# Reply

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## 1. Introduction

In a recent *Weather and Forecasting* article (Weaver et al. 2002, hereinafter W02) we utilized a severe-thunderstorm case from 24 July 2000 to demonstrate the utility of Geostationary Operational Environmental Satellite (GOES) rapid-scan imagery and sounder data in the short-range forecast/nowcast processes. The primary purpose of W02 was to highlight several aspects of the severe-storm environment that could be better observed and understood using GOES data. In passing, we remarked—without much elaboration—on a seeming correlation between storm motion and a tongue of high, surface-based CAPE. The comments received from Klimowski and Bunkers (2002, hereinafter KB02) show that, when it comes to science, one either pays now or pays later. We must now admit to two important oversights. First, we should have either expanded our discussion of the character of the storm and storm motion or not included it at all. Second, we did not give proper attention in our article to updraft–shear interactions as they relate to storm motion. What follows is a reply to the points made in KB02 and an expanded discussion of these issues.

## 2. Reply to specific comments

### *a. The right-moving component*

References to both vertical shear and storm motion were kept intentionally brief in W02 in order not to distract the reader from what we felt was the main focus of our paper—thermodynamic features of the environment as revealed by satellite observations. Perhaps, in hindsight, it would have been wiser not to address storm motion at all, but certain aspects seemed interesting enough at least to mention them. At the same time, we do not feel that any of our comments were entirely inaccurate. For example, we noted that the 0–3-km storm-relative environmental helicity (SREH) value associated with the shear profile on the morning North Platte, Nebraska, (LBF) sounding was 122 $m^2 s^{-2}$. W02 stated that this value was marginally favorable for supercell development but that SREH would increase throughout the day. As noted in Bunkers et al. (2000), only about one-third of the supercells that they documented had SREH values of less than 125 $m^2 s^{-2}$. We feel that our statement in W02 conveys the idea that SREH was *somewhat* on the low side in the morning (marginally *favorable*) using SREH as a measure but that these values were expected to improve throughout the day, that is, that shear *would* become more favorable for supercell storms. The problem here likely resulted from utilizing descriptive adjectives such as ''marginal'' and not spending enough effort on the question of storm motion to compute other important measures of environmental vertical shear.

Another issue addressed by KB02 is one of nomenclature. KB02 consistently refer to the right-moving storm discussed in W02 as a ''classical'' supercell. There were, however, certain aspects of the storm that suggest this was not entirely the case. Marwitz (1972a,b) described differences between supercell and multicell storms, and Weaver and Nelson (1982) documented an event in which a supercell–multicell hybrid propagated

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along a low-level thunderstorm outflow (LTO) boundary. In the Weaver and Nelson case, discrete cells formed separately from the main storm and then slowly (within 10–15 min) merged with the supercell core. This behavior is what occurred on 24 July during a large segment of the storm's lifetime. However, this notion was not pursued in any great detail in W02, because we did not want to distract the reader with a lengthy, off-topic discussion. Thunderstorm structure and morphology were never the intended focus of the paper.

KB02 state (in their section 2b) that, ''most of the apparent discrete development occurred during the first 93 min of the supercell's lifetime (2207–2340 UTC).'' We must challenge the use of the word ''apparent.'' The 24 July storm actually formed more than 30 min earlier (Fig. 1). In fact, the first trace of a small radar echo was observed at 2126 UTC. By 2207 UTC, a broad, cyclonic circulation had developed within the storm, and reflectivities had reached 50 dBZ. As stated in W02, the storm initiated where a north–south-oriented line of low-level convergence intersected an LTO boundary generated by an early-morning mesoscale convective system (MCS). The main core then remained locked in place for more than 40 min before it began moving south. Its ''motion'' was clearly dominated by boundary layer features during this stage. At 2212 UTC, the storm began moving south.

Over the following 140 min, several discrete cells were identified on both satellite and radar images as they formed to the west-southwest of the main core (e.g., Fig. 2). These new cells subsequently merged with the main body of echo, which was observed to have had supercell characteristics. However, because the activity was about 100 n mi (185 km) from the radar at that time—placing the center of the beam at nearly 13 500 ft (~4.0 km) above ground level—it would have been impossible to know what was occurring within the lower levels of the storm. Also, the beamwidth at that range would have smeared smaller-scale interactions/changes. However, the observation of discrete growth and merging on the flanks of the storm clearly suggests that the storm was undergoing behavior similar to that of the supercell–multicell hybrid described by Weaver and Nelson (1982). Note that this period includes the first two tornado touchdowns (2250 and 2305 UTC, respectively).

Over the next 30 min, no discrete development was identified on either satellite or radar imagery along the right flank of the storm. Then, at 0053 UTC, the storm moved close enough to the Thedford, Nebraska, (KLNX) radar to reveal a storm-induced LTO boundary trailing off to the west (Fig. 3). Radar data suggest that new cells formed on this boundary—cells that appeared as appendages that attached to the western edge of the primary cell. These small echoes merged rapidly with the main core. The radar data indicate that the propagation at this point may not have been a continuation of the multicell–supercell hybrid process, but may have been closer to what Browning (1977) describes as ''feeder cells,'' or what Foote and Frank (1983) discuss in their Westplains example. However, photographs taken of the approaching storm from just east of the North Platte, Nebraska, National Weather Service (NWS) forecast office show that, even during this phase, some discrete propagation may have been taking place (Fig. 4).[1]

The point of our brief comment in W02 was intended to convey the idea that the primary storm was traveling along the north–south convergence axis (illustrated in Fig. 1 herein and in Fig. 7 in W02). It was along this axis where the most unstable air accumulated (i.e., the highest surface-based CAPE) and where the low-level cap was eroding [the area of zero convective inhibition (CIN)]. These features allowed us to argue that the north–south convergence boundary was intense enough to be affecting the low-level instability distribution. Traveling along this axis, therefore, the storm's gust front was encountering the most unstable air available. This was where new towers were being lifted—towers that subsequently merged with the main updraft. However, in the end we must concede that our phrasing was a definite overstatement of the role of the low-level convergence boundary in the process. Our comment that asserted (in part), ''the right-mover's motion could readily be explained by factors other than shear-induced pressures, though the effects of the shear cannot be eliminated'' would have been more objectively stated as, ''though there was sufficient shear to produce supercell propagation, there are clearly other factors that may have played a role in storm behavior. One such process was revealed by new, discrete cells forming along the storm's own LTO boundary just to the west of the main core throughout a significant portion of the storm's lifetime. These new cells were observed to merge with the central core within 20–30 min. This discrete development occurred while the storm was traveling along a north–south convergence boundary where satellite sounder data show the highest CAPE and lowest CIN values had accumulated.''

That having been said, KB02's final statement at the end of their section 2 might also have been stated more carefully. When a numerical or conceptual model, based on a limited set of selected variables, is able to reproduce a realistic looking result, the temptation is to assume that other factors present in the real atmosphere are unimportant to the event being simulated. Such simplified models seldom capture the complete, and typically more complex, evolution, however. This is not to suggest that reasonable models should be avoided in the forecasting process. Rather they should be used with a full understanding that actual events are most probably a lot more convoluted. What we had originally intended to convey by including the storm-motion sidebar was that sounder data might be utilized to identify other

[1] A loop of these photos could be found online at http://blight.cira.colostate.edu/july24/jul2400.htm.

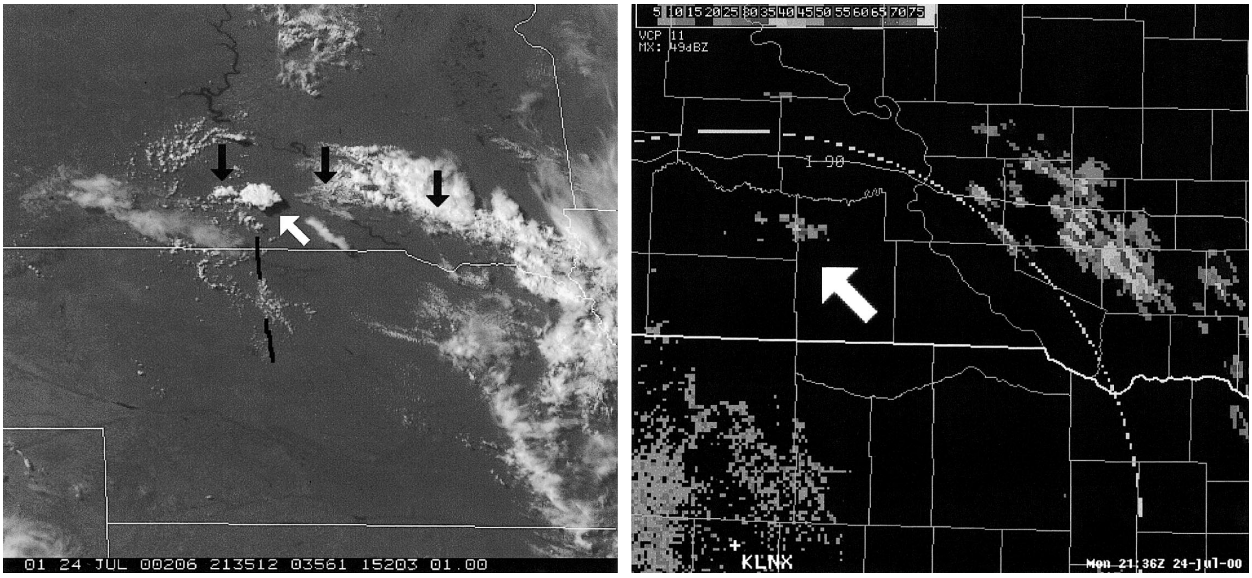


FIG. 1. (left) *GOES-11* visible-wavelength satellite image at 2135 UTC 24 Jul 2000, and (right) base reflectivity from the Thedford, NE, (KLNX) WSR-88D taken at 2136 UTC 24 Jul 2000. White arrow points to developing storm. Dark arrows indicate the position of the LTO boundary associated with the morning MCS, and dashed line points to the location of the Rapid Update Cycle (RUC) analyzed north–south convergence boundary.

aspects of the storm's evolution not brought out by simple—though, as KB02 show, effective—indices. Indeed, the thermodynamic data in the 24 July case are a reasonable reflection of the important low-level convergence boundary that focused high CAPE and vertical motion (enough to eradicate CIN just ahead of the storm). This convergence boundary was obviously affecting the atmosphere on multiple scales, was definitely a factor in storm intensity and longevity, and might even have played a role in storm motion. However, it is clear from the points made in KB02 that updraft–shear interactions likely do account for a portion of the storm's deviant motion on 24 July.

### *b. Acceleration of the storm*

On a different topic, KB02 note that the right-moving storm accelerated its forward motion at around 0140 UTC and suggest that the acceleration may be a result of the storm's transition from a classic (CL) to a high-precipitation (HP) supercell as per Moller et al. (1994). We would describe this transition in a slightly different way. The discussion of the so-called supercell spectrum presented in Moller et al. *does* show that certain CL supercells in transition may accelerate their forward speed, though the accelerating storms in that paper were supercells that made a transition to derecho-dominated storms with bow echoes. This was not what occurred in this case. The 24 July storm showed no sign of bow-echo development but simply increased its forward speed somewhat and, at around 0230 UTC, turned left. We calculated storm motion from the KLNX radar over various intervals for the 24 July right-mover and estimated the following for selected intervals: from 2126 to 2207 UTC the storm was more or less stationary, from 2212 to 2350 UTC the storm moved from 357° at 16 kt, and from 2350 to 0255 UTC the motion vector was calculated to be from 342° at 26 kt (1 kt = 0.52 m $s^{-1}$). After turning left, storm motion deviated by more than 30° from the Bunkers et al.–predicted supercell motion. Note the gradual leftward curve beginning about halfway along the path shown in Fig. 5.

In this case, we believe the explanation for the acceleration might be better understood by relating the change in storm behavior to the arrival of the shortwave trough and associated stronger winds aloft (Figs. 6 and 7). As noted earlier, for much of its life the right-moving storm had a well-defined, trailing outflow along which new cells were observed to be forming and then merging with the main core. We feel that the onset of stronger, entraining winds aloft intensified the low-level outflow, which, in turn, increased localized lift. This produced a greater moisture flux into the storm's updraft. The acceleration of the LTO boundary would account for both the 10-kt acceleration and the subsequent increase in both the size of the rain core and rainfall amounts. This series of events could provide an explanation for why the cold pool became more dominant with time, why the rain area increased, and why the storm made a transition to an HP-type storm. In other words, we do not agree that the transition from CL to HP was the *reason* for the storm's acceleration or for the cold pool to become increasingly dominant, but rather we believe that the transition to an HP-type storm was the *consequence* of the latter two.

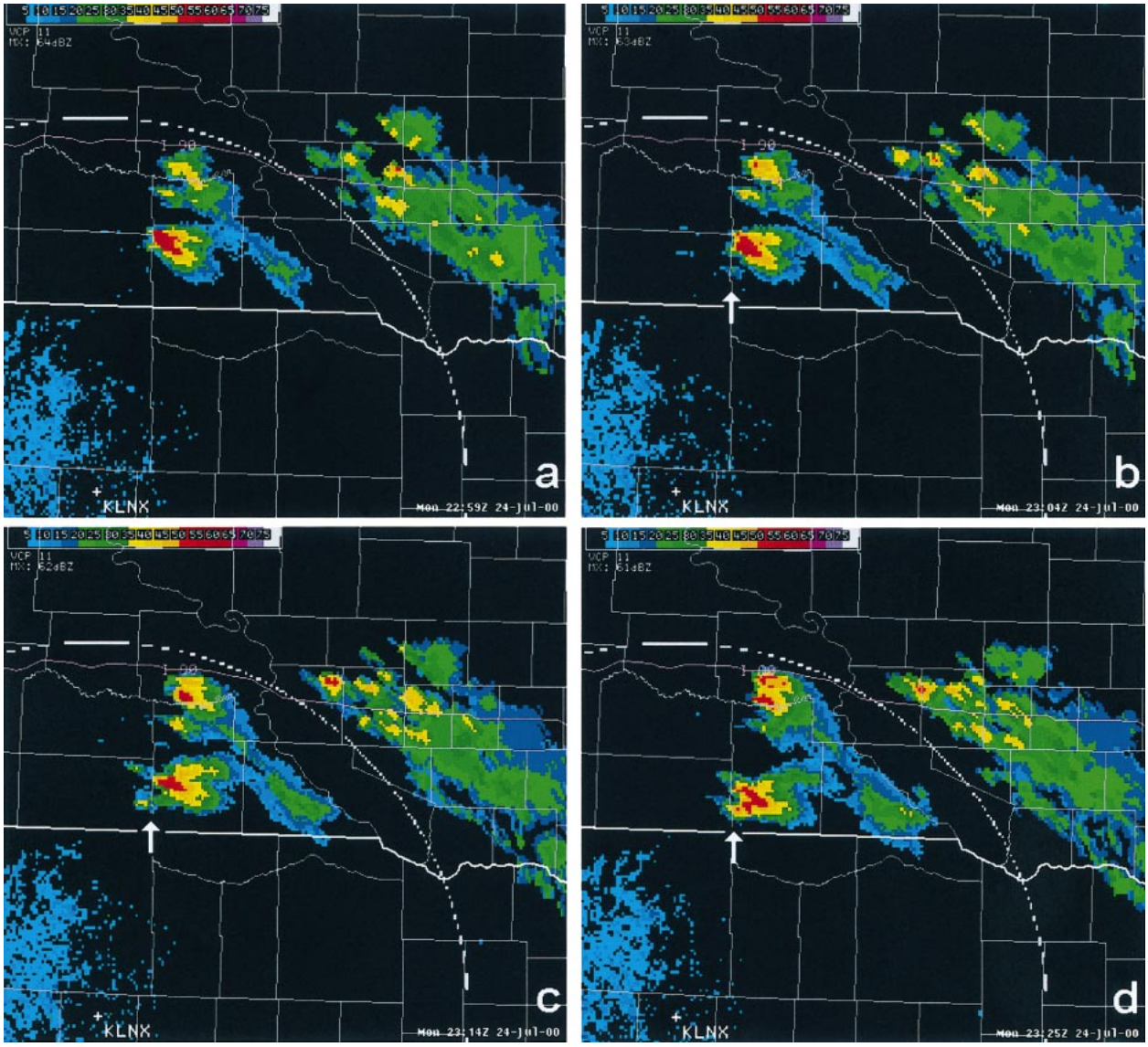


FIG. 2. WSR-88D base reflectivity from the KLNX radar on 24 Jul 2000. Times shown are (a) 2259, (b) 2304, (c) 2314, and (d) 2325 UTC. Arrows point to an example of a discrete cell forming nearly 10 km to the southwest of the main storm core and then merging with it over about a 20–25-min period.

*c. The left-moving component*

As with the right-moving component, we did not intend to get into this aspect of the case in any great depth. Again, it is evident that the topic should have been addressed in more detail or not discussed at all. At the outset, we note that we are in substantial agreement with most of the points made by KB02 regarding the behavior of the left-moving component. In fact, there are only two points on which we differ.

At the time we were putting together the data for W02, some of us were also working on a study of outflow-generated, left-moving severe storms that occurred in the Texas Panhandle on 25 May 1999. Those storms propagated north in a manner similar to that described in Brown and Meitín (1994) and became severe. In the Texas case, visible satellite imagery reveals outflow boundaries moving northward from the north side of individual, right-moving storms. New cells can be seen forming along those boundaries. Weather Surveillance Radar-1988 Doppler (WSR-88D) data from Lubbock, Texas, show that at least one of these left-moving storms developed an anticyclonic circulation at midlevels. Because the left-moving component did not form in the classic manner, we were focused on a study of this aspect of the activity. It was most certainly this research that led to the speculative statements made in W02.

In the case of 24 July 2000, we were unable to confirm specifically how the left-moving component formed.

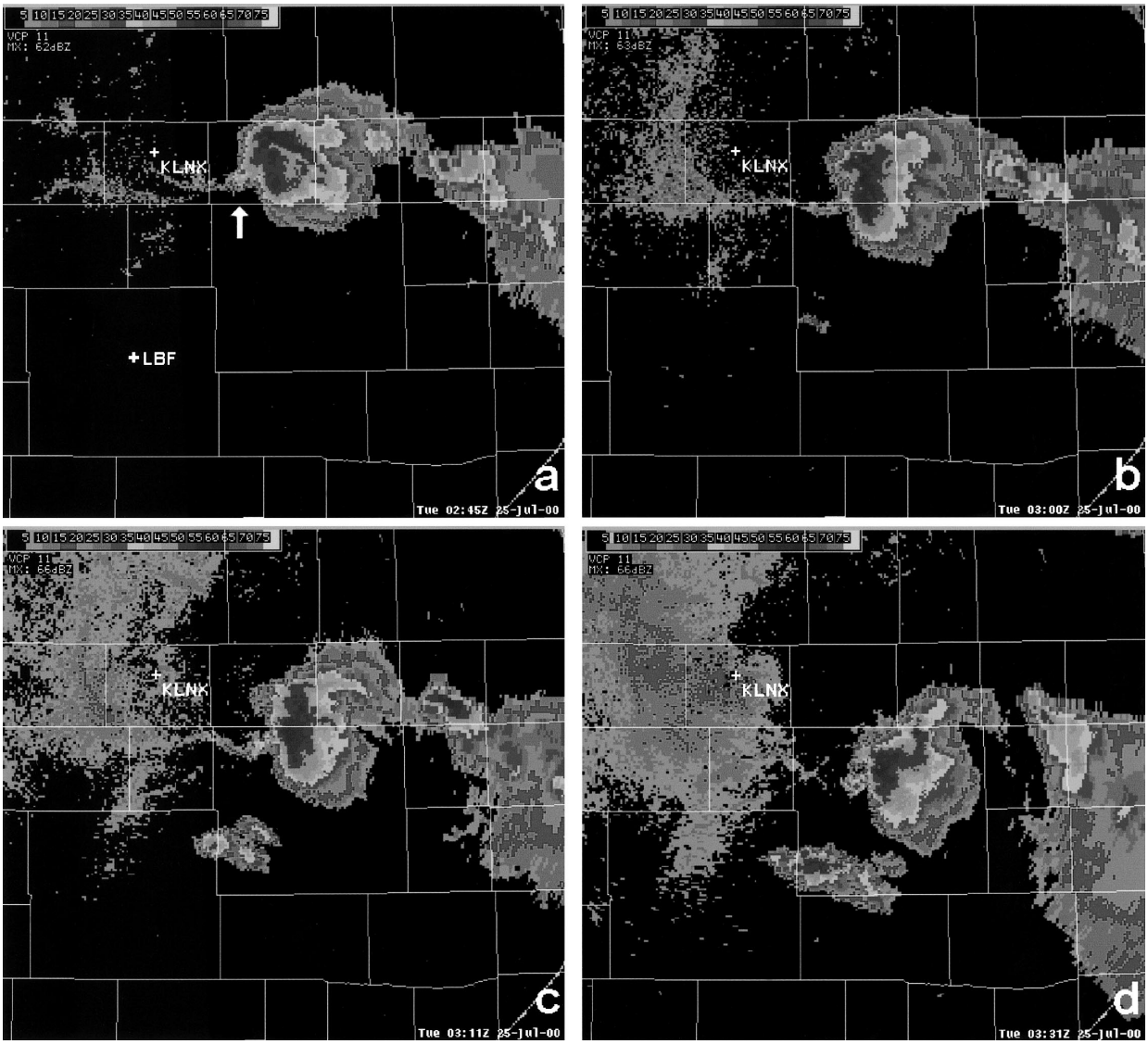


FIG. 3. WSR-88D base reflectivity from the KLNX radar on 25 Jul 2000. Times shown are (a) 0245, (b) 0300, (c) 0311, and (d) 0331 UTC. Note appendage of new activity being lifted by the outflow boundary to the west of the main storm core.

The storm had a large anvil that blocked our ability to see any interactions that may have been occurring at low levels on the north side of the storm. Also, the radar was about 100 n mi (185 km) from the activity at that time, placing the center of the beam at nearly 13 500 ft (~4.0 km) above ground level. Low-level features and interactions were well below the radar horizon. The suspicious factors that called our attention to this particular left-mover were that 1) while the larger core (the one that was to become the right-mover) remained stationary in the face of moderately robust storm-layer winds for about 40 min the left-moving component traveled from about 240° at 16 kt from its inception and that 2) once the left-mover emerged from beneath the anvil, visible satellite imagery revealed that it was locked onto what appeared to be an LTO boundary associated with the primary core. However, we did not have the velocity data at the time of the initial analysis and did not check those data when they did become available. This was an oversight. In looking at Fig. 4 in KB02, it is clear that an anticyclonic circulation was present from the time the left-mover first developed. Also, the motion seems to match that calculated by Bunkers et al. for the left-moving component. Therefore, we agree that the preponderance of evidence supports the notion that the formation mechanism of this component was likely to have been a shear-induced, upward-directed pressure gradient force. Nevertheless, it is still a question of what, if any, role the northward-moving LTO boundary played in the complex life cycle of this component.

Our last comment addresses the contentions by KB02

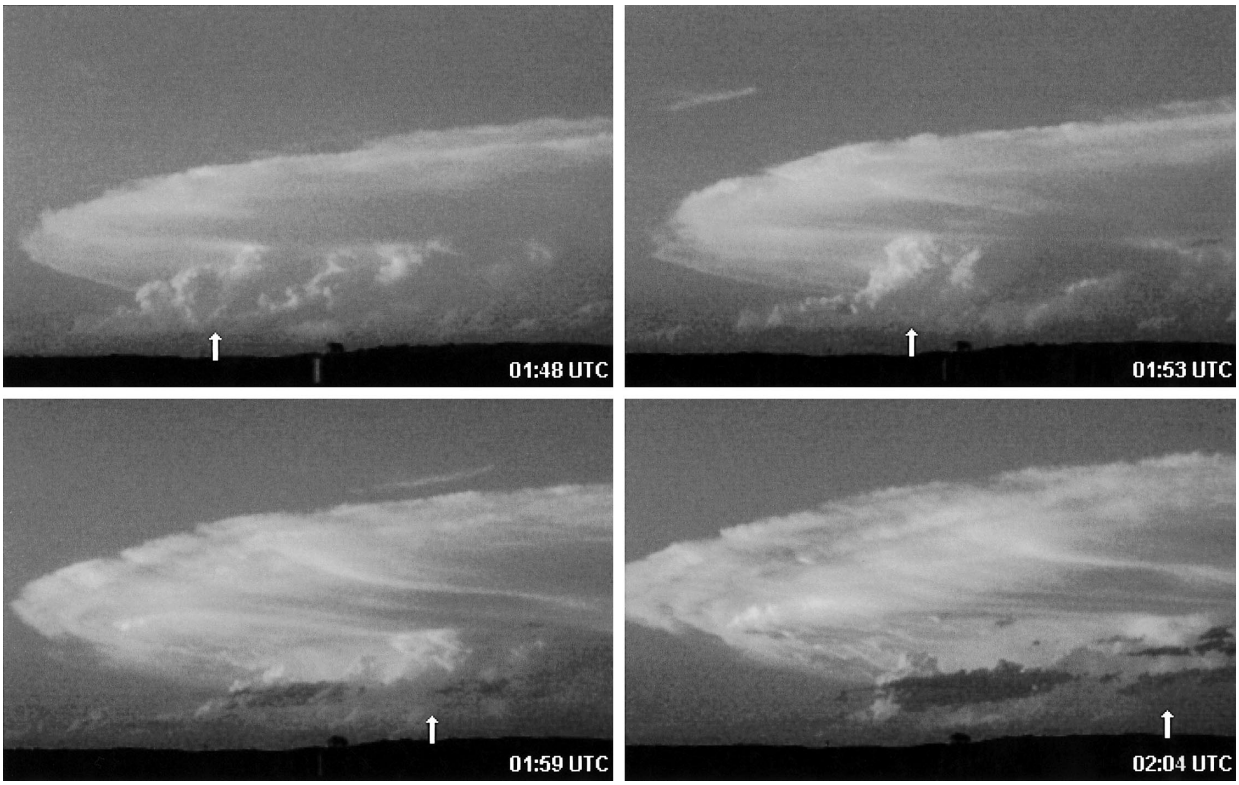


FIG. 4. Series of photographs of the right-moving storm on 24 Jul 2000 taken from just east of the North Platte, NE, (LBF) NWS Forecast Office. Times are as shown. The sequence (white arrows) shows a discrete cell developing and then moving east before merging with the main storm core. Photographs courtesy of D. Sheets, NWS, North Platte.

that 1) radar data *do not* show that the left-mover intersected the MCS-generated LTO boundary and that 2) radar data *do* show that the left-mover dissipated after only 45 min. The first problem is easily explained by the fact that the storm was approximately 100 n mi away from the radar. Low-level boundaries would have been well below the radar horizon at this distance. However, satellite images (e.g., Fig. 1) show remnants of the mesoscale boundary throughout most of the afternoon.

The history of the left-mover is both interesting and complex. Figure 8 presents a series of nine radar images that illustrate the right- and left-moving components at various times. Our original interpretation of this sequence went as follows. From 2207 through 2254 UTC, the core associated with the original left-mover (LM1) was easily tracked on the reflectivity data as it moved northeastward. Then, for a 12-min period beginning around 2254 UTC, LM1 appears to have weakened, though it can still be identified as a small reflectivity maximum. One could justifiably describe this as a ''dissipation of the first left-moving supercell.'' However, our interpretation is that the weakening seems to have occurred as a new left-mover (LM2) broke away from LM1 and as new convection (RM2) appears to have formed spontaneously to its southwest. The formation of RM2 may have been outflow-related regeneration, but once again low-level interactions were blocked on the satellite imagery by an intervening anvil and were below the horizon for radar.

Because the midlevel echo associated with LM1 never lost continuity, we felt that the original storm probably survived beyond this time (see last three images of Fig. 7 herein) and actually reintensified following the complex evolution at around 2300 UTC. Indeed, Doppler velocity data (not presented) show that the reintensifying core at LM1 retained an anticyclonic velocity signature through 0012 UTC, when it finally did dissipate. Radar data also show that, for the last hour of its lifetime, this component moved slowly southeastward, roughly in the direction of the mean wind in the cloud-bearing layer and along the approximate position of the old MCS boundary. However, in light of the KB02 interpretation, which seems just as valid as our own, it is not clear which sequence (if either) actually took place at the lowest levels of the storm. The range to the radar is simply too great to be more specific.

## 3. Final remarks

We believe that the comments received concerning our recent paper on *GOES-11* data (KB02) were insightful and brought out many important points regarding supercell behavior that should have been made in our original submission. We agree with KB02's primary

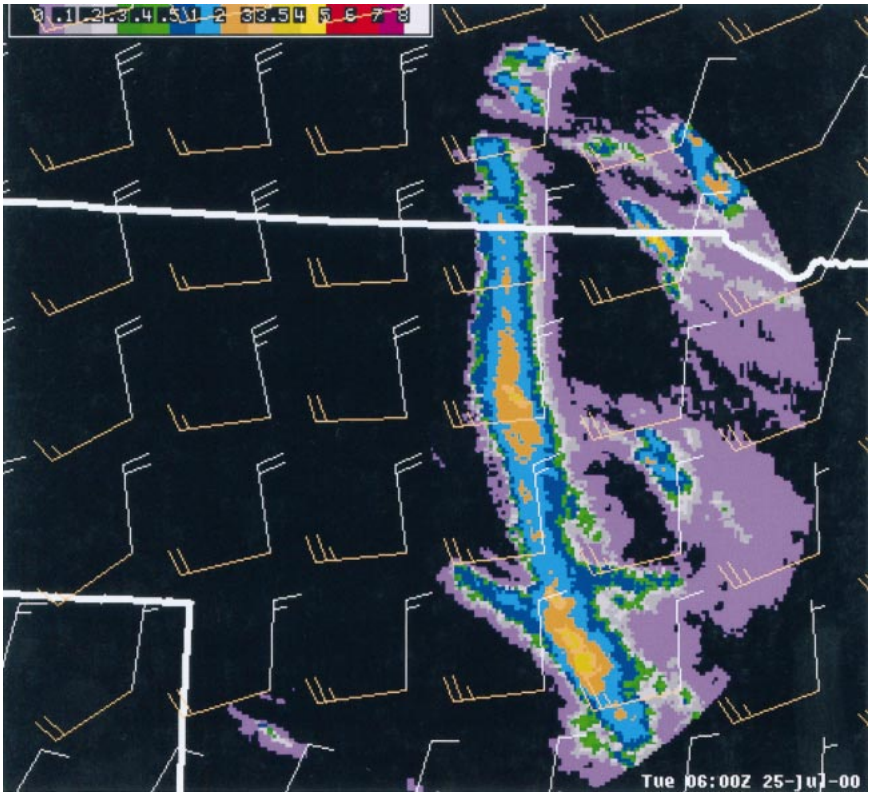


FIG. 5. Radar-estimated storm total precipitation from 2200 (24 Jul 2000) through 0600 UTC (25 Jul 2000). Wind barbs represent predictions from Bunkers et al. of supercell motion, where white vectors are for the right-mover and orange vectors are for the left. Wind field is from the Eta Model 6-h forecast field.

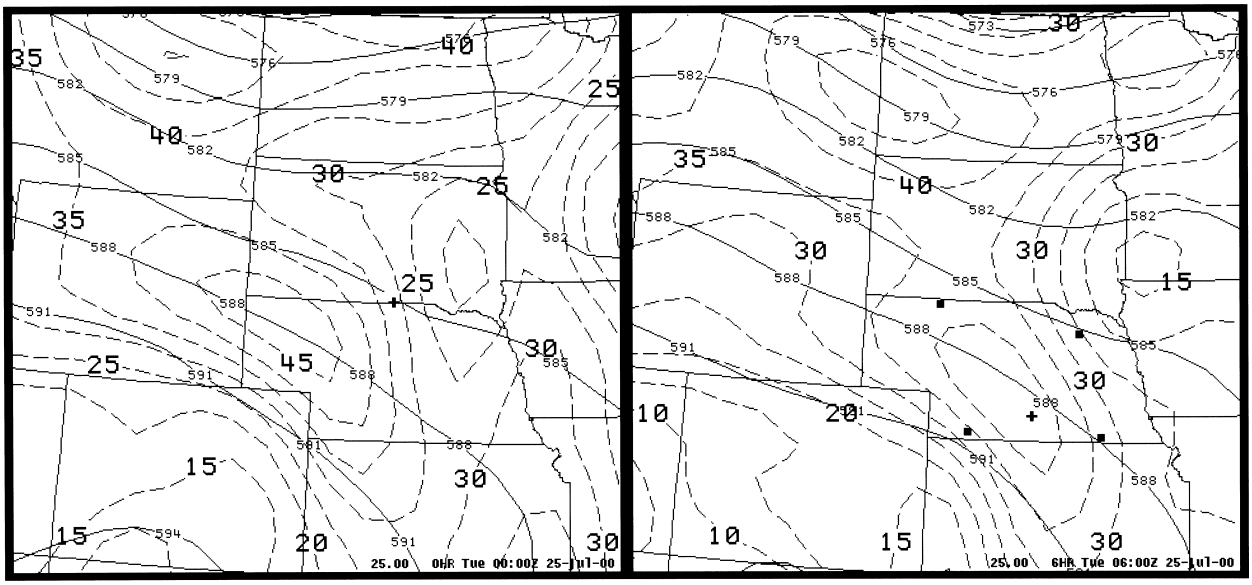


FIG. 6. Eta Model 0- and 6-h forecasts of 500-hPa heights (dam) and wind speeds (kt) valid at (left) 0000 and (right) 0600 UTC 25 Jul 2000. Plus sign indicates approximate position of the storm core at the time of the analysis/forecast. Small boxes (right side) are proximity profiler sites. Numerical output gives the specific values near the storm cores as 34 (0000 UTC) and 43 kt (0600 UTC), respectively. The north–south components associated with these 500-hPa winds are 16 and 25 kt, respectively.

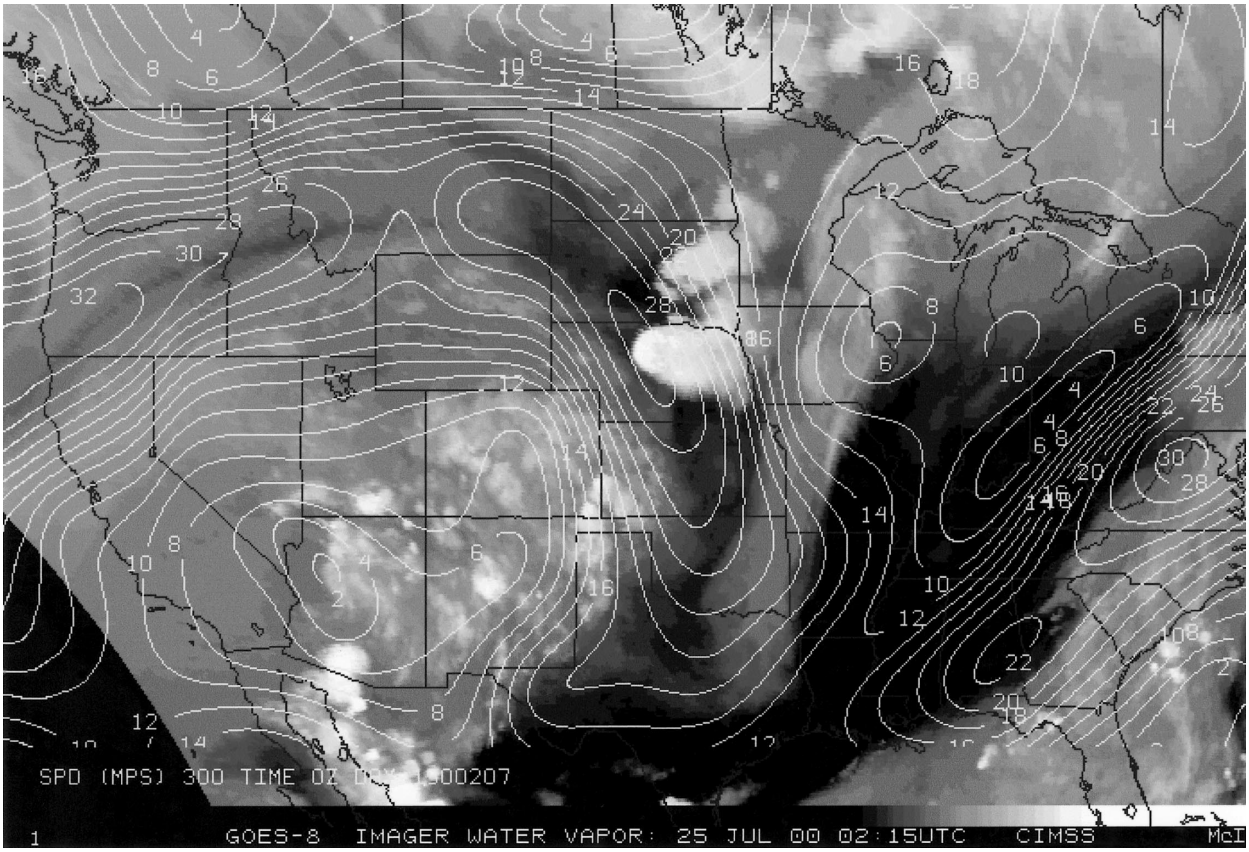


FIG. 7. GOES-derived, 300-hPa (layer from 250–350 hPa) wind speeds (m $s^{-1}$) calculated at 0000 UTC 25 Jul 2000 placed on a *GOES-8* water vapor image taken at 0215 UTC. Note the 28 m $s^{-1}$ jet maximum over central NE.

concern—that we did not address the importance of the relationship between vertical wind shear and supercell behavior—and have attempted to rectify that oversight in this reply.

Based on our responses in the previous sections, we will answer each of KB02's final remarks (see section 4 of KB02) in the order listed, first repeating them in italics for reference.

1) *Updraft–shear interactions provide a simple and scientifically sound explanation for supercell development and motion on 24 July 2000.* We agree with this statement but reiterate that there were clearly other factors that were playing a role in thunderstorm morphology. One such process was revealed by new, discrete cells forming along the storm's own LTO boundary to the west of the main core throughout much of the storm's most severe period. This process suggests there was low-level lift along the outflow that supplemented the nonhydrostatic vertical pressure gradients aloft. For a large part of the severe period, the storm seemed clearly to be a supercell–multicell hybrid of the Weaver and Nelson (1982) variety, though as Moller et al. (1994) point out, this type of storm can easily be fitted into the broader supercell spectrum. We feel that at least a part of the propagational component of the storm motion may have been related to cells that developed on the storm's own outflow as it moved down a preexisting north–south convergence line where satellite sounder data show that the highest CAPE and lowest CIN in the region were accumulating.
2) *It is beneficial to make thorough use of all available data sources when examining both the convective environment and thunderstorm evolution, and overreliance on any single data source should be avoided.* Again, we agree with this point and have now expanded our discussion—through this reply—to reflect the fact that we actually did look at many other data sources, though we did not present sufficient data in W02 to justify some of the statements made in the original paper. Also, we purposely overemphasized satellite data in our discussions of storm morphology. This caused problems in the way we presented certain aspects of the storm behavior. At the same time, one must remember to look at *all* data sources objectively. The fact that the primary storm was actually a supercell–multicell hybrid during a lengthy portion of its lifetime may not have been critical in this instance and might, in one sense, be reasonably overlooked or dismissed entirely. How-

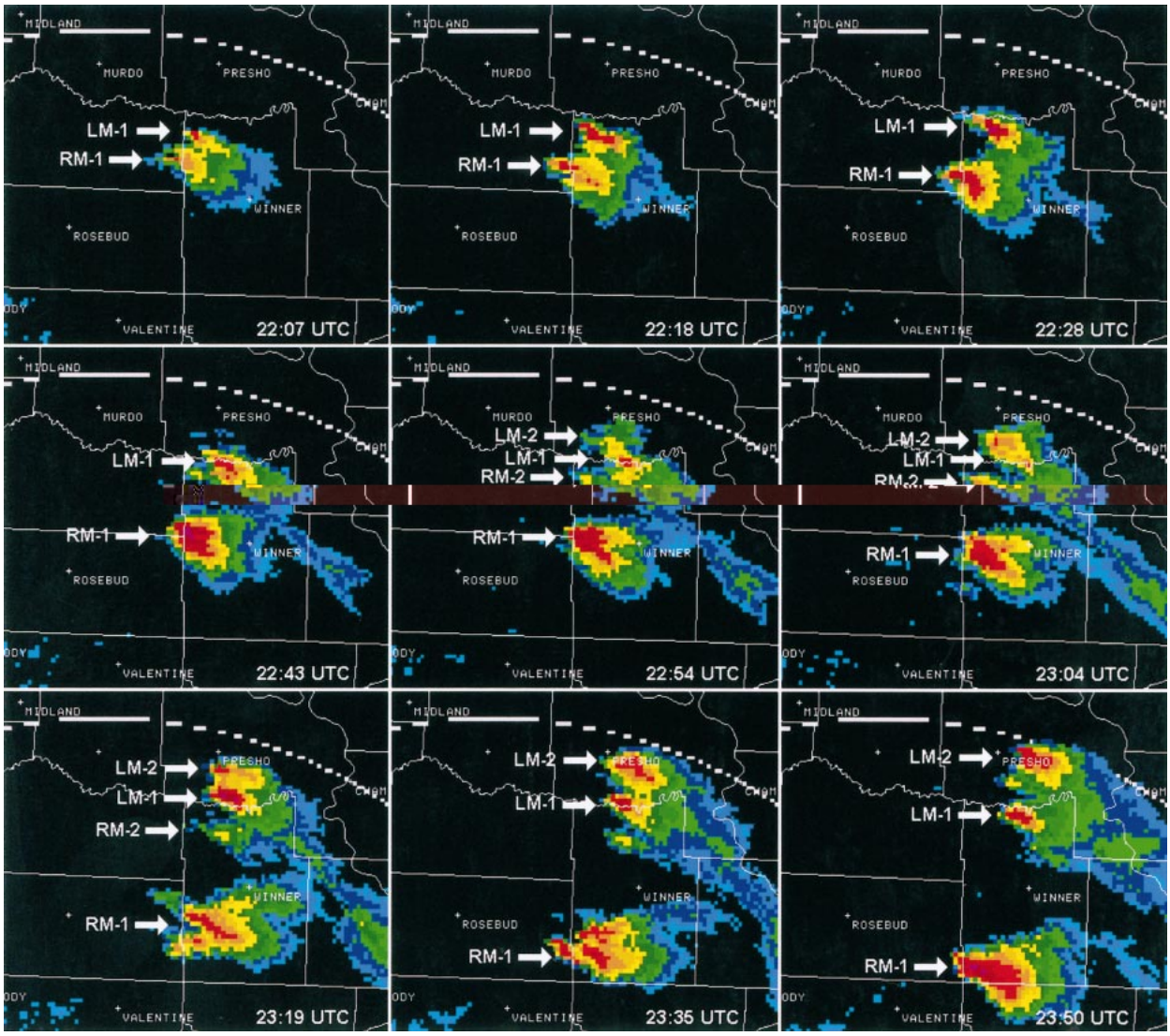


FIG. 8. WSR-88D base reflectivity from the KLNX radar on 24 Jul 2000. Times shown are 2207, 2218, 2228, 2243, 2254, 2304, 2319, 2335, and 2350 UTC. Arrows are as follows: RM1 and LM1 are the primary right- and left-moving storms, respectively, and RM2 and LM2 appear to be new storms associated with LM1.

ever, this process may be important in other cases and is certainly a characteristic worth noting.

3) *Care must be exercised when observing thunderstorm motion in order to examine the effects of continuous propagation (shear induced) versus discrete propagation (external factors).* This was the whole point in our bringing to light some of the sidebar issues, so we agree wholeheartedly. We agree with KB02 that storm motion in this case was most likely supercellular in nature and that the hodograph technique presented in Bunkers et al. (2000) did a good job of predicting this motion—at least during the time period from around 2212 UTC (24 July) through 0230 UTC (25 July). On the other hand, we contend that the simplified assumption does not represent all aspects of the storm. The period from roughly 2126 to 2212 UTC corresponds to a time during which the storm's updraft was apparently locked onto the intersection point where the original convection had formed, even though reflectivities reached 50 dBZ by the end of that period. That is, storm motion was quasi-stationary during this initial period, and the storm certainly did not move as the hodograph technique predicted. During the greater part of the tornadic phase of the storm's lifetime, discrete propagation could be seen on WSR-88D reflectivity scans, satellite imagery, and cloud photography, marking this storm as a supercell hybrid of the type described by Weaver and Nelson (1982). However, because the north–south convergence boundary was aligned along the north–south path the supercell was already traveling, there was no de-

tectable effect on storm motion in this case. Nevertheless, we feel the point was one well worth making. Last, the transition in storm behavior that occurred between 0200 and 0230 UTC represents another deviation from supercell behavior, because 1) the storm accelerated within an area where the Bunkers et al. technique predicted a reduced translational speed (Fig. 5) and 2) the storm took a left turn, instead of moving even farther right, as suggested by the forecast algorithm. The storm lived another several hours after that.

4) *The simultaneous display of radar reflectivity data with both the mean wind and forecast supercell motion can enhance the ability of forecasters to identify developing supercells.* We agree that this combination of products would certainly be beneficial in the warning decision-making process and would have been useful in our presentation. In fact, this entire case is an excellent example of the need for looking at multiple data sources. Forecast hodographs from model output allowed a reasonably accurate forecast to be made of supercell motion throughout a large segment of the 24 July right-mover's lifetime. Satellite imagery helped to identify critical prestorm boundaries, and satellite sounder data confirmed the importance of a north–south boundary and provided information that showed the right-moving storm to be traveling along the axis of highest CAPE and lowest CIN. That axis continued to be present after dark, suggesting that the storm would be long lived, as it was. The contribution of the northward-moving outflow boundary to the propagation of the left-mover is unknown. However, all low-level interactions were totally below the radar horizon because of the extreme range of the activity. At the same time, the discrete propagation that occurred during the most severe part of the right-mover's evolution was evident in both satellite and radar data. In situ photography also confirms this visually. Last, note that the upper-level jet maximum managed to slip through all of the available profiler sites (Fig. 6), though the jet was resolved well both by the evening Eta Model output and by the GOES-derived winds. This point was not brought out in W02 but should have been.

The first author of both W02 and this formal reply must mention, with some chagrin, that he was one of the reviewers of the Bunkers et al. (2000) paper and accepted it for publication feeling that it had significant merit. The results of that research provide an effective and accurate forecast of supercell motion in most severe-thunderstorm situations. Again, the only reason the technique was not noted in W02 was that the focus of W02 was on unique aspects of satellite imager and sounder data. We simply did not give storm motion enough attention in the original manuscript. We hope that the discussion presented in this exchange clarifies that facet of the 24 July 2000 case.

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