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Catastrophic flooding and atmospheric circulation anomalies

Katherine K. Hirschboeck

ABSTRACT

An analysis of the atmospheric circulation patterns associated with twenty-one catastrophic floods in the conterminous United States demonstrates that each flood can be linked to anomalous patterns of circulation. Extreme regional floods over broad areas evolve from different types of large-scale anomalous behavior: uncommon locations of typical circulation features, unusual combinations of atmospheric processes, rare configurations in circulation patterns, and exceptional persistence of the same circulation pattern. Extreme local flash floods over small drainage areas can be classified into synoptic categories of existing flash-flood forecasting schemes, and in addition, these small-scale catastrophic events exhibit sensitivity to large-scale circulation anomalies. Blocking configurations in the upper-air flow pattern are important features during catastrophic flooding episodes. A clustering of catastrophic events in time is evident and may be related to the frequency of blocking or the existence of alternate states of equilibria in the atmosphere. This episodic behavior has important implications for geomorphology, especially in terms of recovery times between recurring catastrophic events, and the probability of occurrence of channel-forming sequences of extreme floods.

INTRODUCTION

With the exception of dam failures, ice jams, jökulhlaups and tsunamis, nearly all incidents of extreme flooding evolve from definable large-scale atmospheric circulation patterns and specific meteorological features embedded within them. Certain floods -- due to their great magnitude, sudden occurrence, or extreme destructiveness -- have been labeled "catastrophic." The extreme nature and rarity of these hydrologic events raises the question of whether or not they have been spawned from equally extreme and unusual atmospheric conditions.

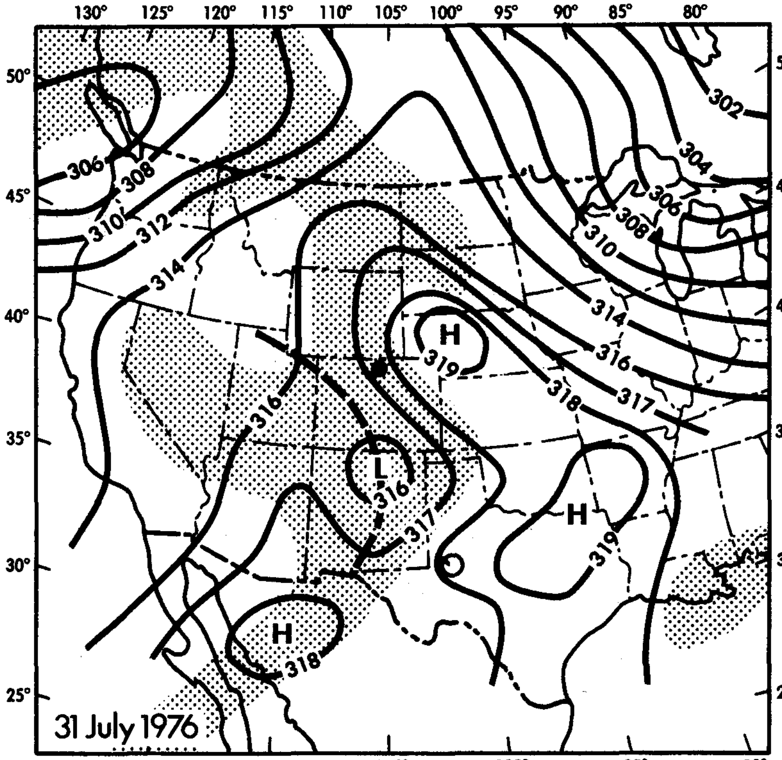

Figure 1. Upper air weather map just before the catastrophic Big Thompson Canyon flood. This detailed 700 mb map for 1200 GMT, 31 July 1976, shows a short-wave low pressure trough (dashed line) moving through a broad upper air ridge of high pressure. Height contours of the 700 mb surface are given in dekameters. (Modified from Maddox et al., 1977).

After the recent catastrophic floods of Rapid City, South Dakota (June, 1972), Big Thompson Canyon, Colorado (July, 1976), and Johnstown, Pennsylvania (July, 1977), detailed analyses were undertaken of observed precipitation patterns, radar displays, satellite imagery, and synoptic weather charts to better understand the evolution of the storms that generated these momentous flash floods (Dennis et al., 1973; Maddox et al., 1977; Hixit et al., 1982). The key meteorological features for each of these extreme events were relatively small-scale atmospheric phenomena such as intense thunderstorms, squall lines, and short-wave troughs. These in turn developed within, and were influenced by, the larger synoptic-scale wave pattern of upper-level steering winds.

For example, in the Big Thompson flash flood, supercell thunderstorms developed to great heights in anomalously moist unstable air, aided by upslope winds, and convergence associated with a short-wave trough (Fig. 1). A similar wave pat-

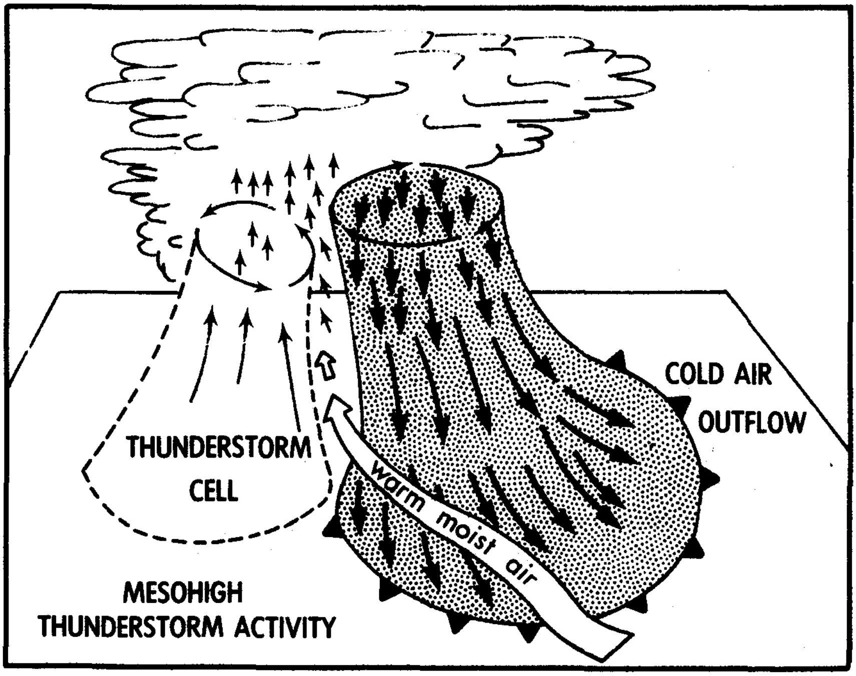

Figure 2. Schematic diagram of thunderstorm activity associated with mesohighs. Cold air outflow from the rainy area of a large thunderstorm complex spreads out ahead of the storm, acting like a localized cold front, and having some of the attributes of a small high pressure center. The mesohigh activity induces subsequent intense convective activity by forcing warm, moist air to rise over the outflow boundary. (Modified from Eagleman, 1983)

tern produced the Rapid City flood. Precipitation totals from these storms were excessive because winds aloft were weak and the thunderstorm cells remained nearly stationary for several hours (Maddox et al., 1977). Similarly, in the Johnstown flash flood, a short-wave trough, topographic relief, and anomalously high values of precipitable water vapor in the atmosphere played a role in generating the flood. Furthermore, in the Johnstown flood, *mesohigh* features associated with quasi-stationary thunderstorm activity (see Fig. 2) were key factors in concentrating heavy rains over relatively small areas (Hoxit et al., 1982).

These case studies illustrate how a variety of meteorological elements at various scales can combine to produce the anomalous atmospheric conditions that result in a catastrophic flood. Due to their small spatial scales and short durations, many of the localized meteorological features important for flash flood generation in small catchments are not easily identified on large-scale weather maps, nor do they exhibit readily discernable anomaly patterns in the broad scale atmospheric circulation. In contrast, extensive regional catastrophic flooding in larger drainage basins tends to be produced by quite obvious large-scale synoptic features that are either persistent or recurrent over a given area.

In this paper, I will examine the atmospheric circulation features responsible for generating the largest maximum observed floods in the United States in drainage areas ranging from less than 0.5 km^2 to 3,000,000 km^2. My purpose is to assess how well catastrophic flood events can be linked to various atmospheric circulation anomalies. I will then discuss the geomorphic implications of atmospheric circulation anomalies in terms of response times and recovery periods following catastrophic flooding episodes.

CATASTROPHIC FLOODING IN THE UNITED STATES

Although many floods that have occurred in the conterminous United States have been described as "catastrophes," there are no standard criteria for classifying a given flood as a catastrophic event. I will consider as catastrophic the maximum floodflows that have been observed and officially recorded for various drainage basin areas. My selection of catastrophic flood peaks is taken from the compilations of Crippen and Bue (1977) and Rodier and Roche (1984). In the catalog by Crippen and Bue (1977), United States maximum floodflows that occurred through September 1974 in areas less than 25,900 km^2 are listed and plotted against drainage area to form an envelope curve. Rodier and Roche's (1980) World Catalogue of Maximum Observed Floods presents a more recent listing (through 1980) for a smaller sample of U. S. floods.

Figure 3 depicts an envelope curve for twenty-one selected catastrophic peak flow events in the United States, plotted against drainage area. These twenty-one floods were compiled as follows. For small basins (less than 370 km^2), I reviewed the largest floods from Crippen and Bue's nationwide envelope curve and selected from these on the basis of Costa's (1985) identification of the twelve largest rainfall-runoff floods in the United States (solid circles in Fig. 3). Costa's twelve floods all occurred in relatively small catchments in the western states or in Texas, so for a wider regional representation, I included four floods (#4, 6, 14, 15) from the Colorado Front Range and central Great Plains regions that appear as maxima on the Crippen and Bue nationwide curve, but were not included by Costa because they plotted slightly below the curve defined by his twelve maximum floods. To represent intermediate and larger drainage areas, I included five floods (#16, 17, 18, 19, 20) from basins larger than 500 km^2 that are listed in the Rodier and Roche catalog. Finally, to reflect an "upper limit" for drainage area on the envelope curve, I added an entry (#21) for one of the more extreme flood events on the Mississippi River (Chin et al., 1975). (Because of diversions, levees, and changing stage-discharge relations (see Belt, 1975), the "maximum observed" flood peak on the Mississippi is highly debatable.) In order to emphasize catastrophic rainfall-runoff relationships, my selection of floods excluded events due to nonclimatic fac-

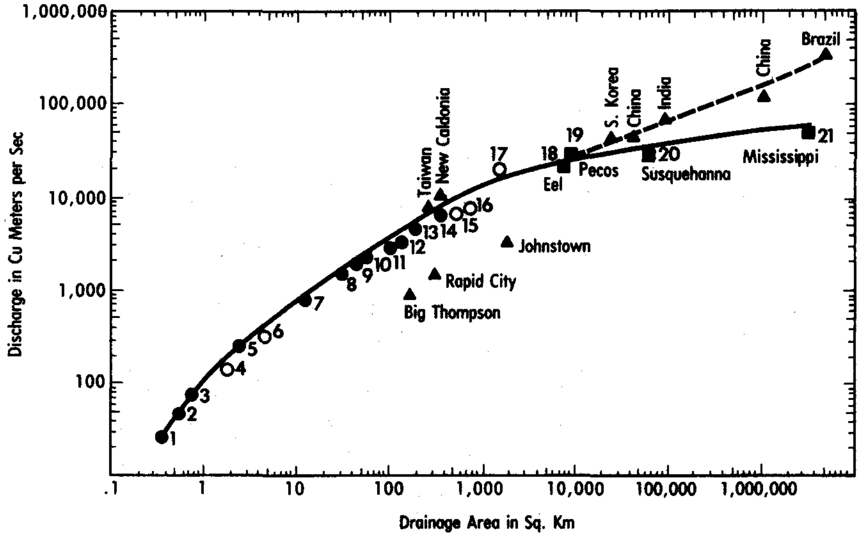

Figure 3. Envelope curve for catastrophic peak flow events in the United States. See text for sources. Flash floods are indicated by circles; large regional floods by squares. Solid circles indicate the twelve largest rainfall-runoff floods in the United States identified by Costa (1985). Triangles indicate other floods of interest. The dashed line represents the world curve as defined by Rodier and Roche (1984).

tors such as dam breaks, as well as floods arising from snowmelt or ice jams.

Due to the varied sources from which my data have been selected, I cannot claim that the resulting curve represents a definitive upper limit of flooding in the conterminous United State. Nevertheless the portion of the curve defined by the Costa data is highly representative and the overall curve is a fair approximation of the extreme upper limits of United States flooding through 1980. The floods defining the envelope curve are listed in Table 1 and their geographic locations are given in Figure 4. Also included in the table and plotted on the figures are three of the more noteworthy United States catastrophic flash floods: Big Thompson, Rapid City, and Johnstown, Pennsylvania. In addition, some of the world's largest floods (selected from Rodier and Roche) have also been plotted on Figure 3. The curve defining the largest flood peaks in the world coincides fairly well with the United States curve for basins up to about 10,000 km^2, and then departs dramatically (dashed line). Those extreme global floods that exceed events on the U.S. curve for the same drainage area are in tropical and monsoon climates that are not represented in the conterminous United States.

Table 1 and Figure 3 reflect the relative higher frequency of localized catastrophic flash flooding in small and medium size basins, in comparison with the more rare large-scale catastrophic flooding that encompasses broad regions. Most

Table 1. United States catastrophic floods and atmospheric circulation anomalies

ID#	Station Name	Area (sq km)	Peak Q (cms)	Date	Circulation Classification	Additional Anomalous Circulation Behavior
1	Wenatchee R. Trib at Monitor, WA	.39	25.6	8-2-56	Western III	Intense cutoff low, blocking ridge in central Pacific
2	Lahontan Res Trib nr Silver Springs, NV	.57	47.6	7-20-71	Western I	Abrupt change from deep Aleutian trough to strong ridge.
3	Little Pinto Ck trib nr Old Irontown, UT	.78	74.5	8-11-64	Western II	High latitude flow exhibited strong blocking pattern.
4	Boney Draw at Rockport, MO	1.97	144.0	7-18-65	Frontal	Hot, humid conditions prevailed beneath central U.S. ridge.
5	Humboldt R. Trib nr Rye Patch, NY	2.20	251.0	5-31-73	Western III	Strong cutoff low and deep trough.
6	Stratton Ck nr Washta, IA	4.92	311.0	8-09-61	Mesohigh	Deep trough over SE U.S. displaced cold fronts to south.
7	Lane Canyon nr Molin, OR	13.10	807.0	7-26-65	Western I	Extremely deep Aleutian low in unusual location.
8	Meyers Canyon nr Mitchell, OR	32.90	1,540.0	7-13-56	Western I	Abnormal southward displacement of westerlies; split flow.
9	Bronco Ck nr Wikieup, AZ	49.20	2,080.0	8-18-71	Western IV	Subtropical High ridge extended far westward from Atlantic.
10	Eldorado Canyon at Nelson Landing, NV	59.30	2,152.0	9-14-74	Western II	Upper level closed low; thunderstorm cell moved downvalley.
11	North Fork Hubbard Ck nr Albany, TX	102.00	2,920.0	8-04-78	(combination)	TS Amelia; cold front; dry layer; Balcones uplift
12	Jimmy Camp Ck nr Fountain, CO	141.00	3,510.0	6-17-65	Synoptic	Very strong amplification of Rossby waves; deep cutoff low.
13	Mailtrail Ck nr Loma Alta, TX	195.00	4,810.0	6-24-48	(combination)	Cold front; Balcones uplift; easterly wave?
14	Seco Ck above D'Hanis, TX	368.00	6,510.0	5-31-35	(combination)	Balcones uplift; strong thunderstorm; MCC?
15	Little Nemaha R nr Syracuse, NE	549.00	6,370.0	5-09-50	Synoptic	Stronger than normal southerly flow at surface and aloft.
16	East Bijou Ck at Deer Trail, CO	782.00	7,760.0	6-17-65	Synoptic	Same as Jimmy Camp Creek (#12).
17	West Nueces R nr Brackettville, TX	1,813.00	15,600.0	6-14-35	(combination)	Balcones uplift; strong thunderstorm; MCC?
18	Eel R at Scotia, CA	8,063.00	21,300.0	12-23-64	Large-Scale I	Strong blocking ridge in Pacific; slipt flow; persistent jet.
19	Pecos R at Comstock, TX	9,300.00	27,440.0	6-28-54	Large-Scale II	TS Alice remnant stalls; 500 mb wave; Balcones uplift.
20	Susquehanna R at Harrisburg, PA	62,400.00	28,900.0	6-24-72	Large-Scale III	Unusual path of TS Agnes; anomalous SSIs; Atlantic blocking.
21	Mississippi R at Vicksburg, MS	2,964,300.00	55,600.0	5-12-73	Large-Scale IV	Repeated development of trough in roughly same position.
	(peak of record at Vicksburg)		58,900.0	2-17-37		
	Big Thompson Canyon at mouth, CO	155.00	884.0	7-31-76	Western I	Stationary supercell thunderstorm; high precipitable water.
	Rapid Ck at Rapid City, SD	236.00	1,433.0	6-09-72	Western I	Stationary supecell thunderstorm; high precipitable water.
	Johnstown (Conemaugh R at Seward, PA)	1,850.00	3,260.0	7-20-77	Mesohigh	Mesohighs; large and long-lived MCC.

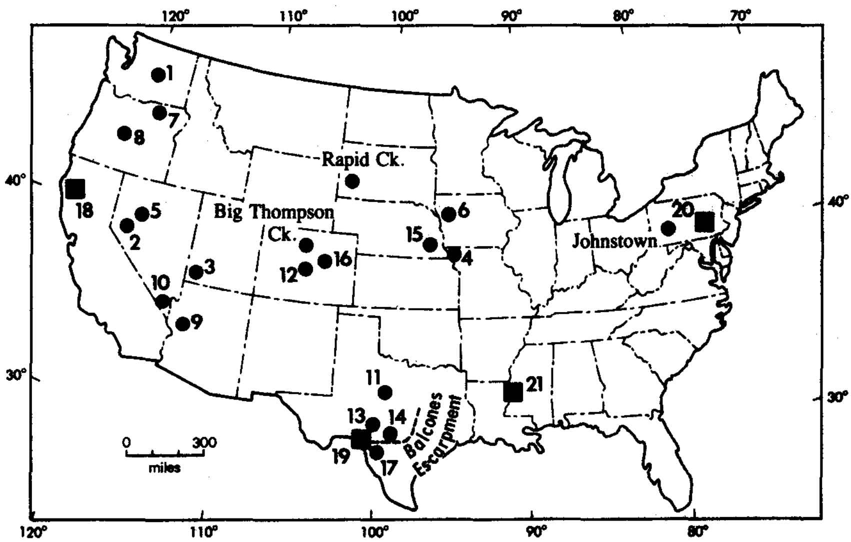

Figure 4. Location map of catastrophic events. Small-basin flash floods are indicated by circles; large regional floods by squares.

extreme flash flood events have been concentrated in western United States, although the eastern slopes of the Colorado Front Range, the central Great Plains, and central Texas have also experienced small-basin catastrophic floods. This geographic clustering appears to be related to both physiographic and climatic factors.

ATMOSPHERIC CIRCULATION ANOMALIES

Highly unusual atmospheric circulation patterns might be considered the atmospheric equivalents of "catastrophic" events. Anomalous atmospheric activity can occur over a wide spectrum of space and time scales. Figure 5 depicts a simplified version of the standard subdivision of scales for atmospheric processes proposed by Orlanski (1975), with some illustrations of potentially anomalous activity at each scale. At the *meso-β* scale, areas of unusually deep convection, intense squall lines, and persistent and severe "supercell" thunderstorms might be viewed as anomalous circulations that concentrate part of the enormous energy and moisture of the atmosphere into relatively small areas. At larger *meso-α synoptic* scales of activity, anomalous circulation features tend to be exhibited in particularly strong or persistent fronts, unusually intense or atypically-located tropical cyclonic storms, mesoscale convective complexes (MCCs) (Maddox, 1980; Rodgers et al., 1983), and short-wave troughs that migrate through larger-scale quasi-stationary upper air waves, triggering convection and intense precipitation.

The term "atmospheric circulation anomaly" is most commonly used to refer to unusual configurations or persistence in the *macroscale* features of the upper atmosphere. The *macro-β scale* is characterized by long (Rossby) waves, their ridges and troughs, and their attendant cyclonic and anticyclonic eddies; while the *macro-α scale* includes the ultra-long thermally- and topographically-anchored planetary waves that reflect the mean state of the circumpolar vortex. Current research on macroscale anomalous atmospheric flows has focused on: blocking, persistent anomalies, the possibility of multiple equilibria in the atmospheric circulation, and forcing of the anomalies by either internal or external factors. Each of these topics has some relevance for the question of how catastrophic floods are related to atmospheric circulation anomalies.

Blocking

Blocking is a large-scale perturbation in the typical zonal (west-east) movement of high and low pressure systems that takes the form of a quasi-stationary long wave. It is characterized by high-amplitude meridional flow aloft and the presence of high-latitude anticyclonic and low-latitude cyclonic eddies, known also as cutoff (omega) highs and cutoff lows (Fig. 6). The blocking generally persists for one to two weeks and exhibits an abrupt transition from zonal to meridional flow that oc-

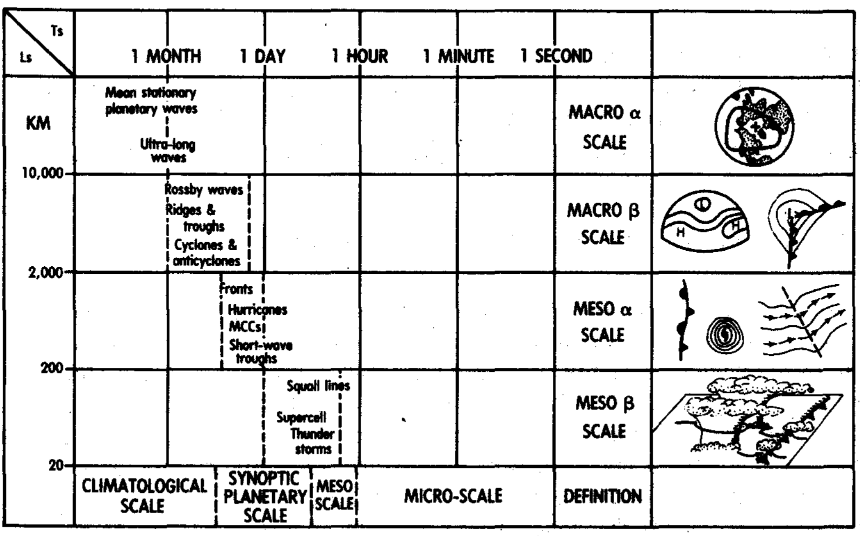

Figure 5. Standard subdivision of scales for atmospheric processes, modified from Orlanski (1975). The time scale (Ts) refers to the typical period between events. The length scale (Ls) refers to the typical wavelength between features; e.g., the distance from one ridge axis to the next ridge axis. Only the meso-β through macro-α scales are shown.

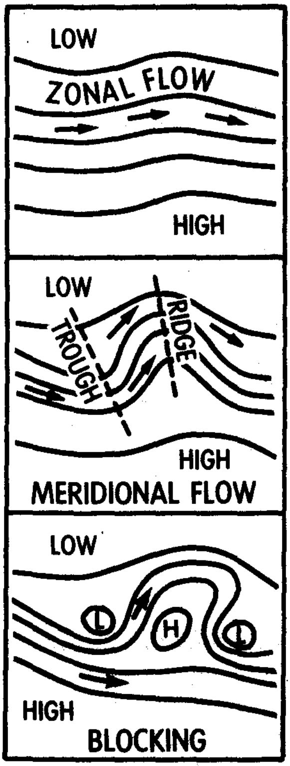

Figure 6. Schematic diagram of blocking in relation to more typical zonal and meridional flow. (Modified from Oliver and Fairbridge, 1987).

curs where the basic westerly jet stream splits into two branches (Rex, 1950a, b). Blocking occurs most often over the northeastern Atlantic and northeastern Pacific Oceans, with the latter location having a particularly strong influence on the weather of western United States. It is noteworthy that the occurrence of Pacific blocking has been linked to variations in tropical sea surface temperatures, El Niño, and the Southern Oscillation (White and Clark, 1975; Horel and Wallace, 1981). Blocking in the Atlantic Ocean can also influence the weather of the United States, as demonstrated by Resio and Hayden (1975) who linked Atlantic blocking to increased extratropical storm activity along the east coast. Blocking plays a major role in generating episodes of extreme flooding because of the persistent and anomalously-located storm tracks that tend to be associated with the phenomenon. The Northern California floods of February 11-19, 1986 resulted from a blocking pattern in the North Pacific ocean that shifted the main branch of the winter jet stream to a more southerly location for longer than a week. This circulation anomaly repeatedly supported the development of massive low pressure systems off the California coast, and steered a succession of devastating storms into the region over a nine-day period (Fig. 7).

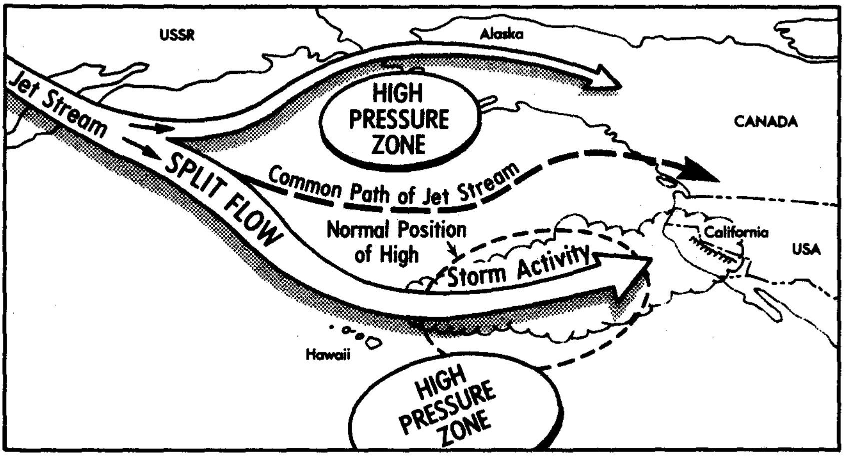

Figure 7. Diagram depicting the blocking action that led to severe flooding in Northern California during 11-19 February 1986. (Modified from Hart, 1986).

Persistent Anomalies

In climatology, the term "anomaly" does not always refer to a highly unusual atmospheric event, since it is used frequently to refer to any departure of a value from the long-term climatic mean. If however, the departure from the mean is sufficiently great and remains so for an unusually long period of time, the event is often referred to as a "persistent anomaly" (Dole, 1986). Blocking is one mechanism that is likely to generate persistent anomalies, and most of the current research in this area has revolved around the persistence of blocking over the North Pacific and North Atlantic oceans.

Over the continents, various configurations of the Rossby waves that are similar to blocking can exhibit anomalous persistence by either remaining quasi-stationary for extended periods of time or by repeatedly developing in roughly the same location. These preferred continental ridge and trough positions may or may not be linked to blocking over the ocean, but they have a substantial influence on the climate of specific areas -- often bringing droughts to regions underlying persistent high pressure ridges, and floods to regions underlying the southeastern sectors of troughs (where frontal activity and storm tracks are concentrated).

Multiple Equilibria

Ever since the earliest observations of variations in the mid-latitude westerlies, meteorologists have noted a tendency toward two different states of large-scale motion in the atmosphere. Under a zonal flow regime (see Fig. 6), motion is strongly west-to-east, reflected in low amplitude Rossby waves. Under meridional flow conditions, winds are steered in more northerly and southerly trajectories and amplitudes in the Rossby waves are high. Blocking is an example of an extreme high-amplitude condition, which will eventually break down when cutoffs occur and zonal flow is resumed. Episodes of dominance by zonal and meridional flow conditions have been successfully linked to twentieth century climatic variations (e.g. Dzerdzeevskii, 1969; Lamb, 1977), and specifically to flood variability (Knox et al., 1975; Knox, 1984).

Recent theoretical work and modeling have suggested the possibility of multiple equilibria in the atmospheric circulation, with one stable steady state that corresponds to relatively strong zonal flow in the ultra-long planetary waves, and another that corresponds to a higher-amplitude, more meridional state with an apparent tendency toward more frequent blocking (Charney and DeVore, 1979; Hansen, 1986; Sutera, 1986). The importance of this new research, as suggested by Sutera, is that if "more than one regime occurs, then the mean state of the atmosphere would not be adequately represented by its long-term average, but rather by the set of average states obtained by considering, separately, each individual regime." (Sutera, 1986, p. 227). The possibility of two modes of operation in the planetary waves -- with one mode perhaps more prone to anomalous blocking activity -- has important implications for flood variability and could be reflected in a temporal clustering of catastrophic events during high-amplitude circulation regimes.

Internal and External Forcing

An area of active debate among dynamic and synoptic meteorologists centers around the importance of various forcing mechanisms for large-scale wave activity. It is widely agreed that external forcing by orographic drag and land-sea thermal contrasts is an important mechanism for developing the long-term, macro-α scale mean planetary waves (Wallace, 1983). However, internal, as well as external, factors have been advanced as the dominant forcing mechanisms for anomalous wave patterns, and blocking, at other macro-α and macro-ß scales. Those who promote internal forcing mechanisms have demonstrated that interactions between ultra-long planetary waves and synoptic-scale traveling systems can form and sustain large-scale blocking patterns in a process referred to as eddy forcing (e.g., Shutts, 1986; Pierrehumbert, 1986; Egger et al., 1986). Similarly, Lindzen (1986) and Reinhold (1987) suggest tha interference and interaction between waves and flow configurations of different scale can produce planetary-wave anomalies by a mechanism that is purely internal to the dynamics of the atmosphere. Furthermore, Lindzen (1986) maintains that these interactions alone can explain the observed evidence of multiple equilibria.

An alternative view is expressed by those who have promoted external forcing mechanisms as explanations for atmospheric circulation anomalies and blocking wave patterns. This perspective is presented most notably in the works of Jerome Namias, from 1944 to the present. Self-enhancing feedback between continental surfaces and the atmosphere, due to persistent soil moisture conditions or snow cover, is one external mechanism that has been linked to climatic anomalies (Namias, 1962; 1963). Of much greater significance is the interaction between the atmosphere and the ocean, especially as it is manifested in teleconnections between sea surface temperature (SST) anomalies and corresponding atmospheric circulation anomalies. The major El Niño/Southern Oscillation (ENSO) event of 1982/83 has been linked to persistent global circulation anomalies (Chen, 1983; Quiroz, 1983; Yarnal, 1985) and episodes of major flooding at diverse locations in the western hemisphere, including Peru, Bolivia, and Ecuador in South America, the Pacific coast of North America from Oregon to Baja California, the Lower Mississippi Valley, and coastal areas of the Gulf of Mexico (Quiroz, 1983). On the basis of varying modeling results and the strong evidence for internal control mechanisms, the overriding influence of SSTs on the thermal forcing of anomalous wave configurations has been questioned (Lindzen, 1986; Reinhold, 1987). Nevertheless, success in long-range forecasting and strong correlations with regional climatic anomalies have made SSTs and teleconnections a primary research area with important implications for catastrophic flooding.

Classification of Large-Scale Anomaly Patterns

Most of the recent theoretical and observational research on circulation anomalies has focused specifically on blocking, but other forms of large-scale anomalous behavior are also possible. Inspection of surface and upper air synoptic charts during unusual climatic episodes reveals that anomalous atmospheric behavior can manifest itself in a variety of ways -- some related to true blocking regimes, and others that are not necessarily tied to blocking. I have classified large-scale circulation patterns into four types of anomalous behavior. These types are not based on internal atmospheric dynamics, but on how a point on the earth's surface would experience the unusual circulation pattern. This kind of response-based classification can better define the ways in which rare atmospheric patterns result in catastrophic flooding events.

The four large-scale anomaly types are: an anomalous location or unseasonal occurrence of an otherwise typical circulation mechanism (*Large-Scale I*), an unusual combination of several common meteorological mechanisms occurring simultaneously (*Large-Scale II*), an extremely rare configuration in the upper air pattern itself (*Large-Scale III*), and the unusual persistence in space and time of a specific wave configuration (*Large-Scale IV*). While Large-Scale II might occur during any kind of circulation regime, due purely to random factors, Large-Scale I, III, and IV are more likely to occur during either true blocking regimes, or during meridional regimes characterized by high-amplitude, quasi-stationary waves.

Classification of Small-Scale Anomalies

Due to their small spatial scale and short duration, mesoscale events that produce flash floods do not exhibit anomaly patterns that are as obvious, and as persistent, as larger-scale anomalies, such as blocking. However, the conditions necessary to transform a "typical," mesoscale storm into one with catastrophic effects are often linked to larger-scale features such as thick and laterally extensive layers of unusually high precipitable water vapor, and specific upper-air flow patterns that affect the path, strength, and persistence of severe storms.

Recently, efforts by R. A. Maddox and his colleagues to improve flash flood forecasting by using synoptic observational techniques have produced an extremely useful classification scheme for meteorological events that generate flash floods. Maddox and Chappell (1978) and Maddox et al (1979) introduced a four-fold classification for circulation features that are associated with flash floods, dividing them into *Synoptic events, Frontal events, Mesohigh events, and Western events.* Maddox et al (1980) subsequently refined the classification by subdividing the Western flash flood category into four additional types (*Western I-IV*). The diagnostic characteristics that define each category are related to local properties of temperature, moisture, instability, wind speed, and wind direction at various levels in the atmosphere. In addition, each type is associated with a particular synoptic-scale pattern of both surface and upper-level circulation features. The patterns are distinguished primarily on the basis of how short-wave troughs move through specific configurations of longer-wave ridges and troughs. An advantage of the scheme is that it bridges small-scale and large-scale atmospheric activity, ultimately tying a local flash flood event into the broader regional pattern that is linked to macro-scale circulation features.

The diagnostic details of the classification for central and eastern United States flash flood events can be found in Maddox et al (1979), and for western events in Maddox et al (1980). The Maddox classification is based on the detailed analysis of at least 180 flash flood events of varying sizes that occurred during 1973-78. Due in part to the time period sampled, only a few of these floods are among the catastrophic floodflows being considered in this paper. An initial stage in the Maddox analysis was a pilot study of twenty-one "significant" flash flood events (Maddox and Chappell, 1978). These included the catastrophic floods of Rapid City (1972); Eldorado Canyon, Nevada (1974); Big Thompson Canyon (1976); and Johnstown, Pennsylvania (1977) all of which are plotted on Figures 3 and 4 and listed in Table 1. However, of these, only the Eldorado flood (#10) falls on the envelope curve of maximum discharge versus drainage area shown in Figure 3.

In a sense, any flash flood occurrence can be considered "catastrophic" because of the suddenness of the event. Therefore the synoptic patterns of the Maddox classification can be viewed as circulation "mini-anomaly" patterns that produce small-scale catastrophic flood events. The maximum floodflows that define the envelope curve of Figure 3 raise an interesting question, however. Do the atmospheric circulation patterns associated with these extreme events also fit the Maddox classification scheme, and if so, is their catastrophic nature linked to any additional anomalous atmospheric behavior, such as that seen during larger-scale catastrophic flood events? In the following section I will explore these questions as I discuss the specific circulation anomalies responsible for the 21 events plotted on Figure 3.

CIRCULATION CLASSIFICATION FOR UNITED STATES MAXIMUM OBSERVED FLOODS

Classification Procedure

My circulation classification for the twenty-one maximum events that define the envelope curve in Figure 3 is based on interpretation of: surface and 500 mb height daily weather maps (NOAA Daily Weather Maps - Weekly Series); monthly and weekly mean 700 mb height and departure-from-normal 700 mb height maps (Monthly Weather Review, weather and circulation summaries by month); and a variety of additional references that addressed specific floods. The original Maddox classification -- designed for forecasting purposes -- was based on detailed interpretation of hourly synoptic charts, including analysis of wind speeds, temperature, dewpoints, precipitable water, and stability indices. For the non-forecasting purposes of this study, each of the flash flood events was assigned to one of the Maddox categories on the basis of information found on daily weather maps alone. The large-scale flood events were treated individually and not tied into the Maddox classification.

Thirteen of the twenty-one events were classified as one of the standard types described in Maddox et al (1979) and Maddox et al (1980). The four flash flood events in Texas (#11, 13, 14 and 17) did not conform as well to the Maddox prototypes, but this was not unexpected because events associatioed with weather systems of tropical origin were specifically excluded from the Maddox et al (1979) and Maddox et al (1980) samples. The remaining large floods, on the Eel, Pecos, Susquehanna, and Mississippi rivers, were each associated with major large-scale circulation anomaly patterns (Large-Scale I-IV). In the following sections I will briefly describe the Maddox flash flood types and the catastrophic events from Figure 3 that are associated with each type.

Western Catastrophic Flash Floods

Western Type I Events. The Western Type I event occurs when a weak 500 mb short-wave trough moves northward along the western side of a long-wave ridge (Figure 8a). The Big Thompson Canyon flood depicted in Figure 1, and the Rapid City flood, were both Type I events (Maddox et al., 1980). In this type, the short-wave trough often originates from a stationary long-wave trough or cutoff low, situated just off the west coast. Heavy precipitation occurs in the warm air just ahead of the short wave, where instability and moisture values are high.

This pattern was associated with the extreme flash floods of the Lahontan Reservoir tributary in western Nevada (#2), Lane Canyon in northeastern Oregon (#7), and Meyers Canyon in central Oregon (#8). All three events occurred in July and each was associated, in the macro-scale, with an upper-level low pressure system

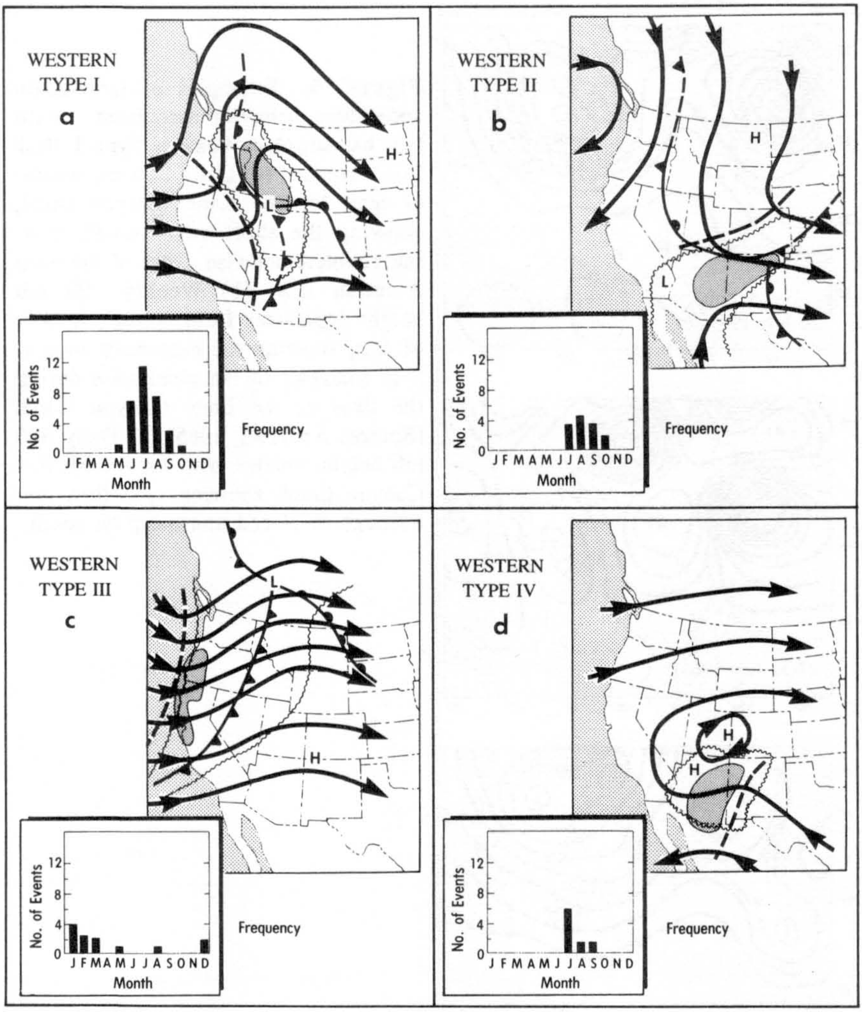

Figure 8. Generalized combined 500 mb and surface patterns for typical western flash flood events. Heavy dashed line shows location of 500 mb short-wave trough. Shaded area shows region of potential for heavy precipitation and flash flooding. Also shown are monthly frequencies for each type, based on the 1973-78 sample of Maddox et al (1980). (Modified from Maddox et al., 1980).

off the west coast that was located unusually far south for this time of year. During the week of the Lane Canyon flood, blocking in Asia and the Arctic was apparently responsible for an extremely deep Aleutian Low that was situated in a rarely-observed location for July (Andrews, 1965) (Figure 9a and 9b). During the time of the Meyers Canyon flood, split flow in the westerlies resulted in their abnormal southward displacement and the development of a trough in the eastern Pacific in a

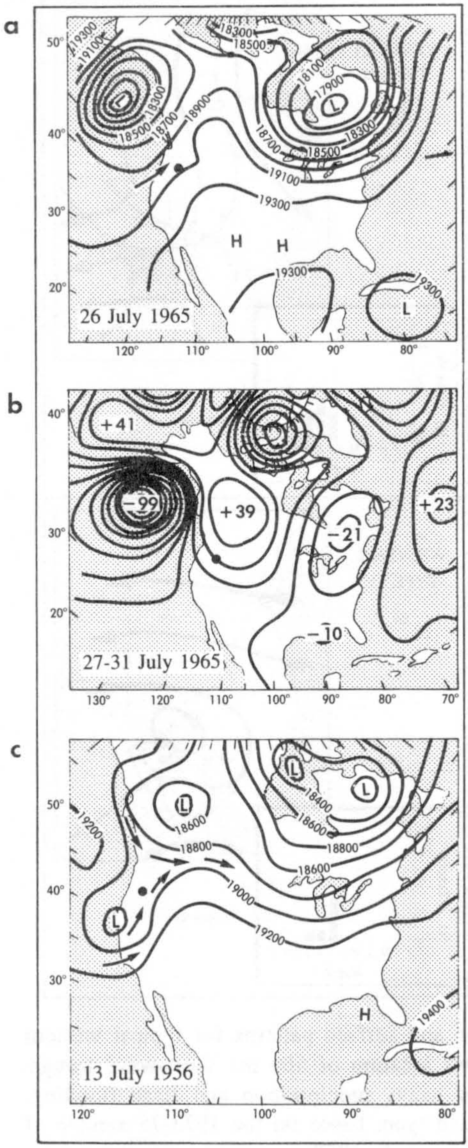

Figure 9. Examples of large-scale anomalous behavior associated with two catastrophic Western Type I flash flood events. (a) Daily 500 mb weather map for the Lane Canyon flood, showing the short-wave trough moving counterclockwise out of the deep Aleutian low. (b) Weekly 700 mb height departures from normal, in tens of feet, showing the extremely anomalous character of the circulation during the time of the Lane Canyon flood. (Source: Andrews, 1965) (c) Daily 500 mb height weather map for the Meyers Canyon flood, showing split flow and a trough displaced unusually far south.

region usually dominated by ridges (Krueger, 1956) (Figure 9c). The Lahontan tributary flood was associated with somewhat different macro-scale features, but did occur soon after a major mid-month upheaval in the global circulation (Wagner, 1971). Each of these cases illustrates that, in addition to nicely fitting into the Maddox classification, the catastrophic nature of these extreme flash floods also can be linked to major global circulation anomalies.

Western Type II Events. These events are associated with a 500 mb short-wave trough that moves southward along the eastern side of a long-wave ridge (Fig. 8b). Heavy rains occur in the unstable air ahead of the short wave, especially when moist air from the Southwest "summer monsoon" is available at low levels.

The catastrophic Eldorado Canyon flash flood of 14 September 1974 (#10) was a Type II event (Maddox et al., 1980). Its short-wave trough was unusually deep, and formed an upper-level closed low over Nevada during the time of the flood. An important factor in the severity of this event was the eastward track of the major thunderstorm cell as it moved down the length of the canyon, toward its mouth. The storm's movement caused intense rainfall and runoff to be superimposed on previously generated flood waves coming from upstream (Glancy and Harmsen, 1975). It is important to emphasize, therefore, the well-known fact that many small-scale meteorological factors and local basin characteristics can have a major effect on the catastrophic nature of a flash flood, and may therefore be more significant than the presence of any large-scale circulation anomalies.

Western Type III Events. Heavy precipitation from this type affects large areas and is associated with a strong synoptic weather system that moves into the west coast from the Pacific Ocean. The type is characterized by a surface front and a 500 mb trough aloft (Figure 8c). Occasionally the trough will develop into an intense upper-level cutoff low. Local flash flooding occurs in response to this pattern when mountainous terrain triggers thunderstorm activity in the moist air that is being steered in at low levels by the synoptic system.

The floods of the Wenatchee River tributary in central Washington (#1) and the Humboldt River tributary in northwestern Nevada (#5) each occurred in conjunction with Type III features -- a deep upper-level cutoff low, and the passage of a surface cold front. In the Wenatchee flood the center of the upper-level low moved directly across Washington state with westerly flow circulating counterclockwise around it bringing moist oceanic air into central Washington from the southwest ahead of the front. (Not unlike a higher- amplitude version of Figure 8c, which shows conditions after the rain-producing front passed.) The Humboldt tributary circulation pattern also was characterized by higher-amplitude waves in the westerlies than are indicated in Figure 8c, and eventually developed into a blocking-like configuration at higher latitudes, with an omega high situated between two deep upper-level lows.

Western Type IV Events. These events occur when a weak short-wave trough moves through zonal flow, and a strong east-west 500 mb high pressure ridge is situated to the north or south of the short-wave's path. When the ridge is to the north, the zonal flow will be from the east and the short wave is called an easterly wave. This type tends to be associated with the Southwest "summer monsoon" season.

The catastrophic flash floods of Little Pinto Creek tributary in southwestern Utah (#3) and Bronco Creek in central western Arizona (#9) were each associated with a broad west-to-east trending 500 mb high-pressure ridge over southwestern United States. A weak short-wave trough moved over south- western Utah from the west, around the north side of the elongated ridge, to produce the Little Pinto flood; and a weak easterly short-wave moved across Arizona to the south of the ridge, in a manner similar to that depicted in Figure 8d, to generate the Bronco Creek flash flood. Both of these events corroborated the statement in Maddox et al., 1980) that Type IV events tend to have weak and ill-defined surface patterns. Their anomalous nature therefore can best be evaluated by a more detailed analysis of moisture-layer thicknesses and instability indices. For both of these cases, the amount of available moisture was significantly above the mean. On the large scale, the elongate upper-level high-pressure ridge was stronger than normal for both events, suggesting intense surface convectional heating and a thick, moist atmosphere during these monsoon-season floods.

East Slope and Central Plains Catastrophic Flash Floods

Synoptic Events. Flash flood events of this type tend to develop with an intense synoptic-scale cyclone and a quasi-stationary front at the surface, in conjunction with a major trough aloft at the 500 mb level (Figure 10a). A strong short-wave trough often moves through the larger trough, increasing instability and triggering convection. Storms and heavy rains are concentrated in the warm, moist air ahead of the front. Synoptic events can be fairly widespread and long-lived, affecting several states and lasting two to three days in some cases. General widespread flooding may occur, but local flash flooding is associated with convective storms which develop repeatedly over the same general area, delivering heavy rains. The pattern is most frequent in spring, early summer, and fall during periods of adjustment in the global circulation.

Two of the maximum flash floods on the envelope curve (#12 Jimmy Camp Creek, and #16 East Bijou Creek in east central Colorado) were produced by the same Synoptic type event in June of 1965. The upper-air pattern associated with this event (Fig. 11) shows a highly-anomalous 500 mb configuration, dominated by an intense cutoff low over the west that steered warm, unstable air northward into eastern Colorado. This blocking pattern caused the attendant surface cold front to become stationary and remain in roughly the same position for at least three days, causing extreme rains. The situation closely resembled an especially persistent version of Figure 10a. According to Posey (1965a) the extreme amplification of the upper-air ridges and troughs occurred when three separate Rossby wave-trains came into phase during the third week of June.

The circulation pattern for the 1950 flood event in the Little Nemaha River in southeastern Nebraska (#15) was much less dramatic, but was characterized by an upper-air trough and a surface cold front, fitting the Maddox Synoptic event description. In addition, a short-wave trough moved over the area and triggered intense thunderstorm activity ahead of the front.

Frontal Events. This type is distinguished by a stationary or slowly-moving front at the surface that is usually oriented west to east. The upper-air pattern is characterized by a broad ridge, through which a weak, meso-scale short-wave trough often moves (Fig. 10b). Storms and heavy rains are triggered on the cool side of the surface warm front when warm unstable air flows over the frontal zone. The July 1965 catastrophic flash flood in Boney Draw in northwestern Missouri (#4) best resembles the Frontal type of event. During the week of the flood, a broad upper-level ridge prevailed over the central plains, allowing hot humid conditions to build and promote intense convective activity. A weak short-wave trough aloft and a west-to-east trending stationary front at the surface were the triggers for the heavy rainfall that produced the flash flood.

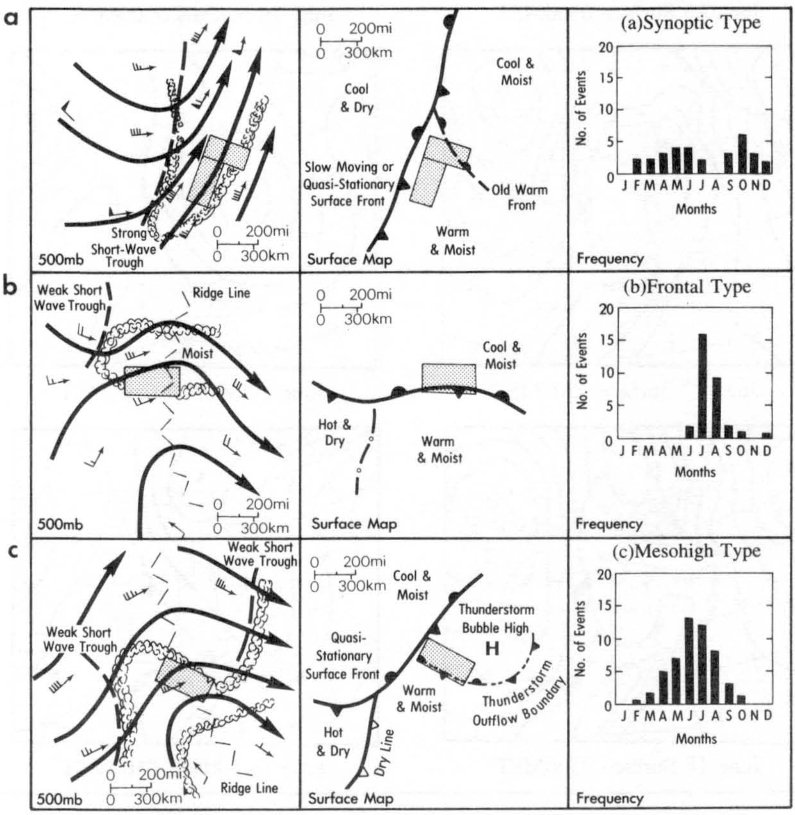

Figure 10. Generalized 500 mb and surface patterns for typical East Slope and Central Plains flash flood events. Heavy dashed line shows location of 500 mb short-wave trough. Zig-zag line shows axis of 500 mb ridge. Shaded and boxed areas show regions of potentialfor heavy precipitation and flash flooding. Also shown are monthly frequencies for each type, based on the 1973-77 sample of Maddox et al. (1979). (Modified from Maddox et al., 1979).

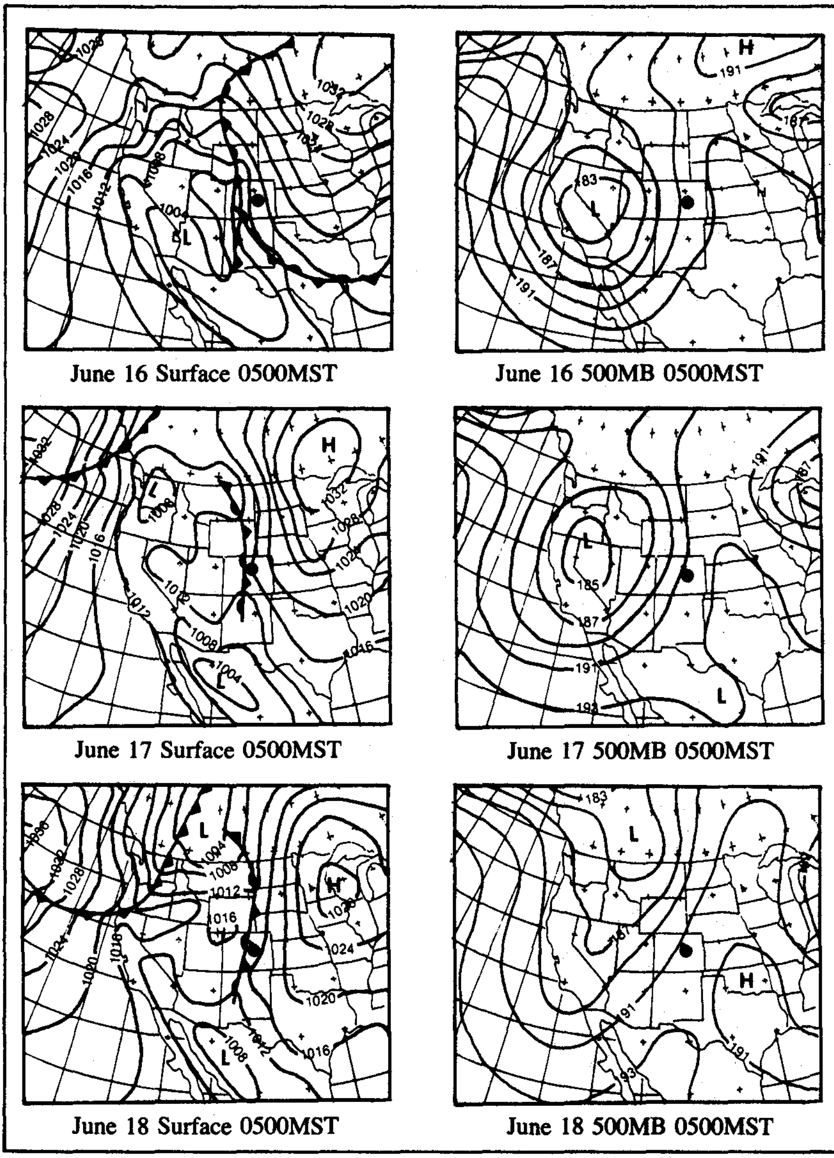

Figure 11. Surface and 500 mb weather maps for the Synoptic Type catastrophic flash floods of Jimmy Camp Creek (#12) and East Bijou Creek (#16), showing an intense "blocking" cutoff low and associated stationary surface front. (Source: Miller et al., 1984).

Mesohigh Events. The distinctive characteristic of a Mesohigh event is the heavy precipitation that occurs due to instability and convection along a nearly stationary cold-air outflow boundary (e.g. Fig. 2). This mesohigh outflow boundary is usually generated by thunderstorm activity occurring earlier in the afternoon or evening. Although conditions are similar to the Frontal event type, an identifiable front may or may not be in the vicinity. The corresponding upper-air pattern consists of a large-scale ridge over the area of heaviest rain, with weak short-wave troughs moving through the ridge, helping to trigger and focus storm activity (Fig. 10c).

It is likely that the Stratton Creek flash flood in western Iowa (#6) was caused by mesohigh-induced convective activity. At the time of the flood, no frontal activity was evident, but the event occurred not long after a cold front had passed through the region, inducing thunderstorms that could have provided the necessary antecedent conditions for mesohigh activity.

Although not detectable on daily weather maps, another possible cause for the flooding in Stratton Creek and the other central Plains drainages is the mesoscale convective complex (MCC). MCCs are huge (50,000 - 100,000 km^2) organized, convectively-driven systems characterized by numerous cold outflow boundaries and mesohighs that generally produce widespread and locally-intense rains (Maddox, 1980). The systems are so large that they can interact with and modify their larger-scale environment, rendering traditional ways of forecasting from the macroscale less effective. A large and long-lived MCC played an important role in the catastrophic Johnstown flood of 1977 (Bosart and Sanders, 1981). Maps of typical MCC tracks show a strong concentration of the systems in the vicinity of the three central Plains catastrophic floods (Maddox, 1980; Rodgers and Howard, 1983).

Texas Catastrophic Flash Floods

Four Texas flash flood events help to define the maximum floodflow curve of Figure 3: (#11) North Fork Hubbard Creek, (#13) Mailtrail Creek, (#14) Seco Creek, and (#17) West Nueces River. As noted earlier, the circulation patterns from which these floods were generated did not fit exactly into the Maddox classification scheme. Texas has its own unique "combination" flood regime because of a variety of factors, most notably its proximity to the Gulf of Mexico moisture source, and the effects of tropical storms and easterly waves. Another important element is the exceptionally strong orographic uplift of moist Gulf air masses along the Balcones Escarpment, which has produced some of the highest rainfall intensities in the world (Patton and Baker, 1977). Mesoscale processes, such as intense mesohigh activity and MCCs, also contribute to extreme precipitation events, in conjunction with, or independent of, the escarpment. In fall, winter, and spring, deep troughs and surface cold fronts traverse the state, resulting in great air-mass contrasts, uplift, and widespread precipitation. Under certain circulation patterns, upper air flow brings in a layer of dry air that enhances instability aloft. All of these activities can be exacerbated if a still-organized tropical system moves in-land, or if remnants of the system enter at upper levels. This complexity of flood-generating circulation features makes classification of the Texas events quite difficult, requiring detailed information for an accurate assessment of all the factors involved.

The Texas Hill Country flash floods of 2 August 1978 were analyzed in detail by Carcena and Fritsch (1983) and they found that a variety of distinct mechanisms interacted to focus and anchor the large stationary thunderstorm complex that produced the floods. Among these were an elevated dry layer, a mesohigh remnant of tropical storm Amelia, and forced uplift along the Balcones Escarpment. The North Fork Hubbard Creek flood (#11) occurred two days later, about 300 km to the north, and was produced by many of the same features, with a slow- moving cold front replacing the mesohigh as a lifting mechanism (Carcena and Fritsch, 1983). In the large-scale, a stronger-than- normal Atlantic subtropical high enhanced the easterly and southeasterly flow of Amelia into Texas and at the same time, brought in the dry layer at upper levels.

Examination of the somewhat rudimentary weather maps of May-June 1935 and June 1948, without additional information for enhancement or re-analysis, did not allow me to assess the Mailtrail Creek (#13), Seco Creek (#14), and West Nueces (#17) flood events in any detail. Each of these floods occurred in close proximity to the Balcones Escarpment, and each was associated with strong thunderstorm activity and southerly and southeasterly surface flow. Fronts were present in northern Texas at the times of the Mailtrail and Seco Creek floods and may have induced some large-scale instability. Low-level flow was from the east just prior to the West Nueces flood, suggesting an easterly wave, which would also explain the deep westward penetration of moist air into Texas. It is certainly possible that some or all of the Texas flood- producing mechanisms mentioned above were present during these early catastrophic events as well.

Large-Scale Catastrophic Floods

The storms that generate a typical regional flood event can usually be traced to an easily-identified synoptic weather pattern. Catastrophic regional floods, however, tend to be distinguished from more common regional floods by the anomalous behavior of the macroscale circulation patterns that drive and steer flood-generating synoptic weather systems. The largest floods on Figure 3 each evolved from different types of large-scale anomalous behavior.

Eel River Flood of December 1964 -- (Large-Scale I). Heavy rains throughout the northwestern states produced record-breaking and severely damaging floods over an unusually large area during December 1964 and January 1965. Among these was the catastrophic flood peak recorded on the Eel River at Scotia (#18) on 23 December 1964, during which the Eel transported more than ten times its maximum sediment load of record (Waananen et al., 1971). Numerous small catchments in the Eel and other northern California basins experienced dramatic geomorphic changes in response to this event (e.g. Stewart and LaMarche, 1967; Helley and LaMarche, 1968). The circulation pattern that produced this catastrophic flood was characterized by intense blocking action over the Aleutians. A split westerly airstream, similar to that of February 1986 (Fig. 7), directed the flood-producing storms into the northwest along a jet stream track that was located unusually far south, coming from the vicinity of Hawaii (Posey, 1965b). This pattern, an example of an anomalous location for an otherwise typical storm track (Large-Scale I type), also occurred, with less intensity, in December 1955 and produced major floods in the same areas.

Pecos River Flood of June 1954 -- (Large-Scale II). The storm period of June 24-28 in southwestern Texas was a direct result of the movement of Hurricane Alice from the Gulf of Mexico up the Rio Grande Valley. The hurricane in itself was not anomalous in size or strength; in fact, in the lower Rio Grande Valley the rains were only moderate for a hurricane, and it had lost most of its surface identity by the time it reached the upper valley. Rather, it was an unusual combination of events (Large-Scale II type) involving the hurricane that triggered the catastrophic Pecos River flood on the 28th, the largest flood on record in Texas and estimated as having a recurrence interval in excess of 2000 years (Patton and Baker, 1977). The key factor was that the upper-level remnant of the hurricane stalled in the vicinity of the uplift-enhancing Balcones Escarpment. At the same time, the system interacted with a weak 500 mb wave in the westerlies and transformed from a warm core tropical cyclonic system to a cold core extratropical cyclonic system (Miller et al., 1984). The resulting vigorous vertical motion, in what was still a very deep layer of moist air, produced intense thunderstorm activity and anomalously heavy rains.

Susquehanna River Flood of June 1972 -- (Large-Scale III). The flooding from Hurricane Agnes that devastated the East Coast of the United States has been called "the greatest natural disaster ever to befall the Nation" (U. S. Department of Commerce, 1973, p. 1). The outstanding aspect of this event was the great areal extent of flooding, which resulted in many very large drainage basins experiencing record-breaking flows. Peaks having recurrence intervals in excess of 100 years were recorded throughout the length of the Susquehanna River basin, which is more than 70,000 km^2 in area (Bailey and Patterson, 24th). The Susquehanna's peak at Harrisburg on June 24th is believed to be the largest for any basin of comparable size in the United States.

Although not an unusual storm at its outset, the area covered by Agnes was exceptionally large, and its slow development and movement permitted large amounts of moisture to be entrained into the system from the tropics. However, it was the influence of a highly-abnormal blocking configuration over the North Atlantic ocean (Large-Scale III type) that steered Agnes' unusual path and fed large amounts of moisture into the storm during its latter stages, as it merged with a trough in the westerlies and stagnated (Fig. 12). Anomalously warm sea surface temperatures in the western North Atlantic, that had been developing since February or March,

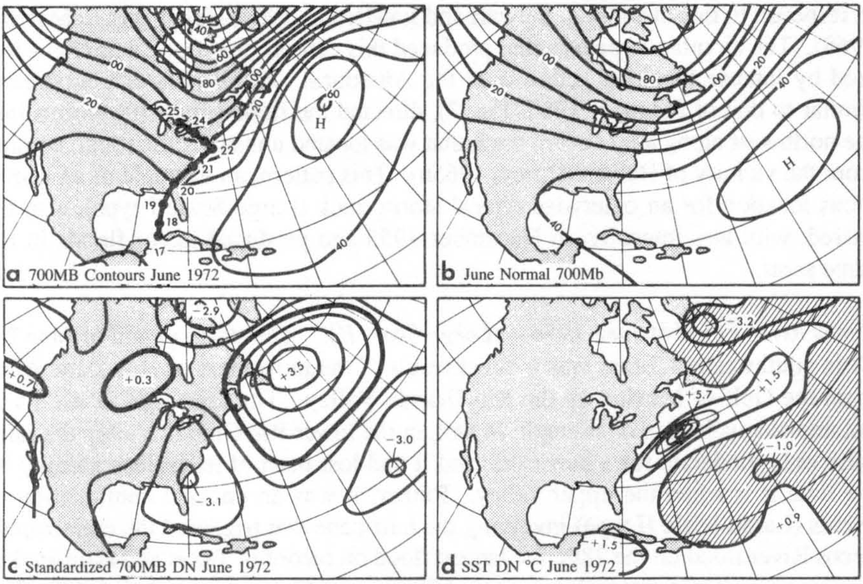

Figure 12. Anomalous circulation during the Agnes floods of June 1972. (a) June 1972 700 mb height pattern showing path of Agnes and blocking high over Atlantic. (b) Normal June 700 mb pattern based on the mean of Junes from 1947-63. (Contours are labeled in tens of feet with hundreds omitted,) (c) Deviations of the June 1972 700 mb heights from the normal pattern. (Isopleths are in standard deviations with a contour interval of 1). (d) Sea surface temperature departures from normal for 1 - 26 June. (Source: Namias, 1973).

probably played a major role in both sustaining the Atlantic blocking pattern through external forcing and positive feedback, and in directing the hurricane's path to unusually high latitudes (Namias, 1973). Furthermore, the anomalous nature of both the SSTs, and the abnormal macroscale wave configuration, may have been linked to the 1972/73 El Niño event (Namias, 1973).

Mississippi River Flood of Spring 1973 -- (Large-Scale IV). Although catastrophic, neither the flood stages nor the peak discharge volumes that occurred on the Mississippi during the great flood of 1973 were the largest ever recorded. However, the duration of this flood was unprecedented, and new records for consecutive days above flood stage were set for most of the main-stem gaging stations on the Mississippi from southern Iowa to Louisiana: St. Louis, Missouri, 77 days; Chester, Illinois, 97 days; Memphis, Tennessee, 63 days; and Vicksburg, Mississippi, 88 days (Chin et al., 1975). In fact, the cumulative runoff at Vicksburg for the first nine months of water-year 1973 was greater than in any other recorded flood year. On this basis, and because flood stage and discharge relationships have changed significantly over time, I have selected the 1973 flood at Vicksburg as an example of a catastrophic flood of extremely long duration occurring in an exceptionally large basin.

The duration and persistence of the large-scale atmospheric circulation pattern that produced this flood was equally anomalous (Large-Scale IV type). Throughout March and April of 1973, the repeated development of a trough over the south-

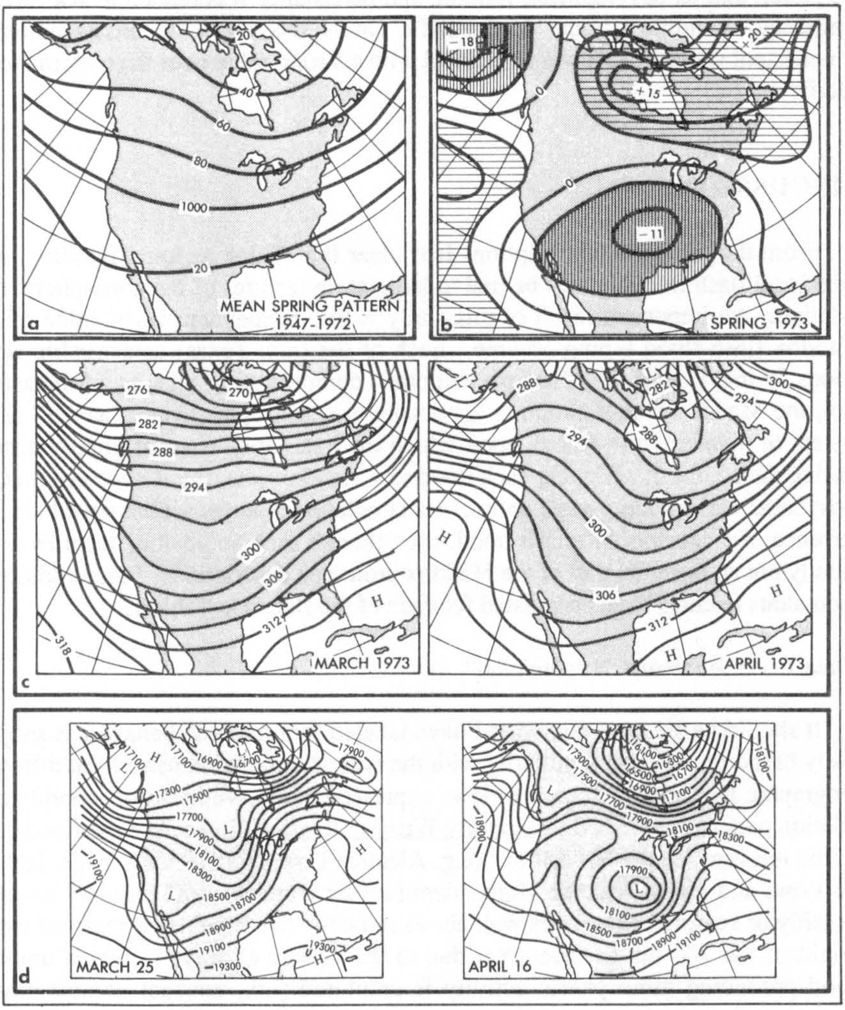

Figure 13. Anomalous circulation during the Mississippi River flood of spring 1973. (a) Mean spring 700 mb height pattern in tens of feet. (Based on March-May over the period 1947-72.) (b) Spring 1973 departure pattern from the 26-year mean, in tens of feet. Contour interval 50 ft. (Source for (a) and (b): Namias, 1979). (c) Mean monthly 700 mb height patterns for individual months of March and April 1973, in dekameters. (d) Selected daily 500 mb charts for March and April showing the position of the trough. (Source for (c) and (d): Chin et al., 1975).

ern United States steered numerous fronts and extratropical cyclones across the Mississippi basin (Fig. 13). An analysis of daily weather maps shows that the trough was positioned in roughly the same location for 60 percent of the days during March and April. Furthermore, Namias (1974) was able to trace the continuity of this remarkably persistent trough from September 1972 through August 1973 and suggested that its development, motion, and persistence was related to sea surface temperature conditions in the North Pacific On the macro-β scale, this exceptionally persistent wave pattern was associated with a strong ridge over the eastern North Pacific ocean.

DISCUSSION

From the preceding descriptions it is clear that major regional flooding, and even local flash flooding, can be tied to large-scale features of the atmospheric circulation. An important result of this study is the independent verification of the Maddox flash-flood typing scheme. Each of the (non-Texas) catastrophic flash floods fit into one of the Maddox categories, demonstrating that, as a forecasting tool, the Maddox classification is applicable to catastrophic events, as well as to the set of smaller flash floods upon which the categories were originally based. During the course of assigning each flood to a Maddox categroy, I observed that, in most cases various large-scale anomalous circulation features accompanied the occurrence of a catastrophic flash flood, even though such anomalous features were usually not an essential part of the Maddox prototype descriptions. These additional anomalous features have been listed for each of the floods in Table 1.

When Is An Anomaly "Anomalous?"

It should be stressed that what I have labeled "anomalous" behavior is subjectively based on my own familiarity with the typical circulation patterns at different geographic locations, and on the views expressed in the syntheses of monthly circulation patterns published in Monthly Weather Review. In each of the flood cases, the relevant "centers of action," (e.g. Aleutian Low, North Pacific High, Icelandic Low, and North Atlantic High, identified by Namias, 1981) usually showed monthly or seasonal departures well above or below the monthly or seasonal mean height of the 700 mb surface. Yet due to the variety of ways in which unusual flood-producing atmospheric activity is exhibited (i.e., unusual combinations, anamolous locations, repeated patterns) a single set of threshold criteria for 700 mb height departures would be difficult to objectively establish, the existence, strength, or persistence of, flood- producing anomalies.

The most general conclusion that can be drawn about the flood-producing anomalies is that various forms of blocking were instrumental in setting up most of the catastrophic events: both small-scale flash floods and large-scale regional floods. The exact location of the blocking was, of course, quite important for specific floods, but even distant blocking may have had an effect. Teleconnection studies have shown that anomalous activity at remote centers of action can significantly affect the circulation at downstream locations (e.g. Namias, 1981; Wallace and Gutzler, 1981). The importance of blocking -- an attribute of meridional as opposed to zonal long-wave configurations -- corroborates earlier claims by Knox et al (1975) and Knox (1976, 1984), that meridional circulation periods are more likely to experience large floods in North America. Moreover, the sample of flash flood events upon which this conclusion is based underscores the importance of large-scale circulation patterns for creating a favorable atmospheric environment for flooding -- even in small watersheds where flash floods have usually been attributed to the random occurrence of local thunderstorms.

Blocking is currently the center of attention for much of the theoretical, observational, and numerical modeling in progress on anomalous atmospheric flows. Blocking in itself, is a fairly normal stage in the weekly progression of circulation in the westerlies, especially in winter. The determination of when a situation becomes truly "anomalous" lies in the strength, frequency, and persistence of blocking, and these are the factors that must be examined more closely in relation to flooding.

Of particular interest to catastrophic flooding is the possibility of multiple equilibria in the large-scale circulation, ie., a blocking and a nonblocking mode (Hansen, 1986; Sutera, 1986). Figure 14 shows a time series plot of the catastrophic floods listed in Table 1. The distinct clustering of events may well be reflecting alternate modes of operation in the atmosphere.

Observational studies have shown similar episodic behavior in blocking, but most of this work has focused on winter months when the action is typically much stronger. A study of blocking during summer, when most extreme floods tend to occur, would be an important test of this hypothesis.

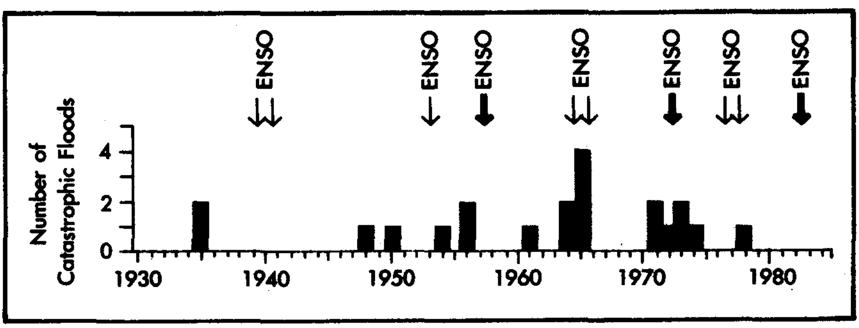

Figure 14. Time distribution of the twenty-one catastrophic floods discussed in this paper. Years of strong (heavy arrow) and moderate (thin arrow) ENSO events are also indicated. The mid-60s and early 70s seem to have been especially prone to the occurrence of extreme events. Various synoptic studies have shown that meridional types of circulation have been more frequent since 1950 (see Knox, 1984).

Strong and moderate ENSO events, as summarized by Yarnal (1985), are also indicated on Figure 14. The two main clusters of catastrophic flooding occurred in association with ENSO-related SST anomalies, but the correlation is not consistent for the other events. It appears that the complexities of the relationship between atmospheric circulation anomalies and catastrophic flooding will have to be further unraveled by a better understanding of internal and external forcing mechanisms for anomalous atmospheric activity, as well as a better discrimination of "catastrophic" floods (according to geographic location, basin size, physiography, season, and type of event).

Geomorphic Implications of Anomalous Atmospheric Circulations

One of the critical factors in determining the geomorphic effectiveness of a catastrophic flood, ie., its ability to make either a permanent or a temporary change in the landscape, is the length of the "intervening interval" until the next catastrophic event (Gupta and Fox, 1974; Wolman and Gerson, 1978; Beven, 1981). In humid regions, intervening moderate events can return a channel to its pre-flood condition in a matter of months (Costa, 1974), whereas recovery times in arid and semi-arid environments may be much longer (Wolman and Gerson, 1978; Harvey, 1984). Basin factors such as geology, topography, vegetation cover, slopes vs. streams, and bedrock vs. alluvial channels, may further complicate the effectiveness and recovery time associated with a given catastrophic flood (Costa, 1974; Patton and Baker, 1977; Newson, 1980).

The results of this study suggest that there may be an episodic tendency in the likelihood of occurrence of catastrophic events, due to variations in blocking and possible multiple modes of anomalous atmospheric behavior. The actual recurrence of another catastrophic event of equal magnitude in the same basin will always be an extremely rare event. However, during blocking episodes, it seems probable that a higher frequency of large floods will occur, even within the same watershed. Sequences of large floods can be an important factor in major channel changes and geomorphic effectiveness (Burkham, 1972; Beven, 1981), and these, too, are more likely to occur during periods dominated by blocking-related atmospheric circulation anomalies.

Another factor in the geomorphic response to catastrophic flood events is the length of time during which a river is at flood stage or out of its banks. Although this may be of minor importance for flash floods, in larger drainage basins, the duration of flooding can greatly affect the degree of erosion and overbank deposition (e.g., Kesel et al., 1974). Persistent anomalous atmospheric behavior, such as that which resulted in the long-lived 1973 Mississippi River flood, would be a major generator of this kind of geomorphic activity.

Finally, on an applied note, the geographic areas influenced by different types of circulation anomalies play a role in assessing a region's susceptibility to catastrophic flood hazards. In Texas, hydrogeomorphic and remote sensing techniques have been successfully used to delineate areas that have a high flood potential

(Baker, 1976). This circulation study has shown that, in addition to hydrogeomorphic factors, central and western Texas are especially prone to a unique type of anomalous atmospheric behavior that manifests itself in unusual combinations of meteorological processes operating together. In other parts of the country, different types of anomalies may dominate. The high occurrence of catastrophic flooding in the western states (Fig. 4) appears to be related to the strength of blocking in the North Pacific ocean, a major center of action for the circulation of the whole Northern Hemisphere. Great Plains catastrophic flash floods may be more attuned to the occurrence of mesoscale convective complexes, but extreme regional flooding in the upper and lower Mississippi Valley appears to be linked to the preferred development and anomalous persistence of a trough in the southern and western United States. Catastrophic flooding along the eastern seaboard is more likely to be affected by unusual Atlantic blocking patterns and/or sea surface temperature anomalies that influence both tropical and extratropical storm tracks.

This study has shown that some type of anomalous circulation pattern appears to be necessary to produce a catastrophic flood, however it must be emphasized that catastrophic floods do not always occur when circulation anomalies are present. Many other factors, such as basin physiography, thunderstorm cell movement, and antecedent soil moisture conditions, will ultimately determine whether or not a catastrophic flood will occur in response to an anomalous circulation pattern.

CONCLUDING REMARKS

The rare occurrences of both local and regional catastrophic flood events can be linked to anomalous atmospheric circulation patterns. These atmospheric circulation anomalies appear to develop in preferred locations, and to exhibit episodic behavior due to zonal and meridional tendencies in the large-scale atmospheric flow. The geomorphic effectiveness of catastrophic flooding may be significantly related, in both space and time, to variations in large-scale anomalous atmospheric activity. Nevertheless, it is obvious that even a very unusual anomaly pattern will not always produce a catastrophic flood. Furthermore, in the case of flash floods, the flooding response to a large-scale anomaly may be very localized, occurring in one basin and not another. The challenge awaits both hydroclimatologists and geomorphologists to continue to sort out the numerous variables which control the occurrence and the impact of catastrophic flooding.

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Edited by

L. Mayer and D. Nash

Department of Geology, Miami University

Department of Geology, University of Cincinnati

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pp. 23 - 56