Synoptic and Meso-α Scale Aspects of Flash Flood Events[1]

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Abstract

Meteorological conditions associated with more than 150 intense convective precipitation events have been examined. These heavy rainfalls caused flash floods and affected most geographic regions of the conterminous United States. Heavy rains associated with weather systems of tropical origin were not considered. Analyses of surface and standard level upper-air data were undertaken to identify and define important synoptic and mesoscale mechanisms that act to intensify and focus precipitation events over specific regions. These analyses indicated that three basic meteorological patterns were associated with flash flooding in the central and eastern United States. Heavy convective precipitation episodes that occurred in the West were considered as a separate category event. Climatological characteristics, composite analyses, and upper-air data are presented for these four classifications of events.

The large variability of associated meteorological patterns and parameters (especially winds aloft) makes identification of necessary conditions for flash flood-producing rainfall quite difficult; however, a number of features were common to many of the events. An advancing middle-level, short-wave trough often helped to trigger and focus thunderstorm activity. The storm areas were often located very near the mid-tropospheric, large-scale ridge position and occurred within normally benign surface pressure patterns. Many of the intense rainfalls occurred during nighttime hours. These elusive characteristics further complicate a difficult forecast problem.

1. Introduction

During the 1970s flash floods have become the most significant natural disaster problem within the United States. Concern and interest in improving forecasts and warnings of these events extend from local National Weather Service (NWS) forecast stations through the American Meteorological Society (AMS) and National Weather Association (NWA) to Congress. The recent AMS statement of concern (*Bull. Am. Meteorol. Soc.*, **59**, 585–586) summarizes the seriousness of the problem and lists several needed actions and studies. Killer flash floods that struck New Orleans, La.; Palo Duro Canyon, Tex.; and Rochester, Minn. within a month after the issuance of the statement emphasize the public's vulnerability and the urgent nature of the problem.

In many respects the flash flood forecast problem is similar to that of severe thunderstorm and tornado prediction, detection, and warning. The severe storm forecast problem has been effectively handled by the establishment of a national center at Kansas City whose primary responsibility is the delineation of regions of potential storm development (the watch phase). However, the flash flood system is decentralized, with responsibility for both watch and warning phases remaining at the state forecast offices. Mogil *et al.* (1978) have explained the details of the present NWS flash flood warning program and suggested ways in which it might be improved. Belville *et al.* (1978) recently reported on the local procedures being used at the NWS office at Lubbock to monitor the flash flood potential over west Texas. Changes in quantitative precipitation guidance products supplied to NWS offices have been designed to help improve forecasts of excessive convective precipitation (NOAA, 1978a).

The development of more effective forecast procedures requires the study of a number of flash flood situations in considerable detail. Mogil and Groper (1976) examined a small sample of heavy convective precipitation events in an attempt to identify common features. Maddox and Chappel (1978) studied meteorological conditions associated with 20 flash flood events. They developed an event classification scheme, presented mean values of important meteorological parameters, and showed typical meso-α (250–2500 km) scale patterns associated with the floods. Results from their initial study are already being used and evaluated in the NWS Eastern and Southern Regions (for example, see NOAA, 1978b). Huff (1978) listed characteristics of Illinois flash flood storms that were in general agreement with the data presented by Maddox and Chappell. This paper presents results obtained from an expanded sample of 151 intense, flood-producing precipitation events.

2. Flood events

a. Data and sampling procedures

The NOAA publication *Storm Data* was surveyed each month of the years 1973–77 and a five-year climatology of flash flood events was compiled. Unfortunately, there are no specific criteria required in reports of flash floods and the amount and quality of information available for individual events vary considerably. Reports on the time of occurrence were often vague, while specific details on the timing, duration, and amount of precipitation were sometimes totally lacking. In some but not all cases this was due to an occurrence in a relatively remote region. Many events are probably never reported. One event in northern California was brought to the authors' attention by Collins (personal communication, 1978)

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[1] A condensed version of this paper appeared in the Preprints of the AMS Conference on Weather Forecasting and Analysis and Aviation Meteorology.

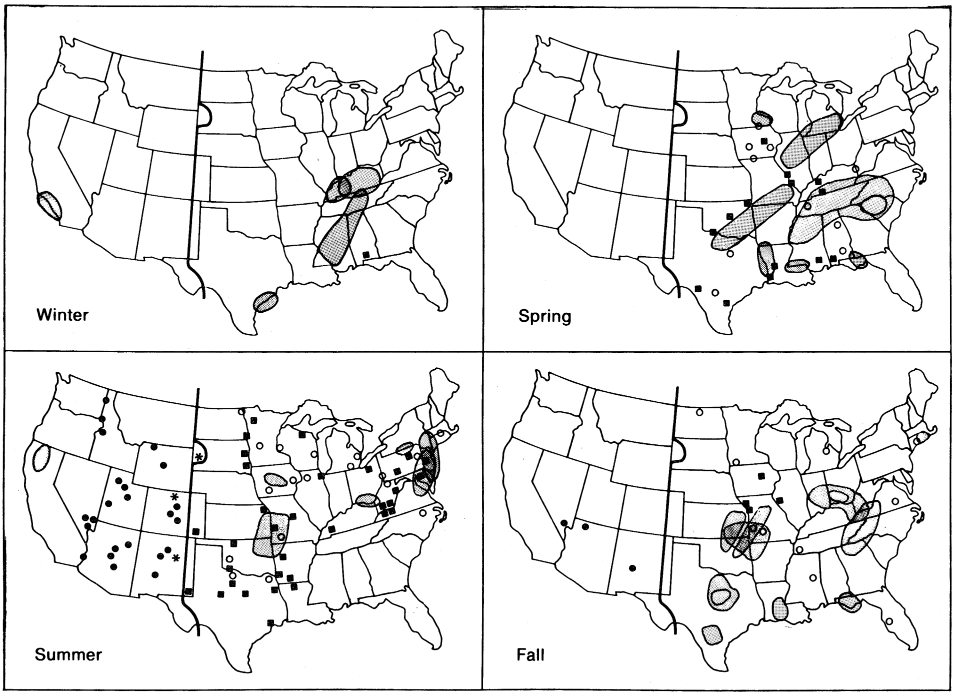

FIG. 1. Locations of 151 flash floods shown by season (Winter = Dec., Jan., Feb.; Spring = Mar., Apr., May; etc.). Synoptic events are denoted by the shaded areas; mesohigh events by squares; and frontal events by open circles. All events west of the heavy line were designated western events (indicated by the solid circles). The five stars and shaded areas in the west are explained in Section 6.

and was included in the sample even though no mention of it appears in *Storm Data*. An obvious need exists for development and maintenance of a national log documenting intense precipitation events. Although this climatology of flood events is not totally comprehensive, it did provide the basic information needed to identify a large sample of intense precipitation events. Flash floods associated with weather systems of tropical origin have been specifically excluded from the sample.

The approximate locations of the flash floods studied are shown, by season, on the maps of Fig. 1. Event classifications are indicated, and the characteristics of the four types of flash flood will be considered in detail in subsequent sections. Generally, synoptic events were associated with significant large-scale weather systems and tropospheric wind fields that were quite strong. Frontal events were associated with quasi-stationary, generally W to E frontal zones embedded within weak large-scale patterns. Mesohigh events were associated with quasi-stationary, cool-air outflow boundaries that had been generated by prior thunderstorm activity. A geographical criterion was used for Western events, with all flash floods that occurred west of the heavy line placed into a single category. (The dividing line was located at 104°W with bulges added to include mountainous terrain in western South Dakota and the Big Bend region of Texas.) The events were reasonably well distributed across the country. Paucity of occurrences for the entire year in some regions is likely a result of sampling and/or reporting deficiencies. However, the area of the country that stretches from the Appalachian Mountains westward to the Missouri River Basin and southwestward over eastern Oklahoma and Texas apparently experiences a large number of flash flood events. Significant flash flooding appears to be especially rare in the southeast during the summer months.

Data packages were assembled for each of the 151 events. Included were 3-hourly surface analyses and twice daily standard level charts for 850, 700, 500, 300, and 200 mb levels. Subjective interpolations were made (both in time and space) to estimate meteorological conditions that existed *just prior* to the heavy rain events. For synoptic events (which typically affect large areas for a considerable time period) conditions were estimated for westernmost portions of the region affected just prior to the onset of the event. Mean sounding data were developed solely from surface and standard level conditions. Because of this restriction only two stability indices (the Showalter Lifted Index (SI) and the K-Index (KI)) were computed. These indices are described in Showalter (1953) and George (1960). The mean monthly climatological value of precipitable water for the surface-to-500 mb layer was determined for each event from the maps presented by Lott (1976). Precipitable water calculations were made only for the mean sounding data.

b. Common characteristics

The monthly distribution for all 151 events is shown in Fig. 2. July was clearly the predominant month of occurrence, accounting for almost 25% of the sample. Since

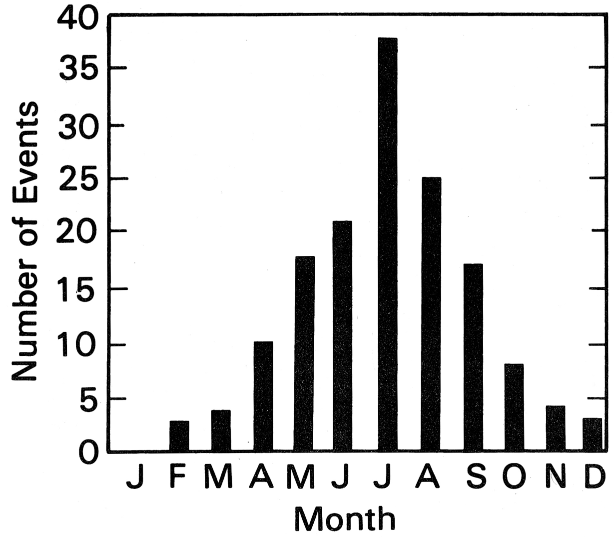

FIG. 2. Monthly distribution of flash flood events studied.

events were of a convective nature, it is not surprising that about 86% of the entire sample took place during the warm season months (April–September).

Maddox and Chappell (1978) noted that many flash flood events occurred at night. The time of the onset of the heavy rains is shown for three event types in Fig. 3. (Note that in both Fig. 3 and Fig. 4 the number of events totals less than 151 because specific details were sometimes lacking.) The data are for 6 h periods since the vagueness of many *Storm Data* reports precludes attempts at more precise timing. The nocturnal nature of mesohigh and frontal events is apparent, while western United States events seem more closely tied to afternoon destabilization processes. Synoptic events were not included because of the longer time periods involved; however, the periods of most intense rain and flooding often occurred at night in these larger scale events. The nocturnal nature of flash flood storms over the eastern two-thirds of the country complicates an already difficult forecast problem, since watches and warnings are likely to reach a restricted number of people. Hoxit *et al.* (1978a) have examined possible mechanisms and effects that contribute to the development of intense convection after sunset.

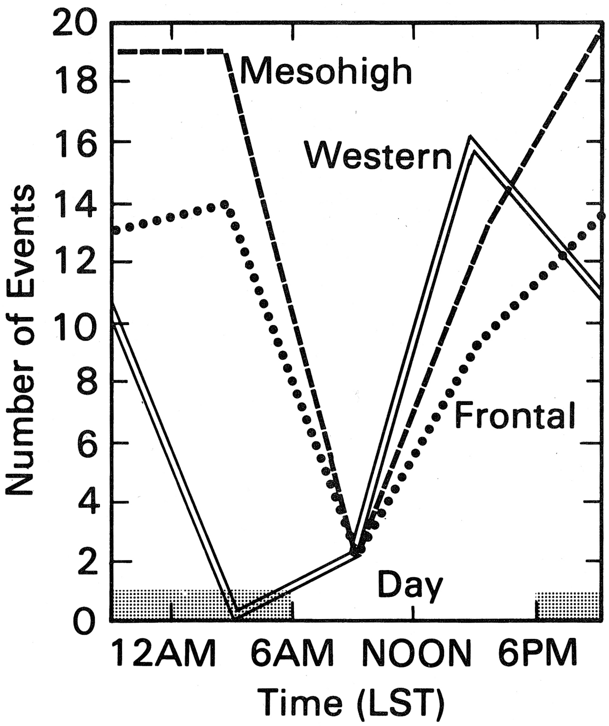

FIG. 3. Timing of the onset of heavy rains for three types of flash flood events. The number of events that began in each 6-hour interval is plotted at the midpoint of the interval.

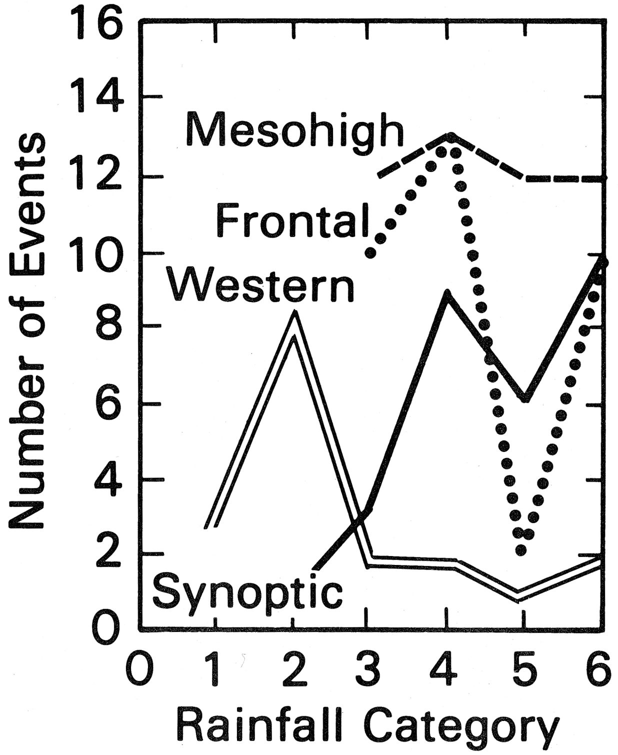

FIG. 4. Maximum precipitation amounts reported for flash flood events. The rainfall categories are: 1) <2 inches; 2) 2 to <4 inches; 3) 4 to <6 inches; 4) 6 to <8 inches; 5) 8 to <10 inches; and 6) ≥10 inches.

The maximum rainfall amounts reported for the events studied are presented in Fig. 4. The flash floods in the eastern U.S. were almost always associated with rainfalls of more than 10 cm (4 inches) and 32 were produced by rain amounts of 25 cm (10 inches) or more. The period of most intense rain usually lasted for only a few hours, typically less than six hours. Western events tended to be characterized by short duration and intense rainfalls of 5–10 cm (2–4 inches). Rugged terrain often couples with the intense precipitation to produce a very difficult warning situation because of the extreme "flash" nature of the rapid runoff that occurs.

If severe thunderstorms (storms that produce damaging winds, and/or large hail, and/or tornadoes) occur in association with the heavy precipitation event, forecaster

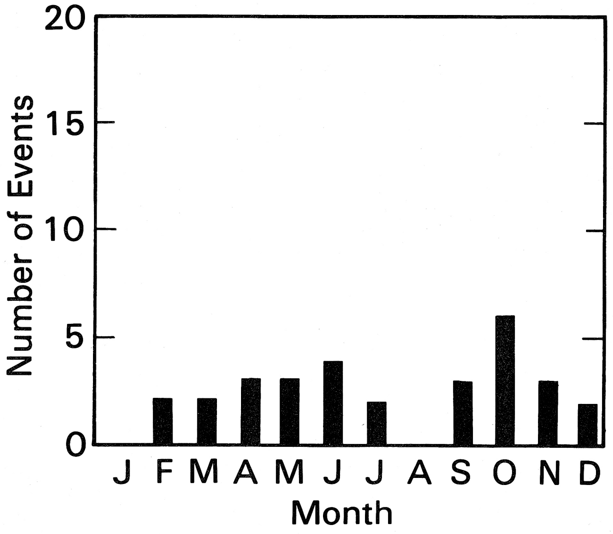

FIG. 5. Monthly distribution of synoptic type flash flood events.

concern for flash flood possibilities may become subordinate to that caused by other aspects of the storms. In the sample of 151 flash flood events, severe thunderstorms were reported 56 times in association with the heavy rains, and 17 times prior to the heavy rains. This means that, conservatively (since not all severe storm occurrences are reported), the state forecast office must contend simultaneously with both severe storm and flash flood problems in about half the flash flood situations.

Certain features were found to be common to almost all flash flood events, regardless of type. These important common characteristics are as follows:

1) Heavy rains were produced by convective storms.
2) Surface dewpoint temperatures were very high.
3) Large moisture contents were present through a deep tropospheric layer.
4) Vertical wind shear was weak to moderate through the cloud depth.

The characteristics of each of the four types of flash flood events are discussed in detail in the following sections.

3. Synoptic events

This type of flash flood event comprised 20% of the sample. Synoptic events developed in association with a relatively intense synoptic scale cyclone or frontal system. A major trough at 500 mb was usually moving slowly eastward or northeastward, and the associated surface front was often quasi-stationary. Convective storms repeatedly developed and moved rapidly over the same general area. Severe thunderstorms often occurred in association with the heavy rains (24 events or 80%). These events sometimes affected portions of several states (Fig. 1) and on occasion lasted as long as two to three days. Several individual flash floods sometimes occurred within the area affected by heavy rains, and large areas of general flooding often occurred.

The monthly distribution of synoptic events is shown in Fig. 5. As would be expected, this type event occurs most frequently in the spring and fall months when favorable combinations of dynamic processes and thermodynamic conditions exist. Table 1 lists the mean values of temperature and wind fields at the standard levels and shows the standard deviation computed for each mean. The difference in wind speed between 850 and 300 mb is only 25 kt with about 40 degrees of veering noted. Surface pressures average 1009 mb at the start of the event and dewpoint temperatures are high. Considerable variability in parameter values is indicated, especially for the wind fields. The orientation of the synoptic scale systems affects the variance of the wind fields, and although most fronts attending these events tend to be oriented SSW to NNE, a few were oriented essentially W to E. Regardless of frontal orientation, winds aloft tend to parallel the frontal zone. The composite sounding is unstable with a KI of +36 and an SI of −2. Precipitable water in the surface-to-500 mb layer totals 3.75 cm (1.48 inches), which is 181% of the mean monthly climatological value.

Surface features and flow patterns for 850 and 500 mb are shown in Fig. 6 for a typical synoptic type event. Areas with a potential for heavy rains and flash flooding are indicated by the shaded rectangles. The eastward extension is shown since a warm frontal boundary often limits the northward spread of heavy rains while helping trigger new developments farther eastward. Flash floods that were associated with the heavy rain-producing patterns discussed by Smith and Younkin (1972) and Gilhousen (1974) would likely be classified as synoptic events.

TABLE 1. Mean values and standard deviations of temperature and wind associated with synoptic type flash flood events (surface pressure reduced to sea level).

Level		T	T_d	Wind Direction	Wind Speed
Surface					
1009 mb	Mean	74(°F)	67(°F)	165°	13 (kt)
6	Std. Dev.	7	4	33	3
			$T - T_d$		
850 mb		15(°C)	2(°C)	195	32
		3	1	28	11
700 mb		5	3	215	36
		2	3	29	11
500 mb		−11	8	220	47
		3	9	29	14
300 mb		−38	10	230	57
		3	7	30	21
200 mb		−57	—	235	66
		3		32	21

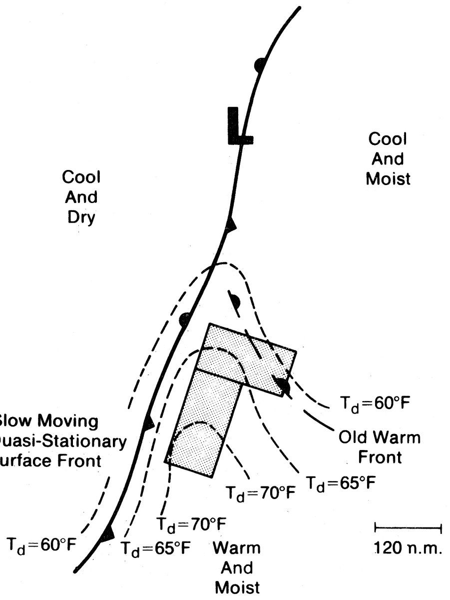

FIG. 6a. Surface pattern for a typical synoptic type flash flood event. Potential for heavy rains and flash flooding exists in the shaded areas.

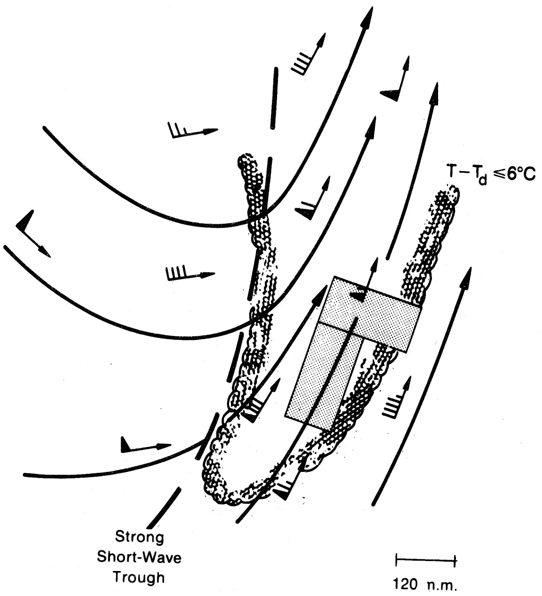

FIG. 6c. The corresponding 500 mb flow pattern for a typical synoptic type flash flood event.

4. Frontal events

Frontal type flash floods comprised 38 events or 25% of the sample. The presence of a stationary or very slowly moving synoptic scale frontal boundary (usually oriented W to E) that helped to trigger and focus heavy rain storms was the primary distinguishing characteristic of this type event. Heavy rains occurred on the cool side of the surface front as warm unstable air flowed over the frontal zone to feed the storms. This situation was distinctly different than the synoptic event, in which the storms usually developed and remained on the warm side of the front. Winds aloft nearly paralled the front, and convective storms repeatedly developed and moved over the same region. Frontal events were found to be distinctly nocturnal in nature (Fig. 3). Severe thunderstorms occurred in conjunction with the heavy rains in only seven events. The 500 mb analyses indicated that a detectable meso-α scale short-wave trough was associated with 31 of the events.

The monthly distribution of frontal events is shown in Fig. 7. These events occur fairly uniformly during the months March–September with the small number of June occurrences probably due to sampling deficiencies. Table 2 lists the mean values and standard deviations of

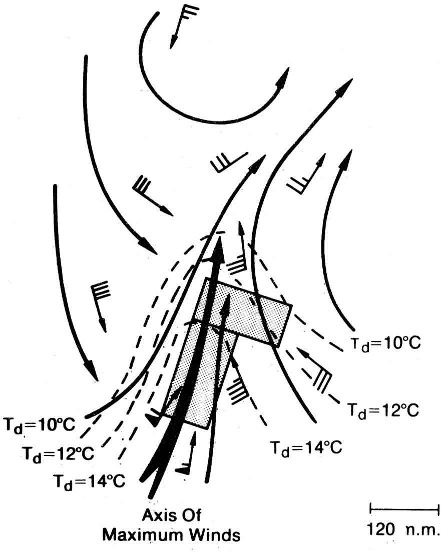

FIG. 6b. The corresponding 850 mb flow pattern for a typical synoptic type flash flood event. Winds are in knots with full barb = 10 kt and flag = 50 kt.

TABLE 2. Mean values and standard deviations of temperature and wind associated with frontal type flash flood events (surface pressure reduced to sea level).

Level		T	T_d	Wind Direction	Wind Speed
Surface					
1013 mb	Mean	70(°F)	65(°F)	100°	9 (kt)
4	Std. Dev.	6	5	36	2
			$T - T_d$		
850 mb		17(°C)	4(°C)	200	20
		3	2	26	8
700 mb		7	3	235	20
		2	3	30	10
500 mb		−10	6	250	28
		3	7	34	12
300 mb		−36	15	260	40
		3	11	29	16
200 mb		−56	—	270	47
		3		22	21

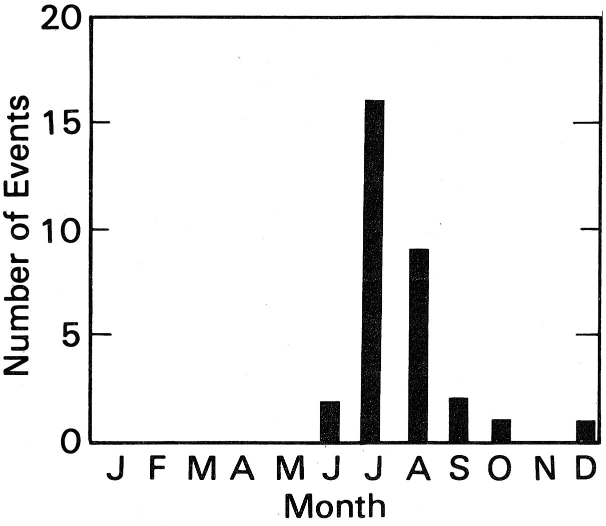

FIG. 7. Monthly distribution of frontal type flash flood events.

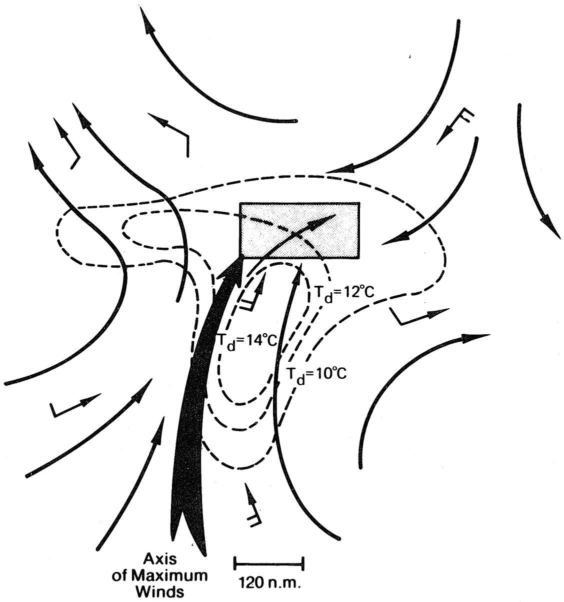

FIG. 8b. Corresponding 850 mb pattern for a typical frontal event.

temperature and wind associated with these events. Wind speeds increase little from 850–300 mb, although significant veering occurs. This veering favors the movement of storms roughly parallel to the forcing frontal boundary, while an inflow of unstable air continues unimpeded on their right flank. Surface pressures are relatively high and wind fields display the largest variances. The composite sounding has a KI of +38 and an unstable SI of −4. Precipitable water in the surface-to-500 mb layer totals 4.06 cm (1.60 inches), or 158% of the mean monthly climatological value.

Surface features and flow patterns for 850 and 500 mb are shown in Fig. 8 for a typical frontal event. Although weak 500 mb meso-α scale troughs usually act to help intensify frontal overrunning and initiate convection, the actual location of heaviest rainfalls is often near the large-scale ridge position. In some cases a weak mesolow moves eastward along the frontal boundary, increasing small scale convergence and inflow to the storm area. Analyses by Smith (1978) of the recent New Orleans flood indicate that this event was probably of the frontal type.

5. Mesohigh events

Mesohigh type events were the most numerous in the sample, comprising 52 events (34%). These flash flood events were associated with a nearly stationary thunderstorm outflow boundary that had been generated by prior convective activity. The heaviest rains occurred on the cool side of the boundary, usually to the south or southwest of the mesohigh pressure center. About half of the events occurred to the east of a slow moving large-scale

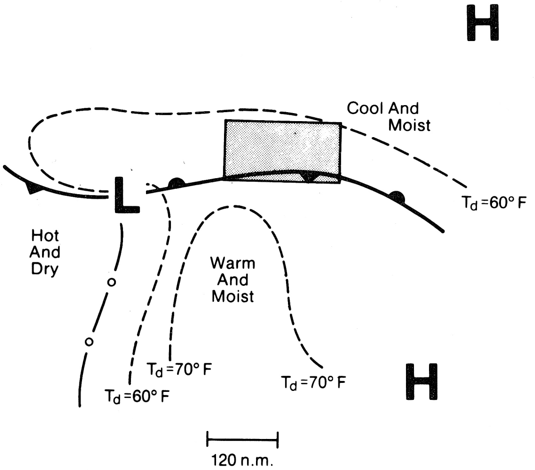

FIG. 8a. Surface pattern for a typical frontal event with details as in Fig. 6.

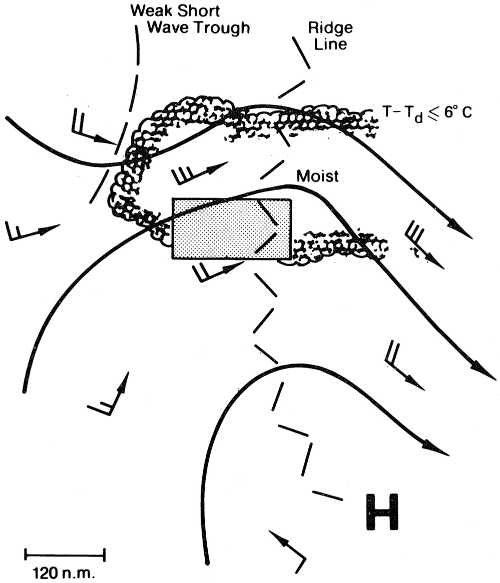

FIG. 8c. Corresponding 500 mb pattern for a typical frontal event.

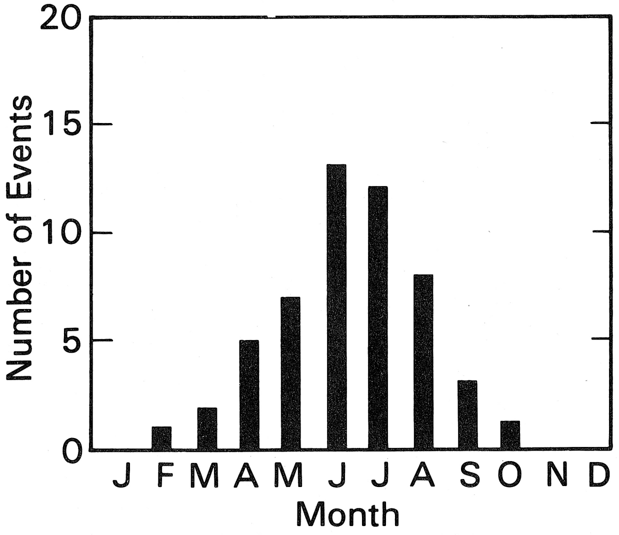

FIG. 9. Monthly distribution of mesohigh type flash flood events.

frontal system, while the other events were far removed from any notable surface fronts. Winds aloft nearly paralleled the outflow boundary and storms repeatedly developed and moved over the same area. Severe thunderstorms attended the heavy rains in 12 events, and were noted prior to the heavy rains in 12 others. These events were also distinctly nocturnal (Fig. 3). The 500 mb analyses indicated that a detectable meso-α scale trough was associated with 31 of the events.

The monthly distribution of mesohigh events is shown in Fig. 9. This type of event occurs primarily during June, July, and August, with occasional occurrences in the spring and fall months. Table 3 presents mean values and standard deviations of temperature and wind at the standard levels. Conditions are very similar to those of the frontal type event. There is little change in wind speed from 850–300 mb, although significant veering occurs. The composite sounding has a KI of +39 and an unstable SI of −5. Precipitable water in the surface-to-500 mb layer totals 4.16 cm (1.64 inches), which is 162% of the mean monthly climatological value.

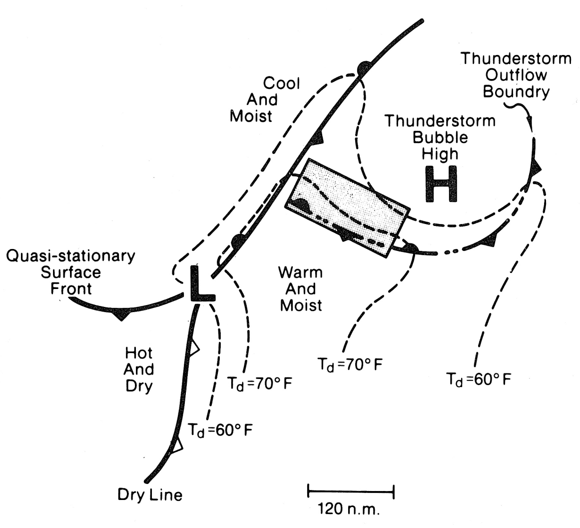

FIG. 10a. Surface pattern for a typical mesohigh event with details as in Fig. 6.

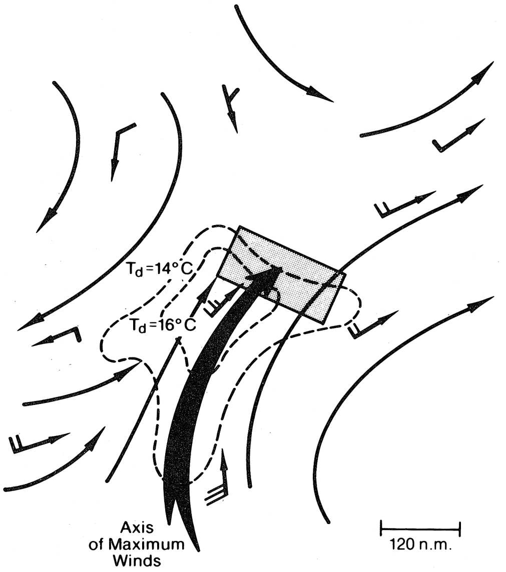

FIG. 10b. Corresponding 850 mb pattern for a typical mesohigh event.

Surface features and flow patterns for 850 and 500 mb are shown in Fig. 10 for a typical mesohigh event. Although weak 500 mb short waves are usually associated with these events, the actual heavy rain area is again often very near the large-scale ridge position. Detailed analyses of mesohigh type events have been presented by Labas (1976), Hales (1978), and Hoxit *et al.* (1978b).

6. Western events

Western events comprised 31 events or 21% of the sample. Of these, two were of the synoptic type and oc-

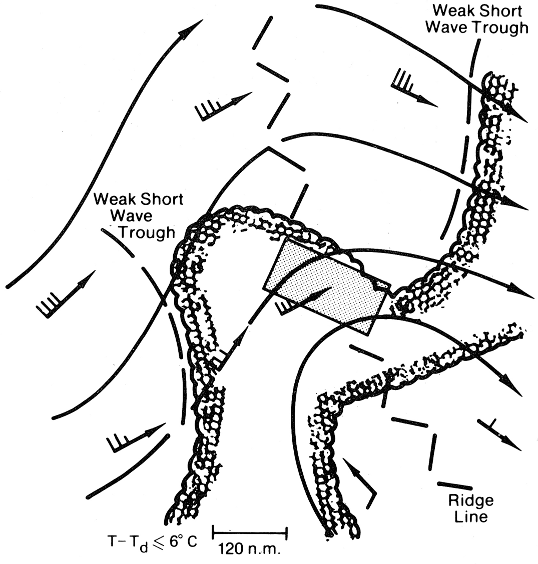

FIG. 10c. Corresponding 500 mb pattern for a typical mesohigh event.

TABLE 3. Mean values and standard deviations of temperature and wind associated with mesohigh type flash flood events (surface pressure reduced to sea level).

Level		T	T_d	Wind Direction	Wind Speed
Surface					
1014 mb	Mean	71(°F)	66(°F)	090°	9 (kt)
4	Std. Dev.	4	4	41	3
			$T - T_d$		
850 mb		18(°C)	3(°C)	205	22
		3	2	33	8
700 mb		7	4	230	21
		2	3	32	10
500 mb		−10	6	240	27
		3	6	27	11
300 mb		−36	10	255	37
		4	8	32	16
200 mb		−57	—	260	41
		3		40	20

curred west of the Sierra Range, while three floods were east-slope events characterized by strong, moist easterly flow to the rear of a polar front (the locations of these five events are indicated by the areas and stars shown in Fig. 1). These five events differed considerably from the bulk of the western sample (the 26 events shown as solid circles in Fig. 1) and were not included in the averaging. Detailed descriptions of two of the significant east-slope type events are presented in Maddox *et al.* (1978). Most western events occurred under relatively weak large-scale patterns without well-defined surface patterns. Most western events might have been classified according to the three types used to categorize eastern U.S. events; however, the paucity of surface observations precluded detailed classification. In most events it is likely that old frontal boundaries, thunderstorm outflow, or orographic features interacted with larger scale features to produce the localized heavy rains. No attempt was made to develop maps of typical surface or upper-air patterns. Fig. 11 shows the monthly distribution of these events. The distinct maximum in July and August indicates a strong link with the moisture intrusion attending the monsoon season in the Southwest. Severe thunderstorms were reported in conjunction with the rains in 13 of 26 events and an identifiable short-wave trough at 500 mb was noted in 24 of the events.

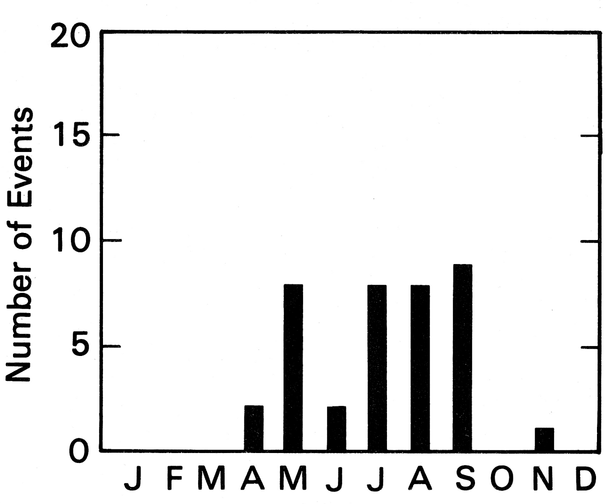

FIG. 11. Monthly distribution of western type flash flood events.

Table 4 presents mean values and standard deviations of parameters associated with the western events. Note that the wind fields are light and highly variable. The composite sounding had considerable conditional instability with a KI of +42 and an SI of −5; however, these values cannot be directly compared with the KI and SI values obtained for eastern U.S. events since the 850 mb level and the surface are nearly coincident in much of the West. Drier and hotter subcloud conditions, along with the pronounced afternoon maximum in occurrence (Fig. 3), help explain the high frequency of severe storm occurrences associated with these events. Precipitable water in the surface-to-500 mb layer totals 2.58 cm (1.02 inches), which is 143% of mean monthly climatological values. The general threat area in these type events is best delineated by high moisture contents (surface through at least 500 mb), weak vertical wind shear, and large conditional instability in an area that lies ahead of an advancing mid-tropospheric, meso-α scale trough. The flash floods often occurred very near the large-scale ridge position.

7. Summary

Meteorological analyses have been made of 151 significant heavy precipitation events. The events were classified according to four basic types, and detailed descrip-

TABLE 4. Mean values and standard deviations of temperature and wind associated with western type flash flood events (surface pressure reduced to sea level).

Level		T	T_d	Wind Direction	Wind Speed
Surface					
1012 mb	Mean	86(°F)	56(°F)	120°	9 (kt)
4	Std. Dev.	6	6	57	4
			$T - T_d$		
700 mb		10(°C)	6(°C)	190	11
		2	4	73	7
500 mb		−9	4	210	16
		2	3	79	11
300 mb		−34	10	220	27
		3	7	62	19
200 mb		−55	—	235	34
		2		65	20

tions of the meso-α scale environment associated with each type have been presented.

A number of features were common to many of the events. These included:

1) Flash floods were associated with convective storms.
2) Storms occurred in regions with high surface dewpoint temperatures.
3) Relatively high moisture contents were present through a deep tropospheric layer.
4) Weak to moderate vertical shear of the horizontal wind was present through the cloud depth.
5) Convective storms and/or cells repeatedly formed and moved over the same area.
6) A weak, mid-tropospheric, meso-α scale trough helped to trigger and focus the storms.
7) The storm area was very near the mid-tropospheric, large-scale ridge position.
8) Storms often occurred during nighttime hours.

The problem of determining a flash flood threat, or "watch area," appears very similar to that of determining severe thunderstorm or tornado watch areas. A number of meteorological processes interact on several scales of motion to eventually define the region of excessive rainfall. Data indicate that, as in severe thunderstorm situations, marginal values of one important parameter may be compensated by more intense values of another parameter. This large natural variability makes definition of a set of necessary conditions, much less sufficient conditions, extremely difficult.

The forecast and warning problem is complicated by the nocturnal nature of many of the events. Unlike many severe thunderstorms, flash flood storms frequently occur very near the large-scale ridge position and with normally benign surface pressure patterns. This elusive characteristic further complicates the forecast problem. It is hoped that the results of this study of a large number of flash flood events will be of use in the further development and improvement of local forecast techniques.

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