P3.4

A COOL SEASON SEVERE WEATHER EPISODE IN NORTHERN ARIZONA

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1. INTRODUCTION

Outbreaks of severe thunderstorms in northern Arizona are most likely to occur during the transition between the moist, tropical environment of the warm-season North American Monsoon regime (NAM; Adams and Comrie 1997) and the first incursions of mid-latitude baroclinic systems in September. The presence of copious tropical moisture, combined with increased convective instability and deep-layer shear, is supportive of long-lived supercells which are responsible for most of the severe weather. The transition season typically occurs during the first half of the month of September.

A late-season severe weather episode occurred in mid October 2005—well after the normal transitional season had ended. During the early morning hours and continuing into the afternoon of 18 October 2005, long-lived severe supercells occurred across central and northern Arizona. Damage surveys indicated that at least four tornadoes (including one long-track tornado) and numerous occurrences of large hail occurred across northern Arizona.

In section 2, we present some historical perspective on this event. Section 3 examines the background environmental conditions that likely supported the development of long-lived supercells. In section 4 we present the radar data. Finally, in section 5 we discuss the implications of this event.

2. HISTORICAL PERSPECTIVE

Although severe thunderstorms in Arizona that produce large hail or tornadoes are possible any time both adequate deep-layer shear and convective instability are present, the most likely period of occurrence is during the transition season in September. October tornadoes are generally uncommon across northern Arizona. An examination of *Storm Data* reveals that only eight tornadoes have been documented in the months of October for all years between 1950 and 2004. In comparison, four tornadoes were documented on 18 October 2005, including one long–track tornado (Fig. 1). It should be recognized that reporting and documentation of tornadoes in past years was likely to be less rigorous than in the current era and a direct comparison between these numbers is difficult. Nonetheless, the occurrence of four tornadoes on this day represents a significant severe weather event.

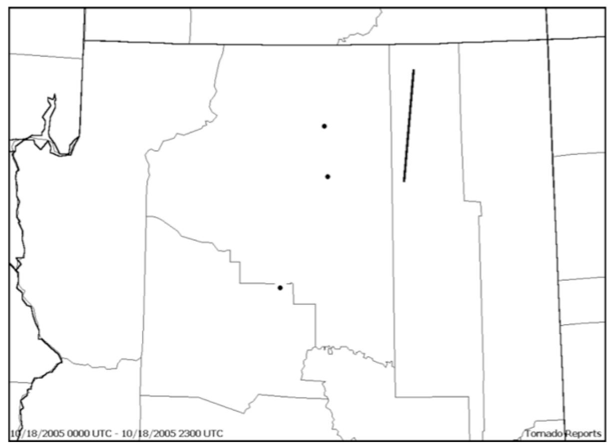

Figure 1. Tornado events for 18 October 2005 over northern Arizona.

3. THE STORM ENVIRONMENT

A large and deep closed-low pressure system developed and approached the southwestern United States (Fig. 2) on 18 October 2005 placing Arizona in the warm sector of this system.

3.1 *Synoptic environment*

The synoptic-scale forcing for this system can be readily determined from an analysis of the Q-vector field, specifically the divergence of the Q-vector (Hoskins et al 1978); convergence (divergence) of **Q** infers upward (downward) forcing. Figure 3 shows that a broad area of moderate upward forcing was moving across the state during the day. This synoptic-scale upward forcing (and its implied upward motion) would be expected to gradually destabilize the region owing to the steepening of lapse rates through synoptic-scale layer lifting.

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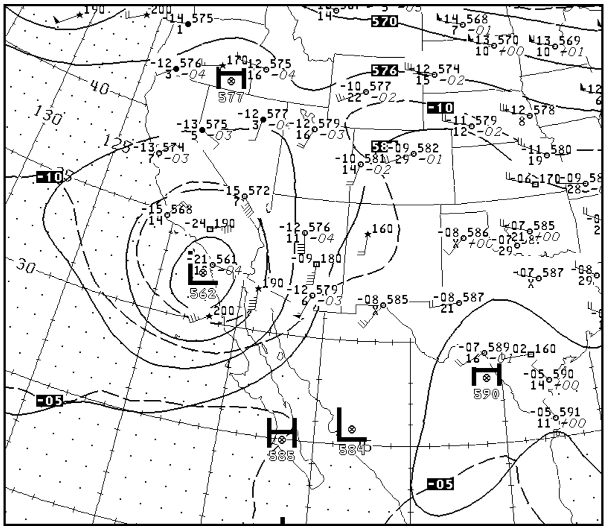

Figure 2. NCEP analysis at 500 mb for 0000 UTC 18 October 2005.

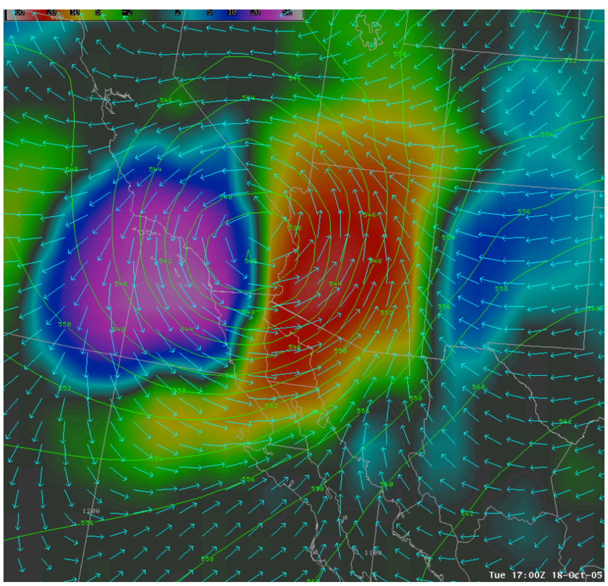

Figure 3. Divergence of Q-vectors in the 700–300 mb layer at 1800 UTC. Warm (cool) colors indicate upward (downward) forcing. Mean heights for the layer are shown with contour interval of 200 m.

3.2 *Upper Air and Instability Analysis*

The upper-air sounding from KFGZ (Flagstaff, AZ; Fig. 4), taken at 1200 UTC 18 October 2005, indicates moderately steep lapse rates below about 550 mb with more stable lapse rates above. There is a layer with near saturated conditions from the surface up to about 650 mb. This sounding contains similar lapse rates but more moisture than was present in the 0000 UTC 18 October 2005 sounding (not shown). The low-level moistening was likely the result of a persistent south–southwesterly flow in the warm sector of the low-pressure system advecting moisture northeastward from the eastern Pacific Ocean and across Arizona.

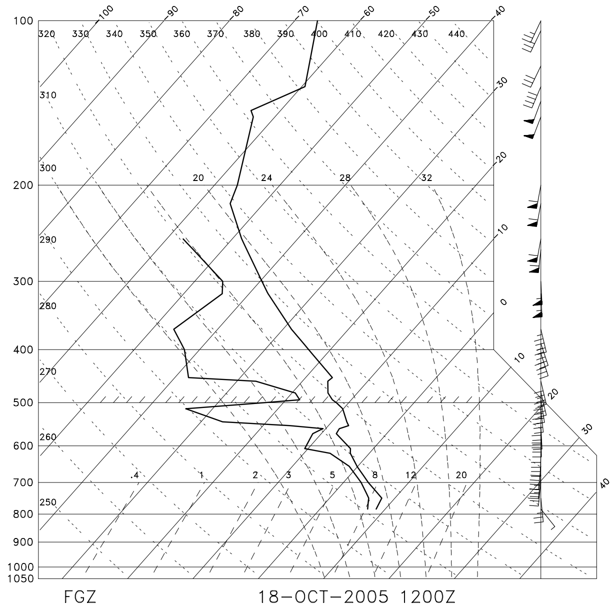

Figure 4. Skew T – log p sounding from Flagstaff (KFGZ) at 1200 UTC.

Buoyant instability, as determined by the convective available potential energy (CAPE), indicated that the atmosphere was only marginally unstable, despite the moderate lapse rates and moisture advection. The maximum surface temperature observed at KFGZ this day was 51°F (10°C). Using this value in the interactive sounding results in CAPE of only about 100 J kg^{-1}. Using the same values in the 0000 UTC 19 October 2005 sounding (not shown) yields a larger CAPE of about 550 J kg^{-1}. Examination of the two soundings indicates there were significant changes occurring in the thermodynamic profile during the course of the afternoon and neither the 1200 UTC morning sounding nor the 0000 UTC evening sounding were representative of what occurred during the afternoon.

To assess the CAPE at times between the standard synoptic sounding times, Eta BUFR soundings from three nearby locations [Flagstaff (KFLG), Winslow (KINW), and Grand Canyon (KGCN)] were assessed for the period 1600-1900 UTC (Table 1). This corresponds to the period when all of the tornadoes occurred. In the table there are two entries for CAPE. The first is a surface-based CAPE (SBCAPE) and the second is a mean-layer CAPE (MLCAPE). The two values for CIN correspond to the SBCAPE and MLCAPE values.

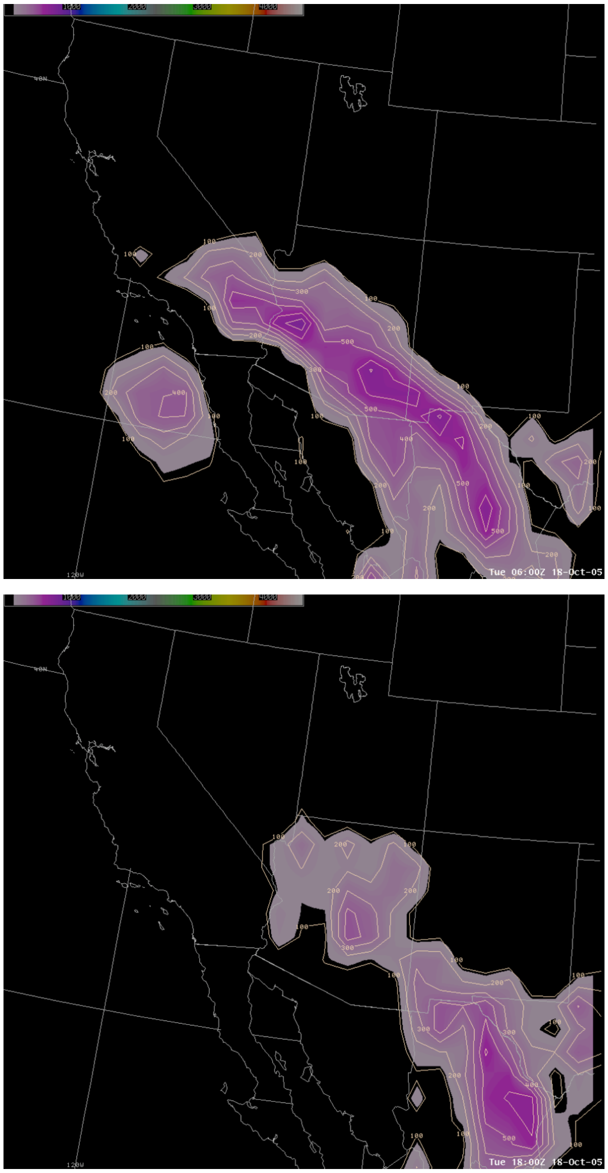

Figure 5. CAPE at (a) 0600 UTC and (b) 1800 UTC. Contours every 100 J kg^{-1}.

The results show that the SBCAPE values were generally larger than that observed from the 1200 UTC rawinsonde data but smaller than the 0000 UTC soundings from KFGZ. MLCAPE values were smaller than SBCAPE for all locations and times.

The areal distribution of CAPE from the 0600 UTC Eta model (Fig. 5a) was generally less than 600 J kg^{-1} primarily over southern and central Arizona with little or no CAPE over much of northern Arizona. This time corresponds to the period when the first series of hail producing supercells developed over central Arizona. Peak values of CAPE had diminished to about 300-400 J kg^{-1} by 1800 UTC and had shifted northward to include northern Arizona (Fig. 5b).

These results emphasize that while there were some differences in the estimated CAPE between the rawinsonde data and the model data, all clearly indicated that the convective instability was meager with values generally less than 300–400 J kg^{-1} over northern Arizona. These values all fall into the lowest quartile for tornadic storms in the climatology of Rasmussen and Blanchard (1998; hereafter RB98).

3.3 *Wind and Shear Analysis*

The approach of this low-pressure system resulted in strengthening winds aloft and increasing shear across the region. Deep-layer "bulk shear" in the 0–6 km layer is shown in Fig. 6. There is a broad area of bulk shear of ~25–35 m s^{-1} that is approaching and moving across Arizona during the morning and afternoon hours. These values correspond to the upper quartile for tornadic storms in RB98. Accompanying the deep layer shear were regions of large 0–3 km storm-relative helicity (SRH; Fig. 7). The values for the various times and sites range from ~135–360 m^2 s^{-2}, corresponding to the 2nd, 3rd and 4th quartiles in RB98. Clearly, these SRH and bulk shear values are large and should be considered strong contributing factors to the development of rotating storms with the potential for large hail and tornadoes.

3.4 *Composite Parameters*

The Energy-Helicity Index (EHI) (Hart and Karotky 1991; Davies 1993) indicated only low values across the region since it is a product of the SRH and CAPE and, as already noted, CAPE values were marginal for this event. Vorticity generation potential (VGP; RB98) was also low and for the same reason as EHI. Thus, both of these parameters, which have been shown by RB98 to signal which environments are supportive of supercells with tornadoes failed in this event because of the marginal instability.

4. RADAR ANALYSIS

Strong thunderstorms developed shortly after midnight local time (0700 UTC) and the first severe thunderstorm warning was issued at 0745 UTC. Radar imagery from this time (Fig. 8a) shows strong thunderstorms located between Flagstaff and Phoenix. These early morning storms from this band of convection generally resulted in large hail. Numerous reports of 1.0–1.5 inch hail were received during and after the event. As these storms moved rapidly to the north, at least a few were observed to split with both left- and right-moving storms.

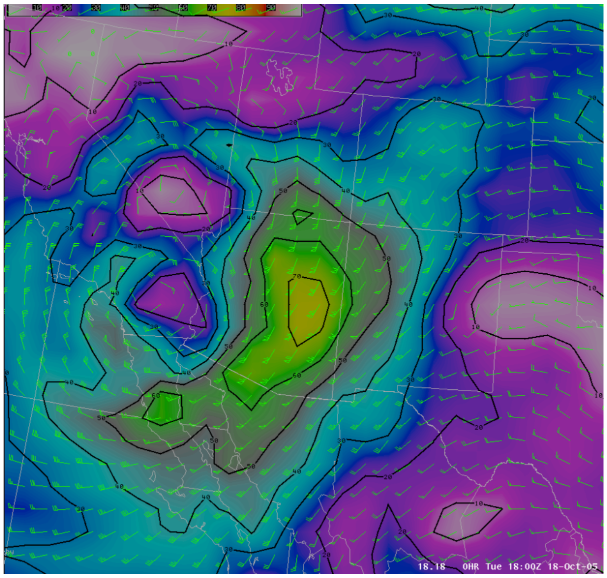

Figure 6. Deep-layer "bulk shear" in the 0–6 km layer for 1800 UTC 18 October 2005. Contour interval 10 knots (5 m s^{-1}).

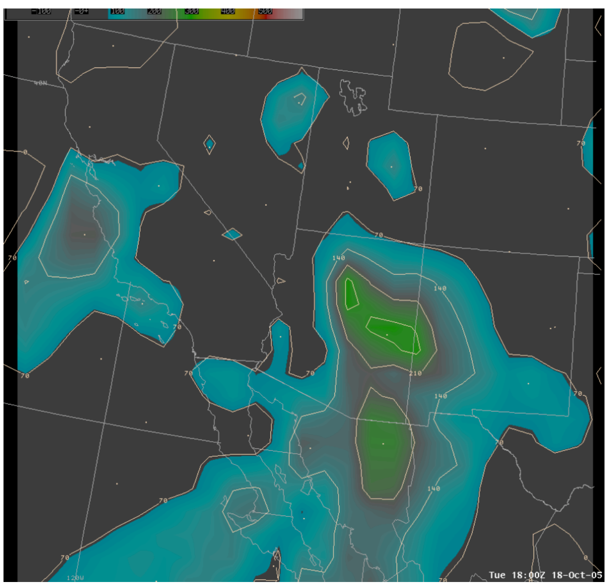

Figure 7. Storm relative helicity (SRH) for the 0–3 km layer for 1800 UTC. Contours every 70 m^{-2} s^{-2}.

Additional bands of convection developed during the late morning and early afternoon and were responsible for the tornadic activity that occurred. These bands can be seen in the radar data in Fig. 8b. The isolated supercell located just above (i.e., north) of the center of the image of Fig. 8b was responsible for an extremely long-lived supercell (> 6 h) and produced a long-track tornado (Bunkers et al 2006).

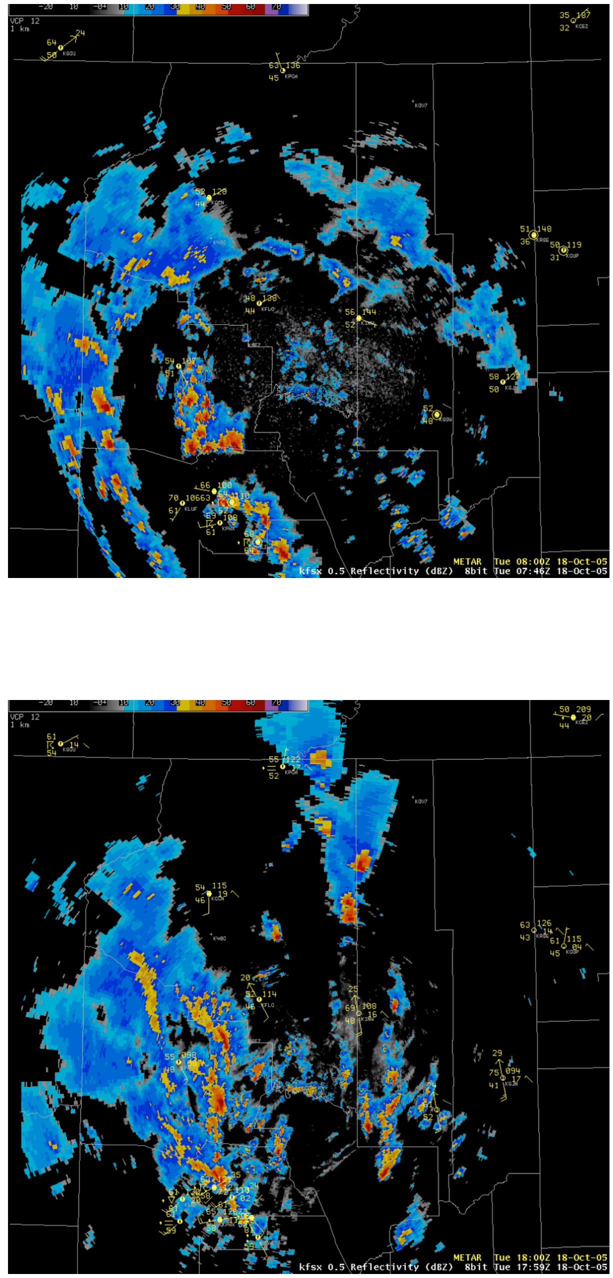

Figure 8. Radar images of reflectivity from KFSX. (a) 0749 UTC. Severe hail producing cells were located just to the lower-left of the image center. (b) 1759 UTC. Long-lived tornadic supercell is located just above (north) of the center of the image.

5. DISCUSSION

The thunderstorms that occurred over northern Arizona during the early morning and afternoon hours of 18 October 2005 constitute a severe weather outbreak. Four tornadoes were documented on this day. This compares with only eight tornadoes for all months of October from 1950–2004, inclusive.

The large-scale environment for this event, including buoyant instability and shear, was similar to the events documented by Monteverdi and Quadros (1994; hereafter MQ94) and Monteverdi et al (2003; hereafter MDL03) for central and northern California tornadoes. In their studies, they noted that CAPE was small but shear was large and even comparable to shear observed with springtime severe storms of the central Plains.

In fact, the CAPE for the event presented here was smaller than that observed in the studies by MQ94 and MDL03. Shear, however, was large and comparable to that observed by MQ94 and MDL03 as well as RB98.

The results from the current study—and those of MQ94 and MDL03—strongly suggest that large instability is not a requirement for the development of tornadoes within supercells if adequate deep-layer shear is also present. As noted by MDL03, "…the inference to be made is that there are various combinations of buoyancy and shear that permit supercell tonadogenesis. In low-buoyancy environments in which the deeper-layer shear is sufficient for supercells, vertical perturbation pressure gradient forces related to low-level shear are significant in augmenting the updraft..."

Clearly, the evidence is mounting that shear may at least as important as instability—and perhaps more so— and the forecaster must be ever vigilant for rotating thunderstorms with potential for tornadoes under a variety of instability/shear scenarios.

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Table 1. Stability and shear parameters from Eta BUFR soundings for three representative sites for the period 16–19 UTC. For CAPE, the first value is a surface-based CAPE (SBCAPE) and the second is a mean layer CAPE (MLCAPE). The two values for CIN correspond to the SBCAPE and MLCAPE values. Units of CAPE and CIN are J kg^{-1}; SRH has units of m^2 s^{-2}.

KGCN	**16 UTC**	**17 UTC**	**18 UTC**	**19 UTC**
CAPE	247/NA	268/30	190/31	319/59
CIN	-5/NA	0/-8	0/-5	0/0
SRH	161	199	224	260

KFLG	**16 UTC**	**17 UTC**	**18 UTC**	**19 UTC**
CAPE	199/NA	225/111	351/101	346/103
CIN	0/NA	0/0	0/0	0/0
SRH	273	348	360	360

KINW	**16 UTC**	**17 UTC**	**18 UTC**	**19 UTC**
CAPE	29/5	519/30	250/62	200/71
CIN	-32/-52	0/-44	0/-10	0/-8
SRH	136	188	210	249