Reply

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We appreciated the comments by Dr. Smith on our recent article (Weaver and Purdom 1995), which we will refer to as WP to be consistent with his convention. It is apparent from his critique that at least some readers may have misunderstood the purpose of our presentation. Dr. Smith has afforded us an ideal opportunity to clarify a couple of points, as well as to offer a bit more explanation on some of the intricacies of interpreting Geostationary Operational Environmental Satellite imagery. We will try to address each of the points raised in the order they appear.

The first point is an important one. Any effort to utilize sequential satellite imagery to reach conclusions about cumulus cloud movement and/or evolution is always vulnerable to the simple fact that cumulus cloud lifetimes can frequently be less than 15 min. When tracking a cumulus target on 15-min-interval satellite imagery, the meteorologist is always faced with the possibility that the ''cloud'' he or she is tracking might actually be two or more different clouds. In this case, however, we were fairly certain that the small line of cumulus congestus we were tracking had formed due to lift along the leading edge of subsiding air from a small, dissipating thunderstorm. Since we were concerned with the location and movement of the *outflow boundary*, and not the individual cumulus, we decided that the identities of individual elements were irrelevant. As long as the approximate size and shape of the outflow feature (as outlined by the cumulus) held reasonable continuity, we felt comfortable in making the assumption that we were viewing the same *feature* throughout the relatively short period considered.

Dr. Smith's second point, that is, his discussion of the small shower to the north of the Hesston storm, was extremely interesting and imaginative. The authors of WP noticed this small shower early in our study, but dismissed it. We will summarize our reasons for doing, but first we offer a clarification. Though Dr. Smith suggests that storm N seems to have merged with the Hesston storm, it is clear from both 15-min-interval satellite imagery, and radar data, that storm N actually dissipated before merging—producing a small, short-lived outflow in the process. Also, we do not believe that the large outflow indicated in Dr. Smith's Fig. 1c is the outflow from storm N. The western edge shown in the figure is actually a cumulus cloud line that had been there all along. The anvil from the Hesston storm covered N before much of its outflow became evident. However, we do agree that an outflow interaction from the north did occur.

There have been several mechanisms suggested as to how a very small outflow might trigger a tornado in a mature, but nontornadic, supercell. One example is that an outflow approaching the updraft of a strong thunderstorm might temporarily enhance the low-level inflow vectors just ahead of itself; that is, low-level winds could be accelerated and backed by an approaching cold dome. The increased convergence could then briefly accelerate the larger storm's updraft. This process does not seem possible in the case of Dr. Smith's storm N; it seems unlikely to us that such a small storm would have produced an outflow deep enough to penetrate through the precipitation core of its larger neighbor. As a second possible mechanism, suppose that horizontal vorticity vectors associated with a smaller storm's outflow becomes tilted into the updraft of a mature cell. This added vorticity might alter the vorticity distribution in the rotating supercell. However, as in the case of increased convergence, the outflow from storm N would first have had to penetrate the strong precipitation core of the Hesston storm, intact (not likely in this case), in order for there to be any organized horizontal vorticity left to be tilted. While such inferential reasoning does not completely eliminate storm N as a possible triggering mechanism for tornadic development, it seems clear that the storm to the south had much freer access to the Hesston storm's updraft.

The next point in Dr. Smith's comment is well taken. Both authors of WP agree that the lead time from first detectable precipitation echo through tornadogenesis can be on the order of hours. The point of our note was to ask the question of the research community, Are there any detectable, small-scale events (factors), that might

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contribute to the evolution of a supercell from nontornadic to tornadic? That is, Why did the Hesston supercell travel along for 105 min, displaying only a weakly rotating updraft to in situ storm chasers, then suddenly develop into an F5 tornado? The authors of WP believe it unlikely that the Hesston tornado appeared simply because it was ''time.'' Not all supercells develop tornadoes. A recent study of mesocylones detected on 10-cm Doppler radar (Burgess et al. 1993) suggests that only about one-third of all mesocyclones produce tornadoes. That study's lead author tells us (D. W. Burgess, 1996, personal communication) that more recent statistics indicate a ratio closer to 1:5. Furthermore, environments that produce strong mesocyclones without tornadoes are typically undifferentiable from those that do, and nontornadic mesocyclones are frequently detected in the nearby vicinity of tornadic storms. The last sentence in Dr. Smith's discussion of this point says, ''For any given storm, the actual time that elapses from the initiation of radar-detectable precipitation until tornadogenesis is undoubtedly dependent on many factors.'' We agree. In our case, we were able to show that a mesoscale interaction occurred just before the Hesston storm changed character. A paper currently in press (Browning et al. 1996)[1] shows similar interactions. That study utilizes 1-min-interval imagery that eliminates any potential ambiguity in feature recognition.

In his final criticism, Dr. Smith employs thermodynamic data to suggest other factors that may have been important in the Hesston evolution. Those arguments are somewhat marred by his use of the 1200 UTC upper-air observations for a storm that occurred nearly 12 h later. In a paper dealing with the same case, Davies et al. (1994) present an estimated sounding that is meant to be more representative of storm time and location. Nevertheless, it is likely that the *trends* illustrated in Fig. 2 of Dr. Smith's comments are fairly representative. In point of fact, convective available potential energy (CAPE) values that increase with diurnal heating are not unusual: both tornadic and nontornadic environments generally behave in that manner. However, we do disagree with Dr. Smith's interpretation of tornado development in this case, since we do not assign the key role in tornadogenesis to increasing CAPE. As Dr. Smith himself points out, there was increasing CAPE and an intense thunderstorm with rapid cloud-top cooling during the period 2001–2201 UTC, a period during which there was no tornado. Indeed, Smith's Fig. 2 shows that maximum CAPE comes and goes, without there being a tornado. It also shows (Fig. 2b) that the maximum vertically integrated liquid (VIL) varies appreciably through the time of increasing CAPE. As we point out in WP, buoyancy and helicity were both conducive to large tornadoes throughout the Hesston storm's lifetime, but none occurred. Again, we ask the question, Could there be mesoscale events that are responsible (if not necessary) for triggering actual tornadogenesis?

Finally, we would like to reiterate the intent of WP by stating that we were not trying to prove any hypothesis, nor suggest new forecast techniques. Rather, we had hoped that the questions implicit in the paper would serve as a call to action for the mesoscale forecast research community. We completely and wholeheartedly agree with Dr. Smith's final suggestion that sound scientific principals must accompany any new forecast techniques provided the field forecaster.

[1] A preliminary copy of this paper can be accessed at the Cooperative Institute for Research in the Atmosphere home page by going to URL http://www.cira.colostate.edu and choosing Overview, RAMMB, then ''recent paper.''

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