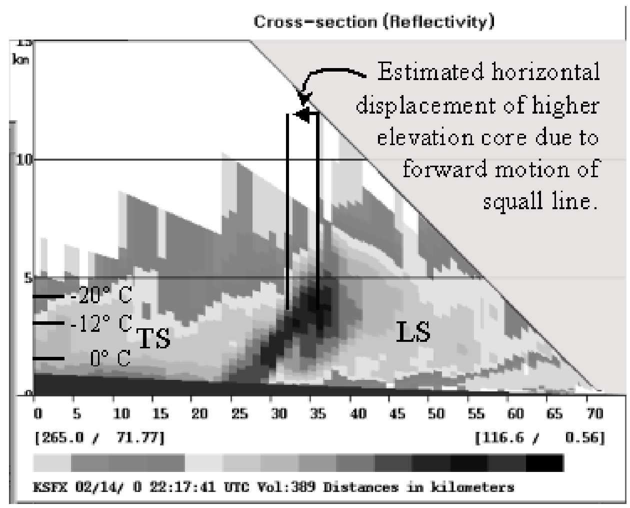

Figure 1. Reflectivity cross-section from the WSR-88D at Pocatello, ID to a point 265° 71.7 km from the radar. The labels TS and LS represent Trailing and Leading Stratiform precipitation regions respectively. The temperature levels were derived from the 12 UTC MM5 run valid for 21 UTC. The ordinate is height above the radar in kilometers.

Comparing these positions with surface observations and meteograms from several stations in southern Idaho (Cox et al. 2000) suggests that the leading edge of the squall line also marked the effective surface position of the pacific cold front. Most of the deep convective cloud resides behind the surface front at 2200 UTC, suggesting the squall line was of the trailing stratiform variety (Parker and Johnson 2000) where anvil material was mostly ejected rearward from a linear updraft source. However, during its early phase, convective cells were developing mostly behind the surface cold front in eastern Oregon southwestward into central Nevada. Special 18 UTC soundings at Boise and Elko and the 18 UTC RUC 2 analysis (not shown) indicated no SBCAPE ahead of the cold front suggesting that any CAPE (possibly elevated) was available only at or behind the front in a region of forced ascent. Between 18 and 22 UTC, the individual postfrontal convective cells gradually merged to form a continuous anvil sheet with broken precipitation. It is possible that the postfrontal convection helped to increase the already strong convergence along the cold front through the development of a cold pool and downward transfer of higher elevated westerly momentum.

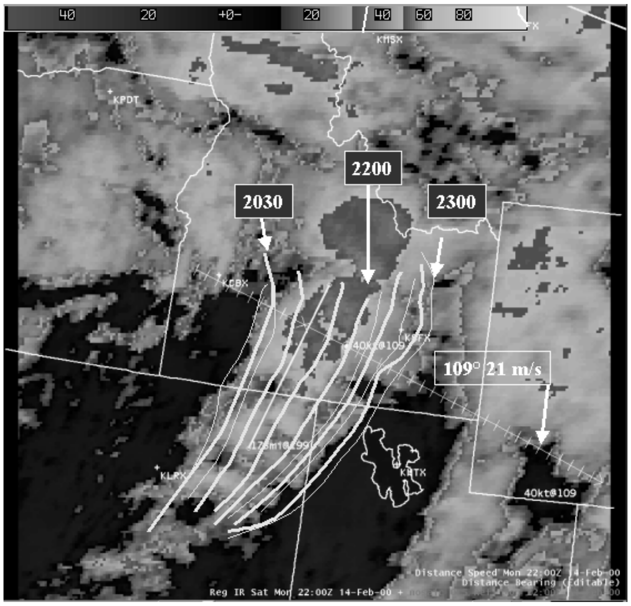

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Figure 2. A time series of squall- line leading edge positions from 2015 UTC to 2315 UTC February 14, 2000. The thick(thin) lines indicate positions at the top and 30 minutes (15 and 45 minutes) past the hour. The line with tickmarks represents the motion of the line toward 109° at 21 m/s. A GOES-10 2200 UTC 10.7um image provides the background.

By 21 UTC, the Elko, NV sounding, modified to represent the higher dewpoints found further north in Idaho, shows the development of at least 200 J/kg of CAPE and no convective inhibition (CIN) with a 100 mb mixed surface-based parcel (Fig 3.). A combination of strengthening low-level convergence and destabilization may have initiated occasional lines of strong updrafts along the cold front mainly east of Boise, ID and toward Pocatello, ID.

The normal development of a trailing stratiform (TS) described by Parker and Johnson (2000) was not observed here. Instead, what is viewed as the TS region of the squall line in Fig. 1 more likely had its origins in the original post-frontal convection which was then followed by the initiation of strong convective lines along the surface cold front position.

3. CAUSES OF THE UPRIGHT SQUALL LINE UPDRAFT

With an explanation of the precipitation trailing the line, this section provides a possible explanation as to how this updraft can maintain its erect posture in the face of extremely strong 0-6 km shear. In Fig. 1, the cross-section shows a forward-tilted core with a well defined BWER and a significant Leading Stratiform (LS) region. Note that the rapid motion of the squall line (26 m/s) leads to a spuriously forward tilt of the line with the upper regions of the reflectivity core offset up to 6 km relative to the reflectivity core in the lowest slice. Therefore the squall line updraft exhibits a less eastward tilt with height in reality.

An isolated cell fully utilizing the approximately 400 J/kg of SBCAPE and a 0-6 km shear of 29 m/s yields a BRN equal to 3. Even considering the shallow nature of this convection, the 0-3 km shear is still in excess of 25 m/s. Based on numerical experiments of isolated convection, Weisman and Klemp (1982) suggest the environmental shear is too strong to permit persistent updrafts. However the intense phase of this squall line developed rapidly starting at 2107 UTC and persisted for over two hours. Attempting to explain the upright nature of this squall line using indices based on isolated convection is insufficient in this case.

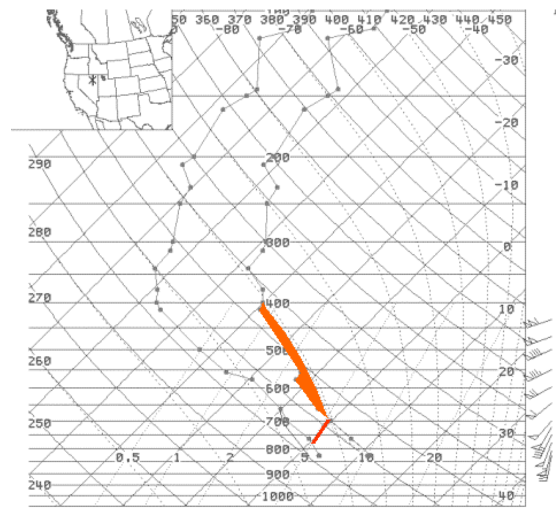

Figure 3. Elko, NV sounding for 2100 UTC, 14 February2000. The shaded area represents the positive area given a parcel ascending up the mixing ratio line marked by the red line.

The intense part of the squall line developed along the surface Pacific cold front. Perhaps the cold front in this case is creating an incentive to prevent the updrafts from shearing apart to the east. There are two possibilities for explaining the upright nature and longevity of the bow echo:

1. The local vorticity balance theory by Rotunno, Klemp and Weisman (1988) known as RKW88,
2. And the deep tropospheric shear containing a steering layer theory discussed by Moncrieff and Liu (1999), referred to as ML99.

In examining 1., it is difficult to apply the RKW88 theory directly in this situation to anticipate the balanced nature of this line because the development of the cold pool circulation cannot be separated from the vertical wind profile associated with the post-cold frontal airmass. However, a velocity cross-section taken through the WSR-88D at Pocatello, ID (fig. 4) shows a 40 m/s elevated Rear-Inflow Jet structure peaking at 1km above Radar Level (ARL). This value is almost 20 m/s above the background environmental post-cold frontal flow at this altitude. Weisman (1993) reported that the most severe numerically simulated bow echoes were accompanied by elevated RIJs. The depth of this elevated RIJ at the leading edge of the outflow/cold front is certainly significant enough to force a strong vertically oriented updraft through the lowest 2 km ARL. This layer contained nearly 25 m/s of the total 35-40 m/s of shear in the lowest 4 km. Therefore, during the mature stage of the bow, the updraft was forced to be vertically erect until 2 km AGL where the updraft was then exposed to only 15-20 m/s of shear throughout the rest of the convective layer. This may partially allow the convective updrafts to persist even in the presence of extreme shear in the prestorm environment.

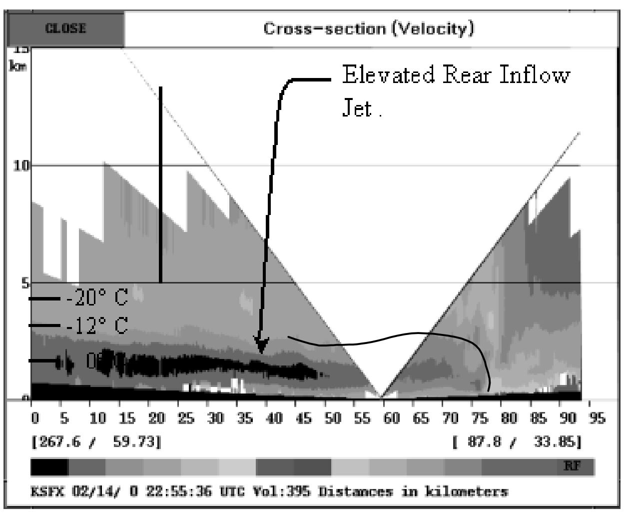

Figure 4. A velocity cross-section from the WSR-88D in Pocatello, ID at 2255 UTC. All velocities to the right(left) of the radar are outbounds (inbounds). The dark shaded area left of the radar represents inbounds > 40 m/s. The thin black curve starting on the right side encompasses the outflow boundary where radial winds are stronger than that of the pre-storm environment.

As part of the second explanation, the cold frontal motion may have allowed incipient surface-based convection to remain anchored to the boundary achieving a long residence time and allowing the cell to survive in the presence of strong shear. Wilson and Megenhardt (1997), WM97, found that any boundary whose boundary-relative storm motion, U_b, was within ±5 m/s tended to be associated with the most convective coverage. In addition, ML99 theorized that intense long-lived squall lines tended to be those propagating downshear in deep tropospheric shear containing the convective steering layer flow, and whose boundary-relative steering-layer flow was minimal. The updrafts of these types of squall lines were supported by the lifting along the boundary while the deep tropospheric shear provided a mechanism for allowing a deep overturning circulation to commence with lifting over the boundary and downshear subsidence.

To refute the theory forwarded by ML99, the measured U_b would have to be large prior to the intense bow echo phase. In addition, there should be no large (>15 m/s) component of the deep (2-6 km) tropospheric shear vector orthogonal and directed ahead of the cold front.

The mean frontal motion shown in figure 2 was estimated to be from 299° at 21 m/s from 20-22 UTC. The frontal motion direction is defined to be the motion from which the front has traveled and perpendicular to its orientation. An average of four radar-identified cells was computed using the Storm Cell Identification and Tracking algorithm (SCIT; Johnson et al. 1998) between 2142 and 2200 UTC from the KSFX WSR-88D. Given an average storm motion of 248° at 30 m/s, the resulting boundary-relative storm motion, easily visualized in Fig. 5, was 2 m/s faster than the frontal motion. Note that in Fig. 5, the boundary-relative motion can be visualized by taking the shortest distance from any motion observation (e.g., wind, storm motion) to the frontal axis. Any motion observation to the right of the frontal axis (dark diagonal line) is positive or faster than the frontal motion.

Deep tropospheric shear is considered to start above the estimated 2 km AGL deep frontal boundary and end near 6 km AGL. The estimated horizontal wind shear from the Pocatello WSR-88D at 2 and 5 km averaged between 2200 and 2211 UTC was from 290° at 13 m/s. No radar-derived winds were available above 5 km AGL. However, the RUC2 analysis of 6 km winds at 21 UTC that the 2–6 km vertical wind shear was almost 20 m/s. Nearly the full component of the 2-6 km shear was directed normal to the frontal boundary.

Both U_b and the 2-6 km shear satisfy the theory presented by ML99. The cold front within this sheared environment possibly provided the background environment where an overturning circulation could be created containing the steering-layer flow.

4. SUMMARY

The intense tornadic squall line that was observed on 14 Feb 2000, in the Snake River Valley of Idaho, persisted in an environment where updrafts would normally have not survived given the weak CAPE and strong shear . In addition, this line exhibited characteristics of both a trailing stratiform and leading stratiform convective system. This case study attempted to answer how this squall line could acquire such a structure.

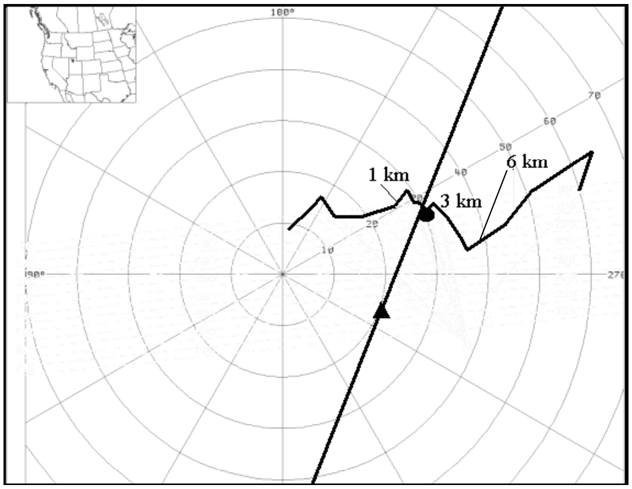

Figure 5. A hodograph showing a vertical wind profile derived from radar, surface, and RUC2 model analysis for 2100 UTC, 14 Feb 00 at Pocatello, ID. The labels 1, 3 and 6 km indicate the altitudes on the hodograph. The diagonal line represents the frontal axis perpendicular to its motion vector (triangle). The dark circle represents the average storm cell motion from 2142 to 2200 UTC prior to the intensification of the bow echo. The rings on the hodograph are in 10 m/s intervals.

During the early evolution of convection associated with the Pacific front, most of the initiation occurred behind the surface frontal position, eventually producing a broken canopy of weak convective precipitation and anvil debris. Mid and upper-level storm-relative flow was oriented ahead of the Pacific front which would have prevented any surface-based convection from ejecting anvil debris rearward.

Later in the afternoon, with the onset of SBCAPE, convection developed along the surface front in the western Snake River Valley. This convection eventually evolved into an intense bowing line just before sweeping through the Pocatello, ID area. This squall line was also accompanied by an elevated RIJ which may have helped maintain the erect nature of the updrafts as theorized by Weisman (1993) throughout the depth of the boundary where the shear was the strongest. However, the cold front was not the type of boundary that was applicable to the vorticity balance theory proposed by RKW88. However, the cold front motion resulted in nearly zero boundary-relative convective steering-layer flow. Confirmed by initial cell motions as observed by the Pocatello, ID WSR-88D, the cold front was conducive to allowing incipient updrafts to remain on the mesoscale lifting zone associated with the front. More modest 2-6 km shear of 15-20 m/s, from rear-to-front relative to the boundary, possibly helped to initiate an overturning zone containing the steering layer flow as theorized by ML99.

There are additional topics that have not been included in this paper. The first is the effects of strong convergence in adding updraft strength and resisting shear. In addition, the topic of tornadogenesis with this squall line has yet to be studied. Preliminary results with both these topics will be presented at the conference.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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