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THE DEVELOPMENT OF SEVERE CONVECTION ALONG A DRY LINE IN NORTHERN ARIZONA

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1. INTRODUCTION

On the evening of 01 July 2013, several mesoscale convective systems (MCS) developed across northern Mexico. These MCSs produced substantial cold pools containing high θ_e air that surged northward into southern Arizona. The leading edge of this moist outflow triggered additional convection over southern Arizona that, again, produced a northward-moving surge of high θ_e air. This surge of moisture made it as far north as the higher terrain of the Mogollon Rim of northern Arizona.

On the afternoon of 02 July 2013, strong-to-severe convection developed along the moisture boundary. During the day, the moist surge retreated to the south. With deep-layer northerly flow aloft, storms that developed along this dryline-like boundary moved southward and into the lower elevations while remaining in proximity to the dryline.

This mesoscale environment is similar to that which occurs in the central United States as large MCSs produce cold pools and outflows that progress westward into the drier higher-elevation regions of the high Plains. Comparisons are made between the dryline convection in these two locations.

2. ENVIRONMENTAL OVERVIEW

The "North American Monsoon"(Douglas et al., 1993; Adams and Comrie, 1997) is noted for a shift in wind patterns in summer as portions of Mexico and the southwest United States warm under intense solar heating. The large-scale pattern aloft evolves as the subtropical high migrates northward allowing a southerly flow to develop which is effective in transporting low-level moisture northward from the Gulf of California and the eastern Pacific. Initially, only modest increases of moisture occur across Arizona during late June and early July often leading to high-based thunderstorms with little measurable precipitation. More significant increases occur as successive pushes of moist low-level outflow from MCSs develop on an almost daily basis across northern Mexico. In addition, mid-tropospheric moisture increases and temperature decreases as the upper-level high shifts northward. Over a period of several days to a week or more, the modest increases in moisture initially experienced across Arizona become more substantial leading to robust thunderstorms producing copious amounts of rainfall. A characteristic of this transitional period is the thermal structure evolution as the dry adiabatic lapse rate and low mixing ratio is replaced by a more stable lapse rate and moderate-to-high mixing ratio.

During this event, a large anticyclone aloft (Fig. 1) was centered over the Great Basin with a deep layer of northeasterly flow across Arizona. This corresponds to the Type II pattern for central Arizona severe weather discussed by Maddox et al. (1995). This flow aloft was advecting warm and dry air across northern Arizona (Fig. 2) with near dry adiabatic lapse rates (9.7 °C km^{-1} 700–500 mb) and low values of precipitable water (1.5 cm) at 0000 UTC 02 July 2013.

On the evening of 01 July 2013, several MCSs developed across northern Mexico (Fig. 3). Over a period of hours these generated a surface-based cold pool.

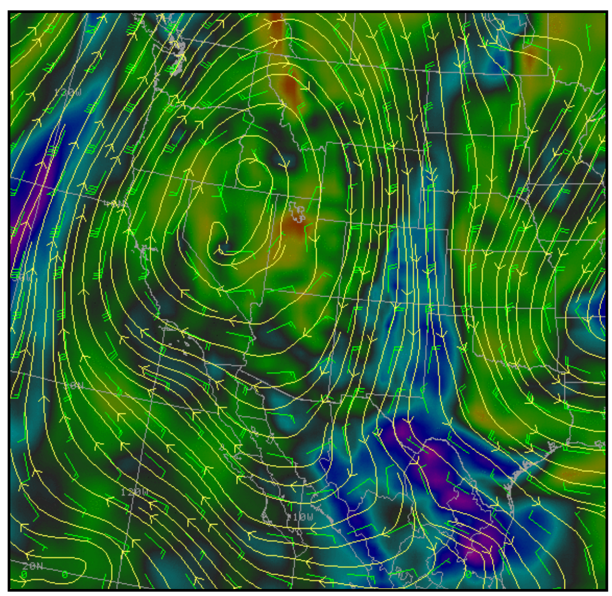

Figure 1. Streamlines and wind barbs are shown for the 700–300 mb layer at 0000 UTC 02 July 2013. Image background depicts the 850–500 mb mean relative humidity with higher (lower) humidity represented by cooler (warmer) colors.

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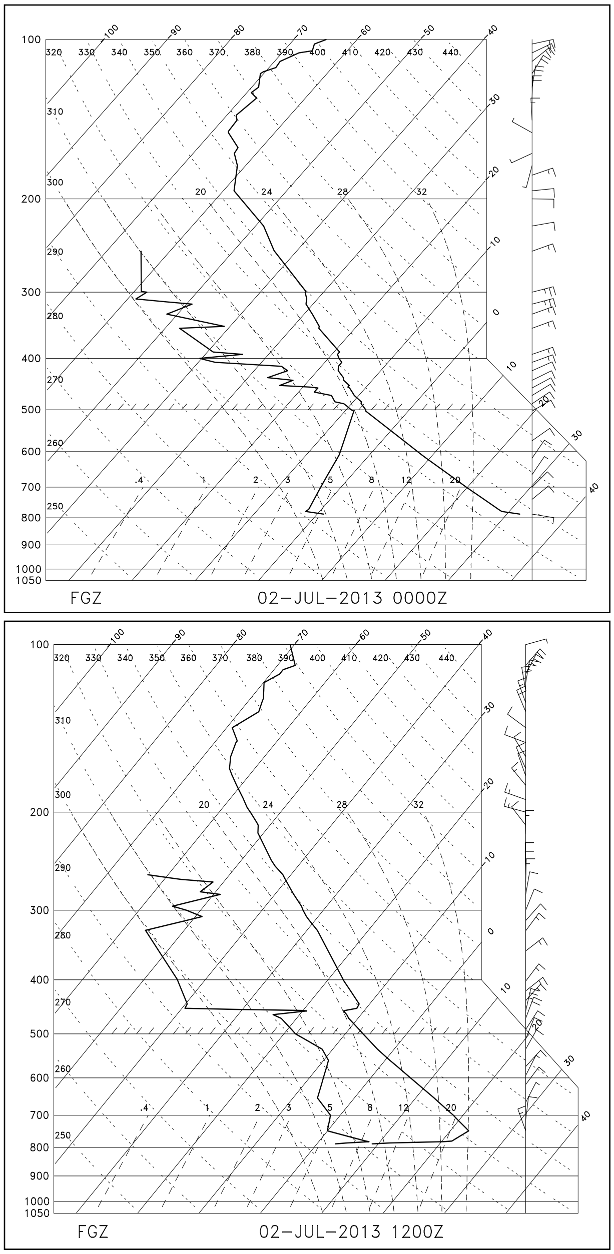

Figure 2. Skew T–ln p for Flagstaff, AZ (KFGZ) at 0000 UTC 02 July 2013 (top) and 1200 UTC (bottom).

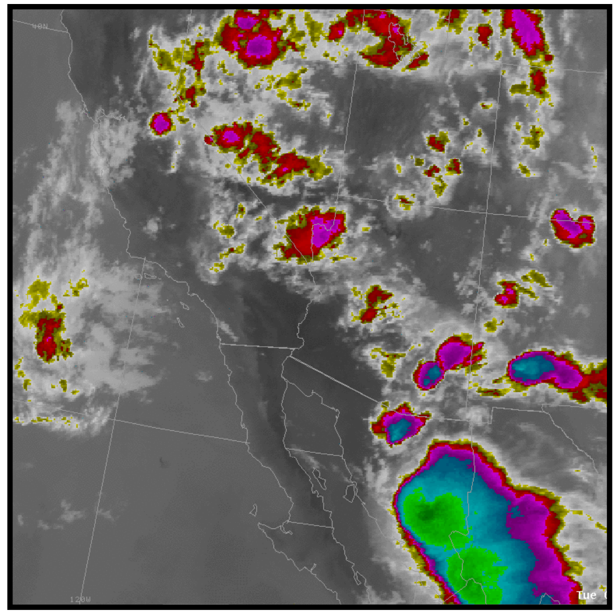

Figure 3. IR satellite image from 0300 UTC 02 July 2013 showing the large convective complexes across northern Mexico.

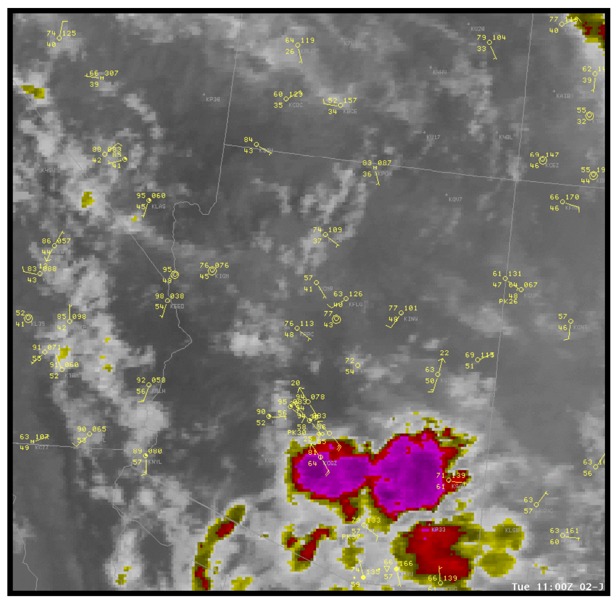

Figure 4. IR satellite image from 1100 UTC 02 July 2013. Additional convective complexes have developed across southern Arizona.

Inspection of satellite imagery and surface observations indicate that these outflows moved northward and into southern Arizona during the late evening with surface dewpoints increasing from the middle/upper 40's to the upper 50's (°F) along with an increase in southeasterly winds. Ongoing high-based and weak convection moving southwestward encountered this moisture boundary and intensified resulting in several new convective clusters developing across southeastern Arizona (Fig. 4).

3. STORM ENVIRONMENT

Significant increases in buoyant energy were realized during the afternoon owing to the substantial increase in low-level moisture overlain by a nearly dry adiabatic lapse rate. A more typical pattern early in the North American Monsoon is for gradually increasing precipitable water accompanied by a concurrent transition from a dry adiabatic lapse rate towards a more stable lapse rate. Consequently, even with the increases in

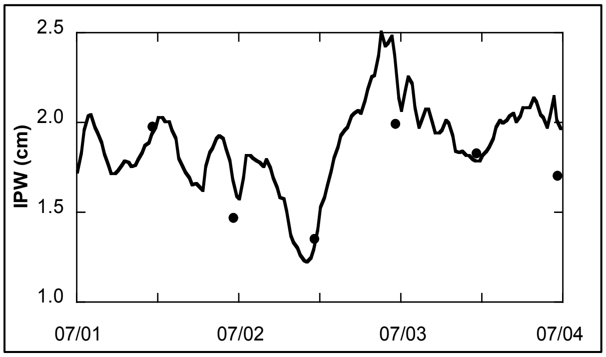

Figure 5. GPS integrated precipitable water (solid line) and KFGZ rawinsonde (dots) from 0000 UTC 01 July 2013 through 0000 UTC 04 July 2014.

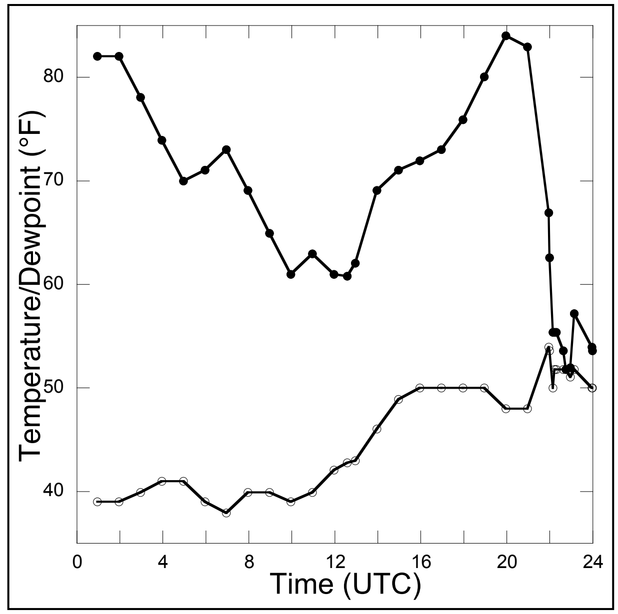

Figure 6. Temperature (top; closed circles) and dewpoint (bottom; open circles) recorded at the KFLG ASOS between 0000 and 2400 UTC 02 July 2014.

moisture, the less steep lapse rates generally limit the amount of available buoyant energy.

The 1200 UTC KFGZ sounding (Fig. 2) suggested an afternoon CAPE of ~525 J kg^{-1}. The morning sounding, however, was taken prior to the passage of the outflow boundary and sampled the drier air that was present across northern Arizona. GPS integrated precipitable water (GPS-IPW; Fig. 5) indicates that a substantial increase in moisture occurred after the 1200 UTC sounding, then peaked and decreased before the evening sounding. A similar trend can be seen in the dewpoint from the KFLG ASOS site (Fig. 6).

Using the temperature and dewpoint from the KFLG ASOS site at the onset of convection (T/Td: 29°C/9°C) produced CAPE values that were closer to 2000 J kg^{-1}. This value is the 98th percentile for CAPE measured at KFGZ and ranks in the 4th quartile for severe storms (Rasmussen and Blanchard, 1998). It is likely that the extreme value of CAPE was a contributing factor for several storms producing large hail (2–4 cm) and rainfall rates that produced over 2.5 cm of rain in under 10 minutes at the Flagstaff airport.

Radar imagery from 1933 UTC (Fig. 7) shows the boundary located from just north of Flagstaff extending eastward to near Winslow with the first indications of convective development along the boundary. About one hour later (2029 UTC), strong storms were developing near and northeast of Flagstaff and these would become severe and produce large hail across portions of the city.

The deep-layer flow was from the northeast and storms moved to the southwest during the afternoon. The moisture boundary was retreating to the south likely as a result of both the large-scale flow as well as vertical mixing along the northern edges. The motion of the storms relative to the boundary was sufficient to keep them over the moist layer and storms remained severe for several hours.

4. DISCUSSION

Several MCSs that developed across northern Mexico and southern Arizona were instrumental in producing a surge of high θ_e air that moved into northern Arizona. The rapid increase in moisture occurred in an environment with a nearly dry-adiabatic lapse rate resulting in a substantial increase in buoyant energy. Mid day CAPE was estimated to be around 2000 J kg^{-1} which ranks in the 98th percentile for this location. The result was several strong, long-lasting storms that produced large hail and torrential rainfall across portions of northern Arizona during the afternoon.

This event is similar to what can occur across the High Plains when an MCS sends a moist outflow westward into the higher terrain. The leading edge of the outflow may provide sufficient low-level convergence to initiate deep, moist convection. Once initiated, these storms are likely to move with the deep-layer mean wind towards the east and remain in contact with the enhanced low-level moisture.

Doswell (1980), in his examination of synoptic and mesoscale environments conducive to High Plains severe weather, discussed an event in which the outflow from an earlier MCS played a role by importing moisture westward into the higher elevations and creating a boundary with sufficient convergence to act as a trigger for deep, moist convection. Similar results were documented by Zipser and Golden (1979). They found that the severe weather and tornadoes that developed in

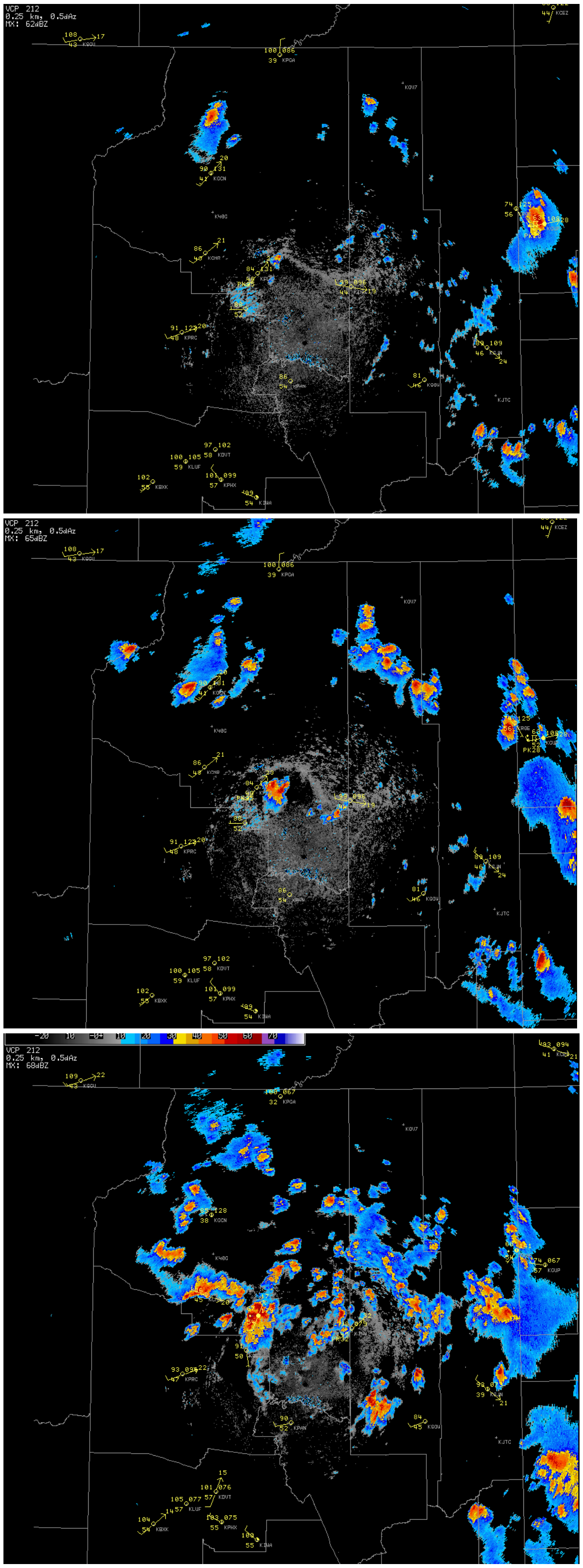

Figure 7. Reflectivity from KFSX WSR-88D radar at 1933 UTC 05 July 2014 (top), 2029 UTC (middle) and 2222 UTC (bottom).

eastern Colorado could be attributed, in part, to a strong mesoscale high-pressure system that developed over Nebraska and pushed an outflow boundary westward into the higher terrain providing enhanced upslope flow and increased low level moisture.

Weaver and Toth (1990) found that the westward-moving outflow from an overnight MCS in Wyoming and Nebraska provided a slightly capped but extremely unstable source of buoyant energy for damaging hailstorms that developed along the Colorado Front Range the following afternoon. Weaver and Purdom (1994) discussed an eastern Colorado tornado and were able to show that an early morning MCS in Kansas and Nebraska played an important role in later storm evolution. They noted that the presence of mesoscale outflow air masses lasting far beyond the convective event was not unique and that such air masses can propagate considerable distances from their parent storm complexes.

McCollum et al. (1995) examined a severe weather event over central Arizona that exhibited some similarities to this event. Most notably, a dramatic increase in buoyant instability occurred as low-level winds increased in speed and veered advecting high θ_e air into the region. In contrast, no prior MCSs were noted in the area and moist outflows were not a likely cause of this advective process.

The northward push of moisture across Arizona is a normal process associated with the transition from the dry and hot late spring into the moist environment of the summertime North American Monsoon. What made this convective event noteworthy was the rapid increase in low-level moisture that was overlain by a near dry-adiabatic lapse rate resulting in large buoyant instability. The push of high θ_e air from mesoscale convective systems into a drier environment with steep lapse rates and producing severe thunderstorms has been previously documented across the High Plains but has been less well-described in Arizona.

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