METEOROLOGICAL ASPECTS OF SOUTH-CENTRAL AND SOUTHWESTERN NEW MEXICO AND FAR WESTERN TEXAS FLASH FLOODS

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Abstract

Deep convection that produces excessive rainfall and flash flooding poses a threat to lives and property over south-central and southwestern New Mexico and far western Texas, primarily during the summer monsoon season. Forecasting these phenomena are difficult across this region due to the irregular terrain, the sparse data and the relatively poor performance of numerical models in the prediction of heavy rain across the southwestern United States. This study, therefore, examines meteorological aspects of flash flood-producing convection for this area over a 30-year period.

Climatologically, it was found the vast majority of flash floods coincided with the southwestern United States monsoon season from late June through early September, during the afternoon and evening hours. The air mass for most events exhibited at least moderate instability, moisture contents well above normal, and low cloud-layer wind speeds. There were four distinct large-scale patterns that were associated with flash flood events, but a common feature was the presence of a surface thermal trough or "heat low" covering western Arizona, southeastern California and northwestern Mexico. The thermal trough supports a low-level easterly or southeasterly surface flow favorable for the advection of abundant moisture from the Gulf of Mexico into the region. In almost half of all cases, a weak surface front or trough appeared to play some role in storm initiation. While there was more variability in the large-scale middle and upper-tropospheric patterns, deep convection frequently developed near an advancing upper-level short-wave trough and/or in the left front or right rear quadrants of upper tropospheric jet streaks. Because these forcing mechanisms may be poorly defined or located in data sparse areas, close examination of satellite images is important in their detection.

1. Introduction

Although the climate of southwestern New Mexico and far western Texas is considered to be semi-arid or desert, during the warm season the region frequently experiences deep convection with attendant heavy rainfall and flash flooding. This is mainly due to seasonal changes in the circulation across the southwestern United States during the early summer. Usually during late June into early July, the prevailing westerly flow that transports drier air masses into the region retreats northward, while the warm surface temperatures induce a broad area of low pressure across the surface of southern California, western Arizona and northwestern Mexico (Tang and Reiter 1984). This pattern evolution periodically supports the transport of moisture into Arizona, southern New Mexico and far western Texas, typically from late June into early September. Thus, the region is considered to have a monsoon period over the summer months (Adams and Comrie 1997; Wallace et al. 1999), with thunderstorms becoming relatively frequent.

As discussed by Doswell et al. (1996), flash floods occur within environments having certain characteristics or "ingredients" favorable for excessive precipitation. These ingredients include a high moisture content, a convectively unstable or buoyant air mass, a mechanism to lift the air mass to its level of free convection, and cloud-layer wind and moisture profiles unfavorable for processes that reduce precipitation efficiency, such as entrainment. Such environments can even develop over the semi-arid or desert regions of the western United States, particularly during the summer months (Maddox et al. 1980).

A number of studies have explored deep convection and heavy rain events over the southwestern United States (e.g., Hales 1974; McCollum et al. 1995; Maddox et al. 1995), but these investigations have been primarily concerned with convection over Arizona. In contrast, little formal research has addressed flash flood-producing thunderstorms over southwestern New Mexico and far western Texas, a region within the County Warning Area (CWA) of the El Paso National Weather Service Forecast Office (NWSFO; actually located at Santa Teresa, New Mexico [KEPZ], shown in Fig. 1). As will be demonstrated, heavy rain and flash flooding also pose major concerns and present significant hazards to residents in this particular area, especially in far western Texas, where the El Paso metropolitan area is located. The danger is expected to worsen in the coming years as the population continues to increase and the area undergoing urban development expands.

As this paper will explain, the meteorological patterns associated with flash flood events over the El Paso NWSFO CWA (henceforth designated as EPZ CWA) can have distinct differences from patterns associated with heavy rainfall over Arizona. For example, whereas the moisture source for the Arizona monsoon is primarily the Gulf of California (Hales 1974), in the lower boundary layer at least, moisture fueling flash flood-producing convection over the EPZ CWA comes most frequently from the Gulf of Mexico. Thus, forecasting techniques derived from previously cited papers will have limited applicability. Precipitation forecasts from numerical models also provide little practical assistance to operational meteo-

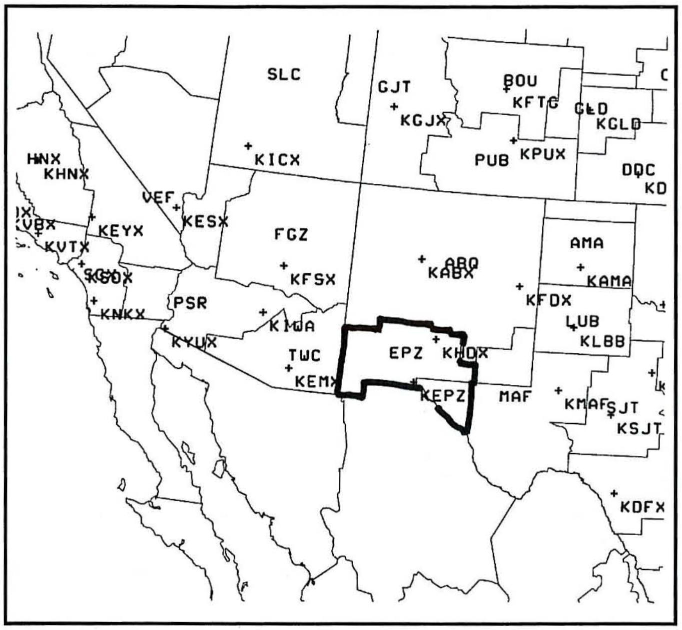

Fig. 1. Map of the southwestern United States and northern Mexico showing regional National Weather Service County Warning Areas (CWA). Dark-bordered area comprising portions of southern New Mexico and far western Texas indicates the El Paso (EPZ) CWA and the focus area of this study.

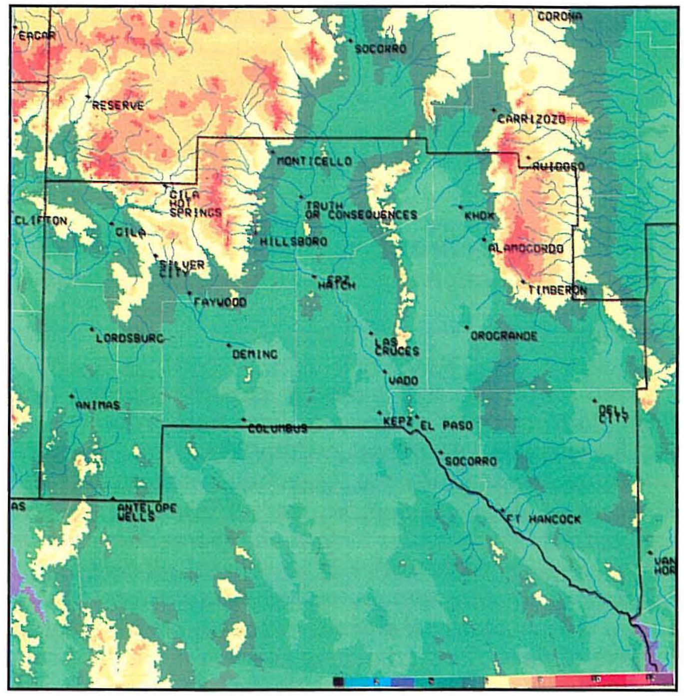

Fig. 2. Topographical map of the EPZ CWA and surrounding areas showing terrain elevations, cities and towns, and larger rivers. Elevations are listed in kft.

rologists, due in part to the irregular terrain and the lack of available meteorological data over northern Mexico and the eastern Pacific, especially data related to moisture and winds aloft. Studies by Junker et al. (1992) and Dunn and Horel (1994) have illustrated the poor performance of NOAA/NWS National Centers for Environmental Prediction (NCEP) models in predicting heavy rainfall over the southwestern United States.

The topography of the EPZ CWA is varied and complex, further increasing the forecasting challenge. As shown in Fig. 2, elevations over the area range from around 3500 ft (1000 m) in the deserts to 12000 ft (3600 m) over the higher mountain peaks comprising the southern portions of the Rocky Mountain chain. The most prominent mountain ranges include the Sacramentos over northeastern portions of the CWA, and the Gila region that extends into the northwest. However, smaller mountain ranges also cover the area, along with a number of valleys of varying sizes, the largest of which is along the Rio Grande River, which flows into central New Mexico through Truth or Consequences, then southward into the El Paso vicinity in extreme western Texas.

Maddox et al. (1978) have described how sloping terrain can initiate and sustain deep convection by acting as a stationary lifting mechanism when and where the low-level wind flow has a component from lower to higher elevations. In addition, the differential heating between the elevated surfaces along the mountains and the adjacent free atmosphere can induce a circulation where warmer air in the lower levels rises along the sloped terrain (Pielke and Segal 1986), a process that can initiate thunderstorms if the lifted air is buoyant. Such terrain-related circulations are usually very localized, often of smaller scale than the grid spacing of the NCEP models.

South-central and southwestern New Mexico and far western Texas do experience strong convection, especially during the summer monsoon when there are episodes of very heavy rainfall. Given the increasing threat to lives and property posed by flash floods over the area, and the difficulty and challenge involved with correctly forecasting these phenomena, this paper investigates meteorological aspects of flash floods within the EPZ CWA.

2. Methodology and Data Analyses

Using the NOAA/National Climatic Data Center (NCDC) publication Storm Data, supplemented by available rainfall data from NWS observations and data collected by cooperative observers and storm spotters, flash flood-producing heavy rainfall events from 1972 to 2002 within the EPZ CWA were examined. Cases were selected based on both subjective and objective criteria. For this particular study, significant flood reports included water damage to homes and businesses, widespread flooding and closures to roads and highways, and river and stream overflows that caused major disruptions. Since this study is limited to flash flooding, events are included only if flooding began within six hours of the onset of rainfall. Rainfall amounts for each case must also be measured or estimated by cooperative observers to be at least 2 inches (50 mm) within the six-hour period.

It is recognized that this study is by no means all-inclusive. Due to the sparse population within the CWA, many heavy rain events go unreported because they are either not observed or do not adversely impact buildings, roads or other man-made structures. This has become especially apparent over the past several years since the implementation of the WSR-88D Doppler radar, which provides reliable rainfall estimates. This author has noted several instances of radar-estimated excessive rainfall totals over remote desert and mountainous terrain, far from residential areas or highways, which are not included in this study. Flash flooding has also been observed in areas of poor drainage where rainfall amounts of no more than an inch occur within a very limited period of time, typically less than 30 minutes. While these brief heavy rain events can pose inconveniences and even short-term danger to the public, they are not included in this study.

For each case selected, surface and upper-air data were examined and analyzed to determine antecedent conditions within three hours of the flash flood events. The proximity soundings were constructed using regularly scheduled or special rawinsondes closest to the flash flood events, which in most cases were the rawinsondes launched from El Paso, Texas or, since 1997, Santa Teresa, New Mexico. Soundings were modified by adjusting surface temperature and dewpoint data to fit conditions as they existed just before the onset of heavy rainfall. Each proximity sounding was further analyzed in detail using the SHARP workstation (Hart and Korotky 1991). Parameters related to moisture content, instability and vertical wind profiles were closely examined, including best lifted index, most unstable convective available potential energy (MUCAPE), K-index, precipitable water (PW), and mean cloud-layer winds.

For each flash flood day over the EPZ CWA, hourly surface maps and twice-daily 850-, 700-, 500-, 300- and 250-hPa maps were inspected for the location of such features as surface boundaries, pressure centers, troughs, ridges, jet streaks and available moisture. After examination, surface and upper-air patterns conducive for flash flooding were determined in a manner similar to Maddox et al. (1980) in their study of heavy rain events over the entire western United States.

3. Climatological Characteristics

For the period 1972 to 2002, there were 48 flash flood episodes across the EPZ CWA. The monthly distribution, as depicted in Fig. 3, shows 29 cases (60%) of all events occurred in July and August, consistent with studies by Maddox et al. (1980) that determined most heavy rain events in the southwest were associated with the summer monsoon pattern. However, there were several flash floods that developed within patterns more commonly associated with baroclinic-dynamic weather systems. Only one flash flood occurred in either May or October. (There were actually several flash floods reported during the winter months within this period, but it was determined these cool-season floods were produced by more prolonged rainfalls and at least one case was associated with melting snow in the higher elevations. Thus, they were not included in this investigation.)

Actual or estimated times of occurrence (Table 1) indicate the majority of cases, 26 events (54 %) occurred during the evening hours between 1800 and 2400 LST, with 17 cases (35%) in the afternoon. For the afternoon flash floods, most developed after 1500 LST, while only a small percentage of floods were reported between midnight and noon. These results are similar to studies by Maddox et al. (1980) and Rogash (1988) for convection over regions of higher terrain. The preference of deep convection occurring in the late afternoon and early evening can be attributed to the diurnal heating cycle, with maximum convective instability usually around the time of warmest surface temperatures. Based on this author's observations along with previous studies (Maddox 1983; Runk and Kosier 1998), convection occurring or developing in the later evening or early morning is believed to be at least partly related to forcing along outflow boundaries associated with earlier activity.

4. Thermodynamic and Vertical Wind Profiles

From the constructed proximity soundings, critical data related to instability, moisture and wind were obtained and are presented in Table 2. Mean values of MUCAPE and best lifted index are 1500 J kg^{-1} and -5°C,

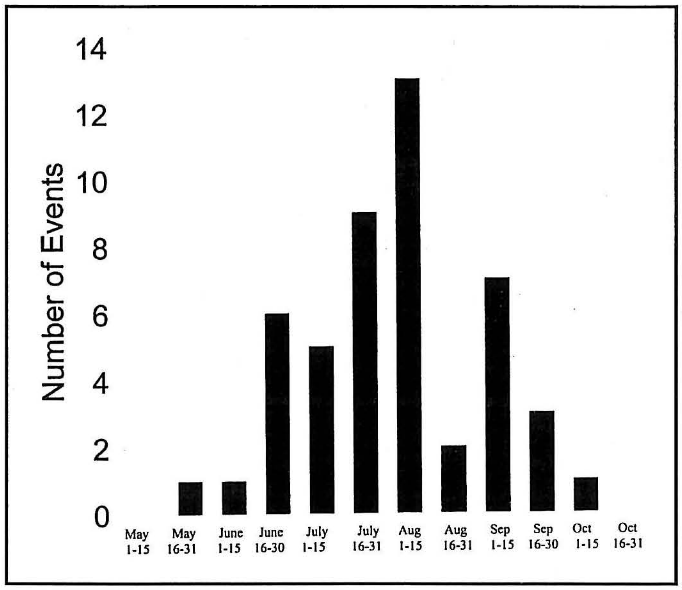

Fig. 3. Semi-monthly frequency distributions for 48 flash flood episodes over the El Paso CWA for the period 1972-2002.

Table 1. Time of occurrences for flash floods within EPZ CWA.

Time of occurrence (LST)	No. of Events
0000-0600	4
0600-1200	1
1200-1800	17
1800-2400	26

Table 2. Selected mean environmental parameters for EPZ CWA flash floods.

Surface dewpoint	57°F (14°C)
Surface mixing ratio	12 g kg^{-1}
Precipitable water	1.3 in. (33 mm)
Most unstable CAPE	1500 J kg^{-1}
Most unstable lifted index	-5°C
K index	38°C
Cloud-layer wind speed	14 kt (7 m s^{-1})

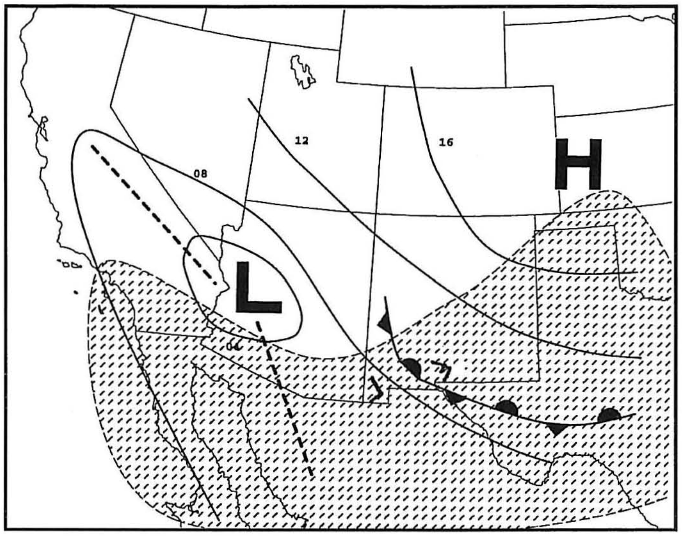

Fig. 4. Surface pattern for a typical El Paso CWA Type I flash flood. Surface low and high pressure centers indicated by large L and H respectively. Bold dashed lines show positions of surface trough axes. Conventional frontal symbols and wind barbs used (full feather = 5 m s^{-1}). Solid lines represent isobars (hPa) with leading '10' missing. Hatched area indicates dewpoints in excess of 55°F (13°C).

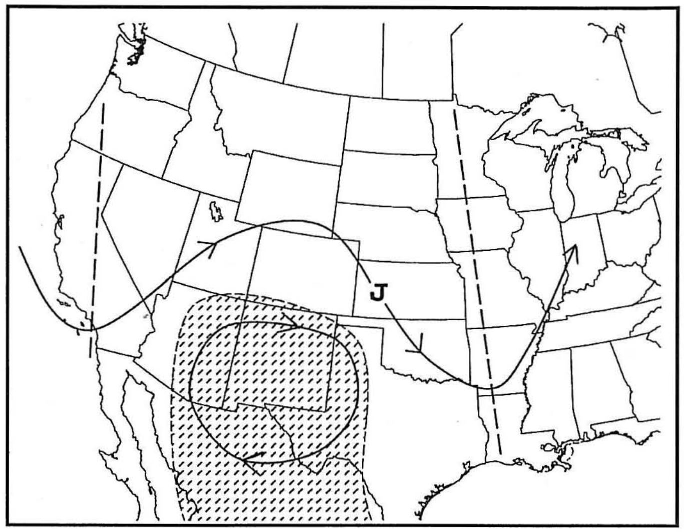

Fig. 5. Mid- and upper-tropospheric features for a typical El Paso CWA Type I flash flood. Thin arrows are 500-hPa streamlines. Dashed lines show 500-mb trough positions. Bold 'J' represents position of upper-tropospheric jet streak. Hatched region indicates 700-hPa dewpoints in excess of 5°C.

respectively. Only six (13%) flash floods occurred where MUCAPES were less than 1000 J kg^{-1}, while only two events (4 %) developed where MUCAPE exceeded 3000 J kg^{-1}. Thus 40 cases (83 %) of the events evolved within an air mass considered "moderately unstable," according to the criteria used by most operational meteorologists. It is speculated that one reason very few events occurred within a more highly unstable air mass is because such environments often include a mass of drier air (and attendant dry adiabatic lapse rates) in the middle troposphere, which would favor greater entrainment and a reduction in precipitation efficiency. In addition, high CAPE is associated with very intense updrafts that can decrease the precipitation efficiency of convection by reducing the residence time of water substance in the updraft. Other studies of flash floods (e.g., Maddox et al. 1980; Rogash 1988) have also suggested heavy rain events usually develop in an environment of weak to moderate instability.

Table 2 also shows abundant moisture present within the flash flood environment, with a mean (and median) PW value of 1.3 in. (33 mm). No flash floods were reported where the PW was less than one inch, and 90% of the events developed where the PW was at least 1.2 in (30.5 mm). On average, flash floods occurred where the PW was 160% of climatological normals. In particular, moisture content in the lower boundary layer was high, with surface dewpoints of at least 55°F (13°C) in a large majority of cases. Finally, both the mean and median K index values were 38°C, indicating ample instability and moisture availability for heavy rainfall in the majority of cases (Funk 1991). For a large majority of cases (81%), the K index was at least 35°C.

An examination of cloud layer winds shows average speeds were rather light at 14 kt (7 m s^{-1}) with cloud layer winds less than 20 kt (10 m s^{-1}) for 36 of the cases. This can be significant for several reasons. First, lighter cloud layer wind speeds indicate a propensity for slower-moving storms, allowing for an individual storm to drop more rainfall over a limited area. Second, lighter wind speeds within the cloud layer reduce the potential for entrainment or the evaporation of water droplets. This is especially important if the atmosphere surrounding the cloud has low relative humidities. Finally, stronger flow aloft can transport water droplets further downstream where they may evaporate elsewhere or fall over a broader area. Therefore, weaker flow generally contributes to higher precipitation efficiencies (Doswell et al. 1996) by allowing water vapor that enters the storm updraft a higher probability of condensing and falling to the ground in a relatively limited area, especially if the storm exhibits slower movement.

5. Flash Flood Synoptic Patterns

a. *Type I pattern*

More flash floods were associated with the Type I or "backdoor frontal" pattern than any other setting, with 21 cases (44% of reported events). At the surface (Fig. 4) this pattern is characterized by a large area of high pressure, associated with a modified Canadian air mass, typically centered over the central Plains. In almost all cases, the movement or expansion of the high and its attendant circulation forces a (usually) weak cold front to move west or southwest into the EPZ CWA before it becomes almost stationary along the Mexican border and/or over the mountains of southwestern New Mexico. To the west a broad area of weak low pressure, the so-called desert "heat low," very frequently covers western Arizona and southeastern California. The surface pressure configuration induces a northeasterly to southeasterly flow in the

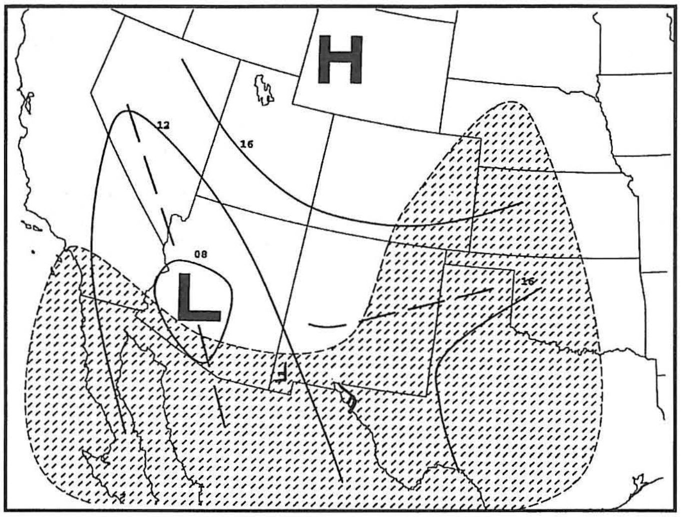

Fig. 6. Same as Fig. 4, except for a typical El Paso CWA Type II flash flood.

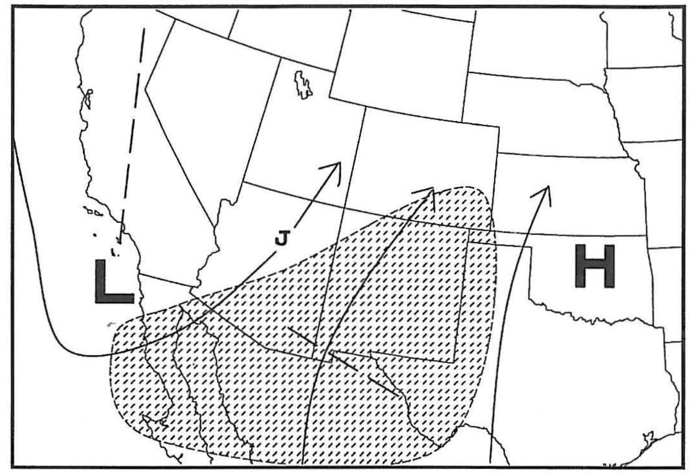

Fig. 7. Same as Fig. 5, except for an El Paso CWA Type II flash flood. Heavy 'L' and 'H' indicate 500-mb minimum and maximum geopotential height centers, respectively.

lower boundary layer across southern New Mexico and far western Texas, with advection or transport of moisture from the Gulf of Mexico into the region. This is in contrast to Arizona monsoon events that are dependent on the Gulf of California as a primary source of low-level water vapor. The easterly flow component also favors upward motion within the boundary-layer over elevated terrain sloping upward from east to west. Thus low-level features associated with the Type I pattern are similar to patterns conducive for flash floods along the front range of the Rocky Mountains further north (Maddox et al. 1978; Rogash 1988).

The mid- and upper-level pattern associated with Type I flash floods (Fig. 5) usually exhibits a medium- or high-amplitude trough of medium wavelength moving across the Plains or Mississippi Valley. Northwest flow and large-scale subsidence west of the trough axis supports the movement of cooler air into the southern Rockies. Frequently, a jet streak with winds in excess of 70 kt is found embedded within this northwest flow, with maximum winds often located over the central or southern Plains. As a result, some Type I flash flood events in the EPZ CWA are located in the right rear quadrant of an upper-tropospheric jet streak suggesting at least weak upward motion in the middle troposphere (Uccellini and Johnson 1979).

In the majority of cases, the Type I pattern is also characterized by a longer wave trough approaching or advancing into the West Coast and the Baja Peninsula, with a flat ridge either extending over Arizona and New Mexico or further south across northwestern or north-central Mexico. Because of this variation in the position of the ridge, there is a corresponding large variability in the wind direction and steering flow in the middle and upper troposphere. For cases where the ridge axis is north of the EPZ CWA, the cloud-layer winds induce a westward storm motion; if the ridge is displaced south, the wind direction and storm motion will be to the east. However, there were several events where winds were very light due to the region being almost directly under a middle-tropospheric height center.

For Type I events, heaviest rains usually (but not always) occur within proximity of, and on the cool side, of the frontal boundary where low-level upward forcing is likely to be strongest. While the wind speeds aloft are typically weak for Type I environments, poorly-defined vorticity maxima or short waves are sometimes embedded within the flow. These act at the middle or upper levels to force upward vertical motion and to contribute to the instability by dynamically cooling the air aloft. Jet streaks in the upper troposphere may also be present over the southern Rockies and northern Mexico, further augmenting any lift and modulating the convection. Unfortunately, because of the limited surface and (especially) rawinsonde data over northern Mexico and the southwestern United States, these features can be difficult to detect. Thus, forecasters may have to rely on satellite information to determine the location and movement of major features.

b. Type II pattern

There were 13 cases (27 % of reported cases) of flash flooding associated with the Type II pattern. At the surface (Fig. 6), a typical summertime thermal trough extends through northwestern Mexico into western Arizona and southwestern California. To the east, high pressure usually covers an area from the lower Mississippi Valley through south-central Texas. Frequently, a weak surface cold front or trough is aligned across northern or central New Mexico just north of the EPZ CWA. The resulting pressure pattern induces an east to southeasterly surface wind, transporting Gulf of Mexico moisture into the region. The easterly flow component also results in an upslope flow component over the eastern slopes of the Sacramento and Gila Mountains, suggesting boundary-layer forcing as the air moves over the elevated terrain. Accordingly, on a typical summer day, thunderstorms initially develop over mountainous terrain during the early afternoon, with the activity forming or propagating over the lower elevations during the late afternoon and evening.

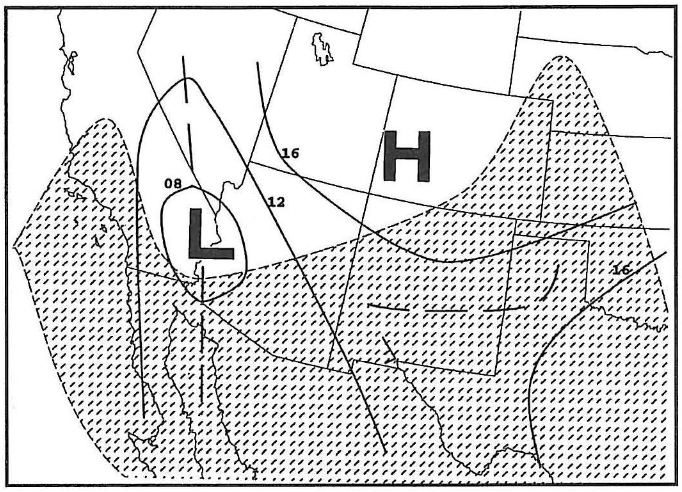

Fig. 8. Same as Fig. 4, except for a typical El Paso CWA Type III flash flood.

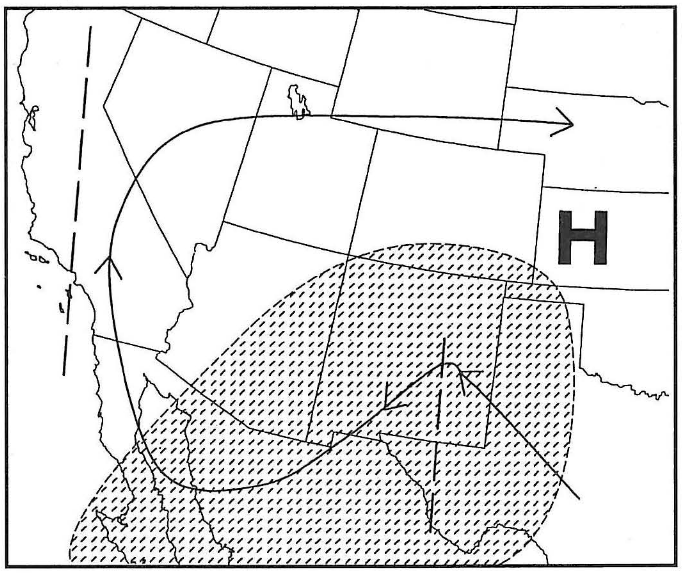

Fig. 9. Same as Fig. 7, except for a typical El Paso CWA Type III flash flood.

In the middle and upper troposphere (Fig. 7), the circulation is usually comprised of a medium- or long-wave trough, with a north-south axis located from the eastern Pacific, just west of the California coast, to the Great Basin and western Arizona region. However, in a few events, this pattern also included a cut-off or closed low centered over Arizona or northwestern Mexico. To the east, a broad area of high pressure, associated with the westward extension of the Bermuda High, covers the western Gulf of Mexico and southern Texas. The circulation induced by the height or pressure field aloft supports a southerly component to the mid-tropospheric winds, with transport of tropical moisture in the lower mid-troposphere (usually between 800 and 600 hPa) from the southern Gulf of California region into southern New Mexico and western Texas, especially if the flow is southerly to southwesterly. However, in several cases, mid-tropospheric winds were southeasterly with streamline and trajectory analyses suggesting the source of moisture aloft was the Gulf of Mexico.

Within the prevailing large-scale flow of the Type II pattern, there are often short-wave troughs or vorticity maxima moving northward from Mexico into the EPZ CWA, acting to initiate or focus convection. As with the Type I pattern, such features may be weak and poorly defined, with the absence of data over northern Mexico making them difficult to detect using rawinsonde information alone. Using satellite images can be essential in determining the location of significant features. Furthermore, while the lower- and mid-tropospheric wind speeds are usually light (< 20 kt [10 m s^{-1}]), stronger winds are almost always present at higher levels, with attendant upper-tropospheric jet streaks extending into northern Mexico and the southwestern United States. Using rawinsonde data alone, it was determined that during the Type II scenario, in at least 8 cases (75 % of Type II episodes), flash floods developed over areas underneath the right-rear or left-front quadrants of an upper-tropospheric jet streak having maximum wind speeds of at least 50 kt (25 m s^{-1}), which was no more than 400 miles from the flood-affected area. For the few cases where this scenario included an approaching closed low aloft, strong quasi-geostrophic forcing associated with differential positive vorticity advection was present. Therefore, during most flash floods, upward dynamic forcing was likely supplementing boundary-layer lift induced by the elevated terrain, diurnal heating and convective outflow boundaries.

c. *Type III pattern*

Eight (17%) of the flash flood cases occurred with the Type III or "easterly wave" pattern, which is somewhat similar to the Type II pattern. As illustrated in Fig. 8, surface features include the warm-season thermal trough aligned from northwestern Mexico across western Arizona into the Great Basin. In the majority of cases a broad area of weak high pressure, associated with a tropical maritime air mass, covers the region across the lower Mississippi Valley into southern Texas. A separate area of high pressure, associated with drier continental air, frequently extends through the central High Plains and the central Rockies into northern Arizona. A weak surface front or boundary, separating the differing air masses, is usually found aligned on an east-west axis across northern or central New Mexico and, in most instances, remains north of the EPZ CWA. The pressure field and the differential heating induced by the elevated terrain thus supports a prevailing southeasterly surface flow with transport of moisture from the Gulf of Mexico into the region.

In the middle and upper troposphere (Fig. 9), the Type III pattern is dominated by the westward expansion and northward shift of the subtropical ridge, with the ridge axis extending across the central Rocky Mountains into the Great Basin. Further west a slow moving or stationary trough is moving into the eastern Pacific or California, although this feature may be as far east as Arizona and Nevada. In the resultant circulation winds are mostly east to southeasterly in the middle and upper troposphere, which also favors moisture inflow from the Gulf of Mexico. The stronger thunderstorms usually occur in proximity to a weak inverted trough, located south of the ridge axis and moving to the west (a so-called "easterly wave") across the EPZ CWA. Due to the depth of the easterly wind component, forecasters must also monitor the eastern slopes of regional mountains where forcing from the sloping terrain would be especially favorable.

d. Type IV pattern

Six flash flood cases (13%) occurred with the Type IV or "westerly flow" pattern. Figure 10 depicts the typical surface conditions which, as with most other flash flood situations, includes a thermal trough through western Arizona. However, a weaker surface trough is usually aligned south or southwestward through south-central or southwestern New Mexico, with high pressure centered over the central and southern Rockies between the Arizona and New Mexico troughs. In three of the six cases, the New Mexico trough was also collocated with a dry line. To the east, the westward portions of the Bermuda high extend across southern Texas, not unlike the flash flood patterns discussed previously. Easterly and southeasterly surface winds associated with this pattern again transport Gulf of Mexico moisture into the CWA, with dewpoints above 55°F over the lower elevations. Thunderstorm initiation is more favorable along the surface trough where low-level convergence and boundary-layer forcing of upward vertical motion is strongest.

The middle and upper troposphere are characterized by a westerly or southwesterly flow across the southern Rocky Mountains, with a short-wave trough or closed low embedded in the mean flow, approaching southern New Mexico and western Texas. The quasi-geostrophic forcing (via differential positive vorticity advection) along and east of the trough axis combines with low-level forcing induced by the surface trough and orography to initiate and sustain deep convection. More organized severe weather may also accompany thunderstorms with the Type IV pattern due to relatively strong low- to mid-tropospheric wind shear and relatively dry air at midlevels.

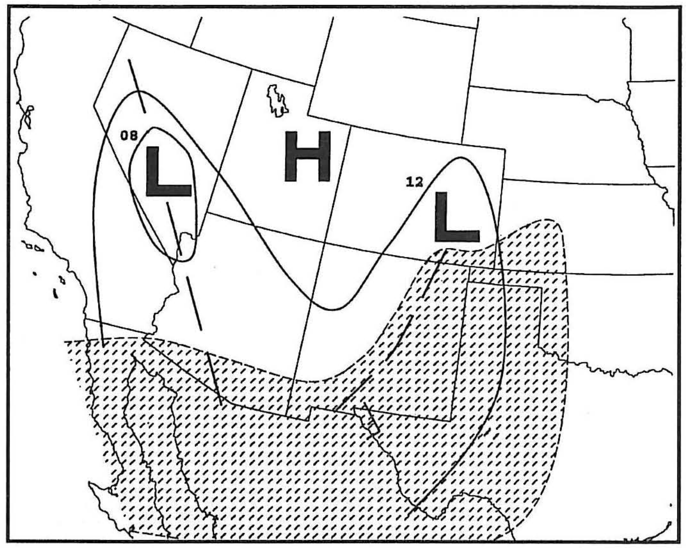

Fig. 10. Same as Fig. 4, except for a typical El Paso CWA Type IV flash flood.

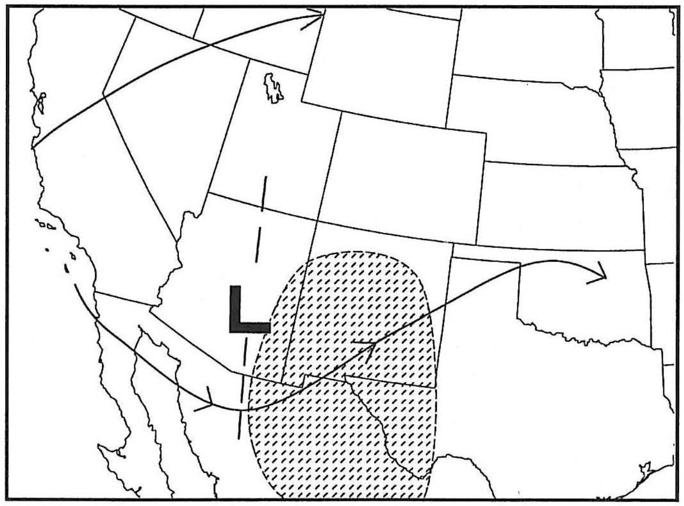

Fig. 11. Same as Fig. 7, except for a typical El Paso CWA Type IV flash flood.

6. Discussion and Conclusion

Flash flood-producing convection poses an increasing threat to both life and property across the southwestern United States, despite the region having a desert or semi-arid climate. However, forecasting heavy rains is especially difficult for this area due to the irregular terrain, the lack of data and the resultant poor performance of numerical models in determining the potential for heavy rainfall. There remains a need to determine environments conducive for flash flooding in order to assist forecasters with short-range excessive-rainfall prediction.

This study investigated flash floods over south-central and southwestern New Mexico and far western Texas for a 31-year period to determine climatological and meteorological aspects of flash floods over the region. It was determined that the overwhelming majority of cases occurred in the summer season during the afternoon and evening hours, in associated with the southwestern United States monsoon. Some common ingredients include an air mass that was usually at least moderately unstable and with a moisture content well above the climatological average; mean MUCAPES were 1500 J kg^{-1} and mean precipitable water amounts were 1.3 in. (33 mm) or 160% of normal. Cloud-layer winds were usually light (average 14 kt [7 m s^{-1}]), suggesting an environment favorable for slower moving thunderstorms with minimal entrainment.

There were four distinct meteorological patterns found conducive for flash floods over the region with common features and differences between each one. One important similarity is that for almost all of the cases studied, a thermal trough or "heat low" covered western Arizona and southwestern California, while high pressure extended over the southern Plains and/or southern Texas. This pressure configuration supports easterly or southeasterly boundary-layer winds that transport moisture into the region from the Gulf of Mexico in the lowest levels.

Storms were initiated by one or more forcing mechanisms, some of which were poorly defined and difficult to detect. One common mechanism was a stationary or slow-moving "backdoor" surface cold front that enters the region from the east or northeast. Most flash floods also occurred in advance of a weak mid-tropospheric short-wave trough approaching from the south, east or west, depending on the mid- and upper-tropospheric flow pattern. Because these features may be poorly defined or in data-void areas, close inspection of satellite images may be the only means to detect their presence. Finally, it appears at least half of all events occurred in the right-rear or left-front quadrant of an upper-tropospheric jet streak, where upward vertical motion is likely to be enhanced.

Acknowledgments

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