NOAA Technical Memorandum NESDIS 13

CHARACTERISTICS OF WESTERN REGION FLASH FLOOD EVENTS IN GOES IMAGERY AND CONVENTIONAL DATA

Satellite Applications Laboratory
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March 1986

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Environmental Satellite, Data, and Information Service

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NESDIS 11 Publications and Final Reports on Contracts and Grants, 1985. Nancy Everson (Compiler), April 1985, 14 pp. (PB85 208460/AS)

NESDIS 12 Monthly Infrared Imagery Enchancement Curves: A Tool for Nighttime Sea Fog Identification off the New England Coast. E.M. Maturi and Susan J. Holmes, May 1985, 40 pp. (PB85 237725/AS)

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CHARACTERISTICS OF WESTERN REGION FLASH FLOOD EVENTS IN GOES IMAGERY AND CONVENTIONAL DATA

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CONTENTS

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ABSTRACT. This memorandum presents characteristics of western region convective and extratropical cyclone flash flood events as observed in (VIS and IR) GOES imagery, and conventional surface and upper air data. One hundred and thirty-seven convective heavy rainfall events from 1981 through 1983 were examined and categorized into time of year, time of day of maximum precipitation, minimum cloud top temperature at time of maximum precipitation, and type of satellite observed convective system. Detailed analyses of conventional data for the largest flash flood producing mesoscale convective systems (MCS's) yielded four distinct atmospheric patterns at the surface, 700, and 500 mb levels. Twenty-four flash flood events produced by extratropical cyclones from 1981-1983 were classified into three main types of satellite observed cloud patterns. These atmospheric composites and satellite observed cloud patterns were designed to aid operational meteorologists in recognizing and forecasting flash flood events in the western region of the United States.

I. INTRODUCTION

The purpose of this paper is to present the results of a study of flash flood producing heavy rainfall events in the western region of the United States as observed in GOES satellite imagery and conventional surface and upper air data. Heavy rainfall and flash flood events produced by both deep convection and extratropical cyclones (winter storms) were studied.

Widespread areas of convection were frequently observed during the summer in the western region. However, possibly due to the sparse population density, only a few heavy rainfall reports were received for such episodes. Thus, satellite imagery provides an important data source for detecting potentially heavy rainfall producing convection. Satellite imagery is also invaluable for monitoring the evolution of intense extratropical cyclones over the eastern Pacific which pose a flash flood threat to the West Coast.

Several scientists have focused on the unique flash flood antecedent conditions in the western region. Maddox (1980) constructed detailed surface and upper air analyses for 61 western region flash flood events that occurred between 1973 and 1978 and grouped them into four categories based on similar 500 mb flow pattern characteristics (see also Augulis, 1970). Several other investigators (NOAA, 1974; Randerson, 1976; Maddox, 1977; Hoxit et al., 1980; and Carle, 1984) have examined individual heavy rainfall events. Dietrich (1979) also examined flash flood events in the western region.

This study examines a large number of heavy rainfall events using both satellite and conventional data. Brief descriptions of all flash flood events examined in this study are contained in Appendices B and C.

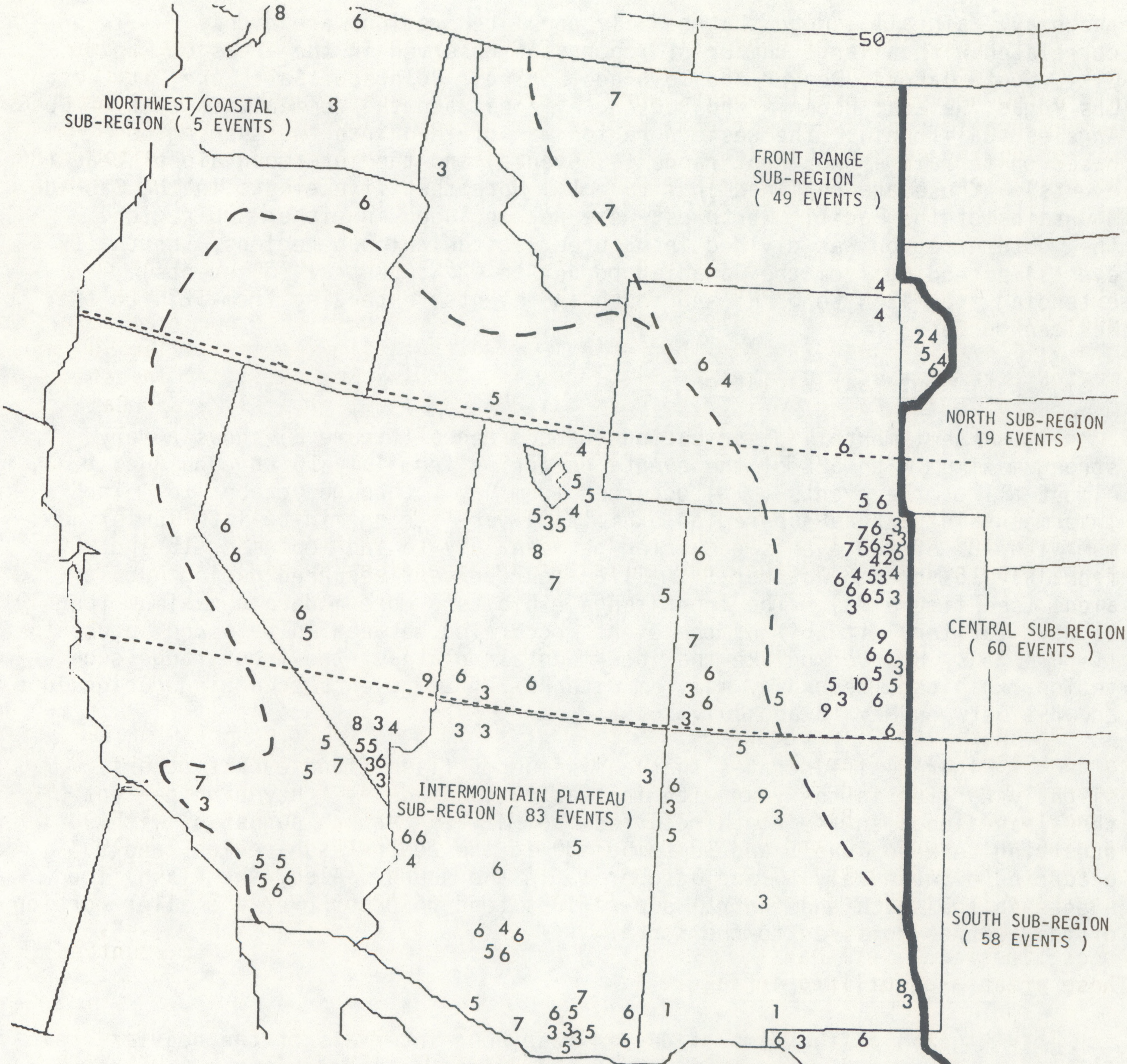
II. DATA AND METHOD OF ANALYSIS

The National Climatic Center's monthly "Storm Data" publications for 1981 through 1983 were examined for heavy rainfall and flooding reports. These reports were examined for Washington, Oregon, California, Arizona, Nevada, Utah, Idaho, Wyoming, the Black Hills region of South Dakota (Fall River, Custer, Pennington, Lawrence, and Butte counties, and the southern and western two-thirds of Meade County), the areas of Colorado and New Mexico west of 104°W longitude (west of and including the Front Range of the Rocky Mountains), and the area of Texas west of the Pecos River (consisting of Terrell, Brewster, Pecos, Presidio, Jeff Davis, Reeves, Culberson, Hudspeth, and El Paso counties). Those areas are outlined in figure 1.

Between 1981-1983, 343 reports mentioned either heavy rainfall or flooding produced by thunderstorms. Upon further examination, 206 of these events were eliminated because of one of the following: (1) brief heavy rainfall with little or no flooding but accompanied by severe weather, (2) rainfall of less than two inches causing only minor flooding, (3) general flooding due to river overflow or dam breakage (a combination of rain, snowmelt, ice jams, and/or other non-heavy precipitation causes), and (4) separate heavy rainfall events on successive days. The remaining 137 reports mentioned rainfall of two inches or more within the previous 24 hours or significant flash flooding and were selected for further study (Table 1). (In some instances two or more separate heavy rainfall reports for adjacent areas were caused by the same convective event and therefore were counted as one flash flood event).

III. RESULTS - HEAVY RAINFALL CONVECTIVE EVENTS

Figure 1 shows the 137 flash flood events plotted at their respective locations according to the type of satellite observed convective system which produced



MAP NUMBER	TYPE OF SYSTEM	NUMBER OF CASES
1	SYNOPTIC SCALE TROPICAL	2
2	SQUALL LINE	2
3	SINGLE CLUSTERED	28
4	MCS-α	13
5	MCS-β CIRCULAR	32
6	MCS-β LINEAR	41
7	SYNOPTIC SCALE CYCLONIC CIRCULATION	10
8	LARGE SCALE OVERRUNNING	4
9	REGENERATIVE	4
10	COMBINATION OF TWO OR MORE SYSTEMS PASSING OVER THE SAME AREA WITHIN 24 HOURS	1

Figure 1. Map of location and type of system for the 137 heavy rainfall convective events in this study.

the heavy rainfall. Note that heavily populated regions are highly correlated with a large number of reports as observed in the areas of Rapid City, South Dakota; Denver and Colorado Springs, Colorado; Salt Lake City, Utah; Las Vegas, Nevada; Phoenix and Tucson, Arizona; and the communities east of Los Angeles, California. The western region was divided into two sub-regions based on terrain - the front range (49 events) and the intermountain plateau (83 events) - these are outlined in figure 1. Note that five events in the Cascade Mountains of the Pacific Northwest were not included in either sub-region. The western region was divided into three latitudinal sub-regions: north (19 events) extending from the Canadian border to 42°N; central (60 events) extending from 42°N to 37°N; and south (58 events) extending from 37°N to the Mexican border.

A. Time of Year Variation

A semi-monthly distribution of occurrence (figure 2) shows a very strong maximum with 62% of the events occurring from July 16 through August 31. Almost all of the events (97%) occurred from May 1 through October 15. The intermountain plateau sub-region exhibits a very strong mid-to-late summer maximum with 78% of the events occurring between July 16 and September 15 and 95% from July 16 through October 15. Fifty-four percent occurred during August alone (see figure 3a). The front range exhibits a more moderate maximum roughly 15 days earlier, with 54% of the events occurring between July 16 and August 15 (figure 3b). However unlike the intermountain plateau, the front range sub-region exhibits a secondary maximum with 24% of the events occurring during June and 39% between May 16 and July 15.

Figure 4 illustrates that a maximum of flash flood events occurs slightly earlier in the year with increasing latitude. Eighty-nine percent of the flash floods in the north occurred from May 16 through August 31 with 98% occurring between June 1 and September 30 in the central sub-region, and 95% occurring between July 16 and October 15 in the south. Also, the flash flood events in the south and central sub-regions tend to occur over a smaller portion of the year as compared to the north.

B. Time of Day Variation

A graph of the time of day in four hour intervals of the heaviest rainfall (figure 5a) indicates that 58% of the events occurred between 4:00 p.m. and 8:00 p.m. local daylight time (LDT). Six hour interval statistics (figure 5b) show that 72% of the events occurred from 2:00 p.m. through 8:00 p.m. LDT.

The front range sub-region exhibited a sharper afternoon-early evening peak with 80% of the events occurring between 2:00 p.m. and 8:00 p.m. LDT and only 6% from 2:00 a.m. through 2:00 p.m. LDT (figure 6a). This is compared with 69% from 2:00 p.m. through 8:00 p.m. and 18% from 2:00 a.m. through 2:00 p.m. in the intermountain plateau sub-region. All three latitudinal sub-regions exhibit a 2:00 p.m.-8:00 p.m. LDT maximum which is sharpest in the central sub-region (85%) as compared with 58% in the north and 64% in the south sub-region (figure 6b).

Table 1

Storm Data Reports	Number of Reports
All reports which mention rainfall or flooding from deep convective systems	343
Reports mentioning very heavy rainfall ($\geq$2 inches) or significant flash flooding (selected for further study)	137
Reports not studied further due to mentioning of:	206
1) Brief heavy rain with little or no flooding, usually accompanied by severe weather	107
2) Rainfall of less than two inches, causing only minor local/urban flooding	61
3) River overflow or dam breakage causing general flooding (due to a combination of rain, snowmelt, ice jams and/or other non-heavy rainfall causes)	28
4) Several separate heavy rainfall events on successive days causing flooding	10

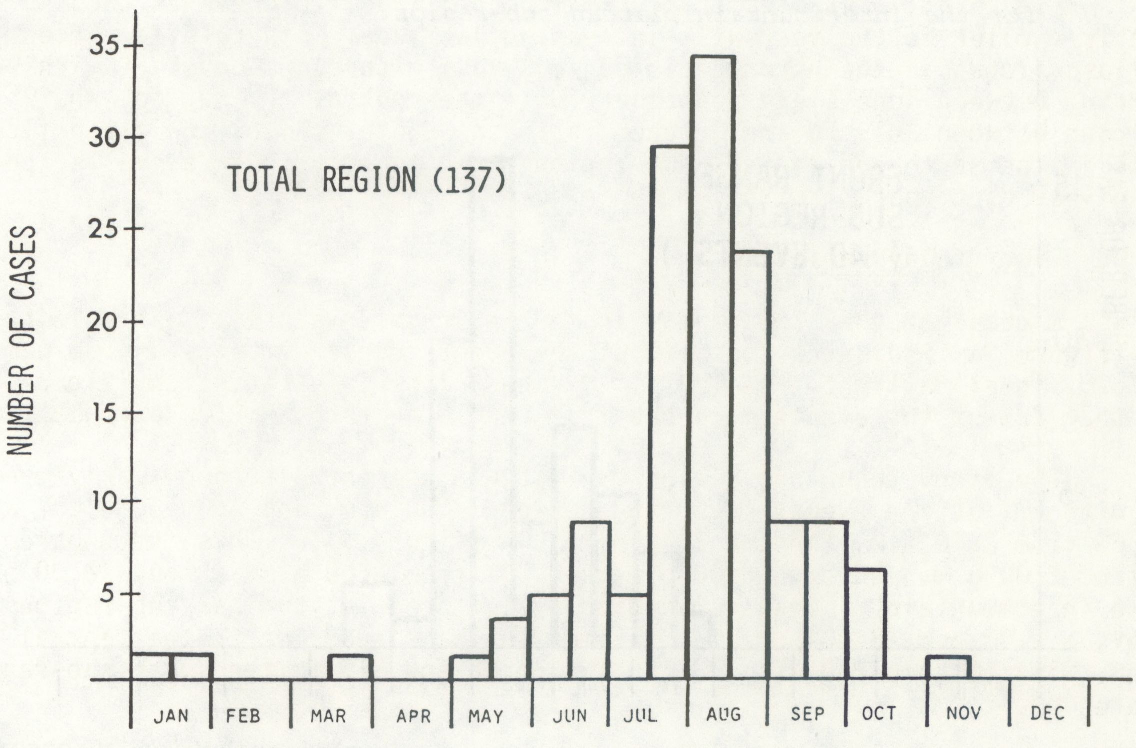


Figure 2. Histogram of the semi-monthly time of year distribution of occurrence for the western region.

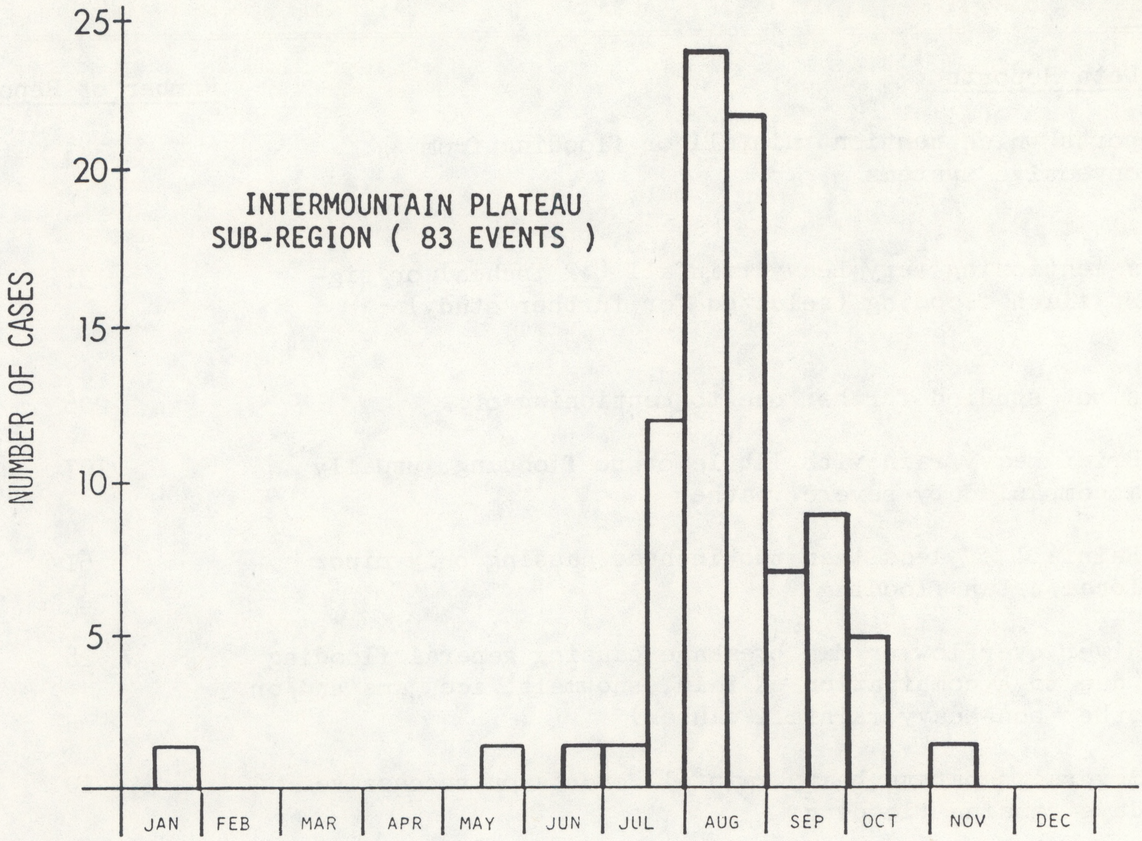


Figure 3a. Histogram of the semi-monthly time of year distribution of occurrence for the intermountain plateau sub-region.

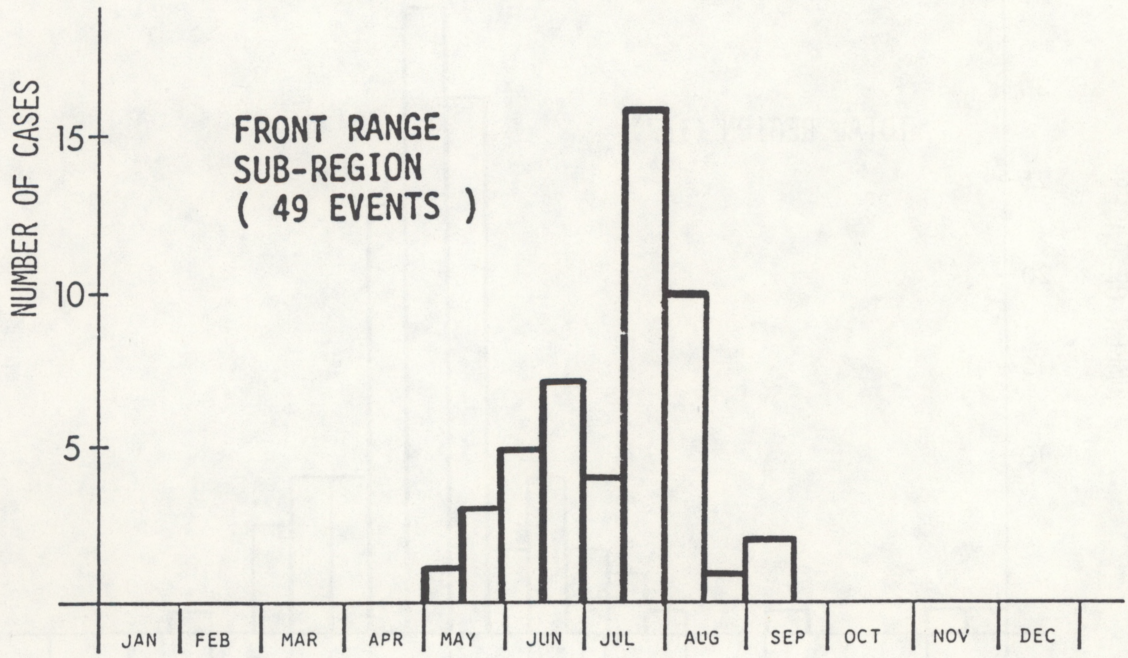


Figure 3b. Histogram of the semi-monthly time of year distribution of occurrence for the front range sub-region.

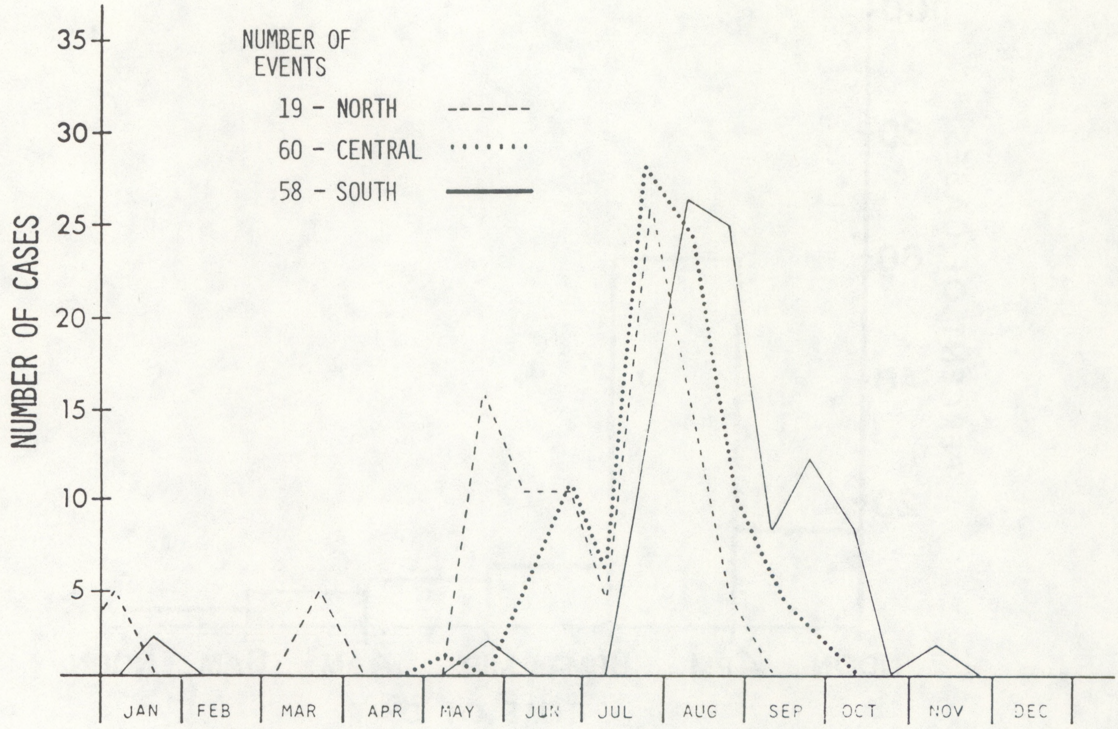


Figure 4. Graph of the semi-monthly time of year distribution of occurrence for the north, central, and south sub-regions.

C. Minimum Cloud Top Temperatures

GOES infrared imagery was examined for each event to determine the minimum cloud top temperature of the thunderstorm complex during the period of heaviest rainfall. The infrared images were enhanced with the Mb curve; gray shades and corresponding temperatures are shown in figure 7. The dark gray shade (-52°C to -58°C) was the most frequently observed minimum cloud top temperature (27% of the total). Scofield and Oliver (1977, 1980) empirically associated heavy rainfall with cold (colder than -62°C) cloud top temperatures. Scofield et al. (1980) determined that heavy rainfall rates may be expected with warm (warmer than -62°C) cloud tops when cloud top temperatures observed from satellite data are equal to or colder than the expected temperature of the convective tops (equilibrium level) computed from the nearest sounding. This generally occurs with an extremely low tropopause or a relatively stable layer beneath the tropopause capping the convection at a relatively warm temperature.

In this study, only 26% of all 137 heavy rainfall events had cold cloud top temperatures with 74% caused by warm-topped convection. The intermountain plateau and front range sub-regions exhibited no differences in minimum cloud top temperatures. The latitudinal sub-divisions revealed only slight differences, with the south having slightly more cold-topped convection (31%) than the central (22%) or north (26%) (table 2).

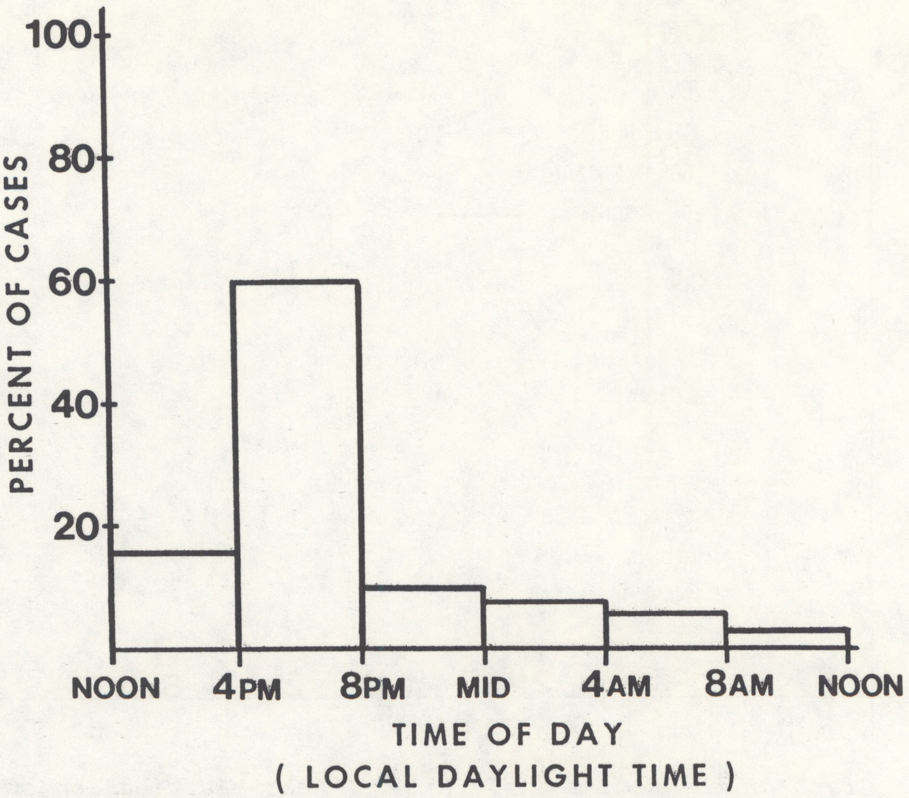


Figure 5a. Histogram of time of day occurrence in four hourly intervals for the western region.

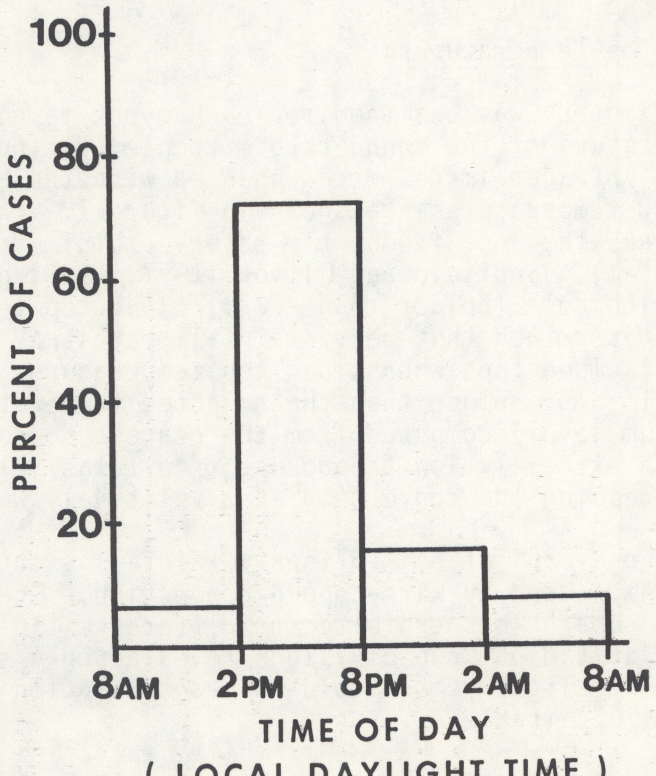


Figure 5b. Histogram of time of day occurrence in six hourly intervals for the western region.

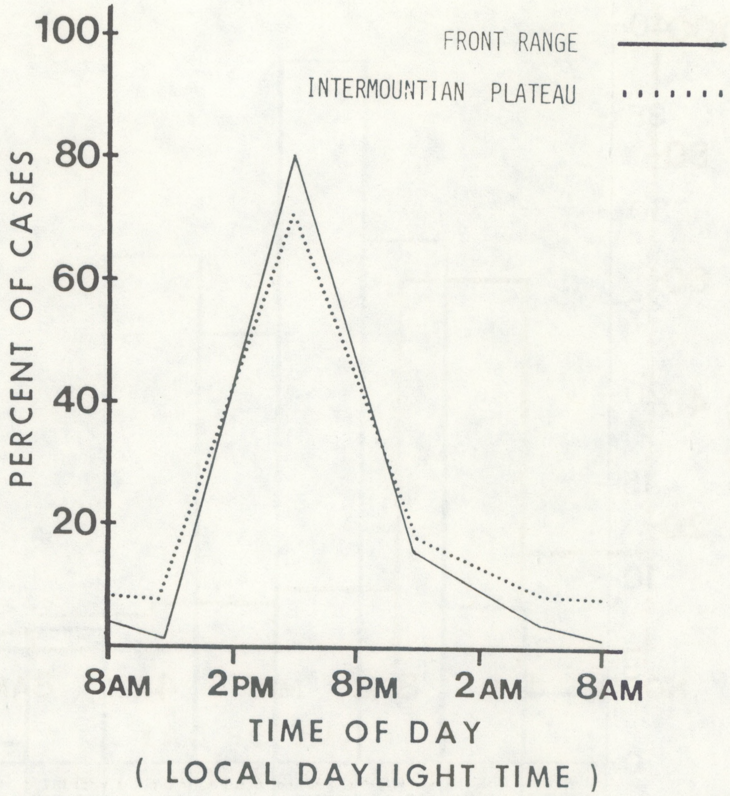


Figure 6a. Graph of time of day occurrence for the front range and intermountain plateau sub-regions.

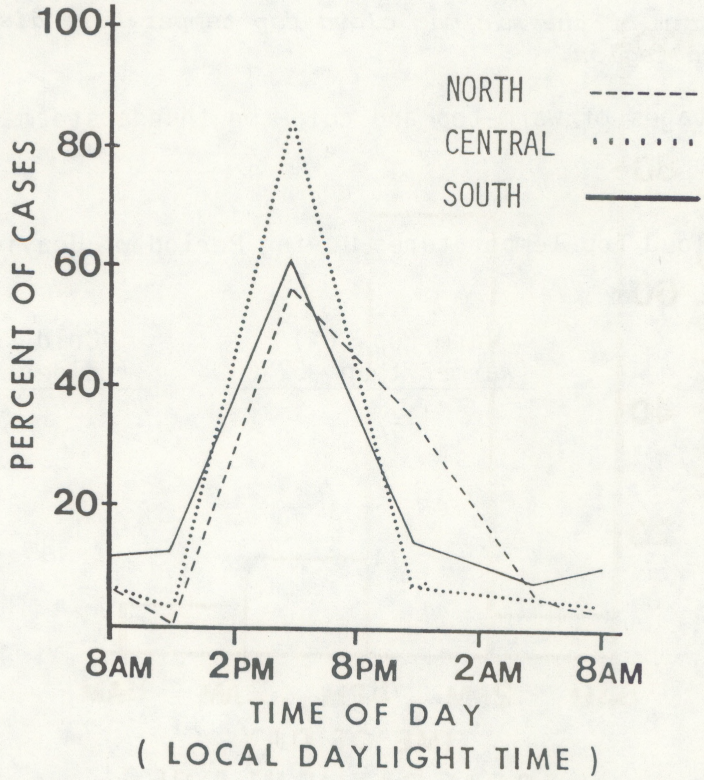


Figure 6b. Graph of the time of day occurrence for the north, central, and south sub-regions.

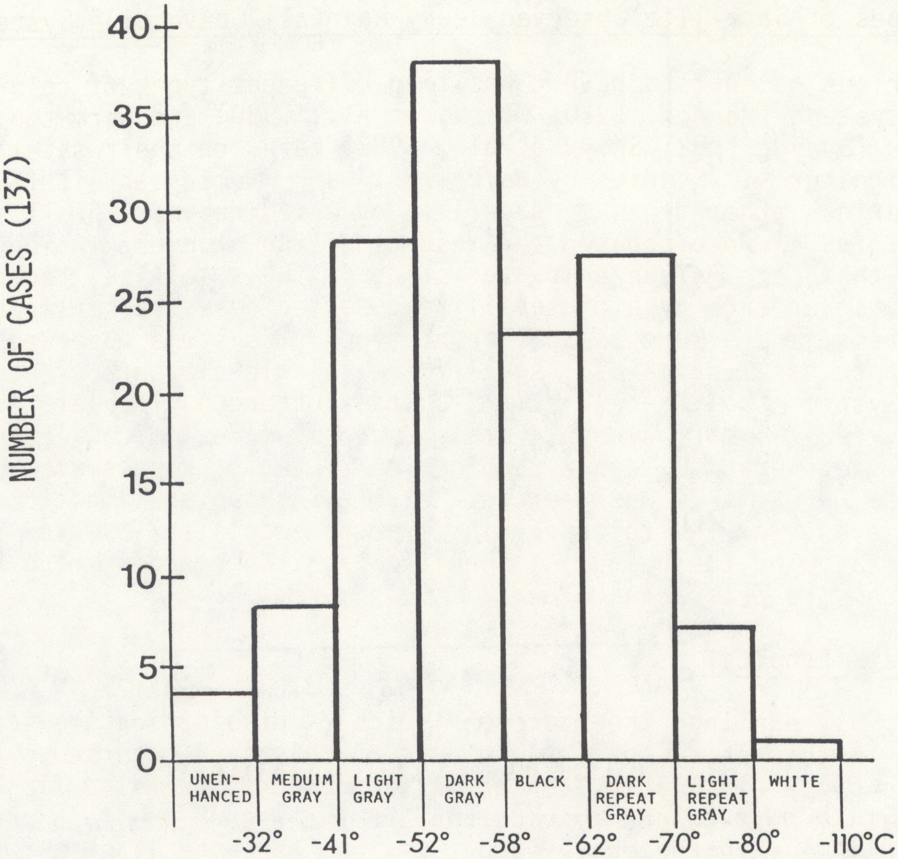


Figure 7. Histogram of the minimum cloud top temperature distribution for the western region.

Table 2. Percentages of warm-top and cold-top thunderstorms observed in this study.

Minimum Cloud Top Temperatures During Period of Heaviest Rainfall

Region	Warm Tops (%) (warmer than -62°C)	Cold Tops (%) (colder than -62°C)
Entire Region (137 events)	74	26
North Region (19 events)	74	26
Central Region (58 events)	78	22
South Region (60 events)	69	31

D. Types of Satellite Observed Heavy Rainfall Convective Systems

Various scientists have classified different types of cold-topped convective systems (Maddox, 1980; Clark, et al., 1980) and warm-topped convective systems (Spayd, 1982; Spayd et al., 1983) based on their satellite observed cloud top signatures. Studies by Ward (1981) and Fleming et al. (1984) have described various other types of satellite observed heavy rainfall systems. Spayd et al. (1984) incorporated the results of the studies mentioned above and showed that there are unique characteristics in the satellite, radar, and conventional data for each type of satellite observed heavy rainfall producing convective system. There were ten different types of systems observed in this study: synoptic scale tropical, squall line, single clustered, Mesoscale Convective System - α (MCS-α), MCS-β (multi-clustered) circular, MCS-β (multi-clustered) linear, synoptic scale cyclonic circulation, large scale overrunning, regenerative, and a combination of two or more systems passing over the same area during a 24 hour period. Figure 1 shows the location of each flash flood event and the corresponding type of satellite observed convective system (indicated by the number). Specific details regarding each type of convective system are presented below.

Synoptic Scale Tropical

Ward (1981) examined the characteristics of dissipating tropical cyclones over land. In this study, only two events of this type occurred. In one case, a tropical cyclone circulation center passed directly over the flash flood area producing mainly warm-topped convection. In the second event, a tropical cyclone induced a moist upper-level jet maximum over the flash flood area triggering quasi-stationary (mainly cold-topped) convective clusters which regenerated for several days. Both events occurred during the last week of September (different years). In figure 8, the remnants of Hurricane Paul passed over El Paso, Texas and southern New Mexico (A) and produced up to five inches of rain and caused considerable flooding on September 30, 1982. This type of heavy rainfall system is rare but very important for operational meteorologists in the western region.

Squall Line

There were only two events of flash flood producing squall lines in the western region from 1981 through 1983. Both events occurred between 6:30 and 9:00 p.m. LDT. Fleming et al. (1984) constructed composites of the atmospheric soundings and surface, 850, and 500 mb analyses for 12 heavy rainfall producing squall lines in the eastern region. Figure 9 shows a small warm-topped squall line (B) which produced 5.1 inches of rain in 45 minutes accompanied by severe weather over southern Weld County (Keenesburg) in Colorado on May 4, 1981.

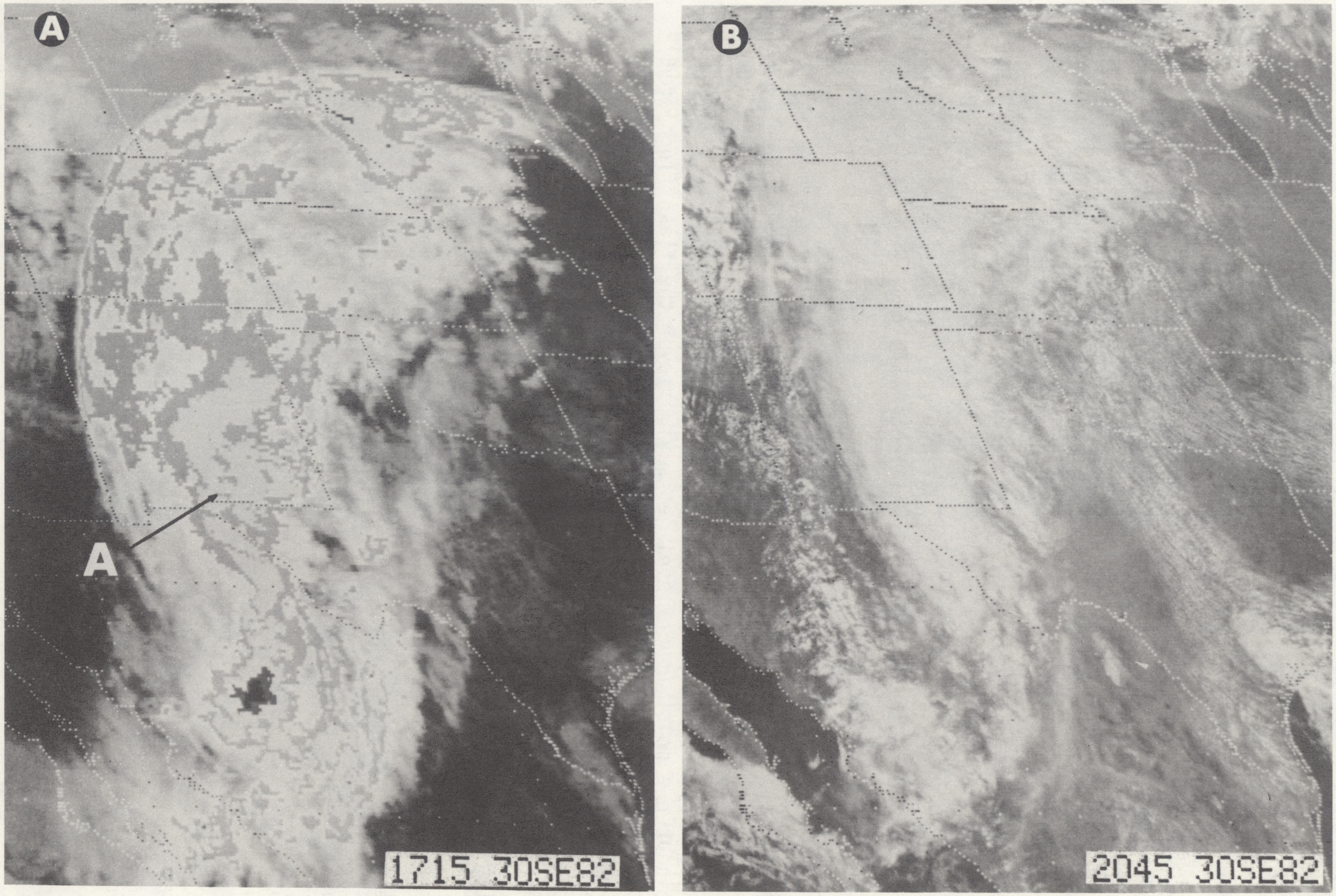


Figure 8. Enhanced IR image (A) (Mb curve) at 1715 GMT and visible image (B) at 2045 GMT on September 30, 1982. The letter A points to the heavy rainfall area in southern New Mexico.

Single-Clustered

Single-clustered convective systems (investigated by Spayd and Scofield, 1983) appear as very small round, oval, or carrot shaped cloud tops in the satellite imagery and comprised 21% (28 events) of the western region convective flash flood events from 1981 through 1983. Single clustered systems are highly correlated with local terrain effects and solar heating as 75% of the events occurred between 2:00 and 7:30 p.m. Local Daylight Time. Twenty-five (89%) of the single clustered events occurred between July 16 and August 31. This type of system exhibited preferred areas of formation with 18 events (64%) occurring south of 38°N in the intermountain plateau sub-region, and seven events (25%) occurring along the Colorado front range (see figure 1). All single clustered events in this study were observed to have warm ($\geq$ -62°C) cloud top temperatures with dark gray (-52°C to -58°C) being the most common gray shade.

A single clustered thunderstorm (C) with cloud top temperatures between -52°C and -58°C formed over the mountains just east of Tucson, Arizona causing severe flash flooding at Tanque Verde Falls on July 26, 1981 (figure 10). A 15 foot high wall of water rushed down the canyon and over the 100 foot waterfalls killing eight people.

A single clustered thunderstorm (D) with cloud top temperatures of -58°C to -62°C occurred near Montrose, Colorado on July 28, 1982 (figure 11) and produced 2.5 inches of rain in 45 minutes causing the areas worst flooding in 70 years. Many bridges were washed out and farms damaged (estimated $500,000 damage). Widespread convection is observed across the western region on this day as major flash flooding was also reported in Boulder, Colorado (Single Clustered System at E), Colorado Springs and Pueblo, Colorado (MCS-β circular system at F), and in the North Portal area of Freemont County in Wyoming (MCS-β linear system at G).

Mesoscale Convective Systems (MCS's)

Using enhanced infrared satellite imagery, Maddox (1980) defined Mesoscale Convective Complexes (MCC's) as having a contiguous cold cloud shield with an infrared black body temperature (T_{BB}) colder than -32°C over an area of at least 100,000 km^2, and an interior cold cloud region with T_{BB} colder than -52°C over an area of at least 50,000 km^2. This satisfies meso- scale size criteria (length scales of 250-2500 km). In addition, both these size definitions must be satisfied for at least six hours, and the cold cloud shield at time of maximum extent must have an eccentricity (minor axis/major axis) of at least 0.7. Although these MCC's are important entities for midwest summertime rainfall, no convective systems producing flash floods which met all these criteria were observed in the western region between 1981 and 1983. However, smaller and shorter-lived convective systems (which did not satisfy one or more of these criteria) comprised 63% (86 events) of the heavy rainfall convective events of this study. These are referred to as Mesoscale Convective Systems (MCS's) and were divided up into two subgroups based on their size and duration, MCS-α and MCS-β .

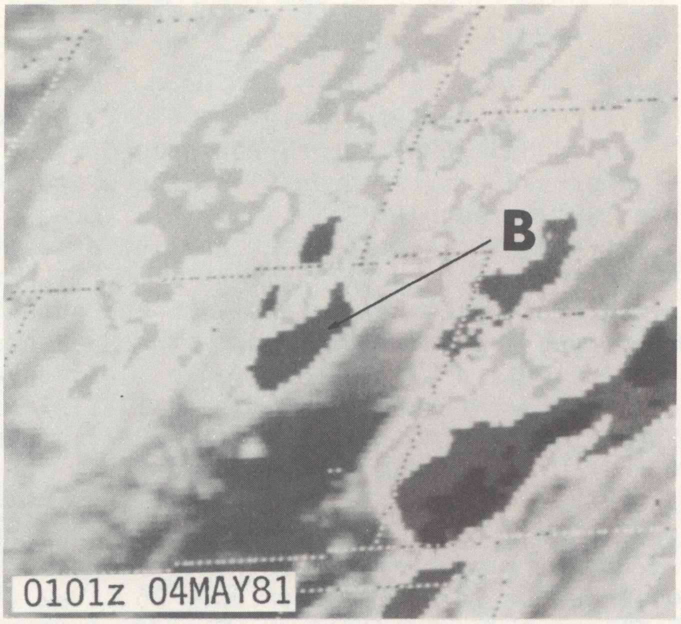


Figure 9. Enhanced IR image (Mb curve) at 0100 GMT on May 4, 1981. The letter B points to the squall line in southern Weld County, Colorado.

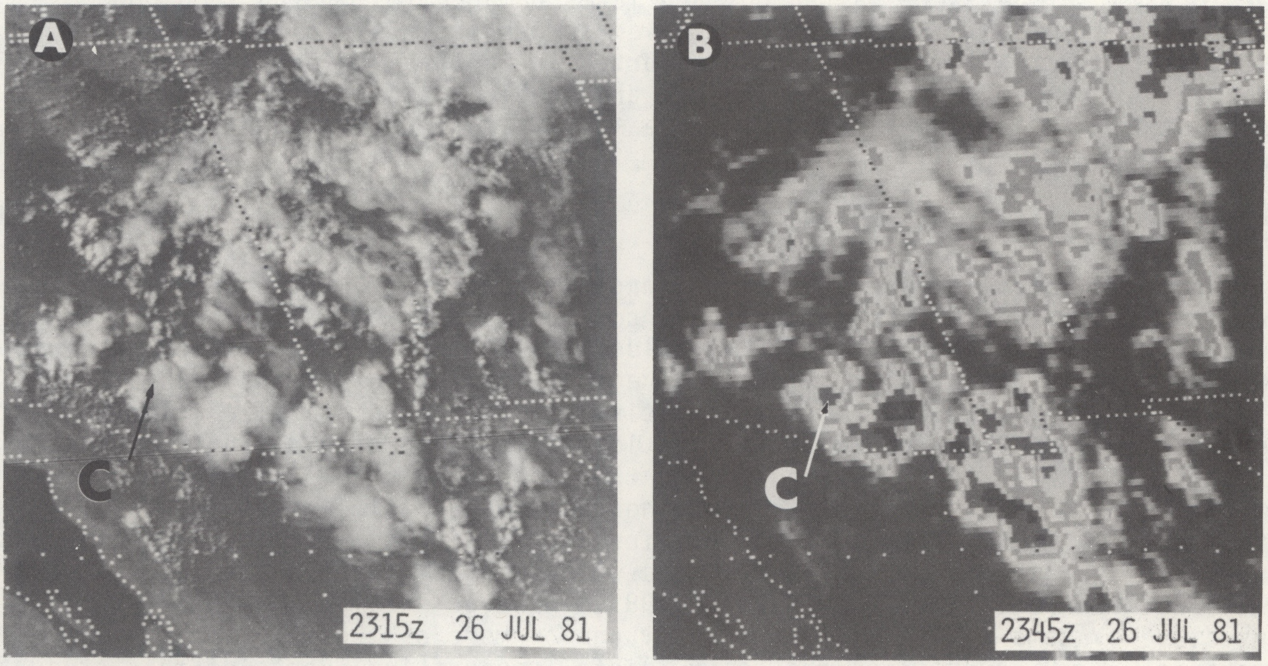


Figure 10. Visible image (A) at 2315 GMT and enhanced IR image (B) (Mb curve) at 2345 GMT on July 26, 1981. The letter C points to the single clustered thunderstorm over Tanque Verde Falls, Arizona.

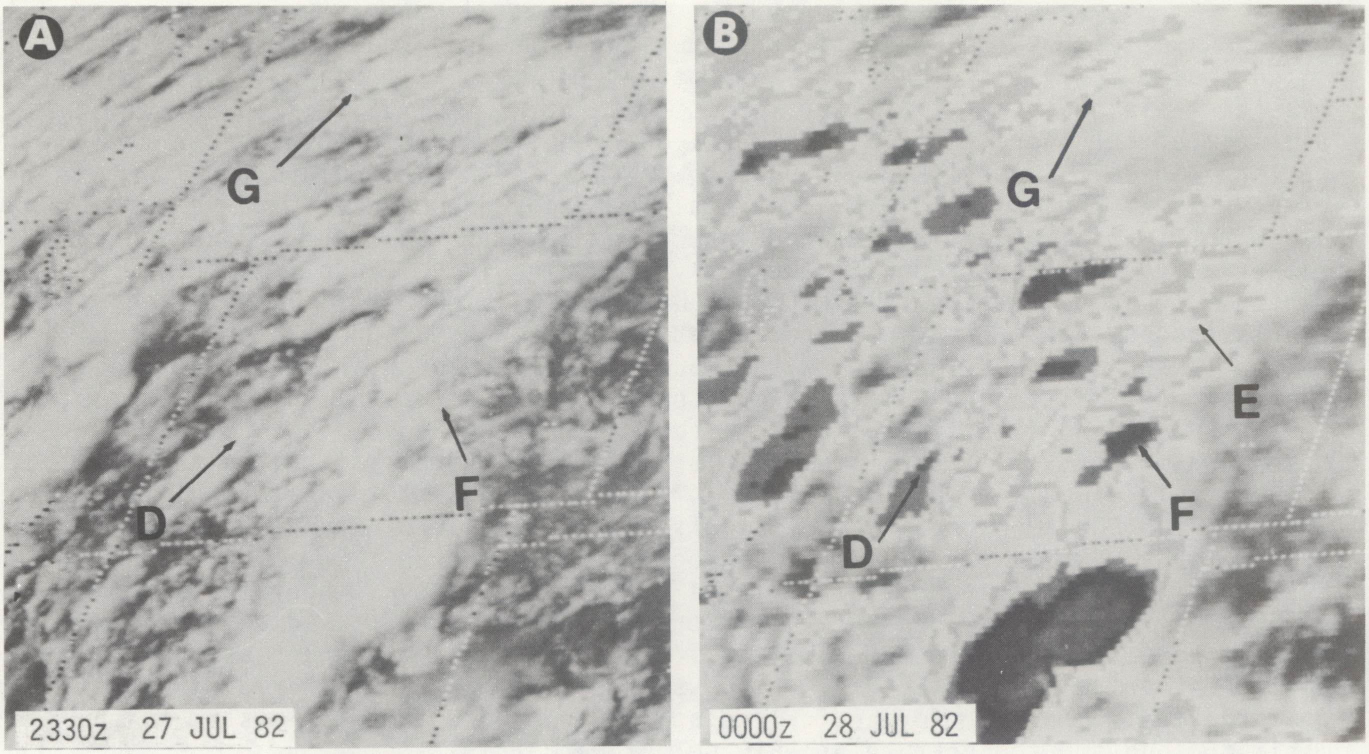


Figure 11. Visible image (A) at 2330 GMT on July 27, 1982 and enhanced IR image (Mb curve) at 0000 GMT on July 28, 1982. The letters D, E, F, and G refer to thunderstorms at Montrose, Boulder and Colorado Springs, Colorado and North Portal, Wyoming, respectively.

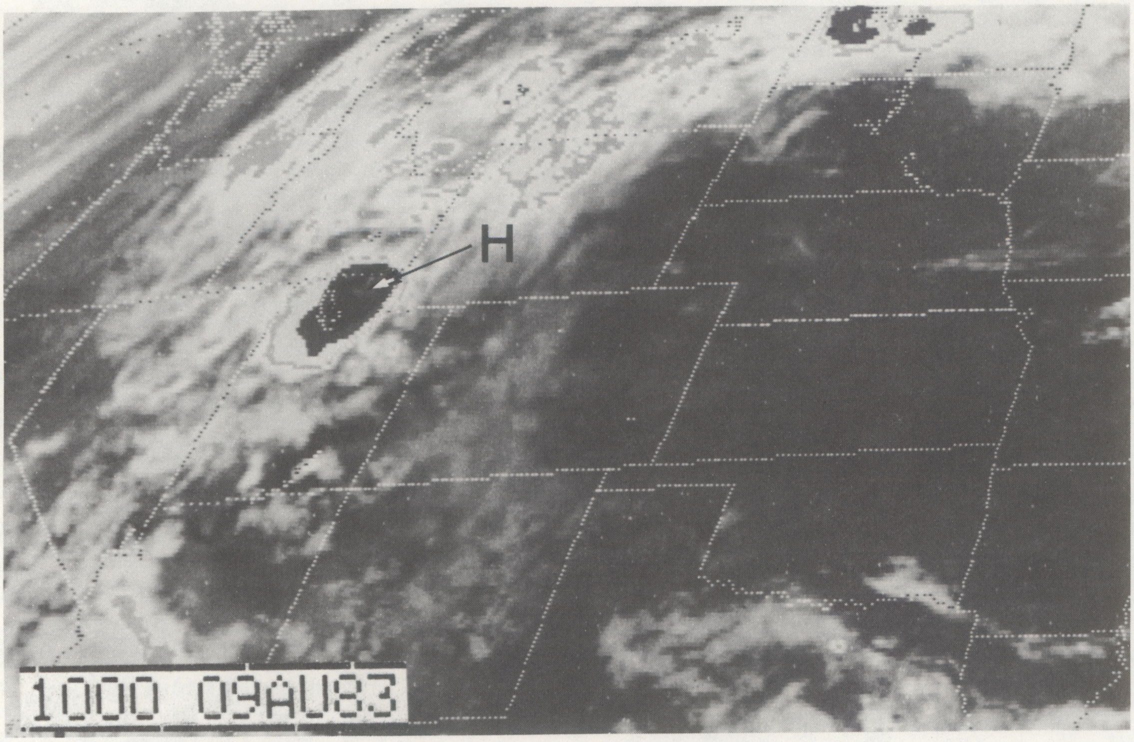


Figure 12. Enhanced IR image (Mb curve) at 1000 GMT on August 9, 1983. The letter H points to a MCS- α over Cache County, Utah.

MCS-α systems are convective clusters which nearly reach the MCC criteria cited above. They either meet one or both of the size criteria but for a period less than six hours, or they last for at least six hours but fail to satisfy both size criteria. There were 13 such MCS-α convective systems observed in the western region between 1981 and 1983, of which 10 (77%) had cold cloud top temperatures ($\leq$-62°C). All of these events occurred between June 1 and September 30, with 11 (85%) occurring between June 1 and August 15. Eight events occurred either along the front range of the Rocky Mountains in Colorado, Wyoming, and Montana, or in the Black Hills of South Dakota (see figure 1). Ten (77%) of the events produced their heaviest precipitation between 4:30 and 7:30 p.m. LDT. Figure 12 shows an MCS- system with cloud top temperatures in the light repeat gray range (-70°C to -80°C) over Cache County in northern Utah (H) on August 9, 1983. Subsequent flash flooding occurred in the Green Canyon area damaging homes and the city's water system. This convective system maintained a contiguous cold cloud shield ($T_{BB} \leq$-32°C) of 50,000-75,000 km^2 (substantially less than the 100,000 km^2 required to satisfy MCC criteria) for 6 to 7 hours before dissipating. Figure 13 illustrates a second example of an MCS-α system on September 29, 1983 over Phoenix, Arizona (I) with cloud top temperatures between -62°C and -70°C (repeat dark gray). Extremely heavy rains caused extensive urban flash flooding with numerous traffic accidents and one underpass was filled with nine feet of water. This system satisfied MCC size criteria for only one to two hours before quickly dissipating. Note that the system reached minimum cloud top temperature at 1515 GMT (figure 13).

MCS-β thunderstorm clusters have length scales of 50 to 150 km and comprised 53% (73 events) of the convective flash flood events in this study. Spayd and Scofield (1984) defined these as multi-clustered systems and divided them into two subgroups (circular and linear) based on the shape of the cloud tops as observed in satellite imagery.

MCS-β circular system (see Spayd and Scofield, 1983) develop in environments with little or no vertical wind shear and appear as round or oval cloud tops in the satellite imagery. There were 32 such events (23% of the total) observed in this study. All events occurred between June 16 and September 15 with 27 events (84%) occurring from July 16 through August 31. Ninety-four percent (30 events) of the MCS-β circular systems occurred between 2:00 p.m. and 8:00 p.m. local daylight time. Minimum cloud top temperatures in the light gray, dark gray, and black ranges comprised 56% of the events, while the remaining 44% were cold-topped ($\leq$-62°C). Five of the ten heavy rainfall events in Southern California were MCS-β circular systems. No other regional correlations were observed.

On August 5, 1983 a MCS-β circular convective system (cloud top temperatures of -70°C to -80°C) dropped 2.89 inches of rain in 38 minutes over southeast Denver (J in figure 14) causing widespread street flooding. On August 18, 1983 three separate MCS-β circular systems produced flash floods (figure 15). Salt Lake County, Utah (point K) was deluged by 1.2 inches of rain in 20 minutes washing out several roads and blocking an underpass with four feet of water. A warm topped (-52°C to -58°C) MCS-β circular system produced one inch of rain in one hour near the Tehachapi Mountains (Kern County) in Southern

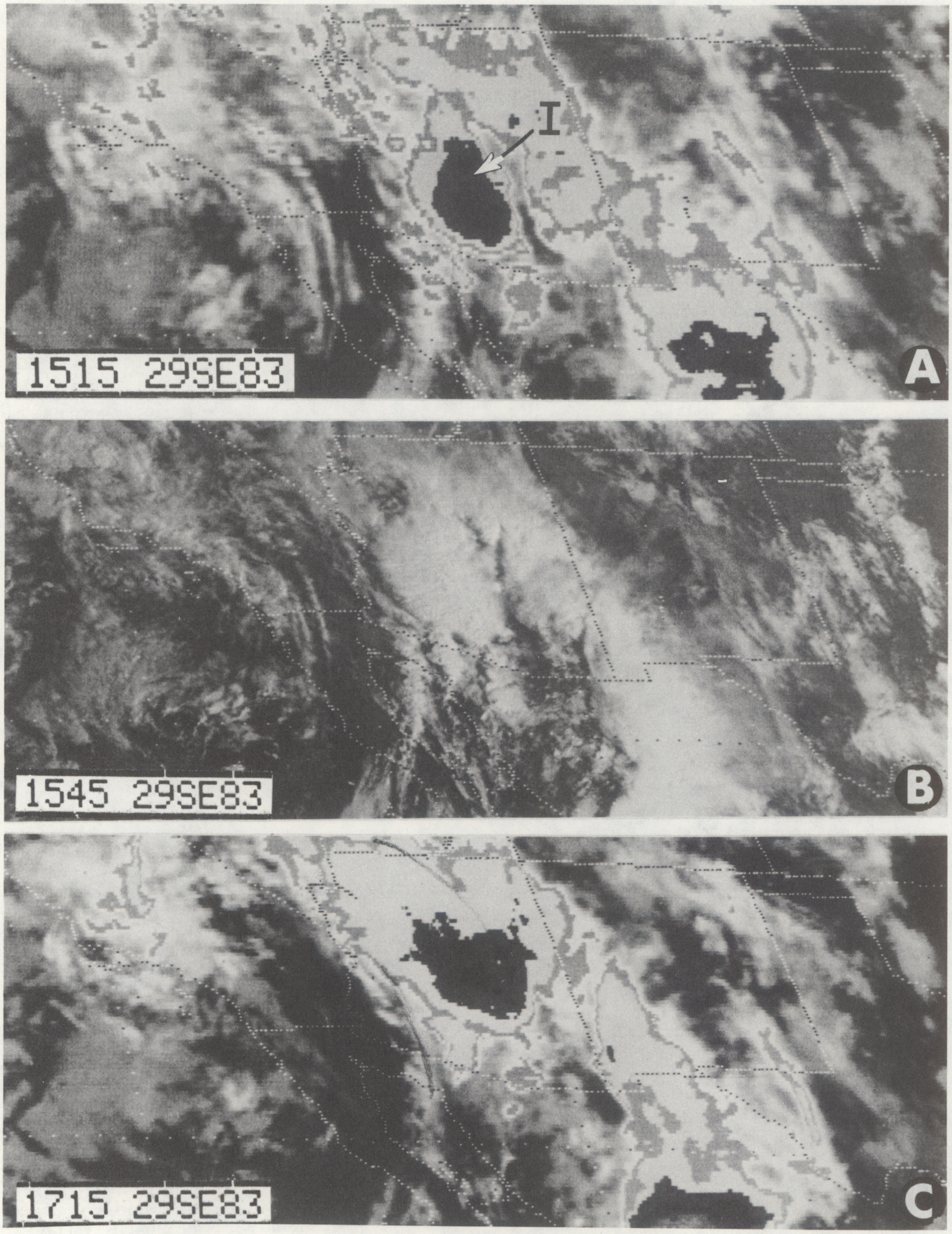


Figure 13. *Enhanced IR images (Mb curve) at 1515 GMT (A) and 1715 GMT (C) and a visible image at 1545 GMT (B) on September 29, 1983. The letter I refers to a MCS-α over Phoenix, Arizona.*

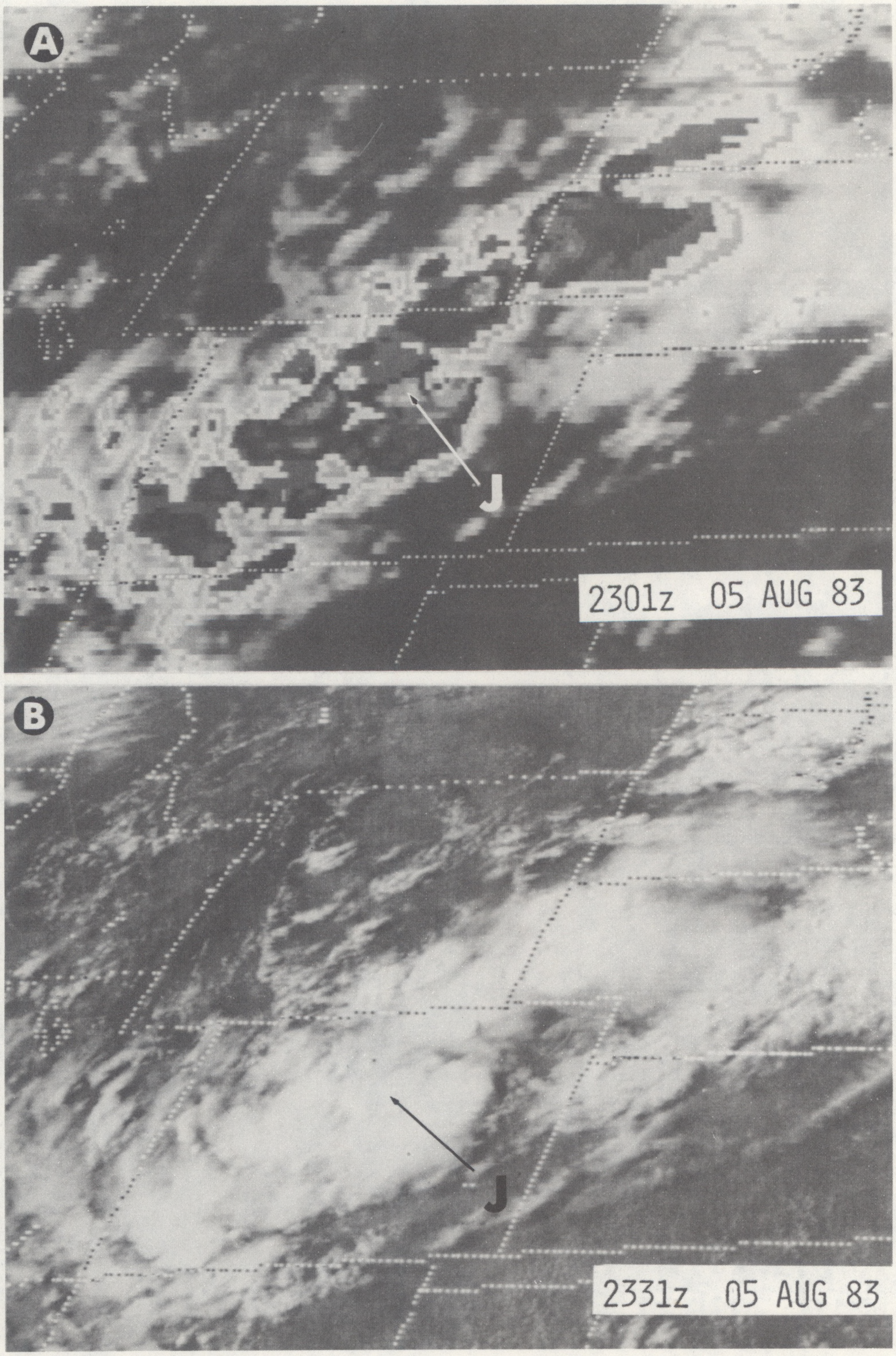


Figure 14. *Enhanced IR image (A) (Mb curve) at 2300 GMT and visible image (B) at 2330 GMT on August 5, 1983. The letter J points to a circular MCS-β over Denver, Colorado.*

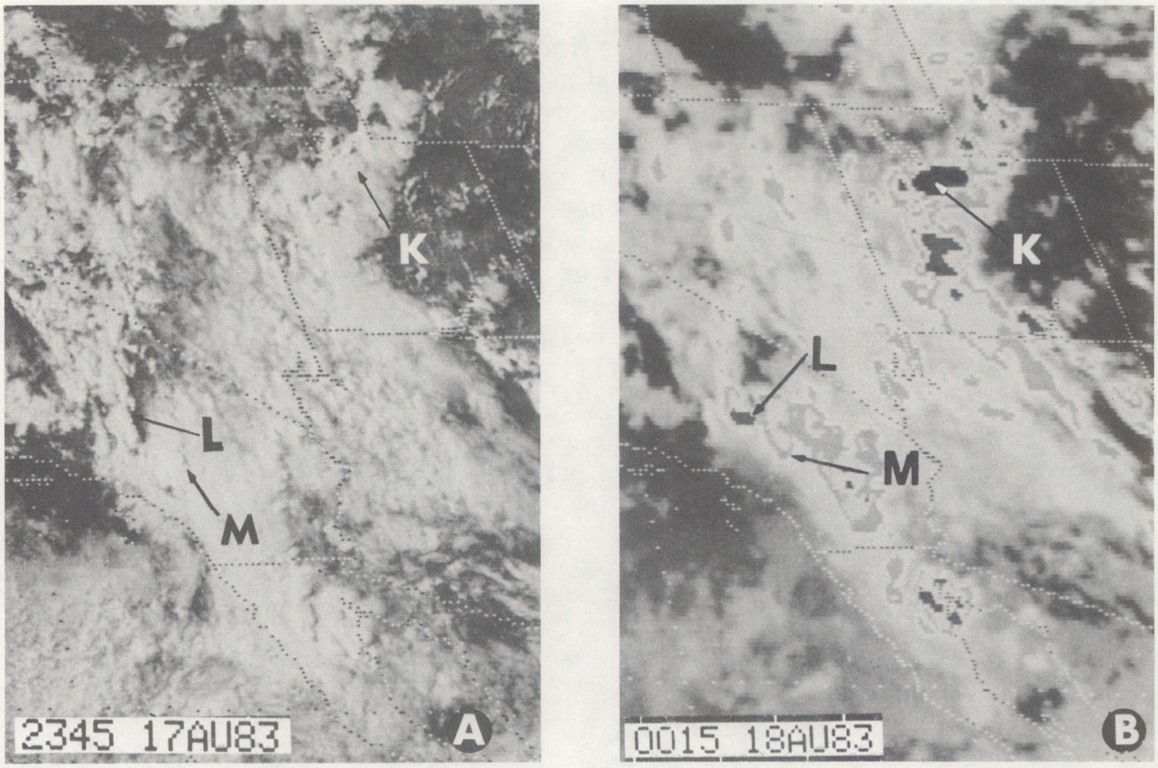


Figure 15. Visible image (A) at 2345 GMT August 17, 1983 and enhanced IR image (B) (Mb curve) at 0015 GMT on August 18, 1983. The letters K, L, M refers to a circular MCS- β over Salt Lake County, Utah and Kern County and San Bernardino, California, respectively.

California (L). Subsequent creek flooding produced water as high as car windows. A third multi-clustered circular heavy rainfall event occurred in San Bernardino, California (M) as considerable urban flooding stranded thousands of motorists.

MCS- β linear systems (see Clark et al., 1980; and Spayd and Scofield, 1983) which occur in environments with strong vertical wind shear appear as small wedge, carrot, or diamond shaped in satellite imagery. Thirty percent (41 events) of the western region convective flash flood events were MCS-linear systems making it the most common type of system observed in this study. All events occurred from May 16 through October 15 with 88% occurring between June 20 and September 30. Sixty-eight percent (28 events) had maximum rainfall between 2:00 p.m. and 8:00 p.m. LDT and all events occurred between 2:00 p.m. and 3:30 a.m. LDT. Convection with cloud top temperatures of -41°C to -61°C (warm topped) occurred in 76% of the cases with the remaining 24% observed to have minimum cloud top temperatures of between -62°C and -79°C.

Figure 16 shows a warm topped (light gray shade) MCS-β linear convective system which produced almost five inches of rain in less than two hours at Hemet (near Riverside), California (N) on September 8, 1981. Many people were rescued from cars trapped in up to four feet of water and many homes were damaged from mud and collapsing roofs.

On September 23, 1983 a MCS-β linear system occurred at Prescott, Arizona (O in figure 17). This isolated nocturnal cluster was observed to have rapid growth and remained quasi-stationary over the Prescott area as three to eight inches of rain fell. Considerable flash flooding of creeks and streets followed, with many cars swept into streams. Sixty persons were evacuated and total damage was estimated at $2.75 million.

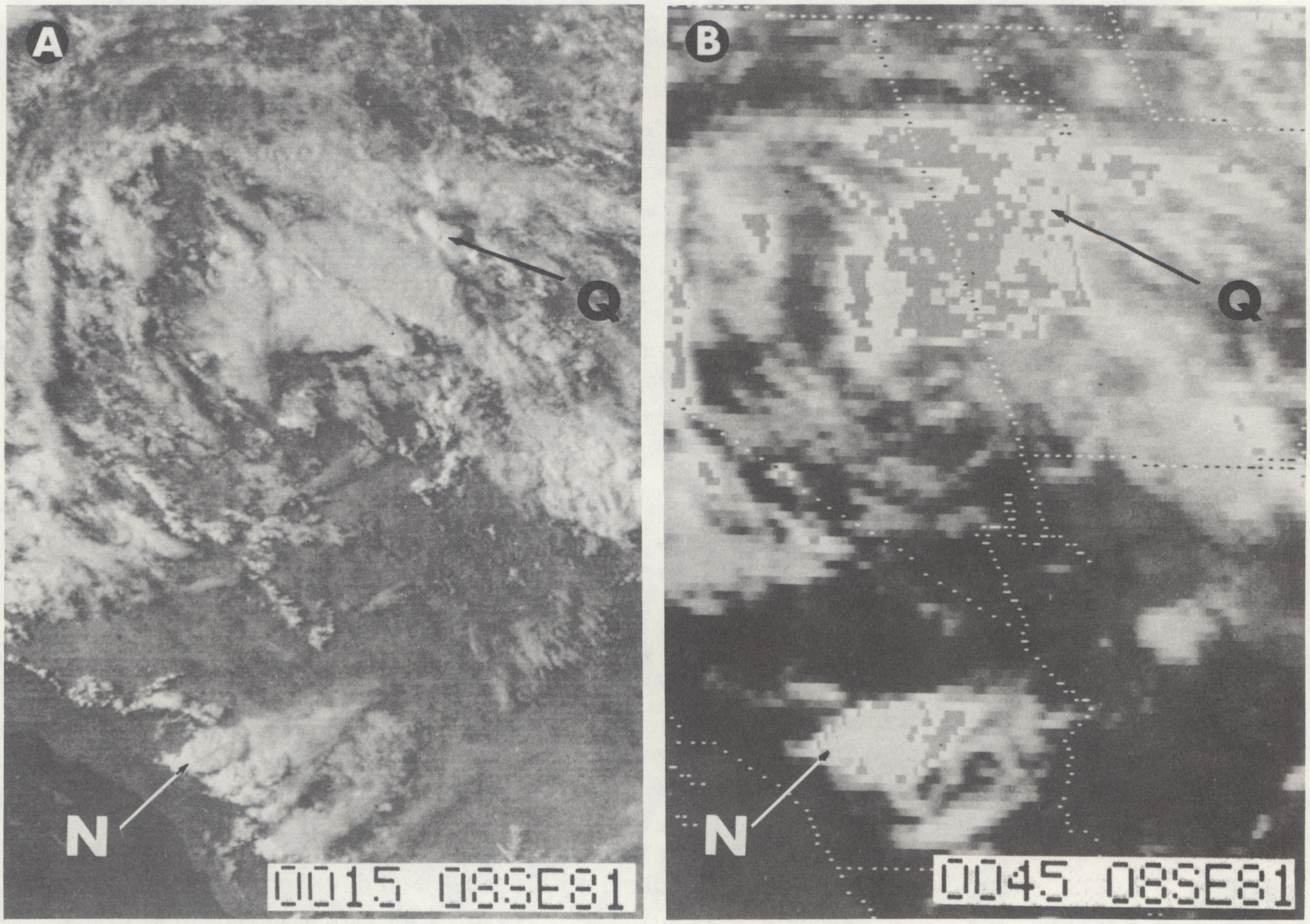


Figure 16. Visible image (A) at 0015 GMT and enhanced IR image (B) (Mb curve) at 0045 GMT on September 8, 1981. The letter N refers to a linear MCS- over Hemet, California and the letter Q refers to thunderstorms embedded in a synoptic scale cyclonic circulation over Juob County, Utah.

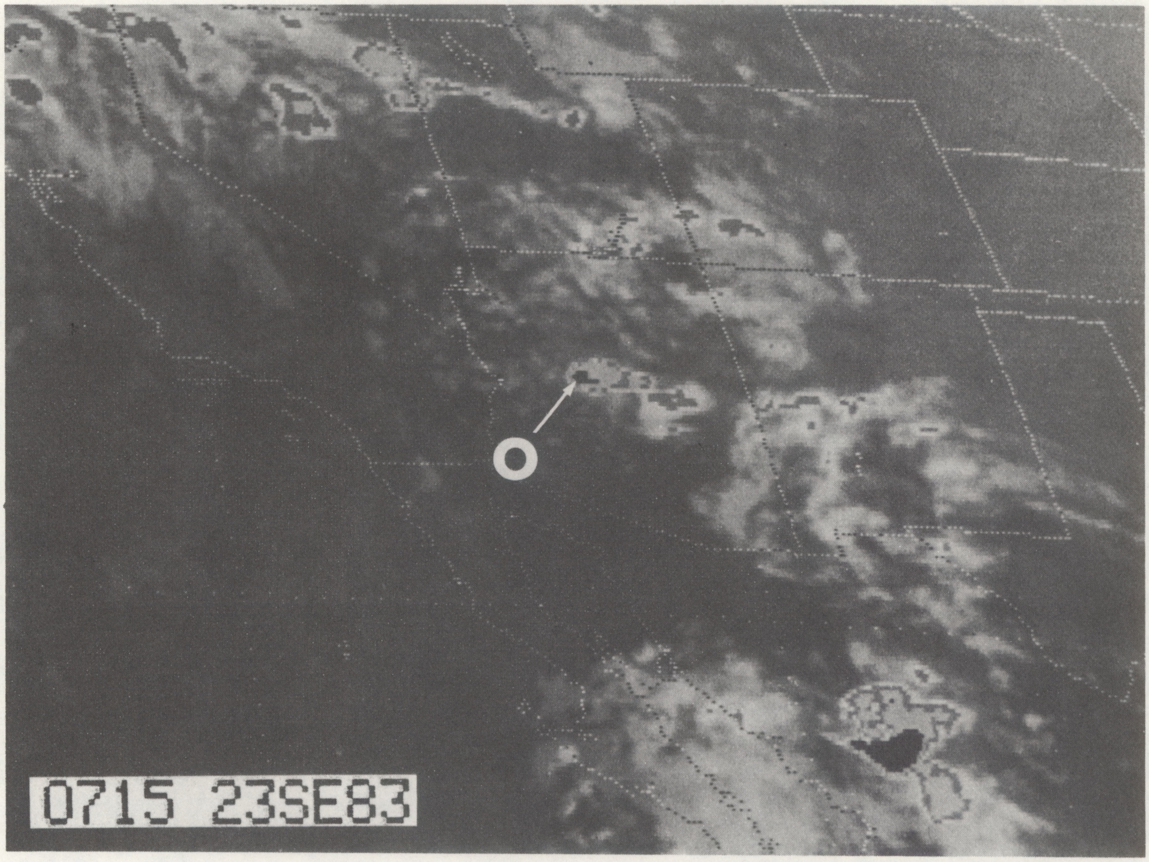


Figure 17. Enhanced IR image (Mb curve) at 0715 GMT on September 23, 1983. The letter O refers to a linear MCS-β over Prescott, Arizona.

Synoptic Scale Cyclonic Circulation

Warm topped convection embedded in a synoptic scale cyclonic circulation often produces heavy rainfall and flash flooding. Spayd (1982) and Spayd and Scofield (1983) summarized characteristics of warm-topped thunderstorms occurring in a synoptic scale cyclonic circulation and produced composite charts and soundings for this type of convective system. These composites were adapted for use in the western region based on the events in this study (Figure 18). Ten synoptic scale cyclonic circulation events (7% of the total) were observed in this study with nine of the ten having minimum cloud top temperatures between -52°C and -61°C (dark gray or black gray shade) and all the events were warm topped. Eight events occurred from 12:00 p.m. to 7:00 p.m. LDT and five events between 5:00 p.m. and 7:00 p.m. LDT. Nine of the events occurred during May, June, September, or October. However, no synoptic scale cyclonic circulation events were observed during July or August - the months of greatest number of flash flood events in the western region. It may be hypothesized that the presence of a large, persistent upper level blocking ridge over the western U.S. during July and August inhibits the passage of any cyclonic circulations.

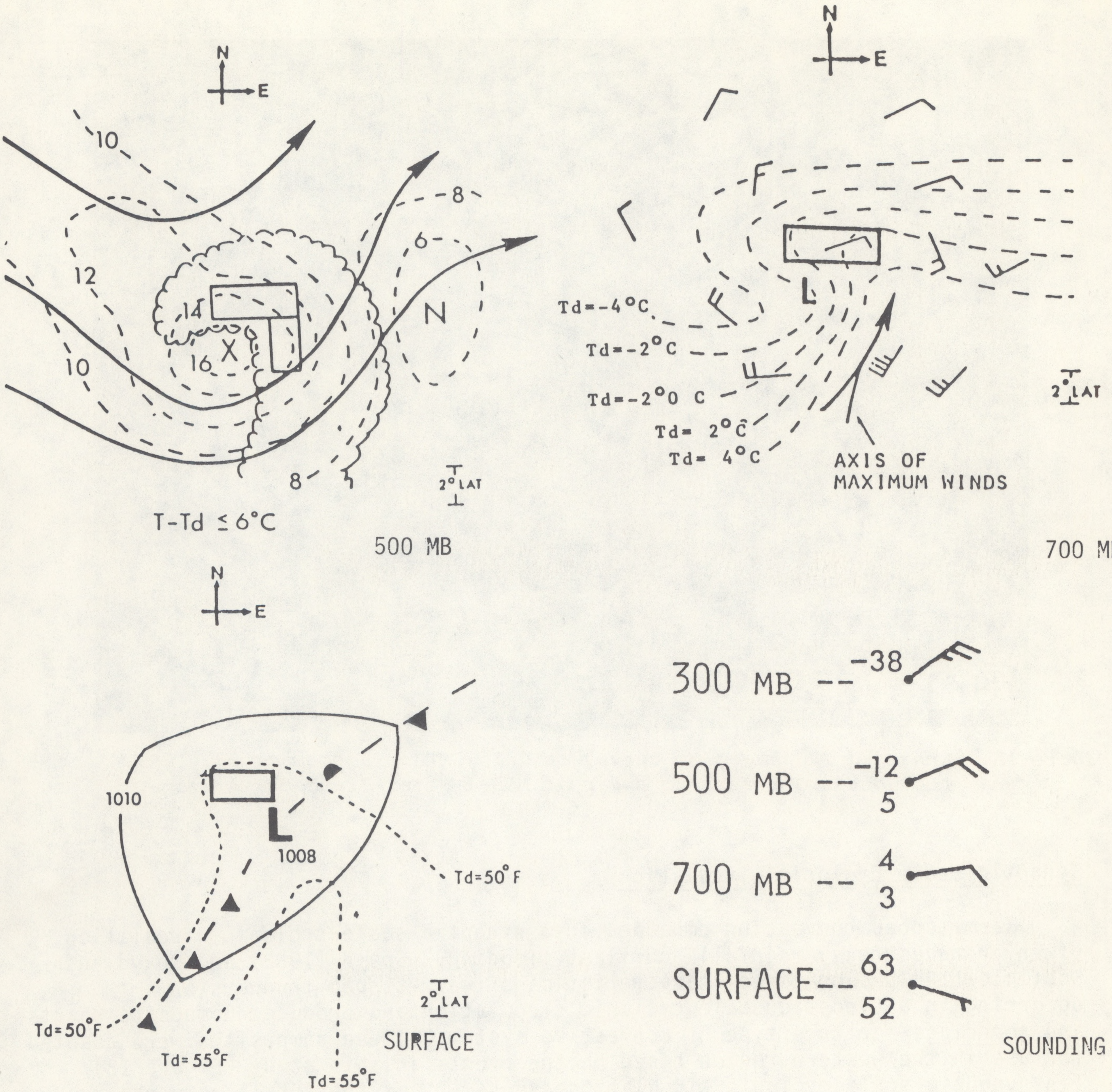


Figure 18. *Atmospheric composites for the 500 mb, 700 mb, surface and atmospheric soundings for synoptic scale cyclonic circulations in the western region.*

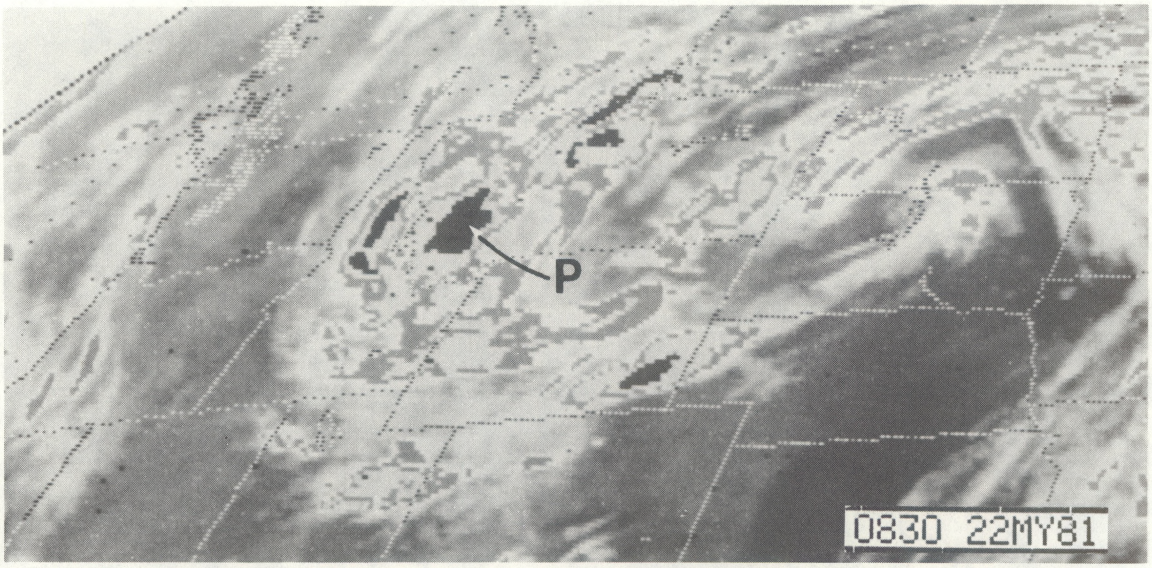


Figure 19. Enhanced IR image (Mb curve) at 0830 GMT on May 22, 1981. The letter P points to a thunderstorm embedded in a synoptic scale cyclonic circulation over Montana.

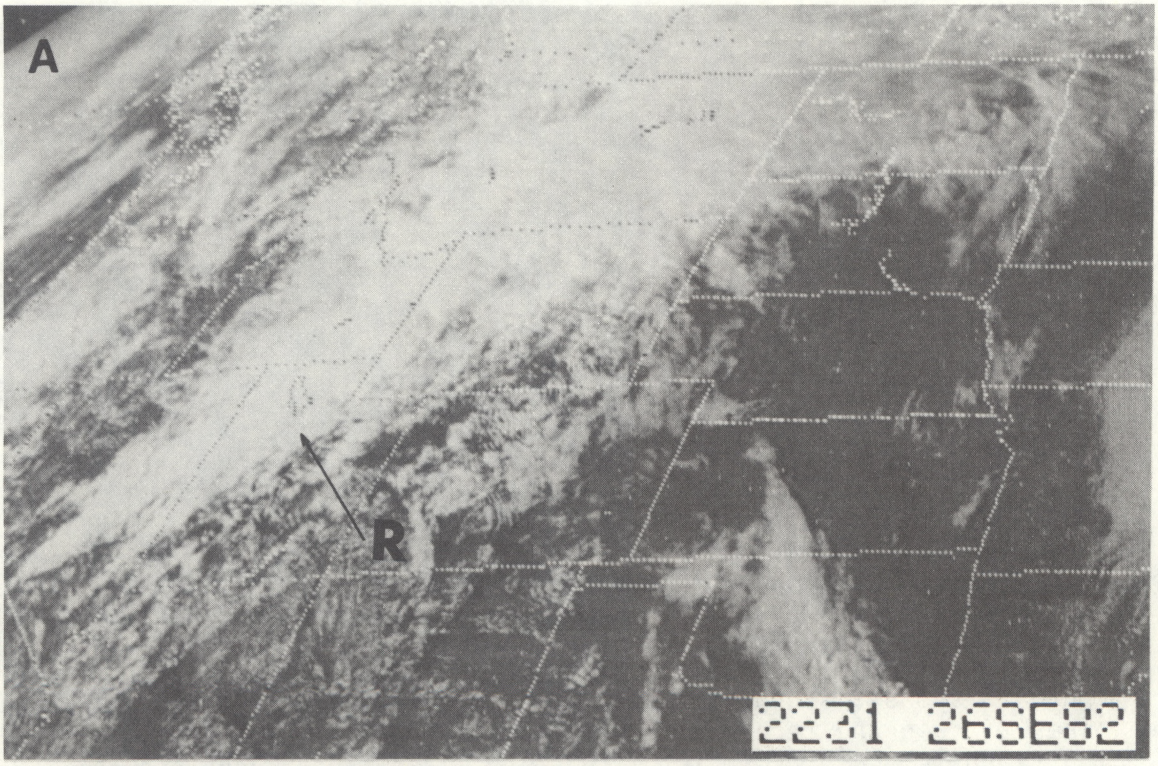
Figure 19 shows a synoptic scale cyclonic circulation which produced up to five inches of rain and record flooding over parts of Montana (P). In figure 16a, b, a synoptic scale cyclonic circulation flash flood event occurred at Juab County, Utah (Q).

Large Scale Overrunning

Spayd and Scofield (1983) identified cases of heavy rainfall producing warm-topped thunderstorms occurring within a large scale overrunning event. Four overrunning events were observed in this study, and all appear as warm-topped convective elements embedded within a large anticyclonic flow of cirrus. All of the events occurred between August 16 and January 15, and three events occurred between 1:30 a.m. and 8:00 a.m. LDT. On September 26-27, 1982, Salt Lake County, Utah (R in figure 20) received two to four inches of rain in 13 hours from warm-topped convection in an overrunning zone. This set a record at Salt Lake International Airport for rainfall in a 24 hour period. Flood damage totalled $15 million in the form of washed out roads, bridges, and damaged houses.

Regenerative

Single clustered and MCS-β (multi-clustered) thunderstorms redeveloping along the upwind portion of a low level boundary and traversing the same path downwind along the boundary appear as regenerative type of convective systems in the satellite imagery (Spayd and Scofield, 1983). Radar data indicates that individual echoes may move at speeds of 15 to 40 knots along the same path and is sometimes referred to as the "train echo" effect. Only four regenerative systems were observed in this study. All events occurred between July 25 and September 20 (three events between July 25 and August 12) and all had warm-topped cloud temperatures. Also, all four events occurred between 11:30 a.m. and 7:30 p.m. On July 28-29, 1982, a series of regenerating thunderstorm cells caused flooding near Coaldale (Freemont County), Colorado (figure 21).



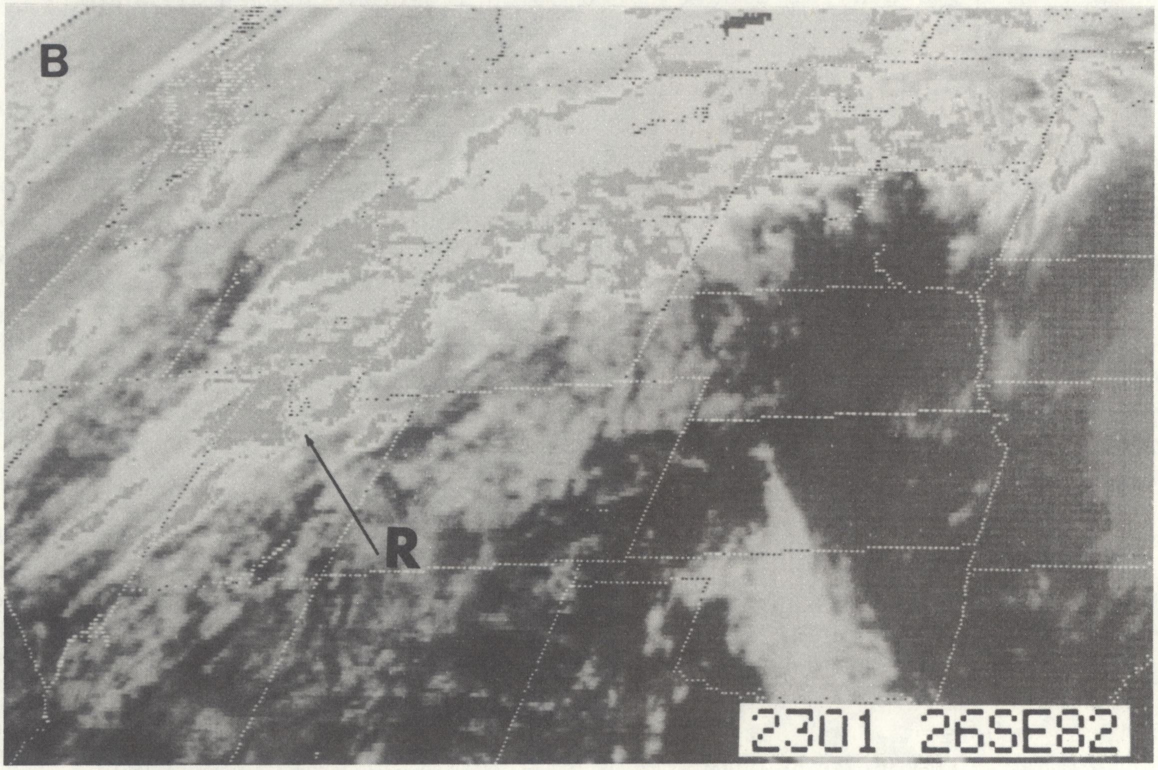


Figure 20. Visible image (A) at 2230 GMT and enhanced IR image (B) (Mb curve) at 2300 GMT on September 26, 1982. The letter R refers to thunderstorms embedded within a large scale overrunning system over Salt Lake County, Utah.

Combination of Two or More Convective Systems Transversing the Same Location

Flash flooding often occurs when two or more unrelated convective systems pass over the same area within a 24 hour period. Each individual thunderstorm system may not produce enough rainfall to cause flash flooding by itself. It is the responsibility of the operational meteorologist to keep a record of the paths of previous convective systems within the last 24 hours in order to properly assess the flash flood potential of current or future convective systems. The only such event in the western region (1981-1983) occurred on June 3, 1982 in which two separate independent convective systems (a single clustered system followed by a squall line) produced up to six inches of rain over Colorado Springs causing street flooding.

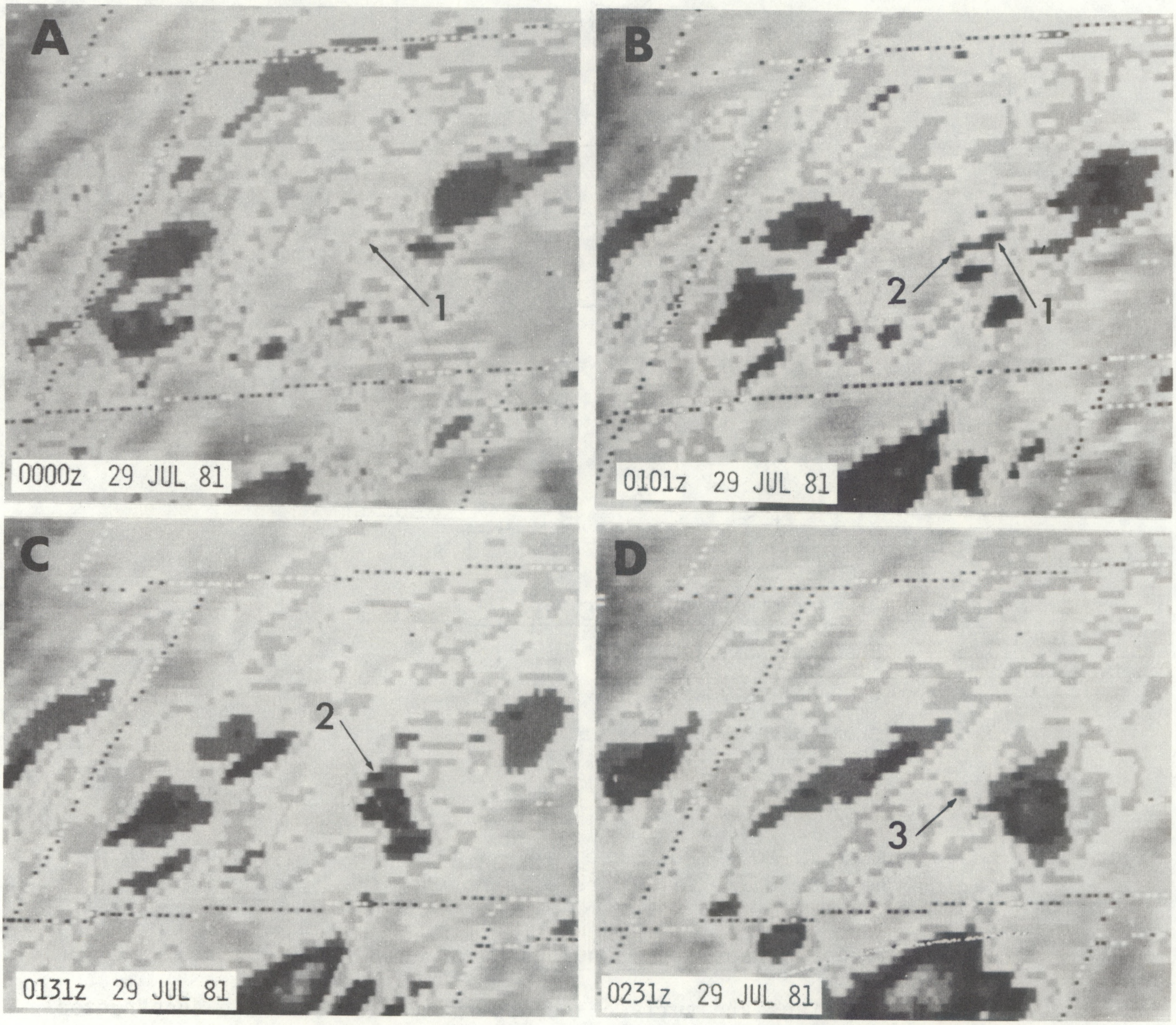
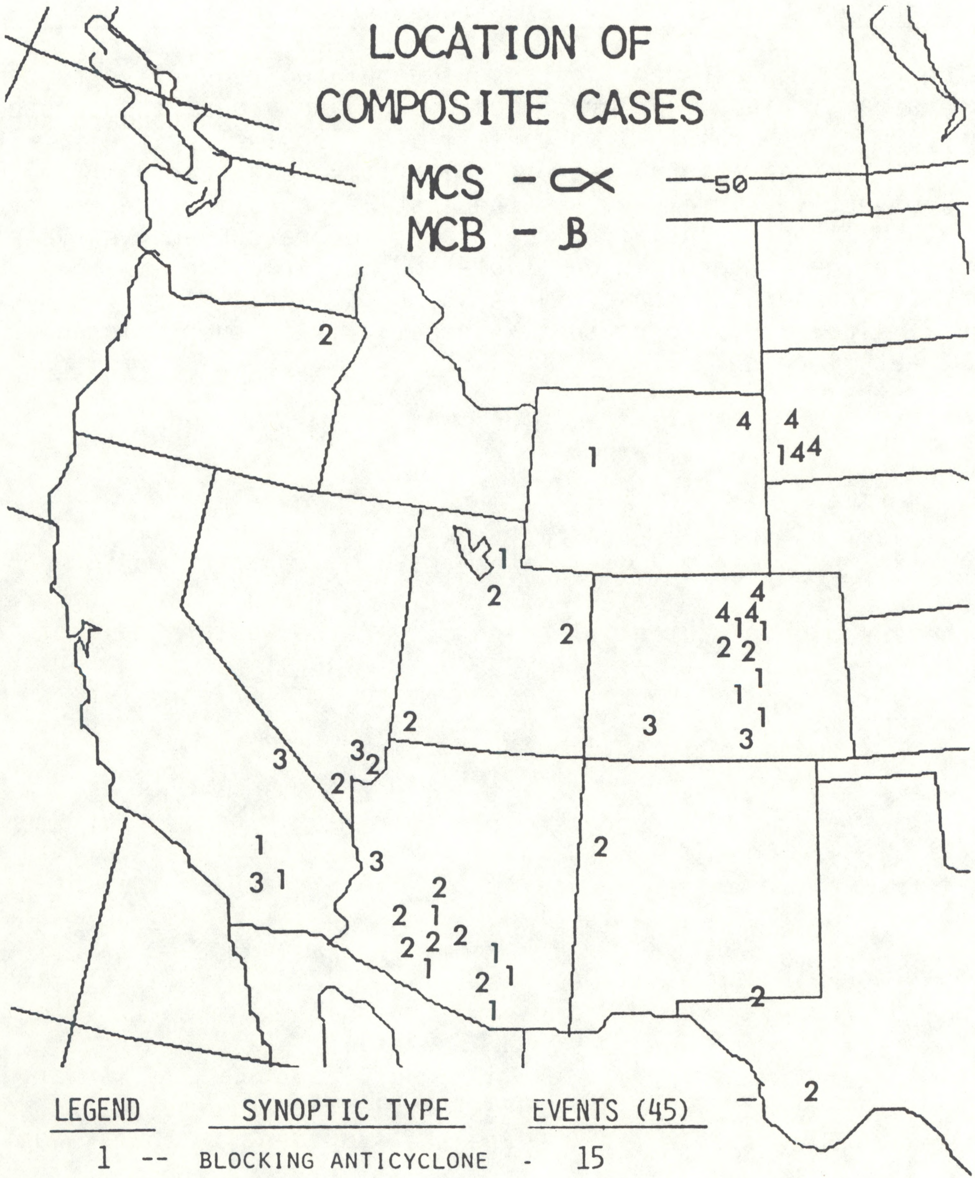


Figure 21. A series of enhanced IR images (A-D) (Mb curve) at 0000 GMT, 0100 GMT, 0130 GMT, and 0230 GMT. The numbers 1 through 3 point to the individual thunderstorms regenerating near Coaldale, Colorado.



LEGEND	SYNOPTIC TYPE	EVENTS (45)
1 --	BLOCKING ANTICYCLONE	- 15
2 --	DEFORMATION ZONE	- 17
3 --	SHORT WAVE TROUGH IN NORTHWEST FLOW	- 6
4 --	SHORT WAVE TROUGH IN ZONAL FLOW	- 7

Figure 22. Locations of 13 MCS-α and the largest 32 MCS-β systems used in preparing the four different types of atmospheric composites.

E. Composite Synoptic Maps and Soundings

Composite soundings and surface and upper air analyses were constructed in order to gain insight into the processes which initiate western region heavy convective rainfall events. Mesoscale Convective Systems comprised 63% (86 events) of the convective events in this study. Forty-five of the largest and longest lived MCS events (all 13 MCS-α and 32 MCS-β systems) were examined for common synoptic scale and mesoscale characteristics in surface and upper air data nearest in time and space to the flash flood event. Based on standard surface, 700, 500 (including vorticity), and 300 mb analyses, four distinct types of mesoscale and synoptic scale patterns were observed and composite soundings and maps at the surface, 700, and 500 mb levels were constructed. The synoptic patterns at 300 mb and 500 mb were very similar; therefore, only the 500 mb composite map is included.

Many of the remaining 41 smaller MCS-β and 28 single clustered systems occurred under generally similar such flow pattern conditions as the larger MCS-β and MCS-α systems. However further research is needed to determine additional atmospheric composites which may be unique to these smaller convective systems.

TYPE-1 Blocking Anticyclone

Fifteen flash flood events occurred under an upper level blocking anticyclone. At 500 mb, this type of event is observed to have a large blocking anticyclone with very high geopotential heights over the western half of the U.S. Figure 22 shows that this type of event has two distinct preferential areas of occurrence: a) southeastern California/southern Arizona; and b) the Colorado-Wyoming front range and South Dakota Black Hills. A separate set of composite maps will be shown for the two locations.

Figure 23a shows the 500 mb composite map for flash floods occurring in the southeastern California/southern Arizona area. The heavy rainfall event generally occurs in the southwestern quadrant of the high under the influence of moist southeasterly flow from the Gulf of Mexico (dewpoint depressions are less than 6°C). A weak upper level low center is typically located just west of Baja, California aiding in the moist southeast flow. A weak vorticity trough may extend just upwind of the flash flood area, inducing slight PVA into the area. A short wave trough is located along the Pacific Northwest coast. The 500 mb schematic for the front range type 1-B events (figure 23b) is very similar, however the flash flood occurs in southwesterly flow of the anticyclone (moist Gulf of Mexico flow and T-Td $\leq$ 6°C are still evident). A weak vorticity lobe is occasionally located just upwind of the flood area. The blocking high is displaced slightly eastward, with a somewhat deeper west coast trough relative to the type 1-A events. For both type 1-A and B events, winds are quite weak near the flood area, and the jet maximum is far to the north.

Figures 24a and 24b show the 700 mb schematics for these type 1-A and B events respectively, revealing very similar features to those at 500 mb. For type 1-A, moist southeasterly flow is present with a weak cyclonic circulation center just to the southwest of the flood area. The type 1-B event lacks this circulation feature but is observed to have moist southeast flow from the Gulf of Mexico. Note also the deeper west coast trough observed with the type 1-B event. Both type 1-A and B events occur in or near an area of maximum dewpoints, with some moisture advection evident.

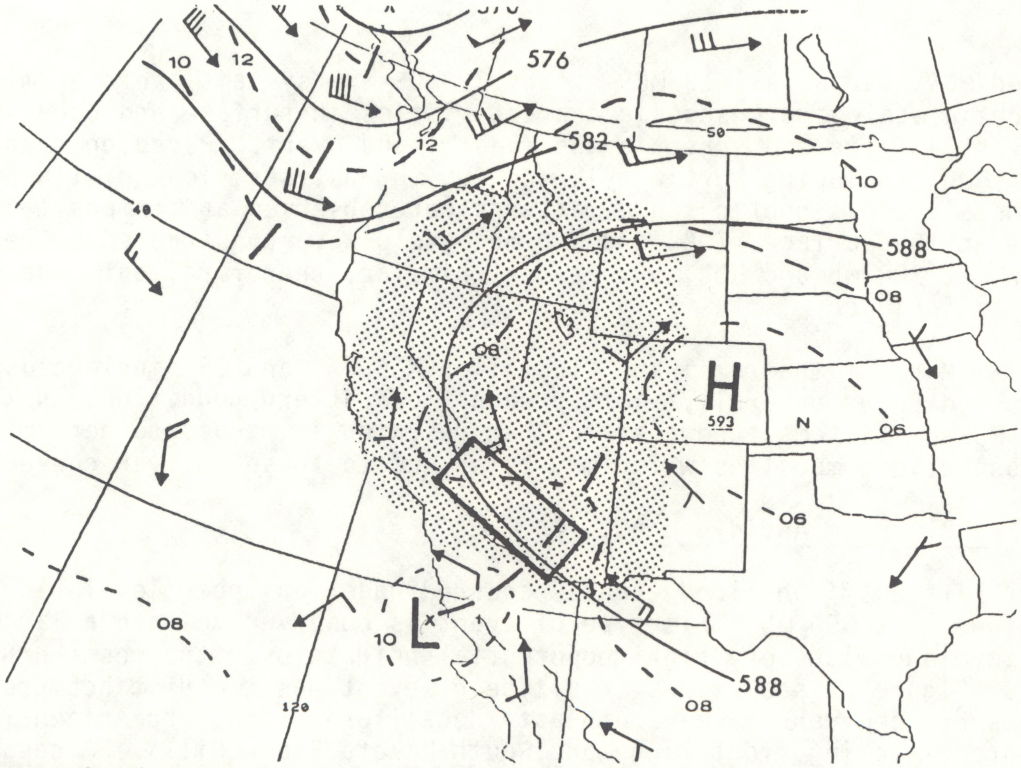


Figure 23a. Atmospheric composite for the 500 mb level Type 1-A Blocking Anticyclone events in southeastern California and southern Arizona

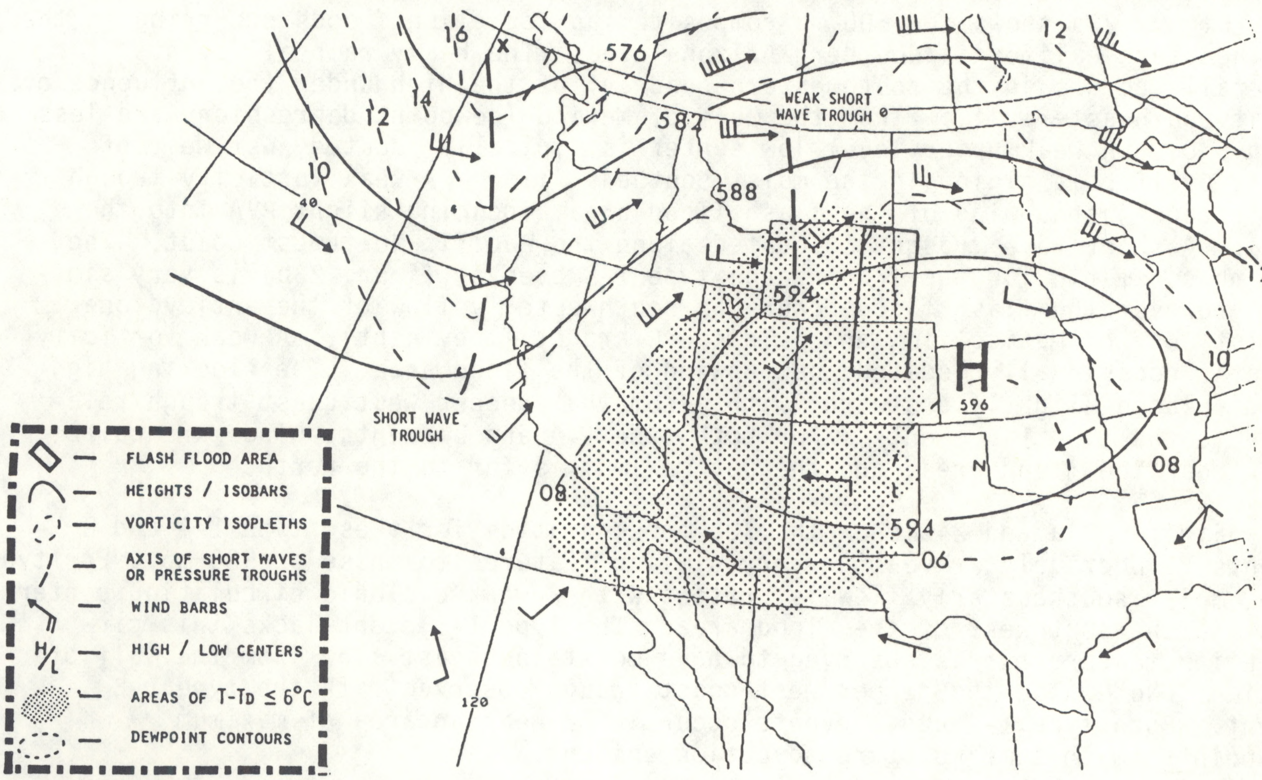


Figure 23b. Atmospheric composite for the 500 mb level Type 1-B Blocking Anticyclone events along the Colorado front range.

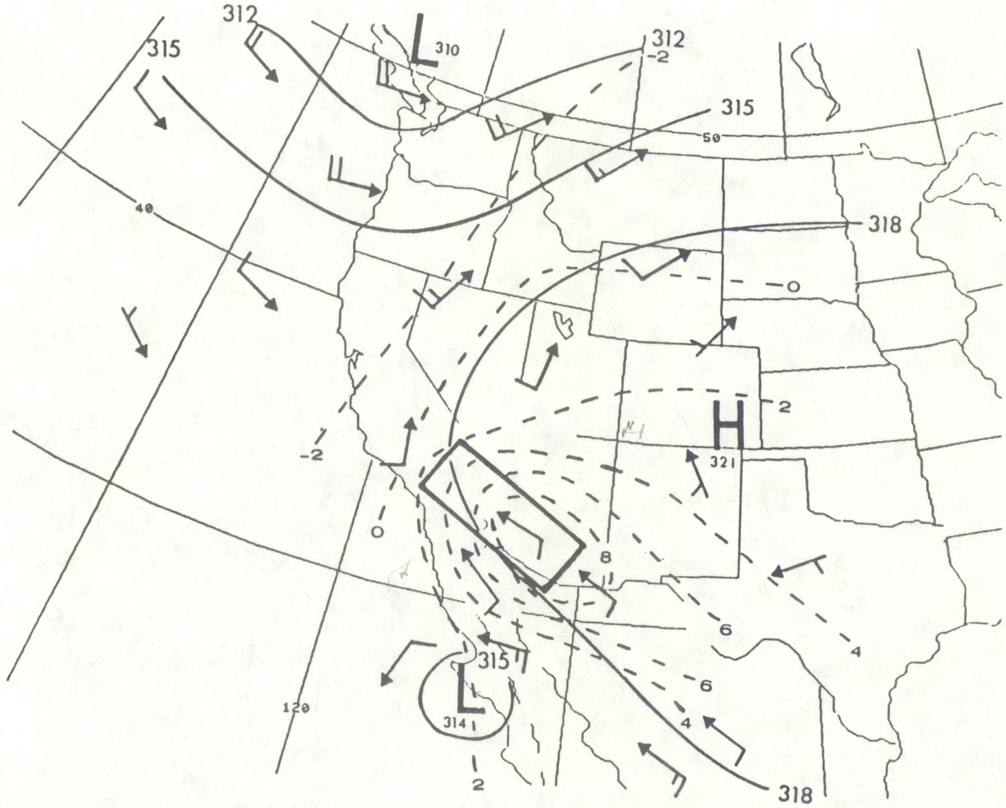


Figure 24a. Atmospheric composite for the 700 mb level Type 1-A Blocking Anticyclone events in southern California and southern Arizona.

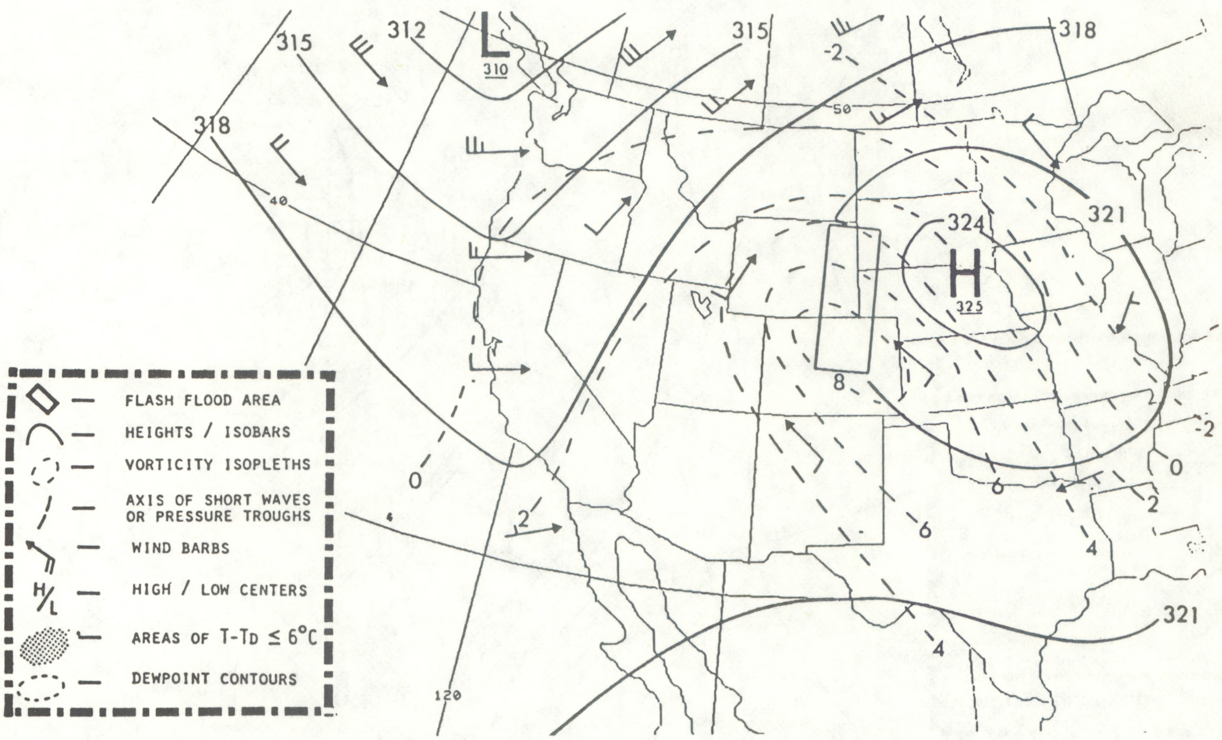


Figure 24b. Atmospheric composite for the 700 mb level Type 1-B Blocking Anticyclone events along the Colorado front range.

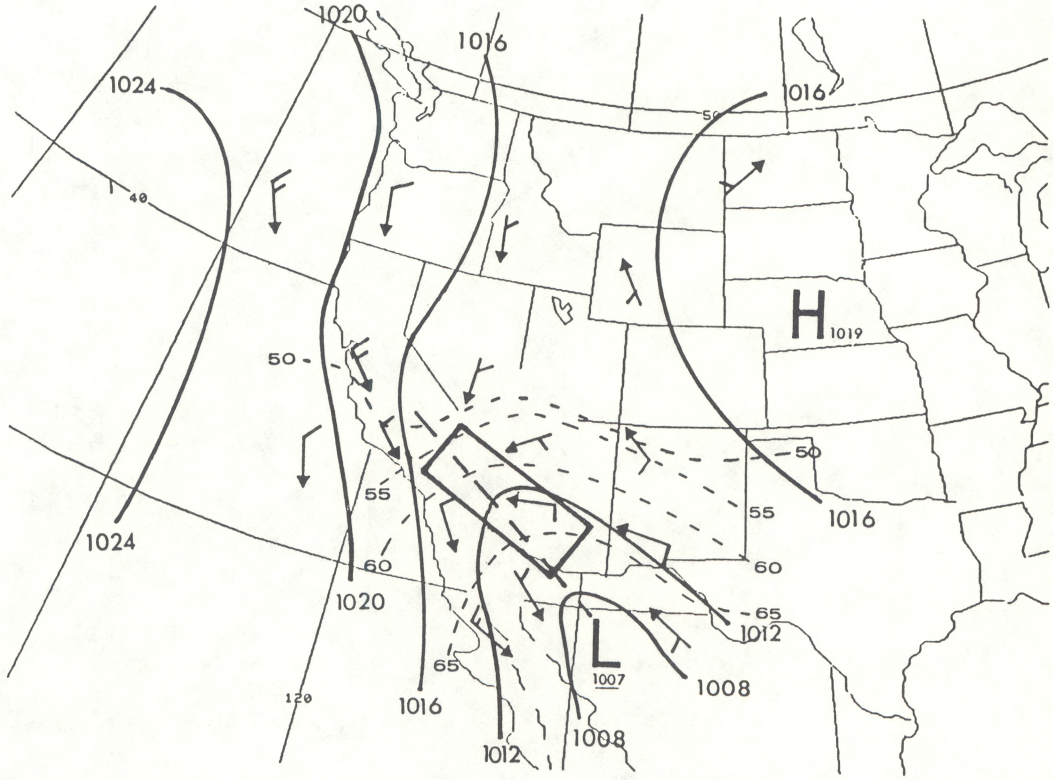


Figure 25a. Atmospheric composite for the surface Type 1-A Blocking Anticyclone events in southern California and southern Arizona.

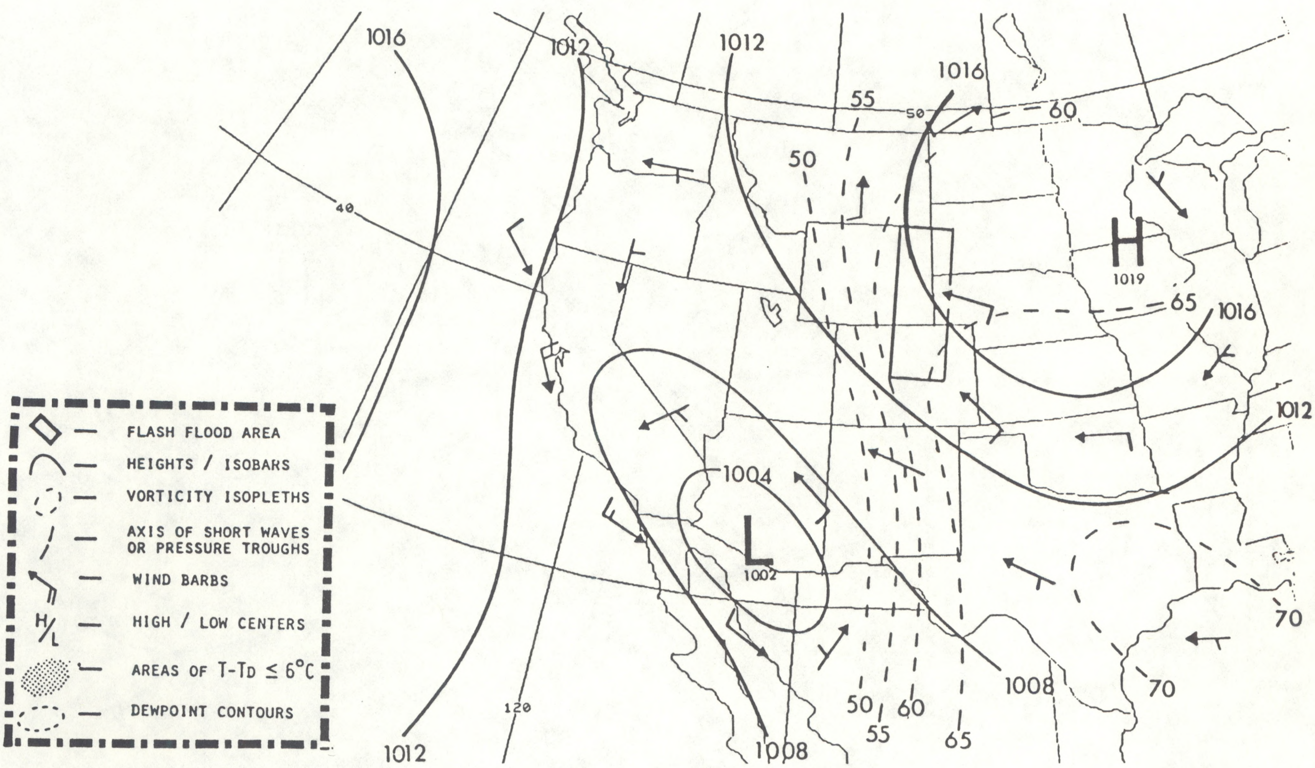


Figure 25b. Atmospheric composite for the surface Type 1-B Blocking Anticyclone events along the Colorado front range.

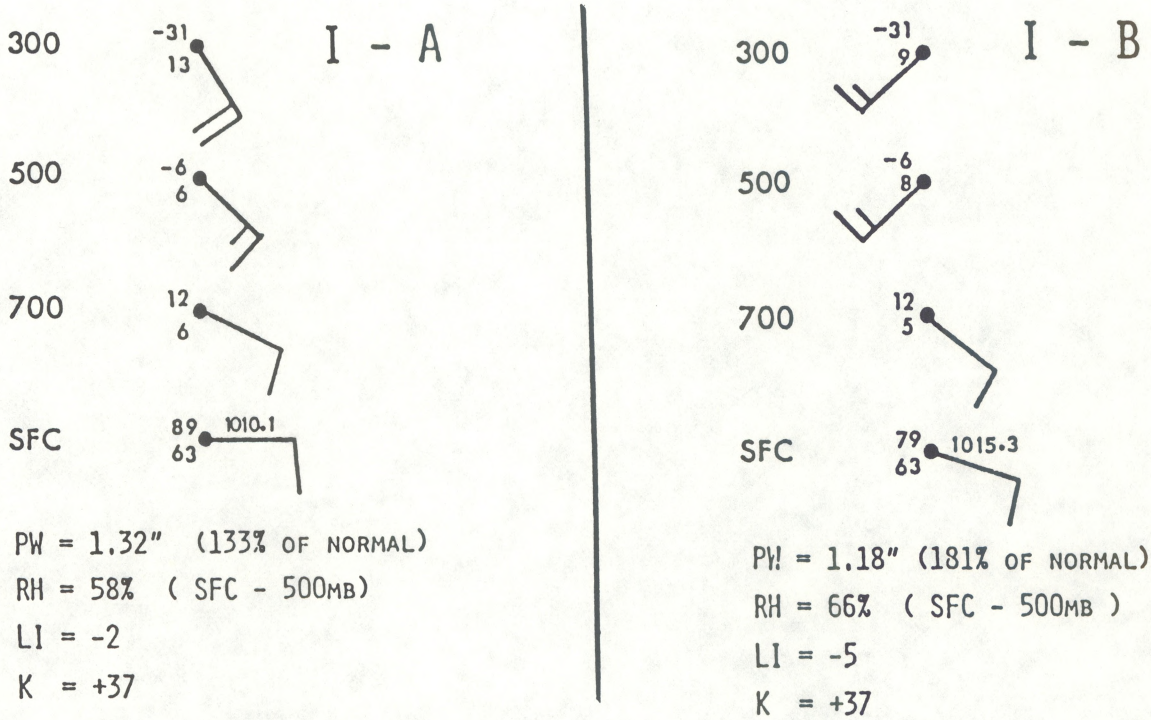


Figure 26. Composite Atmospheric sounding for the Type 1-A and 1-B Blocking Anticyclone events.

The surface patterns (figures 25a and 25b) are also similar for both locations with a (thermal) low pressure center located in southern Arizona or northern Mexico, and high pressure centered over the Great Plains. Southeasterly flow of 5 to 15 knots with some moisture advection is also present in both locales. Note also the strong dewpoint gradient with much drier air to the north or west in both areas. The presence of low level upslope flow is quite evident in the type 1-B front range scenario.

The composite soundings for the type 1 (both A and B) events is shown in figure 26. In both cases, warm advection (winds veering with height) is present in the surface to 500 mb layer but is much stronger for the front range events. Also, high dew points throughout the troposphere, large surface to 500 mb precipitable water, light winds, and a very unstable air mass create conditions highly condusive for flash flooding in both cases.

Fourteen (out of the 15 total) of the type 1 (A and B) events occurred between July 23 and August 17 with several occurring over a few consecutive days. Also, 13 events were observed to have circular cloud tops - an expected result given the very small vertical wind shear present in a large upper level blocking anticyclone.

Figure 27a shows the 500 mb wind and the geopotential height analyses for 0000 GMT July 23, 1982 superimposed on a 0145 GMT IR satellite image. A large MCS- (circular) convective system (S) embedded in a moist southeasterly flow produced flash flooding in Tucson, Arizona. This pattern is typical of a type 1-a event. Figure 27b shows an example of a type 1-b event. A large MCS-(circular) system (T) formed in a moist southwesterly 500 mb flow and produced flash flooding in Chaffee and Freemont Counties, Colorado on June 26, 1981.

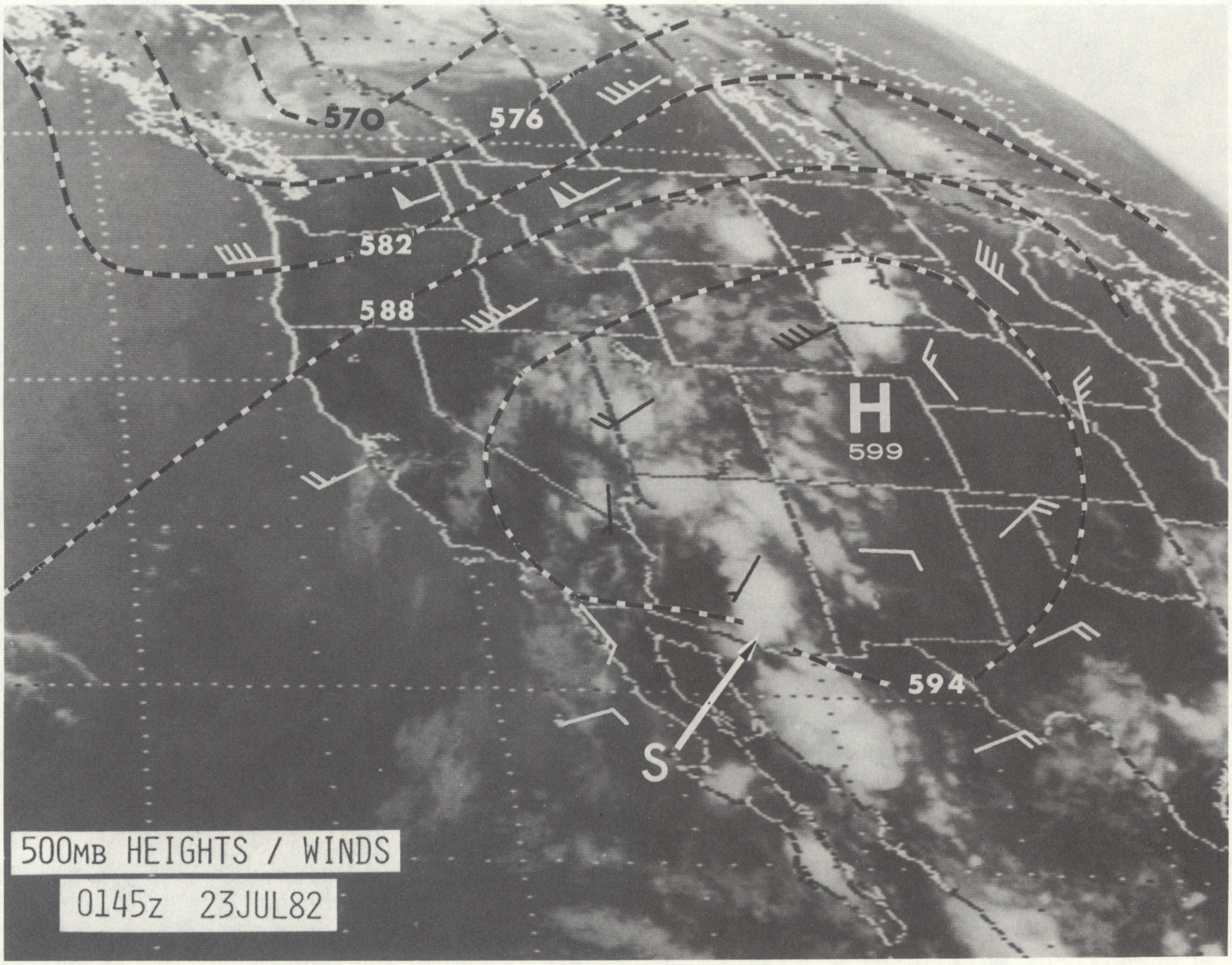


Figure 27a. Infrared image at 0145 GMT July 23, 1982 with 0000 GMT 500 mb geopotential heights and winds overlain. The letter (S) points to a MCS- α system near Tucson, Arizona.

TYPE 2 - Deformation Zone

Seventeen cases were classified into a deformation zone category. The 500 mb composite for the type 2 heavy precipitation event (figure 28) reveals a short wave trough just upwind of the flash flood area. A weak vorticity lobe extends southward from the trough center creating slight to moderate positive vorticity advection (PVA) in the flood area. An anticyclone over the western Gulf of Mexico advects moist air (T-Td $\leq$ 6°C) on the east side of the trough axis, as well as creating a confluent asymptote (see Weldon, 1979) which enhances the upper level mesoscale temperature gradients in the area. In almost half of the cases, a weak cut off low was present over Baja, California, thus enhancing the PVA, moist air advection, and the deformation zone. Winds are rather weak (10-20 knots) around the flood area, as maximum wind speeds are observed to be far to the north.

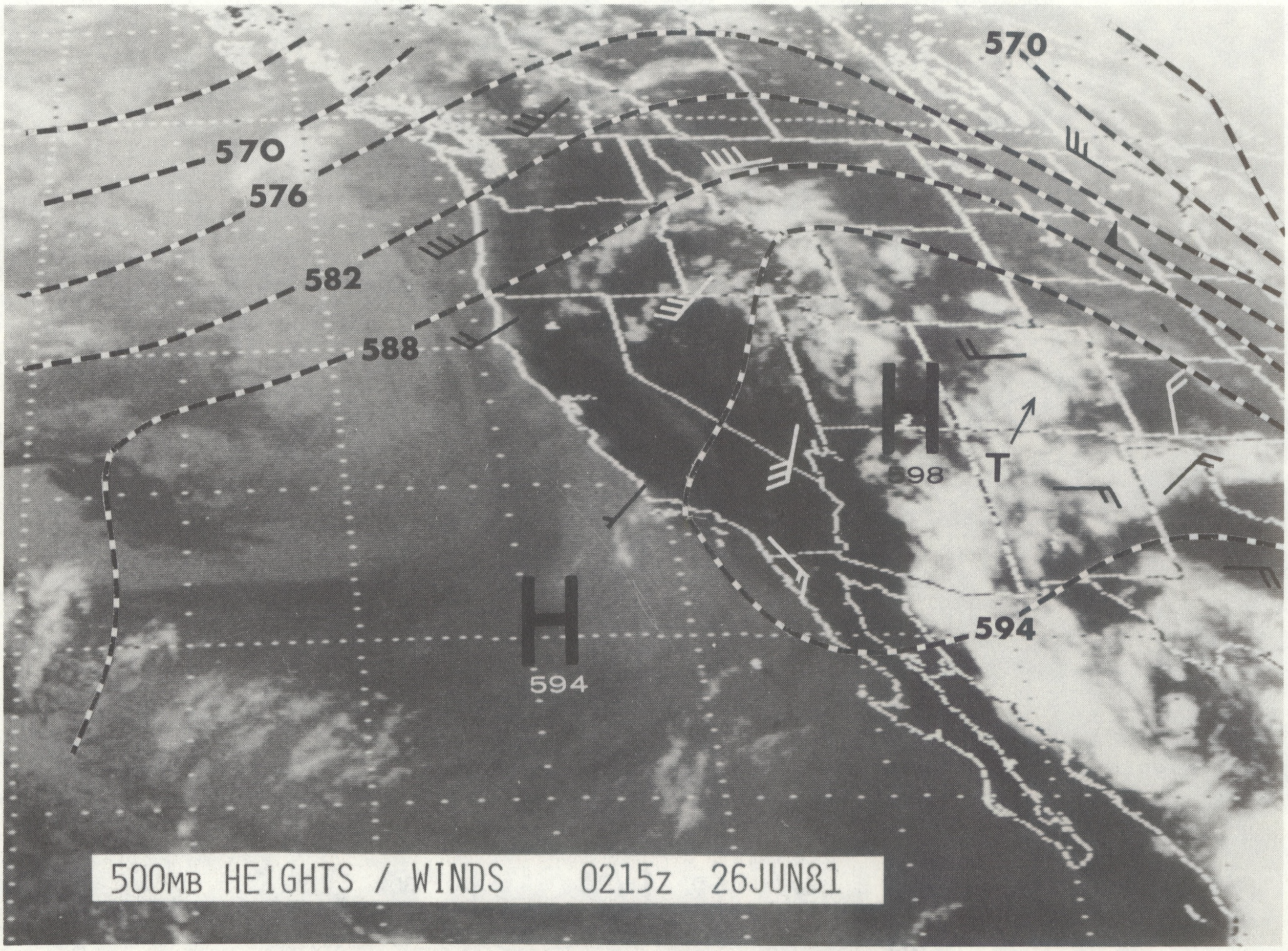


Figure 27b. Infrared image at 0215 GMT June 26, 1981 with 0000 GMT geopotential heights and winds overlain. The letter (T) points to a MCS-α system in Freemont County, Colorado.

Similar atmospheric conditions are present at 700 mb (figure 29) with a short wave trough just to the west and southerly flow of air from the Gulf of Mexico advecting moisture into the flash flood area. The deformation zone again increases the temperature and moisture gradients in the flash flood area. Winds are weak (10-15 knots) and the jet maximum is far to the north. The surface map (figure 30) indicates that the flood area is present just on the northeast side of a relatively strong (thermal) low pressure area. This combined with higher pressures over the Great Plains produces moist southeasterly flow into the flood area. Much drier air is located to the north and west. Roughly 50% of these type 2 events are observed to have an old frontal boundary or pressure trough very near the flood area which acts as a triggering mechanism for the heavy rainfall producing convection.

A composite sounding of the type 2 events is shown in figure 31. Light winds and very moist conditions prevail from the surface to 300 mb, and the surface to 500 mb precipitable water of 1.15 inches is 160% of normal. Rather unstable conditions are also present along with warm advection (veering winds) in the surface to 700 mb layer.

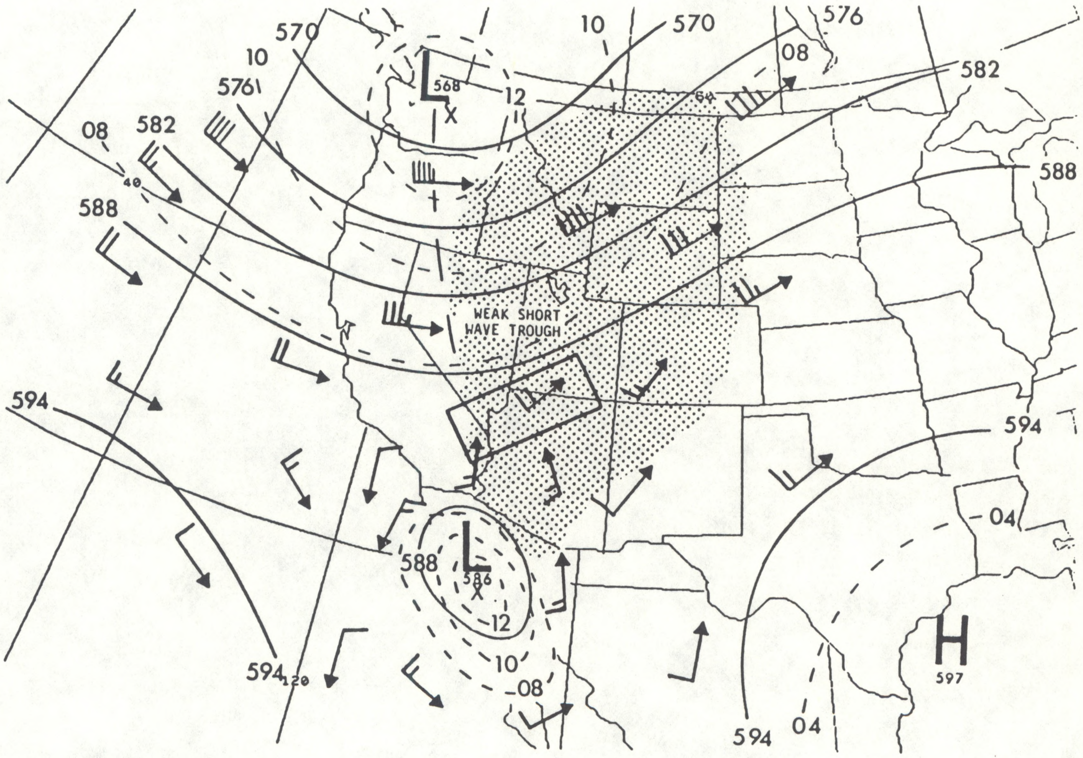


Figure 28. Atmospheric composite for the 500 mb level Type 2 Deformation Zone events.

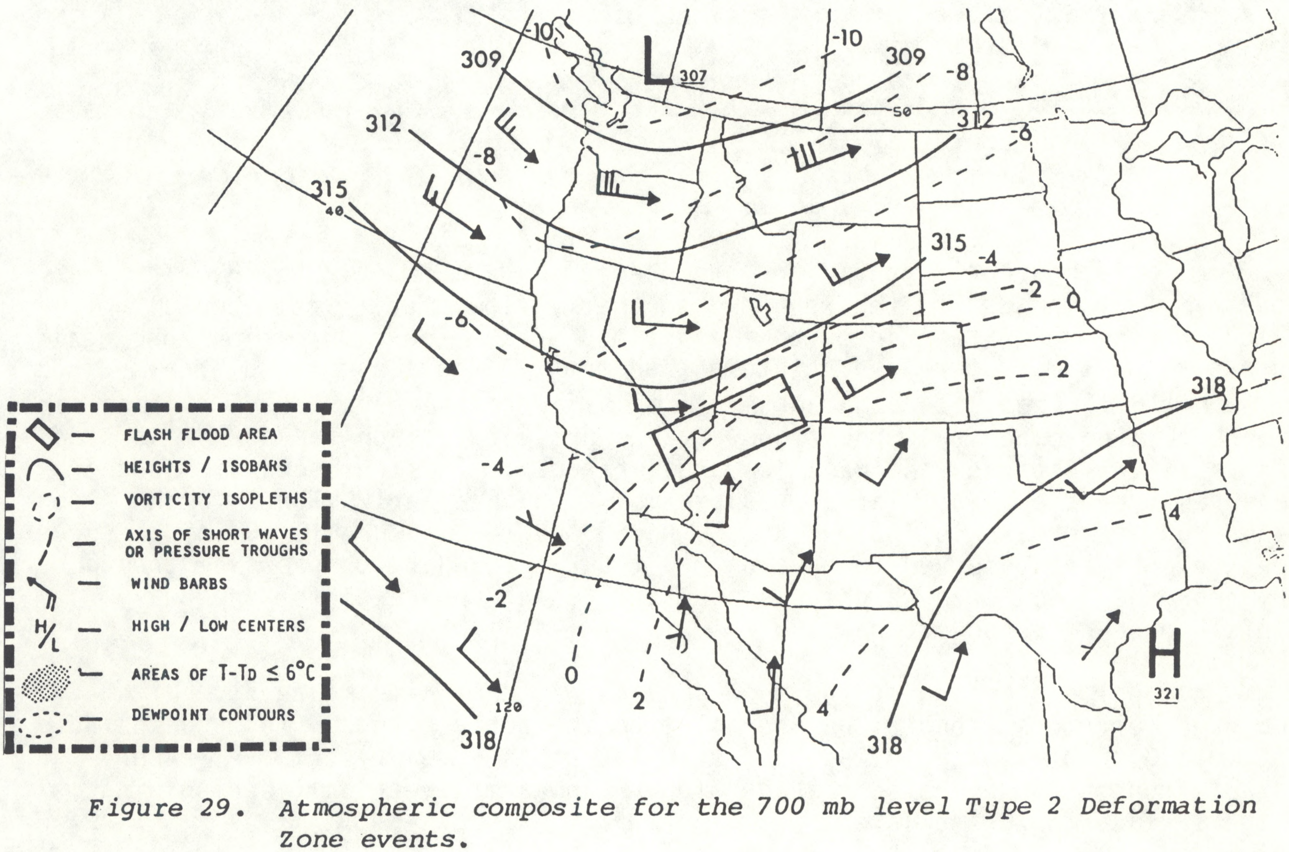


Figure 29. Atmospheric composite for the 700 mb level Type 2 Deformation Zone events.

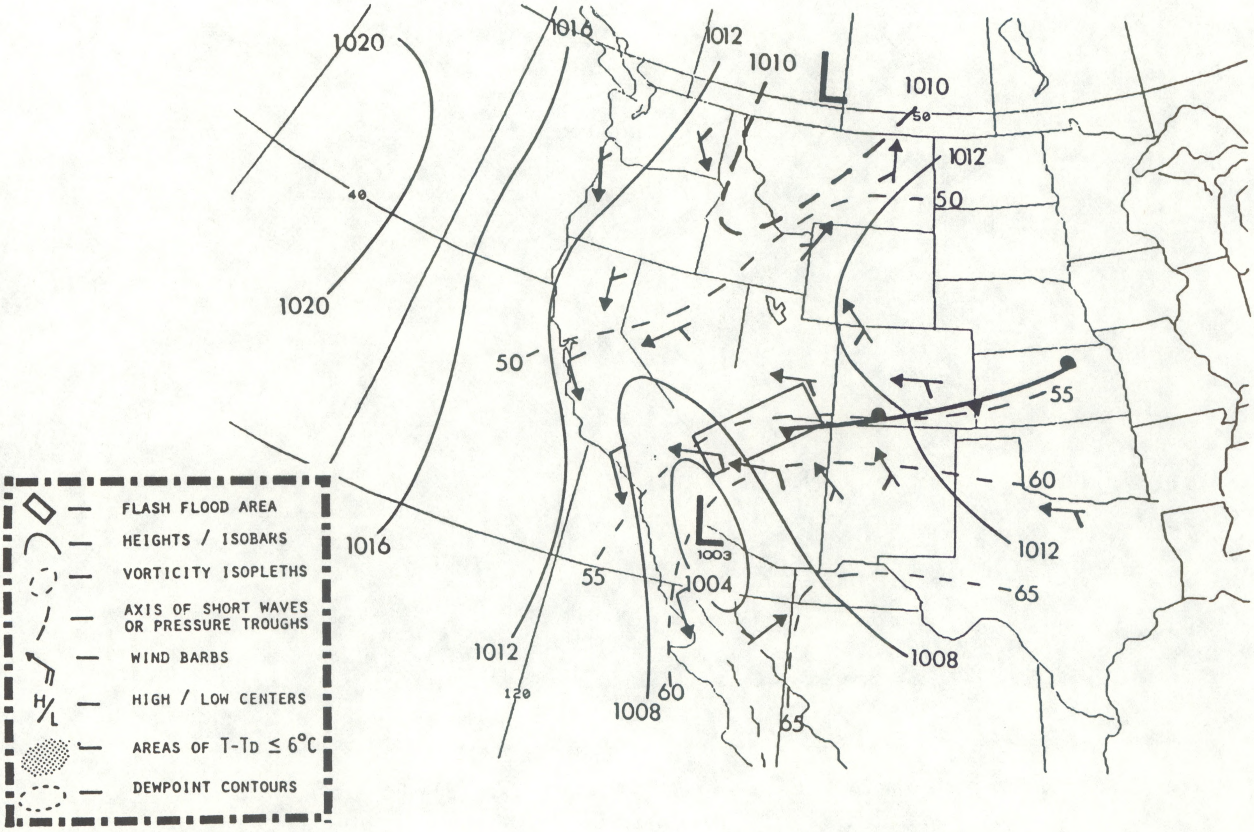


Figure 30. Atmospheric composite for the surface Type 2 Deformation Zone events.

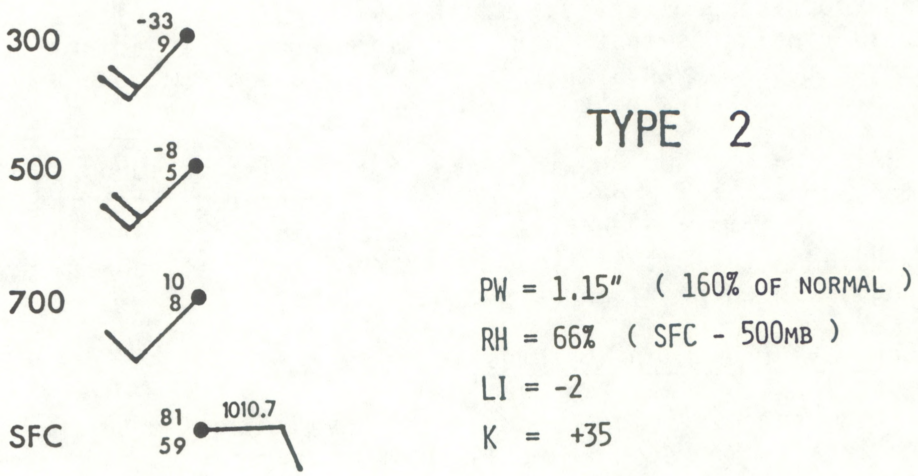


Figure 31. Composite atmospheric sounding for the Type 2 Deformation Zone events.

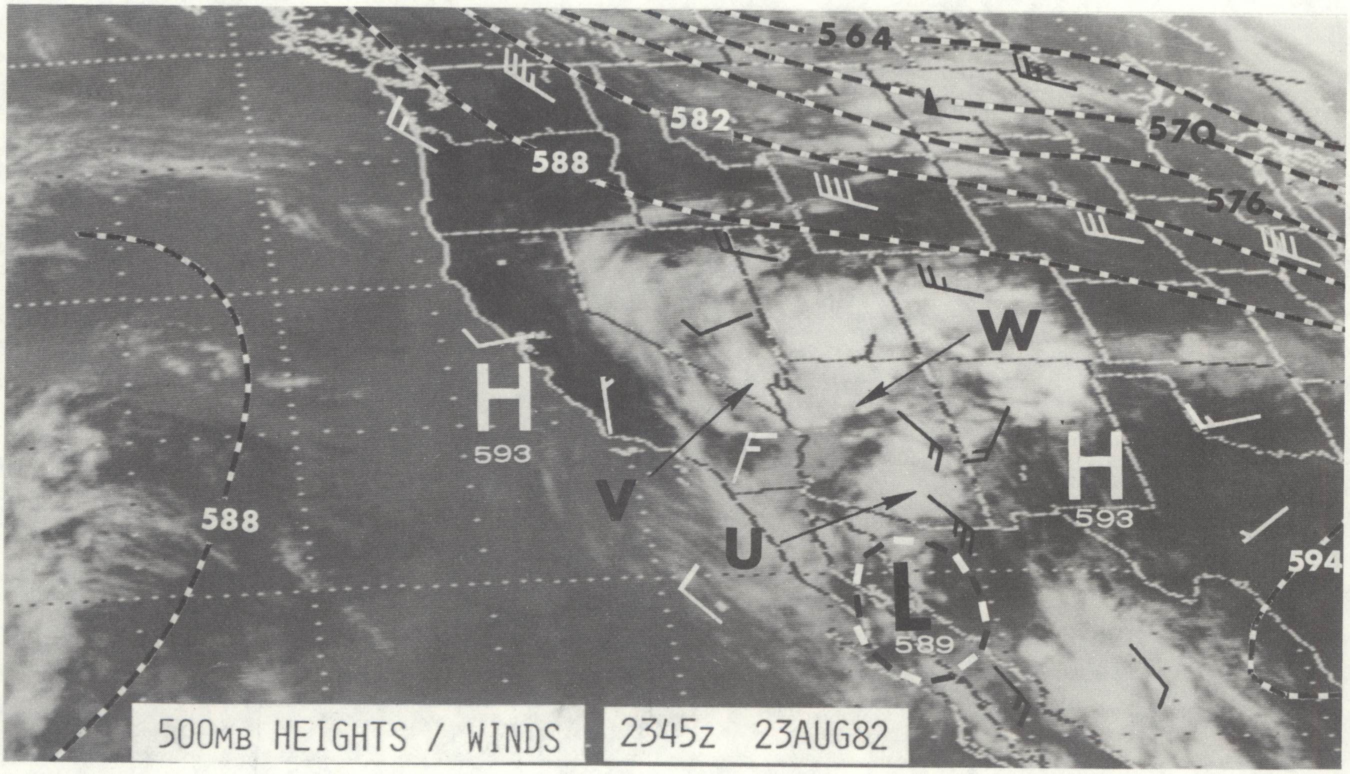


Figure 32. Infrared image at 2345 GMT August 23, 1982 with 0000 GMT 500 mb geopotential heights and winds overlain. The letters (U), (V), and (W) point to MCS- β systems over Tuscon, Arizona and Searchlight, Nevada, and Phoenix, Arizona, respectively.

All events occurred from July 11 through October 8 and 13 cases occurred between July 11 and September 4. Fifty-three percent of the type 2 events had linear-shaped cloud-topped convection, with 47% having circular-shaped cloud tops. Figure 22 indicates that there is a fair amount of variability in the locations of the type 2 events, although the regions of Arizona and southern Nevada are the most likely areas of occurrence.

Figure 32 shows the 500 mb wind and height fields for 0000 GMT August 24, 1982 superimposed on a corresponding unenhanced infrared satellite image. Two MCS-β (circular) systems produced flash flooding in Tucson, Arizona (U) and Searchlight, Nevada (V) at this time. A third MCS- β (circular) system produced flash flooding in Phoenix (W) about two hours later.

TYPE 3 - Short Wave Trough in Northwest Flow

Six events were classified into a short wave trough in northwest flow category, and the location of each event is shown in figure 22. The composite 500 mb pattern for the type 3 events is shown in figure 33. A strong blocking anticyclone is present just off the west coast with the flash flood area located near the base of a strongly positively tilted long wave trough. A short wave trough is observed moving down the back side of the long wave trough, creating weak or moderate PVA in the flood area. Although northwest flow (approximately 25 knots) is present, dew point depressions are less than 6°C ahead of the short wave trough. These conditions are very similar to those of the type 2 events of Maddox (1980). Note that the flood area in figure 33 is located in the

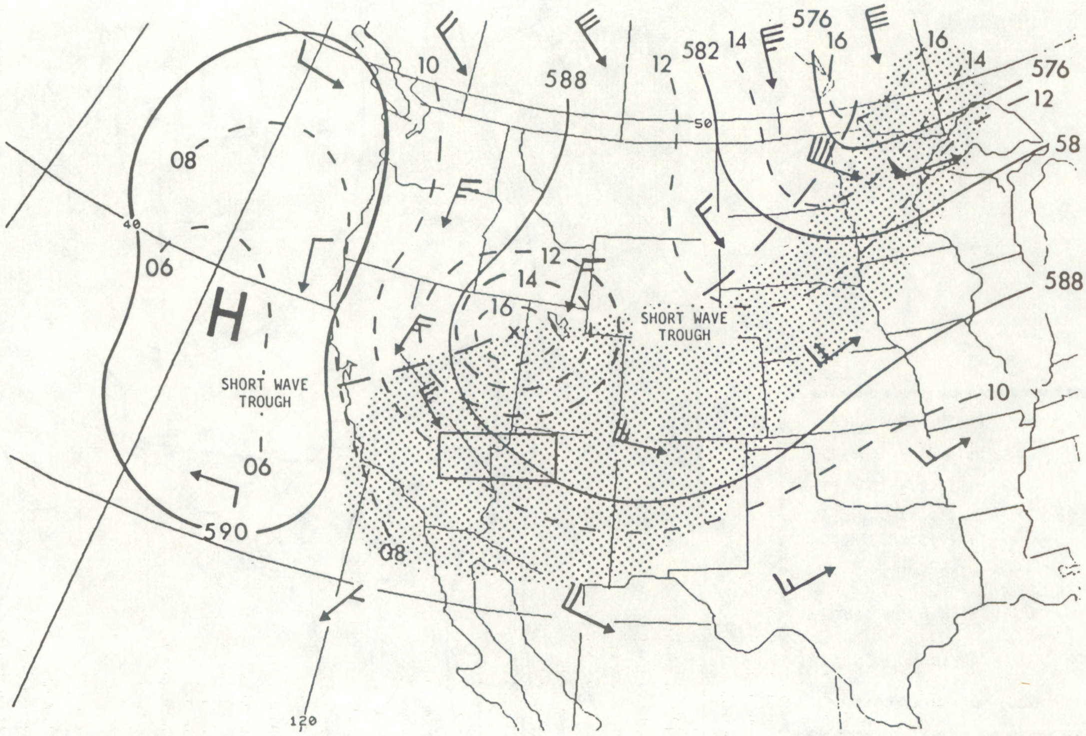


Figure 33. Atmospheric composite for the 500 mb level Type 3 Short Wave Trough in Northwest Flow events.

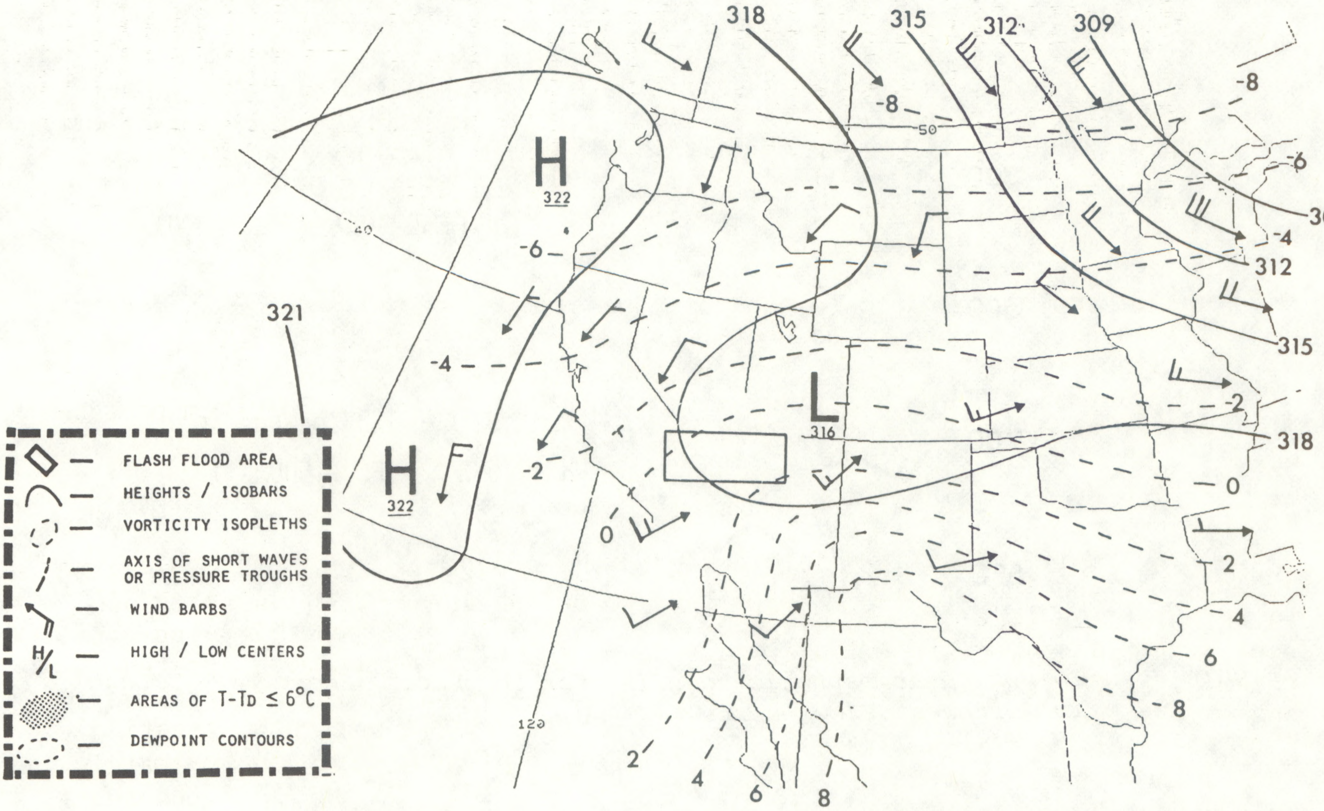


Figure 34. Atmospheric composite for the 700 mb level Type 3 Short Wave Trough in Northwest Flow events.

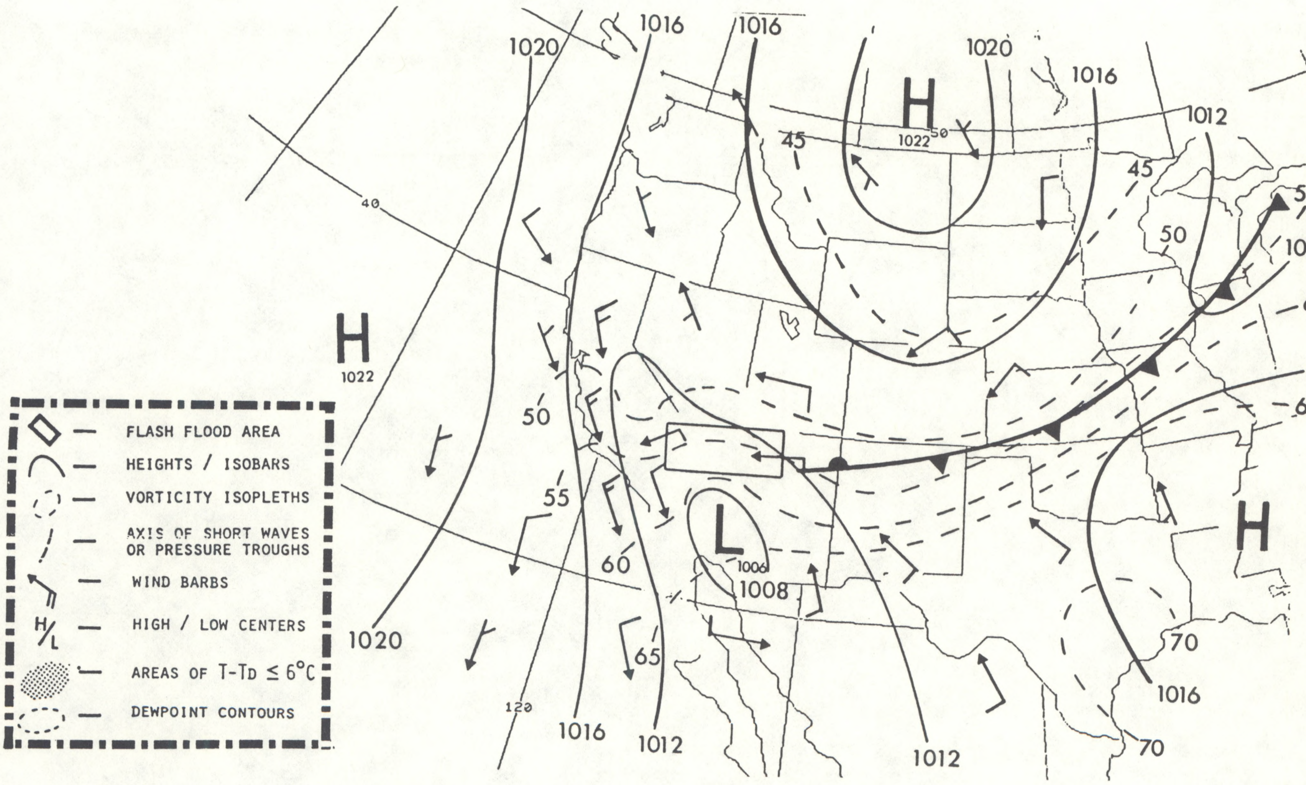


Figure 35. Atmospheric composite for the surface Type 3 Short Wave Trough in Northwest Flow events.

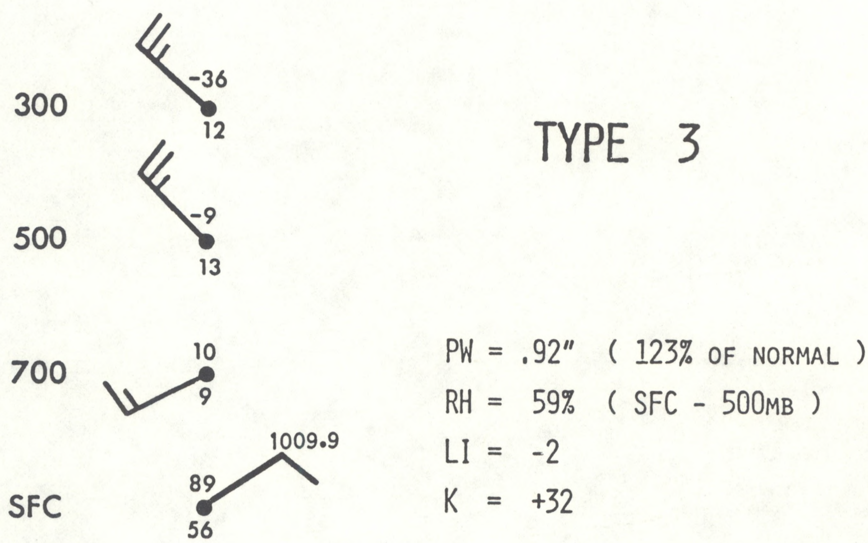


Figure 36. Composite atmospheric sounding for the Type 3 Short Wave Trough in Northwest Flow events.

general area of a deformation zone in the relative flow field which Weldon (1979) empirically associated with mid-tropospheric frontogenesis. In fact, five of the six cases were observed to have linear shaped cloud tops, a phenomenon which can be caused by the presence of such a deformation zone. Similar conditions are present at 700 mb (figure 34), however a relatively strong temperature gradient with cooler air to the east and northeast was usually present producing some warm air advection in the relative flow field into the flood area.

Surface conditions (figure 35) are quite similar to types 1 and 2, with southeast flow advecting in moist air from the Gulf of Mexico. In five of the six events, an old stationary frontal boundary or pressure trough in the flash flood area triggered and maintained the convection. As seen in the composite sounding (figure 36), the wind direction veers almost 180° in the surface to 700 mb layer, and continues to veer up to 500 mb indicating strong warm advection in the surface to 500 mb layer. Precipitable water values of 123% of normal, high instability, and light winds throughout all levels create conditions favorable for heavy rainfall producing convection. It should be noted that four of these events occurred between August 10 and August 12, 1981 and the other two between September 6 and September 8, 1981. This indicates that although this type of pattern is rather uncommon, under the right conditions it can produce several flash flood events over a period of a few days.

A typical type 3 event is shown in figure 37 in which an MCS-α system (X) caused flash flooding in northern Clark County, Nevada on August 11, 1981. The convection formed ahead of a short-wave trough in northerly flow at 500 mb.

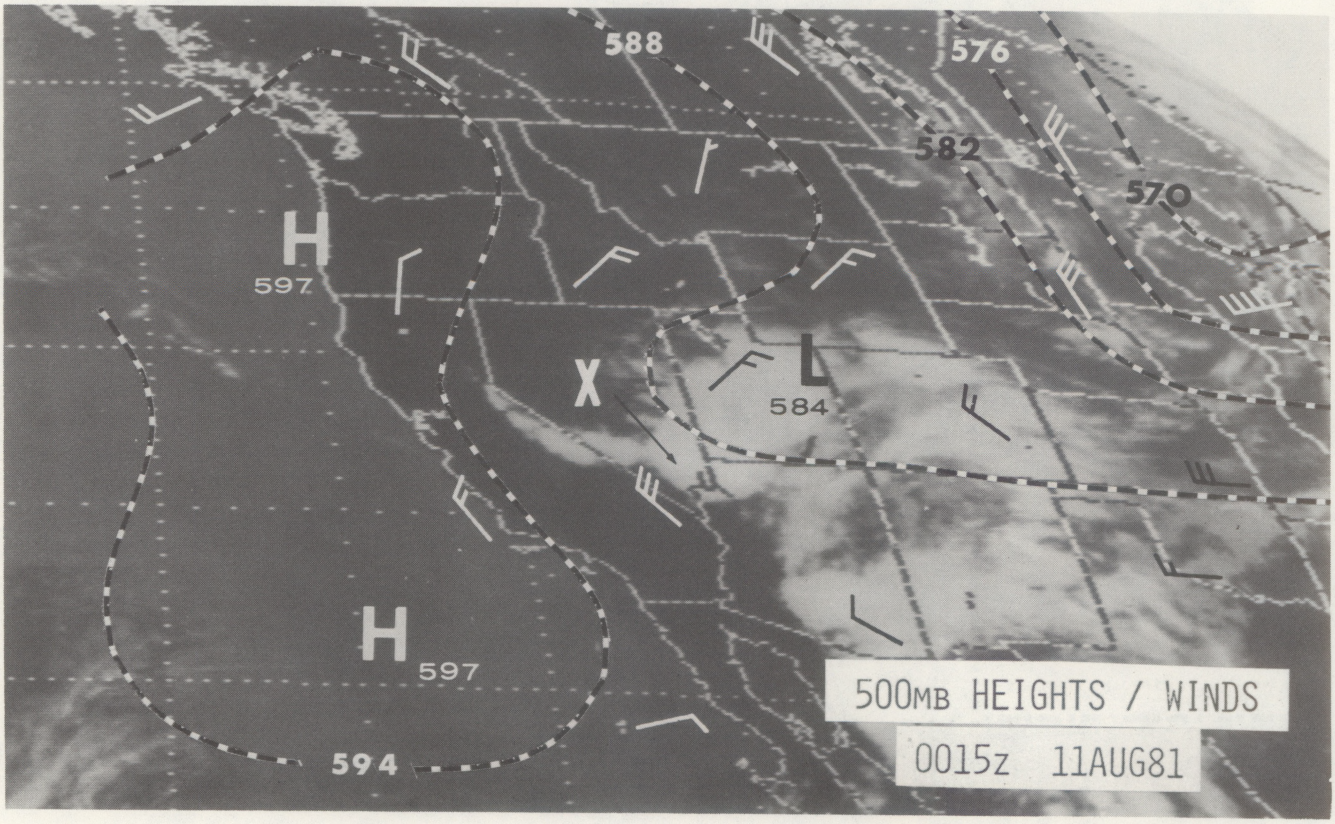


Figure 37. Infrared image at 0015 GMT August 11, 1981 with 0000 GMT 500 mb geopotential heights and winds overlain. The letter (X) refers to the MCS-α system over Clark County, Nevada.

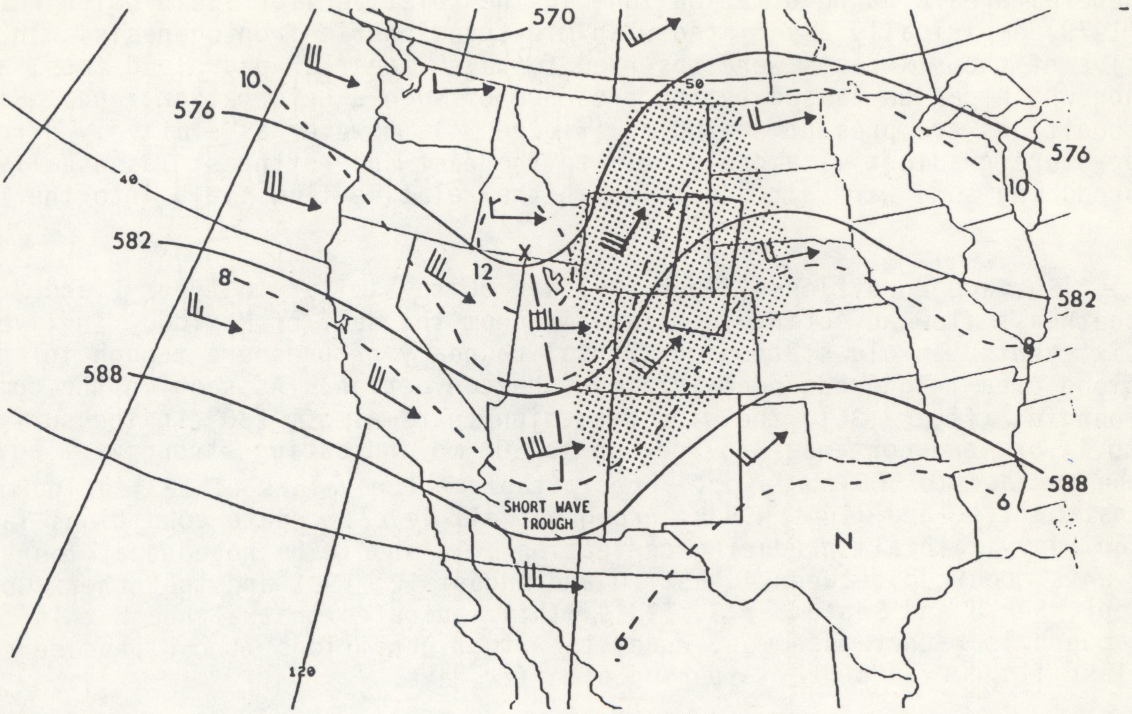


Figure 38. *Atmospheric composite for the 500 mb level Type 4 Short Wave Trough in Zonal Flow events.*

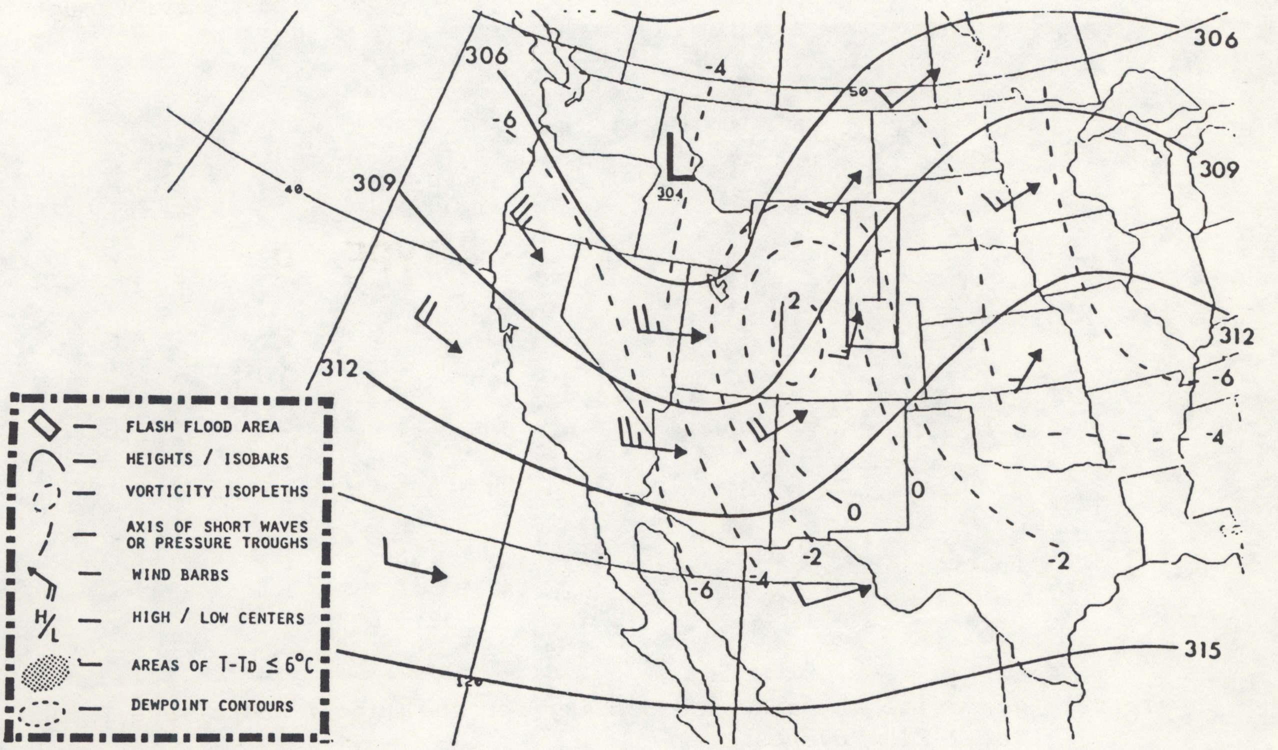


Figure 39. *Atmospheric composite for the 700 mb level Type 4 Short Wave Trough in Zonal Flow events.*

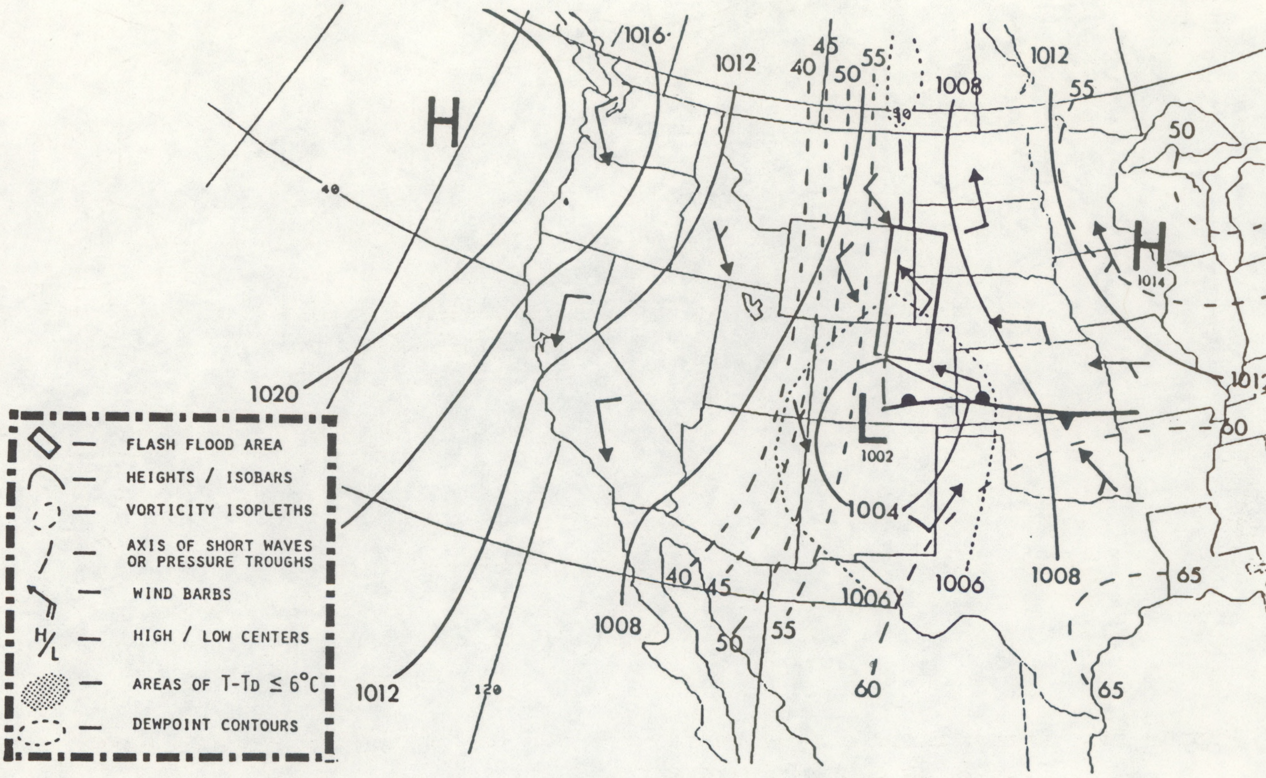


Figure 40. Atmospheric composite for the surface Type 4 Short Wave Trough in Zonal Flow events.

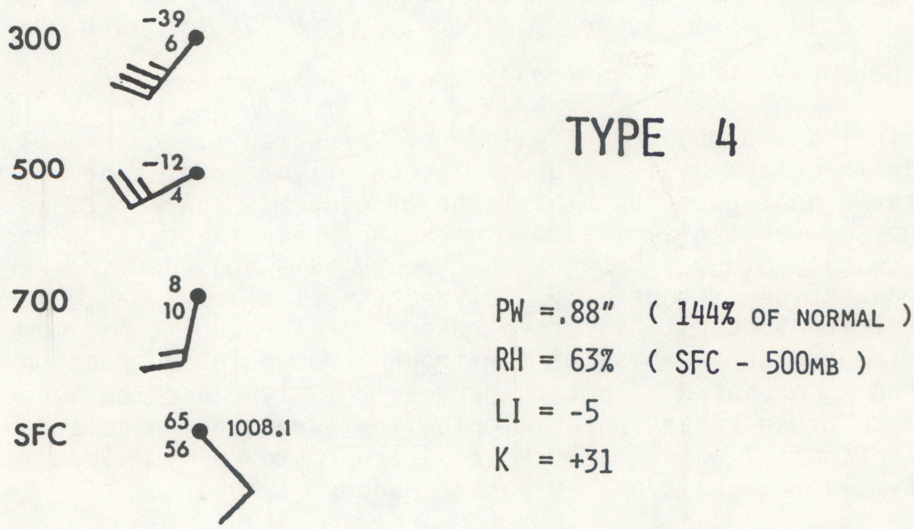


Figure 41. Composite atmospheric sounding for the Type 4 Short Wave Trough in Zonal Flow events.

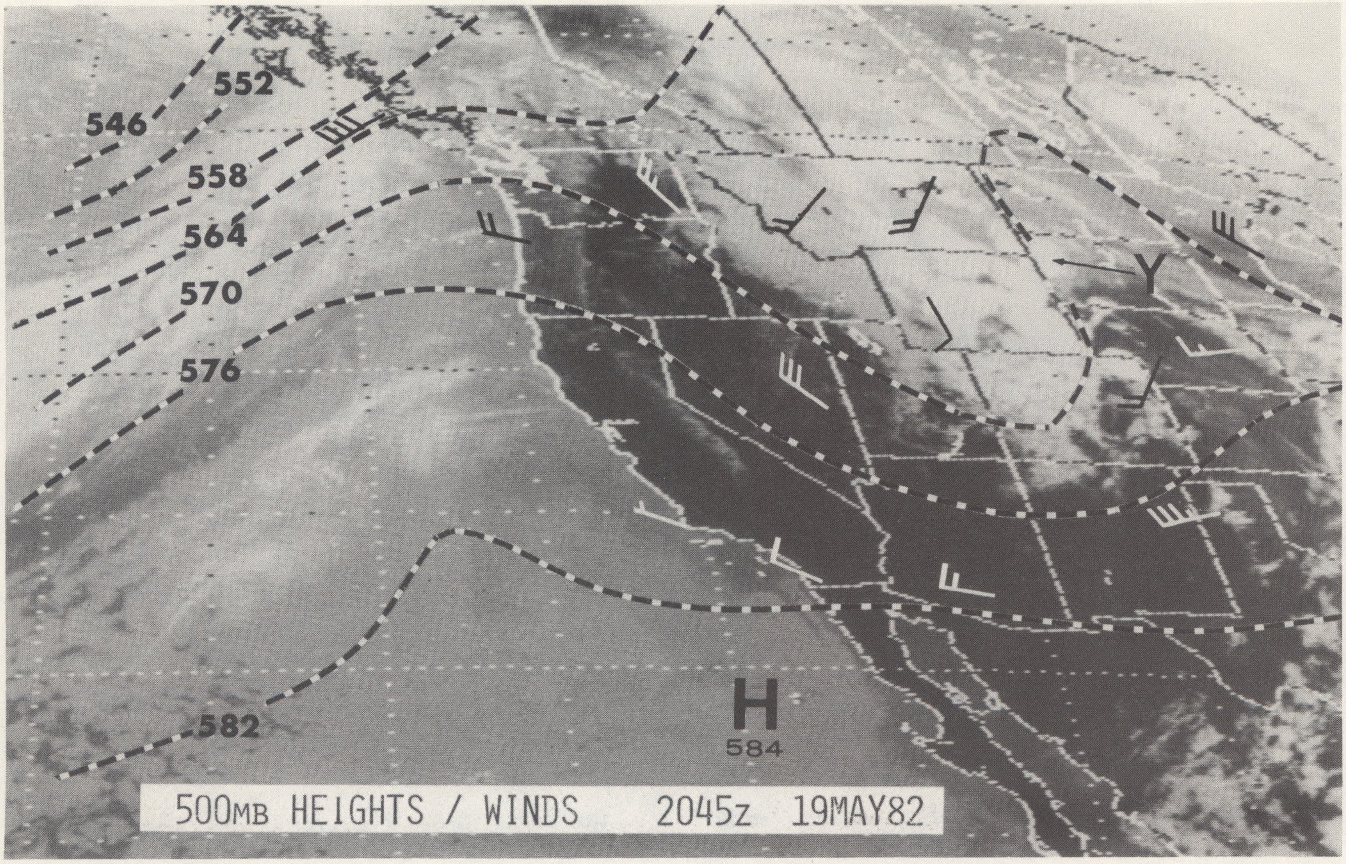


Figure 42. Infrared image at 2045 GMT May 19, 1982 with 0000 GMT 500 mb geopotential heights and winds overlain. The letter (Y) refers to a MCS-β system over the Black Hills of South Dakota.

TYPE 4 - Short Wave Trough in Zonal Flow

The final seven heavy rainfall events occurred along the Colorado front range or in the Black Hills of South Dakota (figure 22). The 500 mb composite chart is shown in figure 38. This type of event is characterized by a short wave trough (of varying amplitude), with the heavy rainfall convective systems occurring roughly mid-way between the trough axis and the ridge crest. Positive vorticity advection is generally analyzed as relatively weak, although a lobe of maximum positive vorticity is often observed. The 500 mb maximum winds occur on the back side and at the base of the trough. Dewpoint depressions are 6°C or less, but an important distinction between this type and the type 2 event is the apparent lack of southeast anticyclonic flow advecting in moisture from the Gulf of Mexico. (Zonal flow is observed equatorward to 25°N). These conditions are somewhat similar to the type I event of Maddox (1980).

The 700 mb composite features (figure 39) are similar to 500 mb although moisture advection is rather small. Warm air advection and a strong southerly ageostrophic component of the wind was observed on the south side of the flood area, which may have triggered or enhanced the heavy precipitation.

The surface composites (figure 40) indicate moist southeasterly upslope flow (5-15 knots) across the Great Plains. A weak low center to the south and pressure trough very near the heavy rainfall area act as triggering and focusing mechanisms for the convection. Warm and very dry conditions exist in the inter-mountain plateau with a sharp dewpoint gradient across the front range. The composite sounding (figure 41) reveals conditions similar to those for types 1, 2, and 3. Warm air advection is present in the surface to 700 mb layer, and weak winds are present throughout all levels (although the 300 mb winds are slightly stronger than for types 1, 2, and 3). Precipitable water is well above normal and very unstable conditions are present.

Six of the seven events were observed to have linear-shaped cloud tops, and all type 4 events occurred from May 19 through July 2. It is postulated that a blocking upper level ridge over the central U.S. becomes dominant in middle and late summer which in turn greatly inhibits the passage of short wave troughs and the occurrence of this type of system.

Figure 42 shows an example of a typical type 4 event. The 500 mb wind and height fields for 0000 GMT May 20, 1982 are superimposed on a corresponding infrared satellite image. Heavy rainfall from a large MCS- β(linear) system (Y) produced flash flooding in the Black Hills of South Dakota.

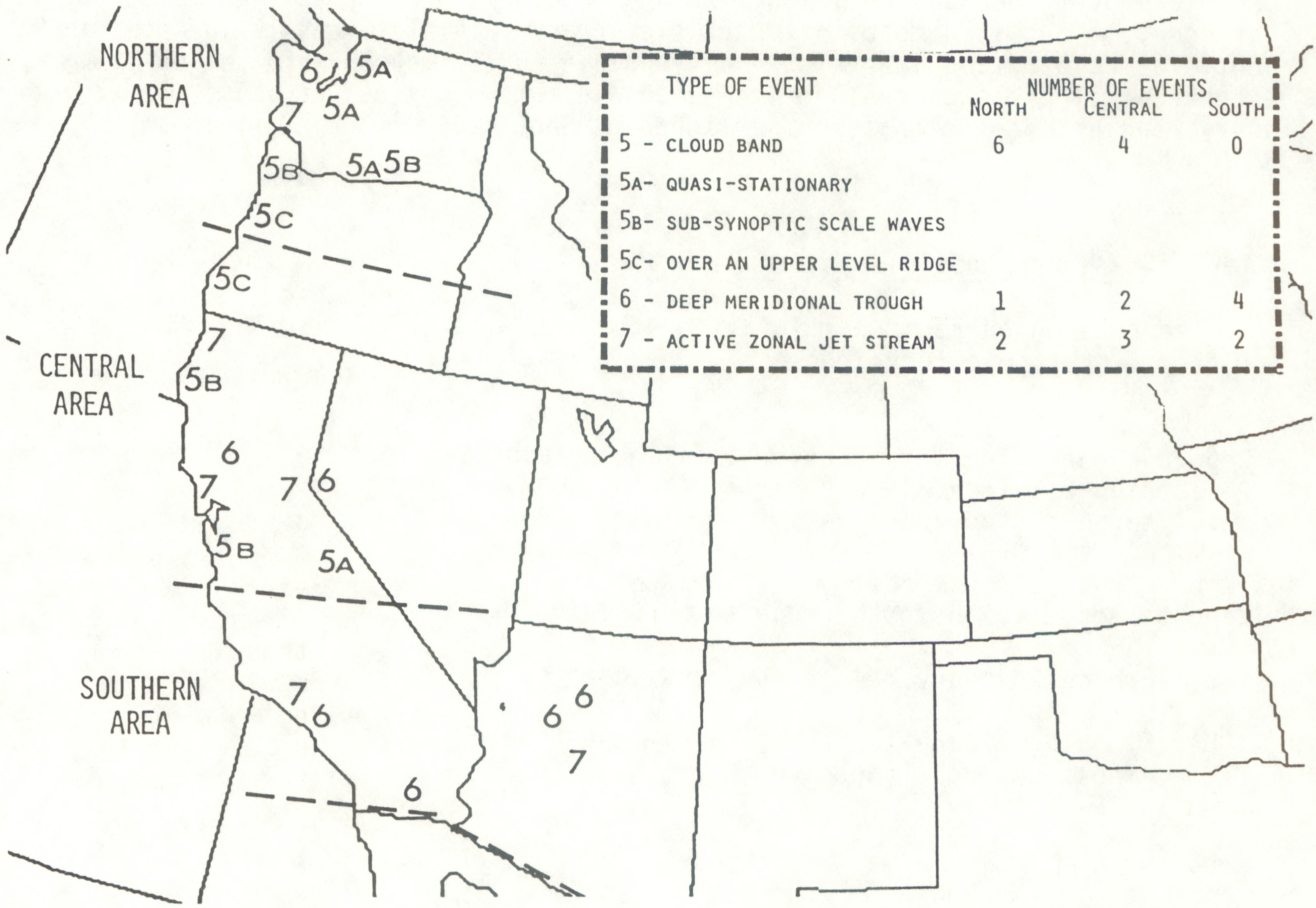


Figure 43. Map of location and type of system for the 24 heavy rainfall extratropical cyclone events in this study.

IV. RESULTS - Heavy Rainfall Extratropical Cyclone Events

Extratropical cyclone heavy rainfall events are an important phenomena for the western region, particularly for the coastal regions of Washington, Oregon, and California. Strong extratropical cyclones moving onshore from the eastern Pacific often produce flash floods when they interact with the mountain ranges along the west coast.

Between 1981 and 1983, 72 reports in the "Storm Data" mentioned either heavy rainfall or flooding from non-convective systems in the western region. Forty-eight of these were eliminated because of prolonged heavy rain on successive days or flooding of coastal areas mainly due to high winds and high tides (Table 3). The remaining 24 events were then selected for further study.

The locations of the twenty-four extratropical cyclone events selected for further study are shown in figure 43. A detailed study of the satellite-observed cloud signatures and synoptic patterns for each event shows these events can be grouped into three main categories: the quasi-stationary cloud band category, the deep meridional trough category, and the active jet stream category. A detailed description of each heavy rainfall event is in Appendix B. Scofield, et al. (1984) developed a technique to estimate precipitation from extratropical cyclones. All of the cases in this study had at least one of the heavy precipitation signatures mentioned by Scofield.

Table 3 - Extratropical Cyclone Reports	Number of Reports
All reports which mention rainfall or flooding from extratropical cyclones	72
Reports mentioning very heavy rainfall or flash flooding within a 24 hour period (selected for further study)	24
Reports not studied further due to mentioning of:	48
1) Prolonged heavy rain on successive days	40
2) Flooding of coastal areas mainly due to high winds and high tides	8

Quasi-Stationary Cloud Band - Type 5

Ten of the extratropical cyclone heavy rainfall events were observed in the satellite imagery to be produced by quasi-stationary cloud bands. These cloud bands were composed of deep layered clouds and were associated with strong baroclinic frontal zones. In four of the events the cloud band appeared very straight and narrow and extended southwest to northeast from the Pacific Ocean inland several hundred miles (Figure 44). The location of the heavy rainfall area beneath the cloud band varied with respect to the location of the low-level baroclinic frontal zone within the cloud band. On December 3, 1982 a quasi-stationary cloud band (Z) and frontal zone produced up to seven inches of rain and considerable amount of river and stream flooding in northwestern Washington (Figure 45). In this case the location of the surface frontal zone and heavy rainfall area occurred in the central portion of the cloud band.

Sub-synoptic scale waves developing along a cloud band produced four heavy rainfall events in this study. The sub-synoptic scale waves appeared as an anticyclonic bulge along the northern edge of the cloud band. The sub-synoptic scale wave head continued to develop and enlarge with the wave head curving more anticyclonic with time (Figures 46a, b, and c). Scofield and Spayd (1984) described the evolutions of heavy rainfall producing sub-synoptic scale waves in the eastern United States. In Figures 47a, b a sequence of visible and enhanced infrared images shows a subsynoptic scale wave along a cloud band on October 28-29, 1982 which caused flooding in Benton Co., Washington (AA). During this event the surface frontal zone and flooding was located in the central portion of the cloud band. The clouds south of the frontal zone are mainly high clouds curving anticyclonically over an upper level east-west oriented ridge. The heavy rainfall occurred when the bulge or curvature of the sub-synoptic scale wave was observed developing along the northwestern edge of the cloud band.

Two heavy rainfall events appeared as quasi-stationary cloud bands which were curved anticyclonically over a large scale ridge. Short-wave troughs passing over the ridge intensified the rainfall along the baroclinic zone/cloud band. Figures 48a,b shows the schematics of evolution for a cloud band curved anticyclonically over a large scale ridge. On December 14, 1983 the south central Oregon coast received up to five inches of rainfall from a quasi-stationary cloud band (BB) which extended over a large scale ridge (Figure 49a,b). As shown in figure 48 the heavy rainfall area occurred along the southern edge of the enhanced clouds where the low-level frontal convergence was located.

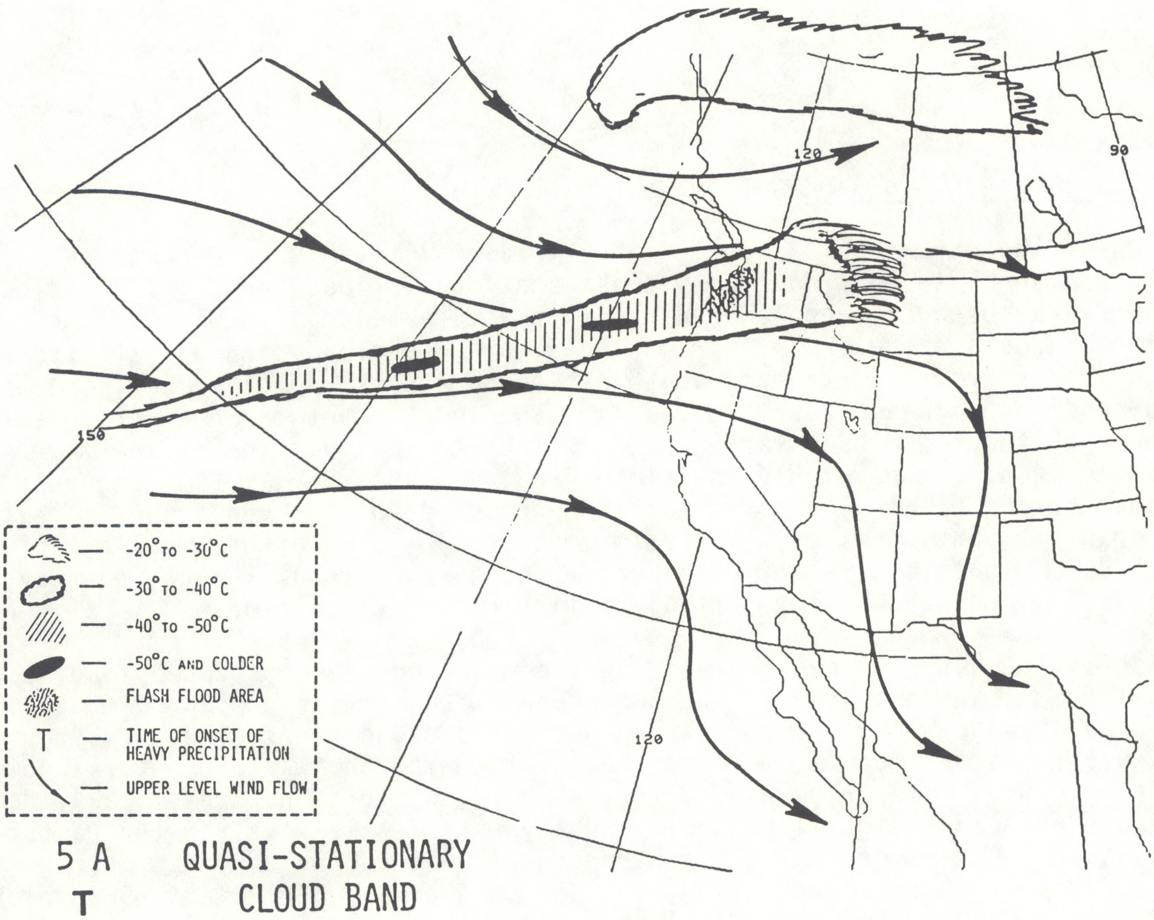


Figure 44. Cloud-top schematics of a heavy rainfall producing quasi-stationary cloud band - Type 5A for time T.

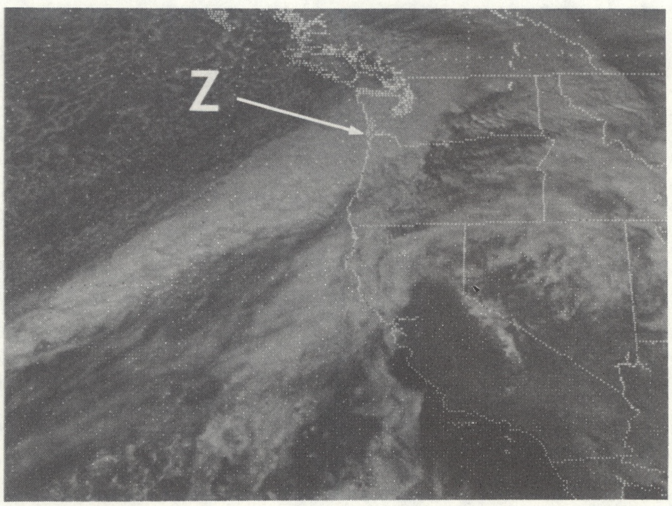


Figure 45. A visible image at 2045 GMT December 3, 1982. The letter (Z) points to a quasi-stationary cloud band over Washington.

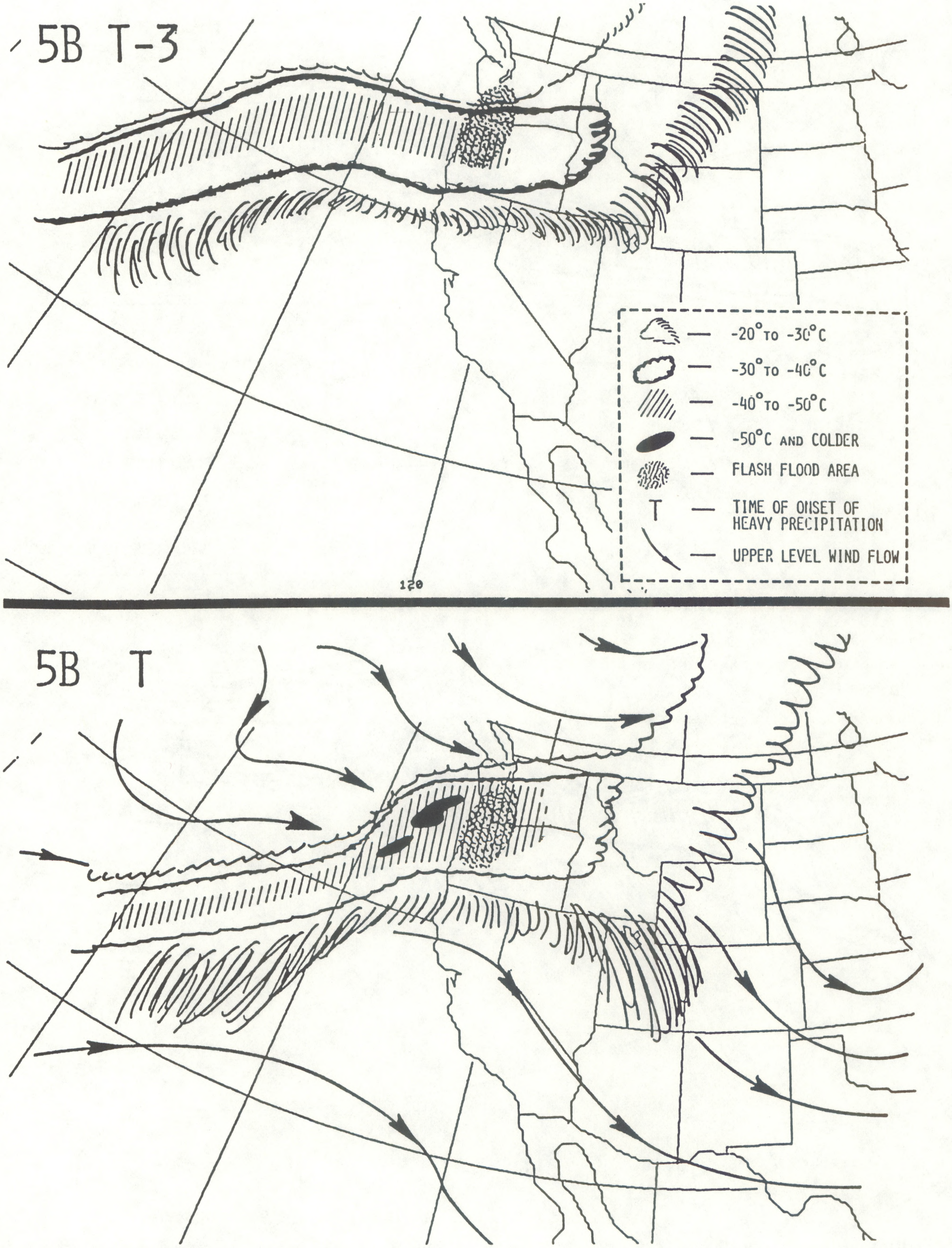


Figure 46a. Cloud top schematic of a heavy rainfall producing cloud band with sub-synoptic scale waves - Type 5B for times T-3 and T.

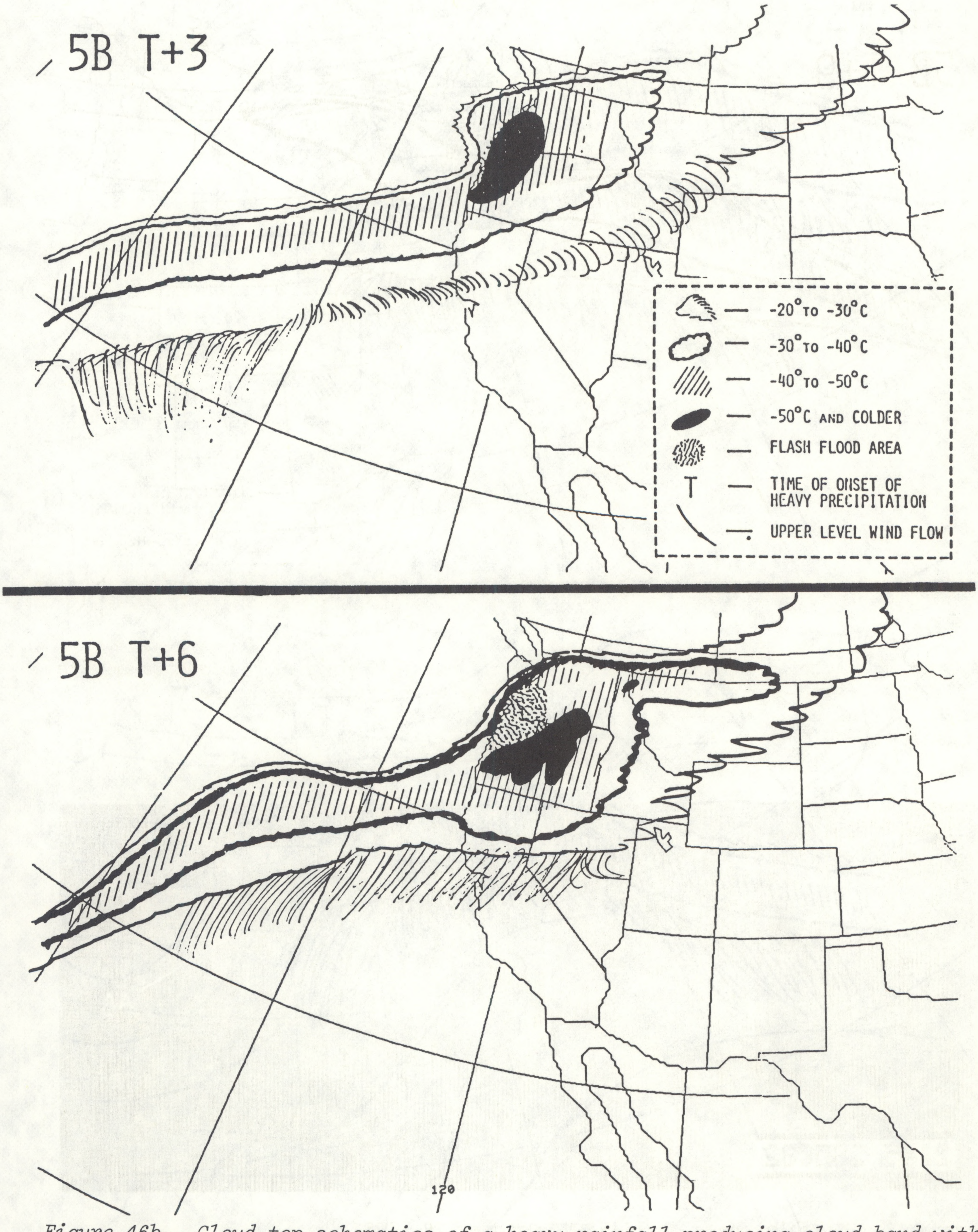


Figure 46b. Cloud top schematics of a heavy rainfall producing cloud band with sub-synoptic scale waves - Type 5B for times T+3 and T+6 hours.

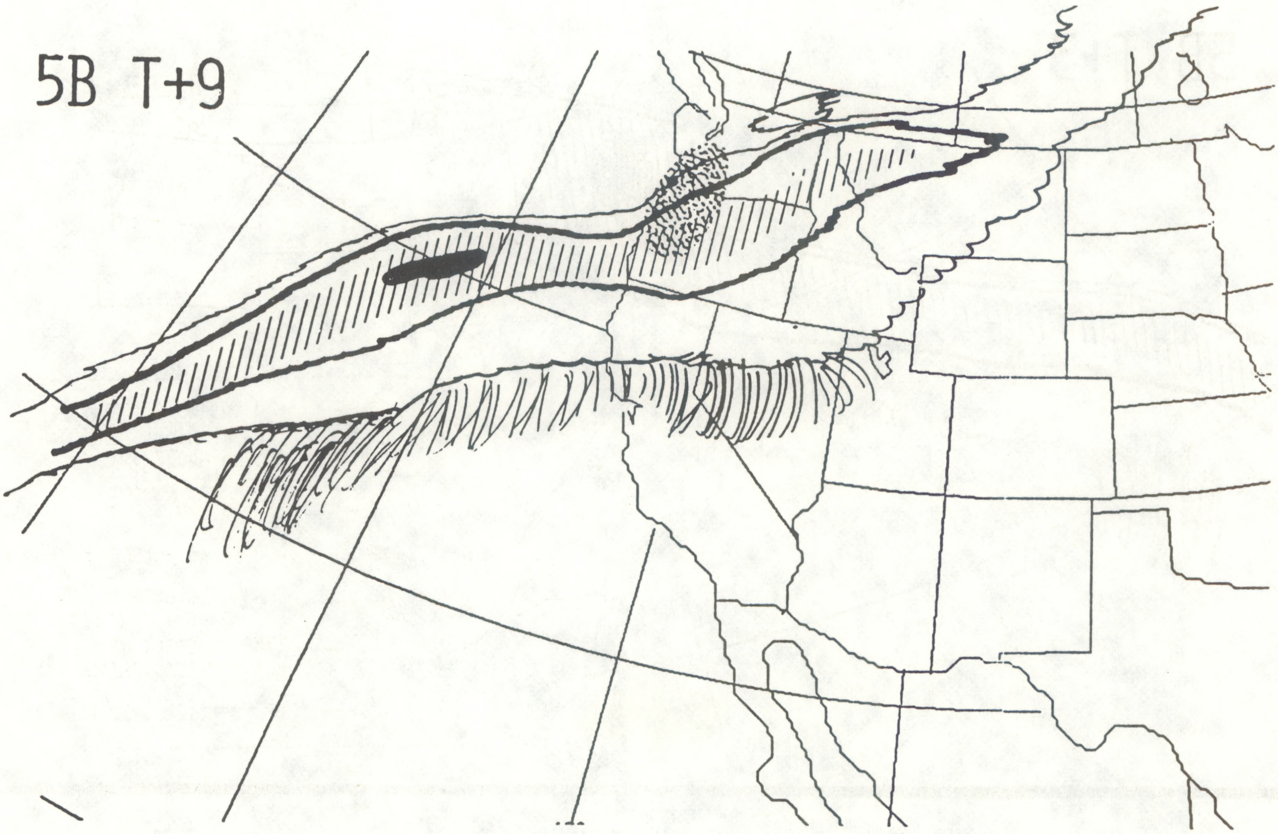


Figure 46c. Cloud top schematic of a heavy rainfall producing cloud band with sub-synoptic scale waves - Type 5B for time T+9 hours.

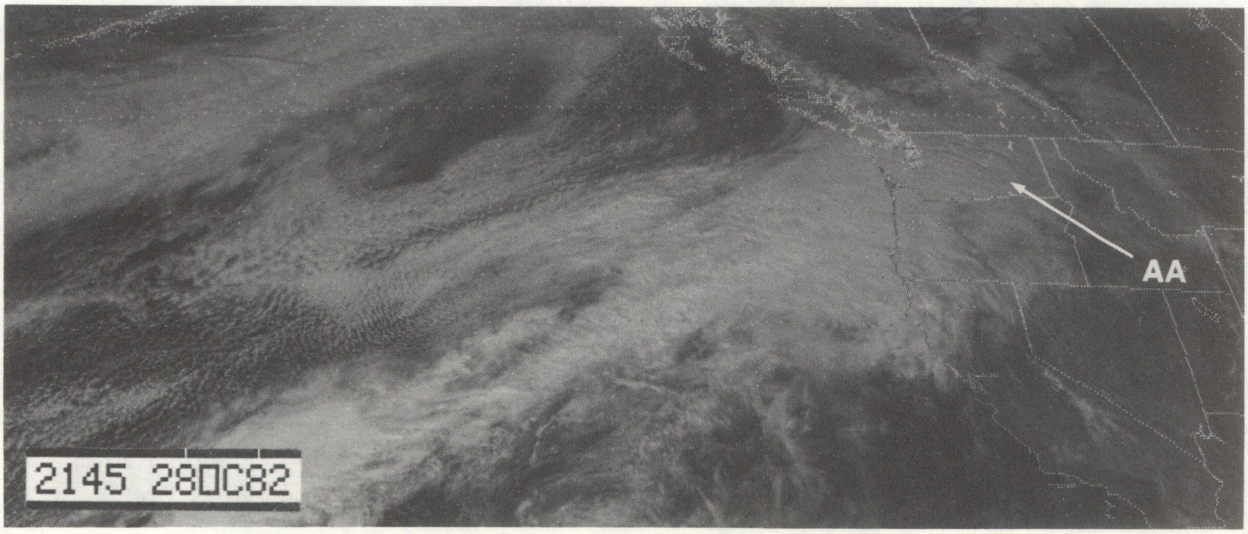


Figure 47a. Visible image at 2145 GMT October 28, 1982.

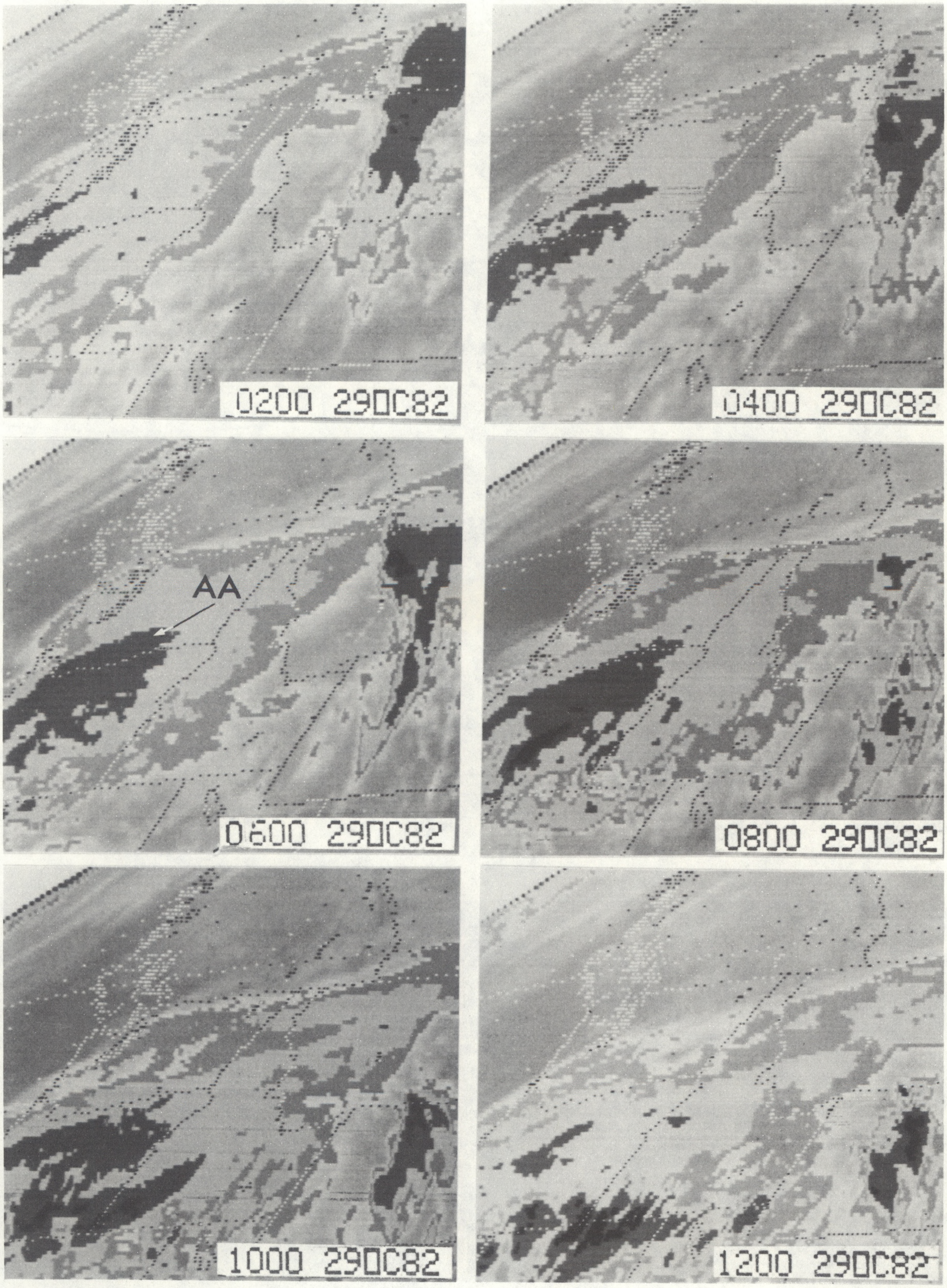


Figure 47b. Enhanced IR images (Mb curve) at 0200, 0400, 0600, 0800, 1000, and 1200 GMT on October 29, 1982. The letters (AA) point to a sub-synoptic scale wave which caused flooding in Benton County, Washington.

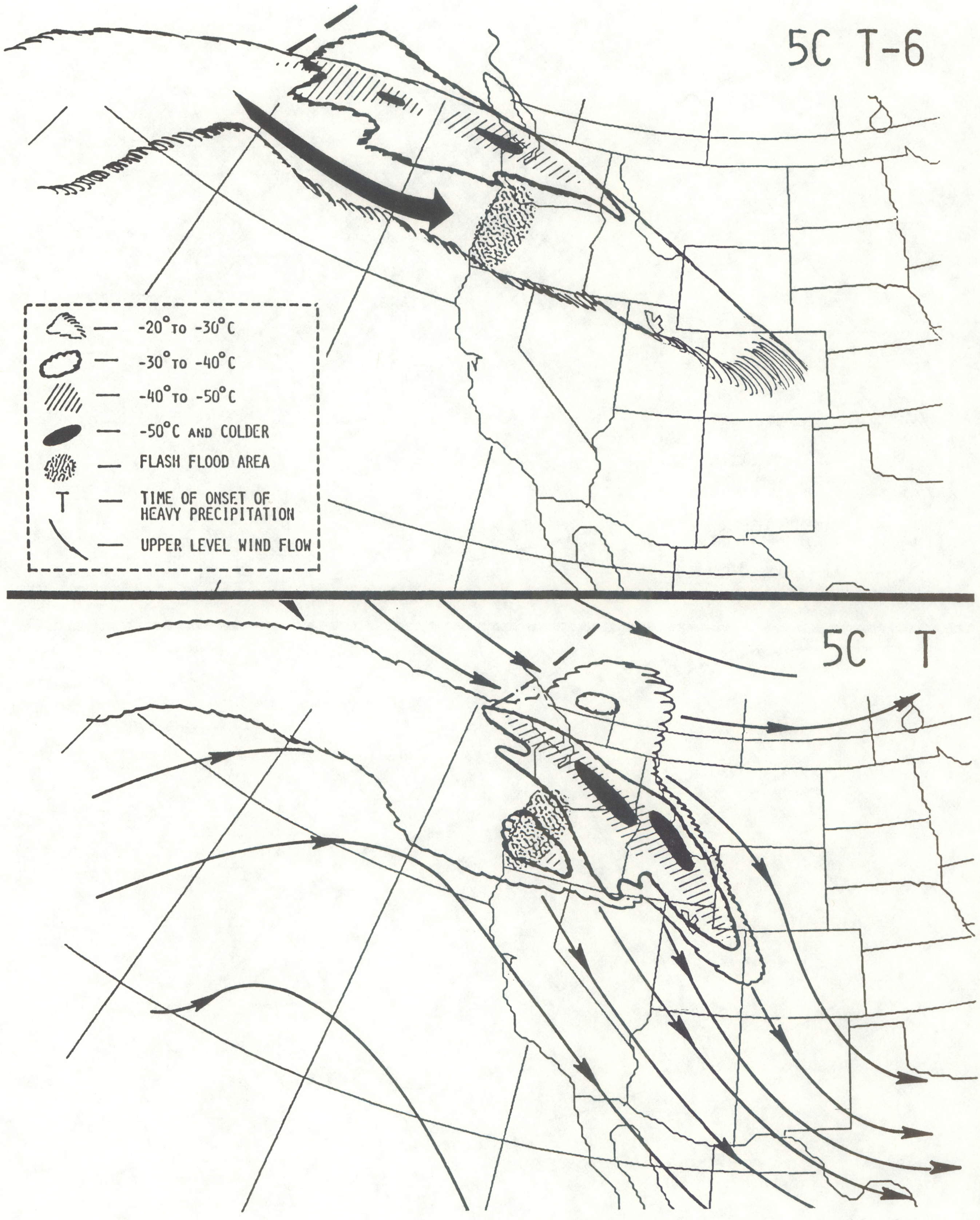


Figure 48a. Cloud top schematics of a heavy rainfall producing cloud band over an upper-level ridge - Type 5C for times T and T-6 hours.

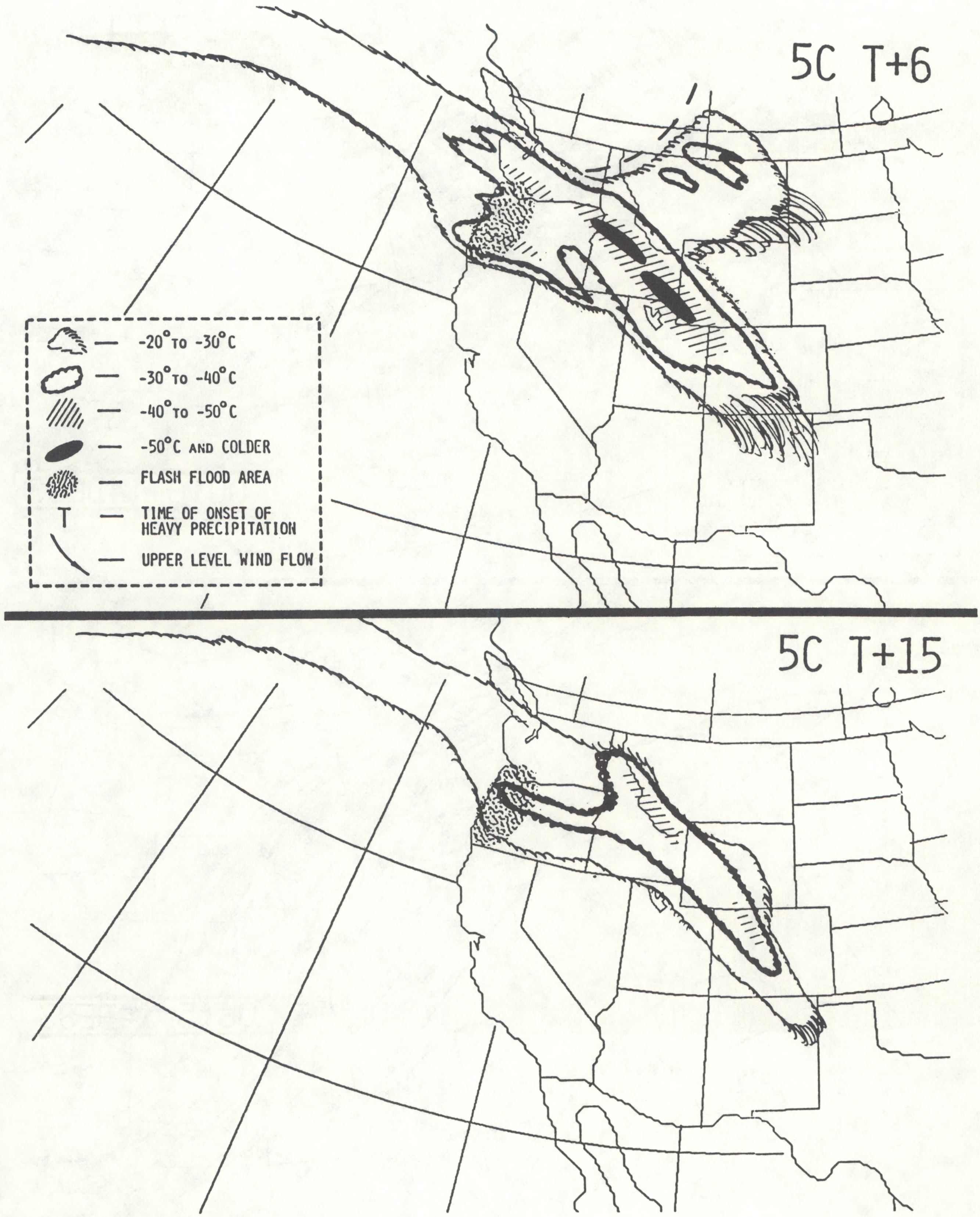


Figure 48b. Cloud top schematics of a heavy rainfall producing cloud band over an upper-level ridge - Type 5C for times T+15 and T+6 hours.

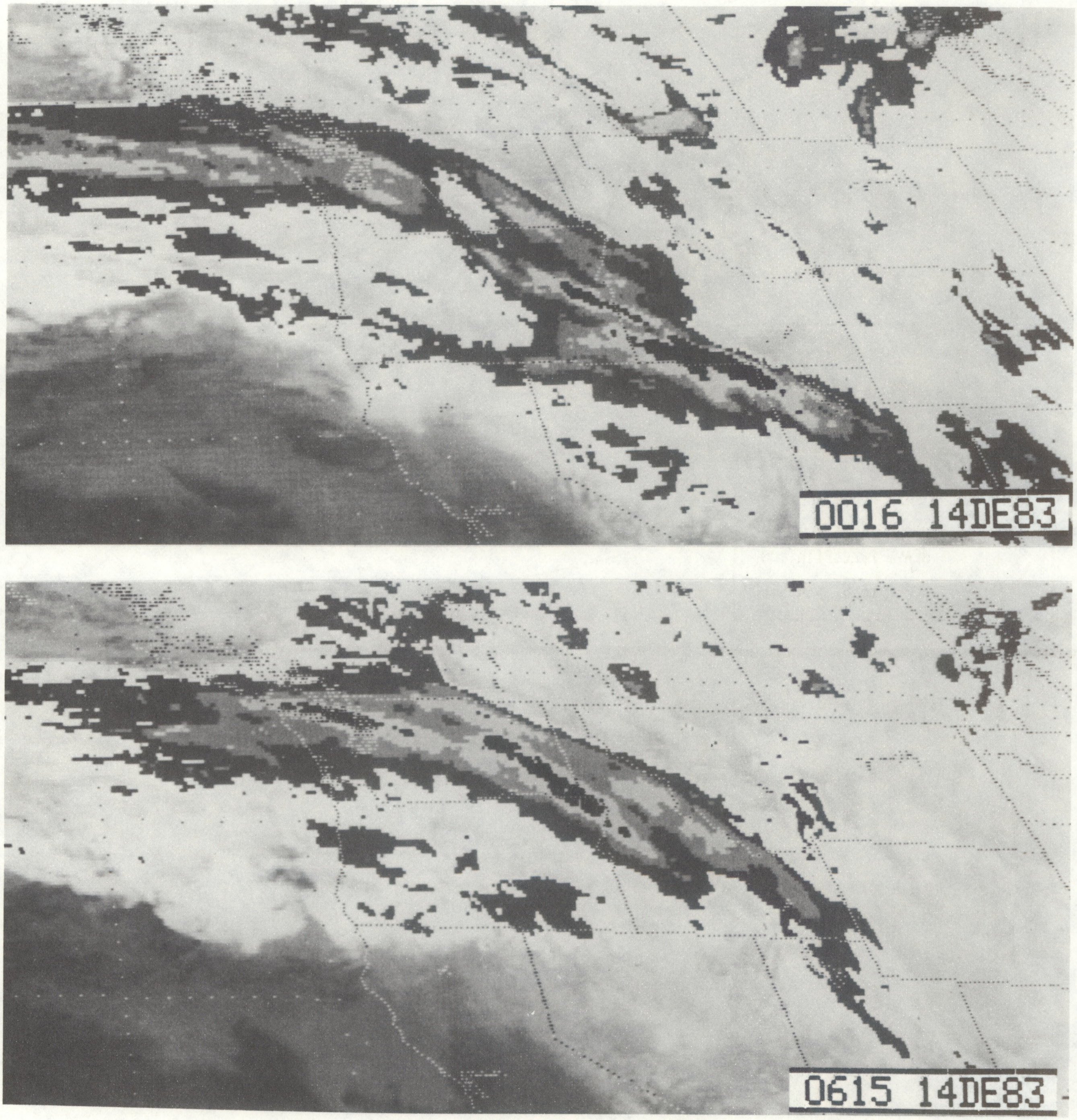


Figure 49a. Enhanced IR images (HF curve) at 0016 GMT and 0615 GMT on December 14, 1983.

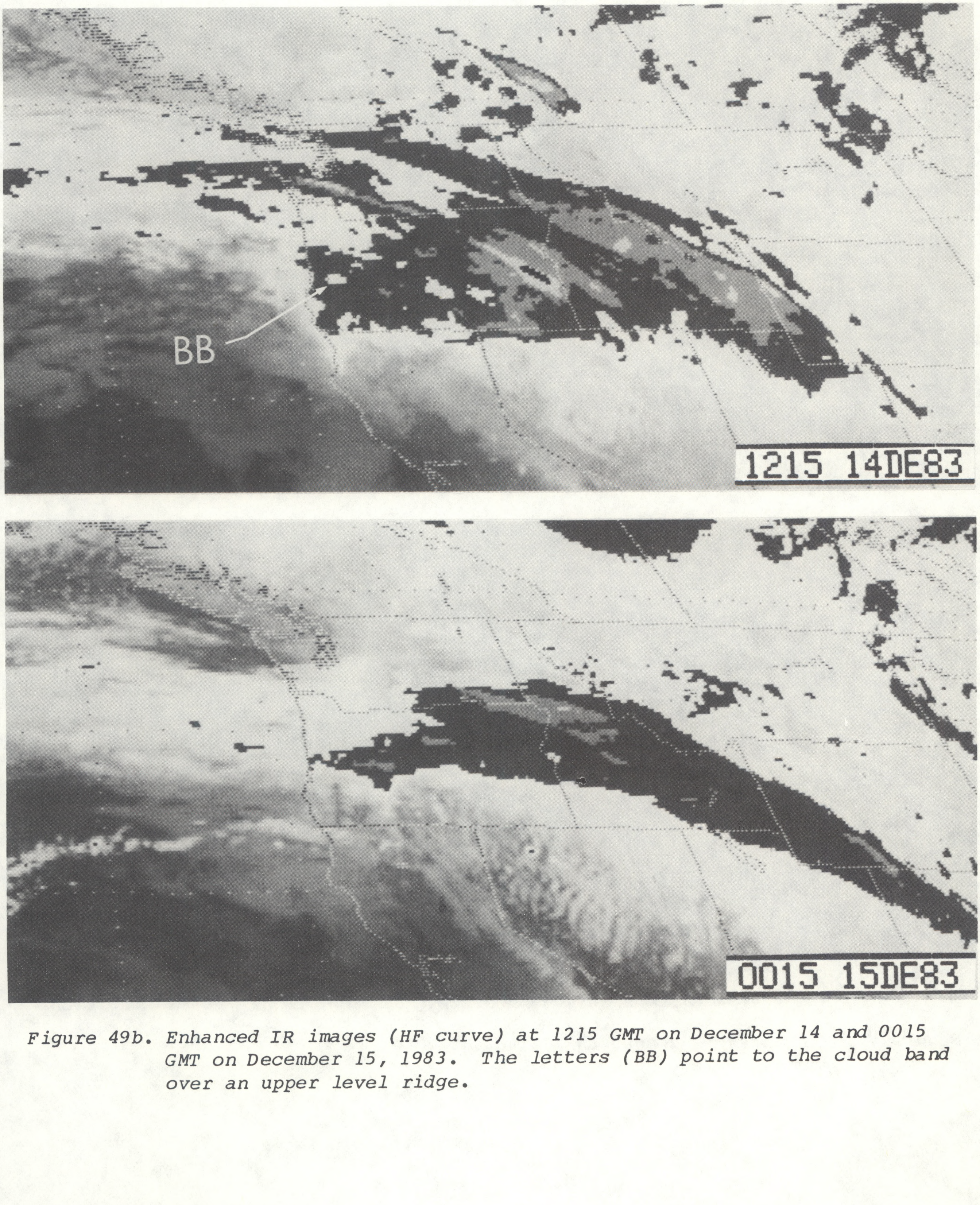


Figure 49b. Enhanced IR images (HF curve) at 1215 GMT on December 14 and 0015 GMT on December 15, 1983. The letters (BB) point to the cloud band over an upper level ridge.

Deep Meridional Trough - Type 6

Seven heavy precipitation extratropical cyclone events were associated with a deep meridional trough in the westerlies. The axis of the long wave trough was about five to ten degrees west of the coastline and a series of short wave troughs/vorticity centers passed through the long wave trough. Often a large anticyclonic flow of cold cloud tops associated with the subtropical jet stream or southern portion of the polar jet was observed. This flow of high clouds bulged northward as the first major short wave started "lifting out" of the long wave trough. As succeeding short waves traversed the base of the trough the cloud tops associated with the short wave troughs expanded, cooled, and took on a pronounced comma appearance. The schematics of evolution in figures 50a, b, c show the typical evolution of cloud top patterns observed with this type of heavy precipitation event. The heavy rainfall areas generally occurred where the "comma head" of the short wave troughs reached their maximum "development" or where successive "comma heads" traversed the same area.

On March 1-3, 1981 a series of short wave troughs produced up to six inches of rainfall in southern California producing flooding and mudslides. Figure 51 is a sequence of infrared imagery showing the evolution of the short wave troughs embedded within a deep meridional trough.

Active Zonal Jet Stream - Type 7

In this study there were seven heavy rainfall events produced by short wave troughs embedded in a strong zonal jet stream. The short wave troughs progressed eastward at speeds of up to 20 degrees of longitude per day. The heavy rainfall area occurred where the largest number of atmospheric features such as comma heads, baroclinic frontal bands, and areas of enhanced cold air advection cumulus traversed the same area. Cloud top schematics of evolution for these short wave troughs embedded in a zonal jet stream are shown in figures 52a, b, c. In areas of strong zonal winds the comma head cloud patterns may elongate in an east-west direction and traverse the same area as they proceed eastward. The heavy rainfall occurred where successive frontal bands and their corresponding comma heads traversed the same location.

On February 26-28, heavy rainfall produced by a series of short wave troughs moving rapidly eastward produced flooding in parts of northern and central California (Figure 53).

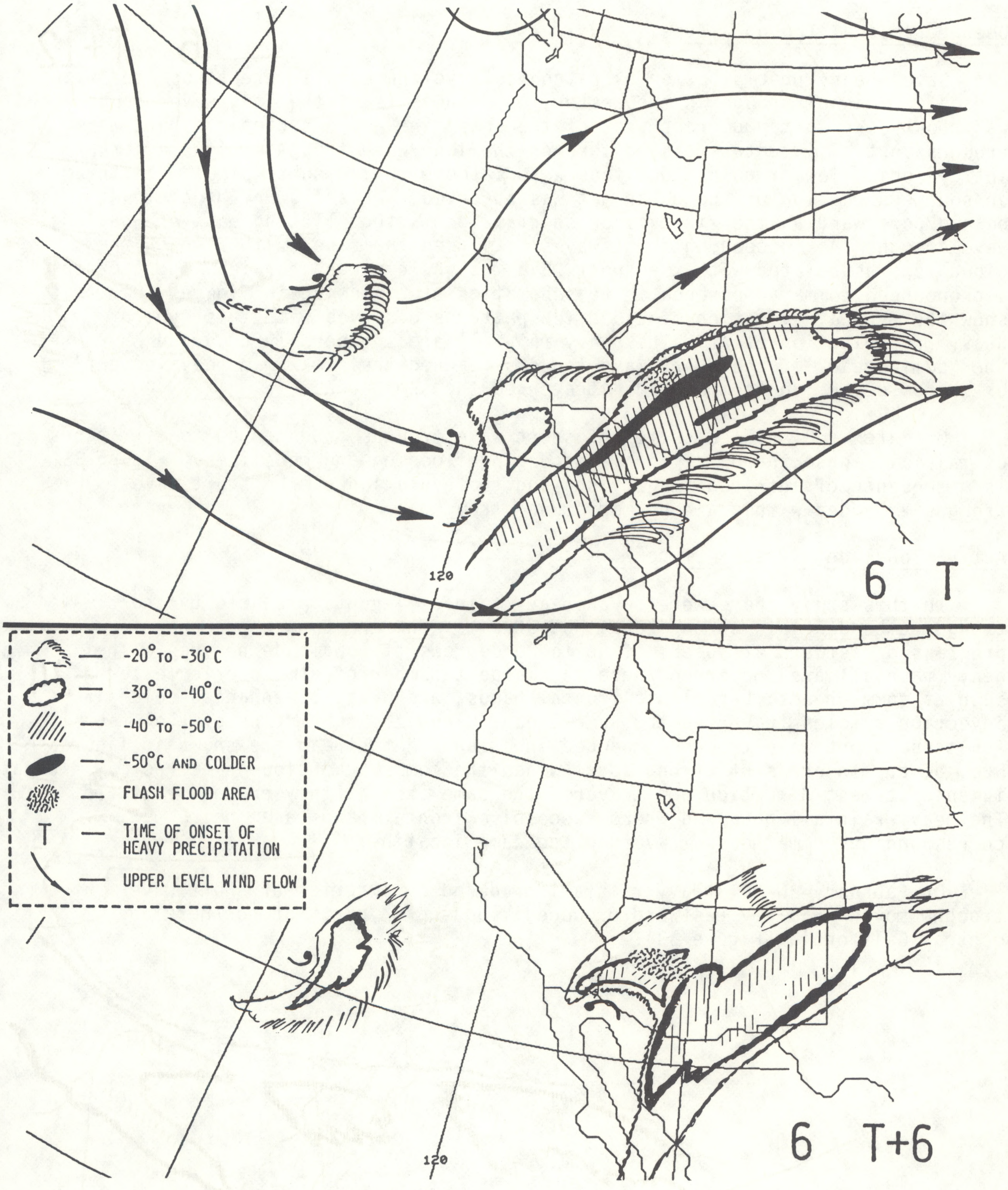


Figure 50a. Cloud top schematics of the heavy rainfall producing deep meridional trough - Type 6 for times T and T+6 hours.

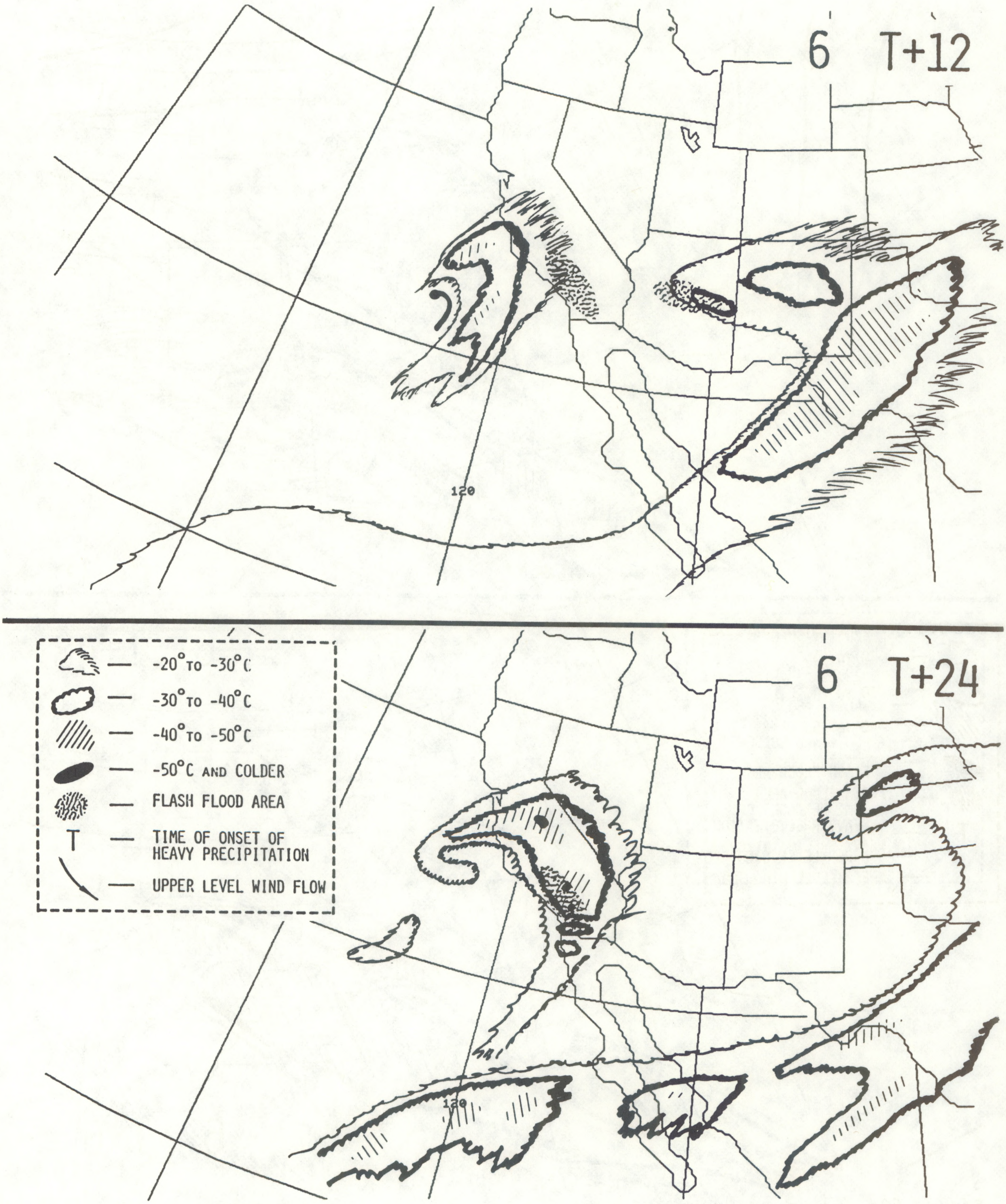


Figure 50b. Cloud top schematics of the heavy rainfall producing deep meridional trough - Type 6 for times T+12 and T+24 hours.

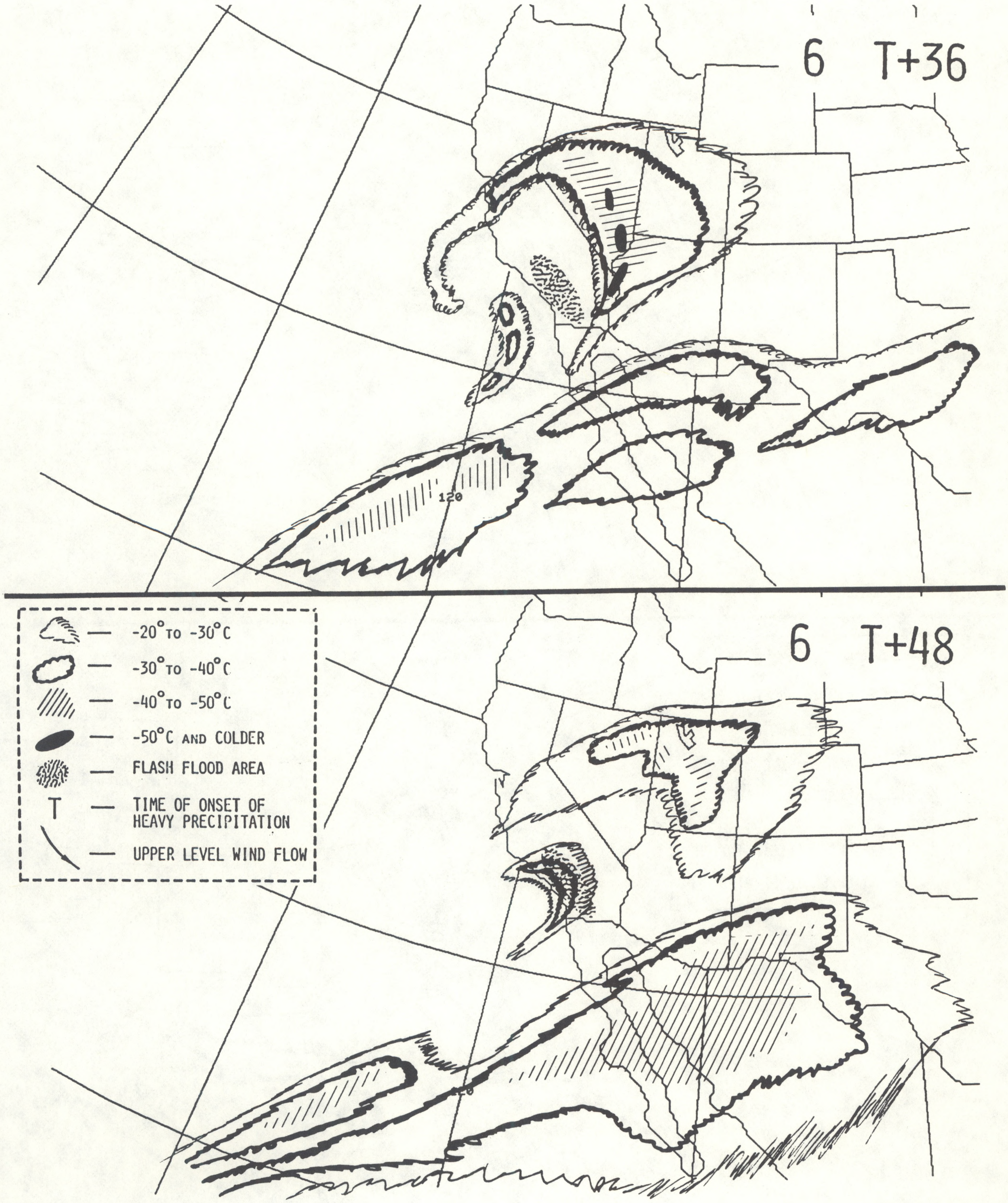


Figure 50c. Cloud top schematics of the heavy rainfall producing deep meridional trough - Type 6 for times T+36 and T+48 hours.

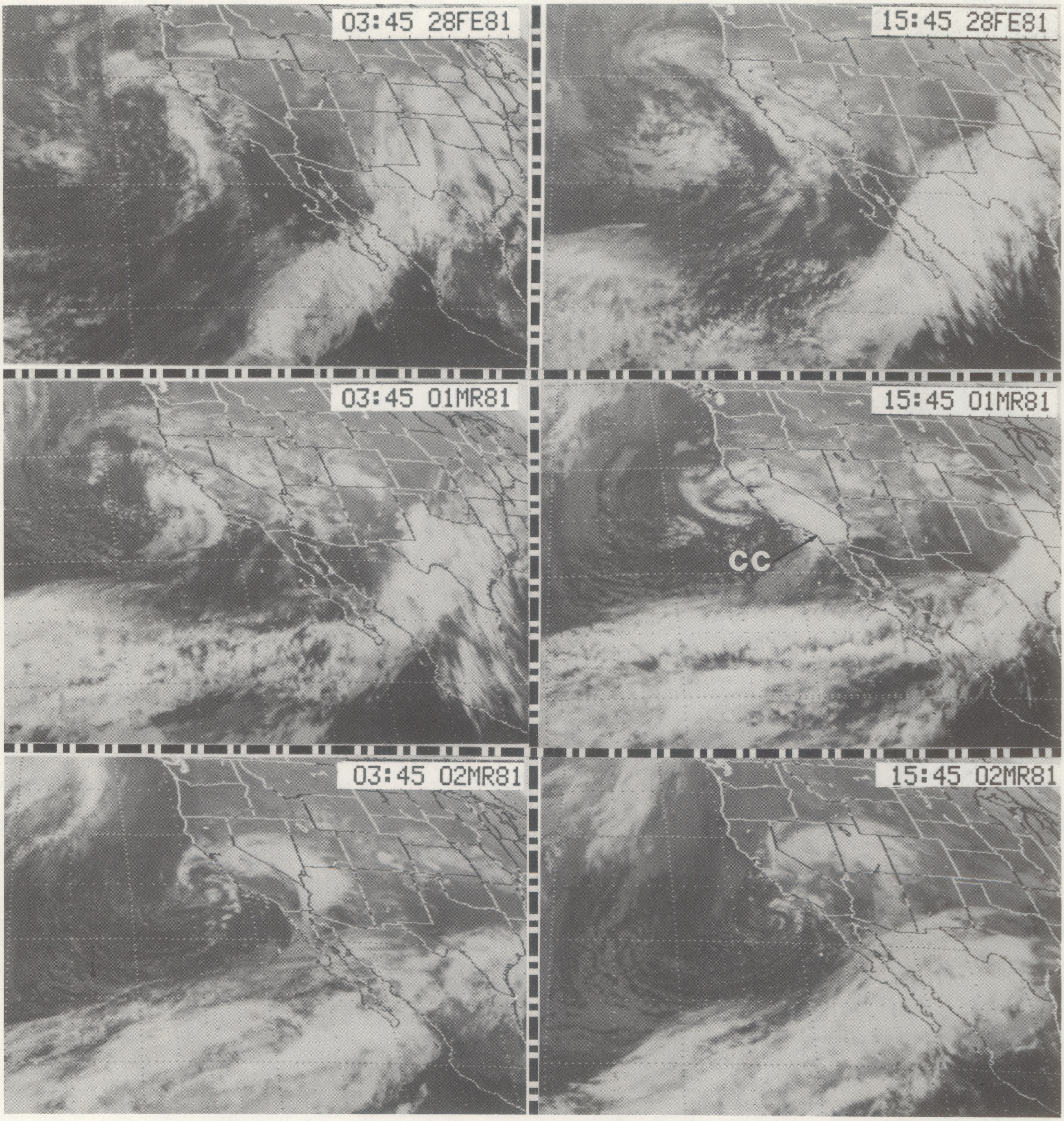


Figure 51. Infrared images at 0345 GMT and 1545 GMT on February 28 through March 2, 1981. The letters CC point to the heavy rainfall area in southern California.

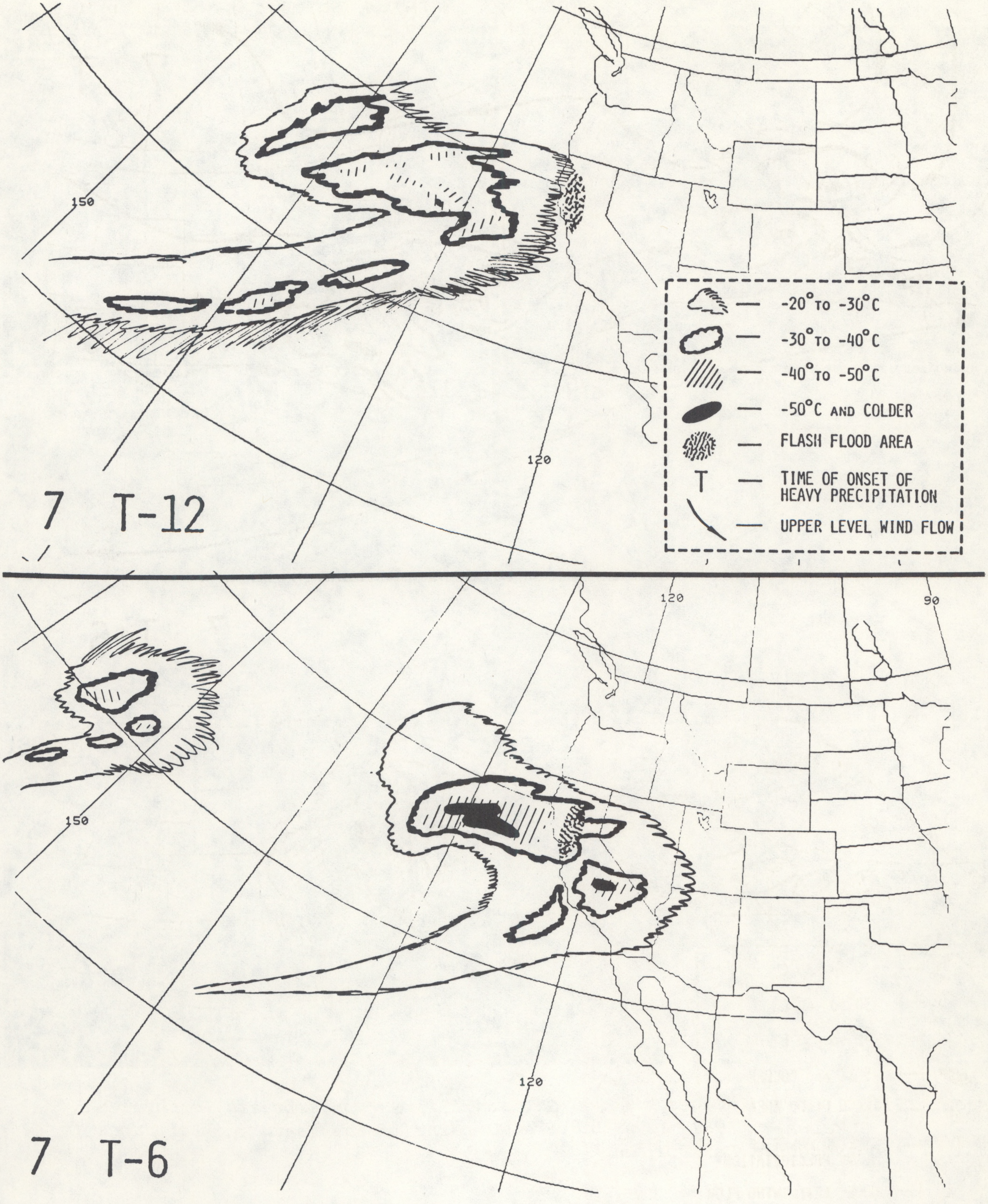


Figure 52a. Cloud top schematics of a heavy rainfall producing active zonal jet stream-Type 7 for times T-12 and T-6 hours.

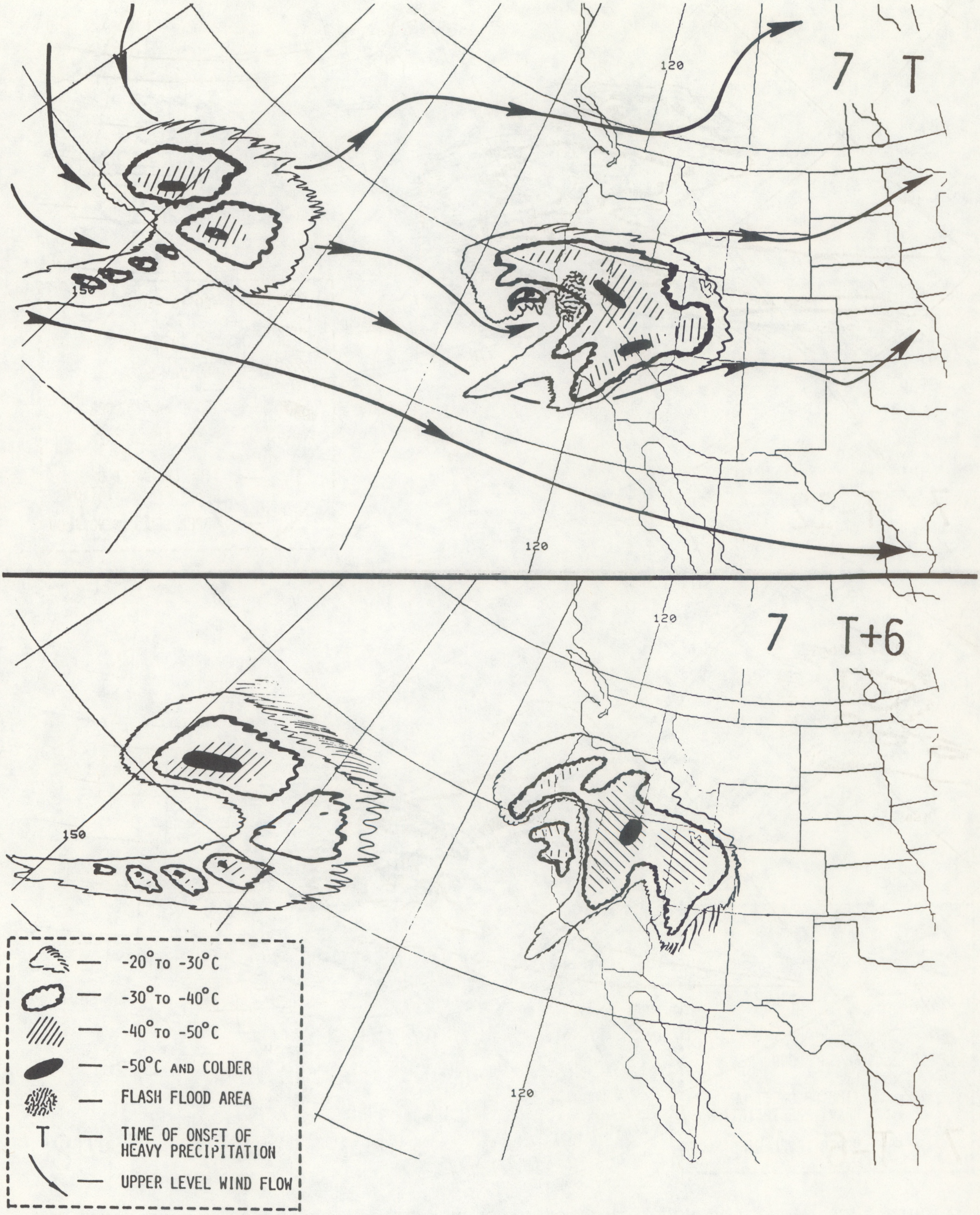


Figure 52b. Cloud top schematics of a heavy rainfall producing active zonal jet stream - Type 7 for times T and T+6 hours.

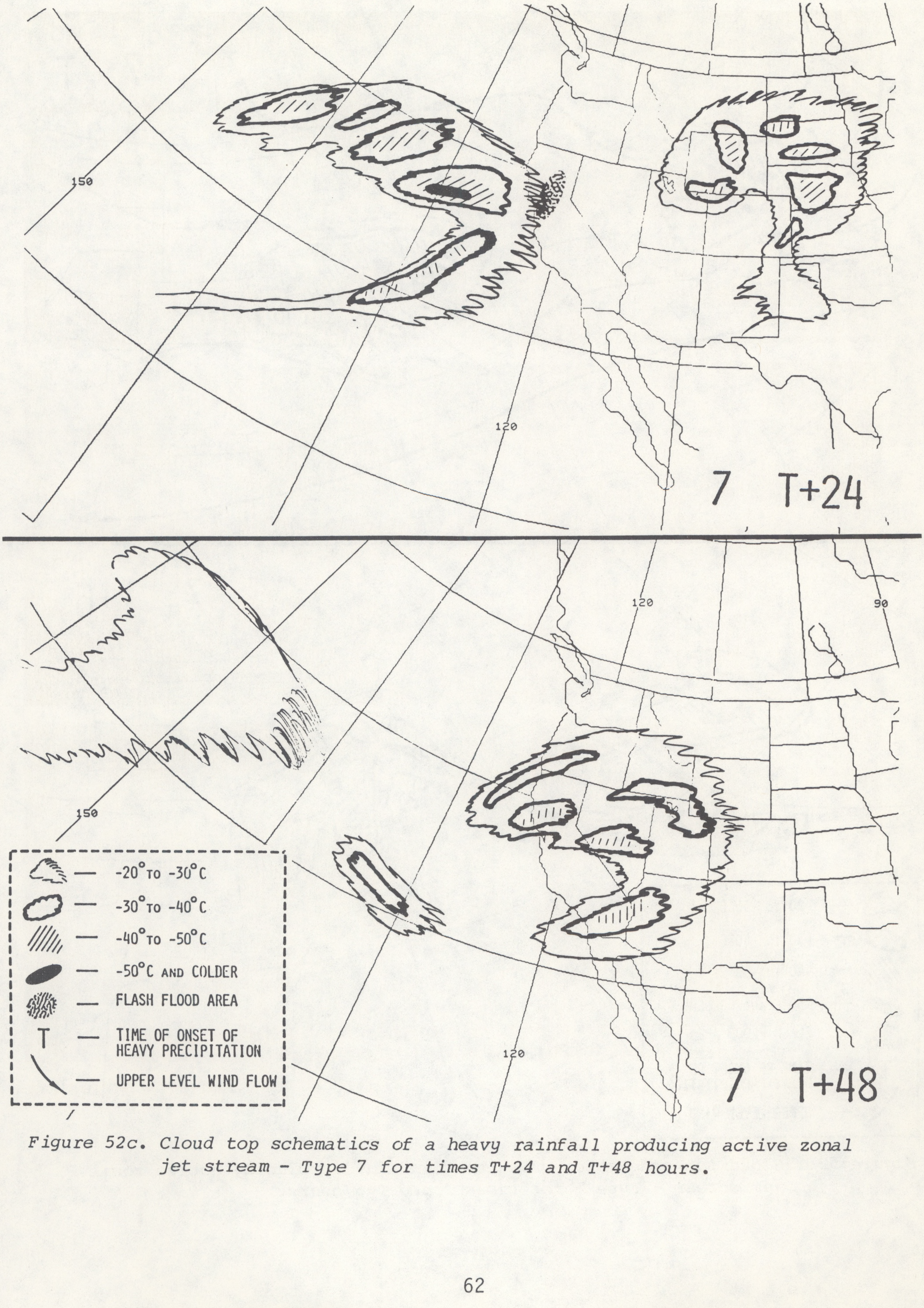


Figure 52c. Cloud top schematics of a heavy rainfall producing active zonal jet stream - Type 7 for times T+24 and T+48 hours.

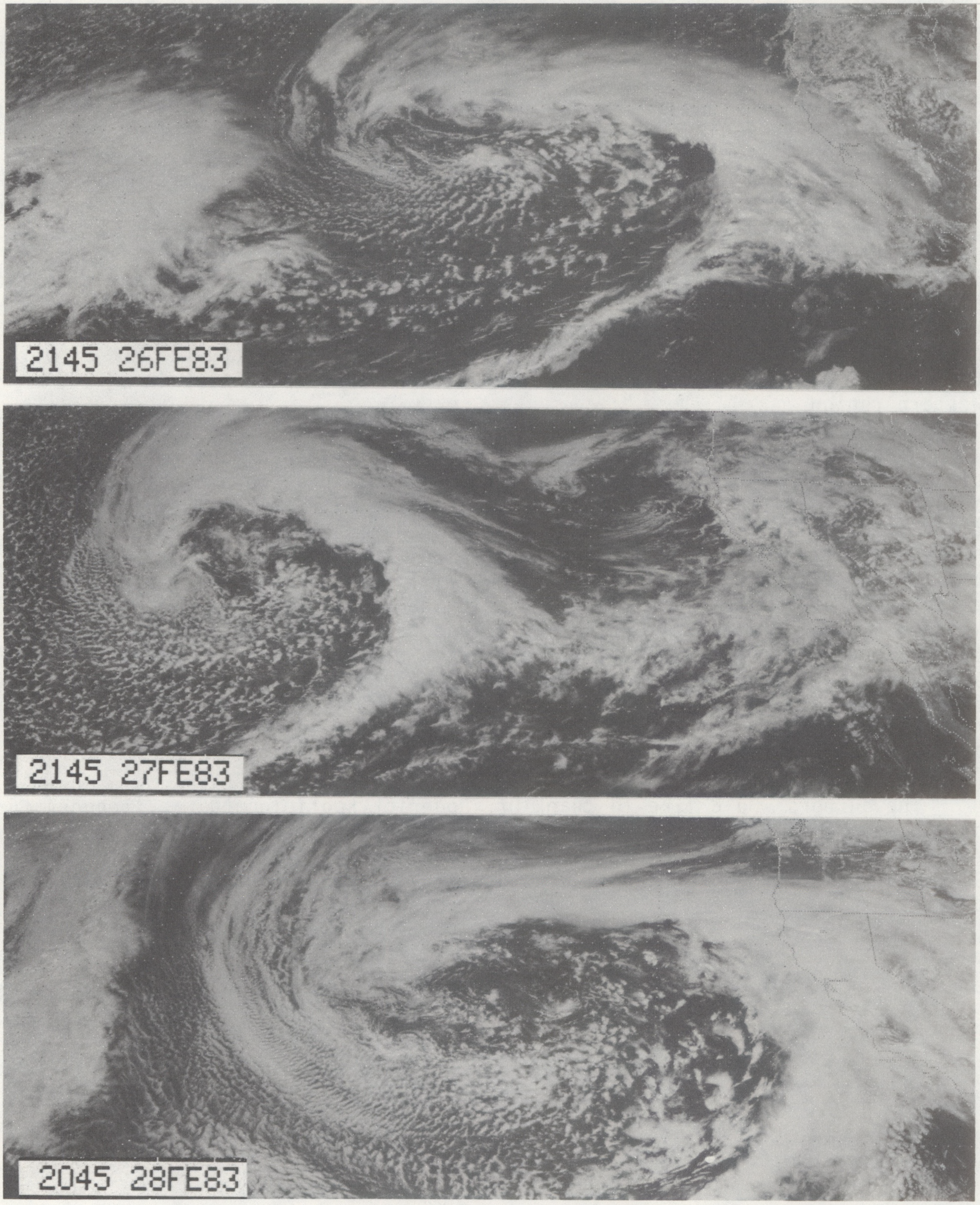


Figure 53. Visible images at 2145 GMT on February 26, 27, and 2045 GMT on 28, 1983.

V. Conclusions and Outlook

This paper presented some distinct satellite-observed characteristics of heavy rainfall producing convective and extratropical cyclone systems over the western region of the United States. Large, cold topped Mesoscale Convective Complexes (MCC's) which are important flash flood producers in the Midwest are relatively rare in the western United States. Smaller Mesoscale Convective Systems (MCS's) and single clustered systems either quasi-stationary or regenerative are responsible for 86% of the western flash floods in this study. These convective systems seem to be highly correlated with daily solar radiation and subsequent differential heating over the mountainous terrain. It is hypothesized that merging outflow boundaries, low level jet maxima, and thunderstorm regeneration - the primary sources of the large nocturnal MCC's over the central U.S. - are greatly inhibited by the mountainous terrain of the western region.

Careful examination of the largest MCS events yielded four distinct types of composite atmospheric conditions. In addition, three main types of satellite observed cloud patterns were constructed from the extratropical cyclone flash flood events. It is hoped that the specific characteristics of each type of heavy rainfall producing convective system and the atmospheric composites for the MCS and extratropical cyclone systems will help operational forecasters detect and anticipate flash flood producing heavy rainfall systems in the western region. Future efforts will include developing sounding, surface, and upper air composites, more detailed evolution schematics and a better understanding of the location of heaviest precipitation for each type of heavy rainfall producing convective system.

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Appendix A - Summary of the Important Statistics Cited in this Study (Convective Events Only)

Time of Year Variation

Entire Region (137 events):	97% May 1 - October 15 62% July 16 - August 31
Sub-Regions:	
Intermountain Plateau (83 events):	95% July 16 - October 15 78% July 16 - September 15
Front Range (49 events):	39% May 16 - July 15 54% July 16 - October 15
North (19 events):	89% May 16 - August 31
Central (60 events):	98% June 1 - September 30
South (58 events):	95% July 16 - October 15

Time of Day of Heaviest Precipitation (Local Daylight Time)

Entire Region:	72% 2 pm - 8 pm 58% 4 pm - 8 pm
Sub-Regions:	
Intermountain Plateau:	69% 2 pm - 8 pm 18% 2 am - 2 pm
Front Range:	80% 2 pm - 8 pm 6% 2 am - 2 pm
North:	58% 2 pm - 8 pm
Central:	85% 2 pm - 8 pm
South:	64% 2 pm - 8 pm

Minimum Cloud Top Temperatures

Entire Region:	26% cold ($<$ -62°C) 74% warm ($>$ -62°C)

Types of Satellite-Observed Convective Systems

Single-Clustered (28 events):	89% July 16 - August 31
	75% 2 pm - 8 pm (LDT)
	100% Warm cloud-top temperatures (> -62°C)
MCS- α (13 events):	100% June 1 - September 30
	85% June 1 - August 15
	77% 4:30 pm - 7:30 pm (LDT)
	77% Cold cloud-top temperatures (≤ -62°C)
MCS- β Circular (32 events):	100% June 16 - September 15
	84% July 16 - August 31
	94% 2 pm - 8 pm (LDT)
	56% Warm cloud-top temperatures (> -62°C)
MCS- β Linear (41 events):	100% May 16 - October 15
	88% June 20 - September 30
	68% 2 pm - 8 pm (LDT)
	100% 2 pm - 3:30 am (LDT)
	70% Warm cloud-top temperatures (> -62°C)
Synoptic Scale Cyclonic Circulation (10 events):	80% Noon - 7 pm (LDT)
	50% 5 pm - 7 pm (LDT)
	100% Warm cloud-top temperatures (> -62°C)

APPENDIX B

BRIEF DESCRIPTIONS OF CONVECTIVE FLASH FLOOD EVENTS

Brief accounts of the 137 convective flash flood events examined in this study are listed below. All the information was taken from the NOAA Storm Data Publications. The events are listed chronologically and each description includes the location and time of day of the event (local daylight time), and the type of satellite observed heavy convective rainfall system.

DATE	LOCATION	TIME(LDT)	TYPE	DESCRIPTION
1981				
Mar. 30	Latah Co., Idaho	11:00 pm	Single clustered	Flash flooding occurred after 1½" of rain fell in less than one hour. The water damaged 20 miles of road, and caused 8' gulleys and large soil losses. At one point, the water rose about 25 feet.
May 3	Southern Weld, Eastern Boulder, and Northern Adams Counties, Colorado	6:00 - 7:30 pm	Squall Line (See figure 9)	A severe thunderstorm dumped 5.1" of rain in 45 minutes near Keenesburg causing street flooding. A large amount of hail also fell.
May 20	Glacier Co., Montana	Evening	Synoptic Scale Cyclonic Circulation	Flash flooding washed out sections of U.S. highway 2 and some railroad tracks.
May 21-22	Western half of Montana	Both days	Synoptic Scale Cyclonic Circulation	Heavy rains of up to 5" fell on ground already saturated from frequent heavy rains earlier in month, causing record flooding in rural areas.
May 27	Riverside Co. California	Afternoon	MCS- β(linear)	Heavy rains caused field and street flooding, and highway 3 was closed for two hours. Several cars had to be pulled out of dry washes just east of Desert Hot Springs.
June 2	Denver, Colorado	5:30 - 7:30 pm	MCS- α	A severe thunderstorm dropped 2" of rain in 20 minutes along with large hail. Local flooding occurred, with up to three feet of water in some streets.
June 3	Denver, Colorado	1:00 - 2:00 p.m.	MCS- β (linear)	One to two inches of rain fell in less than an hour and 3-4 feet of water moved through a trailer park, damaging approximately 200 mobile homes. Large hail and several tornados were also reported.
June 25	Estes Park, Larimer Co., Colorado	Afternoon	MCS- β (circular)	Heavy rain caused mudslides and local flooding causing several thousand dollars damage.
June 25	Chaffee and Fremont Cos., Colorado	Late Afternoon and Evening	MCS- β (circular)	An estimated two inches of rain in 25 minutes caused a flash flood of water, mud, and rocks at a youth camp. Several cabins and utility lines were damaged. One cabin was filled with three feet of mud. Five persons had minor injuries.
July 2	Trinidad, Colorado	10:30 pm	MCS- β (linear)	3.66" of rain fell in less than three hours causing flash flooding. Many roads and a railroad bridge were washed out. Two people were killed when a train plunged into the creek formerly spanned by the bridge.

DATE	LOCATION	TIME(LDT)	TYPE	DESCRIPTION
July 15	Washington Co. Utah	3:45 pm	MCS- β (linear)	Heavy rainfall caused flooding in several areas with one report of 1.73" in 80 minutes. Water of up to 6" accumulated in yards with some basement flooding. Damage estimated at $1 million.
July 16	Colorado City, Arizona	Afternoon	Single clustered	Heavy rains and flash flooding caused $250,000 damage to roads and utility lines. Basements were filled with water and mud. Ravines 3 to 6 feet deep were cut into streets. Large hail also fell. County officials declared the area a disaster area.
July 26	Tanque Verde Falls, Pima Co., Arizona (15 miles east of Tucson)	6:00 pm	Single clustered	A wall of water 15 feet high rushed down a canyon and over the 100 foot high water falls. The flash flooding resulted in eight deaths.
Aug 5	Nogales, Santa Cruz Co., Arizona	5:00 pm	MCS- β (circular)	Heavy thunderstorms produced flash flooding. A trailer park, housing complex, and some streets had two to three feet of water forcing the evacuation of 20 families.
Aug 6	Pine Bluffs, Laramie Co., Wyoming	3:00 am	MCS- β (linear)	Heavy rain estimated between 1.25" to 4" fell in about 40 minutes. Large hail and damaging winds accompanied the storm.
Aug 6	El Paso Co., Colorado (near Black Forest)	7:00 pm	Single clustered	A flash flood washed out five erosion control and livestock water reservoirs causing $80,000 damage.
Aug 9	San Miguel, Montrose Co. Colorado	Afternoon	MCS- β (linear)	Extensive flooding occurred east of Montrose, and crop and property damage was reported. Hail accompanied the storm.
Aug 9	Southeastern Foothills of Colorado	6:00 - 7:00 pm	MCS- β (linear)	Heavy rain was reported in several spots and the town of Penrose received 1 1/2" in 15 minutes. River flooding in Huerfano County damaged 100 acres of crops.
Aug 10	El Paso, Texas	Afternoon	Single clustered	Heavy rains caused flooding with nearly five feet of water occurring in low areas. The Weather Service measured 1.5" of rain.
Aug 10	Northern Clark Co., Nevada and Kingman, Arizona	5:30 - 9:30 pm	MCS- α	Severe thunderstorms caused flash flooding and 762 cows were killed at a dairy. Overall damage damage was over $10 million. In Kingman, flooding closed several streets and highways.
Aug 12	Inyo Co., (near Furnace Creek) California	8:30 - 9:30 pm	MCS- β (circular)	Flash flooding closed Road #178 west for a time. (No other details given.)
Sept 4	Boulder City and Lake Mead, Nevada	3:00 pm	MCS- β (circular)	Thunderstorms caused local flash flooding. Damaging winds were also reported.
Sept 6	Topock-Yucca and Lake Havasu City, Arizona	Early Morning	MCS- β (linear)	Heavy rains of up to 4" caused flash flooding. A 160 foot portion of a steel girder railroad bridge washed away, and water caused a section of Interstate 40 to collapse injuring two persons in a vehicle. Hail was also reported.
Sept 7	Riverside Co., (near Idyllwild) California	5:20 pm	MCS- β (linear)	Three inches of rain (with hail) fell in 45 minutes. A portion of Highway 74 was closed.
Sept 7	Levan, Juab Co., Utah	Evening	Synoptic Scale Cyclonic Circulation	Heavy rain caused flash flooding along creeks. A stream channel and an adjacent concrete ditch were damaged. Thirteen acres were also damaged.

DATE	LOCATION	TIME(LDT)	TYPE	DESCRIPTION
Oct 1	Kern Co., California	6:00 pm	Synoptic Scale Cyclonic Circulation	Heavy rain caused flooding which closed Interstate 58.
Oct 1	Death Valley National Monument, California	6:30 pm	Synoptic Scale Cyclonic Circulation	Heavy rain caused flooding in the south part of the park.
Oct 2	Phoenix, Arizona	3:30 - 4:30 am	MCS-β (linear)	A severe thunderstorm with heavy rain caused considerable street flooding. Strong winds and hail were also reported.
<u>1982</u>				
May 19	Black Hills region of South Dakota	Afternoon	MCS-β (linear)	As much as 3.58" of rain fell on already saturated ground causing widespread flooding which lasted for three days. Extensive damage around the area included washed out bridges, roads, damaged houses, flooded basements, and severely damaged crops. Many people were evacuated.
June 3	Colorado Springs, Colorado	Afternoon	Two separate systems occurred within 24 hours	One to six inches of rain from severe thunderstorms caused local street flooding. Hail was also reported.
June 5	Butle Co., South Dakota	Late Evening	MCS-α	As much as 4" of rain from severe thunderstorms caused flooding of two creeks. Strong winds and hail accompanied the storm.
June 13	Southeastern Crook Co., Wyoming	Late Afternoon-early evening	MCS-α	As much as 7" of rain and subsequent flooding caused considerable damage. Hail was also reported.
June 23	Carbon Co., (near Belfry) Montana	Late Afternoon	MCS-β (linear)	A severe thunderstorm (with hail) produced rains of up to 4".
June 25	Milliken and Windsor, Weld Co., Colorado	1:00 - 4:00 am	MCS-β (linear)	A severe thunderstorm dropped 1.25 to 3" of rain. Much of the town of Milliken was flooded with one to three feet of water, causing 25 evacuations. Damage was estimed at $250,000.
June 25	Fort Collins and Loveland, Colorado	Afternoon	MCS-α	Severe thunderstorms dumped 4.5" of rain in two hours east of Fort Collins, and 3" fell in 45 minutes near Loveland. Severe crop damage was reported and at least 18 head of cattle drowned. Large hail accompanied the storm.
June 27	Okanogan Co., Washington	1:00 - 3:00 am	MCS-β (linear)	A heavy rainshower eroded some farmland in the area and caused extensive damage to three irrigation districts within the county.
July 1	Pennington Co., (Scenic and Hermosa) South Dakota	Evening	MCS-α	Four and one-half inches of rain caused lowland flooding around the Badlands National Park area. Small hail was also reported.
July 22	Kearny, Pinal Co., and Tucson, Arizona	6:00 - 7:00 pm	MCS-β (circular)	A severe thunderstorm produced 2" of rain. Street flooding was widespread and more than 100 homes were flooded. Winds of 60 to 70 MPH and hail 1" in diameter were also reported.

DATE	LOCATION	TIME(LDT)	TYPE	DESCRIPTION
July 24-25	Southeast Big Horn, southern Rosebud, and Powder River Counties, Montana, and Rapid City, South Dakota	4:30 pm - 2:00 am	MCS- α	Severe thunderstorms with heavy rains of up to 4-5" in one to two hours caused flash flooding in Montana. The same system produced 2-3" rains and lowland flooding in the Rapid City area a few hours later. Hail and high winds accompanied the storm.
July 25	Dayton, Nevada	Evening	MCS- β (linear)	County offices were flooded as heavy rain collected on the roof. Flash flooding also occurred.
July 25	San Bernardino Co., (near Twenty-nine Palms) California	6:00 pm	MCS- β (circular)	A heavy thunderstorm with heavy rain caused flash flooding which washed away a mobile home.
July 28	Denver, Colorado	Afternoon	Single clustered	Two and one-half inches of rain fell in 30 minutes.
July 28	Dinosaur, Moffat Co. Colorado	Afternoon	MCS- β (linear)	Heavy rains washed out U.S. highway 40.
July 28	Chaffee Co., Colorado	Afternoon	Single clustered	Heavy rain caused flooding.
July 28	Colorado Springs, Colorado	Late Afternoon-Early Evening	MCS- β (linear)	Heavy rains around the city washed out a bridge and caused creek flooding. 2.75" of rain in one hour fell in the city.
July 28	Coaldale, Freemont Co., Colorado	Early Evening	Regenerative	Heavy rain damaged U.S. highway 50.
July 28	Northwest Yerrington, Wyoming	8:00 pm	MCS- β (linear)	Flash flooding caused nearly $2 million in damages, mostly to a recently cut hay crop.
July 29	Zuni, McKinley Co., New Mexico	Afternoon	Single clustered	Heavy rains flooded the Zuni Indian Village. Roads and some homes were damaged.
Aug 2	Colorado City, Arizona	Late Night	Single clustered	A severe thunderstorm dumped 3.2" of rain in two hours causing flash flooding. Three bridges were washed out and the city's main sewer line was destroyed and other utility equipment was lost.
Aug 2	Tucson, Arizona	3:30 pm	Single clustered	A thunderstorm dropped nearly 2" of rain in 90 minutes flooding roads with one to five feet of water. Two young girls were rescued as they were being swept down an arroyo. Damage to streets, roads, and cars was reported.
Aug 4	Colorado Springs Colorado	Afternoon	Regenerative	Torrential rains caused $400,000 damage to public property and drainage systems. One home suffered severe water damage.
Aug 4	Rapid City, South Dakota	Late Afternoon	MCS- β (circular)	2.6" of rain fell in one hour. Many motorists were forced to abandon their cars in low lying intersections where water was as high as car bumpers.
Aug 5	Westminster and Arvada, Jefferson Co., Colorado	7:30 pm	Single clustered	Thunderstorms dumped up to 2.38" of rain in one hour causing local minor creek flooding. Streets and culverts were damaged.
Aug 6	Denver, Colorado	5:30 - 6:30 pm	Single clustered	Rainfall of up to 2.35" in one hour caused street flooding in downtown Denver. Four to five feet of water covered Interstate 25, closing the highway for a while. An estimated 2000 basements were flooded.

DATE	LOCATION	TIME(LDT)	TYPE	DESCRIPTION
Aug 8	Albuquerque, New Mexico	Afternoon	Single clustered	Thunderstorms dumped one to two inches of rain causing flash flooding and street damage.
Aug 10	Ajo, Pima Co., Arizona	6:50 pm	MCS- β (circular)	A severe thunderstorm with 2.5" of rain, strong winds and hail damaged 200 homes and businesses. Flash flooding was reported.
Aug 11	Uintah Co., (near Bonanza) Utah	Evening	MCS- β (circular)	A flash flood was reported as a wall of water 4 feet high and 60 to 70 feet wide came rushing down Wagon Hound canyon. Five vehicles were destroyed, 11 others damaged, and some construction equipment was damaged. Two persons were injured.
Aug 11-12	Boulder City and Searchlight, Nevada	Night	MCS- β (linear)	A flash flood covered highway 95 with three feet of water.
Aug 12	Lake Havasu City and Parker-Bouse, Arizona	5:00 - 11:00 am	MCS- α	A severe thunderstorm dumped 2-3" of rain causing flash flooding. Roads were covered by rocks, mud, and 2-3 feet of water. Pavements and railroad tracks were ripped up and undermined. Bridges, homes and property were badly damaged. Several cars were carried off by rushing water and motorists had to be rescued.
Aug 12	Caliente-Pioche, Lincoln Co., Nevada	2:00 - 6:00 pm	Regenerative	A flash flood washed out part of a railroad track.
Aug 12	Zuni, McKinley Co., New Mexico	Afteroon	MCS-β (circular)	Thunderstorms dropped considerable rain over the area causing streets to flood and nine families to be evacuated. The next day two boys lost their lives in swollen streams.
Aug 13	Tucson, Arizona	4:00 - 7:00 am	Single clustered	A heavy thunderstorm dumped 2.5" of rain causing flash flooding. Many roads were damaged, and a man floated down a flooded arroyo in his car. Forty main intersections were flooded with one to four feet of water. An eight foot deep hole was scoured out after flood waters washed away the pavement.
Aug 13	Searchlight, Nevada	1:20 pm	Single clustered	Heavy rains caused flash flooding and road flooding. Minor damage occurred.
Aug 16	Safford, Arizona	Evening	MCS-β (linear)	A violent thunderstorm with strong winds and hail caused flash flooding. Homes and farm buildings received extensive flood and wind damage.
Aug 17	Evergreen and Conifer, Colorado	Afternoon-Evening	MCS-β (circular)	Thunderstorms dropped 4.5" of rain in one hour and 15 minutes. 2.66" in 15 minutes was reported nearby. Local flooding was reported.
Aug 19-20	Luis Lopez Socorro Co., New Mexico	11:00 pm - 1:00 am	Single clustered	Two to three inches of rain fell in nearby mountains causing arroyos to overflow damaging 600 to 1000 acres of crops ready for harvest.
Aug 20	Rock Point-chinle, Apache Co., Arizona	6:00 am	Single clustered	Heavy rain on top of already saturated ground caused flash flooding. Fifteen families were made homeless and cars were carried away by flood waters.
Aug 23	Tucson, Arizona	4:00 - 5:00 pm	MCS-β (circular)	A severe thunderstorm dumped 4" of rain causing flash flooding, considerable street flooding, and extensive property damage. High winds and hail were also reported.

DATE	LOCATION	TIME(LDT)	TYPE	DESCRIPTION
Aug 23	Blue Diamond, Nevada	Early Evening	MCS-β (circular)	A flash flood caused one person to drown in an automobile.
Aug 23	Phoenix, Arizona	7:00 - 9:00 pm	MCS-β (circular)	A severe thunderstorm produced up to 3" of rain and flash flooding with extensive damage. The roof of a large supermarket collapsed under the weight of the water. Many streets were covered by several feet of water. Strong winds also occurred.
Aug 24-25	Phoenix, Arizona	11:00 pm - 1:00 am	MCS-β (linear)	A severe thunderstorm dumped up to 2" of rain causing flash flooding and considerable street flooding. Strong winds were also reported.
Aug 25	Searchlight to Laughton, Nevada	Afternoon	Single clustered	Flash flooding closed U.S. highway 95 from the afternoon of the 25th until 10:00 am the next morning.
Aug 25	Garfield Co., (near Escalante) Utah	6:30 - 7:30 pm	MCS-β (linear)	1.24" of rain in hour caused flash flooding. A small bridge was washed out and a road and waterpipe were damaged.
Aug 26	Manhatten Northern Nye Co., Nevada	6:30 am	MCS-β (linear)	Flash flooding was reported with water and debris across U.S. highway 6.
Aug 27	E. Tonopah, Gabbs, and Mina, Nevada	4:45 pm	MCS-β (circular)	Flooding was reported with water across U.S. highway 6. Damage to other roads due to water and debris.
Aug 27	Bisbee, Cochise Co., Arizona	6:10 pm	MCS-β (linear)	Torrential rains of 2.5" in 2 hours caused flash flooding. Streets were flooded and a 4 foot wall of water roared down Brewery Gulch. A man was carried away and drowned while trying to remove his car from flood waters.
Sept 6	Flagstaff, Arizona	2:30 pm	MCS-β (circular)	A severe thunderstorm with over one inch of rain caused flash flooding. Hail was also reported.
Sept 11	Tucson, Arizona	12:00 - 2:00 pm	Synoptic Scale Cyclonic Circulation	Several severe thunderstorms dumped 2 to 4" of rain causing flash flooding. Considerable street flooding closed many intersections. Over a dozen persons were rescued from cars stalled in deep water. One car was swept down an arroyo but the driver escaped without injury.
Sept 13	Boone, Pueblo Co., Colorado	2:30 - 3:00 pm	MCS-β (linear)	A severe thunderstorm produced 3.5" in 30 minutes causing widespread street and basement flooding. Large hail was also reported.
Sept 13	Denver to the Wyoming border, Colorado	Afternoon and Evening	MCS-β (linear)	As much as 4.73" of rain caused local flooding, minor road washouts, and crop damage. Hail was also reported.
Sept 18	San Felipe Pueblo, Sandoval Co., New Mexico	Afternoon	Regenerative	Two to three inch rains caused flash flooding. A small dike broke, flooding some homes.
Sept 20	Artesia to Carlsbad, Eddy Co., New Mexico	Afternoon	Single clustered	Heavy rains from a cloud burst caused flash flooding damaging streets, homes, and highways.
Sept 20	El Paso, Texas	Evening	MCS-β (linear)	Record breaking rain of 1.44" in 30 minutes and 2.18" in one hour caused flash flooding and damaged several homes.

DATE	LOCATION	TIME(LDT)	TYPE	DESCRIPTION
Sept 26	Inyo Co., California and Salt Lake Co., Utah	All Day	Large Scale Overrunning	Heavy rain from the same convective system caused flash flooding in two areas. The worst damage occurred in Utah where a record two to four inches of rain fell in 24 hours. Moisture from dying Hurricane Olivia in the Pacific aided in the rainfall. Flood damage to houses, roads, and bridges estimated at $15 million in Utah. Nearly 2000 people were evacuated in the two states.
Sept 27	Springdale, Washington Co., Utah	1:30 am	Single clustered	Heavy rainfall of more than two inches caused flash flooding. Two feet of debris and mud flowed through the city, and car-sized boulders filled drainages. A road, trailer court and campground were washed out. Damage estimated at $800,000.
Sept 30	El Paso, Texas and southern New Mexico	Night to Afternoon	Synoptic Scale Tropical	The remains of Hurricane Paul dumped up to 4-5" of rain over the area. Flooding deposited rocks and debris on highways and damaged homes and crops.
1983				
Jan 10	Whatcom Co. Washington	Early Morning	Large Scale Overrunning	A four foot wall of water and debris roared down into Lake Whatcom after heavy rains caused log-jams to break upstream. The flash flood damaged or destroyed 50 houses with damage estimated at $12 million. One hundred residents were evacuated. Twenty-four hour rainfall amounts of up to 4.65" were reported with an unofficial report of 4.84" in a four hour period.
Jan 30	Pima Co., (Sabino Canyon) Arizona	2:00 pm	Synoptic Scale Cyclonic Circulation	Flash flooding forced the evacuation of 24 people. Two girls narrowly escaped drowning after being swept off a bridge.
June 25	Ft. Collins-Denver area, Colorado	Afternoon	Synoptic Scale Cyclonic Circulation	Up to 2" of rain in 20 minutes with 1.5" in 30 minutes reported near Denver. No other details given.
June 25	Grand Junction, Colorado	Late Afternoon-Evening	Synoptic Scale Cyclonic Circulation	Heavy rain caused the already swollen Colorado River to rise even higher. The following day, high water closed part of Interstate 70 and a dike broke flooding a small residential area.
June 28	Granby, Grand Co., Colorado	4:30 am	Synoptic Scale Cyclonic Circualtion	A flash flood filled a pumping plant with 30 feet of water, trees and other debris.
July 10	Saguache Co., Colorado	3:00 pm	MCS-β (circular)	A flash flood swept through a ranch causing about $100,000 damage.
July 10	Clear Creek Co., (near Golden) Colorado	Afternoon	MCS-α	A man was injured when he was swept downstream by a flash flood in Clear Creek Canyon.
July 20	Clear Creek Co., (near Idaho Springs) Colorado	Afternoon	MCS-β (linear)	1.9" of rain fell in 10 minutes.
July 20	Montrose, Colorado	7:30 - 10:30 pm	MCS-β (linear)	1.49" of rain (a 24-hour record) caused widespread street flooding and power outages.

DATE	LOCATION	TIME(LDT)	TYPE	DESCRIPTION
July 22	Denver area, Colorado	Afternoon	MCS- β (linear)	Up to 3" of rain in 45 minutes caused a creek to rise five feet in 10 minutes. The town of Morrison was evacuated for 2 hours. Bridges were washed out, homes were damaged and street flooding with water six feet deep in one spot was reported. Hail was also observed.
July 22	Laramie Co., Wyoming	Late Afternoon-Evening	MCS- β (circular)	Stationary thunderstorms over the Laramie mountains produced 4-6" of rain and widespread flash flooding. Creek flooding resulted in the evacuation of a mobile home court. A collapsed aquaduct sent a 10-15 foot high wall of water through a ranch complex.
July 22	Converse and Platt Counties, Wyoming	Evening	MCS- β (linear)	Stationary thunderstorms over the Laramie mountains produced 4-6" of rain and widespread creek and stream flooding. Bridges, roads, and irrigation systems were damaged.
July 23	Pilot Rock, Umatilla Co., Oregon	Late Afternoon	MCS- β (linear)	Thunderstorms caused flash flooding. Hail and heavy winds were also reported.
July 26	Golden, Colorado	Late Afternoon-Evening	MCS- β (linear)	Heavy thunderstorms dropped 2.9" of rain in one hour causing minor street flooding.
July 27	Gallup, New Mexico	6:00 pm	MCS- β (linear)	Heavy rains and flash flooding caused considerable damage to homes and streets.
July 31	Lake Havasu City, Arizona	8:45 - 9:15 pm	MCS- β (linear)	A violent thunderstorm caused flash flooding which damaged gas pipes and water mains. Strong winds were also reported.
Aug 5	Denver, Colorado	5:00 - 5:45 pm	MCS- β (circular)	Rain of 2.89" in 38 minutes caused widespread street flooding. Part of Interstate 25 was covered with two feet of water. Large hail was also reported.
Aug 6	Cedar Hill, San Juan Co., New Mexico	8:00 pm	MCS- β (circular)	Flash flooding damaged houses, roads, and crops.
Aug 7	Tucson, Arizona	5:30 - 6:00 pm	MCS- β (linear)	Flash flooding from a severe thunderstorm trapped several cars in washes. Strong winds and hail accompanied the storm.
Aug 9	Green Canyon, Cache Co., Utah	6:00 am	MCS- α	A flash flood carried mud, rocks, and water into yards and basements, and washed out the cities culinary water system. Sandbags were needed to hold back flood waters.
Aug 10	Green Canyon Cache Co., Utah	Late Afternoon-Evening	MSC- β (circular)	One to two inches of additional rainfall caused flash flooding in the Green Canyon area.
Aug 10	Las Vegas, Nevada	9:30 am	Single clustered	Thunderstorms formed over southern Nevada and moved northward over the city. Flash flooding closed most streets and highways around the city for a time. Damage estimated at $1.5 - 2 million.
Aug 10	Chelan Co., Washington	Late Afternoon	Single clustered	Heavy rains caused a four foot wall of water to rush down out of the hills north of Lake Chelan. Trees were uprooted, boulders moved, roads and irrigation systems washed out, and fields and basements flooded. Damage estimed at $500,000.

DATE	LOCATION	TIME(LDT)	TYPE	DESCRIPTION
1983				
Aug 10	Riverton and Worland, Wyoming	Evening	MCS- α	Severe thunderstorms dumped rains of one to two inches causing minor flash flooding. Hail was also reported.
Aug 12	Salt Lake Co., Utah	4:00 pm	Single clustered	Heavy rainfall in the Big Cottonwood Canyon area caused flash flooding. Rocks and silt were washed over about 1000 feet of highway. Three automobile accidents also occurred.
Aug 13	Denver, Colorado	3:30 - 4:30 pm	MCS- β (circular)	Thunderstorms dropped as much as 1.72" of rain in 30 minutes. Street flooding was widespread.
Aug 14	Salt Lake, Tooele, and Utah Counties Utah	7:00 pm	MCS- β (circular)	A thunderstorm dumped as much as 1" of rain in 30 minutes causing flash flooding. Water one-to-two feet deep and mud four feet deep covered highways.
Aug 16	Morongo Valley, San Bernardino Co., California	10:00 pm	MCS-β (circular)	Three hours of rain caused widespread flash flooding. Two motorists were trapped in their cars by window high water. Several homes were damaged by flood waters.
Aug 16	Phoenix, Arizona	5:00 - 7:00 pm	MCS- β (linear)	A violent thunderstorm produced 1.14" of rain in 10 minutes (a record) and one to two inches overall causing flash flooding of streets, roads, houses and businesses. Strong winds and a funnel cloud were also reported.
Aug 16	Tehachapi Mtns., Kern Co., California	5:00 - 9:00 pm	Single clustered	Rain of 1.5" in an hour flooded a creek and washed out parts of a highway.
Aug 17	San Bernardino, California	Late Afternoon	MCS- β (circular)	Heavy rain collapsed several roofs, and homes and intersections were flooded. Parts of Interstate 10 were closed because of flooding and thousands of motorists were stranded. In two separate incidents, three persons were killed when their cars were swept away by flood waters.
Aug 17	Salt Lake Co., Utah	7:00 pm	MCS- β (circular)	A heavy thundershower caused minor flash flooding with several roads washed out. Four feet of water blocked one underpass. Rainfall of 1.2" in 20 minutes was observed.
Aug 17	Ridgecrest, California City, and the Tehachapi Mtns., Kern Co., California	5:00 - 10:00 pm	MCS- β (circular)	Heavy rain, as much as one inch in an hour, caused creek and street flooding. Water was at window height of cars. One person was killed while attempting to drive through flood waters in a normally dry gully. Another was killed in a weather related traffic accident.
Aug 18	Las Vegas, Nevada	9:00 am	Large Scale Overrunning	Heavy rain caused flash flooding closing streets and highways, causing extensive damage of $1 to 1.5 million (estimated).
Aug 18	Near Cortez, Colorado	Afternoon-Evening	Single clustered	Heavy thunderstorms dropped 1.5" of rain in 30 minutes.
Aug 18	Davis, Salt Lake, northern Utah, and Weber Counties, Utah	6:00 - 10:00 pm	MCS- β (circular)	Flash flooding from thunderstorms caused widespread damage. Homes were flooded and highways and railroads were extensively damaged. One car was swept off the road by flood waters. One strong thunderstorm dumped 1.19" in 30 minutes.

DATE	LOCATION	TIME(LDT)	TYPE	DESCRIPTION
1983				
Aug 20	Albion, Cassia Co., Idaho	6:30 - 7:30 pm	MCS-β (circular)	A cloud burst over nearby higher terrain sent a flash flood of water, mud, and rocks into town. Most businesses and homes suffered some water damage, and several roads were damaged.
Sep 3	Salt Lake City Utah	4:00 - 7:00 pm	MCS-α	Severe thunderstorms caused flash flooding on creeks and highways. Hail and strong winds accompanied the storm.
Sep 23	Prescott, Arizona	4:00 - 7:00 pm	MCS-β (linear)	Severe prolonged thunderstorm activity with 3-8" of rain caused extensive flash flooding. Considerable creek and road flooding. Many homes and utility lines damaged or destroyed and sixty people were evacuated. Many autos were swept into streams. Total damage estimated at $2.75 million.
Sept 27	Guadalupe National Park, Texas	Nighttime	MCS-β (linear)	A five inch rainstorm caused some water damage.
Sept 29	Phoenix, Arizona	10:00 am-1:00 pm	MCS-α	Heavy rain caused extensive flash flooding of streets, highways, homes, and businesses. Many traffic accidents resulted and one underpass was filled with nine feet of water. Strong winds and hail also occurred.
Sept 29	Eastern 2/3 of Arizona and Southwestern New Mexico	Whole Period	Synoptic Scale Tropical	Extremely heavy rains of up to 10" caused massive flash flooding along several rivers. Thousands were evacuated and 13 people were killed. Total damage estimated at $200 million.
Oct 8	Alpine, Brewster Co., Texas	4:30 - 7:30 pm	MCS-β (linear)	Flash flooding in the wake of 4" of rain closed intersections and underpasses. Normally dry creeks carried rocks and debris on highways. One low water crossing had water six feet deep.
Nov 3	Chares Co., (near Artesia) New Mexico	Morning	Large Scale Overrunning	Flash flooding from heavy rains flooded homes and washed out roads. Damage was estimated at $250,000.

Appendix C

BRIEF DESCRIPTIONS OF HEAVY RAINFALL EXTRATROPICAL CYCLONE EVENTS

Brief accounts of the 24 heavy rainfall extratropical cyclone events examined in this study are listed below. All the information was taken from the NOAA Storm Data Publications. The events are listed chronologically and each description includes the date and location of the event and the category of heavy rainfall extratropical cyclone event.

Dates	Location	Type	Description
1981			
March 1-3	Los Angeles, Riverside and San Diego, Counties California	Deep Meridional Trough	Coastal area received 3 inches of rain with up to 6 inches in the local mountains. Widespread reports of street flooding and power outages.
December 20	Reno, Nevada	Deep Meridional Trough	Six to seven inches of rain in the Sierra Nevada Mountains caused rapid rises on rivers and urban flooding.
1982			
January 3-4	San Francisco Bay area, California	Cloud band - subsynoptic scale waves	Up to 24 inches of rain fell over the Bay area.
January 22-25	Central Oregon Coast northward through Washington	Cloud band - over upper level ridge	Rainfall of 5-12 inches in Oregon and up to 9 inches in Washington produced major flooding, mud slides, and avalanches.
February 13-15	Northern Californa to Northwestern Oregon	Active zonal jet stream	Rainfall of 3-6 inches in California and 6-8 inches in Oregon produced moderate stream flooding.
February 21	Klickitat County, Washington	Cloud band - quasi-stationary	Heavy rains flooded the Klickitat River sweeping an automobile away.
March 11-12	Coconino and Yawapai Cos., Arizona	Deep meridional Trough	Rainfall of 3 to 4 inches produced considerable damage and overflowed a dam.
April 11	Mono County California	Cloud band - quasi-stationary	Heavy rains caused damage to roads.

Dates	Location	Type	Description
October 28-29	Benton County, Washington	Cloud band - subsynoptic scale waves	Heavy rains flooded several buildings.
November 30	Arizona	Active zonal jet stream	Rainfall of one to four inches produced extensive flooding in the eastern two thirds of Arizona.
December 3-4	Northwestern Washington	Cloud band - quasi-stationary	Rainfall amounts of up to 7 inches produced river flooding and widespread flooding of homes.
December 8-10	Southern California and Arizona	Deep meridional Trough	Moderate to heavy rains caused heavy flooding in California and considerable highway flooding in Arizona.
December 15-18	Northwest Washington	Active zonal jet stream	A series of storms produced up to 9 inches of rain, strong winds and tidal flooding, prompting a declaration of a disaster area.
December 30-31	Statewide Arizona	Deep meridional Trough	Heavy snowfall occurred above 3000 feet with heavy rains in the lowlands causing flooding.
1983			
January 5	Western Washington	Cloud band - quasi-stationary	Rainfalls of over 4 inches produced river flooding and extensive mudslides.
January 8	Western Washington	Active zonal jet stream	Rainfalls of over 4 inches produced extensive river flooding sweeping away 3 persons.
January 25-26	Northern California	Cloud band - subsynoptic scale waves	Landslides and river and stream flooding resulted from rainfails of 4 to 10 inches. Many roads were washed out.
February 17-18	Del Norte, Humbolt and Mendocino Cos., California	Active zonal jet stream	Rainfalls of 4 to 6 inches swept a bridge away and caused numerous landslides.
February 19	Northwestern Oregon	Cloud band - over upper level ridge	A heavy rainstorm produced 2-3 million dollars of damage to farmlands.
February 26-28	Venturi County and northern and central, California	Active zonal jet stream	Flooding produced by heavy rains of at least 2.7 inches forced the evacuation of many people.

Dates	Location	Type	Description
March 1-3	Kern, Lake, Shasta, Tehama, Glenn, and Butte Counties, California	Deep meridional Trough	The Sacramento River rose to record levels after 6 to 11 inches of rain. Over 600 homes were flooded.
September 1	Island County, Washington	Deep meridional Trough	Heavy rain throughout the county flooded homes, schools, and businesses.
December 3	Sacramento Valley, north coast and San Francisco, California	Active zonal jet stream	A strong storm produced much wind damage and rainfalls of 3 inches produced flooding.
December 13-14	South Coast, Oregon	Cloud band - over upper level ridge	Rainfall of over 4 inches occurred and flood warnings were issued for Coos County.

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