POST-ANALYSIS OF THE 10 AUGUST 1997 SOUTHERN NEVADA FLASH FLOOD EVENT

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Abstract

While both flash floods and severe thunderstorms occur each summer in southern Nevada, the storm of 10 August 1997 was exceptional. Heavy convective rains recurring over the same local area for several hours resulted in a 100-year flash flood, according to a report by the Clark County hydrologist. Flood damage was further aggravated by a period of thunderstorm-related winds exceeding 80 mph. Thermodynamic profiles were quite unstable owing to the influence of the moist "Mexican monsoon" regime. However, strong westerlies aloft impinging on this environment added an element atypical of monsoon conditions. Proximity soundings suggested unusually large CAPE with substantial vertical wind shear, favoring retriggering of storms and potential mesoscale convective system (MCS) development. The evolution of the convective system is of particular interest for at least two reasons. First, this case represents an outstanding example of assembling the ingredients for a slow-moving MCS within a large-scale environment characterized by moderate-to-strong tropospheric winds. Second, the mode of convection changed character in concert with the interaction of the synoptic scale jetstreak and other key mesoscale features including convective outflow boundaries, an apparent low-level wind maximum, and local topography. The storm's severity was clearly impacted by the complex interplay among these meteorological and hydrological factors. Understanding the important processes governing convective structure and organization is crucial to successfully anticipating and accurately forecasting extraordinary events such as these.

1. Introduction

On Sunday, 10 August 1997, severe thunderstorms accompanied by significant flash flooding produced widespread and costly damage across the Henderson and Boulder City areas of extreme southern Nevada. Public facilities in Boulder City sustained an estimated $1.85 million in damages with an additional $350,000 in damages to uninsured property. In Henderson, the cost of storm-related destruction totaled nearly $1.5 million. Tragically, one fatality also resulted from these storms. The Boulder City Public Works Department reported that many of the city's streets were impassable during the rainfall, and some suffered loss of pavement as a result of the undercutting of flood waters. Three automated rain gauges recorded two to three inches of rainfall in less than one hour. The steep desert landscape which characterizes this area simply could not mitigate the effects of such a downpour. According to the Clark County Regional Flood Control District (Sutko 1997), several locations met or exceeded the 100-year flood event criterion. In Boulder City, the impact of the flooding was exacerbated by thunderstorm-driven winds estimated at 80-90 miles per hour, resulting in at least 40 mature trees being snapped in two. This paper will describe the synoptic conditions leading to the development of this event, detail the evolution of several key mesoscale features, then draw some conclusions regarding important relationships between the meteorological and hydrological factors which influenced the system's severity.

2. Synoptic Overview

Analysis of upper air data, valid 1200 UTC 10 August 1997, indicated a mid-tropospheric trough extending from western Montana through a closed low over central Oregon, then offshore through northern California (Fig. 1). Satellite cloud-drift winds and offshore aircraft reports (not shown) depicted a jetstreak of nearly 40 m s^{-1} approaching the southern California coast. These reports were substantiated by a 33 m s^{-1} westerly wind at 250 mb on the Vandenberg, California radiosonde observation (Fig. 2). Over southern Nevada, modest cooling had taken place in the 300-500 mb layer during the preceding 24-hour period (Fig. 3). At the same time, substantial moistening had occurred in the lower levels, as evidenced by an average increase in dewpoint of 4-7 °C below 700 mb. In addition, surface dewpoints exceeding 15 °C were common across the area, and clear skies were expected to allow several hours of unimpeded boundary layer heating, leading to very large lapse rates by early afternoon. Short term extrapolation suggested the development of atypical summer soundings for the area with CAPE values exceeding 2000 J kg^{-1} and pronounced vertical wind shear of ~ 24 m s^{-1} through the 0-6 km layer (Figs. 4 and 5).

The influence of strong westerlies impinging on a lower troposphere rich in moisture produced an environment of potential instability conducive to very high rain rates as defined by $R = Ewq$. R is the Rainfall Rate, E is the Precipitation Efficiency coefficient (a ratio of the mass of water falling as precipitation to the mass of cloud water influx), w is the ascent rate, and q is the mixing ratio of the rising air (Doswell, Brooks and Maddox 1996).

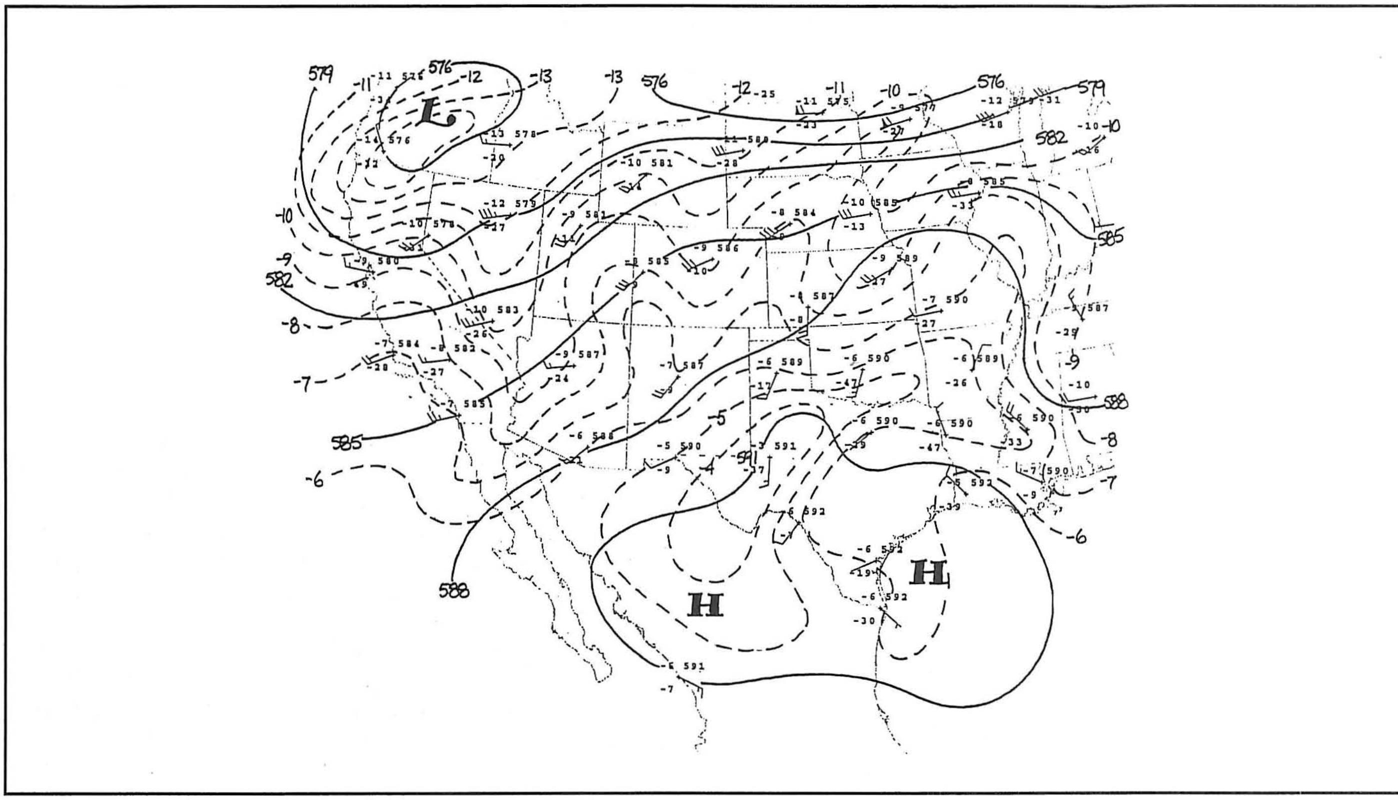

Fig. 1. 500 mb analysis, valid 1200 UTC 10 August 1997 (solid lines = geopotential height in dm; dashed lines = temperature in °C; wind in kt, full barb = 10 kt)

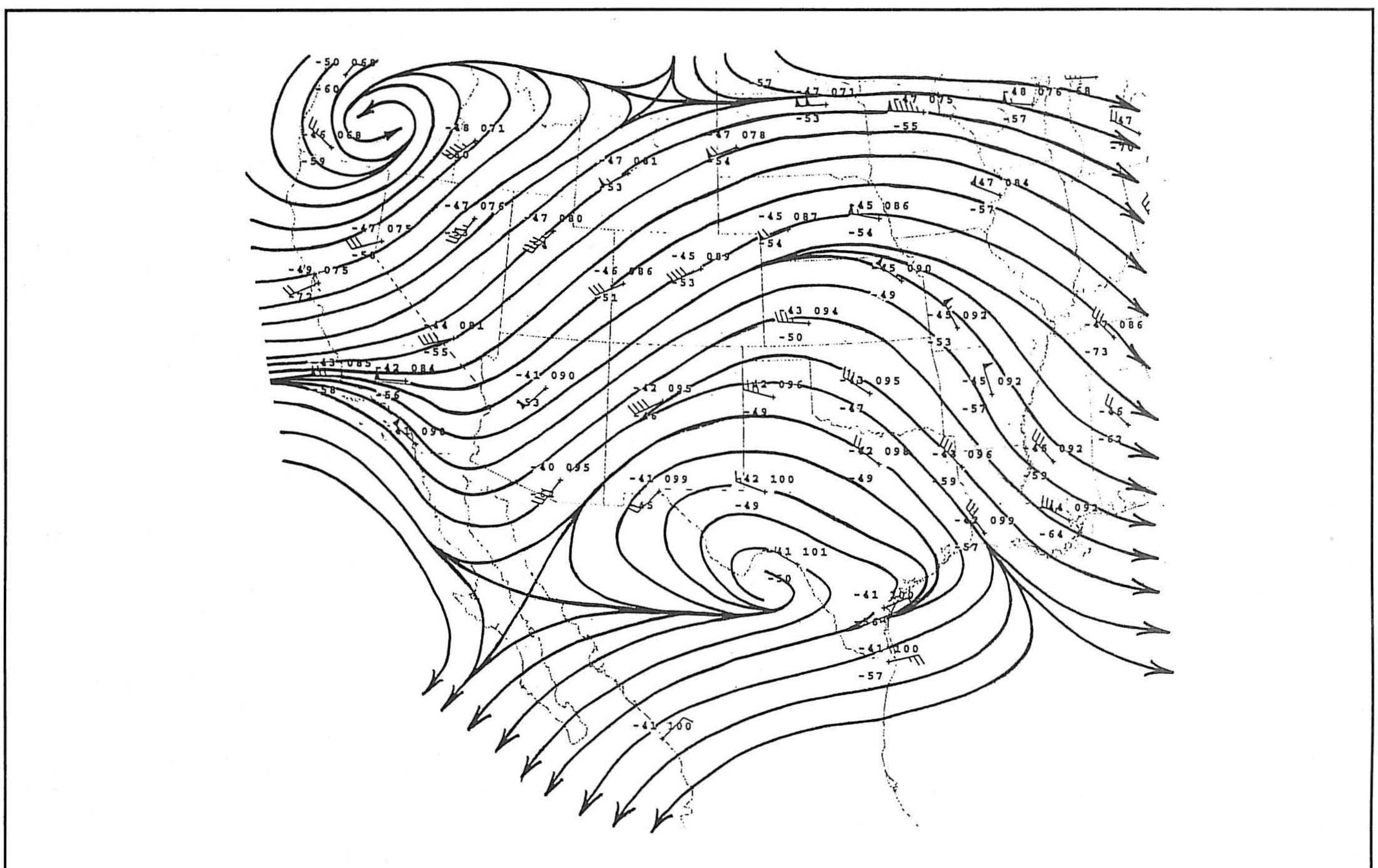

Fig. 2. 250 mb streamline analysis, valid 1200 UTC 10 August 1997 (wind in kt, full barb = 10 kt)

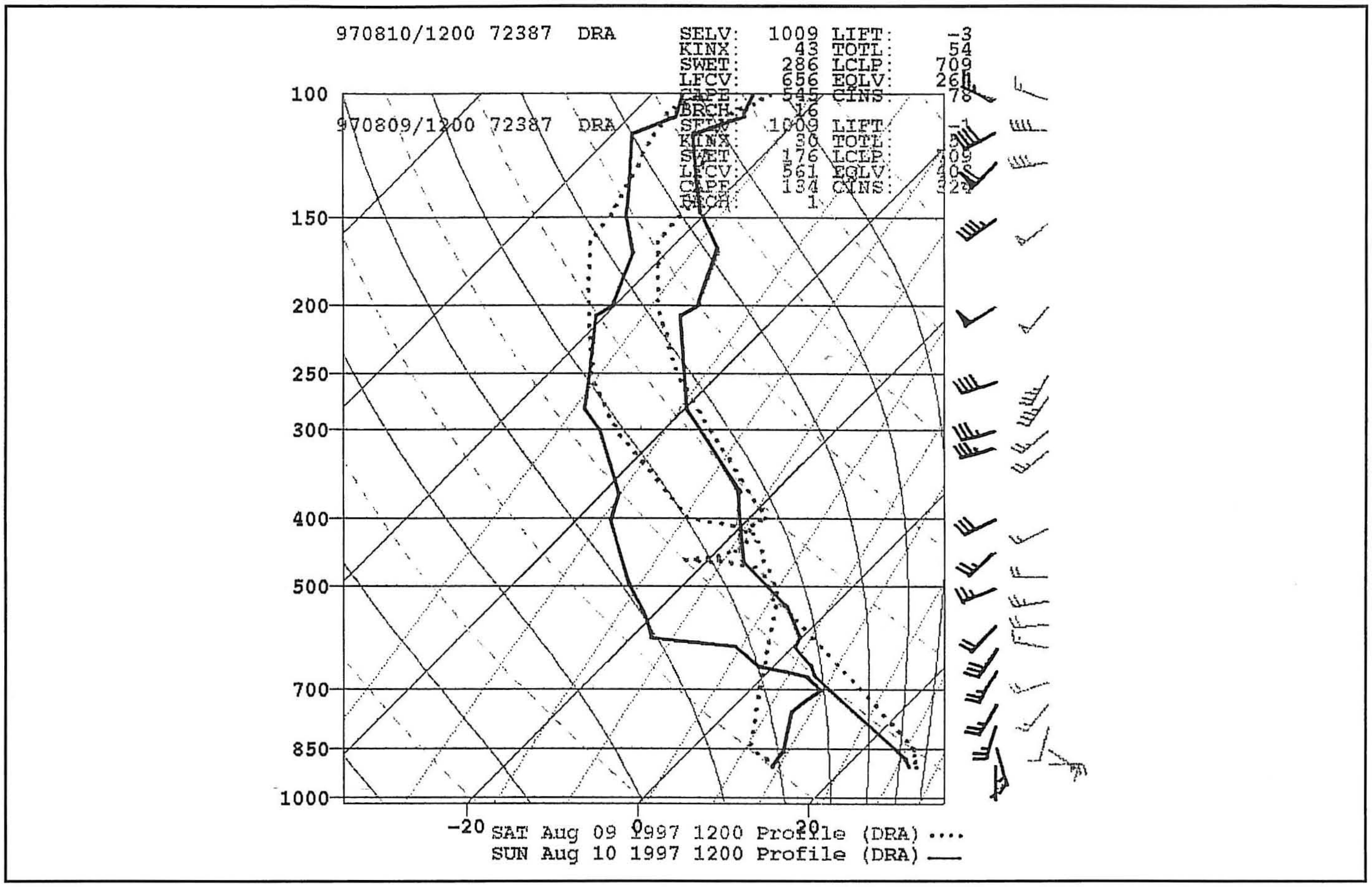

Fig. 3. Comparison of Skew-T diagrams from Desert Rock, NV (solid lines = 1200 UTC 10 August 97, dashed lines = 1200 UTC 9 August 1997, wind in kt, full barb = 10 kt)

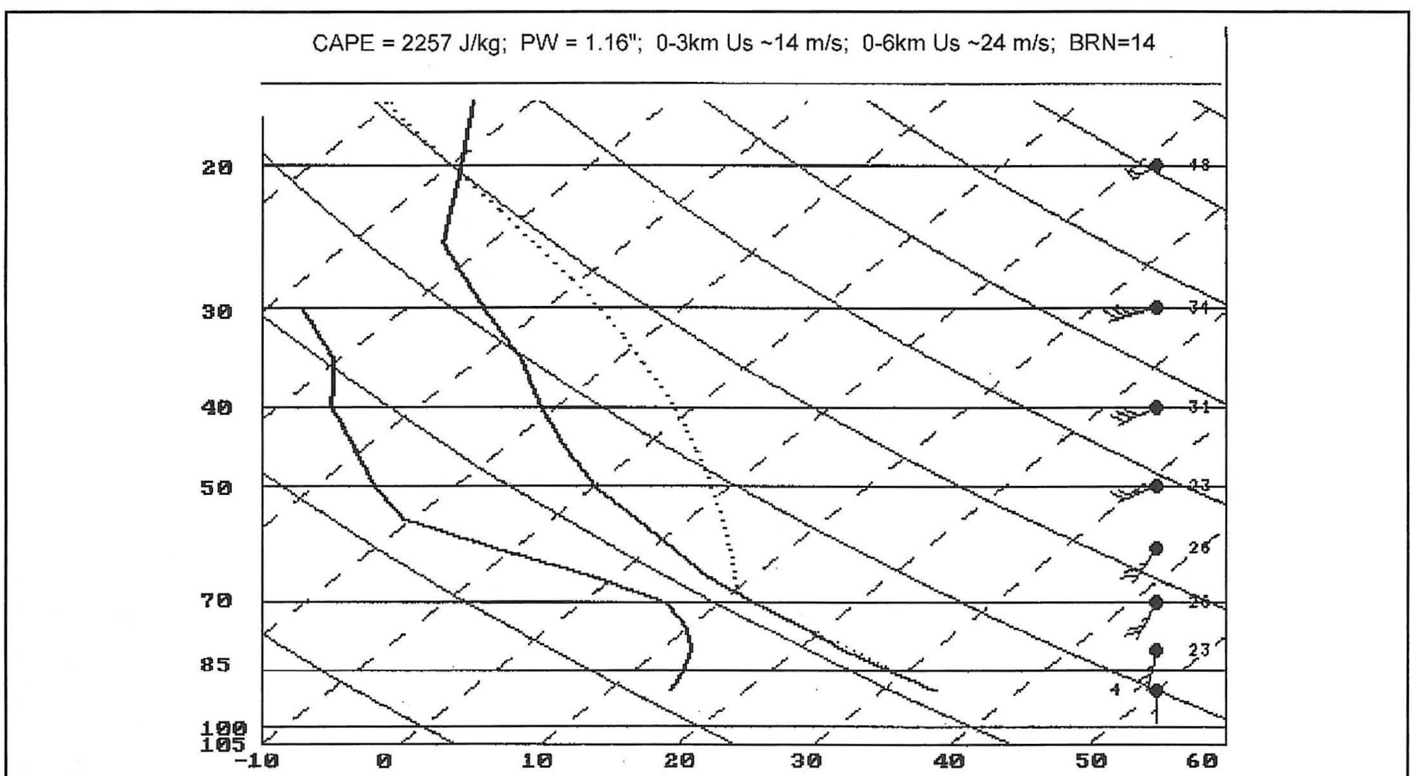

Fig. 4. Desert Rock sounding modified to estimate conditions in the Las Vegas valley for ~ 1900 UTC 10 August 1997

3. Mesoscale Aspects of the Convective Environment

Initial thunderstorm development focused on a quasi-stationary convergence boundary oriented east to west, which had been created by outflow from the previous evening's convective activity (Fig. 6). A small mesoscale convective system (MCS) had persisted through the night over extreme southwest Utah. Between the hours of 1600 and 1800 UTC, animated satellite imagery and radar data revealed an organized outflow boundary, originating from this MCS, being ejected toward the southwest. By 1900 UTC (noon PDT), new cell growth was observed to form at the intersection of this secondary outflow boundary and the western end of the pre-existing convergence zone, which was anchored to high terrain in the McCollough Range west of Lake Mead (Fig. 7). This feature seemed to be the mechanism by which convective updrafts were initially lifted to the level of free convection (LFC).

Additional forcing associated with jetstreak dynamics apparently contributed to the development of organized deep convection along this interface by early afternoon. Satellite animation depicted explosive growth coincident with the approach of the upper-level jet maximum (Fig. 8). While the source of lift was not located beneath the traditionally favored left exit region with respect to the jet maximum, it has been shown that substantial forcing exists around the entire nose of a cyclonically curved jetstreak (Moore and Van Knowe 1992), consistent with this feature's orientation.

Boundary layer moisture had been on the increase for several hours prior to the initiation of deep convection, owing to a strong southerly flow from the Gulf of California up the Colorado River valley in the surface to 850 mb layer. Surface dewpoints climbed to near 20 °C by 1800 UTC. The rapid increase in moisture was likely a combination of quasi-horizontal advection and downward vertical mixing of elevated moisture as the boundary layer deepened with heating. Similar historical cases have been documented in which an elevated wind maximum of about 15 m s^{-1} served to transport moist air rapidly northward above the morning inversion (Douglas 1995; Runk 1996). Observations to verify the existence of such a nocturnal jet on 10 August 1997 were unavailable. However, a southerly low-level wind field of approximately 10-15 m s^{-1} extending from the Gulf of California through the lower Colorado River valley was produced in a post-event modeling simulation using a nonhydrostatic version of the Aster Corporation RAMS model (Pielke et al. 1992) at 10-km horizontal grid spacing (Fig. 9). Moreover, the temporal evolution of the low-level moisture field implies that contribution. Numerical guidance from the NOAA/National Weather Service/ National Centers for Environmental Prediction (NCEP), 29-km version Eta model predicted 800 mb dewpoints of around 12 °C with substantial moisture flux convergence developing in the area by 1800 UTC (Fig. 10). The Eta 00-h 310 °K theta surface depicts the low-level moist tongue well (Fig. 11). It is understood that diabatic heating in this region affects the isentropic

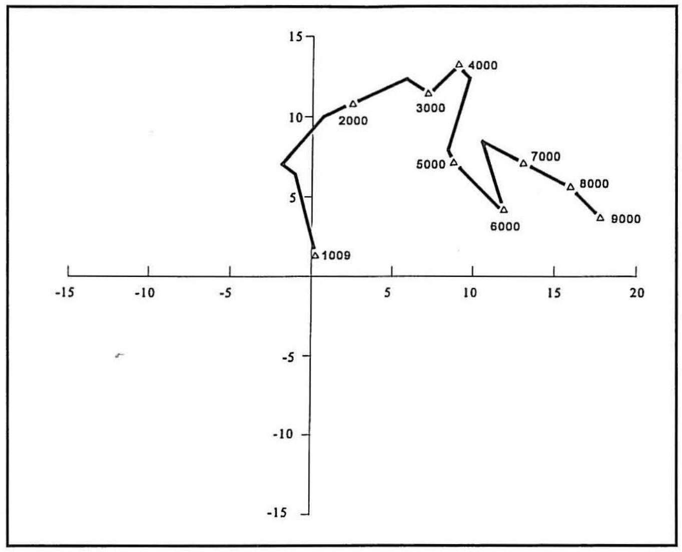

Fig. 5. Desert Rock hodograph, valid 1200 UTC 10 August 1997 (scale = m s^{-1}; hodograph tick marks every 1000 m above mean sea level)

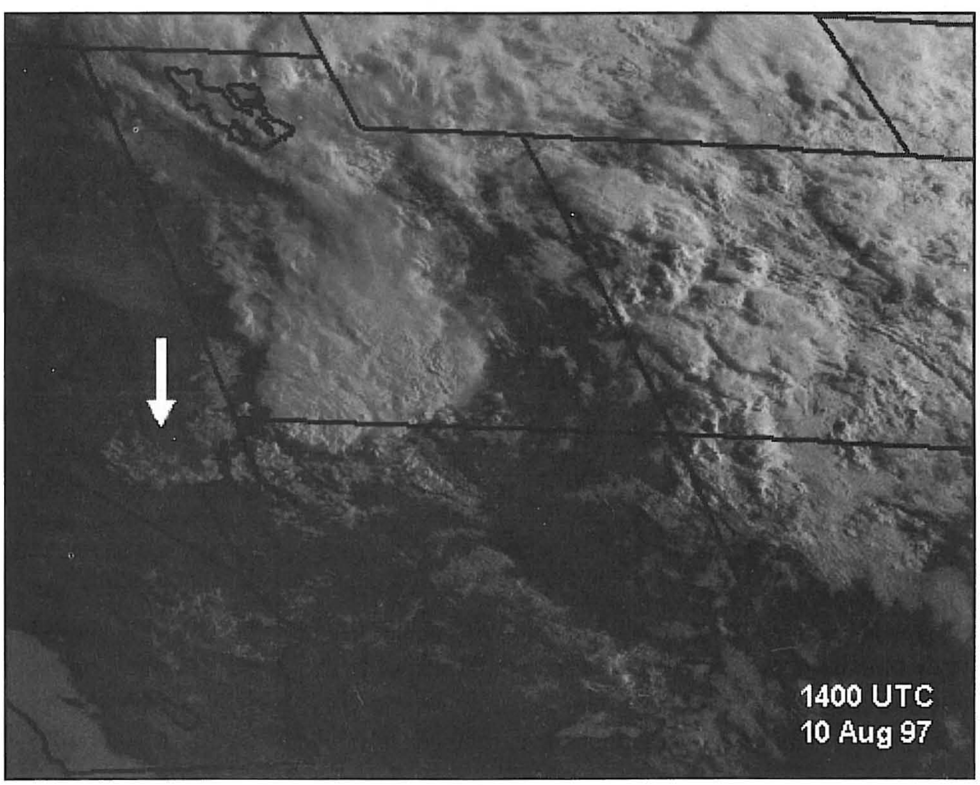

Fig. 6. GOES-9 visible image, valid 1400 UTC 10 August 1997 (convective outflow boundary indicated by arrow)

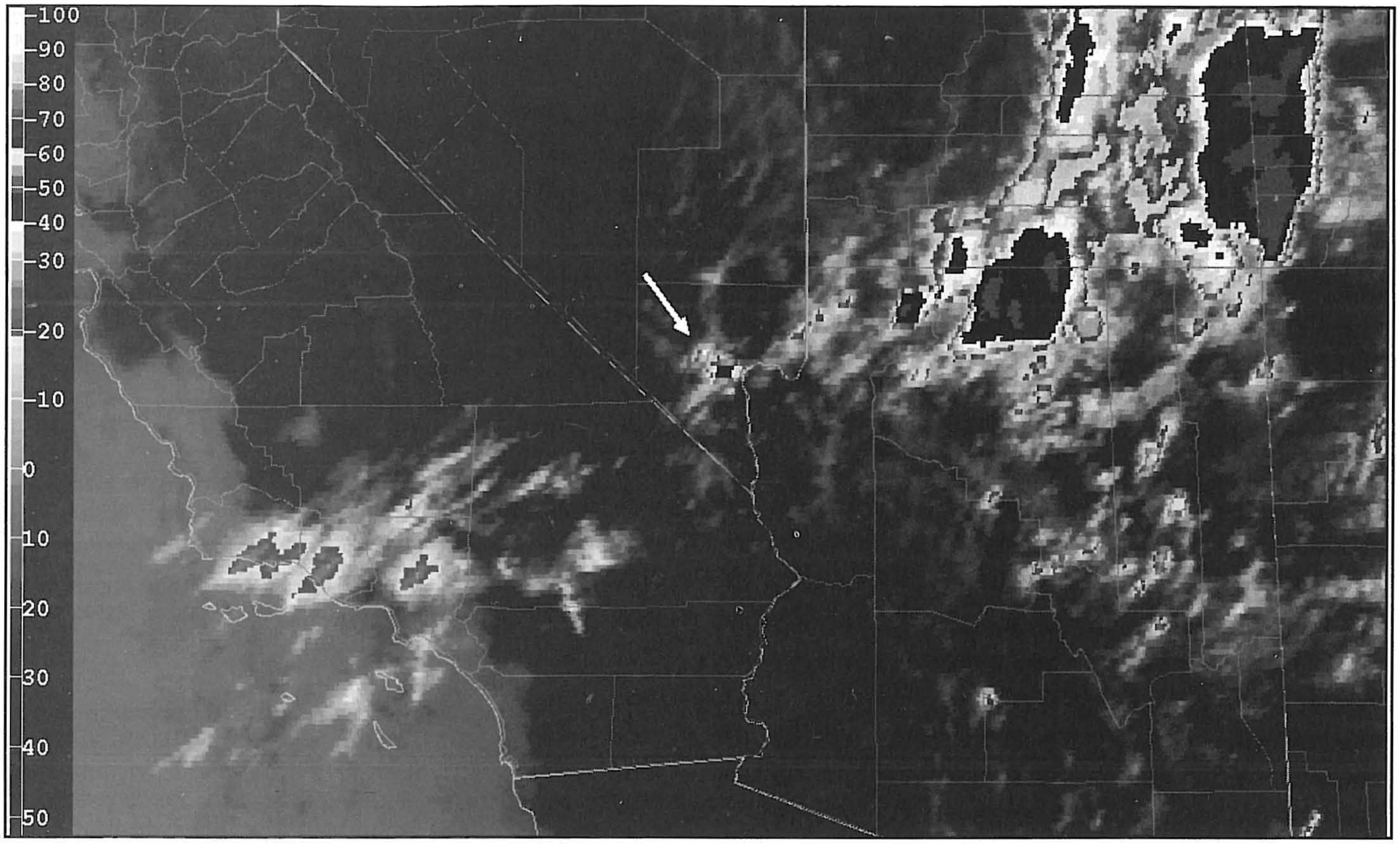

Fig. 7. GOES-9 infrared image, valid 1900 UTC 10 August 1997 (thunderstorms forming at intersection of secondary outflow boundary and pre-existing convergence zone)

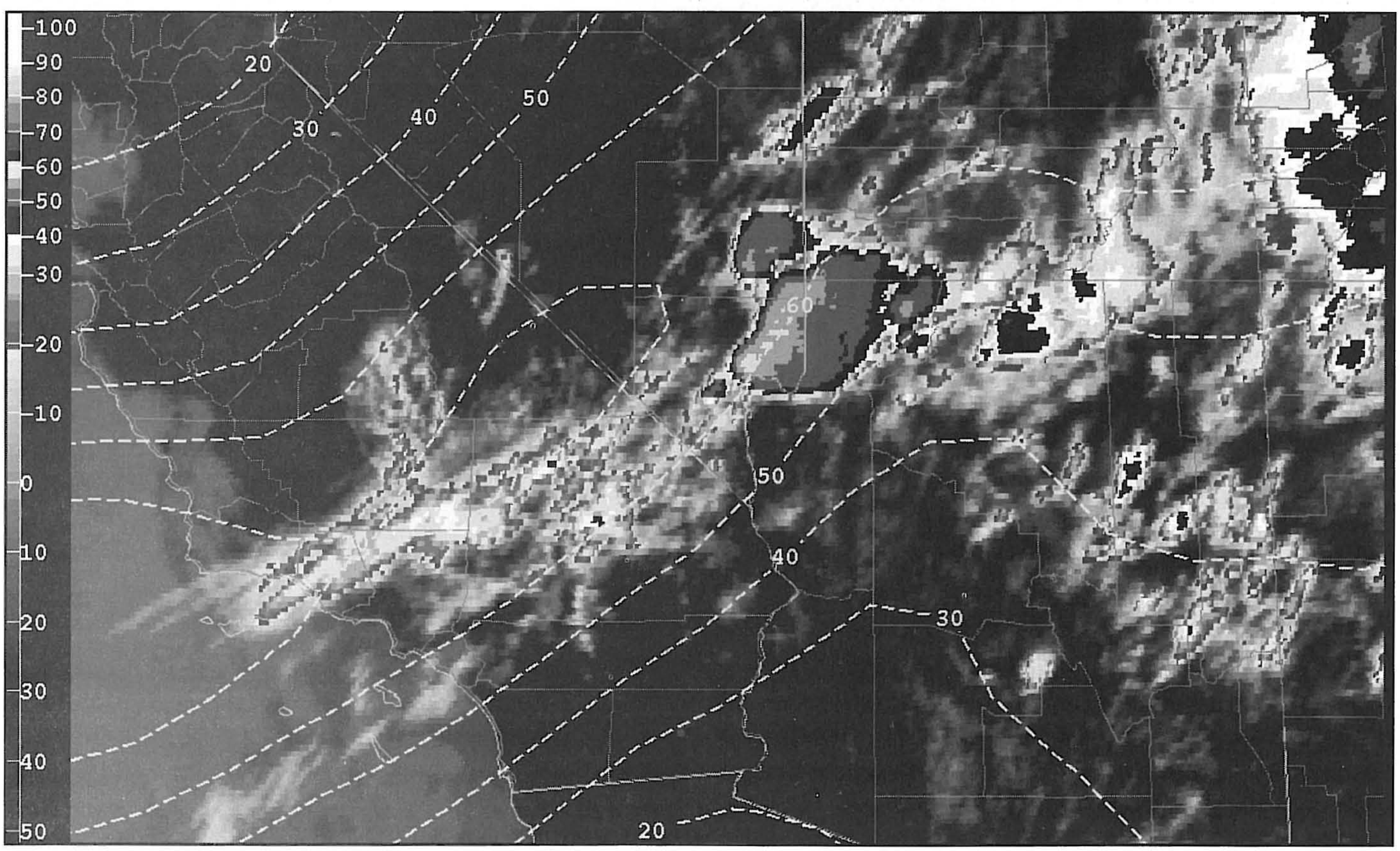

Fig. 8. GOES-9 infrared image, valid 2100 UTC 10 August 1997 (dashed lines = 200 mb isotachs in kt from NCEP/RUC 6-h forecast, valid 2100 UTC 10 August 1997)

surfaces well above this layer, but since this analysis is valid for 1200 UTC (0500 PDT), it is presumed to be fairly representative of the large scale character of moisture advection into the pre-storm environment.

This warm, moist southerly flow, in concert with intense surface heating, continued to destabilize the air mass as suggested by the 850 mb theta-e forecast (Fig. 12), and acted to erode the weak capping layer. Comparison of the 1200 UTC Desert Rock soundings from 9 and 10 August 1997 shows low-level moisture had deepened to a layer nearly 200 mb thick, with 1.04 inches of precipitable water and a mean wet-bulb potential temperature in the surface to 700 mb layer of 21.8 °C. The accompanying hodograph exhibits significant clockwise curvature with vertical wind shear of ~ 24 m s^{-1} in the lower 6 km AGL, and a Bulk Richardson number of 14, suggesting the potential for long-lived rotating updrafts (Weisman and Klemp 1984; Weisman and Klemp 1982; Rotunno 1981). Moreover, the wind profile in the lower 3 km AGL displayed sufficient shear to support organized multicell evolution in the downshear direction, leading

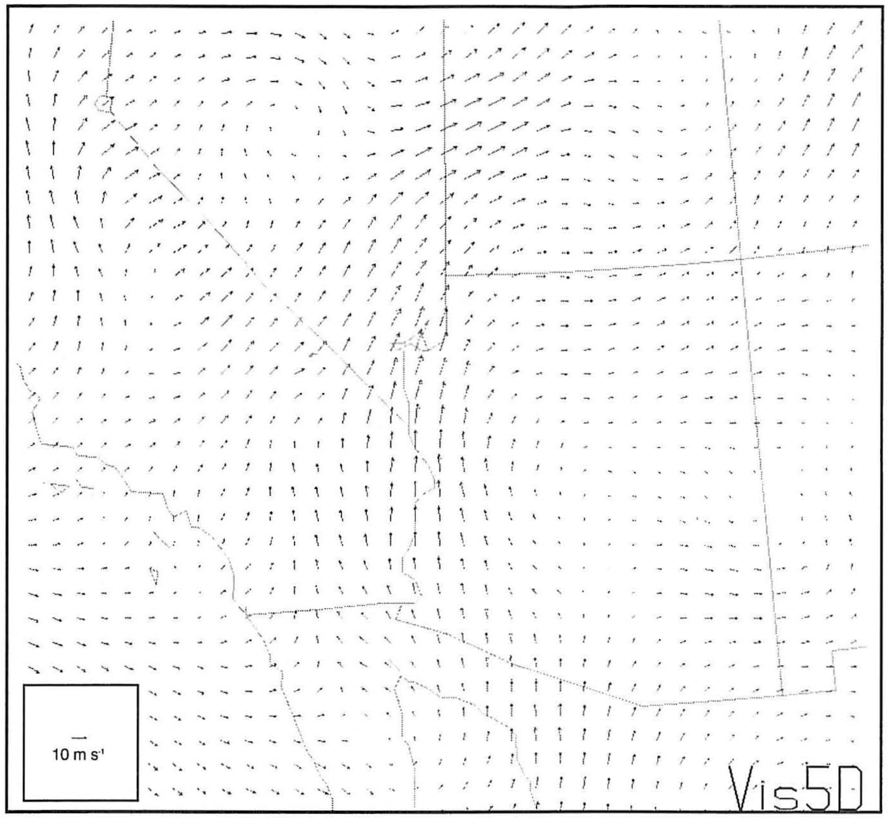

Fig. 9. RAMS low-level wind forecast, valid 1500 UTC 10 August 1997 (level is approximately 2 km above the surface; reference vector = 10 m s^{-1})

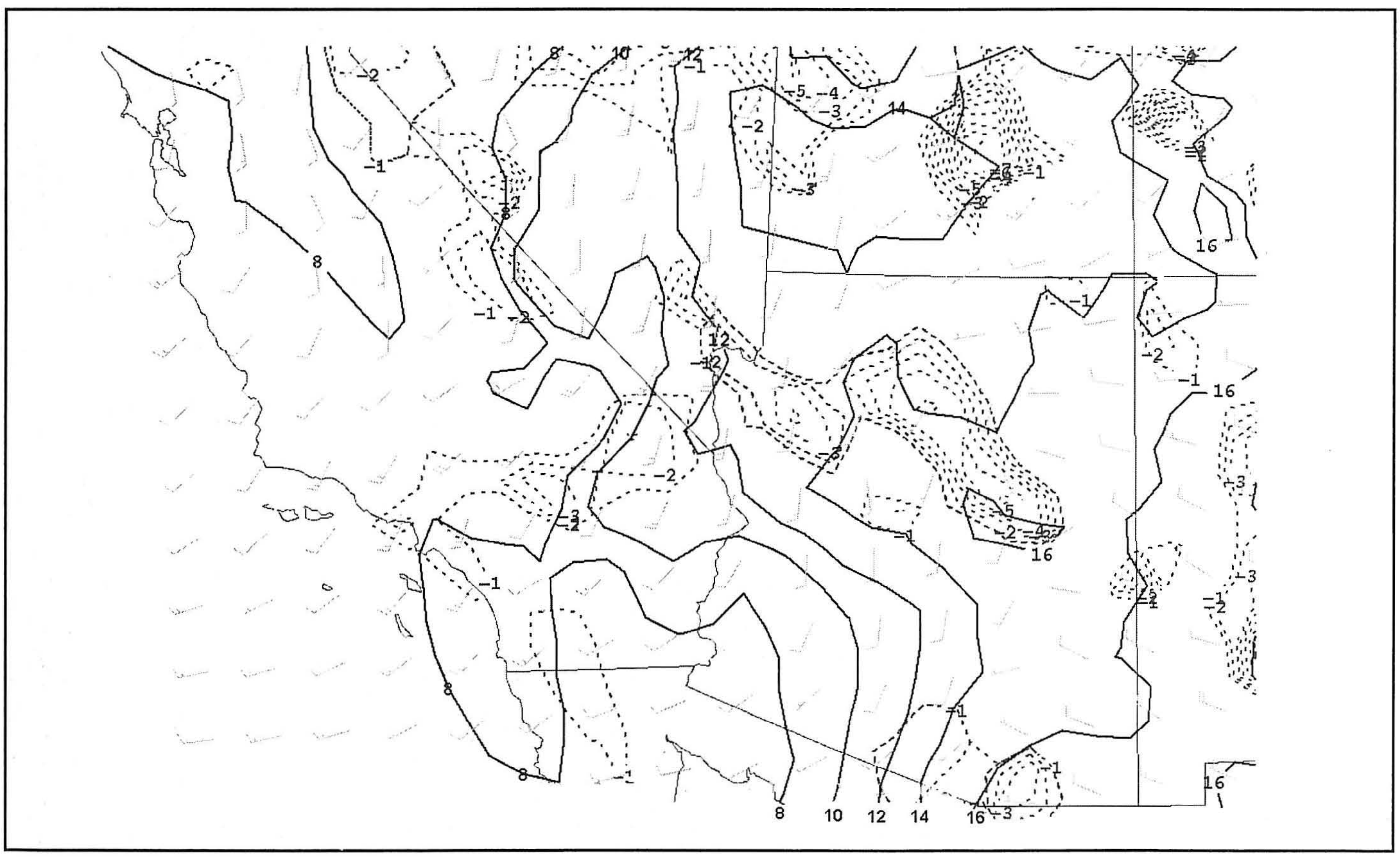

Fig. 10. Eta-29 3-h forecast of 800 mb dewpoints (solid lines, °C) and moisture flux convergence (dashed lines, 10^{-7} s^{-1}); valid 1800 UTC 10 August 1997

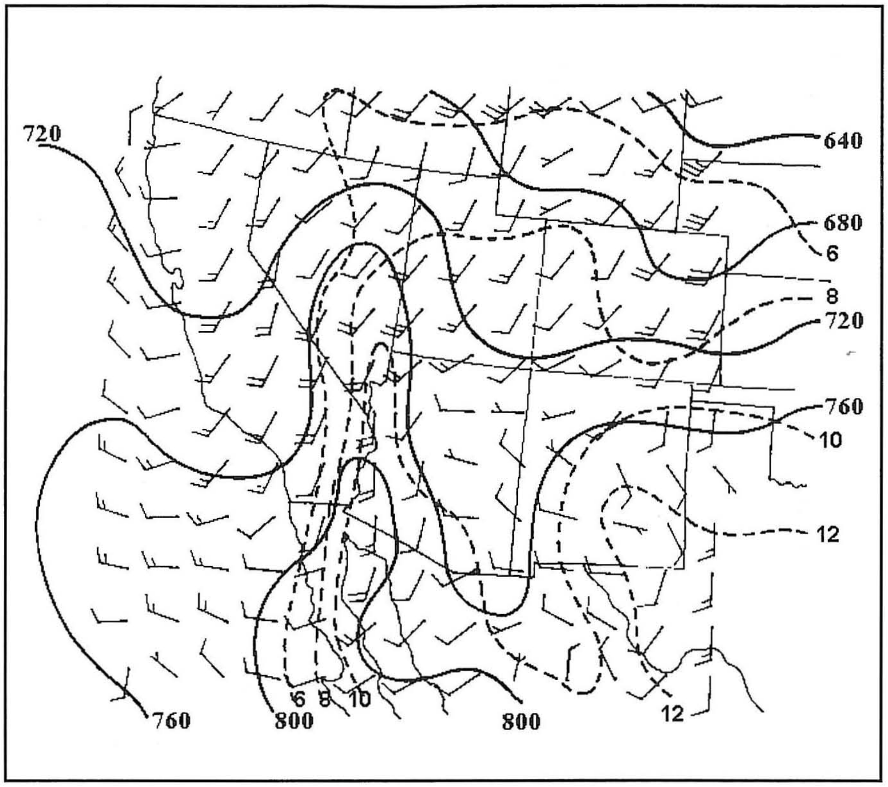

Fig. 11. Eta-48 00-h forecast of 310° K isentropic surface, valid 1200 UTC 10 August 1997 (solid lines = isobars in mb; dashed lines = mixing ratio in g kg^{-1}, wind in kt, full barb =10 kt)

to possible MCS development, given a linear trigger mechanism. Conservative modification of the morning sounding suggested afternoon CAPE values between 1500-2500 J kg^{-1}, implying large ascent rates (w) and large input mixing ratios (q): fundamental factors in the production of high rainfall rates as defined by the equation in Section 2. Indeed, by 2000 UTC, the GOES sounder data indicated CAPE values of about 1800 J kg^{-1} (Fig. 13) and lifted index values in the -5 to -7 °C range (Fig. 14).

During the early stages of system development, storms continued to form along the convergence zone, then move northeast with the mean wind. Reflectivity and velocity data from the KESX (Las Vegas area) WSR-88D radar, as well as visual observations from trained spotters, indicated new cell growth was recurring near the downdraft of preceding storms (Fig. 15). This configuration, suggestive that gust front processes were dominating the retriggering of storms, persisted for about an hour. Given the relatively high environmental humidity, it is assumed that evaporation rates were low enough such that the cold

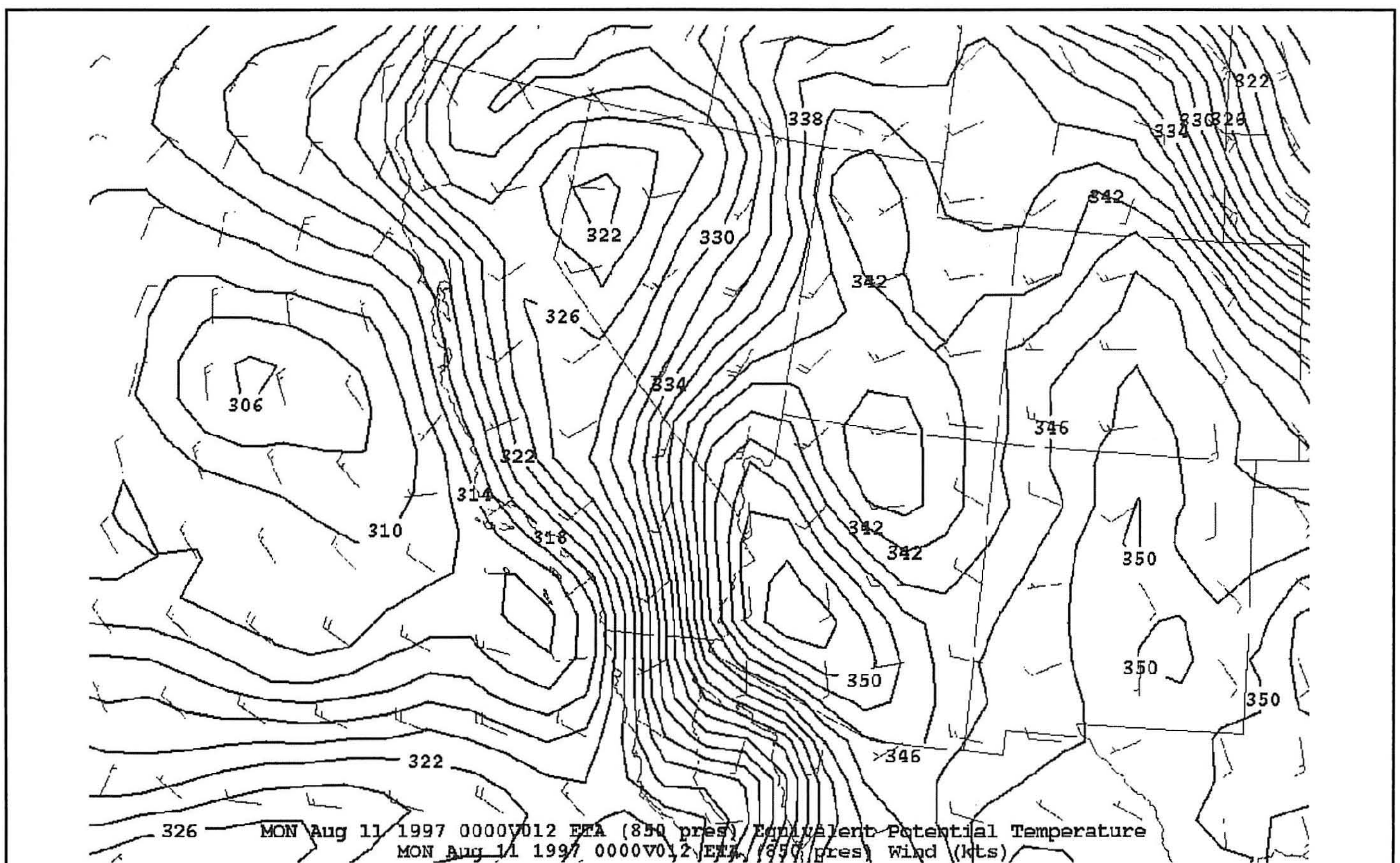

Fig. 12. Eta-48 12-h forecast of 850 mb theta-e (°K) and wind (full barb = 10 kt), valid 0000 UTC 11 August 1997

pool of a decaying cell was not strong enough to disrupt or undercut the moist boundary-relative inflow to new updrafts along the southern flank of the convergence line. Subsequent cells could then track northeast with the mean wind along a trajectory similar to their predecessors. This motion reinforced the boundary and maintained its position relative to the low-level moisture axis.

Following the schematic of Chappell (1986), the cell motion vector was directed toward the northeast, while the propagation vector was oriented toward the southwest (though with a smaller magnitude), resulting in a system motion vector which was nearly stationary (Fig. 16). From an Eulerian viewpoint, east Henderson and Boulder City were located in a region experiencing repeated convective rains from multiple cells for a period of several hours. Thus, the ingredients were in place for a slow-moving MCS to form within a large-scale environment characterized by moderate-to-strong tropospheric winds.

4. Evolution of Storm Structure

By 2020 UTC, thunderstorms had organized into a solid line oriented northeast to southwest from the Lake Mead National Recreation Area through Boulder City and Henderson to the McCollough Range (Fig. 17). Elevated cores of high reflectivity were noted as storms approached Boulder City. Enhanced moisture convergence may have contributed to this intensification as mesonet winds depicted a small but distinct cyclonic circulation in the wind field southwest of Boulder City with well-defined confluence in its northeast quadrant (Fig. 18).

Immediately following this rapid intensification, the strongest reflectivity core was observed to split, with the most intense cell moving to the right of the mean storm motion vector (Fig. 19). This cell displayed marked rotation and triggered

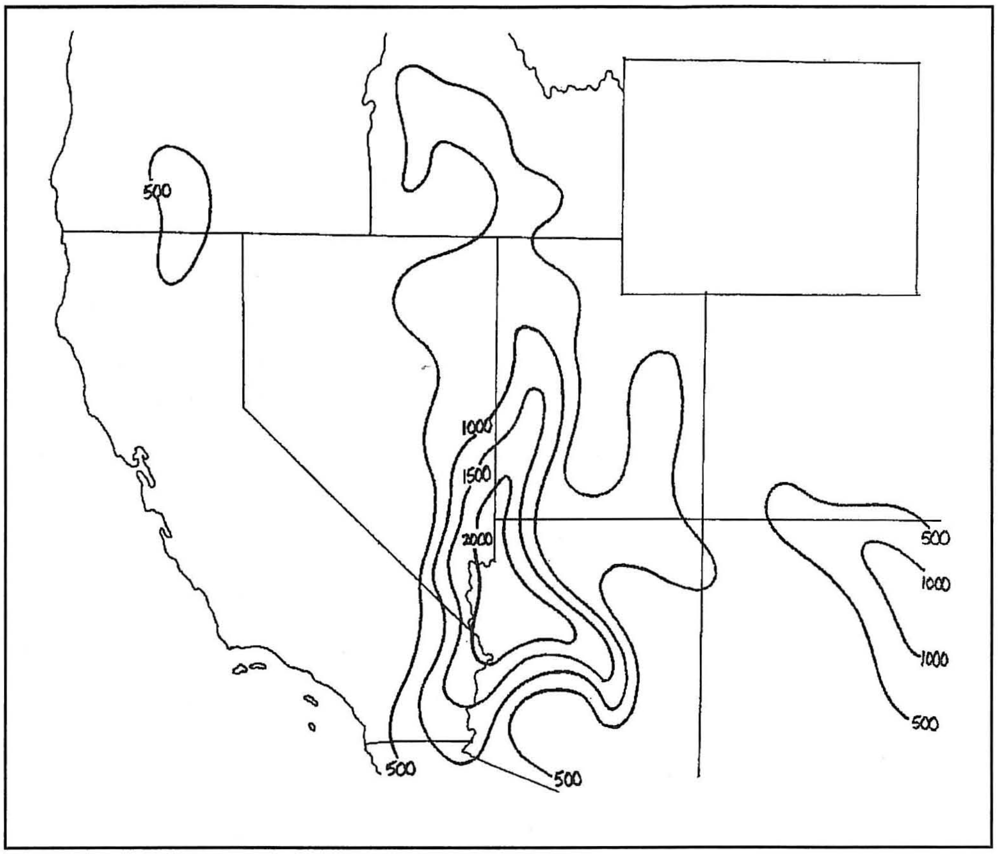

Fig. 13. GOES-9 sounder CAPE (J kg^{-1}), valid 2000 UTC 10 August 1997

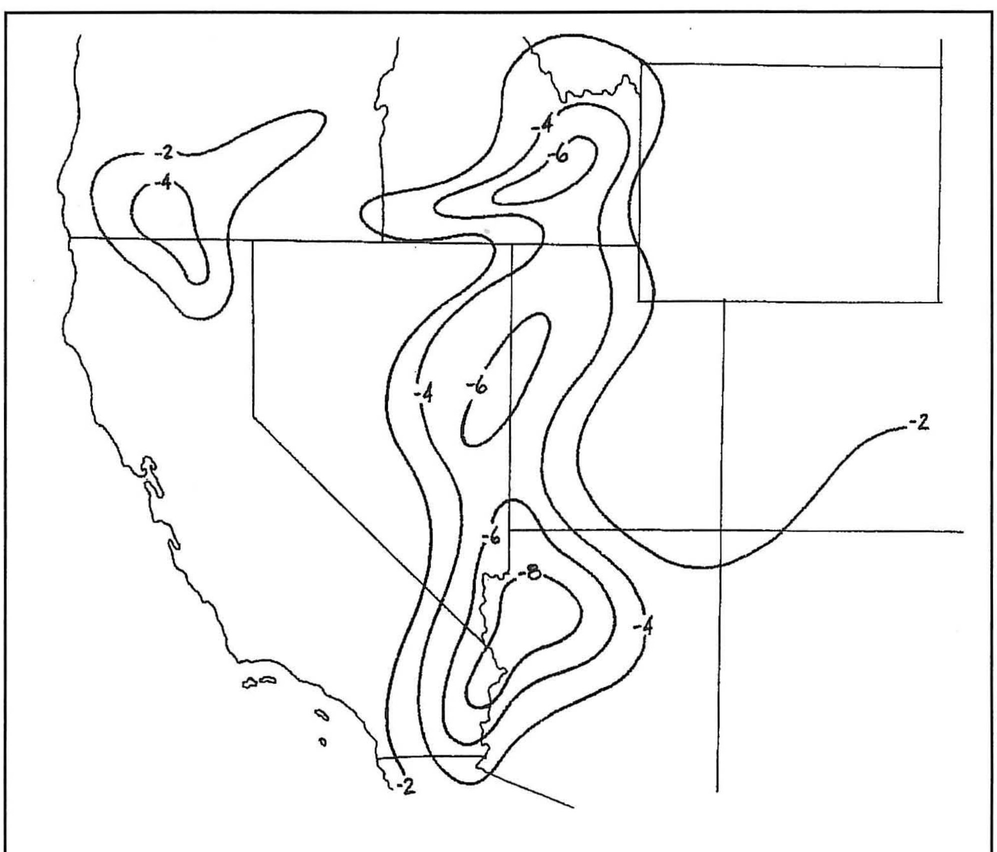

Fig. 14. GOES-9 sounder Lifted Index (°C), valid 2000 UTC 10 August 1997

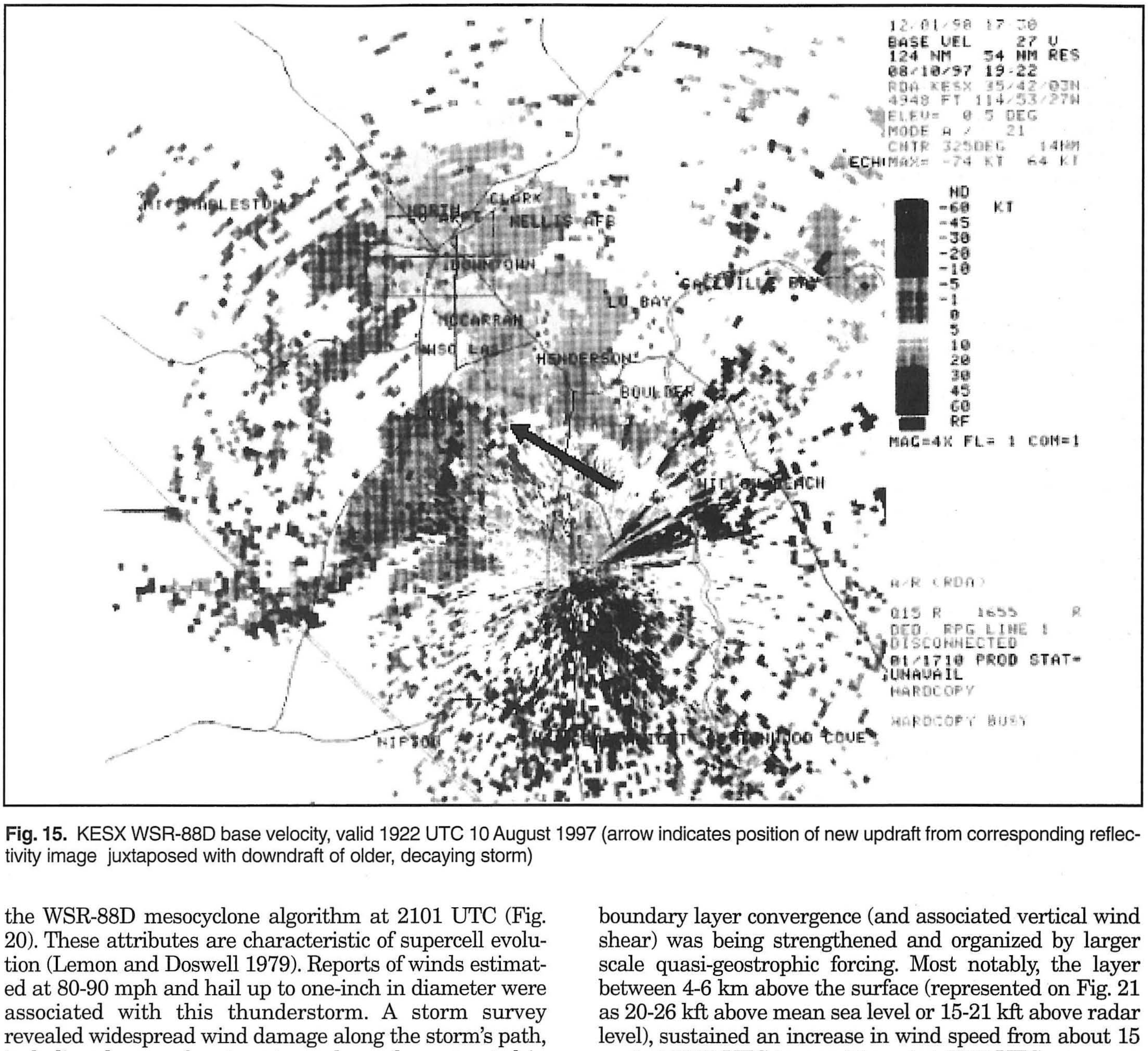

Fig. 15. KESX WSR-88D base velocity, valid 1922 UTC 10 August 1997 (arrow indicates position of new updraft from corresponding reflectivity image juxtaposed with downdraft of older, decaying storm)

the WSR-88D mesocyclone algorithm at 2101 UTC (Fig. 20). These attributes are characteristic of supercell evolution (Lemon and Doswell 1979). Reports of winds estimated at 80-90 mph and hail up to one-inch in diameter were associated with this thunderstorm. A storm survey revealed widespread wind damage along the storm's path, including dozens of mature trees downed or uprooted in Boulder City. The coincidence of this process with the passage of the upper-level jetstreak suggests the zone of boundary layer convergence (and associated vertical wind shear) was being strengthened and organized by larger scale quasi-geostrophic forcing. Most notably, the layer between 4-6 km above the surface (represented on Fig. 21 as 20-26 kft above mean sea level or 15-21 kft above radar level), sustained an increase in wind speed from about 15 m s^{-1} at 1922 UTC to over 25 m s^{-1} at 2020 UTC.

As the influence of larger scale dynamic processes and attendant vertical wind shear increased, the character of the convective structure evolved first into a line echo wave pattern (Fig. 22), then into two small bowed echoes (Fig. 23), which accelerated northeast into Arizona. The VAD Wind Profile for this time (Fig. 24) indicated moderate wind shear in the lowest 2000-3000 ft above radar level, with generally steady winds through the mid-troposphere. Although the bow echoes were neither classic nor intense, the conditions within which they developed were consistent with those favoring bow echo forma-

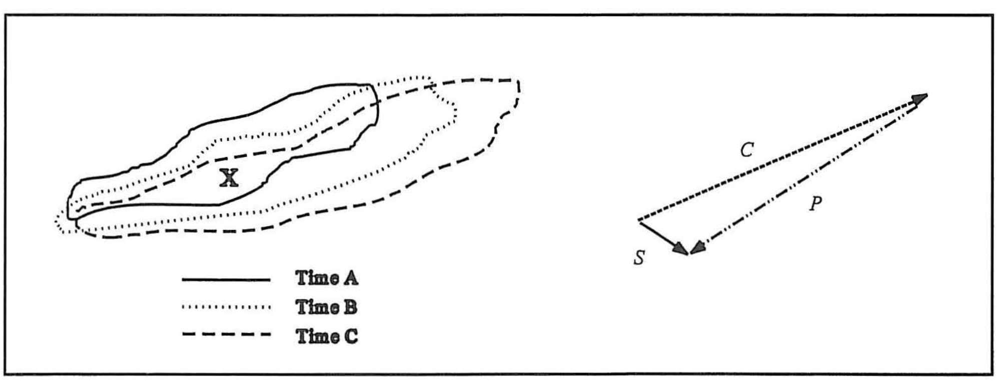

Fig. 16. Schematic of system propagation, valid 2000-2300 UTC 10 August 1997 (C = cell motion vector, P = propagation vector, S = system vector)

tion in numerical simulations documented by Weisman (1993) and confirmed observationally by Johns (1993). In particular, these studies suggest optimum wind conditions for development and maintenance of bow echoes consist of moderate-to-strong vertical shear in the lower 1-2 km AGL, with uniform winds above. Albeit marginal in both depth and strength, the proximity wind shear profile falls within these parameters during the time in which bow structures formed on the afternoon of 10 August 1997.

In summary, the changing nature of the thermodynamics and kinematics, coupled with increasingly complex convective scale interactions, resulted in at least three different stages in the mode and organization of the deep convection on 10 August 1997 (multicellular line, isolated mini-supercells, bow echoes).

5. Hydrological Factors

The process of many cells passing over the same area in rapid succession (the so-called "train echo effect") is arguably the most dangerous of situations for producing life-threatening floods in many areas of the country, the southwest US included. However, in areas of complex topography, the interaction of the meteorology with the specific character of the local terrain plays a crucial role in determining whether a meteorologically modest event might become a locally severe one from a hydrology perspective.

Boulder City is located on the shelf of a broad alluvial fan which drains southward into the El Dorado valley. This valley is bounded to the east by the El Dorado Mountains and to the west by the McCollough Range (Fig. 25). The former is a small range oriented north-south paralleling the west bank of the Colorado River. The El Dorado

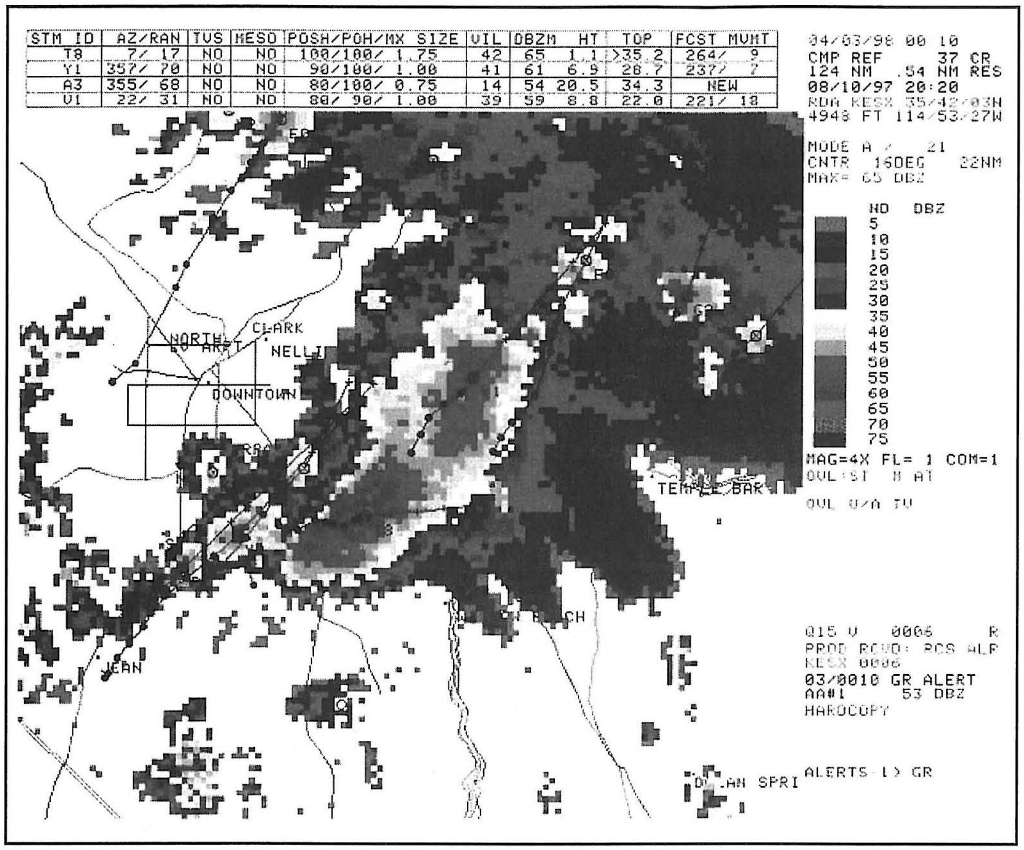

Fig. 17. KESX WSR-88D composite reflectivity image, 2020 UTC 10 August 1997

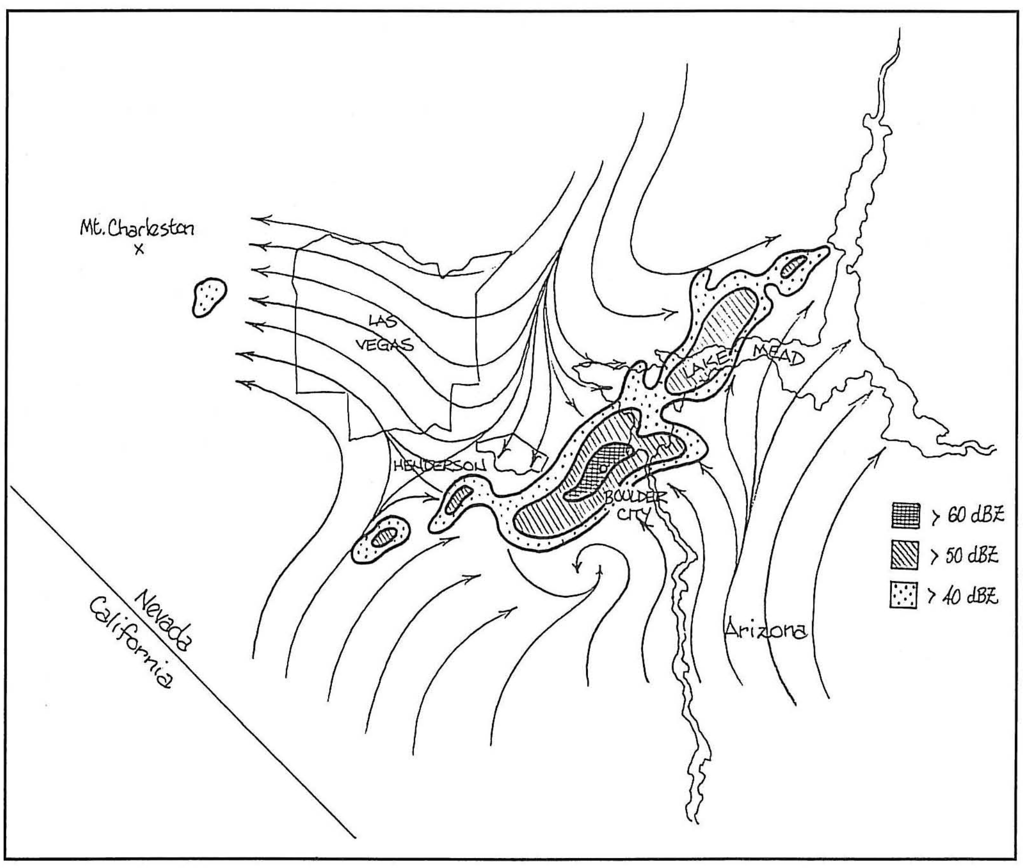

Fig. 18. Diagram of radar echoes and surface streamlines at 2030 UTC 10 August 1997 (based on KESX composite reflectivity and mesonet winds)

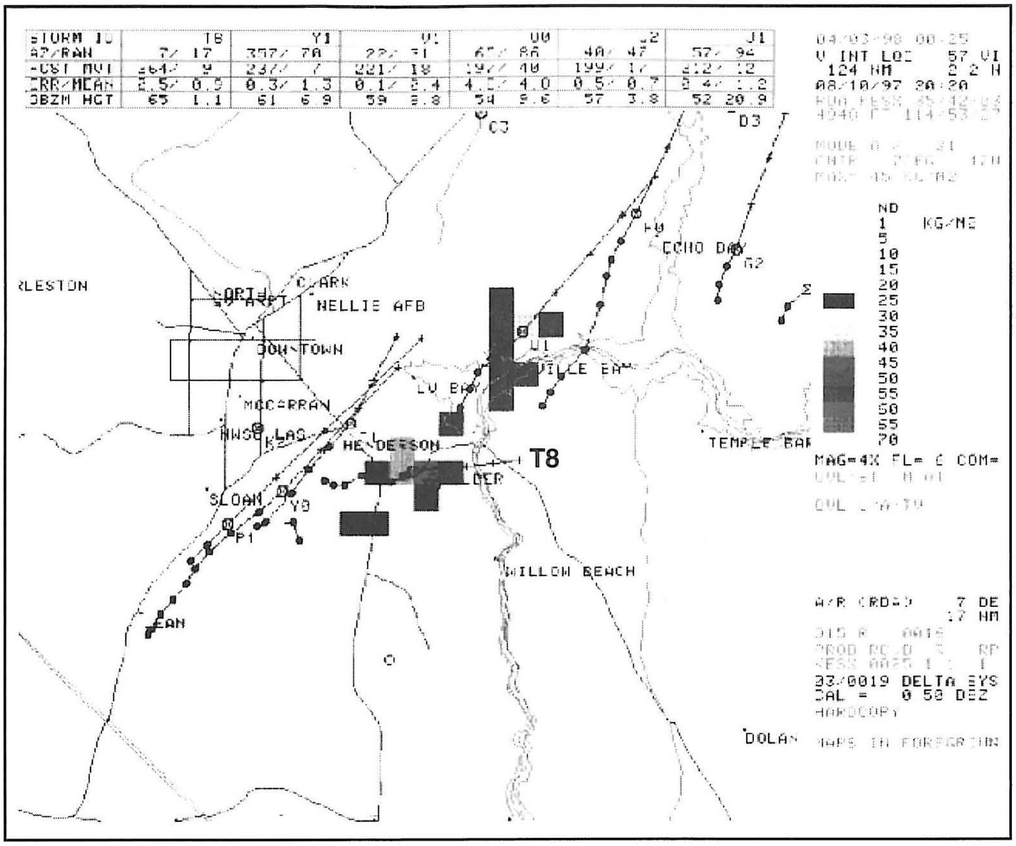

Fig. 19. KESX WSR-88D vertically integrated liquid, 2020 UTC 10 August 1997 (storm track indicates cell T8 moving to right of mean wind)

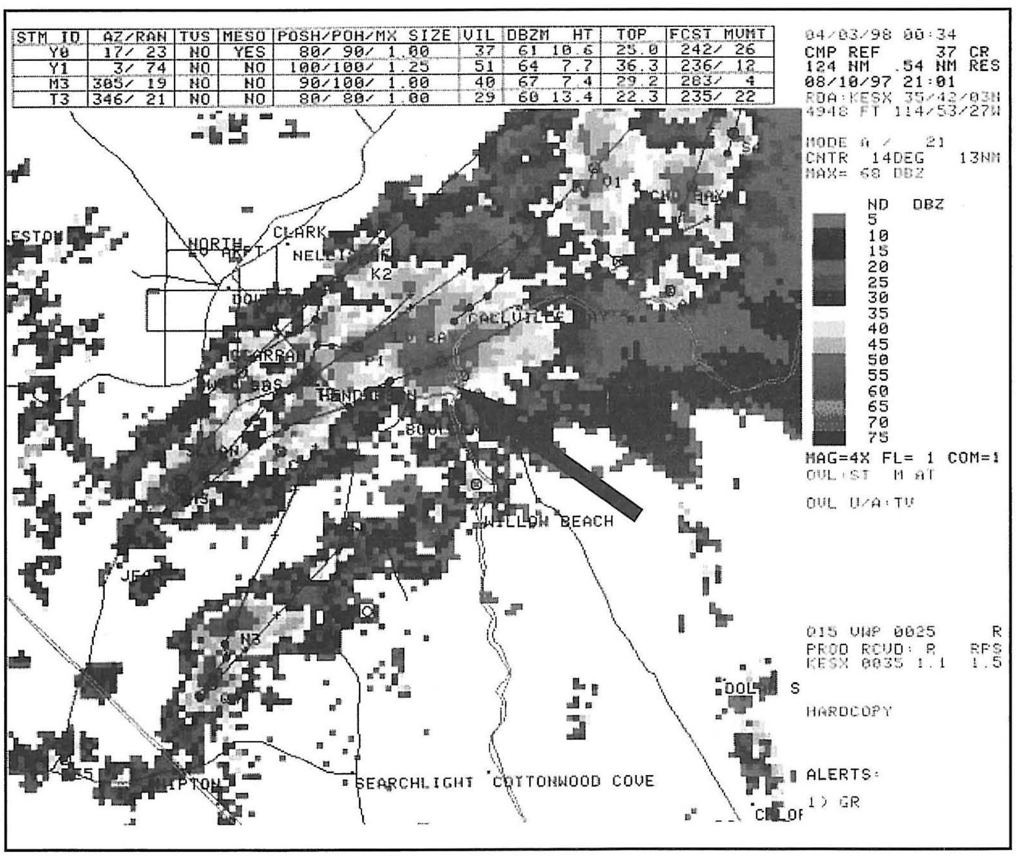

Fig. 20. KESX WSR-88D composite reflectivity image, 2101 UTC 10 August 1997 (arrow pointing to open circle over storm Y0 denotes algorithm-detected mesocyclone)

Mountains extend from just southeast of Boulder City to near the small town of Searchlight. The highest peak in the El Dorado Range is about 5000 feet above mean sea level (MSL). By contrast, the valley floor, only seven miles to the west, is approximately 1900 feet MSL.

The city of Henderson is situated along the foothills at the northern end of the McCollough Range. These mountains extend south-southwest to the Nevada-California border near the small town of Nipton, California. The highest peak in the McCollough Range is just over 7000 feet MSL. The distance from the crest of the McCollough Range to the floor of the El Dorado valley is approximately ten statute miles.

Both the El Dorados and the McColloughs are composed largely of fractured volcanic rock, basalt, and alluvium with very low percolation capacity. Rainfall rates exceeding 0.50 inches in 30 minutes have consistently produced curb-high water flows through urban streets in Henderson and Boulder City. During the event of 10 August 97, one automated gauge on a south-facing slope in Boulder City recorded 2.55 inches of rain in the 58-minute period between 1250 PDT and 1348 PDT. Furthermore, one-minute readouts suggest periods where the rain rate was too rapid for the tipping bucket mechanism to empty and reset in time to record accurately. Therefore, actual rainfall totals may have been higher than some of the automated reports indicated, perhaps on the order of 4-5 inches in the 3-hour period between 1300-1600 PDT. This is consistent with bucket gauge measurements taken in the area the following morning. An analysis of the storm total rainfall as recorded by automated sensors is depicted in Fig. 25.

6. Summary and Conclusions

Portions of extreme southern Nevada experienced significant flash flooding and damaging winds during the afternoon of 10 August 1997 due to recurring periods of heavy rain from multiple convective cells. The slow-moving convective system responsible for generating these rains developed within a large-scale environment characterized by relatively strong mid-tropospheric winds. Furthermore, as the system evolved, the mode of convection was altered by local changes in buoyancy and vertical wind shear.

During the early stages of the system's development, new cell growth appeared to occur near the downdraft of preceding thunderstorms, based on radar velocity displays and visual observations. Given the high environmental relative humidity, it is assumed that evaporation rates were low enough such that the cold pool of a decaying cell was not strong enough to disrupt or undercut the moist boundary-relative inflow to new updrafts. Moreover, the low LFC allowed

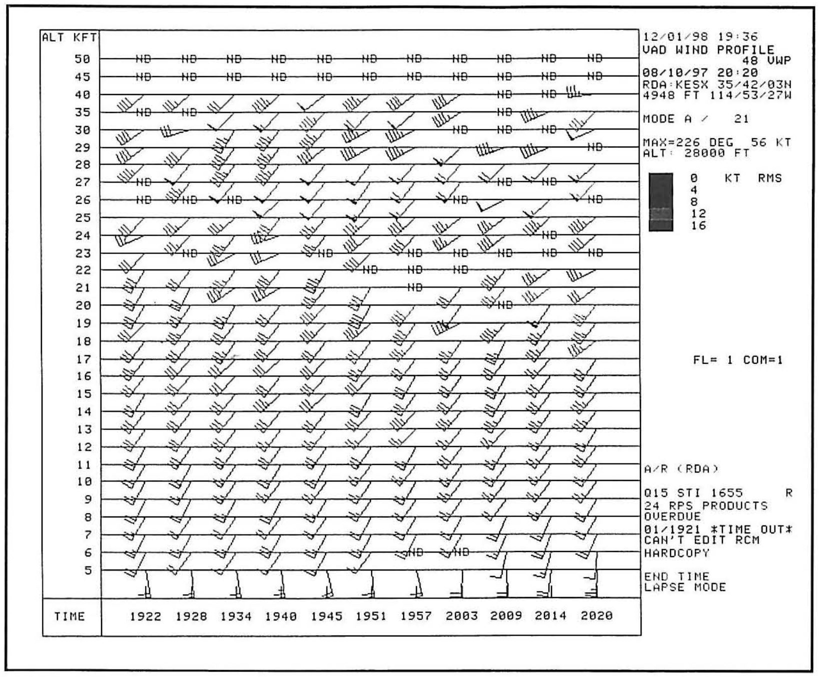

Fig. 21. KESX WSR-88D VAD wind profile, 1922-2020 UTC 10 August 1997 (winds in kt, full barb = 10 kt; altitudes in kft MSL; radar level ~ 4900 ft MSL)

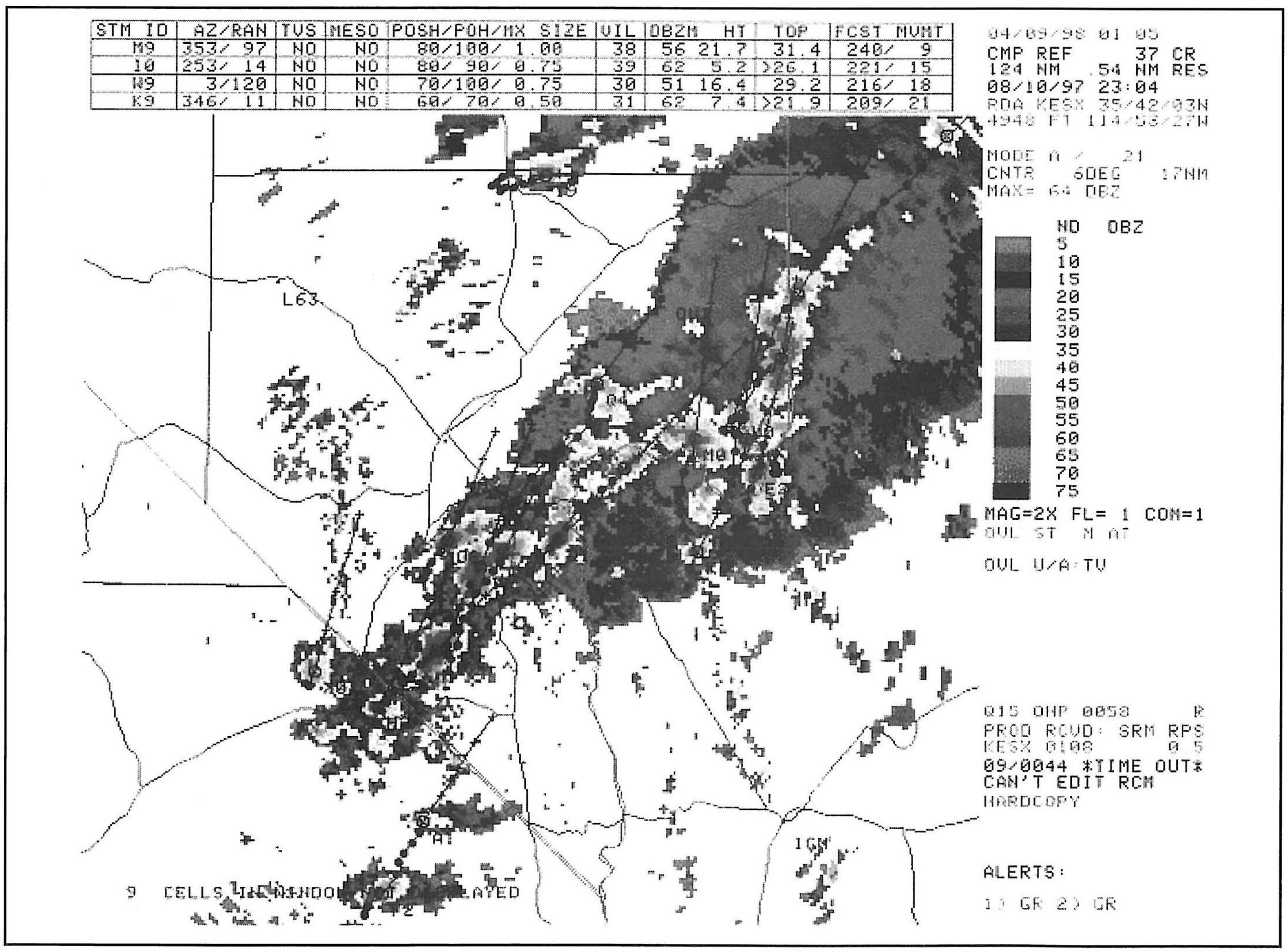

Fig. 22. KESX WSR-88D composite reflectivity image, 2304 UTC 10 August 1997

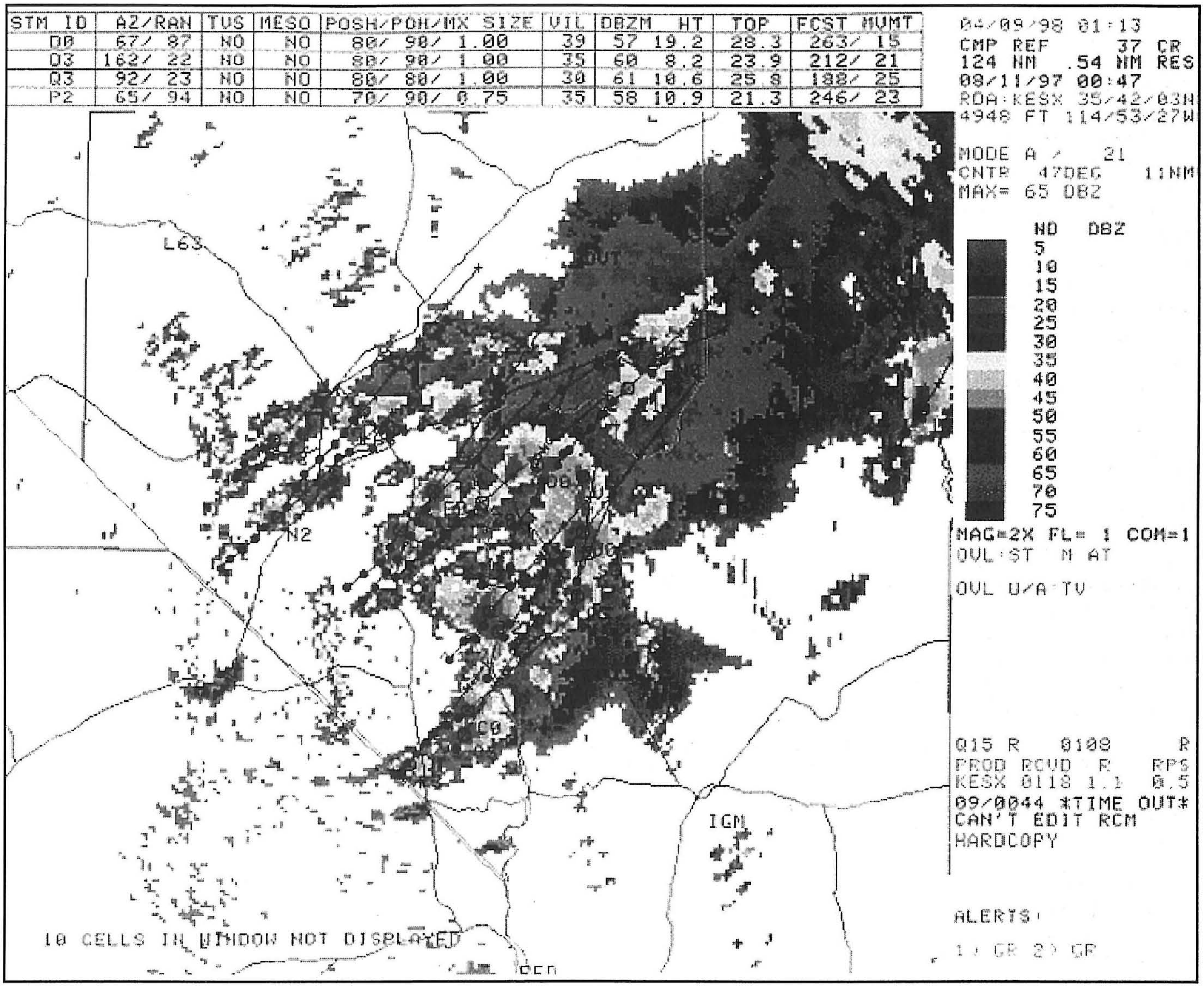

Fig. 23. KESX WSR-88D composite reflectivity image, 0047 UTC 11 August 1997

for easy retriggering by gust fronts. Subsequent cells could then follow a trajectory similar to their predecessors. This motion thus reinforced the convergence boundary and maintained its position relative to the impinging low-level moisture axis, resulting in a linear, multicellular structure dominated by gust front/cold pool processes.

Later in the system's life cycle, significant rotational components were observed, coupled with a storm track which deviated to the right of the mean wind. These attributes are suggestive of mini-supercell structure, and indeed, numerous reports of large hail and damaging winds coincided with this storm's passage through Boulder City. Several factors may have contributed to this development, including increased vertical wind shear associated with response to an approaching upper tropospheric jetstreak, and concentrated boundary layer vorticity being turned into the updraft.

In its final stages, the mode of convection was characterized by the development of a pair of bowed lines with evidence of rear inflow notches on the upshear flank. During this period, the vertical wind shear became concentrated largely in the lowest 2 km AGL with very little shear in the 2-6 km layer. While these structures were too small in scale and duration to be described as long-lived bow echo systems, the environment within which they formed is consistent with conditions known to be common in the development of similar configurations on the larger end of the bow echo spectrum.

Finally, the composition of the surrounding terrain exacerbated the effect of many convective cells passing over the same area in rapid succession. Steep topographic grades composed largely of fractured volcanic rock and alluvium provided very little percolation capacity, resulting in extremely high runoff and discharge rates. This interplay between the meteorology and hydrology multiplied the damage associated with an already dangerous event.

From an operational forecaster's perspective, at least two useful lessons can be derived from this post-analysis. First, to successfully anticipate the potential for severe thunderstorms on a given day, it is crucial to understand the processes which organize the structure of the convection, and in particular, the relationship between (and influence of) buoyancy and shear.

Second, it is important to recognize that the mode of convection frequently changes during the course of an event. Large scale forcing, moisture advection, interaction of boundary layer convergence zones, and the like, can transform an otherwise innocuous convective environment into a dangerous one by effecting local changes in static stability, vertical wind shear, lifting mechanisms, etc. Therefore, the formidable challenge of nowcasting involves continually evaluating the interdependence of relatively large scale, observable trends in atmospheric variables with complex mesoscale and storm scale circulations. This is not a trivial task.

Notwithstanding the difficulty in accurately applying such knowledge within the time constraints of a real-time forecast, the fact remains that improved understanding of the general principles governing convective evolution will undoubtedly result in more correct forecasts and warnings. In climatologically rare events (e.g., a 100-year flash flood) such an approach is crucial. Synoptic patterns associated with such events, because they are so extraordinary, are often not recognized. If the continuing stream of technological advances is to be exploited effectively, it is imperative that training and education efforts at the local forecast office remain focused on acquiring the fundamental knowledge and skills intrinsic to improving the quality and reliability of forecasts.

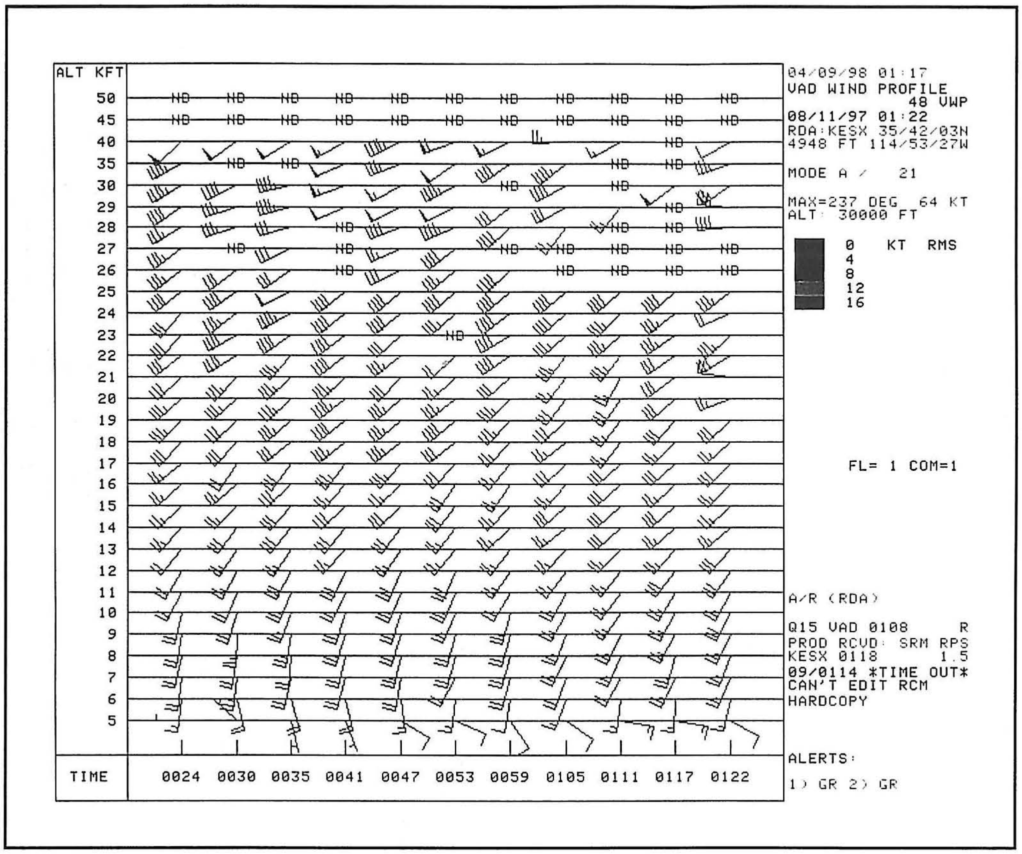

Fig. 24. KESX WSR-88D VAD wind profile, 0024-0122 UTC 11 August 1997 (winds in kt, full barb = 10 kt; altitudes in kft MSL; radar level ~ 4900 ft MSL)

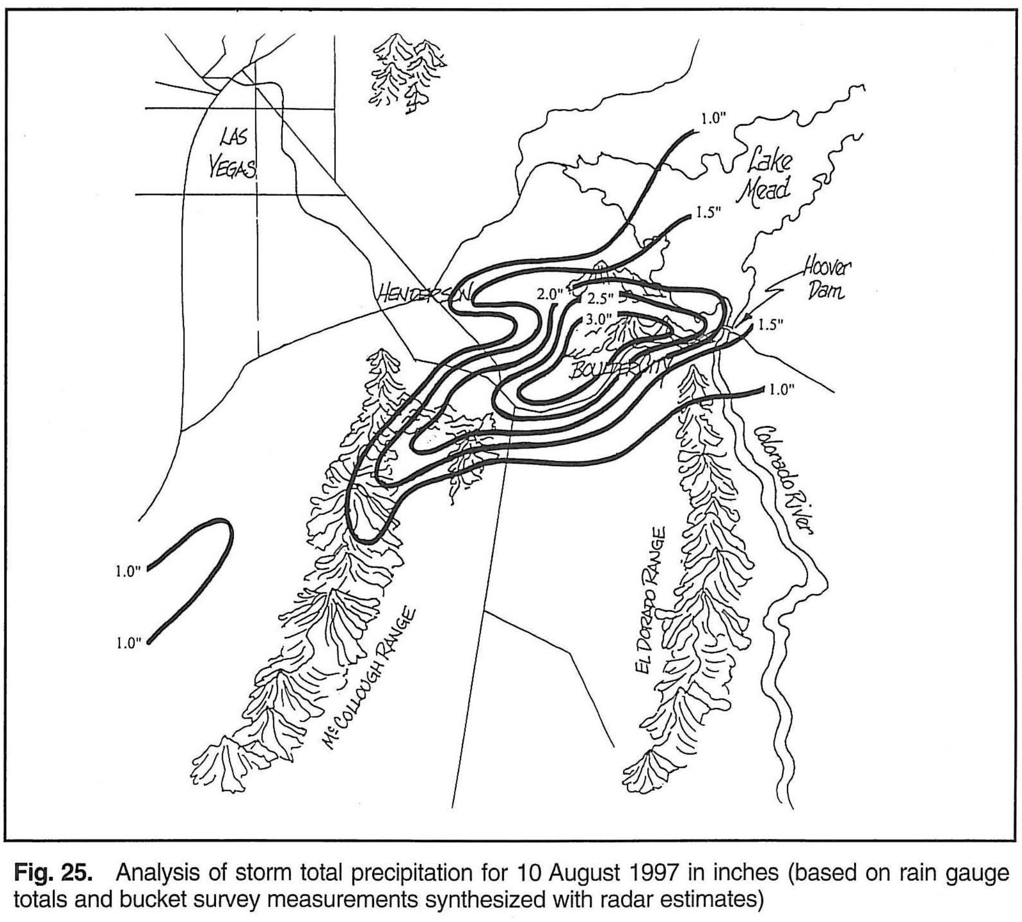

Fig. 25. Analysis of storm total precipitation for 10 August 1997 in inches (based on rain gauge totals and bucket survey measurements synthesized with radar estimates)

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References

Chappell, C.F., 1986: Quasi-stationary convective events. *Mesoscale Meteorology and Forecasting*, P.S. Ray, Ed., Amer. Meteor. Soc., 289-310.

Doswell, C. A. III, H. E. Brooks, and R. A. Maddox, 1996: Flash flood forecasting: an ingredients based methodology. *Wea. Forecasting*, 11, 560-581.

Douglas, M. W., 1995: The summertime low level jet over the Gulf of California. *Mon. Wea. Rev.*, 123, 2334-2347.

Johns, R. H., 1993: Meteorological conditions associated with bow echo development. *Wea. Forecasting*, 8, 294-299.

Lemon, L.R., and C.A. Doswell III, 1979: Severe thunderstorm evolution and mesocyclone structure as related to tornadogenesis. *Mon. Wea. Rev.*, 107, 1184-1197.

Moore, J. T., and G. E. Van Knowe, 1992: The effect of jet-streak curvature on kinematic fields. *Mon. Wea. Rev.*, 120, 2429-2441.

Pielke, R.A., W.R. Cotton, R.L. Walko, C.J. Tremback, W.A. Lyons, L.D. Grasso, M.E. Nicholls, M.D. Moran, D.A. Wesley, T.J. Lee, and J.H. Copeland, 1992: A comprehensive meteorological modeling system - RAMS. *Meteor. Atmos. Phys.*, 49, 69-91.

Rotunno, R., 1981: On the evolution of thunderstorm rotation. *Mon. Wea. Rev.*, 109, 577-586.

Runk, K.J., 1996: The Las Vegas convergence zone: its development, structure and implications for forecasting. *NWS Western Region Tech. Attach.* 96-18, 21 pp.

Sutko, Timothy E., 1997: Clark County Hydrologist's Rainfall Event Report for August 9-10, 1997 to the Clark County Regional Flood Control District, 12 pp.

Weisman, M. L., 1993: The genesis of severe, long-lived bow echoes. *J. Atmos. Sci.*, 50, 645-670.

_______, and J. B. Klemp, 1984: The structure and classification of numerically simulated convective storms in directionally varying shears. *Mon. Wea. Rev.,* 112, 2479-2498.

_______, and _______ , 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Mon. Wea. Rev.*, 110, 504-520.