METEOROLOGICAL ASPECTS OF THE 2006 EL PASO TEXAS METROPOLITAN AREA FLOODS

Joseph Rogash
Mike Hardiman
Dave Novlan
Tim Brice
Val MacBlain

NOAA/National Weather Service
Weather Forecast Office
Santa Teresa, New Mexico/El Paso, Texas

Abstract

The summer monsoon of 2006 was historically wet across far western Texas, south central and southwestern New Mexico. Numerous mesoscale convective systems produced excessive rainfall with attendant and at times destructive flash floods. Heavy rainfall and flooding were particularly severe over El Paso, Texas and adjacent communities where flood damage estimates approached $450 million. The occasionally torrential rains around this area fell between 27 July and 4 August, and were particularly heavy during the morning and early afternoon of 1 August when 3 to 10 inches (75 to 250 mm) of rain fell. This resulted in flooding which severely damaged portions of the region and forced the Rio Grande to overflow as the river reached its highest level since 1912. The series of convective storms occurred in an environment which included unusually high and deep moisture content, weak to moderate instability, and minimal convective inhibition. Light wind speeds with little vertical wind shear through the cloud layer resulted in slow-moving or upstream-propagating cells. Storm initiation and sustenance over the nine day period was due to a combination of several middle-tropospheric troughs (including a convectively enhanced vortex), sustained upslope wind flow over high terrain, and weak surface boundaries. Using buoyancy to derive updraft strength, theoretical sub-cloud moisture convergence, and cloud condensation rates, two techniques were explored to derive rainfall intensities for the 1 August convection. It was determined that for this event, theoretical sub-cloud moisture convergence values provided results consistent with observations. From a climatological perspective, the heavy rainfall episode greatly contributed to daily, monthly, and seasonal records for the El Paso metropolitan area, with the summer monsoon of 2006 becoming the wettest on record.

Corresponding Author: Joseph Rogash
NOAA/National Weather Service,
7955 Airport Road, Santa Teresa, New Mexico 88008
Email: Joseph.Rogash@noaa.gov

1. Introduction

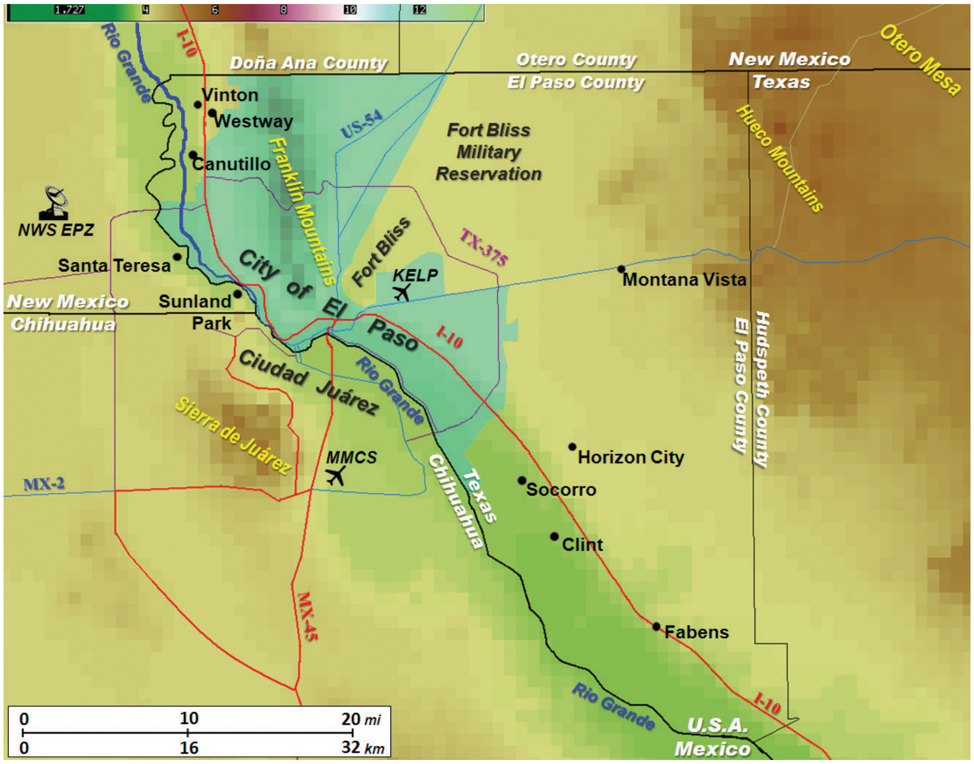


Fig. 1. Topographical map of the El Paso Metropolitan Area (city limits shaded in aqua) showing terrain elevations and pertinent geographical features of western Texas, southern New Mexico,and the adjacent region of Mexico. Principal cities, towns, roads, and airports are also denoted. NWS EPZ represents location of Santa Teresa National Weather Service Office. Elevations are in thousands of feet and shaded as shown by scale at top left.

Heavy rainfall during the summer of 2006 was especially destructive across far western Texas and south central and southwestern New Mexico with the resultant flooding causing at least $450 million damage across the region. Precipitation amounts were especially extreme around the El Paso Texas Metropolitan Area (EPMA; Fig. 1) with the El Paso International Airport (El Paso location in Fig. 1) measuring 15.01 in (375 mm) of rain from July through September. This made it officially the wettest monsoon on record. However, some cooperative observers reported over 30 in (750 mm) of rainfall for the period, with severe water and flood-related damage occurring. During the summer, the Rio Grande overflowed several times in and around the city after attaining its highest levels since 1912, while numerous other smaller rivers and arroyos reached flood stage. Rainfall amounts over the summer were over 300% of normal based on 128 years of data collection. Flood related damage for the EPMA alone was estimated by local officials to have been nearly $400 million for the season.

The rainfall was primarily produced by a number of mesoscale convective systems (MCS; Maddox et al., 1986) which developed over or moved across the Santa Teresa National Weather Service Forecast Office (NWSFO) County Warning Area (KEPZ-CWA; Fig. 2) during the three month period. For the EPMA, which suffered most of the damage, flooding was especially pronounced when a series of convective storms produced heavy rains over or within 100 km of the city limits between 27 July and 4 August 2006. This included the extreme heavy rain event of 1 August when 3 to 10 in (75 to 250 mm) of rain fell over western portions of the city and adjacent locations in western Texas and southern New Mexico.

While the climate of far western Texas, southwestern and south central New Mexico is considered semi-arid or desert during the warm season, the region frequently experiences deep convection which can produce attendant heavy rainfall and flash flooding, especially when particular synoptic-scale weather patterns exist (Maddox et al. 1980; Rogash 2003). However, for most cases over the southwestern United States, flash flood events may persist several hours over a very limited area with little or no heavy rains falling on succeeding days or even for the remainder of the summer period in the vicinity of the affected location. By contrast, flash flood events during the summer of 2006 sometimes affected several locations separated by at least 100 km within a 12 hour period, and locally heavy rains fell on a given area on multiple and even consecutive days during the summer. This is especially true for the EPMA which experienced at least 14 summer heavy rain events where 2 in or more of rain fell within 6 hours.

Heavy rains and flash flooding have brought an increasing threat to the KEPZ-CWA as the population continues to expand and increase across locations susceptible to flooding, particularly in low lying areas, near rivers and arroyos, and along sloping terrain where runoff can be intense. Unfortunately, forecasting heavy rain during the warm season over our region can be more difficult and challenging than over central and eastern portions of the United States. Quantitative precipitation forecasts (QPF) from numerical models generally perform poorly for the southwestern United States (Junker et al. 1992; Dunn and Horel 1994). The lack of data over northern Mexico also hinders the forecasting process since moisture and weather systems associated with flash floods often move northward into the southwestern U.S. by way of Mexico.

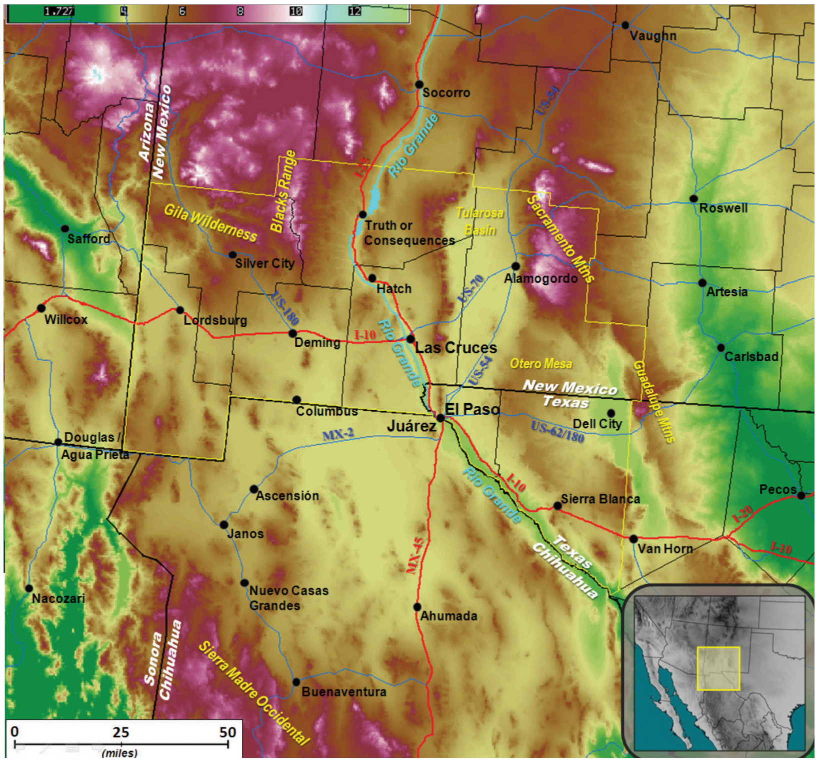


Fig. 2. Topographical map of the Santa Teresa-El Paso County Warning Area (KEPZ-CWA; denoted by thin yellow line) and adjacent areas. Elevations are represented as in Fig. 1.

The topography of the KEPZ-CWA (Fig. 2) including the EPMA (Fig. 1) is rather complex, with elevations ranging from 1100 to 3050 m (3,600 to 10,000 ft) from the desert lowlands to the higher mountains comprising southern portions of the Rocky Mountain chain. This includes the Franklin Mountains which extends through western portions of the city of El Paso. As documented by Maddox et al. (1978), Novlan (1978) and Pontrelli et al. (1999), moist upslope flow over higher terrain can support deep moist convection which produces extreme rainfall amounts.

The character of the terrain itself can determine the degree of the flood threat since soil absorption and the configuration of the local geography can greatly influence such factors as the runoff and drainage of rainfall (Runk and Kosier 1998). Climatology also plays an important role in the forecasting process. Many, if not most, heavy rain events are very infrequent for specific locations in the southwest, suggesting operational meteorologists may lack experience in anticipating major flash flooding. Thus, it is important to understand and recognize the weather patterns which lead to excessive rain situations across the region in order to more accurately anticipate and forecast such phenomena and reduce the threat to life and property.

This paper will examine meteorological aspects of the 27 July to 4 August, 2006 period when flash flood-producing heavy rains moved repeatedly across the EPMA. In particular, this study will provide an overview of the synoptic and meso-alpha scale (approximately 1000-100 km) characteristics of the environment which make conditions particularly conducive for heavy rainfalls, and further examine the storm scale features of the event, especially for the exceptionally damaging torrential rains and flash floods on 1 August.

2. Data and Methodology

Meteorological data for the 27 July to 4 August period includes objectively and subjectively analyzed surface and upper-air data obtained from the standard National Weather Service (NWS) data collection network. In addition, because of the scarcity of data around the region, especially over northern Mexico, wind, temperature and moisture data from both the 80 km and 12 km resolution North American Mesoscale Weather Research and Forecast Model (NAM) and the 40 km resolution Rapid Update Cycle (RUC) model (Benjamin et al., 1994) are applied to present a more complete illustration of the synoptic and meso-alpha scale meteorological scenarios. These models are also applied in the derivation of relevant dynamic and kinematic fields related to deep convection and heavy rainfall. Air mass and vertical wind characteristics are determined from the rawinsonde launched at the NWSFO in Santa Teresa (KEPZ), New Mexico which is located within 120 km of almost all heavy rain and flash flood events described in this study. Archived radar reflectivity and wind velocity data obtained from the NWS Weather Surveillance Doppler Radar (WSR-88D), also located at Santa Teresa, were utilized to investigate storm-scale aspects of the events. Geostationary Operational Environmental Satellite (GOES) images were also examined to observe certain cloud features related to the convection.

Archived Automated Surface Observing System (ASOS) and official Cooperative Observer rainfall data were obtained from the National Climatic Data Center (NCDC). Special multi-sensor analyses of storm rainfall distribution were obtained using observing sites such as ASOS and El Paso's official cooperative observer or storm spotter network established to collect rainfall data used for hydrological purposes by the NWS' West Gulf River Forecast Center. Rainfall amounts were also estimated in data void areas using precipitation totals derived from the KEPZ WSR-88D. Precipitation analyses were further analyzed on a plan view reference using ArcGIS software.

3. Meteorological Overview of the 27 July-4 August 2006 Flash Floods

a. 27-31 July 2006 period

1) Synoptic and mesoscale conditions on the night of 27-28 July 2006

The sequence of events for the EPMA's prolonged period of heavy rains began during the evening of 27 July. As is typical for the southwestern United States during the summer, the meteorological scenario included a quasi-barotropic environment with weak pressure and thermal gradients and light winds through a deep layer of the troposphere; as the polar jet stream was located far north of the region. The 0000 UTC 28 July 2006 500 mb height and wind field, based on both raw data and the NAM initialization (Figs. 3a-b), suggested a poorly defined, positively-tilted trough axis extending from north central New Mexico southwestward to near the southern Arizona-New Mexico border. NAM derived layer-averaged 700-500 mb omega fields (Fig. 3c) showed that upward motion covered the EPMA east of the trough with weak subsidence to the west. Surface analyses at 0000 UTC

Fig. 3-a

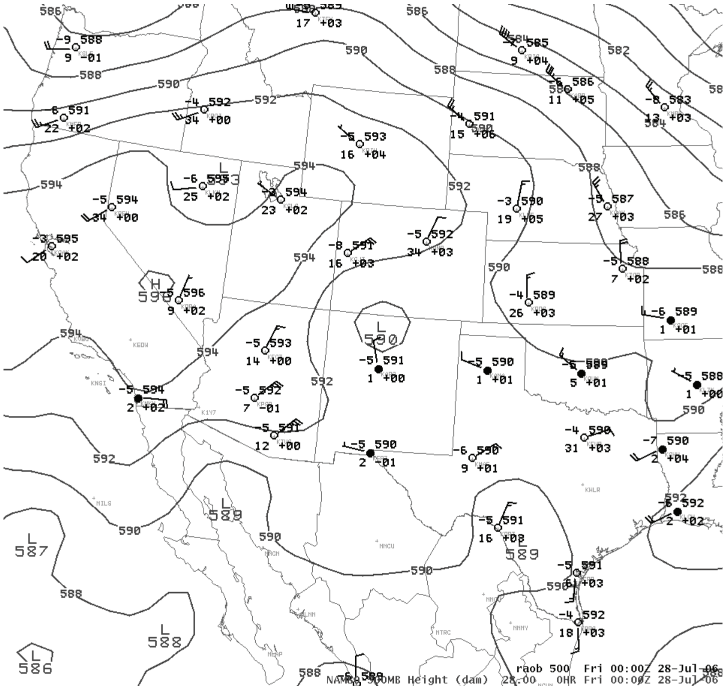


Fig. 3-b

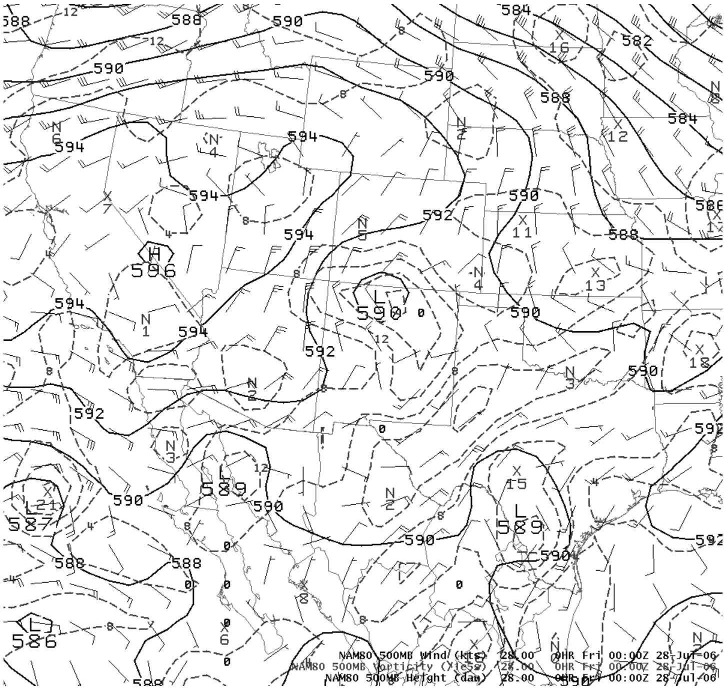


Fig. 3-c

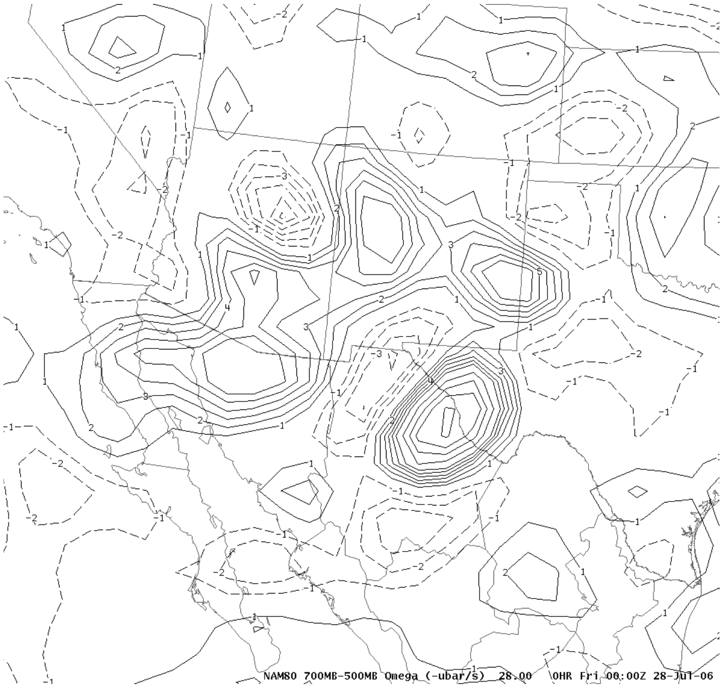


Fig. 3.

a) The 500 mb analyses valid 0000 UTC 28 July 2006. Solid lines represent geopotential heights in dm. For this plot, numbers from top to bottom are height (in dm), temperature, and dewpoint in ^{o} C. A half wind barb is 2.5 m s^{-1}, a full wind barb 5 m s^{-1}, and pendant is 25 m s^{-1}.

b) The 500 mb wind and vorticity analyses as initialized by the 0000 UTC 28 July 2006 NAM model. Dashed lines show absolute vorticity in units of 10^{-5} s^{-1}. Geopotential heights and winds are as in Fig. 3a.

c) The 0000 UTC 28 July 2006 layer-averaged 700-500 omega based on the NAM model initialization. Units are in -μb s^{-1} with solid lines indicating upward motion and dashed lines indicating subsidence.

28 July 2006 (Fig. 4) included a westerly ageostrophic flow across southern New Mexico into far western Texas induced by high pressure over western Arizona and a weak surface low covering southeastern New Mexico. While westerly winds are usually associated with dry air transport in this region most of the year, an examination of wind and dewpoints reveals that in this event the flow was transporting ample low level moisture into the EPMA from northwestern Mexico and southern Arizona, where upstream dewpoints were at least 60° F. Meanwhile a weak cold front and outflow boundary approaching the EPMA from the north, entered the EPMA just after 0300 UTC.

2) Upper air conditions on the night of 27-28 July 2006

Sounding data at 0000 UTC 28 July 2006 (Fig. 5) showed that while instability was weak with a MUCAPE (most-unstable convective available potential energy) of only 260 J kg^{-1}, little convective inhibition (CINH) was present and the air mass was rather moist with a precipitable water (PW) amount of 1.34 in (34 mm), a value 150% of normal. The vertical wind profile

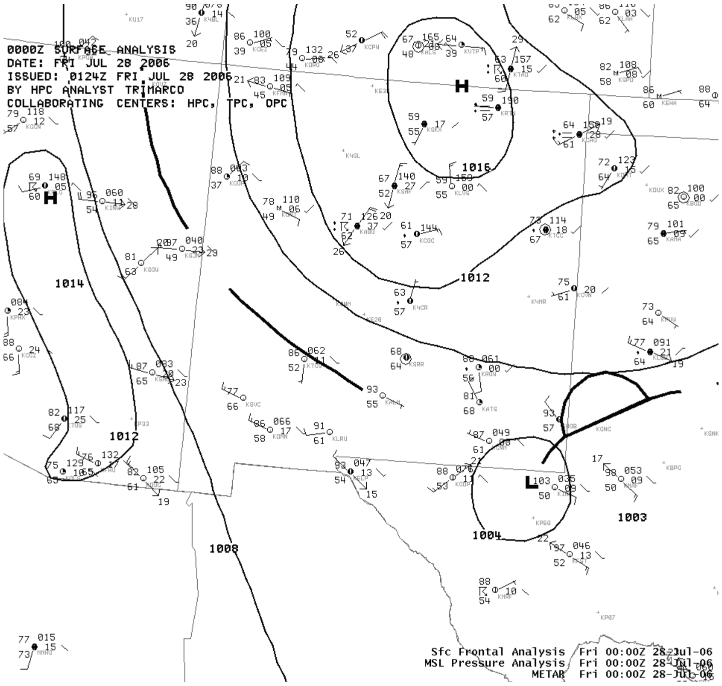
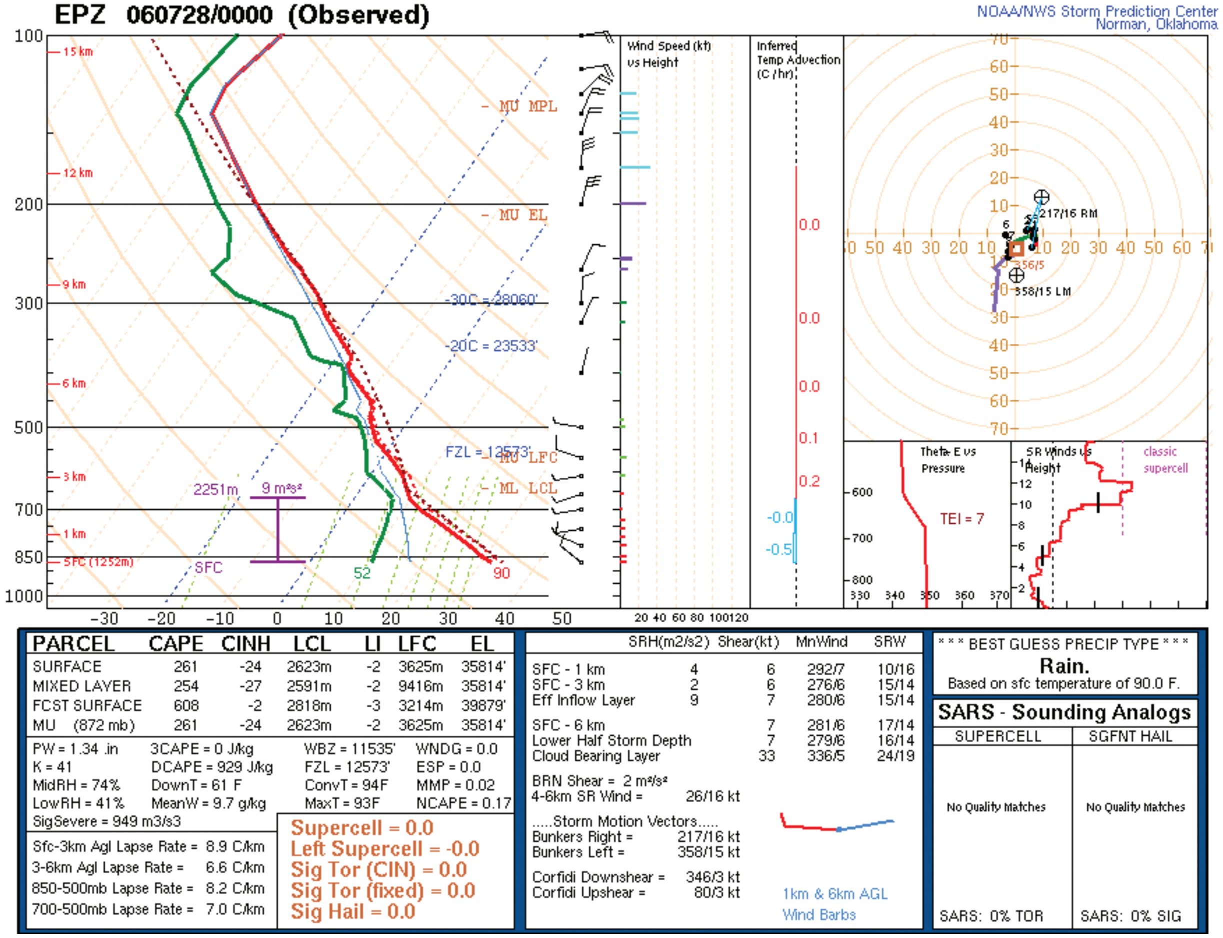


Fig. 4. Surface analyses for 0000 UTC 28 July 2006 from Hydrometeorological Prediction Center (HPC). Station model and synoptic scale feature analyses are standard with temperature and dewpoint in F° and pressure in mb. Heavy dashed line denotes trough.



PARCEL	CAPE	CINH	LCL	LI	LFC	EL
SURFACE	261	-24	2623m	-2	3625m	35814'
MIXED LAYER	254	-27	2591m	-2	9416m	35814'
FCST SURFACE	608	-2	2818m	-3	3214m	39879'
MU (872 mb)	261	-24	2623m	-2	3625m	35814'

PW = 1.34 in 3CAPE = 0 J/kg WBZ = 11535' WNDG = 0.0
K = 41 DCAPE = 929 J/kg FZL = 12573' ESP = 0.0
MidRH = 74% DownT = 61 F ConvT = 94F MMP = 0.02
LowRH = 41% MeanW = 9.7 g/kg MaxT = 93F NCAPE = 0.17
SigSevere = 949 m3/s3

Sfc-3km Agl Lapse Rate = 8.9 C/km
3-6km Agl Lapse Rate = 6.6 C/km
850-500mb Lapse Rate = 8.2 C/km
700-500mb Lapse Rate = 7.0 C/km

Supercell = 0.0
Left Supercell = -0.0
Sig Tor (CIN) = 0.0
Sig Tor (fixed) = 0.0
Sig Hail = 0.0

	SRH(m2/s2)	Shear(kt)	MnWind	SRW
SFC - 1 km	4	6	292/7	10/16
SFC - 3 km	2	6	276/6	15/14
Eff Inflow Layer	9	7	280/6	15/14
SFC - 6 km		7	281/6	17/14
Lower Half Storm Depth		7	279/6	16/14
Cloud Bearing Layer		33	336/5	24/19

BRN Shear = 2 m²/s²
4-6km SR Wind = 26/16 kt

.....Storm Motion Vectors.....
Bunkers Right = 217/16 kt
Bunkers Left = 358/15 kt

Corfidi Downshear = 346/3 kt
Corfidi Upshear = 80/3 kt

* * * BEST GUESS PRECIP TYPE * * *
Rain.
Based on sfc temperature of 90.0 F.

SARS - Sounding Analogs

SUPERCELL	SGFNT HAIL
No Quality Matches	No Quality Matches
SARS: 0% TOR	SARS: 0% SIG

Fig. 5. The 0000 UTC 28 July 2006 sounding from Santa Teresa, NM (KEPZ) plotted on a standard skew T-log p diagram, along with parameters computed from this sounding.

exhibited low wind speeds less than 5 m s^{-1} (10 kt) through the cloud layer, indicating that individual convective cells would move slowly. In addition, as described by Chappel (1986) and Corfidi et al. (1996), the movement of a multi-cell MCS may differ from the motion of its individual cells, depending on the vertical wind shear. More specifically, Corfidi et al. (1996) determined for a moist air mass that if the wind velocity near cloud base equals or exceeds the flow aloft, the convective system will contain updrafts which will develop or propagate upstream of mean cell motion; a process often referred to as "back-building" (Schumacher and Johnson 2005). Using the technique described by Corfidi and his colleagues, the forecast MCS motion for the 28 July case had a near-zero velocity vector, strongly suggesting that an MCS would exhibit upstream propagation of cells, or at least very slow movement.

3) Evolution of storms on the night of 27-28 July 2006

In the hour leading up to 0000 UTC 28 July 2006, slow moving showers and thunderstorms rapidly developed over the Hueco Mountains and surrounding high terrain (east of the EPMA; see Fig. 1), where westerly upslope flow occurred. This activity slowly expanded into the EPMA. Thereafter, heavy rainfall spread across northern Hudspeth County into northeastern El Paso County by 0118 UTC (Fig. 6a). By 0314 UTC, a MCS is evident. The MCS exhibited little movement from the previous 2 hours, although its core of heaviest rainfall amounts translated westward with time (Fig 6b). Observations from storm spotters and radar data indicated that over 2 in (50 mm) of rain fell within a 3 hour period across portions of northwestern Hudspeth and northeastern and southern El Paso counties. Widespread street flooding occurred, while debris from a flooding arroyo damaged homes in Clint and left a layer of mud 4 ft deep over a portion of the town.

At 0612 UTC, strong thunderstorms now covered much of the KEPZ CWA with a secondary axis of deep convection well to the west, oriented along a northeast to southwest axis through southeastern Arizona (Fig. 7). The corresponding GOES IR image at 0615 UTC (Fig. 8) displayed a broad area of cold clouds that indicated the presence of two convective systems. In addition, clouds on the IR images from 0600-1200 UTC (not shown) exhibited a well-defined cyclonic circulation which suggested the flow aloft may have been more intense or organized than the limited and sparse raw data showed. As documented by Menard and Fritsch (1989) and Bartels and Maddox (1991), deep-layer wind and temperature changes, and adjustments induced by longer-lived convective systems encompassing larger areas can generate cyclonic vortices in the middle and even upper troposphere. Such vortices can persist for several days. These convectively-induced midlevel cyclonic vortices may be coupled to a strongly divergent flow at higher

Fig. 6-a

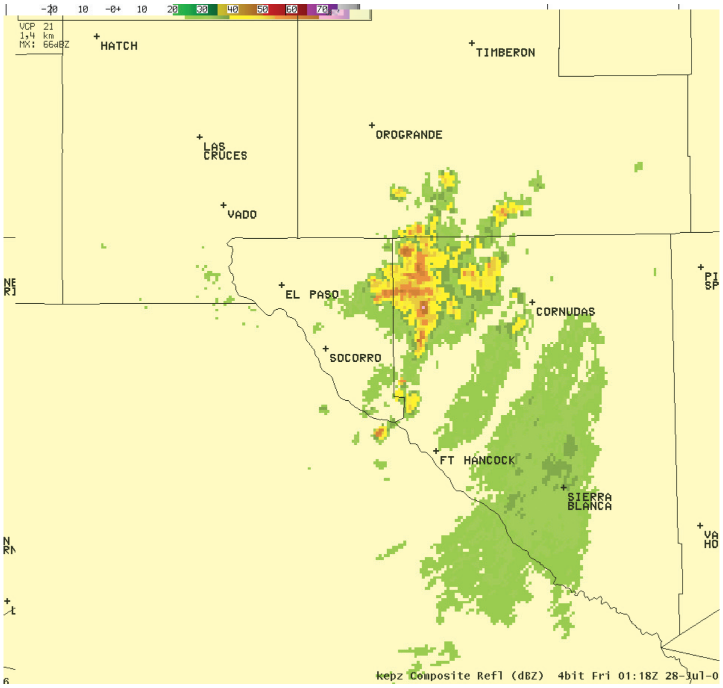


Fig. 6-b

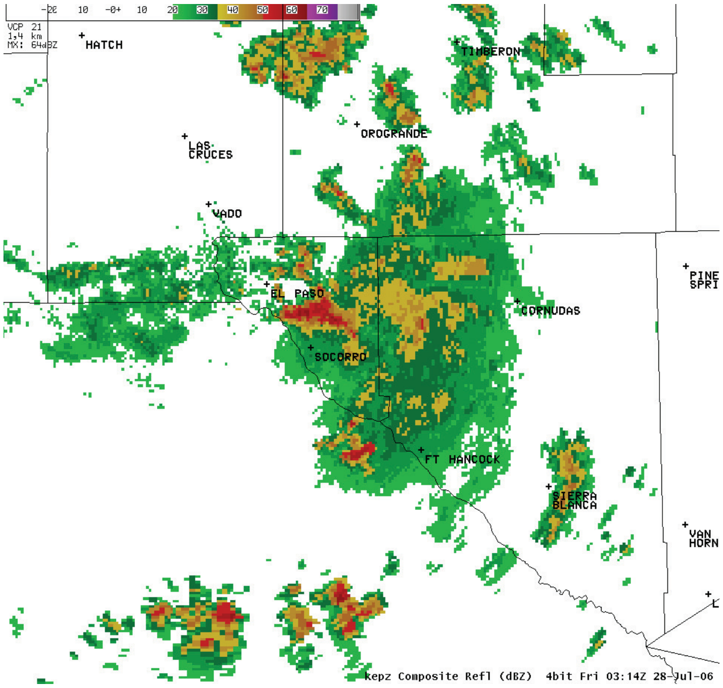


Fig. 6. (a) KEPZ composite reflectivity image at 0118 UTC 28 July 2006. Top left shows dBZ scale. **(b)** KEPZ composite reflectivity image at 0314 UTC 28 July 2006.

levels, differential positive vertical vorticity advection (DPVA), and upward vertical motion; all of which can contribute to the initiation of deep convection in a conditionally unstable environment in the following days.

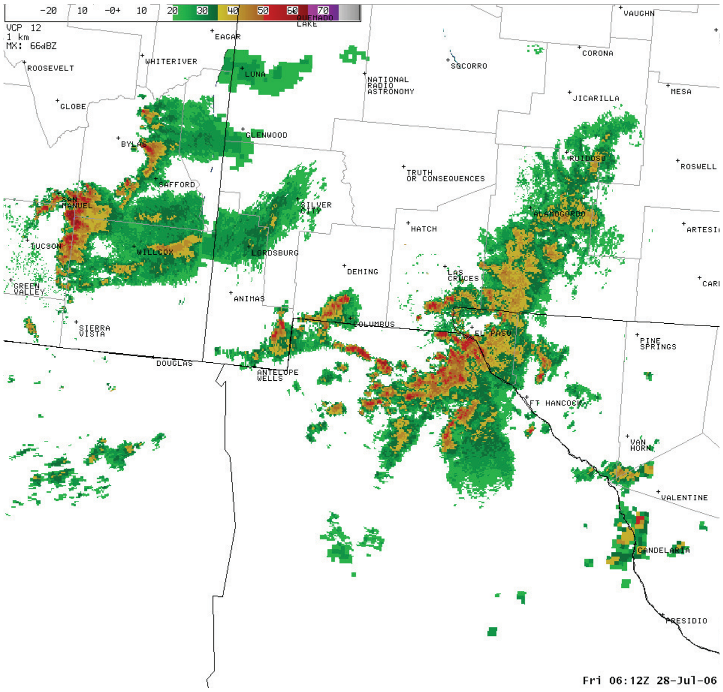


Fig. 7. Regional composite reflectivity image at 0612 UTC 28 July 2006. Top left shows dBZ scale.

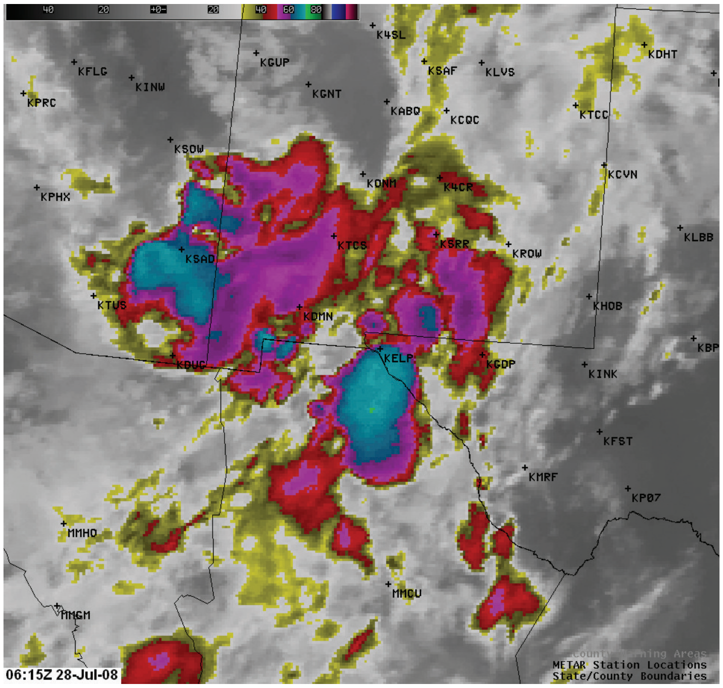


Fig. 8. GOES-8 IR imagery for the southwestern United States at 0615 UTC 28 July 2006. Scale denoting cloud top temperatures in degrees C is shown at top left. Locations of stations reporting surface weather are shown in black.

4) Synoptic and mesoscale conditions on morning of 28 July 2006

Upper air data available at 1200 UTC 28 July 2006 further suggested that overnight convection probably enhanced the initially weak vortex over the region during the previous 12 hours. Limited wind and height data for 500 mb (Fig. 9a) showed the closed cyclonic circulation centered over west-central New Mexico to be even better defined than at 0000 UTC. The more detailed data from the NAM model calculated a 500 mb vorticity maximum value of 22 x 10^{-5} s^{-1} located over north central New Mexico (Fig. 9b), but this was based on an initialized 500 mb wind speed of under 5 m s^{-1} at Santa Teresa. This is significantly less than a measured speed of 12 m s^{-1}, suggesting that the initialized model had filtered or did not include the convective modifications of the wind field produced by the MCS. As a result, middle-tropospheric vorticity and vorticity advection values (not shown) were probably underestimated by the NAM. The 250 mb NAM (Fig. 9c) does detect the pronounced divergence between Santa Teresa and Albuquerque, New Mexico. This is consistent with the NAM 6-hour forecast of upward vertical motion for the EPZ CWA, including the EPMA (Fig. 10).

5) Evolution of storms on the afternoon and evening of 28 July 2006

During the afternoon hours of 28 July 2006, initial shower and thunderstorm activity was especially strong over the mountainous terrain of southwestern New Mexico. Greater than 3 in of rain fell over sections of Silver City, which caused major street flooding and road closures, with rescues needed for some individuals trapped by the floodwaters. In contrast, the weather remained relatively quiescent over the EPMA through the afternoon. However, the 0000 UTC 29 July 2006 sounding (Fig. 11) indicated a moist unstable air mass with a PW of 1.45 in (36 mm or 162% of normal), a MUCAPE of almost 1100 J kg^{-1}, and the relative humidity (RH) greater than 75% through most of the troposphere over 900 m above ground level (AGL). Wind speeds through the cloud layer were generally from 5 to 7 m s^{-1} with a storm motion vector of 4 m s^{-1} from the southwest. As a result, slow-moving convective cells developed over the area (Fig.12) during the evening. This activity persisted until the early morning hours. Almost 2 in of rain fell in an hour in the Horizon City area, where high waters flooded homes, businesses and streets. Similar flooding impacts were also reported in Montana

Fig. 9-a

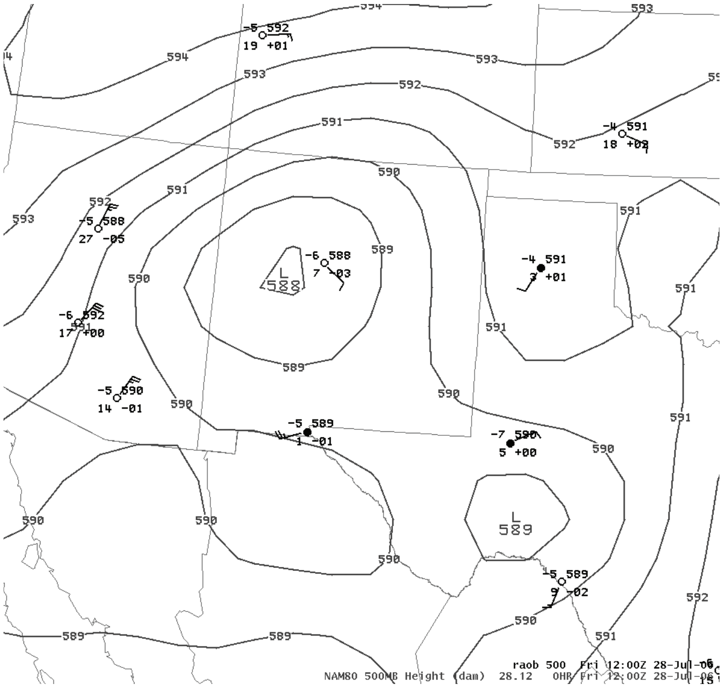


Fig. 9-b

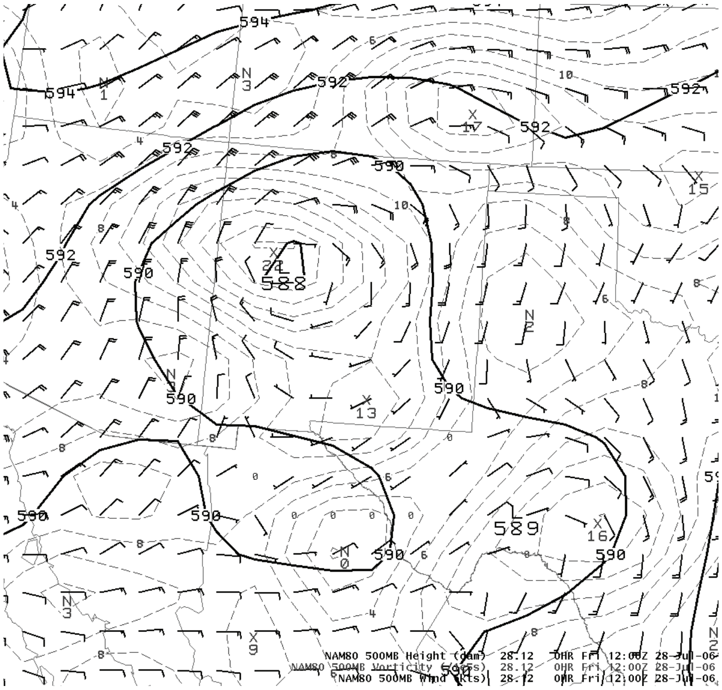


Fig. 9.

a) The 500 mb analyses for 1200 UTC 28 July 2006. Other details same as Fig. 3a.

b) The 500 mb wind and vorticity analyses as initialized by the 1200 UTC 28 July 2006 NAM model. Other details the same as in Fig. 3b.

c) The 250 mb divergence (solid lines) at 1200 UTC 28 July 2006 based on NAM model initialization Units are $10^{-5}s^{-1}$.

Fig. 9-c

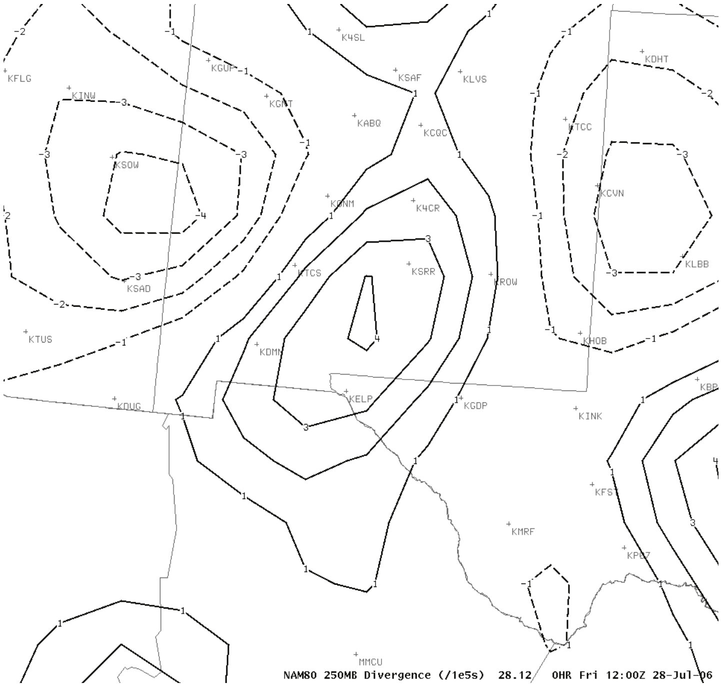


Fig.10. 1800 UTC 28 July 2006 700-500 mb layer averaged vertical motion based on the NAM model 6-hour forecast. Other details same as Fig. 3c.

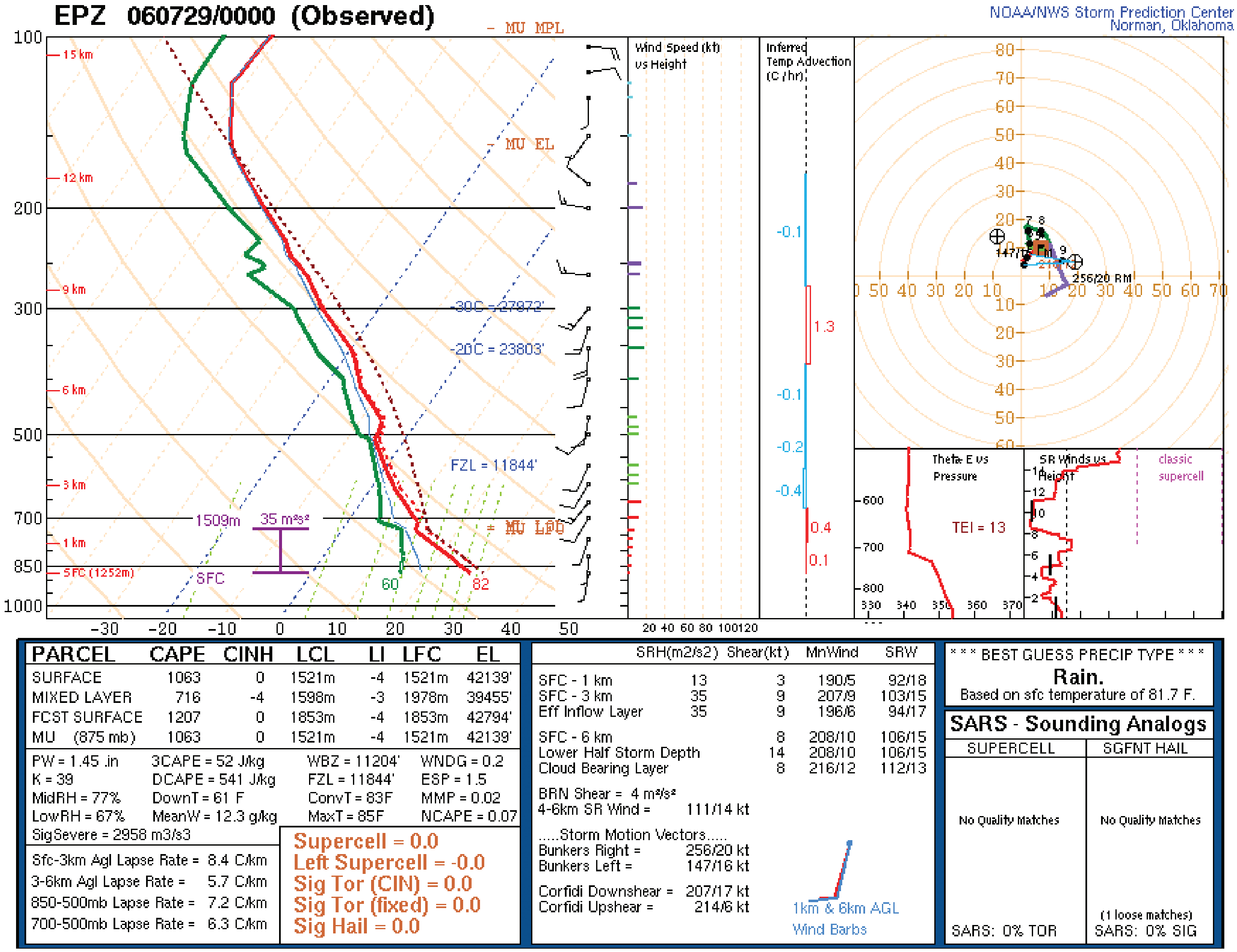
Vista, northeast of Horizon City. The heavy rains again caused rivers of mud to flow into Clint after an arroyo levee broke.

6) Events during the 29-30 July 2006 period

The weather was relatively quiescent for the EPMA during the daytime and evening hours of 29 July 2006 through the afternoon of 30 July. Showers and thunderstorms returned on the evening of 30 July and brought more heavy rains. This was followed by additional rainfall during the morning and afternoon of 31 July. NAM-derived 500 mb analyses for 0000 UTC 31 July 2006 (Fig.13a) showed little change in the larger scale pattern from the previous days. The closed upper low in the middle troposphere was centered around north central New Mexico with a short wave trough and associated vorticity axis extending west of the cyclonic circulation center. NAM-derived vertical velocities revealed barely discernable upward motion in the 700-500 mb layer (Fig 13b), associated with an area of weak DPVA (not shown). At the surface (Fig. 14), the air was unusually moist with dewpoints above 60° F across the entire KEPZ CWA. Climatological data shows that during July and August, the dewpoint exceeds 60° F only 20% of the time at El Paso. In addition, a poorly defined trough of low pressure is positioned across the EPMA.

7) Storms and environmental conditions on the night of 30-31 July 2006

The 31 July 0000 UTC KEPZ rawinsonde (Fig. 15) continued to exhibit very abundant moisture with a PW value of 1.47 in and RH of 70% or greater through most of the 750-350 mb layer. Despite a nearly



PARCEL	CAPE	CINH	LCL	LI	LFC	EL
SURFACE	1063	0	1521m	-4	1521m	42139'
MIXED LAYER	716	-4	1598m	-3	1978m	39455'
FCST SURFACE	1207	0	1853m	-4	1853m	42794'
MU (875 mb)	1063	0	1521m	-4	1521m	42139'

PW = 1.45 .in
K = 39
MidRH = 77%
LowRH = 67%
SigSevere = 2958 m3/s3
3CAPE = 52 J/kg
DCAPE = 541 J/kg
DownT = 61 F
MeanW = 12.3 g/kg
WBZ = 11204'
FZL = 11844'
ConvT = 83F
MaxT = 85F
WNDG = 0.2
ESP = 1.5
MMP = 0.02
NCAPE = 0.07

Sfc-3km Agl Lapse Rate = 8.4 C/km
3-6km Agl Lapse Rate = 5.7 C/km
850-500mb Lapse Rate = 7.2 C/km
700-500mb Lapse Rate = 6.3 C/km

Supercell = 0.0
Left Supercell = -0.0
Sig Tor (CIN) = 0.0
Sig Tor (fixed) = 0.0
Sig Hail = 0.0

	SRH(m2/s2)	Shear(kt)	MnWind	SRW
SFC - 1 km	13	3	190/5	92/18
SFC - 3 km	35	9	207/9	103/15
Eff Inflow Layer	35	9	196/6	94/17
SFC - 6 km		8	208/10	106/15
Lower Half Storm Depth		14	208/10	106/15
Cloud Bearing Layer		8	216/12	112/13

BRN Shear = 4 m²/s²
4-6km SR Wind = 111/14 kt

.....Storm Motion Vectors.....
Bunkers Right = 256/20 kt
Bunkers Left = 147/16 kt

Corfidi Downshear = 207/17 kt
Corfidi Upshear = 214/6 kt

* * * BEST GUESS PRECIP TYPE * * *
Rain.
Based on sfc temperature of 81.7 F.

SARS - Sounding Analogs

SUPERCELL	SGFNT HAIL
No Quality Matches	No Quality Matches
	(1 loose matches)
SARS: 0% TOR	SARS: 0% SIG

Fig. 11. The 0000 UTC 29 July 2006 sounding for Santa Teresa (KEPZ) plotted on a standard skew T-log p diagram, along with parameters computed from this sounding.

moist adiabatic temperature profile above 750 mb, a MUCAPE of almost 1800 J kg^{-1} indicated a moderately unstable air mass. As in the preceding days, CINH was nearly absent and the combination of instability and moisture resulted in a K index of 41, a high value which denotes a heavy rain potential (Maddox et al. 1979).

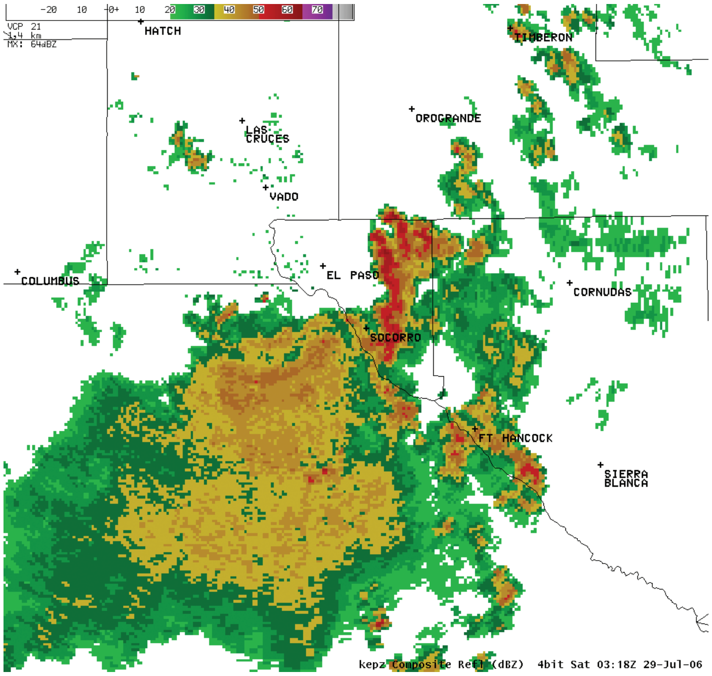


Fig. 12. KEPZ composite radar reflectivity at 0318 UTC 29 July 2006. Top left shows dBZ scale.

The vertical wind profile included west to southwest winds from 5-8 m s^{-1} through the cloud layer, but with Corfidi vectors forecasting an MCS motion of only 2 m s^{-1} from the north. Thus once again, all factors indicated a risk of a slow moving, heavy rain-producing showers and thunderstorms. As a result, during the evening of 30 July a small MCS did in fact move slowly over the EPMA (Fig.16) with two separate thunderstorms within the larger system hitting northeast El Paso. Storm spotters in northeast El Paso reported up to 3 in (75 mm) of rain falling in 40 minutes, causing major street flooding and road closures.

Through the early morning of 31 July, a new area of convection with an almost linear configuration developed over southwestern New Mexico in advance of the above-mentioned short wave trough, which satellite images (not shown) and NAM model data (Fig. 17) indicated had rotated cyclonically around the closed upper low to the northeast. By 1614 UTC (Fig. 18), the slow-moving MCS entered the EPMA from the northwest with showers and embedded thunderstorms dropping 1-2 in of rainfall on ground already saturated from the precipitation of the previous days. Mudslides damaged an apartment in Santa Teresa, New Mexico, while rockslides closed a highway across the Franklin Mountains. By this time the communities comprising the EPMA, including local government officials, were

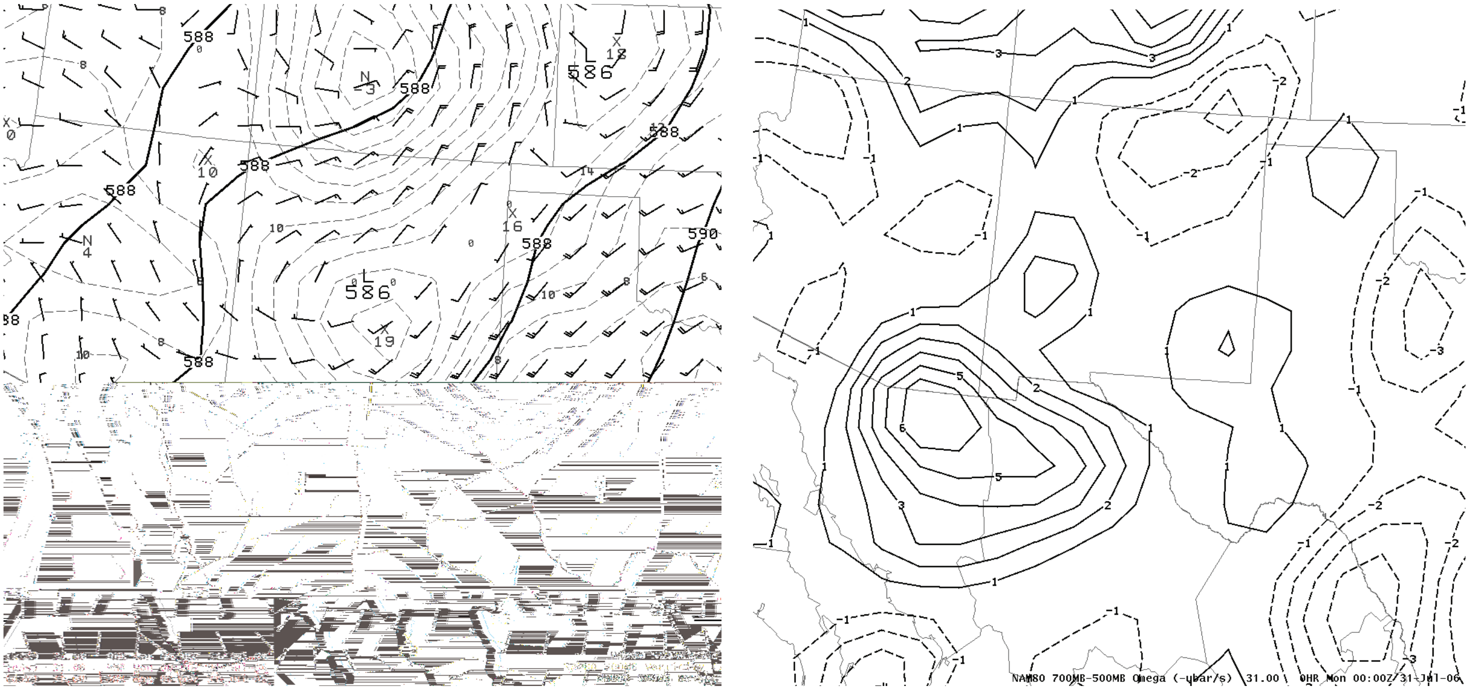


Fig. 13-a

Fig. 13-b

Fig. 13. (a) The 500 mb wind and vorticity analyses as initialized by the 0000 UTC 31 July 2006 NAM model. Other details the same as in Fig. 3b. **(b)** The 0000 UTC 31 July 2006 layer-averaged 700-500 omega based on the NAM model initialization. Other details same as Fig. 3c.

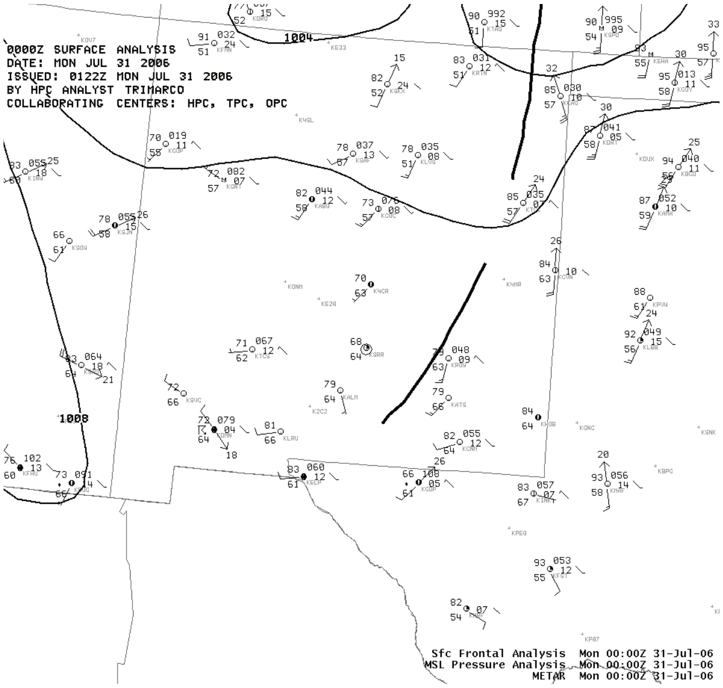


Fig. 14. The 0000 UTC 31 July 2006 surface analyses. Details same as Fig. 4.

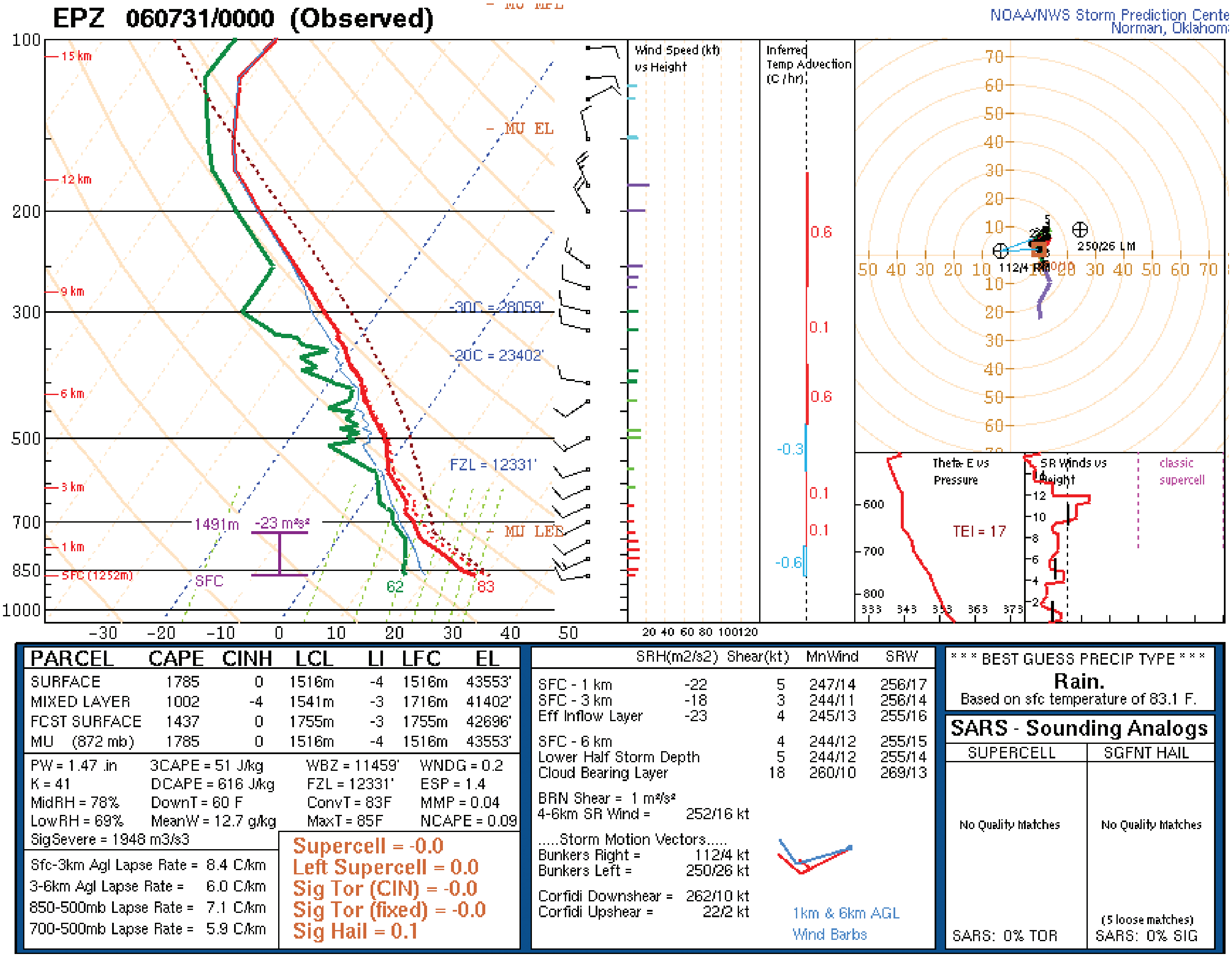
responding to the damage produced by the series of heavy rain events occurring since the evening of July 27, unaware that the next day would bring the most destructive flooding on record over the area.

b. The 1 August 2006 flash floods

1) Rainfall amounts and damage from the 1 August 2006 event

The worst flooding in recorded history for the EPMA occurred on 1 August 2006 when 3 to almost 10 in of rain fell over portions of the region. Figure 19 shows the rain gage and radar estimated composite precipitation amounts across El Paso on 1 August between 1000 and 2000 UTC. Note that the northwestern portions of the city had the heaviest amounts, nearly 10 in

Fig. 15 (below). The 0000 UTC 31 July 2006 sounding for Santa Teresa (KEPZ) plotted on a standard skew T-log p diagram, along with parameters computed from this sounding.



PARCEL	CAPE	CINH	LCL	LI	LFC	EL
SURFACE	1785	0	1516m	-4	1516m	43553'
MIXED LAYER	1002	-4	1541m	-3	1716m	41402'
FCST SURFACE	1437	0	1755m	-3	1755m	42696'
MU (872 mb)	1785	0	1516m	-4	1516m	43553'

PW = 1.47 .in
K = 41
MidRH = 78%
LowRH = 69%
SigSevere = 1948 m3/s3
3CAPE = 51 J/kg
DCAPE = 616 J/kg
DownT = 60 F
MeanW = 12.7 g/kg
WBZ = 11459'
FZL = 12331'
ConvT = 83F
MaxT = 85F
WNDG = 0.2
ESP = 1.4
MMP = 0.04
NCAPE = 0.09

Sfc-3km Agl Lapse Rate = 8.4 C/km
3-6km Agl Lapse Rate = 6.0 C/km
850-500mb Lapse Rate = 7.1 C/km
700-500mb Lapse Rate = 5.9 C/km

Supercell = -0.0
Left Supercell = 0.0
Sig Tor (CIN) = -0.0
Sig Tor (fixed) = -0.0
Sig Hail = 0.1

	SRH(m2/s2)	Shear(kt)	MnWind	SRW
SFC - 1 km	-22	5	247/14	256/17
SFC - 3 km	-18	3	244/11	256/14
Eff Inflow Layer	-23	4	245/13	255/16
SFC - 6 km		4	244/12	255/15
Lower Half Storm Depth		5	244/12	255/14
Cloud Bearing Layer		18	260/10	269/13

BRN Shear = 1 m²/s²
4-6km SR Wind = 252/16 kt

.....Storm Motion Vectors.....
Bunkers Right = 112/4 kt
Bunkers Left = 250/26 kt

Corfidi Downshear = 262/10 kt
Corfidi Upshear = 22/2 kt

* * * BEST GUESS PRECIP TYPE * * *
Rain.
Based on sfc temperature of 83.1 F.

SARS - Sounding Analogs

SUPERCELL	SGFNT HAIL
No Quality Matches	No Quality Matches
	(5 loose matches)
SARS: 0% TOR	SARS: 0% SIG

(250 mm), while 4 to 7 in of rain fell across the north and northeastern sections of the city. Prolonged and occasionally heavy rainfalls forced arroyos and streams to rapidly overflow, causing streets to become raging torrents of water. The floodwaters severely damaged or destroyed homes, businesses and other property and overturned or carried away motor vehicles. Many roads were closed, including Interstate 10, leaving the EPMA literally isolated for several hours. In the city of El Paso, water rescues were required in some neighborhoods. Just north of El Paso, the entire village of Vinton, Texas was evacuated as arroyos overflowed, streets flooded, and water rose to a depth of almost five feet in some neighborhoods. Extensive flooding also damaged or destroyed much of Canutillo where high waters inundated homes and closed roads. Later in the summer, public safety officials declared portions of Canutillo permanently uninhabitable as a result of the floods.

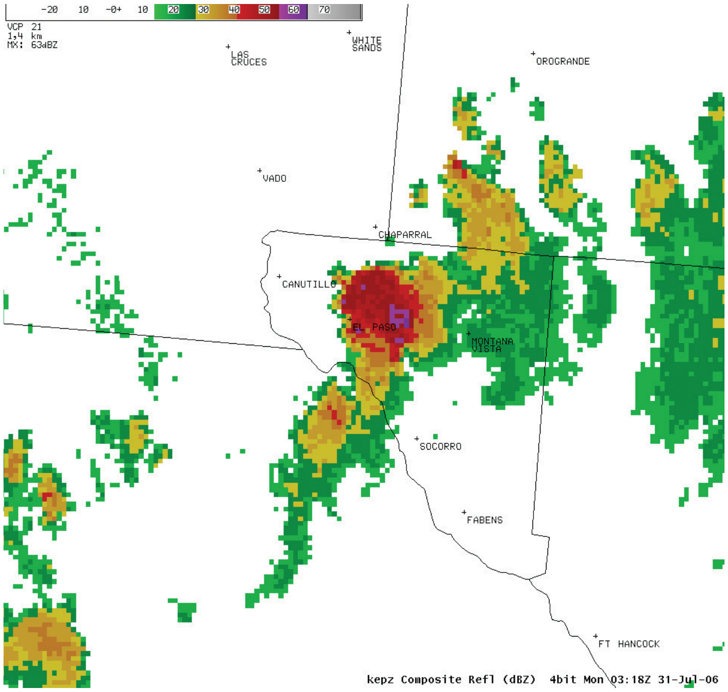


Fig. 16. KEPZ composite reflectivity at 0318 UTC 31 July 2006. Top left shows dBZ scale.

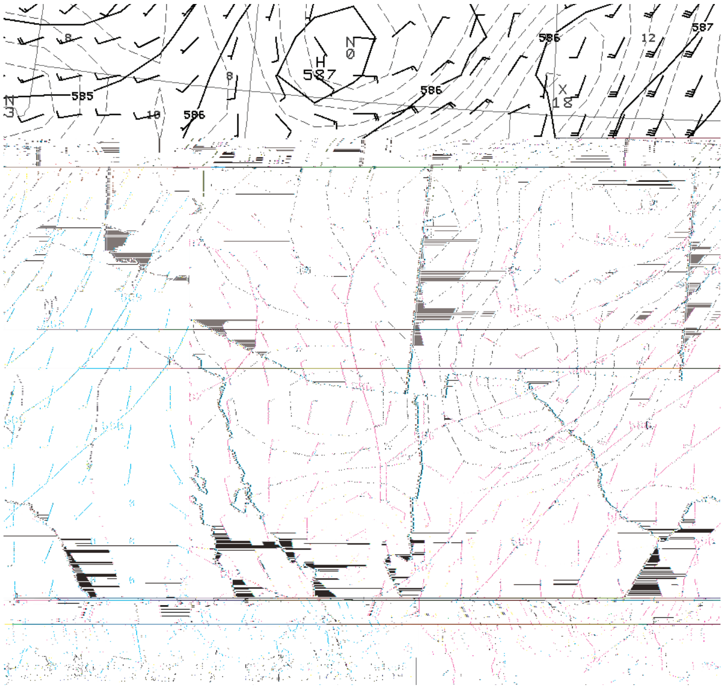


Fig. 17. The 500 mb wind and vorticity analyses as initialized by the 1200 UTC 31 July 2006 NAM model. Other details the same as in Fig. 3b.

In the bordering areas of New Mexico, high-running floodwaters forced 1,200 Sunland Park residents to evacuate as the Rio Grande overflowed its banks, reaching its highest levels since 1912. Just south of the border, Juarez, Mexico also suffered severe flood damage, resulting in mass evacuations and rescue operations. By afternoon a state of emergency was declared across the area with soldiers and helicopters from Fort Bliss providing much needed rescue assistance. Total damage for the event was estimated at nearly $300 million.

2) Synoptic and mesoscale conditions on 1 August 2006

The 1200 UTC 1 August 2006 500 mb geopotential height, wind and vorticity fields, based on the NAM initialization (Fig. 20a) plus actual upper air data (not shown), indicated that the middle and now upper-tropospheric vortex had moved slightly east from

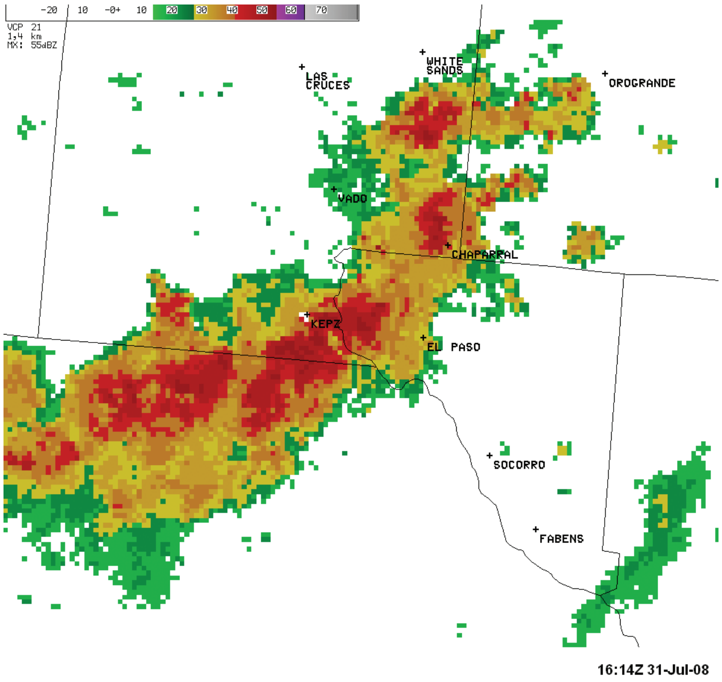


Fig. 18. KEPZ composite reflectivity at 1614 UTC 31 July 2006. Top left shows dBZ scale.

the previous days and was progressing into eastern portions of the EPMA. Model data also suggested the closed circulation had evolved into more of a cyclonic wind shift line, aligned along a trough axis. With the trough axis progressing slowly eastward and with northwesterly winds aloft flowing across western sections of the EPMA, forecasters would usually expect differential negative vorticity advection and associated subsidence to suppress convection within the environment later in the day in such a situation. However, because the 700 mb wind speeds (not shown) slightly exceeded the wind speeds at 500 and even 300 mb, there was actually weak DPVA occurring in the 700-300 mb layer (Fig. 20b) over western areas of the EPMA. In other words, there was negative vorticity advection decreasing with height within this layer. In addition, despite the northwest flow aloft, significantly drier air was not advecting into the area, as much of the southwestern United States remained moist with the 850-500 mb RH greater than 70% upstream to the west (Fig 20c) in agreement with the NAM 6-hour forecast. The 1200 UTC surface analyses (Fig. 21a) continued to indicate high amounts of low level moisture, as dewpoints persisted above 60^{o} F across the KEPZ CWA including the EPMA. A poorly-defined surface trough also remained, aligned on a northeast to southwest axis from northeastern New Mexico into extreme western areas of the EPMA with surface winds weakly convergent along its axis. The RUC model indicated low-level atmospheric moisture convergence nearly aligned along this trough axis (Fig 21b). As discussed by Palmen and Newton (1969), Carr and Bosart (1978), and Banacos and Schultz (2005), areas of moisture convergence are often co-located with deep moist convection and heavy rains, since this is an area of low-level upward forcing and/or moisture flux. In this particular case, moisture convergence values were considerably less than in the previous heavy rain studies, which reflected the weak flow pattern.

3) Analysis of upper air conditions on 1 August 2006

Figure 22 shows the 1200 UTC 1 August 2006 KEPZ sounding from Santa Teresa, released within the temporal span and spatial area of the initial stages of the developing MCS that would bring torrential rains to the EPMA. Thus, this sounding was considered representative of the region's air mass. The rawinsonde data (Fig. 22) illustrates that the moisture content had increased, resulting in an extremely high PW value of 1.71 inches (43 mm) or 200% of normal. The mean RH was also near 90% through the entire layer. Almost no CINH was present, and the MUCAPE for a parcel lifted from the surface was nearly 900 J kg^{-1}, making the air mass almost moderately unstable. An elevated freezing level remained at almost 3700 m (12000 ft), which, when combined with the low cloud base, denoted convective clouds where warm cloud coalescence processes would dominate within a deep layer. The wind profile showed a pronounced westerly directional component from the surface through the middle troposphere, with 10 m s^{-1} (20 kt) winds between 850 and 800 mb decreasing to only 5 m s^{-1} above 500 mb.

The mean wind for the cloud layer was from 290^{o} at 6 m s^{-1} suggesting individual storm cells would move slowly to the east. However, the Corfidi technique (described earlier) forecasts the motion of a regional MCS to be 5 m s^{-1} from 30 degrees. Since this direction deviates

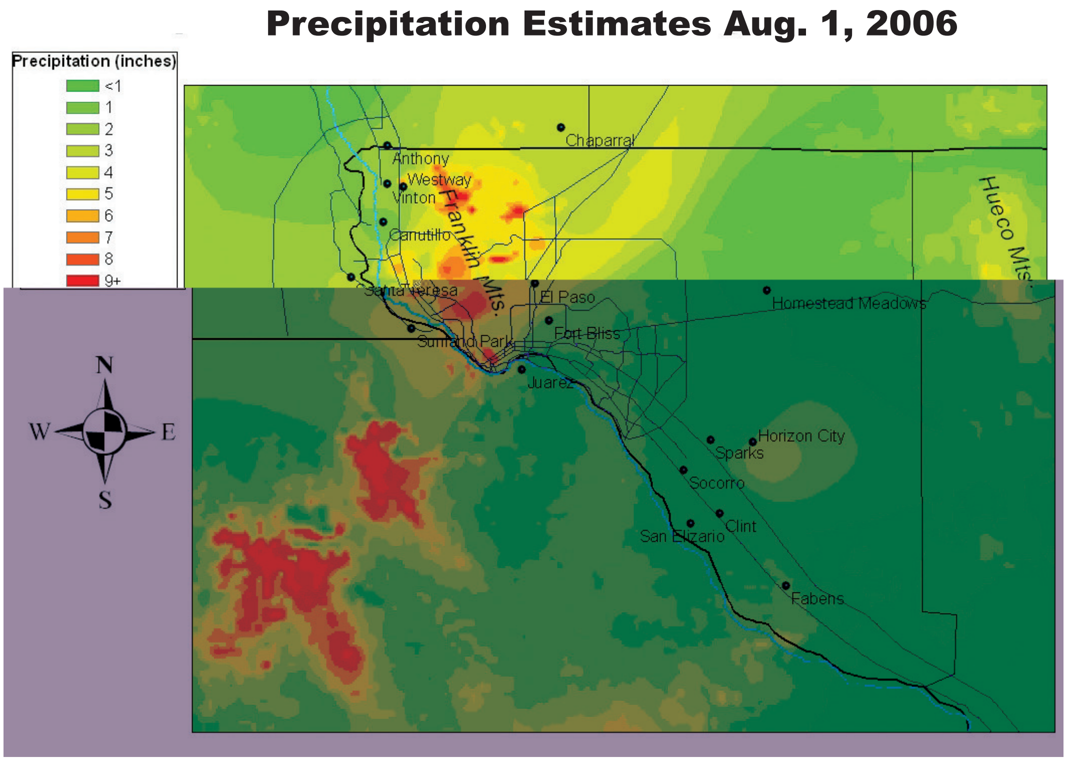


Fig. 19. Rainfall amounts (inches) across the El Paso Metropolitan Area occurring between 1000-2000 UTC 1 August 2006 determined from a combination of rain gages and radar measurements.

from the expected cell motion by 100 degrees, it clearly showed that the wind profile was favorable for pronounced upstream convective propagation toward the west or southwest. The cloud layer wind profile, in conjunction with deep moisture, precluded any significant evaporation or entrainment of water droplets and prevented longer-lived outflow or gust front formation, which could force progressive updraft formation away from a fixed location. It also signifies that rainwater would not be transported a significant distance from the parent updrafts due to the flow aloft. Perhaps of greatest significance was that the deep westerly flow component produced an upslope wind component with associated boundary layer lifting along the western slopes of the Franklin Mountains, which have a peak elevation of 2100 m (6900 ft) above sea level (Fig. 23). All of these factors over the EPMA indicated a potential for heavy rainfall (Doswell et al. 1996; Junker et al. 1999).

Fig. 20-a

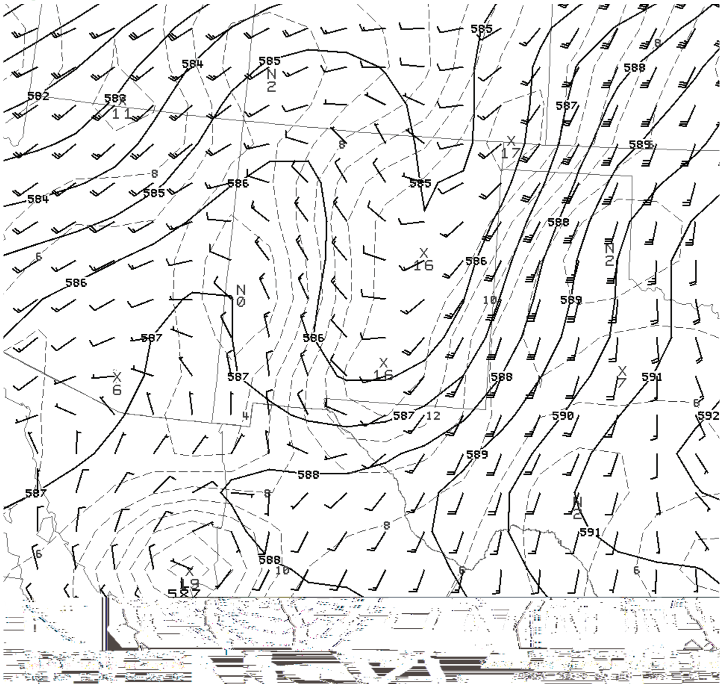


Fig. 20.

a) The 500 mb wind and vorticity analyses as initialized by the 1200 UTC 1 August 2006 NAM model. Other details the same as in Fig. 3b.

b) The 1200 UTC 1 August 2006 700-300 mb differential vorticity advection based on the NAM model analyses. Units are 10^{-9} s^{-2}. Solid lines indicate positive differential vorticity advection with height.

c) The 1200 UTC 1 August 2006 regional 850-500 mb relative humidity. Solid lines show relative humidity for the layer in percent.

4) Evolution of the 1 August 2006 storms

The KEPZ WSR-88D composite radar reflectivity depicted convective cells in progress over the EPMA by 1211 UTC (Fig. 24a), with heaviest rains across western and northeastern El Paso. The developing MCS, which initially entered the area from the northwest, moved very little during the next 2 hours (Fig 24b) as storms redeveloped along the Franklin Mountains (Fig 25). By 1615 UTC, the heaviest rains had propagated to the northwest over extreme

Fig. 20-b

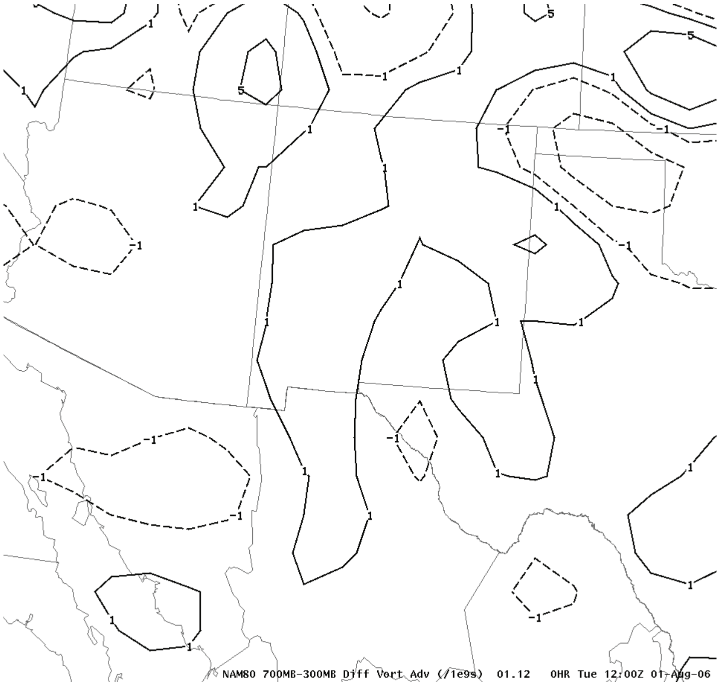
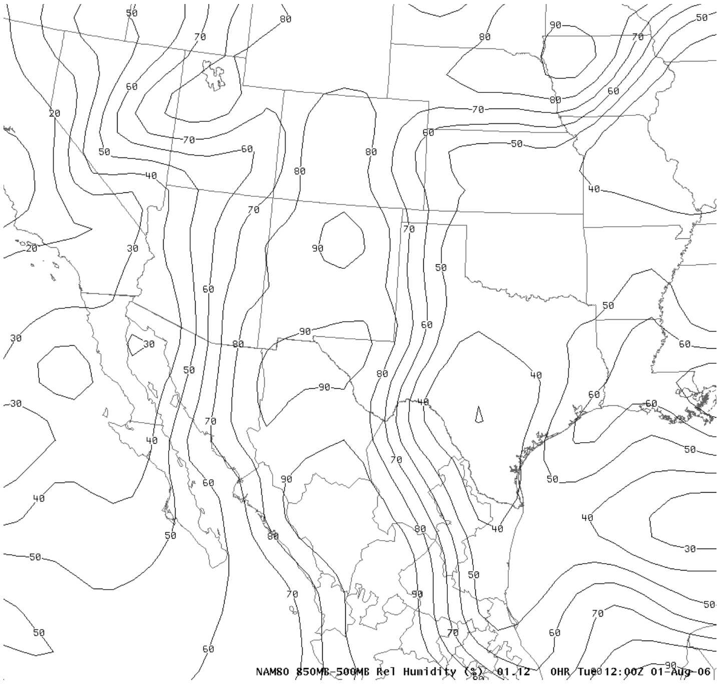


Fig. 20-c



northwestern portions of the EPMA including southern New Mexico (Fig. 26a). Despite a bit lower reflectivity at this time, warm core rain processes were likely occurring below the radar level. Storms developing to the northwest subsequently moved to the southeast consistent with the mean steering flow, dumping heavy rains again over west El Paso and adjacent locations by 1811 UTC (Fig 26b.) In the following 2 hours, rainfall intensity diminished over most of the EPMA. Rapid storm development did occur to the west and northwest through south central New Mexico and also south of El Paso into Mexico, where heavy rains and flash flooding damaged much of the city of Juarez. In addition, the excessive rainfall caused the Rio Grande to overflow, forcing 1200 Sunland Park residents to evacuate.

c. Theoretical versus actual rainfall rates and precipitation efficiency on 1 August 2006

Flash flood producing rainfalls depend on 1) high rainfall rates, 2) prolonged duration of heavy rainfall over a given location and 3), basin hydrological characteristics such as terrain variability and amount of topsoil moisture (Maddox et al. 1979; Doswell et al. 1996). This section will examine the first two factors.

The environment for the 1 August storms included very high moisture content with both an unusually high PW value and RH above 90% through almost the entire troposphere. In addition, wind flow was rather light through the cloud layer above 700 mb. As stated, these factors precluded significant entrainment, suggesting high precipitation efficiency where almost all water vapor ingested into an updraft will condense and fall to the ground as rain. The low-magnitude Corfidi MCS motion vector would also suggest that the rainfall would be prolonged over a localized area.

1) Rainfall rate estimates using theoretical sub-cloud moisture convergence

Following Chappel (1986), we first assume the maximum updraft velocity is dependent on the buoyancy or instability by the relationship $w_{max} = (2*CAPE)^{1/2}$. For the 1 August 2006 storms, the mean CAPE for the period was estimated to be 500 J kg^{-1},which yields a maximum updraft velocity of 32 m s^{-1}, occurring at an equilibrium level of 14 km AGL. Maximum updraft velocities near the buoyancy-derived estimates have been observed for mesocyclones where storm rotation induces upward directed pressure gradients (Klemp 1987). However for most non-rotating storms, factors such as water loading and perturbed vertical pressure gradients aloft reduce updraft vertical velocities to about 50%

Fig. 21-a

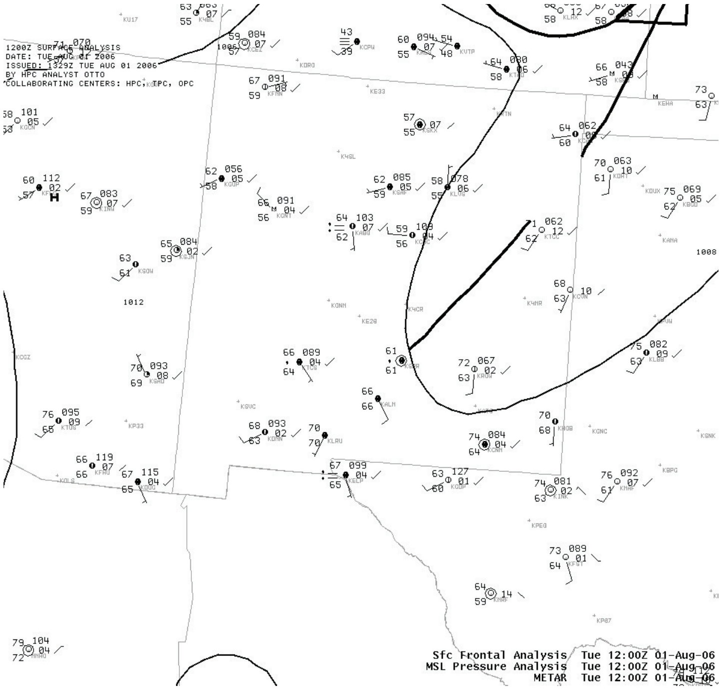


Fig. 21-b

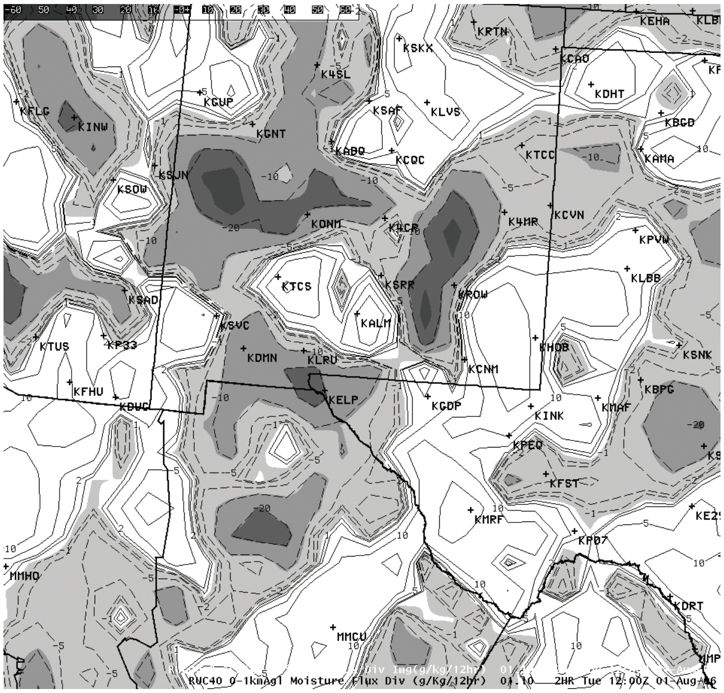


Fig. 21. (a) The 1200 UTC 1 August 2006 surface analyses. Details same as Fig. 4. **(b)** The 1200 UTC 1 August 2006 0-1 km moisture flux divergence derived from the RUC model. Units are g kg^{-1}/12hr. Negative values indicate areas of moisture flux convergence.

of their theoretical values (Weisman and Klemp 1986). Given the high rainfall rates and attendant water loading of the 1 August storms, the actual maximum updraft speeds are considered to be about half the value estimated by the buoyancy relation or 16 m s^{-1}.

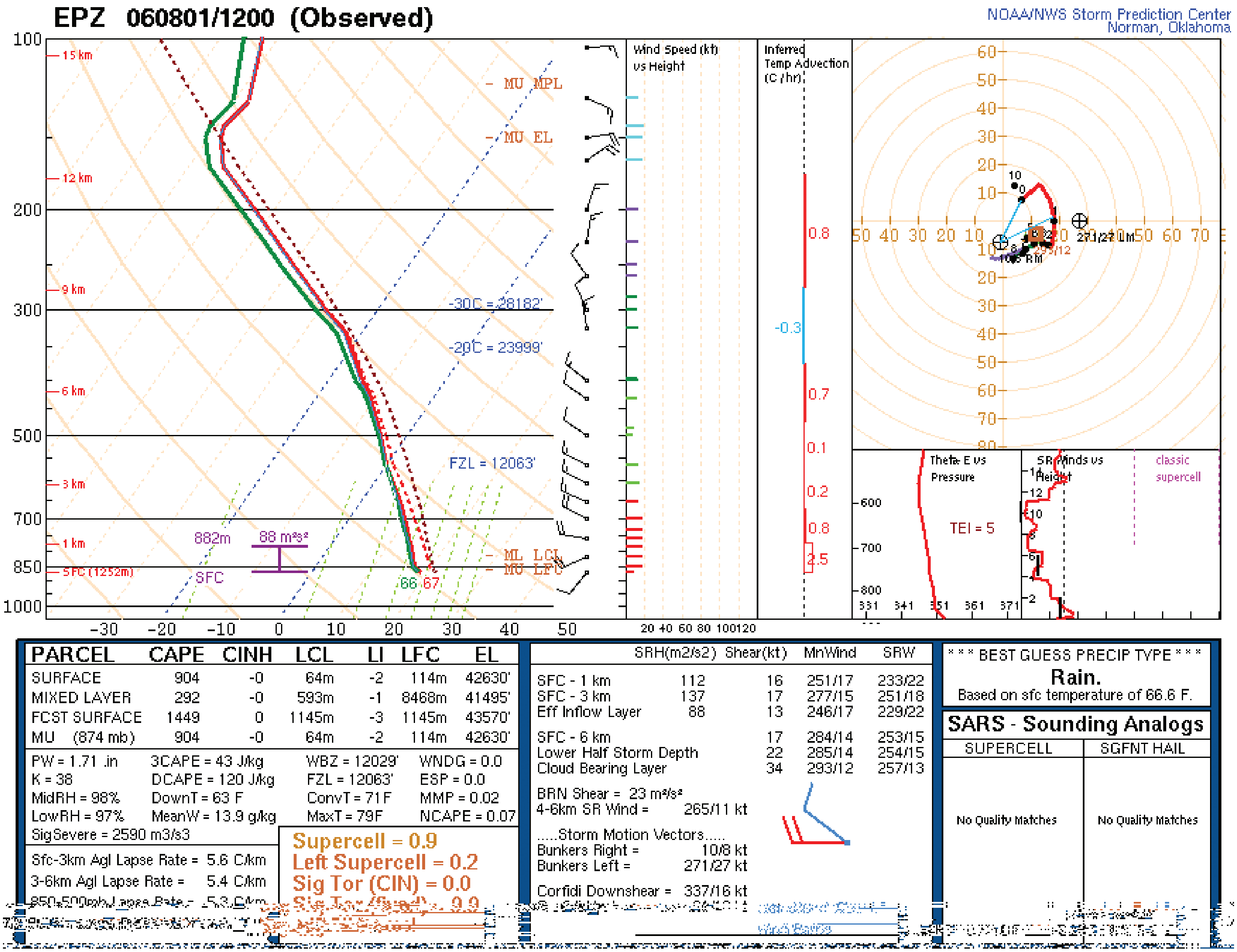
It can also be assumed that for deep convection, most of the air flowing into the updraft is located within the unstable layer below the highest level of free convection. Thus from the continuity equation (ignoring the density term) for convective updrafts, we have:

$$\nabla_h \cdot V = \partial w / \partial z \qquad (1)$$

where $\nabla_h \cdot V$ is the mean divergence of the horizontal wind within the unstable layer feeding the updraft. From the 1 August sounding (Fig. 22), it is determined that parcels lifted in the layer from near the surface (100 m AGL) to 1100 m AGL are convectively unstable. So for a convective system, it is assumed that air entering the updraft originates within this layer, bounded by the 870 and 780 mb pressure surfaces. $\partial w/\partial z$ is the vertical velocity gradient from the base of the unstable layer to the equilibrium level, determined to be near the surface and 14,000 m AGL respectively. A linear relation is assumed with w increasing from 0 at 100 m to 16 m s^{-1} at 14 km AGL, resulting in a maximum low level divergence estimated value of -1.1×10^{-3} s^{-1}. The negative value of the divergence indicates the air is converging or flowing into the updraft.

Moisture flux convergence integrated through the lower troposphere has long been used to estimate

continued on p. 95



PARCEL	CAPE	CINH	LCL	LI	LFC	EL
SURFACE	904	-0	64m	-2	114m	42630'
MIXED LAYER	292	-0	593m	-1	8468m	41495'
FCST SURFACE	1449	0	1145m	-3	1145m	43570'
MU (874 mb)	904	-0	64m	-2	114m	42630'

PW = 1.71 .in
K = 38
MidRH = 98%
LowRH = 97%
SigSevere = 2590 m3/s3
3CAPE = 43 J/kg
DCAPE = 120 J/kg
DownT = 63 F
MeanW = 13.9 g/kg
WBZ = 12029'
FZL = 12063'
ConvT = 71 F
MaxT = 79F
WNDG = 0.0
ESP = 0.0
MMP = 0.02
NCAPE = 0.07

Sfc-3km Agl Lapse Rate = 5.6 C/km
3-6km Agl Lapse Rate = 5.4 C/km
850-500mb Lapse Rate = 5.3 C/km

Supercell = 0.9
Left Supercell = 0.2
Sig Tor (CIN) = 0.0
Sig Tor (fixed) = 0.0

	SRH(m2/s2)	Shear(kt)	MnWind	SRW
SFC - 1 km	112	16	251/17	233/22
SFC - 3 km	137	17	277/15	251/18
Eff Inflow Layer	88	13	246/17	229/22
SFC - 6 km		17	284/14	253/15
Lower Half Storm Depth		22	285/14	254/15
Cloud Bearing Layer		34	293/12	257/13

BRN Shear = 23 m²/s²
4-6km SR Wind = 265/11 kt

.....Storm Motion Vectors.....
Bunkers Right = 10/8 kt
Bunkers Left = 271/27 kt

Corfidi Downshear = 337/16 kt

* * * BEST GUESS PRECIP TYPE * * *
Rain.
Based on sfc temperature of 66.6 F.

SARS - Sounding Analogs

SUPERCELL	SGFNT HAIL
No Quality Matches	No Quality Matches

Fig. 22. The 1200 UTC 1 August 2006 sounding for Santa Teresa, NM. (KEPZ) plotted on a standard skew T-log p diagram, along with parameters computed from this sounding.

Fig. 23. Normal view of the Franklin Mountain across western El Paso County Texas including western portions of the city of El Paso. Photograph taken about 20 km to the west of the mountains.

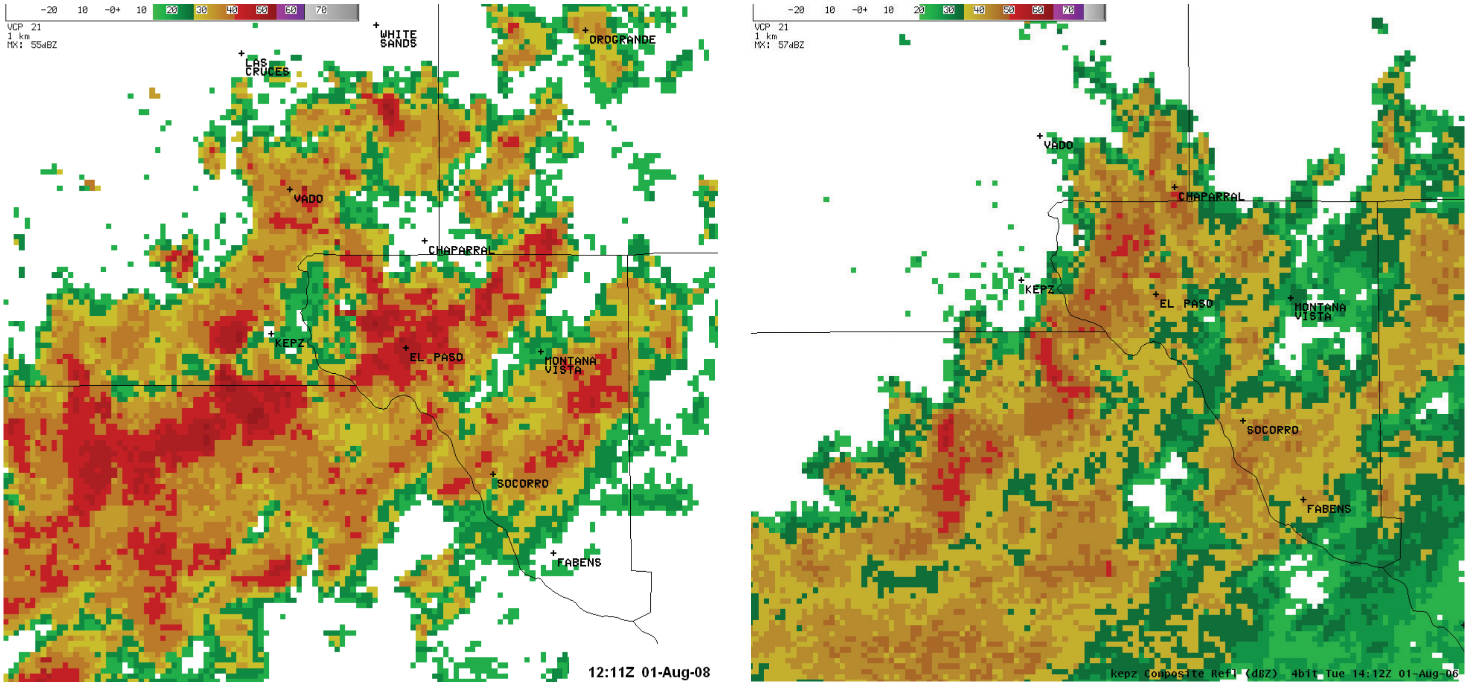


Fig. 24-a

Fig. 24-b

Fig. 24. (a) KEPZ composite reflectivity at 1211 UTC 1 August 2006. Top left shows dBZ scale. **(b)** KEPZ composite reflectivity at 1412 UTC 1 August 2006. Top left shows dBZ scale.

Fig. 25. View of stationary convection along the Franklin Mountains at about 1500 UTC 1 August 2006. Other details same as Fig. 23.

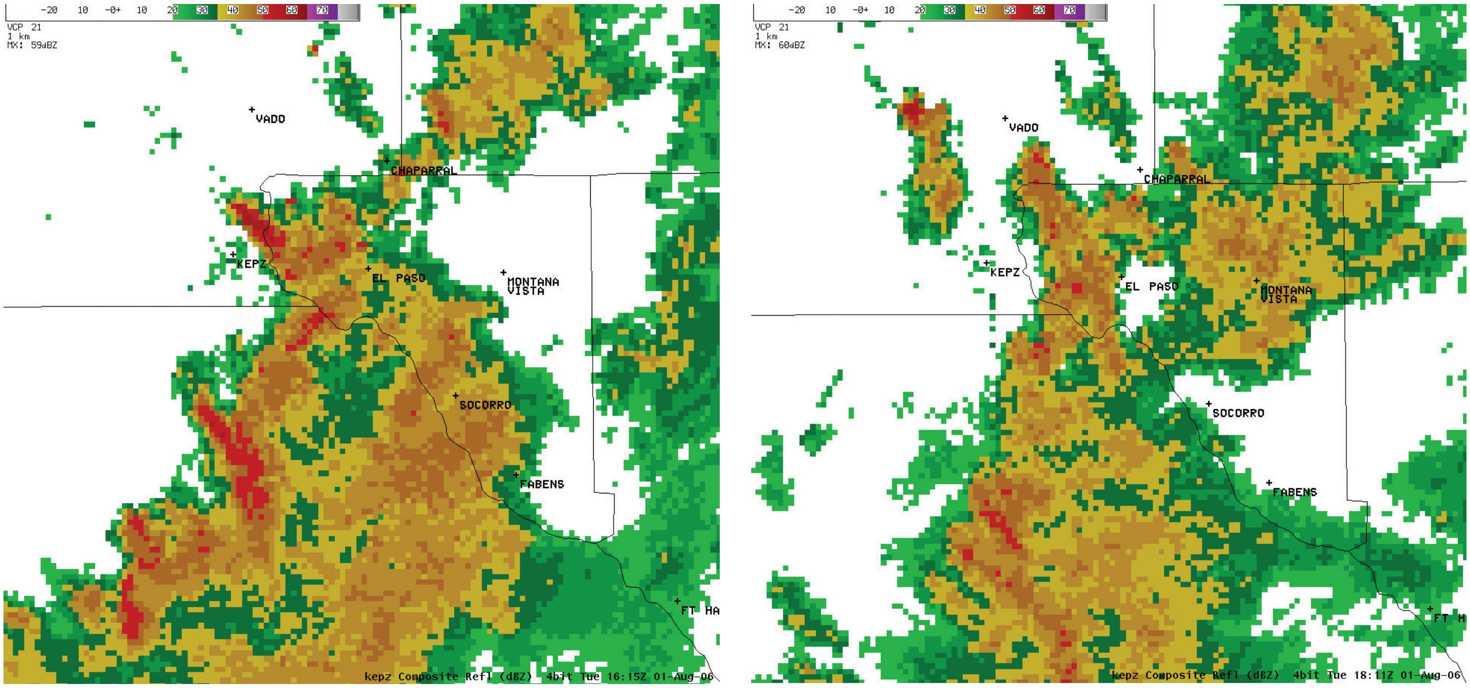


Fig. 26-a

Fig. 26-a

Fig. 26. (a) KEPZ composite reflectivity at 1615 UTC 1 August 2006. Top left shows dBZ scale. **(b)** KEPZ composite reflectivity at 1811 UTC 1 August 2006. Top left shows dBZ scale.

rainfall potential (Palmen and Newton 1969; Carr and Bosart 1978). As previously mentioned, evaporation of rain drops is considered negligible on 1 August, given the high RH of the air mass through a deep layer. In addition, the sounding taken at Santa Teresa on 2 August at 0000 UTC (not shown) revealed the air mass remained rather moist with a PW value of 1.5 inches. From this information, we can neglect both evaporation and changes in water vapor storage during the 1 August storm. Finally, little moisture advection is detected in the storm region as convective cells developed in a nearly homogenous air mass. Modifying the technique from Carr and Bosart (1978) for an area of convective updrafts, the precipitation rate potential P can be roughly approximated from the relationship:

$$P= 1/g \int_{p(870)}^{p(780)} q \nabla_h \cdot V \, dp \qquad (2)$$

where p(780) and p(870) are the pressure levels of the highest level of free convection and the surface. The specific humidity (q) in the storm inflow layer was determined to be 14 g of water per kg of air. From this relationship, P is calculated to be 62 mm or 2.4 in h^{-1}. This is in reasonable agreement with actual maximum rainfall rates occurring on this day which ranged from 3 to 10 in, most falling within an 8 hour period. The results suggest that the Carr-Bosart technique could be applied toward improved short range quantitative rainfall prediction within convective systems.

2) Rainfall Rate Estimates Using Saturated Updraft Technique

Assuming a saturated updraft, a second methodology was tested modifying and combining approaches used by Fritsch et al. (1976) and Doswell et al. (1996) by the relation:

$$P = -\int_{Cb}^{Ct} \rho_a \rho_w^{-1} w \, \partial q_s/\partial z \, dz \qquad (3)$$

where ρ_a and ρ_w represent the densities of air and water respectively, w the updraft speed within a vertical layer, q_s the saturation mixing ratio, and C_t and C_b the respective heights of the top and bottom of the cumulonimbus cloud. The relationship indicates that precipitation rate is proportional to the ascent rate of an updraft and vertical gradient of the moisture content as water vapor is being condensed in the rising air parcel. For this example, w is assumed to increase linearly from the lifting condensation level (300 m AGL) to the equilibrium level and sounding data is used to determine q_s at 1000 m increments for Δz. The air density changes through the layers are estimated to be near that for a standard atmosphere. Summing the products of w and Δq_s over 1000 m increments, results in a theoretical rainfall rate of about 200 mm (8 in) per hour. This is about an order of magnitude too high for the period. However radar analyses and public reports do suggest there were smaller time intervals (less than 15 min) where rainfall rates may have equaled this theoretical value. Variations in updraft strength plus individual cell movements and upwind propagation effects also caused rainfall intensities to vary in both time and space.

2) Precipitation efficiency calculations

Applying the technique described by Caracena et al. (1979), a mass rainout rate was also computed for the EPMA period between 1200 and 2000 UTC. Utilizing both radar estimated rainfall amounts and available rain gage data, the rainfall totals shown in Fig. 19 were derived. From the total rainfall information, it is estimated that an average of 4.6 in or 116 mm of rain fell over a 510 km^2 area during the time period, which converts to a rainfall rate of $2.1 * 10^6$ kg s^{-1}.

Using 1200 UTC 1 August 2006 rawinsonde, hourly surface data from Santa Teresa and NAM forecasted winds and mixing ratios for the storm inflow layer through 2000 UTC, the mass of water vapor moving into the quasi-stationary convective system was estimated. The mean inflow into the storm complex between the surface and the 1100 m storm inflow layer during the eight hour period was estimated at 7 m s^{-1} with the average mixing ratio within this layer almost constant at 14 g kg^{-1}. The length of the convective complex facing the storm inflow was about 22 km which results in a net water vapor flux of $2.4*10^6$ kg s^{-1}. From the rainfall rate determined above, the precipitation efficiency was calculated to be almost 88 %. This value is considered rather high compared to most continental convective systems, where strong wind shear and evaporation can reduce values to less than 50%.

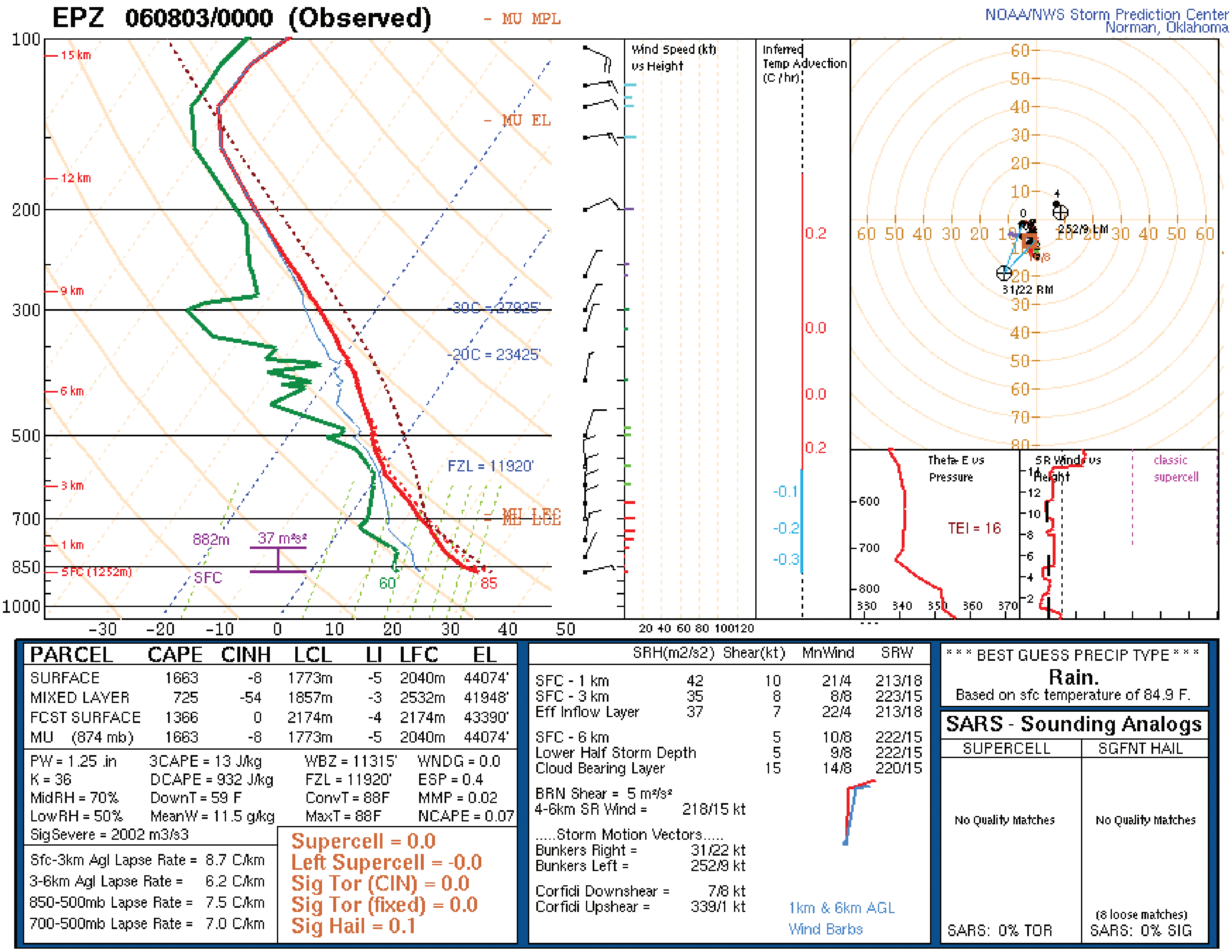
d. 3-4 August 2006 Events

1) Upper air conditions on 3 August 2006

Dry weather provided the EPMA with a much needed respite on 2 August 2006, but the relief would be rather short-lived. The Santa Teresa sounding taken at 0000 UTC 3 August (Fig. 27), indicated that the instability had actually increased to moderate levels as can be inferred from a MUCAPE of almost 1700 J kg^{-1}, with little CINH present. While the 1.24 in PW provided evidence that the air mass had diminished water vapor content from the previous days, this amount is still 124% percent of normal. The RH in the lower layer had also decreased from previous days, with amounts less than 60% below 700 mb. Local surface analyses at 0300 UTC (not shown) showed winds flowing from the east into southeastern New Mexico with a moist (dewpoints above 60° F) upslope component along the southern Rocky Mountains. A weak inverted trough aloft was also located over southeastern New Mexico just east of the mountains.

2) Storm evolution on 3 August 2006

Thunderstorms developed accordingly over the higher terrain to the northeast of the EPMA by 0615 UTC 3 August 2006 (Fig. 28a), and the activity organized into a MCS as it moved into the EPMA during the next hour (Fig. 28b). However, unlike the heavy rain-producing systems of the previous days, the MCS does not exhibit back-building or upstream propagation but instead moves to the southwest at 12 m s^{-1}, consistent with the cloud-layer winds. In addition, as suggested by Fig. 27, the decreased layer RH and higher instability of the air mass was significantly more conducive for evaporative cooling and downdraft generation, especially in comparison to conditions on 1 August (Fig. 22). This is supported by surface winds which gust from the northeast at almost 14 m s^{-1} at El Paso International



PARCEL	CAPE	CINH	LCL	LI	LFC	EL
SURFACE	1663	-8	1773m	-5	2040m	44074'
MIXED LAYER	725	-54	1857m	-3	2532m	41948'
FCST SURFACE	1366	0	2174m	-4	2174m	43390'
MU (874 mb)	1663	-8	1773m	-5	2040m	44074'

PW = 1.25 .in
K = 36
MidRH = 70%
LowRH = 50%
SigSevere = 2002 m3/s3
3CAPE = 13 J/kg
DCAPE = 932 J/kg
DownT = 59 F
MeanW = 11.5 g/kg
WBZ = 11315'
FZL = 11920'
ConvT = 88F
MaxT = 88F
WNDG = 0.0
ESP = 0.4
MMP = 0.02
NCAPE = 0.07

Sfc-3km Agl Lapse Rate = 8.7 C/km
3-6km Agl Lapse Rate = 6.2 C/km
850-500mb Lapse Rate = 7.5 C/km
700-500mb Lapse Rate = 7.0 C/km

Supercell = 0.0
Left Supercell = -0.0
Sig Tor (CIN) = 0.0
Sig Tor (fixed) = 0.0
Sig Hail = 0.1

	SRH(m2/s2)	Shear(kt)	MnWind	SRW
SFC - 1 km	42	10	21/4	213/18
SFC - 3 km	35	8	8/8	223/15
Eff Inflow Layer	37	7	22/4	213/18
SFC - 6 km		5	10/8	222/15
Lower Half Storm Depth		5	9/8	222/15
Cloud Bearing Layer		15	14/8	220/15

BRN Shear = 5 m²/s²
4-6km SR Wind = 218/15 kt

.....Storm Motion Vectors.....
Bunkers Right = 31/22 kt
Bunkers Left = 252/9 kt

Corfidi Downshear = 7/8 kt
Corfidi Upshear = 339/1 kt

* * * BEST GUESS PRECIP TYPE * * *
Rain.
Based on sfc temperature of 84.9 F.

SARS - Sounding Analogs

SUPERCELL	SGFNT HAIL
No Quality Matches	No Quality Matches
	(8 loose matches)
SARS: 0% TOR	SARS: 0% SIG

Fig. 27. The 0000 UTC 3 August 2006 sounding for Santa Teresa (KEPZ) plotted on a standard skew T-log p diagram, along with parameters computed from this sounding.

Airport. It is therefore likely that storms initiated or redeveloped along the outflow boundary as they moved to the southwest, while cooling and stabilization inhibited upwind propagation, in contrast to the storms on the previous days. Despite their relatively rapid movement, the storms dropped an additional 1 to 2 in of rain within 2 hours as the freezing and wet bulb zero levels were only slightly lower than on 1 August, while updraft speeds and condensation rates were likely greater due to higher CAPE values. The rain caused localized flooding and street closures over central and western portions of the EPMA during the early morning hours.

3) Upper air conditions on 4 August 2006

The southwestern United States weather pattern showed some changes by 1200 UTC 4 August 2006 as the vortex-trough associated with previous convection had moved southeast of the EPMA. However, south of the border across northern Mexico, another weak short wave, aligned on an almost east-west axis, was drifting northward (Fig. 29) with the NAM forecasting upward motion (Fig 30) by 1800 UTC. Surface data at 1800 UTC (Fig 31) showed an easterly flow extending across southern New Mexico and far western Texas, with moisture transport from the Gulf of Mexico sustaining dewpoints greater than 60° F. The 1200 UTC 4 August Santa Teresa sounding (not shown) modified for early afternoon conditions, displayed a moderately unstable and moist air mass with a MUCAPE of about 1500 J kg^{-1} and a PW of 1.52 in. As in the past events of the period, CINH was almost absent, denoting little lift was required to generate deep convection. The vertical wind profile was dominated by pronounced easterly flow from the surface to the middle troposphere and highest

Fig. 28-a

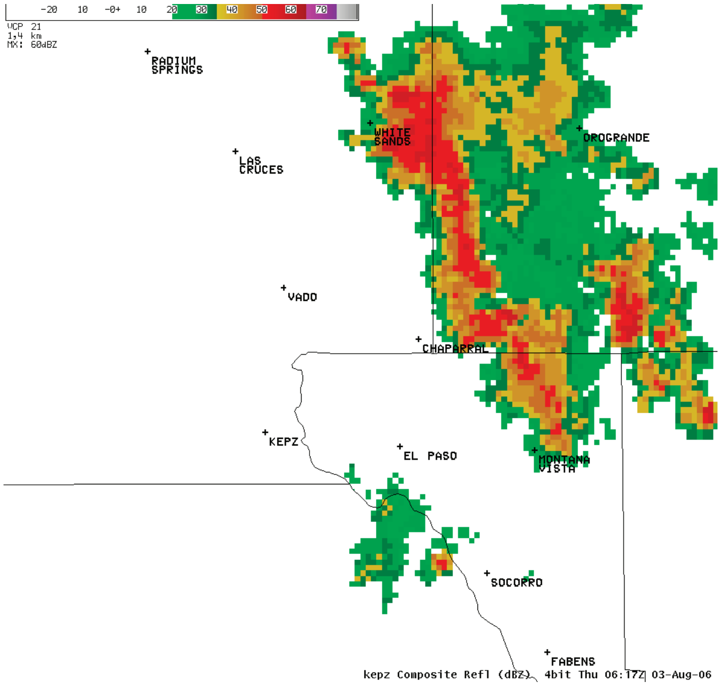


Fig. 28-b

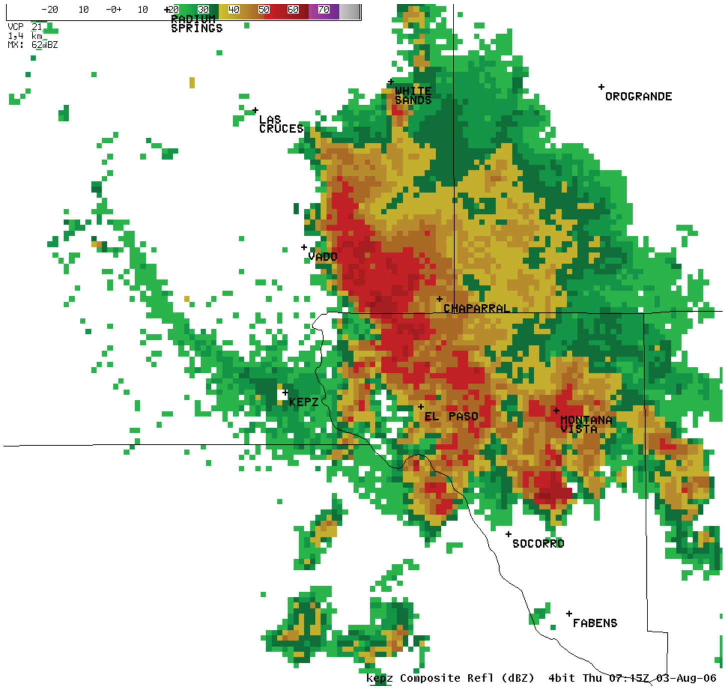


Fig. 28. (a) KEPZ composite reflectivity at 0617 UTC 3 August 2006. Top left shows dBZ scale. **(b)** KEPZ composite reflectivity at 0715 UTC 3 August 2006. Top left shows dBZ scale.

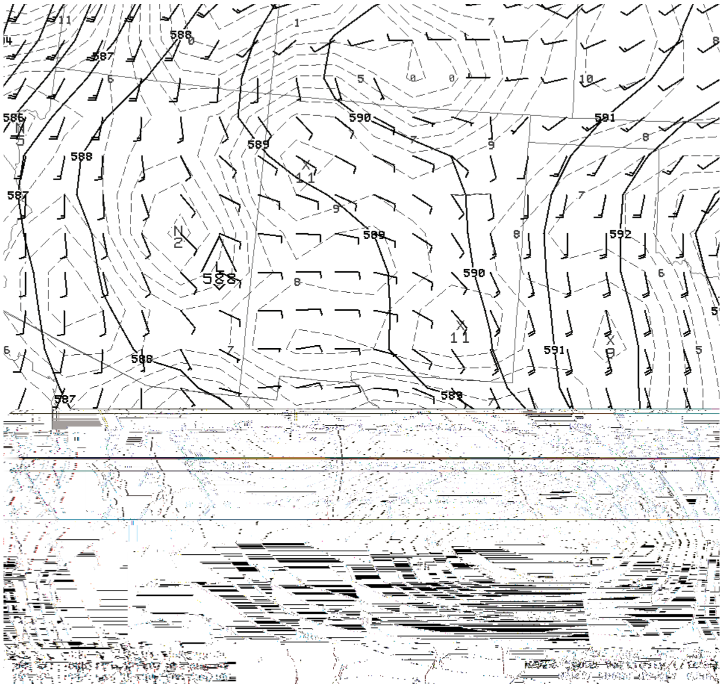


Fig. 29. The 500 mb wind and vorticity analyses as initialized by the 1200 UTC 4 August 2006 NAM model. Other details the same as in Fig. 3b.

wind speeds were in the lowest 1500 m layer. Once again, use of the Corfidi technique resulted in a mean individual storm motion from 150 degrees at 5 m s^{-1} but with an MCS movement vector near zero, indicating potential upstream propagation of storms to the east.

4) Storm evolution on 4 August 2006

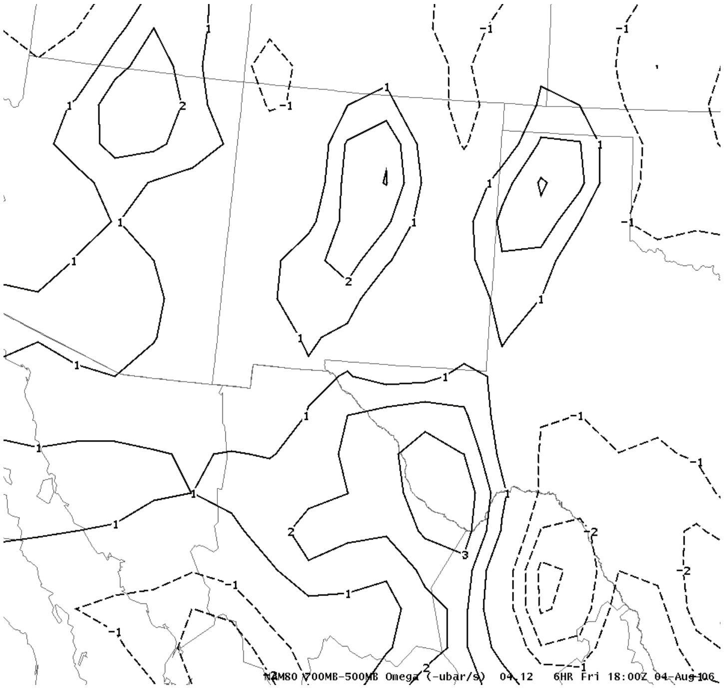


Fig. 30. 1800 UTC 4 August 2006 700-500 mb layer averaged vertical motion based on the NAM model 6-hour forecast. Other details same as Fig. 3c.

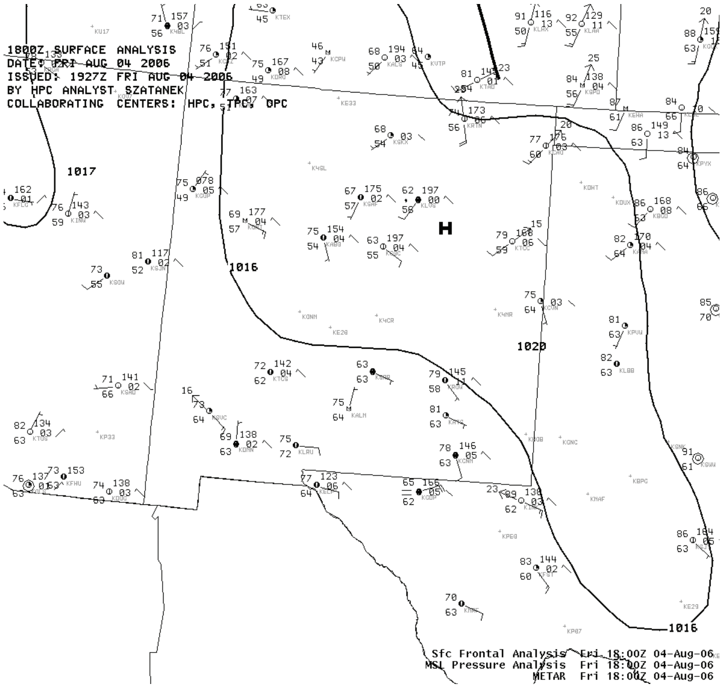


Fig. 31. 1800 UTC 4 August 2006 surface analyses. Details same as Fig. 4.

Early on the afternoon of 4 August 2006, deep convection developed rapidly along an east-west axis ahead of the short wave trough. Showers and thunderstorms were in progress over central and western portions of the EPMA by 2044 UTC (Fig. 32a). During the next hour, upstream propagation of storms occurred resulting in a linear MCS extending east into southeastern El Paso County, with convection persisting elsewhere (Fig.32b). The torrential downpours again deluged portions of El Paso County; at least 600 people were evacuated from central El Paso, Vinton, Socorro and Westway as streets flooded, arroyos overflowed and water from the Ft. Bliss Dam spilled into neighborhoods. In central El Paso, water depths reached over three feet in some locations.

In the days which followed, showers and thunderstorms with heavy rains caused flooding farther north and west over portions of south central and southwestern New Mexico while the EPMA experienced comparatively dry conditions. In the latter half of August and again into September however, several further episodes of deep convection and attendant heavy rains with flooding again affected the area. The Rio Grande overflowed its banks one more time before summer's end.

4. Discussion

The flash flood- producing rainfalls which affected the El Paso Metropolitan Area between 27 July and 4 August 2006 were very unusual from several perspectives. First, the rainfall totals were excessive, with portions of the area experiencing over a climatological year's worth of rain within a nine day period. At least one station received almost a climatological year's amount of rain in a single day. The second almost unique characteristic of the event is that multiple flooding rain events occurred during this limited time within a small region encompassing only a 4000 km^2 area. Previous studies of heavy rain over the EPMA (Rogash 2003) have demonstrated that most significant heavy rain events with 2 in or more of rain falling within 6 hours rarely occurred more than once a season, if at all, within such a limited area. Finally, much of the rain fell during the morning hours, again unusual since most previous floods around this region have been recorded during the afternoon and evening (Rogash 2003).

The deep convection producing the flash flooding developed within an environment exhibiting moisture contents well above normal, including mean PW amounts 160 % of normal and surface dewpoints exceeding 60^{o} F. The air mass for each event was also weakly to moderately unstable with MUCAPE's generally from 500 to 1500 J kg^{-1} and little or no CINH. Wind flow or attendant vertical wind shears were weak and favorable for slow cell movement and/or storms exhibiting upstream propagation. On 1 August 2006 in particular, precipitation efficiencies were high compared with more typical continental United States convection, reflecting the slow system movement and lack of entrainment due to the high RH through almost the entire troposphere over a relatively large region.

The 27 July - 4 August 2006 period was unusual in that there was a prolonged period of lower heights or low pressure in the middle-troposphere, whereas the North American Monsoon period is normally characterized by subtropical ridging extending across the El Paso area. It is believed that this troughing contributed to deep convection by providing periods of dynamic upward motion with induced cooling aloft. This may explain why CINH due to warmer more stable air in the middle troposphere was lacking most of the period.

Larger-scale upward vertical motion associated with upper-level features such as the closed low and short wave troughs also appeared to be weak based on the available data and short-range numerical model forecast information. Low level moisture convergence, while present for part of the period, was also considerably less pronounced than for other heavy events studied over the central and eastern United States (Junker et al. 1999). However, upward motion induced by lower and middle-tropospheric forcing mechanisms was at times supplemented by uplift over higher terrain, especially on 1 August when the heaviest rains fell. In addition, the abundant moisture, instability, and the absence of CINH all suggested little upward motion would be necessary to initiate storms. The conditions for the floods are in general agreement with previous studies (e.g., Maddox et al. 1980) demonstrating that warm-season heavy rains over the western United States are most frequent within environments of high and deep moisture content, weak to moderate instability, low-velocity wind speeds (but at times climatologically stronger-than-average), and where atmospheric forcing mechanisms are feeble or poorly defined but where uplift may be induced by sloping terrain. The high moisture content and associated elevated freezing levels were further conducive for heavy rains by favoring warm-cloud rain processes. Calculations using buoyancy and moisture to estimate sub-cloud moisture convergence and updraft condensation rates also revealed an environment very conducive for heavy rainfalls.

From a forecasting perspective, the meteorologists at the Santa Teresa-El Paso NWSFO issued both timely Flash Flood Watches and Flash Flood Warnings for the heavy rain events due to both the very moist and at least weakly unstable nature of the air mass, plus the presence of lifting mechanisms and lack of CINH. Forecast discussions also mentioned the potential for upwind cell propagation or

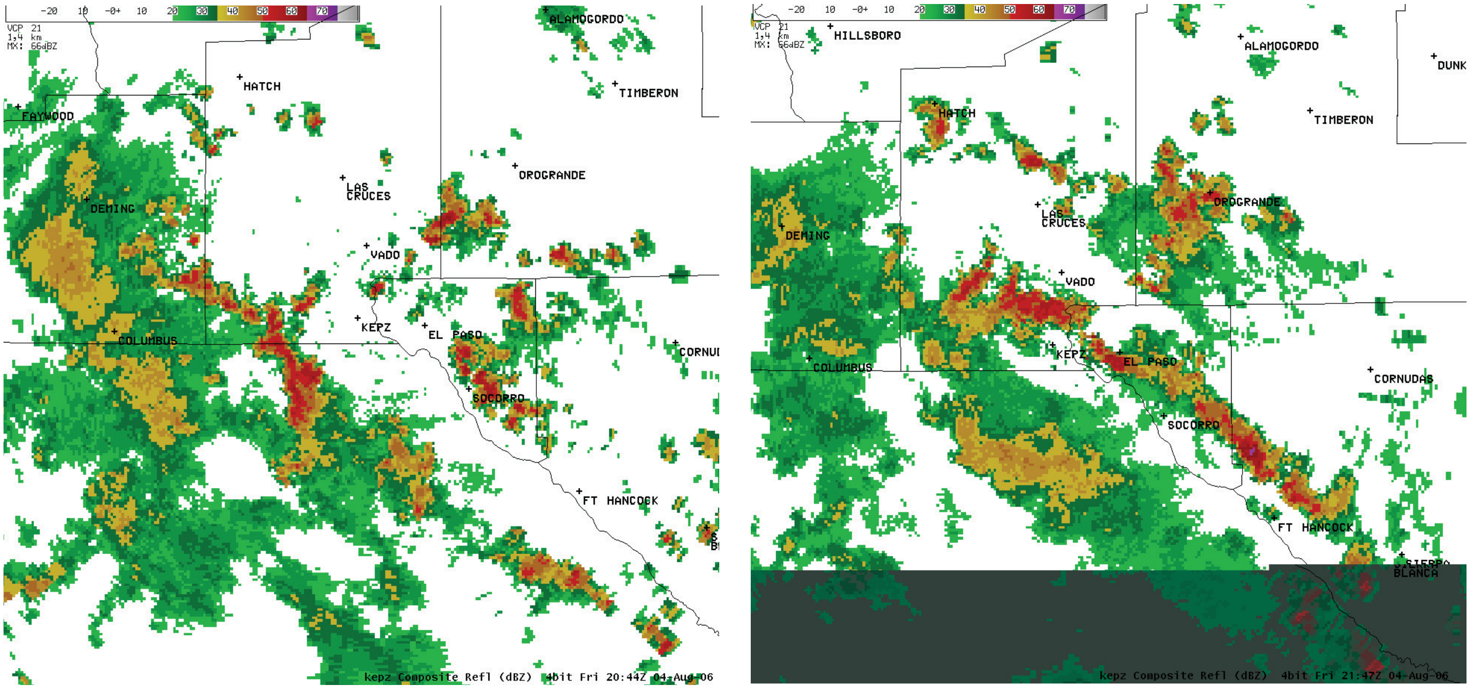


Fig. 32-a

Fig. 32-b

Fig. 32. (a). KEPZ composite reflectivity at 2044 UTC 4 August 2006. Top left shows dBZ scale. **(b)** KEPZ composite reflectivity for 2147 UTC 4 August 2006. Top left shows dBZ scale.

slow storm motion due to the environmental wind shear. However, the Flash Flood Watches also included large portions of the forecast area which did not experience heavy rains, indicating the continuing challenge in determining more precisely, beyond 12 hours, smaller scale regions where locally excessive rains will fall over the western United States.

Authors

Joseph Rogash is currently lead forecaster at the National Weather Service Forecast Office (NWSFO) in El Paso, Texas (located in Santa Teresa NM). He has previously been a lead forecaster at the NWS Storm Prediction Center in Norman, Oklahoma, at the NWSFO in Memphis, Tennessee, and for the Department of Defense at White Sands Missile Range in New Mexico. Mr. Rogash has also been adjunct professor of meteorology at the University of Memphis, where he taught dynamic meteorology and currently gives guest lectures at the University of Texas at El Paso. He received his B.A degree in History in 1975 and a B.S. degree in Physics in 1980 from the University of Massachusetts and completed his M.S. degree in Atmospheric Science from Colorado State University in 1982. His main interests are flash flood and severe thunderstorm forecasting and he has written a number of papers on these topics.

Michael P. Hardiman is a Journeyman Forecaster with the National Weather Service (NWS) El Paso Area Forecast Office located in Santa Teresa, NM. He started as an Intern at the El Paso office in 2003, and has also worked as a forecaster at the Lincoln, IL NWS office. He earned his B.S. in Meteorology from Lyndon State College of Vermont in 2003.

David Novlan is the Climate Focal Point for the National Weather Service (NWS) at the El Paso, Texas (Santa Teresa, NM) office (KELP). He has served as a meteorologist/forecaster at this office since 1999. Prior to that, he served as Chief Forecaster for the Department of Defense at the U.S. Army Meteorological Team at White Sands Missile Range. He holds a B.S. in Mathematics from the University of Colorado and also a M.S, in Meteorology/Atmospheric Science from Colorado State University, where his thesis work focused on hurricane–spawned tornadoes. His professional interests include Synoptic Climatology and the characterization of uncertainty in meteorological predictions. He is a guest lecturer in Climate Science at the University of Texas at El Paso and Mathematics tutor at local colleges and the El Paso Independent School District.

Tim Brice graduated from the University of Missouri in 1992 with dual Bachelor degrees in Journalism and Atmospheric Science. He is currently a lead forecaster and serves as the office GIS (geographic information system) and hydrologic focal point. Tim joined the National Weather Service in 1994 and has served in the El Paso area office for the last 14 years. He has led the way in helping the National Weather Service develop its internet presence and incorporating the latest technologies into operational uses.

Val MacBlain is the Science and Operations Officer (SOO) at the National Weather Service Office in Santa Teresa, NM. A graduate of the Pennsylvania State University with a B.S. in Meteorology, Mr. MacBlain worked in private and civilian military meteorology positions before joining the National Weather Service as the SOO at Lake Charles, LA in 1994. He is an American Meteorological Society Certified Consulting Meteorologist.

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