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MESOSCALE INTERACTIONS TRIGGERING SEVERE THUNDERSTORMS AND FLASH FLOODING IN SOUTHWESTERN CALIFORNIA JULY 1999

Ivory J. Small and Ted Mackechnie
NWSO San Diego, CA

Brent Bower
NWSFO Los Angeles/Oxnard, CA

[Note: Because of the large number of figures, only the text will be published in hard copy. The figures can be accessed on the Web version.]

Introduction

On 11-14 July 1999, three episodes of severe thunderstorms and flash flooding developed in southern California (Fig. 1). The events occurred near 0000 UTC on 12 July 1999, 13 July 1999, and 14 July 1999. The worst flooding occurred in the San Bernardino Mountains and adversely impacted the area of Forest Falls (Fig. 2). Photographs, such as the one shown (Fig. 3) captured the severity of flooding in the Forest Falls area, marking the depth of the water which was capable of posing a threat to life and property, especially to any vehicles attempting to cross this main roadway. Historical records have shown that similar flooding events have occurred in the past, (Fig. 4), with another flooding event occurring in Forest Falls on the afternoon of 4 September 1997. Forecasters closely monitor conditions whenever thunderstorms develop in and near the area since the topography is conducive to hazardous runoff of walls of water into lower lying canyons.

A review of the meteorological conditions present during these significant flash flooding events points to some synoptic scale forcing, but most of the evidence indicates that the development of deep convection was mainly driven by mesoscale features. It was determined that the heavy rainfall occurred as a result of collisions between the westerly sea breeze, the southeasterly monsoon/gulf surge flow, and thunderstorm outflow boundaries. The rapid growth of convection in this abnormally moist environment, within the rugged mountainous terrain was the right mix for an equation which would produce severe thunderstorms and flash flooding.

In the past over southern California such outbreaks of flash flooding were very difficult to forecast and warn for. One of the complicating factors is the uneven distribution of surface observing sites. Although some areas of southern California have a dense network of surface observations, the extensive areas of mountainous terrain lack this luxury. Satellite observations have been used, but sometimes a large convective anvil can make it difficult to pinpoint areas where heavy rainfall is actually occurring. With the installation of Doppler weather radars (WSR-88D) throughout southern California after the mid 1990s, the task of providing timely warnings for flooding events has improved considerably. This Technical Attachment (TA) will provide extensive discussion on how satellite and Doppler weather radar was used to successfully capture critical interactions between the sea breeze, the monsoon flow, the gulf surge, thunderstorm outflow boundaries, and the rugged mountainous terrain. The data also help to show why some areas are favored convective areas while others are not.

The utility of new technologies to perform critical tasks such as providing timely warnings to the public requires the forecaster to know when and where significant mesoscale features interact with the complex topography of southern California, since this can make a big difference between the development of severe and non-severe convection. Therefore, the following section will briefly describe the complex topography that can be a significant player in directing moisture laden flows into favorite trigger areas. The Mexican Monsoon and the Gulf of California Surge will be discussed, since these are the features which directly feed rich tropical moisture into areas primed for thunderstorm development. Convergence zones and arcs which play essential roles in the explosive development of severe thunderstorms with heavy rainfall will be defined. The reader will also be familiarized with multi-cellular thunderstorms. Having provided the background for the flash flood-producing mechanisms, a review of the hydrometeorology that produced the 11-14 July 1999 flash flood events in the Forest Falls area will be presented. A second case that occurred in the same area on 4 September 1997 will also be discussed. Lastly, there will be a final discussion of some of the more important points in the TA with some final thoughts on the importance of understanding these phenomena.

The Terrain of Southern California

The terrain of southern California is quite complex. The densely populated coastal areas are bounded to the west by the Pacific Ocean. It is bounded to the north and east by the coastal ranges with peaks of over 11,500 feet. The Santa Ana Mountains, with peaks near 5,800 feet, are located between the highest peaks of the coastal ranges and the coastline. To the east of the coastal ranges are the desert areas.

The San Bernardino Mountains, while very scenic and popular to campers and hikers, have some high risk areas which are susceptible to flash flooding. Steep canyons lead from very high mountain tops to deep valleys below. Perhaps the best example of such a place is Forest Falls. Disastrous conditions can develop in this flashy topographical location in San Bernardino County (Fig. 5). Therefore, the steep topography is a major concern during heavy precipitation events, especially since this type of varied terrain can result in complex wind patterns. These complex wind patterns can create convergence zones that become a focus for enhanced cell development. The situation becomes even more critical during the monsoon season.

The Summer Monsoon and Gulf Surge

Convection over southern California during the summer months is very dependent on moisture which is imported from sources to the south and southeast. It has been found that thunderstorms develop when a moist unstable airmass moves north from Mexico. The moisture can track directly north into southern California, but during the majority of cases, moves first into southern Arizona, then pushes northwest in a southeasterly flow across the deserts. This occurs during the "monsoon season" . The monsoon season typically begins in early July as the region of highest mean convective activity in Mexico begins to shift from the east coast to the west coast of Mexico (Stensrud et al. 1997). The monsoon typically ends in late September as the region of highest mean convective activity in Mexico shifts back eastward. In southern California the monsoon generally results in periods of showers and thunderstorms in the mountains and deserts. At times, the moisture which produces thunderstorms with heavy rainfall over southern California is directly related to decaying tropical systems (Garza 1999), especially during El Nino years when the proximity of these dying storms import rich moisture into southern California.

The monsoon can be detected when the mean relative humidity in the 1000-500 mb layer exceeds about 40 percent. Generally, if there are east to southeast winds between 850 mb and 300 mb levels, and only a very weak easterly wave (or none at all), thunderstorms can develop as far west as the coastal valleys. Additionally, winds near 20 knots at the 300 mb level (upper-level support) are also conducive to helping drive thunderstorms west into the coastal areas.

The monsoon usually arrives in the form of middle and high level moisture between about 850 mb and 300 mb. However, at times, a low-level southerly surge of moist, tropical air also occurs, and helps to moisten the airmass in the mountains and deserts at the lower levels. This "gulf surge" (Hales 1972) can be observed with progressive below normal temperatures, higher dew point temperatures, and gusty southerly winds at successive desert surface observing stations located in the path of the surge. The surge typically results in dew point temperatures in the "lower deserts" (below 2000 feet) climbing into the 70s and occasionally reaching the lower 80s. For the "upper deserts" (above 2000 feet), dew point temperatures can reach 45 degrees or more, which is the typical lower boundary for thunderstorm episodes in the mountains and deserts. The moisture surge is usually seen on the Yuma WSR-88D (McCollum and Bright 1999) as well as on the Yuma upper-air sounding below the 850 mb level.

Stenstrud et al. (1997) investigated this "gulf surge" using a mesoscale model. Based on their evaluation of the model output, they envisioned a conceptual model that would identify strong gulf surges over the Gulf of California. The mechanism for the transport of moisture and instability are identified in their study as the result of the mesoscale processes and convective initiation associated with an easterly wave in the middle or southern Gulf of California.

Past experience has verified that explosive thunderstorm development often occurs when monsoonal moisture entering southern California is lifted as it flows up the mountain slopes. It has also been found that intense elevated heating of the mountain slopes can destabilize the airmass over the mountains and result in rapid thunderstorm development. As described earlier, the complex terrain is conducive for generating unique wind flow patterns which play important roles when interacting with thunderstorm outflow boundaries, and all combine to become primary focus regions for explosive thunderstorm development. A final factor that can also help maintain this precipitation producing regime over the mountainous terrain is the sea breeze from the colder Pacific coastal marine layer which is warmed on its journey inland and can create its own convergence zones.

This TA focuses on these types of flows and the resulting convection in and around the mountains of southwestern California. The favorite areas for this monsoonal moisture to blossom into potentially life threatening convection extends from the central San Diego County Mountains north into the San Gabriel Mountains, however strong convection can develop over any of the mountains. The adverse impacts of heavy rainfall can devastate communities found in valleys in and around this mountainous terrain. Some of these potentially threatened areas are the Antelope Valley, Apple Valley, Lucerne Valley, Morongo Valley, Yucca Valley, Coachella Valley, Borrego Valley, and Carrizo Valley (all shown in Fig. 1).

Several convergence zones west of the coastal mountains which develop mainly due to westerly flow have been studied and utilized (during drier conditions) by soaring pilots in southern California (Aldrich 1970). However, recent severe weather events have occurred when east to southeasterly monsoonal flows emerging below the passes from the deserts create volatile conditions west of the mountains. Little, if any attention has been given to this situation. These convergence zones often contribute to rapid thunderstorm development. These convergence zones will be reviewed in the following section since they can act as forcing mechanisms for development of heavy precipitation.

In order to understand some of the processes which contribute to major flooding episodes, such as the Forest Falls events, it is necessary to understand some of the synoptic and mesoscale features which play a role in triggering the development of strong thunderstorms in southern California. By possessing this knowledge, forecasters are better equipped to identify pre-cursors to development of potential flood producing precipitation events.

Significant Convergence Zones in Southern California

It has been noted that during certain conditions, boundaries can develop around very small topographical features in southern California. Island effect phenomenon (Small 1999) in the southern California Bight region has resulted in severe weather even though the highest elevations on the islands are less than 3000 feet MSL. Clearly, the development of convergence zones during monsoon conditions can be a focus for convection, as the peaks of the coastal mountains are much higher than those on the islands. For this reason, numerous convergence zones develop, and the major features can be seen in Fig. 6 and Fig. 7.

A. The Elsinore Convergence Zone

The Inland Empire is unique in that it is bordered to the north and east by mountains rising to over 11,500 feet, and to the west by the Santa Ana Mountains which extend to close to 5,700 feet near Santiago Peak. This topographical configuration lends itself to allowing the late morning and afternoon sea breeze to extend inland with two branches working their way around the northern and southern ends of the Santa Ana Mountains and towards Lake Elsinore (Fig. 6). Where the two airstreams meet, a convergence line is created known as the Elsinore Convergence Zone (ECZ) (Aldrich 1970). A similar type of convergence zone develops in northwest Washington State known as the Puget Sound Convergence Zone (Whitney et al. 1993).

Occasionally, the ECZ can be modified from the above by mesoscale phenomena. This "Modified Elsinore Convergence Zone" (MECZ) can become established when a moist, unstable east to southeast flow develops in the Inland Empire after the gulf surge pours through the passes from the east, or thunderstorm outflow boundaries modify the flow. This scenario can result in a complex and explosive convergence pattern involving several convergence zones generated by flow from several different directions (Fig. 7). After the occurrence of several severe thunderstorm episodes resulting from the development of the MECZ during the last few years, meteorologists now anticipate its development when the appropriate conditions are present.

Both the ECZ and the more volatile MECZ can result in enhanced convergence and instability, and initiate strong organized convection over the Inland Empire. This is especially true on days when a steep lapse rate is created by afternoon high temperatures that are well above normal. It is during these days when the airmass is ripe for "microbursts" as well as large hail and very heavy rain.

At other times, the easterly flow can be so strong (due to a strong outflow boundary or synoptic scale easterly flow), that the entire Inland Empire can be under low-level easterly flow. During these situations, convergence between the moist easterly flow and westerly flow occurs where the flow enters the Inland Empire on the northern and southern ends of (as well as over) the Santa Ana Mountains. The importance of being able to identify patterns, which may result in the development of severe thunderstorms with heavy rain, becomes much more evident when one realizes that there are nearly 3 million people who live in the Inland Empire.

B. Convergence Zones in the Mountain and Desert Areas

As discussed, the mountainous terrain over southwestern California contains significant gaps through numerous valleys and passes (Figs. 6 and 7). Synoptic and mesoscale features occasionally produce winds which funnel through these gaps in the terrain, and experience acceleration from normal venturi type effects. In California, one such condition, which can produce a strong acceleration of the winds through mountain passes occurs during Santa Ana wind conditions (Small 1995). During these Santa Ana events, winds from a northerly to easterly direction are funneled through the passes toward the Pacific. In the opposite direction, a typical afternoon sea breeze flows inland from the Pacific to the valley areas west of the mountains, and is funneled through the mountain passes to the deserts east of the mountains (Small and Shah 1999).

Although the modified sea breeze does result in upslope flow on the western slopes of the mountains, the flow through the mountain passes results in increased velocity as the air flows through the passes and exits in the deserts. They can be seen as arcs of convection downwind from the passes. The locations where one or more arcs collide are locations of enhanced convergence. When the moisture and instability are sufficient, the arcs (essentially the sea breeze front) are marked by cumulus. During more unstable conditions, thunderstorms form on the arcs.

A mixture of these different types of convergence zones is often responsible for the strengthening of thunderstorms throughout the mountain areas of San Bernardino County. By possessing some knowledge of the existence of such boundaries, meteorologists can be better prepared to identify conditions that are ripe for development of severe thunderstorms.

Mesoscale Convective Systems

Mesoscale Convective Systems can also play important roles in producing flooding in southern California. Documented cases by Fleming and Spayd (1986) discussed a significant event in September 1981 where an MCS produced nearly 5 inches of rain in less than 2 hours at Hemet, CA. Many people were rescued from cars trapped by up to 4 feet of water and many homes were damaged by mud and collapsed roofs. Another multi-clustered circular heavy rainfall event occurred in San Bernardino, just north of Hemet, in August 1983, which also resulted in urban flooding, stranding thousands of motorists.

The studies by Fleming and Spayd resulted in the development of four different types of atmospheric composites. Their 500 mb composite map (Fig. 8) showed very high geopotential heights over the western half of the U.S. There is an area of low pressure just south of southern California, perhaps an easterly wave. This type of pattern was found to result in significant thunderstorm development that produces very heavy rainfall and flooding. This "strong, blocking anticyclone" was found to be prominent during the heavy precipitation events of July 1999 (however, in a slightly different location), and will be discussed in the following section.

Severe Thunderstorms And/or Flash Flooding in and Around the San Bernardino Mountains on 11-14 July 1999

A. Synoptic Scale Overview for the Entire Period

On the synoptic scale, the 0000 UTC 12 July 1999 ETA (32)80 (not shown) indicated a large "blocking anti-cyclone to the north" pattern, with the High stretching from the eastern Pacific eastward over northern California and Nevada. There was an easterly wave near Las Vegas which was visible as an inverted trough under the High, and these features can usually be seen in the upper-air sounding data where an increase in easterly winds is evident. The ETA on this date indicated that the wave would remain stationary through the next 48 hours, thereby adding lift to the mesoscale forcing throughout the next two days.

The 0000 UTC 12 July 1999, 500 mb analysis showed a very strong 5970-meter High over the coastal waters of northern California. As previously shown, studies by Fleming and Spayd present similar cases of major flooding resulting from cluster-type thunderstorms when a strong High center is located over east-central Colorado. In comparison, the location of the High for the Forest Falls events has been noted as being further north and west of the Fleming and Spayd position.

The ETA prognostic charts through 14 July 1999 showed that the High was forecast to remain centered north of southern California. It appears that the 0000 UTC 12 July 1999 ETA (32)80 (not shown) showed very little movement of the major synoptic features, and thus had a good handle on this pattern. Upper-level high pressure areas in this position (northwest through northeast of southern California) typically result in above normal temperatures in southern California. The added bonus during the monsoon season is that it allows copious monsoon moisture and easterly waves to enter the area without being blocked. The higher than normal temperatures associated with this pattern result in high lapse rates and large CAPE values, along with severe thunderstorms and flash flooding. Temperatures of 90 degrees or higher at Anaheim/Fullerton and near 100 degrees at Riverside (indication of a warm sea breeze), coupled with the composite sounding values close to those as described by Fleming and Spayd, is a common scenario for events that propagate across the Inland Empire along boundaries such as arcs, convergence zones, and outflow boundaries.

Application programs written locally assist the forecasters in assessing this situation. One such program forecasts the maximum temperature in the Anaheim/Fullerton area (written by Small) and the other calculates the potential height of the afternoon thermals (written by Mackechnie). The Fleming and Spayd sounding contained lifted index of -2, a K index of 37, precipitable water of 1.32, and an easterly surface wind veering to the southeast, indicating warm advection. To more easily compare the Fleming and Spayd sounding to the soundings found during the July 1999 cases, Table 1 has been compiled.

Table 1 shows the parameters as found in the upper-air soundings from Miramar (NKX) for the 11-14 July 1999 flash flooding events. All of the soundings indicated very light winds extending from the surface through all levels.

Upper Air Sounding Data for July 11-14, 1999

Date: 1999	Time (UTC)	Lifted Index	K Index	Precipitable Water
07 -11	1200	2	41	1.62
07-12	0000	4	33	1.57
07-12	1200	-3	37	1.69
07-13	0000	2	34	1.49
07-13	1200	-2	36	1.77
07-14	0000	2	38	1.79

Table 1. Miramar (KNKX)...... San Diego, California

Comparing these to the upper air data values from Fleming and Spayd:

1. The precipitable water was higher for all cases in the 11-14 July events.
2. The winds were weaker for all cases (thus increase potential for flooding)
3. K index was as high or higher in 3 of the 6 soundings during the 11-14 July 1999 case.
4. The LI was as low or lower in 2 of the 6 soundings in the 11-14 July 1999 case.

B. Mesoscale and Hydrologic Aspects of the First Severe Thunderstorm and Flash Flood Event Occurring on 11-12 July 1999

Doppler Weather Radar data

The Santa Ana Mountains (KSOX) Doppler weather radar (located about 5 miles southwest of Corona, California at an elevation of just under 3,100 feet) is used to track significant convective development in the San Bernardino Mountains area. The San Diego Miramar (KNKX) Doppler weather radar can also detect activity in that area when convection builds to significant depths in the atmosphere.

The 11 July 1999 Forest Falls event is an excellent example of MCS development involving a combination of several arcs, convergence zones, and outflow boundaries interacting with mountains (topographic updraft) extending to over 11,500 feet. Monsoonal moisture and very warm conditions combined to trigger thunderstorms over the San Bernardino Mountains and desert areas on Sunday, 11 July 1999. Using Doppler weather radar, the severe weather in and around the San Bernardino Mountains can be tracked to inception where an east-west line of thunderstorms developed at the intersection of several features. The Cajon arc and Morongo arc were found to be the primary features which initiated the development of large thunderstorms, and the arcs were defined by the associated convection by 2100 UTC. By 2234 UTC, the strengthening arcs drifted southward to a position from Victorville (VCV) to Apple Valley. Two large thunderstorms, which formed on each arc, merged to create the northern end of the Lucerne Valley Convergence Zone (LVCZ). At this point, thunderstorm propagation (along the arcs and the along the LVCZ) became a primary characteristic of storm development and dictated storm motion. Reports received approximately 14 minutes before, indicated that trees had been uprooted and were down in the Victorville (VCV) area near Apple Valley, indicating severe thunderstorms in progress.

In Fig. 9, the 2234 UTC 11 July 1999 KSOX composite reflectivity shows the east-west line of thunderstorms. This MCS was formed by a large thunderstorm on the Morongo arc interacting with the outflow boundary from a large thunderstorm on the Cajon arc to form the northern segment of the LVCZ.

At the same time (2234 UTC) a line of thunderstorms had developed further south on the Morongo arc just southeast of Big Bear City. The Cajon Pass arc can be identified just west of the Big Bear City thunderstorm as a line of convection extending southeast from a thunderstorm over Victorville (VCV) to Forest Falls. Later, the area between these arcs in the south will be the site of the formation of the southern segment of the LVCZ and the worst flooding.

In Fig. 10, the 2249 UTC 11 July 1999 KSOX composite reflectivity, the east-west oriented MCS over the Apple Valley has generated an outflow boundary, which can be tracked on the arcs as enhanced convection as it moves southward along the arcs. This outflow boundary provided sufficient lift and instability so that both arcs experienced rapid thunderstorm development. Only about 15 minutes had elapsed, yet this was all the time required for rapid growth in cell development southward along the arcs.

By 2324 UTC, shown in Fig. 11, the outflow boundary had reached Forest Falls and can be seen along a line from Wrightwood to San Bernardino to Forest Falls to just north of Yucca Valley. This large outflow boundary had enhanced the convection on both arcs (the thunderstorm on the Cajon Arc near Forest Falls and the thunderstorm on the Morongo arc southeast of Big Bear City in Fig. 10). There was boundary interaction between the enhanced thunderstorms, which combined to form a huge MCS over Forest Falls. This MCS become the southern segment of the LVCZ.

Upstream from this southern segment of the LVCZ yet another interaction between the arcs forms an MCS and a new segment (a middle segment) of the LVCZ develops. At this point, three critical segments of the LVCZ had formed. In the order of development, there was a Lucerne Valley (northern) segment, a Forest Falls (southern) segment, and now a Big Bear City (middle) segment.

Also in Fig. 11, the middle segment was formed by the two arcs which combined into a huge MCS north of Big Bear City. The two arcs and the LVCZ between them can be clearly seen as the middle segment of the LVCZ. (The minimum in radar reflectivity north of this second complex shows that this is, in fact, the development of a new segment of the LVCZ, separate from the northern segment formed earlier in the Apple Valley).

This middle segment of the LVCZ and its associated MCS results in a second large outflow boundary that moves south and enhances the MCS on the southern segment of the LVCZ over Forest Falls. The convection becomes explosive since it is the collision of two very strong outflow boundaries in a location where a very strong MCS was in progress (in addition to the arcs and convergence zones which provide additional lift). Both outflow boundaries can be seen in Fig 12. The first outflow boundary can be seen extending from Forest Falls westward into the Inland Empire. The second outflow boundary can be seen extending from Forest Falls northwest to near Lake Arrowhead. Since the low-level flow was easterly, the Banning Pass Convergence Zone/Arc and/or a Modified Elsinore Convergence Zone were likely to extend northeast into the Forest Falls area to give additional enhancement to the storm on the southern segment of the LVCZ.

Both the rainfall and runoff for this flash flood event were enhanced. Typically, thunderstorms in southern California are high-based due to relatively dry low-level air, even during monsoonal flow. Hence, there is a lot of evaporation of the rainfall by the time it reaches the surface. There have been cases where radars indicate thunderstorms with reflectivities of 60-65 dBZ for six volume scans or more, with 1-Hr precipitation rates of 2 to 3 inches and yet did not produce commensurate amounts of rainfall at the surface nor did they cause flooding. However, the airmass for these events were moist all the way to the surface, where surface dew point temperatures were in the 70's, allowing the heavy rain to reach the ground with little evaporation. In addition, the upper-portion of Rattlesnake Creek Basin (south of the red flag in Fig. 5) is bowl-shaped, which concentrates runoff from a larger area into the creek than a linear basin would. This creek is one of several that drop down from Oak Glen Divide (an east-west ridge just south of Forest Falls), that towers 3500 - 4000 feet above Forest Falls to an elevation of 9000 feet. Heavy rain falling on the very steep, rocky slope resulted in near instantaneous runoff.

While there are some homes and businesses close to or in Mill Creek, most of the population at risk is along the base of the north slope of Oak Glen Divide, above the risk of flooding from Mill Creek. However, they are at much greater risk of flooding from the steep slopes behind them and creeks that flow through the town.

Storm Damage from the 11-12 July 1999 Utc Event

Preliminary reports of wind damage, heavy rainfall and localized flooding were received from the Apple Valley/Hesperia area. Between 2200 UTC 11 July 1999 and 0100 UTC 12 July 1999, nearly an inch of rain in less than 45 minutes flooded a one mile section of Highway 18, stranding several motorists. Fifty homes and businesses were flooded in the same area with a half a foot of water and mud. Also in nearby Victorville, strong winds knocked over two large trees, one landing on top of a parked car. The same thunderstorm later contributed to flash flooding just east of Victorville. As the outflow boundary moved south, it initiated MCS development first over the Forest Falls area, then over the Big Bear area, with the most intense MCS over the Forest Falls area.

Rainfall rates were exceptionally high. A spotter from within Forest Falls reported over an inch falling in less than half an hour. The top portion of Fig. 13 shows the 1-Hr Precip product from KSOX valid for the hour ending 00:41 12 July 1999. Forest Falls (FF on the Figure) is in an area of 0.5 to 1.0 inch rates. A rainfall rate of 2+ inches with a maximum of 3.5 inches covers an area just south of Forest Falls over the Oak Glen Divide. Just on the south side of that ridge, an automated rain gage (OKG on the Figure) in the maximum rainfall rate area of the radar, reported 4.1 inches of rain in the same time period with 2.92 inches in the last 30 minutes. The Storm Total Precipitation product, at the bottom of Fig. 13, shows a rainfall distribution for the entire event that was similar to that of the 1-Hr Precipation with most rainfall centered over the Oak Glen Divide above Forest Falls rather than on top of the town and Mill Creek.

As a result, creeks on the slopes of Oak Glen Divide rapidly filled and created a 25 foot high wall of water, rocks, and mud on Rattlesnake Creek that burst through a residential section of town at approximately 4:50 p.m.. Seven homes were destroyed, 11 sustained moderate to severe damage, and 35 others had minor damage. Some 25 vehicles were crushed, buried, or swept away. Roads were covered with 10 feet of rocks, mud, and debris. Most of the flood damage was from these creeks though there was some lesser flood damage along Mill Creek itself at Big Falls Campground, the Torrey Pines Road bridge, and other roads and homes in and along Mill Creek. Flooding in Redlands was also reported as the storm propagated southwest. Although substantial damage occurred during the event, there would be another round of activity for this same general area in 24 hours (NOAA 1999).

Using new technologies, the San Diego NWSO issued timely Special Weather Statements, Flash Flood Watches, and Flash Flood Warnings for the Forest Falls flash flooding event. Table 2 shows some of the products that were issued.

Date	Time	Product	Remarks
7/10 7/11	10:30 pm 6:00 am	SPS's	Text included "...main threat with thunderstorms the next couple of days will be the potential of flash flooding"..
7/11	10:00 am	NOW	For thunderstorm over southern San Bernardino Mountains. Discussed storm being stationary and potential of causing localized flooding.
7/11	12:05 pm	NOW	For San Bernardino Mountains indicated that "heavy rain was still occurring near the Forest Falls area".
7/11	2:00 PM	FFA	Valid until 7:00 pm for San Bernardino, Riverside, and San Diego Counties.
7/11	3:17 pm	FFA	Extended expiration time until 9:00 pm and included Apple and Yucca Valleys.
7/11	3:15 pm	FFW	Valid until 4:15 pm for the Apple Valley
7/11	4:00 pm	FFW	Valid until 5:00 pm for the San Bernardino County mountains, and including the Apple Valley. Warning indicated that "residents living along streams and creeks in the warning should move to higher ground immediately.
7/11	4:55 pm	FFW	Valid until 6:00 pm specifically mentioning Doppler weather radar showing heavy rain near Forest Falls.
7/11	5:55 pm	FFW	Valid until 8:00 pm mentioning Forest Falls and that heavy rain was still occurring over the southern mountains of San Bernardino County.

Table 2. Select NWSO San Diego weather products issued for the July 11, 1999 Forest Falls Flash Flood event.

The satellite was also very useful. The complex was followed on satellite. It produced a well-defined outflow boundary that triggered additional development of thunderstorms over Yucca Valley as well as the mountains and deserts of San Diego County.

C. Mesoscale Aspects Existing for the 12-13 July 1999 Event

Doppler Radar Data

With little change in conditions between 11 July 1999 and 12 July 1999, another round of thunderstorms developed during the late afternoon and early evening of 12 July 1999 over the San Bernardino Mountains and began to propagate to the southwest.

Using the San Diego Miramar Doppler weather radar (KNKX), a convergence zone was observed to quickly develop by late afternoon . The convective line that formed extended from the Big Bear area southwest through Beaumont and into the Lake Elsinore area. Convection fired up by 0200 UTC 13 July 1999, and by 0326 UTC, a significant convective line (Fig. 14) with composite reflectivity values of 50 dBZ was again impacting the same flash flood prone areas which had been affected the day before.

Storm Damage on 12-13 July 1999

Thunderstorms moved over the same area that had experienced flash flooding during the previous afternoon. In San Bernardino County, four creeks overflowed as the area was drenched with heavy rains on already saturated ground from the previous day. Thunderstorms developed in the Big Bear area at around 0200 UTC 13 July 1999 with flooding reported in the Big Bear area to the north of Forest Falls (including the nearby cities of Moonridge and Sugarloaf). Spotters reported over 1.5 inches of rain being recorded in a 20 minute period.

Beginning at 0300 UTC 13 July 1999, flooding was reported along Highway 247 between the Apple Valley and the Yucca Valley, with many streams flowing over their banks. Again, the convergence zone near Warner Springs became active, and 1.30 inches of rainfall was recorded in one hour (NOAA 1999).

As with the previous day, numerous unscheduled products were issued to inform the public that potentially dangerous conditions existed. Table 3 shows a selection of products issued.

Date	Time	Product	Remarks
7/12	3:30 am	FFA	Valid until 9:00 pm for San Bernardino Mountains and surrounding areas including Riverside and San Diego County mountains.
7/12	10:00 am	FLS	Updating FFA with fresh information concerning potential of flash flooding.
7/12	12:05 pm	NOW	Indicating that thunderstorms were developing as expected and on schedule. Updates were written approximately every 2 hours through 6:00 pm
7/12	6:30 pm	FLS	Reminding residents that a FFA was still in effect and discussed development of thunderstorms in San Bernardino Mountains that were continuing to increase in strength.
7/12	7:15 pm	FFW	San Bernardino County valid until 8:30 pm.
7/12	7:55 pm	FLS	Update information on FFW for San Bernardino County
7/12	8:30 pm	FFW	Indicating that heavy rainfall was continuing in FFW area.
7/12	9:00 pm	FLS	Including flooding reports received for areas in San Bernardino and other Counties

Table 3. Select NWSO San Diego weather products issued for the Flash Flood event.

D. Mesoscale Aspects of the Third Event Occurring on 13-14 July 1999

Doppler Radar Data

By day three, there was still very little change in the meteorological conditions which had been present since Sunday, 11 July 1999, and another round of thunderstorms again developed over the mountains which moved to the southwest along the favorite backbone of a convergence zone.

Early indications of this development were evident as early as 1831 UTC as composite reflectivity data from the Santa Ana Mountains Doppler radar showed a line developing from Riverside to just north of Forest Falls near Big Bear. The thunderstorm near Big Bear developed during the next few hours and by 2000 UTC maximum reflectivity values of over 50 dBZ were noted with that cell. It appeared to be a primary candidate for producing the outflow boundary that tracked south and interacted with weak convective activity extending southwest along the initial convergence zone.

Intersecting boundaries over Forest Falls resulted in explosive development of an MCS as shown in Fig. 15 at 2321 UTC 13 July 1999. This MCS propagated slowly southward for the next hour and a half producing heavy rainfall before dissipating.

Storm Damage on 13-14 July 1999 Utc

A severe thunderstorm developed over Forest Falls. About 1.8 inches of rain fell in 25 minutes. The heavy rain produced a 10-foot wall of mud and debris. With the recent destruction from floods two days earlier, it was much easier to have additional flooding. Stream beds were full of debris and stream banks had been eroded or breached, allowing flooding to occur with a lower volume of water than it would normally take. There were four houses destroyed, 10 homes received major damage, and 16 others received minor damage. In addition, 3/4 inch hail was reported.

Again, as with the previous day, numerous unscheduled products were issued to inform the public that potentially dangerous conditions existed. Table 4 shows a selection of products issued.

Date	Time	Product	Remarks
7/13	3:30 am	FFA	Valid until 9:00 pm for San Bernardino Mountains and surrounding areas including Riverside and San Diego County mountains.
7/13	12:50 pm	NOW	Thunderstorms developing over the San Bernardino County mountains.
7/13	4:21 pm	FFW	Valid until 6:20 pm for area including Forest Falls
7/13	4:55 pm	FLS	Updating information and again mentioning threat of flooding for Forest Falls.
7/13	5:35 pm	FLS	Providing latest spotter rainfall reports from Forest Falls along with Doppler radar and automated rain gage information.

Table 4. Select NWSO San Diego weather products issued for the Flash Flood event at Forest Falls.

E. Synoptic, Mesoscale and Hydrologic Aspects of the Event Occurring on 4-5 September 1997

Other similar flash flooding events have occurred in the Forest Falls area throughout the past decade. Some documentation has been located to verify that these life-threatening episodes can occur rather frequently, as there had been three flash floods in the past three years. The dynamics behind all seem very similar, with intersecting boundaries contributing to the rapid development of MCS type complexes, resulting in heavy rainfall. One such event occurred on 4-5 September 1997. Briefly, the synoptic-scale pattern was typical for events of this type, with a "blocking anti-cyclone to the north" pattern.

The afternoon upper-air data for both the July 1999 and the September 1997 events, although quite similar, did possess some differences. The represented sounding data can be seen in Fig. 16 for the 1997 event and in Fig. 17 for the 1999 event. The comparison between the two days can be seen in Table 5.

Parameter	July 12, 1999	Sept. 5, 1997
Showalter Index	01	02
Lifted Index	04	01
K Index	33	27
Precipitable Water	1.57	1.43
Total Totals	47	45

Table 5. Upper-air data for 0000 UTC on dates shown.

In viewing the soundings, it was found that on both days, the atmosphere was conditionally unstable, in a very moist airmass environment. Winds above the sea breeze indicated a warm advection pattern, most pronounced in the 1997 case with southeast winds veering to the southwest aloft.

Doppler Weather Radar Data

Early indication of boundary interaction was evident by 0025 UTC as composite reflectivity data from the Miramar Doppler radar (Fig. 18) showed thunderstorms forming along a quasi-stationary boundary, which stretched from the Inland Empire northeast over Forest Falls, and continued through the mountains to the upper deserts. Approaching this boundary was a line of thunderstorms associated with an outflow boundary generated by earlier convection to the southeast. It is the interaction between these two boundaries that would lead to flash flooding.

There were three cells that were critical to the development of the flooding. The first cell developed on the quasi-stationary convergence zone over Forest Falls. The second cell developed southwest of Forest Falls, at the intersection of an outflow boundary moving to the northwest and the quasi-stationary convergence zone. This second cell tracked northeast over Forest Falls. The third cell was on the outflow boundary that was moving northwest toward Forest Falls. The three cells can be seen developing near Forest Falls on Fig. 18. The 0112 UTC composite reflectivity data (Fig. 19) showed a 65+ dBZ cell over Forest Falls, the result of the three thunderstorms merging. This MCS propagated slowly southward producing heavy rainfall before dissipating

Storm Damage on 4-5 September 1997

The 4 September 1997 event resulted in 2.5 inches of rain in 45 minutes along with golf-ball sized hail. As seen in the top portion of Fig. 20, precipitation estimates from the WSR-

88D showed the heaviest rainfall further north and east than on 11-12 July 1999, putting it more out over Mill Creek Canyon and further upstream. There is an area of 2.6+ inch rainfall rates over Forest Falls and Mill Creek Canyon with a maximum rate of 3.74 inches per hour, shown in the top portion of Fig. 20.

The Storm Total Precipitation of 4.31 inches over the Mill Creek area, shown in the bottom of Fig. 20, is greater than that of the 11-12 July 1999 event for the same area. The Oak Glen rain gage, being outside the area of greatest rainfall in this case, recorded only 1.26 inches of rain. This very heavy rain in the narrow Mill Creek Canyon sent a 100-foot wide wall of water 20 feet deep down Mill Creek. The volume of flood waters was greater in this case than 11-12 July 1999 but the greatest portion of it was in Mill Creek rather than on the creeks of Oak Glen Divide. Flood waters raced down Mill Creek Canyon for at least 15 miles, reaching the Santa Ana River near San Bernardino. Property along Mill Creek sustained greater damage in this event, especially at Big Falls Campground, though the two homes destroyed were hit by flooding associated with one of the side creeks. There was evidence of significant flooding unrelated to any creek, but just from the shear amount of runoff from the steep slopes.

This event resulted in the worst flooding in nearly 30 years up until that time. In all, there were 3 million dollars in damage to a total of 80 structures. Included were a bridge, two homes that were completely destroyed, and 20 homes that were severely damaged. Additionally, 10 propane tanks dislodged and/or damaged and six cars were damaged or destroyed including one that was bent in half. The main highway and side streets were closed, and 400 residents were unable to reach their homes. About 200 residents were without power for two days. Additional millions of dollars were also spent on clearing away mud, boulders, and debris left in the aftermath of the storm. With all of this damage, there were no fatalities, and only two minor injuries were reported (NOAA 1997).

Numerous unscheduled products were issued to inform the public that potentially dangerous conditions existed. Table 6 shows a selection of products issued.

Date	Time	Product	Remarks
9/4	5:30 pm	FFW	Valid until 6:00 pm for San Gorgonio Mountains and Big Bear area
9/4	6:00 pm	FFW	Flash flood warning for San Gorgonio Mountains and Big Bear area extended to 6:30 pm.
9/4	6:15 pm	FLS	Flash flood statement issued for San Gorgonio Mountains and Big Bear area. Statement indicated that storm has the potential of causing a flash flood in Mill Creek, and could affect the town of Forest Falls.
9/4	6:30 pm	FFW	Flash flood warning for San Gorgonio Mountains and Big Bear area extended to 7:00 pm.

Date	Time	Product	Remarks
9/4	7:00 pm	FLS	Flash flood warning is allowed to expire.

Table 6. Select NWSO San Diego weather products issued for the Flash Flood event at Forest Falls.

Final Discussion and Conclusion

On the synoptic scale, it was shown that a strong blocking NW-NE High north of southern California is a common pattern for severe thunderstorms and flash flooding in southern California. This was the predominant pattern during the July 11-14 case. During this pattern, upper-level troughs and their associated drying westerly flows cannot displace the blocking High. This allows a very moist and unstable easterly monsoon flow to develop under the high, and easterly waves move freely (and generally very slowly) through southern California. This pattern has recently proven to be associated with prolonged episodes of severe thunderstorms with flooding that occur on consecutive days. Two additional examples are 9-12 August 1998 and 31 August through 2 September 1998.

On the mesoscale, in many cases, the interaction of boundaries (such as outflow boundaries or convergence zones) over high terrain resulted in severe thunderstorms and/or flash flooding under very moist, unstable conditions. The WSR-88D and satellite imagery allowed meteorologists to identify where the convergence zones are, and also detect the location and movement of outflow boundaries.

In reviewing past episodes of flash flooding in southern California, it can be shown that converging boundaries play a significant role whenever temperatures rise above 90 degrees in the Fullerton/ Anaheim area and near 100 degrees in the Inland Empire. During these extremely warm conditions, the sea breeze remains warm and can contribute moisture which becomes convectively active as it drifts inland. When there is a monsoon flow, then usually the 100 degree temperatures are very close to the convective temperature. Additional thunderstorms develop via additional lift due to sea breeze boundaries, outflow boundaries, or orographic effects. When these forcings combine, severe convection can be the result. The Inland Empire is especially prone to the combination of these features since thunderstorms developing on the very high terrain surrounding the valley can send outflow boundaries into the valley, and these outflow boundaries can have numerous other convergence zones to interact with since the low-level flow into the valley through the passes can occur in virtually every direction (for example, the development of a Modified Elsinore Convergence Zone).

Even without well-developed terrain forced convergence zones, severe convection can develop with simply the intersection of outflow boundaries. The example of 11-12 July 1999 at Forest Falls was a very good (extreme) example of a common scenario for severe thunderstorms and flash flooding, which is when outflow boundaries collide over higher terrain. Also the severity of this event was increased, in part, because of the convergence zones that were involved.

Due to the light winds, propagation is frequently the dominant component of storm motion. Therefore, it was very critical to know where the development was likely to occur on a particular storm so that the motion could be properly predicted. Movement along convergence zones was very common in the light flow cases.

Days when the convergence zones become active were being identified well in advance by meteorologists who now recognize the dynamic interactions of such boundaries. Examples of such recognition are normally included in the Area Forecast Discussions which highlight the potential development of thunderstorms along these convergence zones. A discussion written by one of the co-authors (Mackechnie) for the 11-14 July 1999 Forest Falls event approximately 40 hours before the first episode of flash flooding read:

> ***"With heating getting a good start Monday before the next moisture surge...we could see very strong thunderstorms over the San Bernardino Mountains Monday PM...extending westward down local convergence zones into the Inland Empire."***

The thunderstorms did indeed occur (as expected) along the convergence zones on Monday 12 July 1999, however the storms began a day early, with the worst flooding on Sunday, 11 July 1999.

Strong thunderstorms forming in favored convergence areas can often be severe without producing flash flooding. One key ingredient in southern California for flash flood-producing convection is for the moisture to be great enough, especially in the lower levels, to allow the rainfall to reach the ground without too much evaporation. This has yet to be quantified.

The important role the highly complex terrain of southern California plays in determining flooding was inferred by the differences between the flood damage on the 11 July 1999 and 4 September 1997 events. Where the rain falls within a watershed over distances as small as one mile can make the difference in the location and degree of flood damage. It can mean whether the flood waters overwhelm small creeks or are contained in a larger stream. It can even mean the difference of which side of a mountain, and hence which communities, will be affected. This can be true of winter flood events as well and points to the need for hydrologic tools with high resolution terrain for use with radar, rain gages, and spotter reports.

Clearly the most widespread (and potentially the most damaging) summertime convective events are associated with tropical cyclones (Garza 1999). Even without tropical cyclones, there can be fairly widespread convection with locally severe thunderstorms and flash flooding. A thorough analysis of the mesoscale features in the flow will help the forecaster focus on the most volatile convective areas, which is an absolute must during periods of high moisture and instability in southern California. With the introduction of higher resolution mesoscale models, improvements in this area will continue.

Acknowledgments

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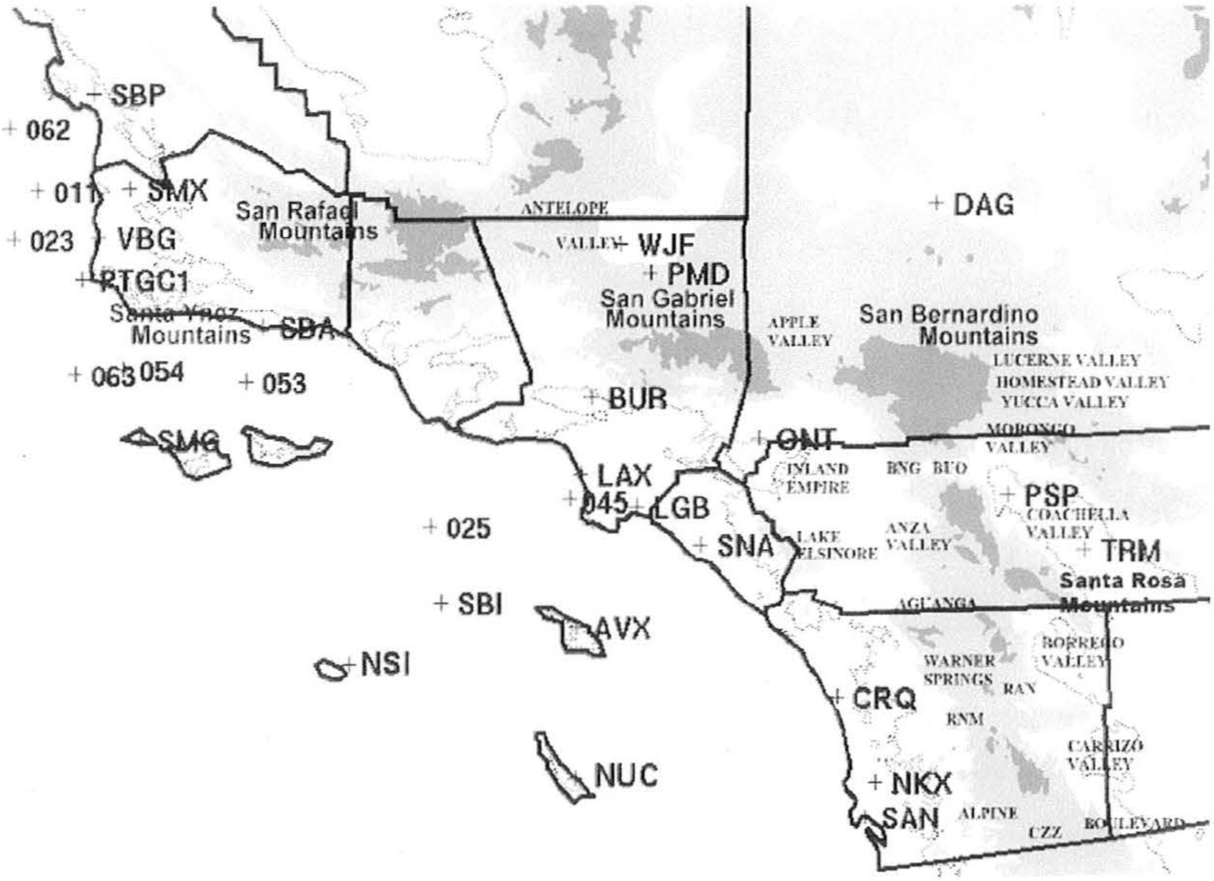

FIG. 1. Topographical features in the Southern California Bight Region.

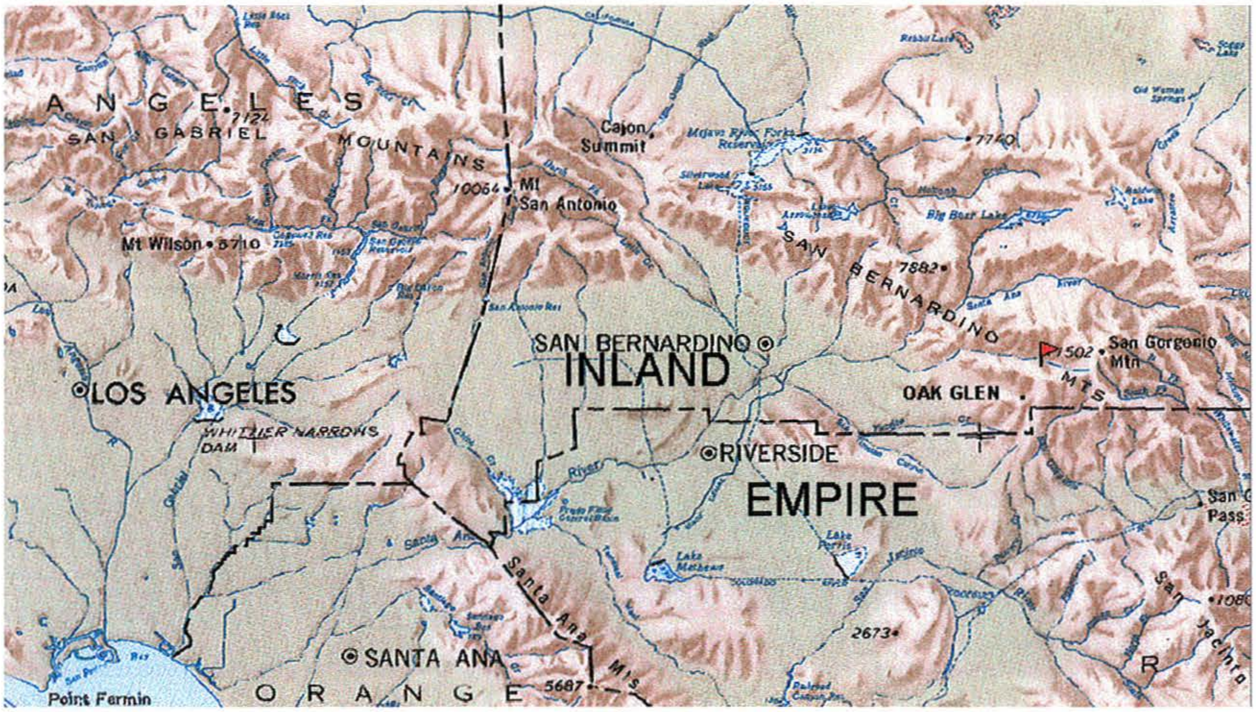

FIG. 2. Map of the Inland Empire and surrounding area. Forest Falls is indicated by the red flag.

FIG. 3. Mill Creek at Torrey Pines Road. Arrow shows height of flood waters.

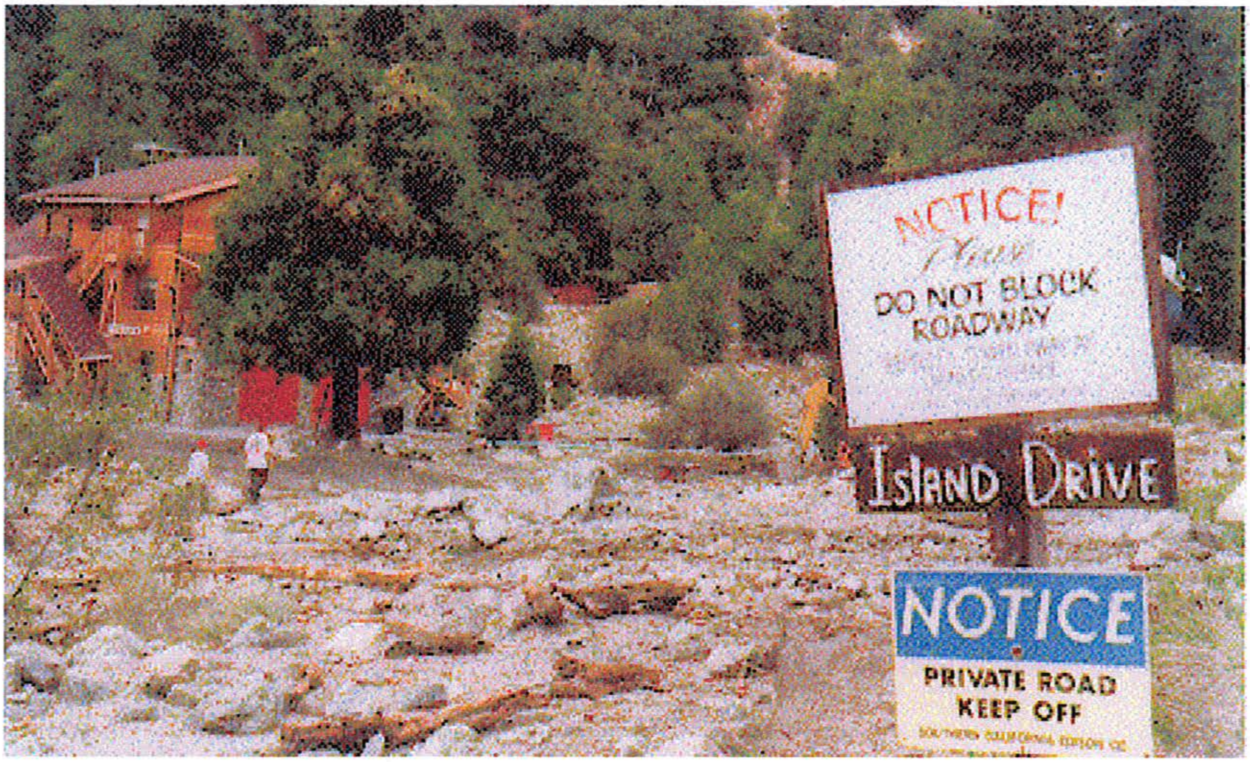

Fig. 4. Roadway covered by large boulders.

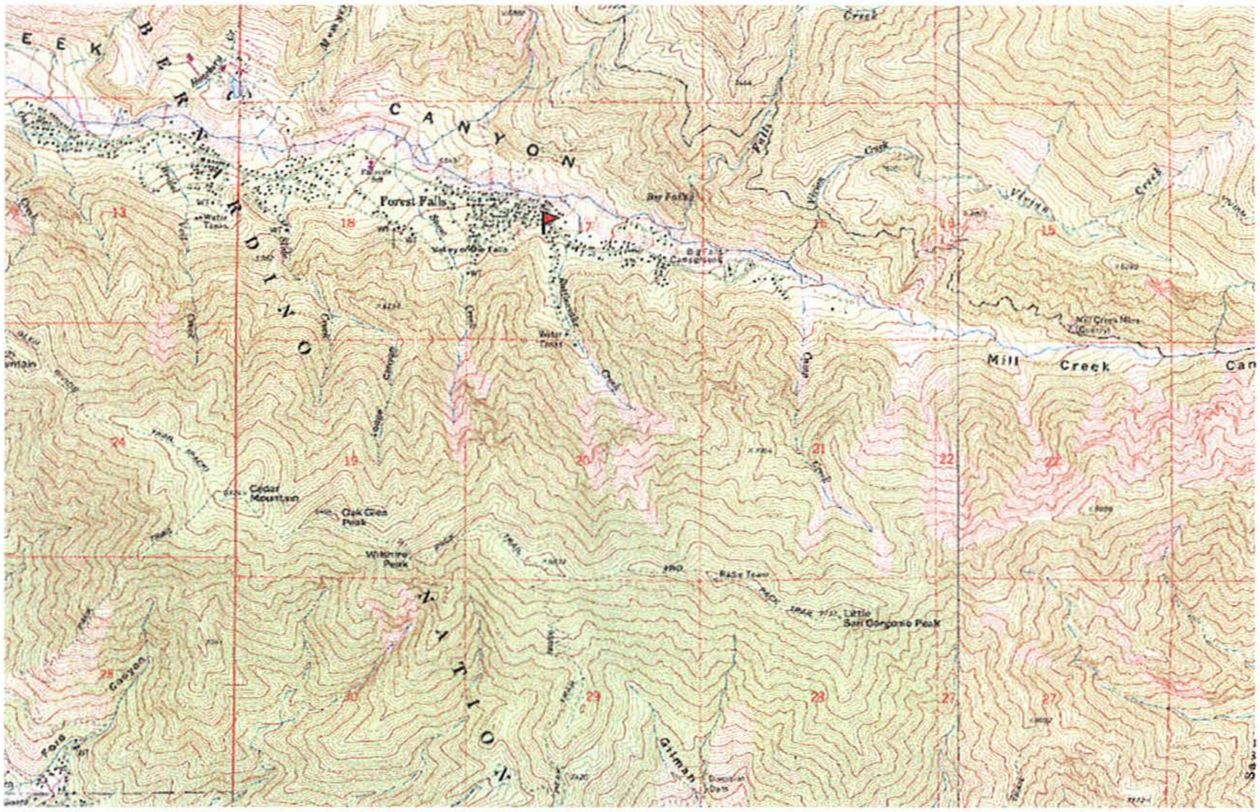

FIG. 5. Map of the Forest Falls area.

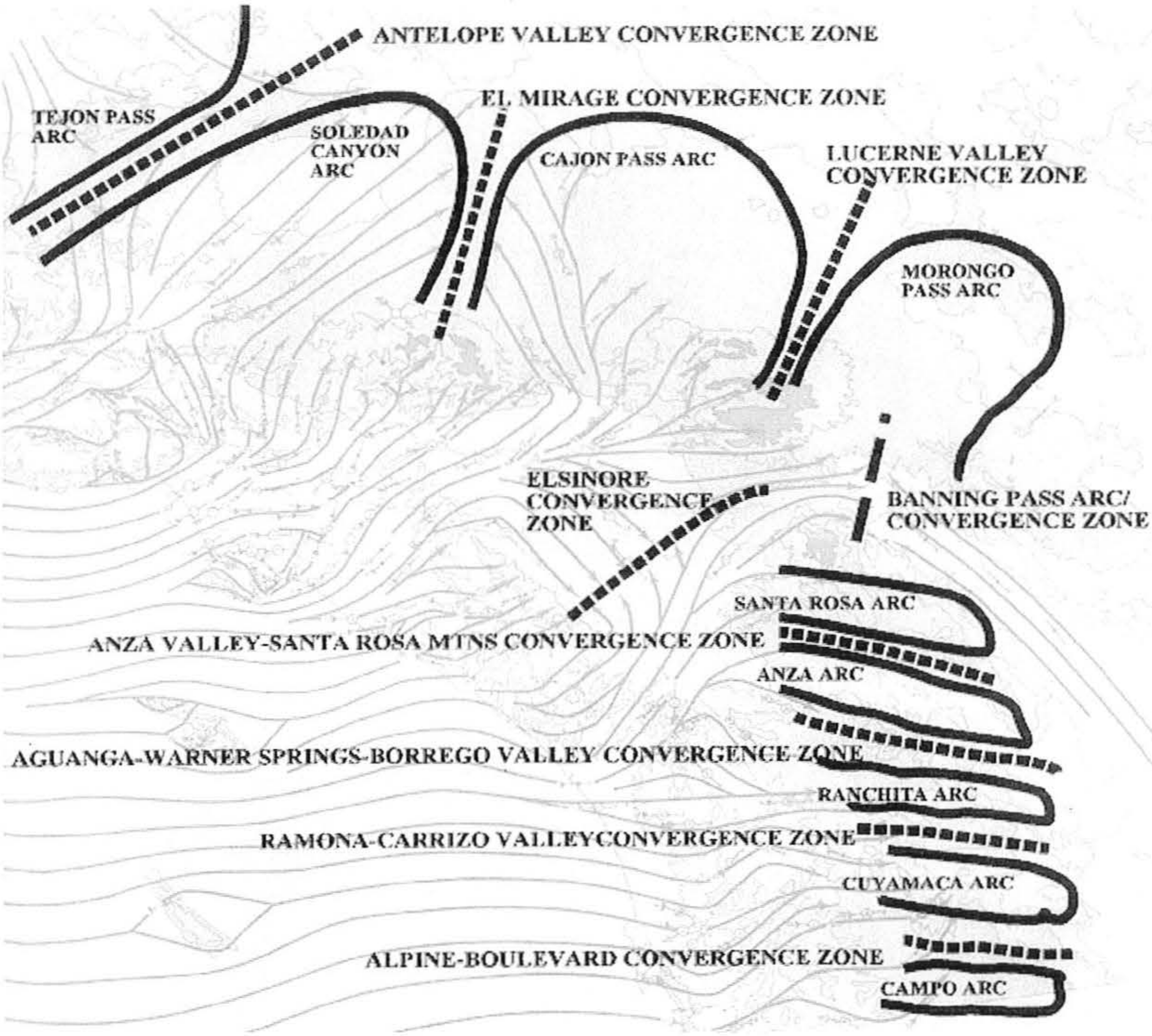

FIG. 6. Map of the terrain, low level flow through passes and canyons, and convergence zones for patterns when the westerly sea breeze flow pushes into the deserts (Adapted from DeMarrais et al. 1965).

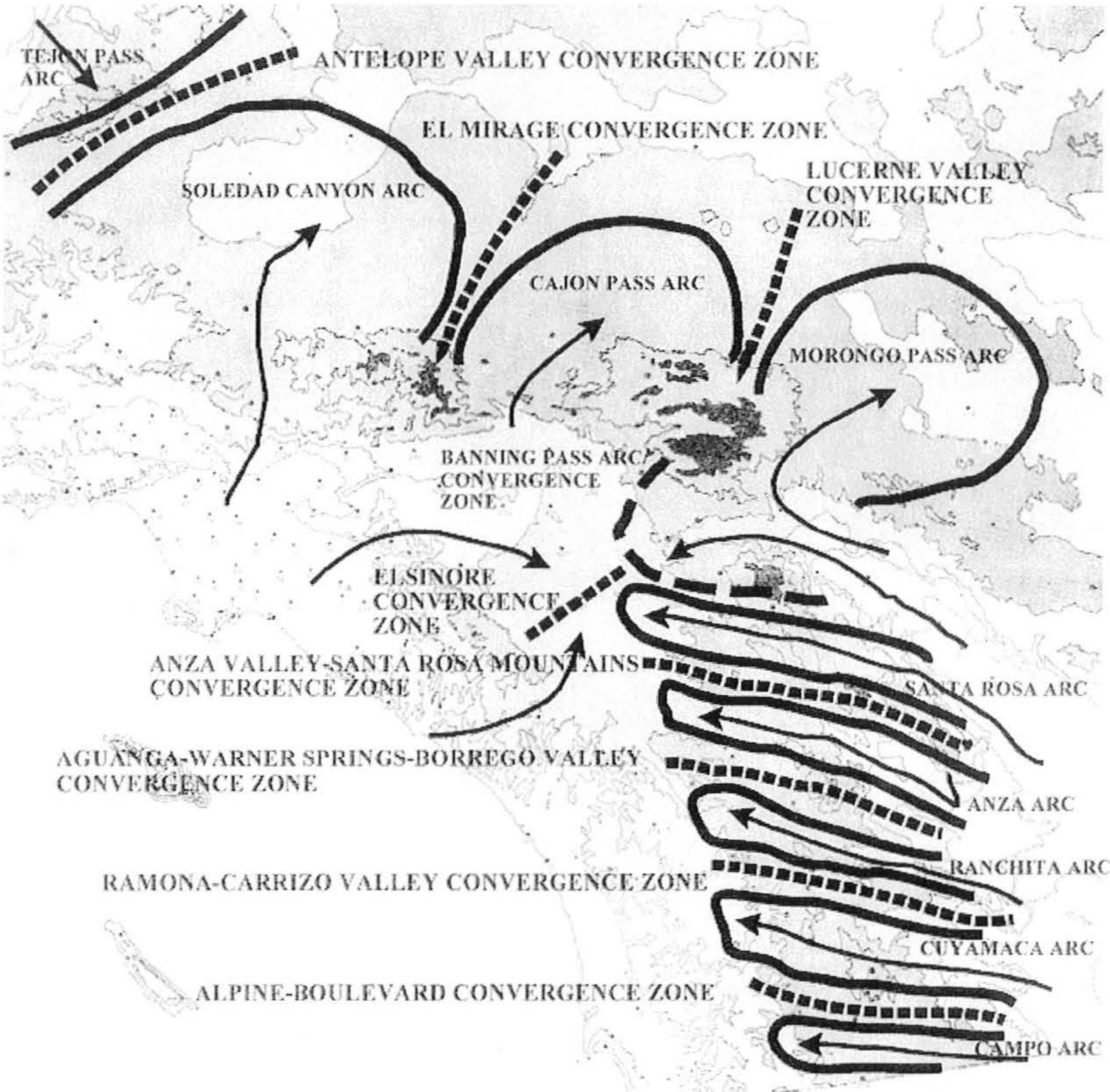

FIG. 7. Map of the terrain, low level flow through passes and canyons, and convergence zones for patterns when the southeasterly flow reaches the valley areas west of the mountains (Adapted from DeMarrais et al. 1965).

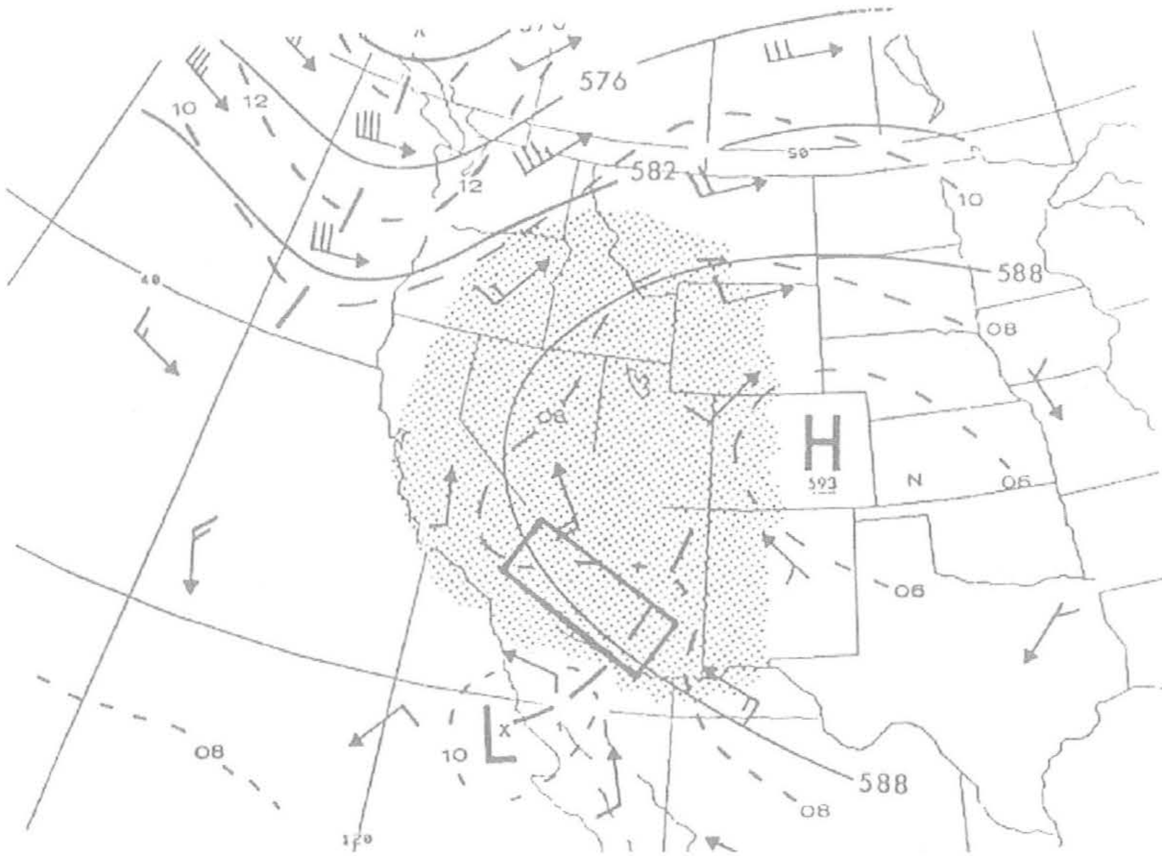

FIG. 8. Composite 500 mb heights and winds for Type 1-A Blocking Anticyclone events in southern California and southern Arizona (After Fleming and Spayd 1986).

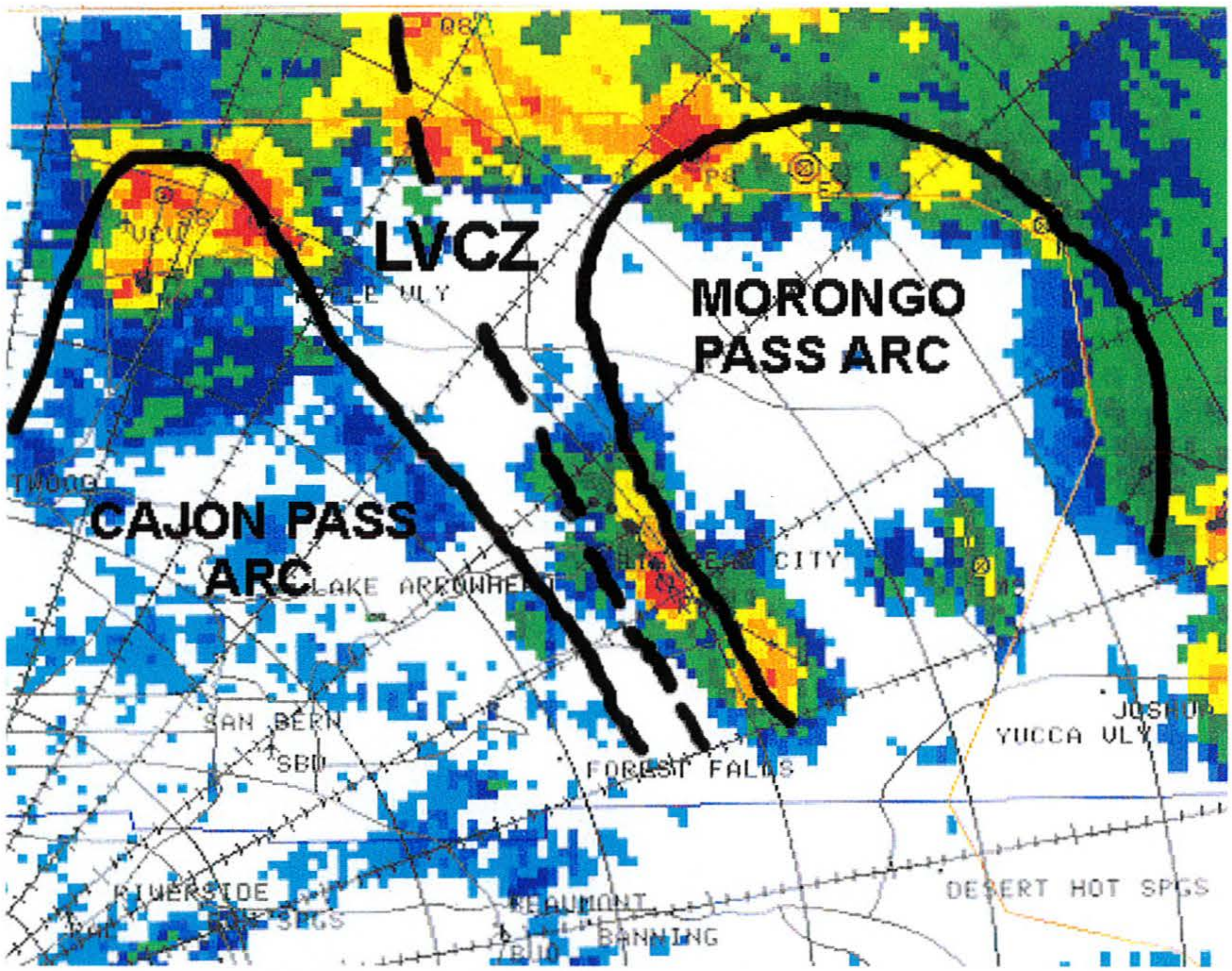

FIG. 9. 2234 UTC 11 July 1999 KSOX composite reflectivity.

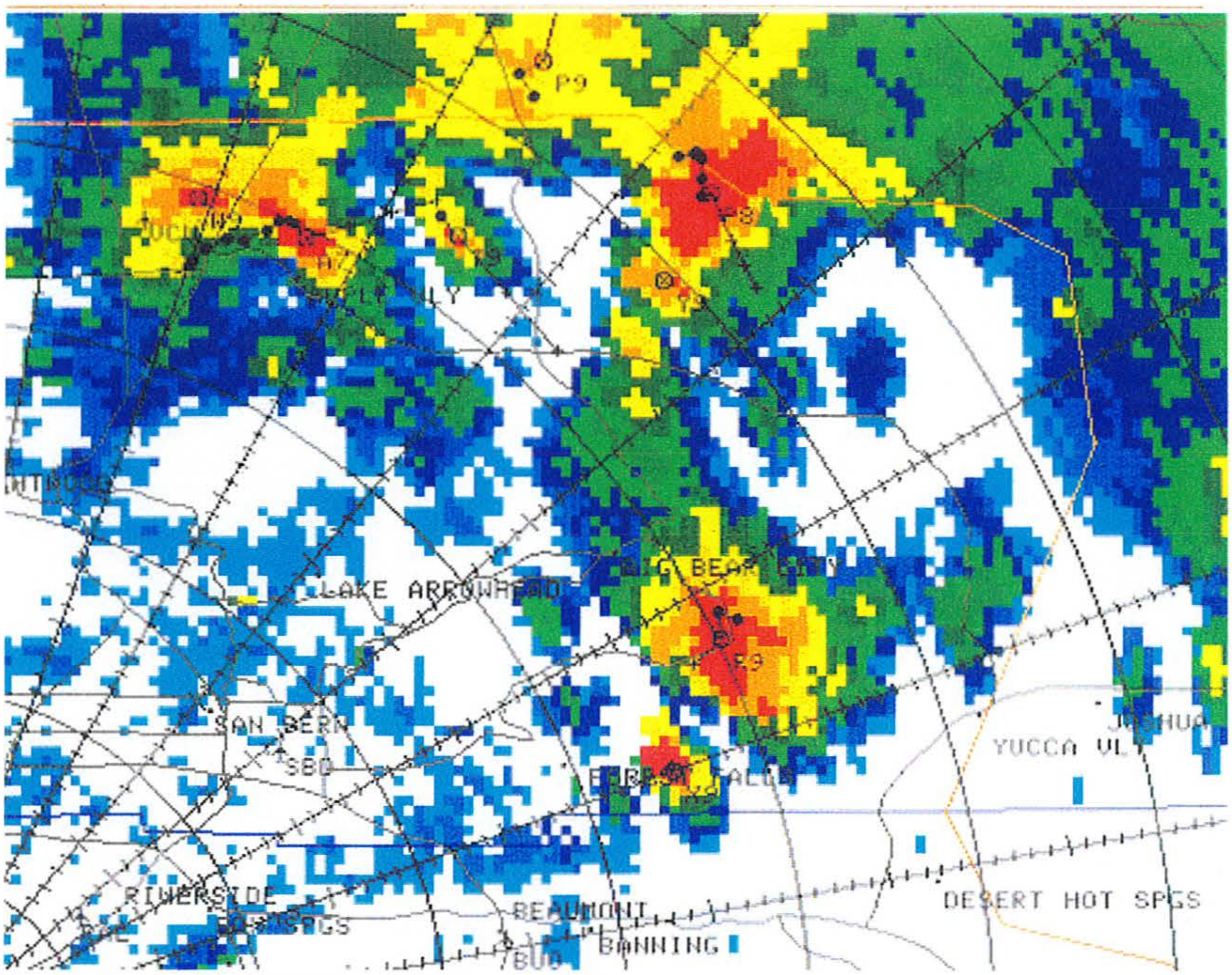

FIG. 10. 2249 UTC 11 July 1999 KSOX composite reflectivity

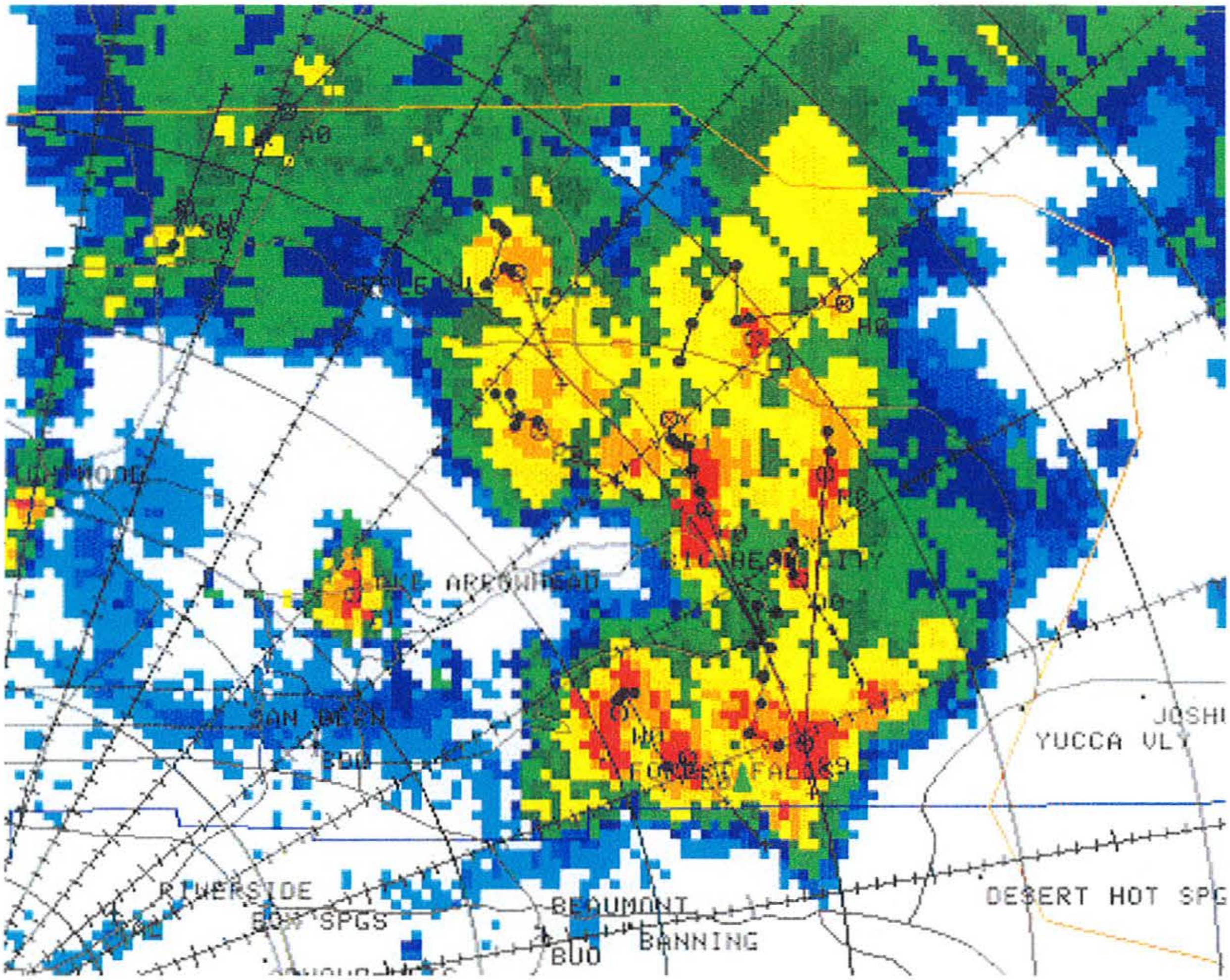

FIG. 11. 2324 UTC 11 July 1999 KSOX composite reflectivity.

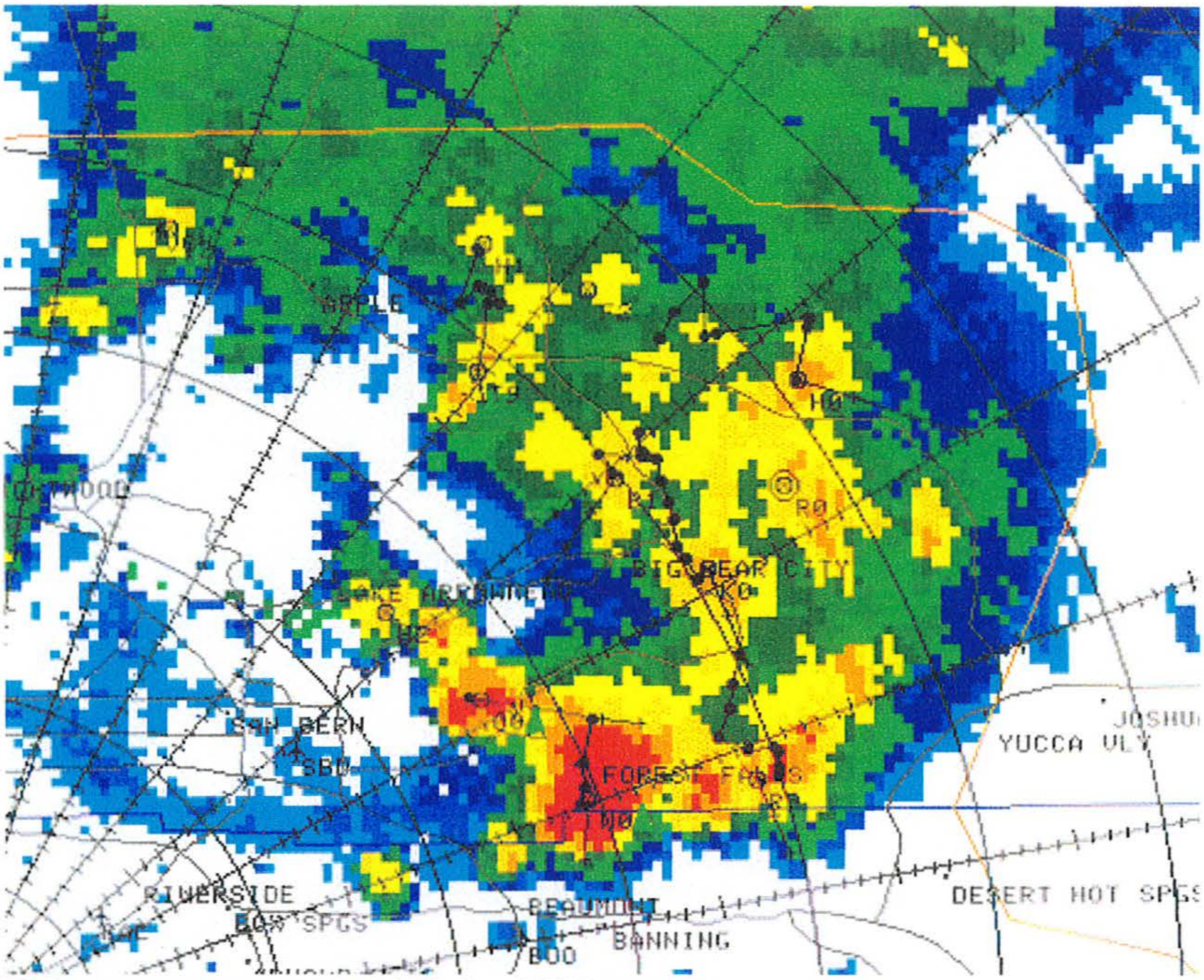

FIG. 12. 2334 UTC 11 July 1999 KSOX composite reflectivity.

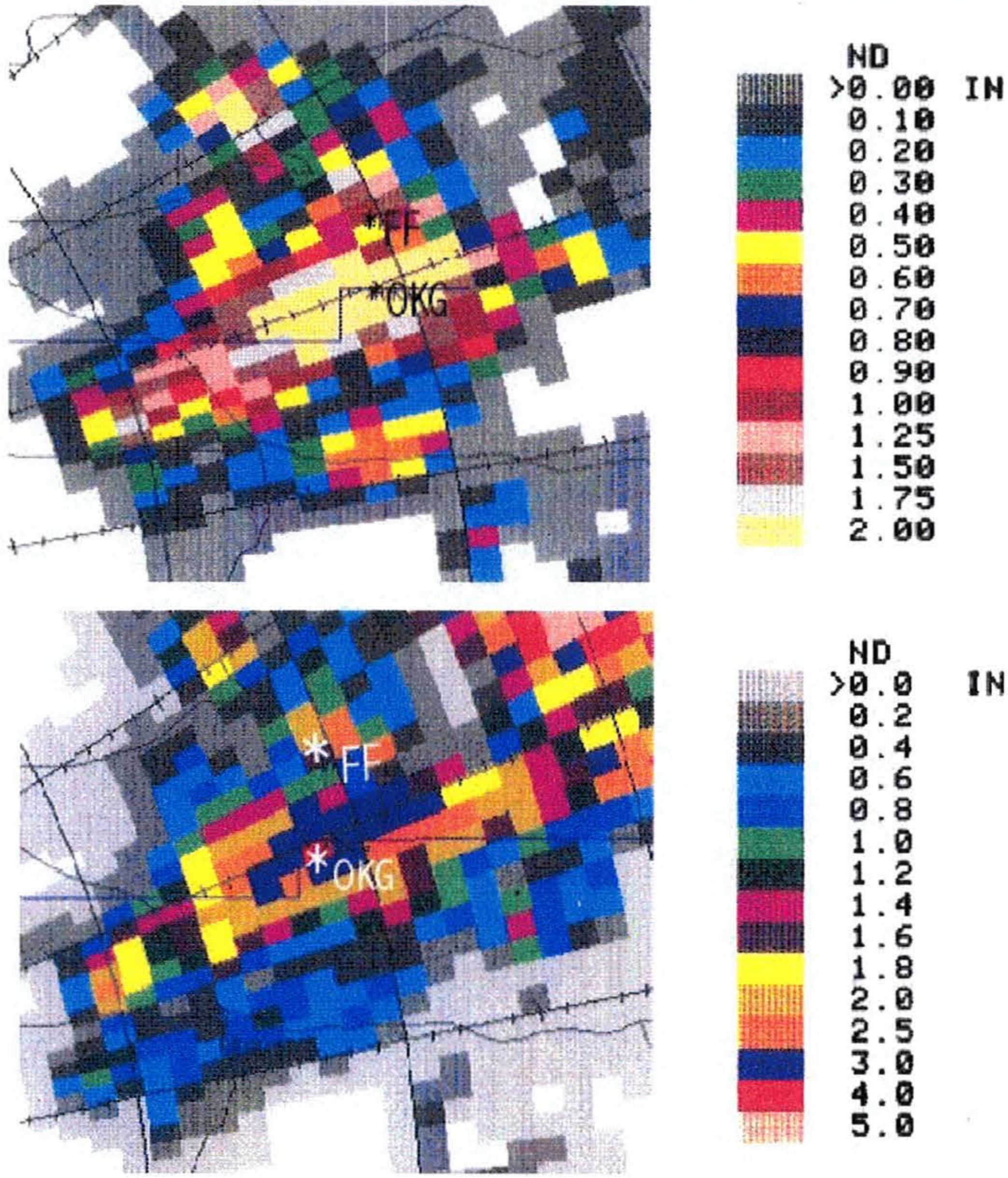

FIG. 13. One-hour precipitation estimate from the KSOX Doppler radar ending at 0041 UTC 12 July 1999 (top), and the Storm total precipitation estimate from the KSOX Doppler radar beginning at 1557 UTC 11 July 1999 and ending at 0101 UTC 12 July 1999 (bottom).

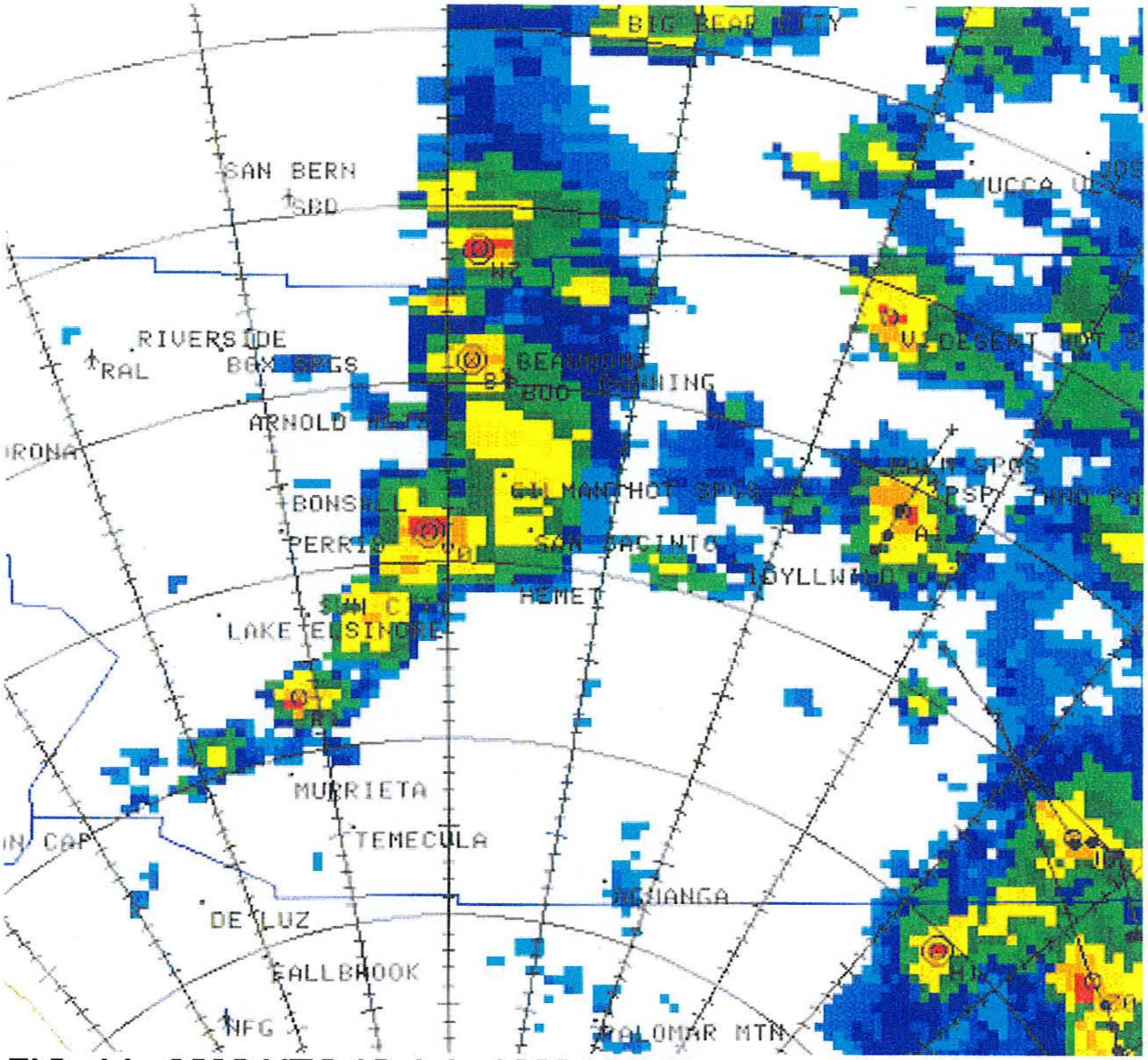

FIG. 14. 0326 UTC 13 July 1999 KNKX composite reflectivity.

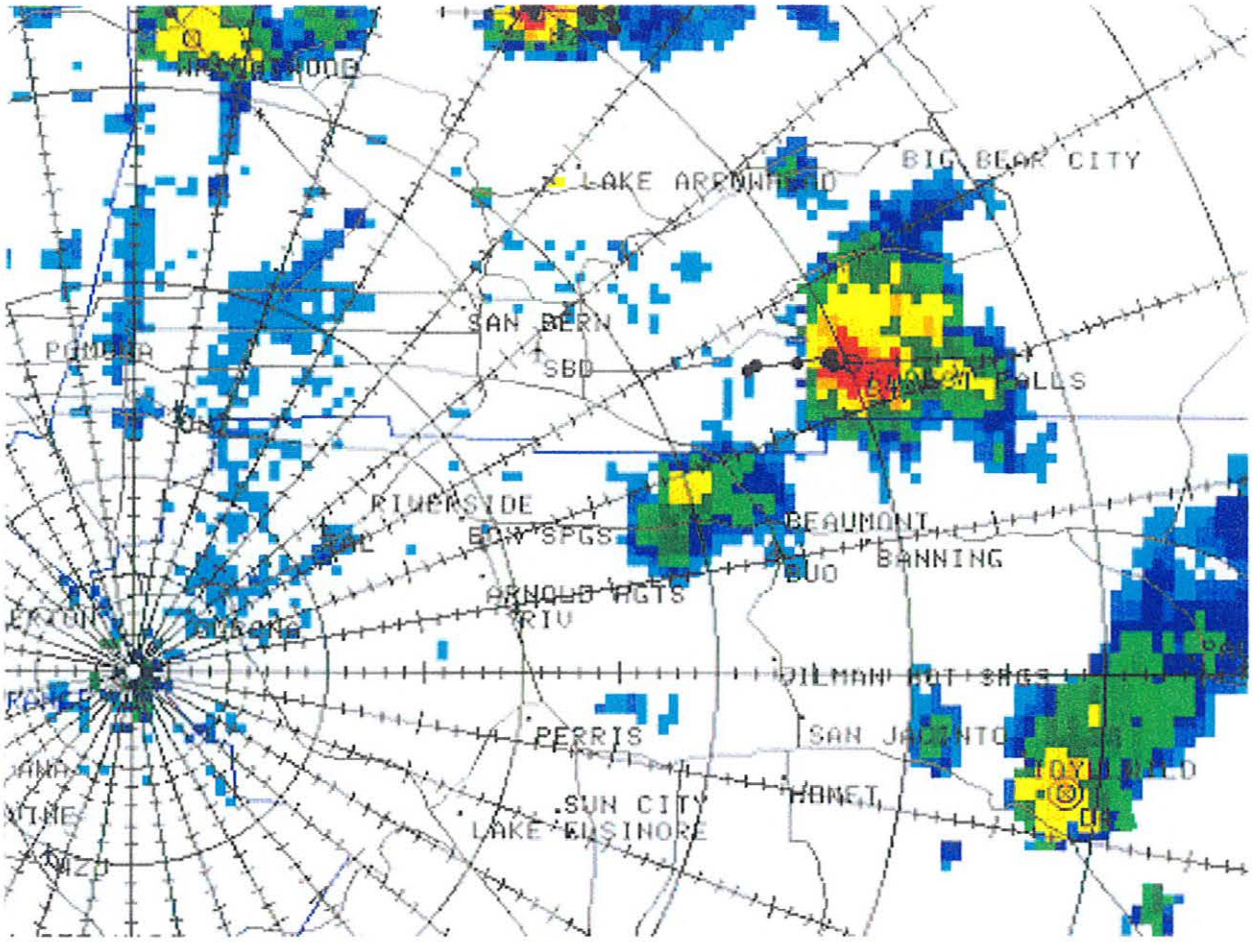

FIG. 15. 2321 UTC 13 July 1999 KSOX composite reflectivity.

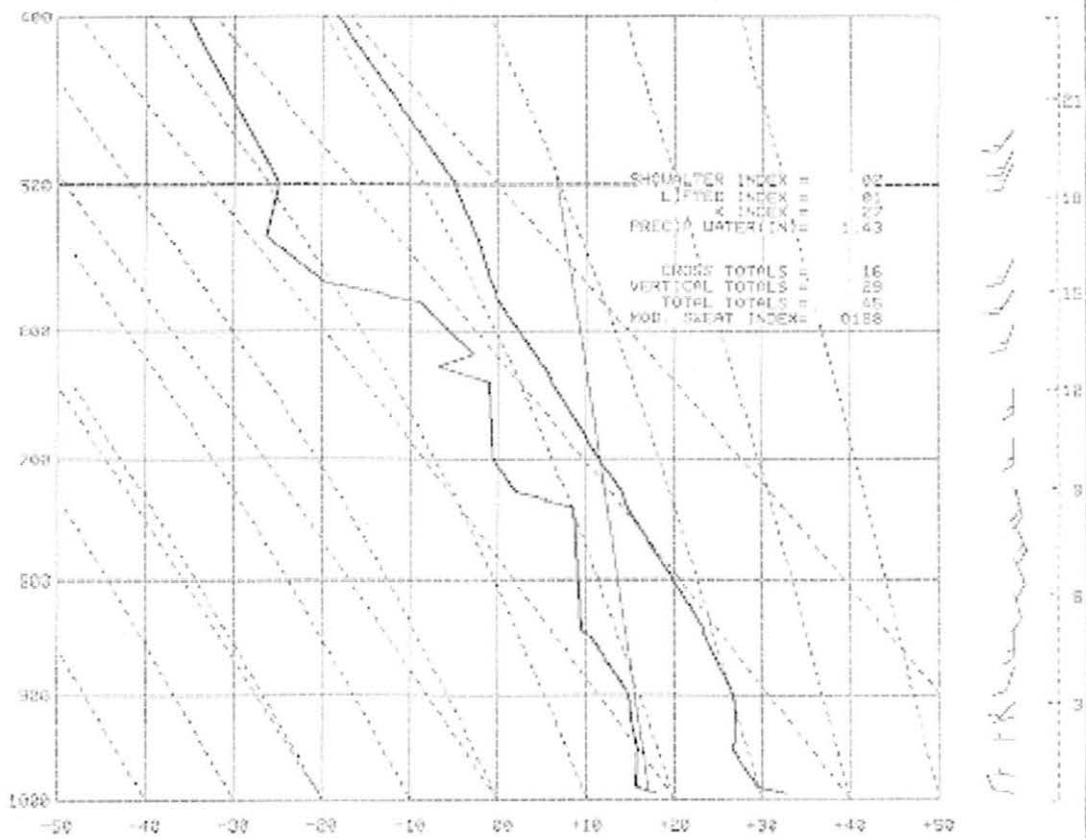

FIG. 16 NKX 00Z/SE/ 05/ 97

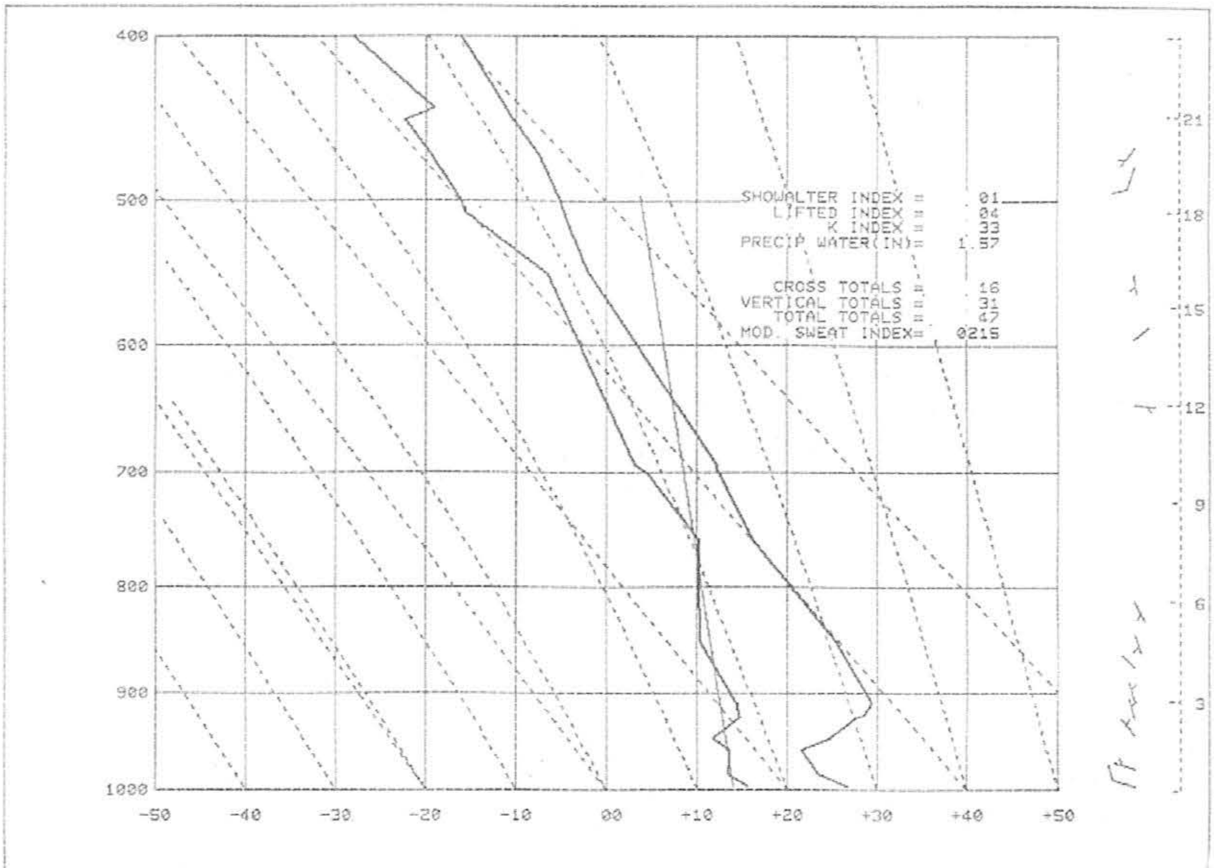

FIG. 17 NKX 00Z/JY/ 12/ 99

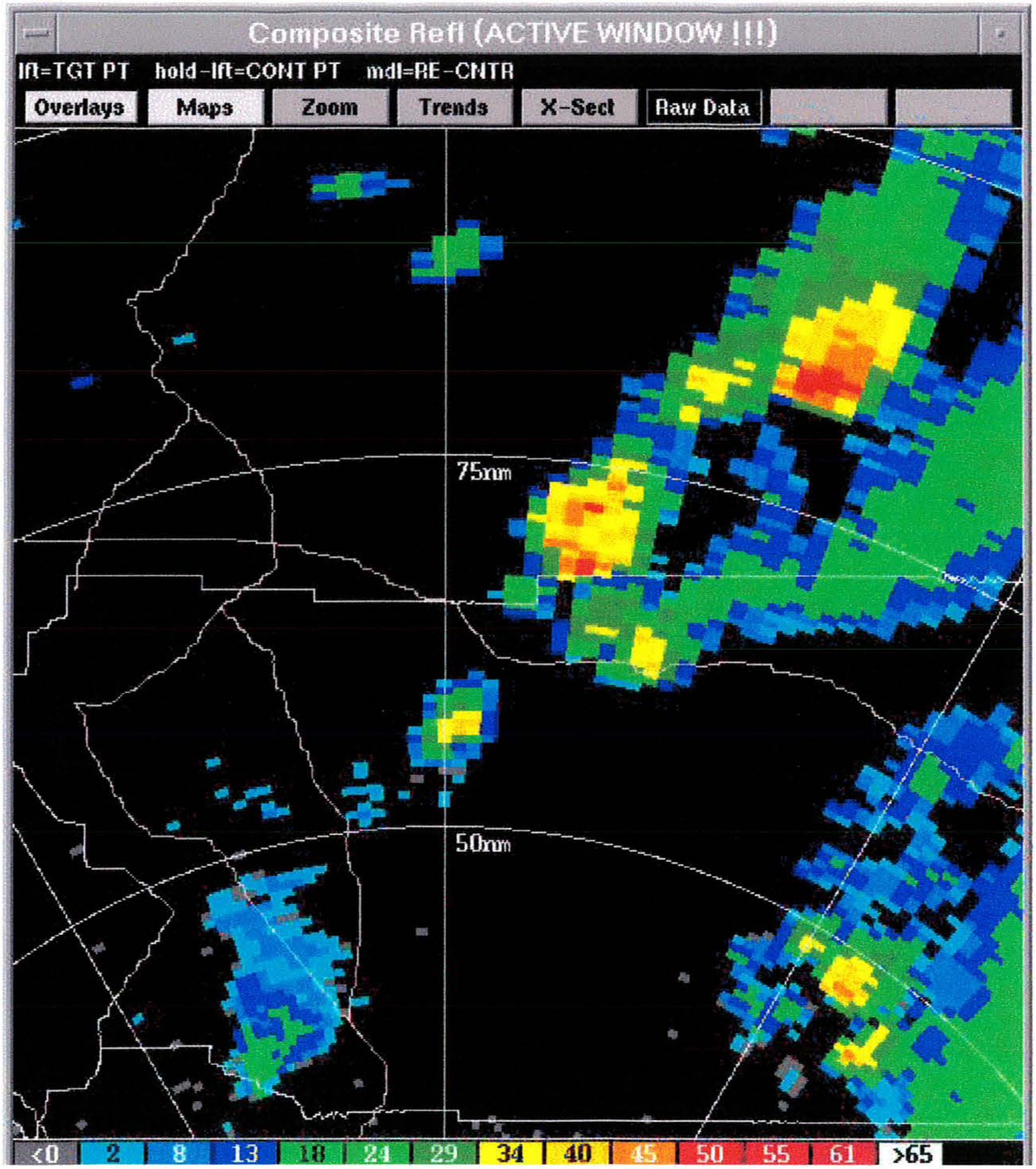

FIG. 18. 0025 UTC 5 September 1997 KNKX composite reflectivity.

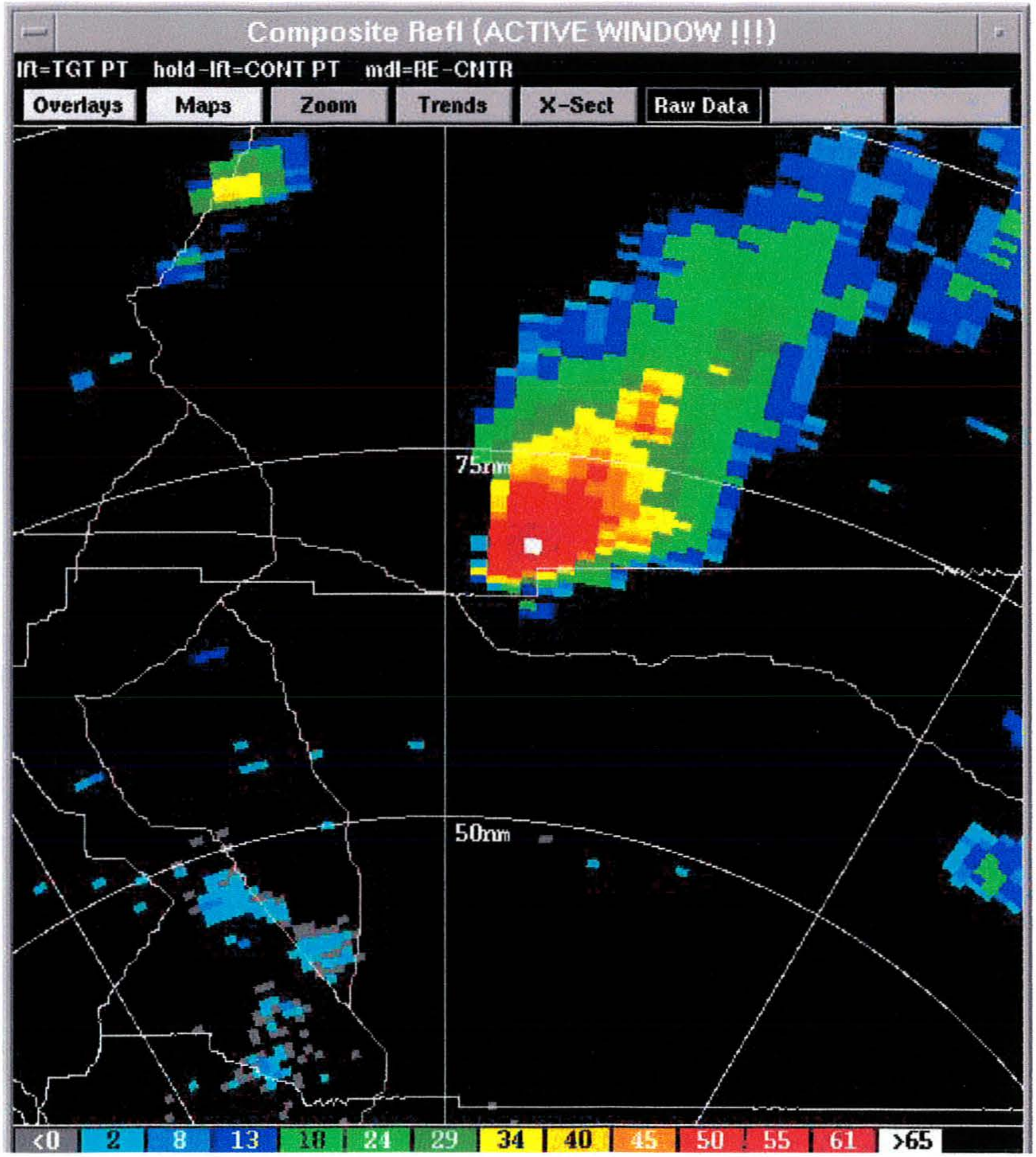

FIG. 19. 0112 UTC 5 September 1997 KNKX composite reflectivty.

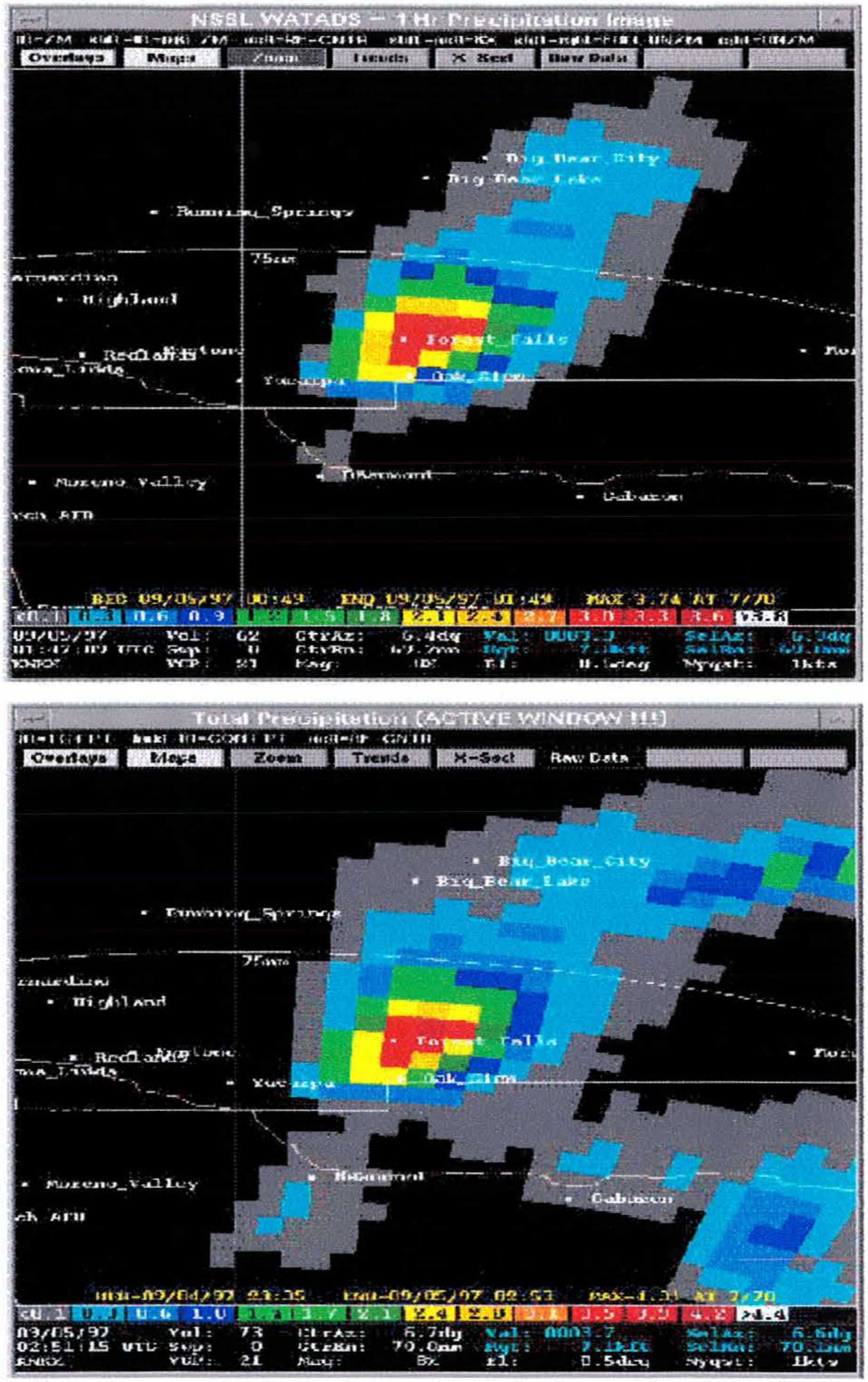

FIG. 20. One-hour precipitation estimate from the KNKX Doppler radar ending at 0149 UTC 5 September 1997 (top) and the storm total precipitation from the KNKX Doppler radar ending at 0253 UTC 5 September 1997 (bottom).