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FLOOD HYDROCLIMATOLOGY

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INTRODUCTION

Until very recently, the status quo in many forms of flood analysis has been to treat events in a hydrologic time series as a set of varying time-ordered numerical values. The methodologies that have been developed and refined through the years to manipulate, model, and predict flood values have become increasingly sophisticated. In some circles, however, the obvious fact that these values represent a response to varying processes in the physical world has tended to become less important than the urge to statistically model flood values in search of the best fit of the observed data and therefore (ideally) the best predictive capability for future flows:

> The main emphasis in stochastic analysis of hydrological processes, which basically is the domain of pure hydrology, has been on the fitting of various preconceived mathematical models to empirical data rather than on arriving at a proper model from the physical nature of the process itself. The empirical data representing a hydrologic event are treated as a collection of abstract numbers that could pertain to anything or to nothing at all. Their hydrologic flavor, the physical substance that makes, for instance, a precipitation record an entity entirely distinct from, say, a record of stock market fluctuations, is not reflected in the analysis. Thus what we usually find is not, in fact, statistical or stochastic hydrology but merely an illustration of statistical and probabilistic concepts by means of hydrologic data. Such an approach can hardly contribute to the hydrological knowledge.
>
> In trying to improve this situation, the main problem is to find the ways in which the physical features of a phenomenon can be introduced into the analysis.
>
> —(Klemeš, 1974, p. 2)

The cross-discipline of hydroclimatology is an approach to studying hydrologic events within their climatological context. By focusing on atmospheric inputs to flooding, hydroclimatology provides one way to integrate the physical sources of variability in a hydrologic time series with the statistical properties of the varying series itself, thus both enhancing our understanding of the flooding process and improving the quantitative assessment of its variability. In a hydroclimatic approach to flood analysis the events recorded in a flood series are viewed not only as numerical values, or as isolated hydrologic occurrences, but as real-world physical events occurring within the context of a history of climatic variations in magnitude and frequency. The physical basis of the approach emerges when these events are analyzed within the spatial framework of regional and global networks of changing meteorologic features and circulation patterns.

SPATIAL AND TEMPORAL SCALES OF HYDROCLIMATIC ACTIVITY

Flood-producing atmospheric circulation patterns operate within a space–time domain that at times is quite different from the domain of hydrologic activity within a drainage basin. Figure 1 depicts the characteristic spatial and temporal scales at which selected meteorologic, climatologic, and hydrologic phenomena vary. The figure displays the variety of scales over which climatic activity can generate flooding, ranging from small downpours that quickly fill culverts and drainage ditches, to global-scale circulation anomalies that have the ability to steer one major storm after another into an area along the same persistent track. This wide range of interactions between the atmosphere and the hydrosphere illustrates the concept of *proximate* versus *ultimate*

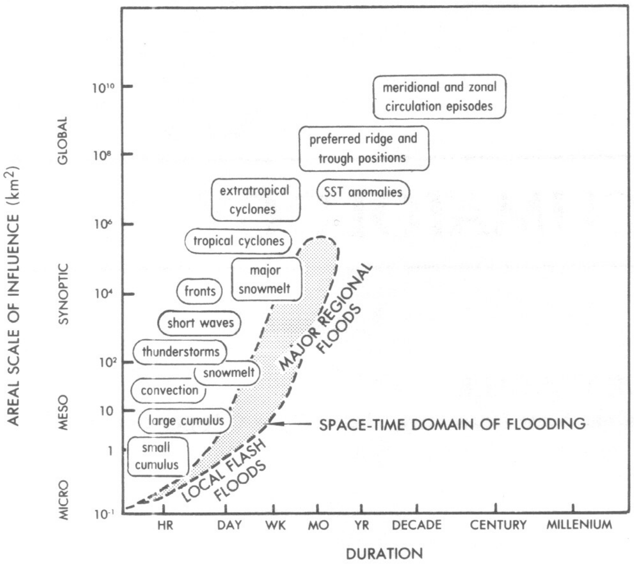


FIGURE 1. Space–time domain for selected meteorologic, climatologic, and hydrologic phenomena. The spatial domain is represented by the typical areal scale of influence of each phenomenon, in kilometers squared. The temporal domain is represented by the typical duration of each phenomenon.

causes for flooding. The proximate, or most immediate climatic causes of flooding are readily apparent to any observer of the small-scale, short-duration relationship between rainfall and subsequent runoff. Climatic activity operating at much larger spatial scales and longer temporal scales is less often perceived as a source of flooding, yet the configuration of the atmosphere at these scales provides the ultimate framework from which the more immediate causes of flooding are generated.

In Figure 1 the spatial dimension is approximated by the typical areal extent of influence exhibited by different types of features, while the time dimension is represented by the characteristic duration of each type of event. For example, a typical summer thunderstorm with a diameter of 10 km covers an area of about 100 km^2 at any one time and has a life span of several minutes to over an hour, while a mature extratropical cyclone with a diameter of 1000 km affects about 10^6 km^2 at any one time, and has an influence over an even larger area during its characteristic life span of 3–6 days. At larger spatial scales, in the upper atmosphere, long wave ridges and troughs with dimensions of 10^6 km^2 or greater migrate around the globe from day to day, at times reforming again and again in a preferred location to produce a pattern that may persist throughout a season or longer. This persistence of certain upper-air patterns has been linked to anomalous pools of warm and cool sea surface temperatures that may extend over areas as large as 10^6 km^2 and persist for several months to over a year (Namias, 1974; Namias and Cayan, 1981). At the global scale the meandering pattern of the circumpolar vortex of upper-air winds (10^7 km^2) is reflected in hemisphericwide features. These include the position of the polar front, the jet stream, and the tendency toward zonality or meridionality in the long wave pattern (Fig. 2).

The spatial domain of flooding, unlike that of climate, is constrained by the areal dimensions of a given drainage basin or by a group of basins responding similarly within a hydroclimatically homogeneous region. The upper spatial limit of flooding in Figure 1 has been chosen as 10^6 km^2 to reflect the areal dimensions of the Mississippi River basin, a reasonable upper limit for widespread regional flooding resulting from large-scale climatic inputs. The temporal domain of flooding is related to either the length of time specific flood-generating atmospheric phenomena are positioned over a basin or the interval of time during which a series of flood-producing events affects a basin. The lag time between an atmospheric input and the corresponding hydrologic output is heavily dependent on factors internal to a drainage basin system such as basin area and shape, channel form and roughness, drainage density, vegetative cover, permeability of the substrate, and land use (i.e., type of agricultural practice, degree of urbanization, etc.). In general, however, the duration of flooding will nearly always exceed the duration of the atmospheric input that generated the flood. This is depicted in Figure 1 by the shift in the domain of flooding toward longer durations than those of atmospheric phenomena at the same spatial scale.

Hydrometeorology and Hydroclimatology

The cross-discipline of *hydrometeorology*, which Bruce and Clark (1980) define as "an approach through meteorology to the solution of hydrologic problems" (p. 2), has evolved to analyze the relatively short-term interactions between the atmosphere and hydrosphere at micro-, meso-, and synoptic spatial scales of influence (Fig. 1). These scales of inquiry are extremely effective for a variety of flood climate studies, including predicting and analyzing flash-flood events (Maddox et al., 1979, 1980), developing real-time river forecast models for specific drainage basins (Georgakakos and Hudlow, 1984), and identifying and compiling the characteristic synoptic features that generate flooding in selected areas (Hansen and Schwarz, 1981).

The cross-discipline of *hydroclimatology* encompasses larger scale interactions between the atmosphere and the hydrosphere and has been defined by Kilmartin (1980) as the "modeling of long-term climatic fluctuations in water resources systems analysis" (p. 166). In his call for the active development and growth of hydroclimatology, Kilmartin cited the need to close some gaps between the closely related disciplines of hydrology, meteorology, cli-

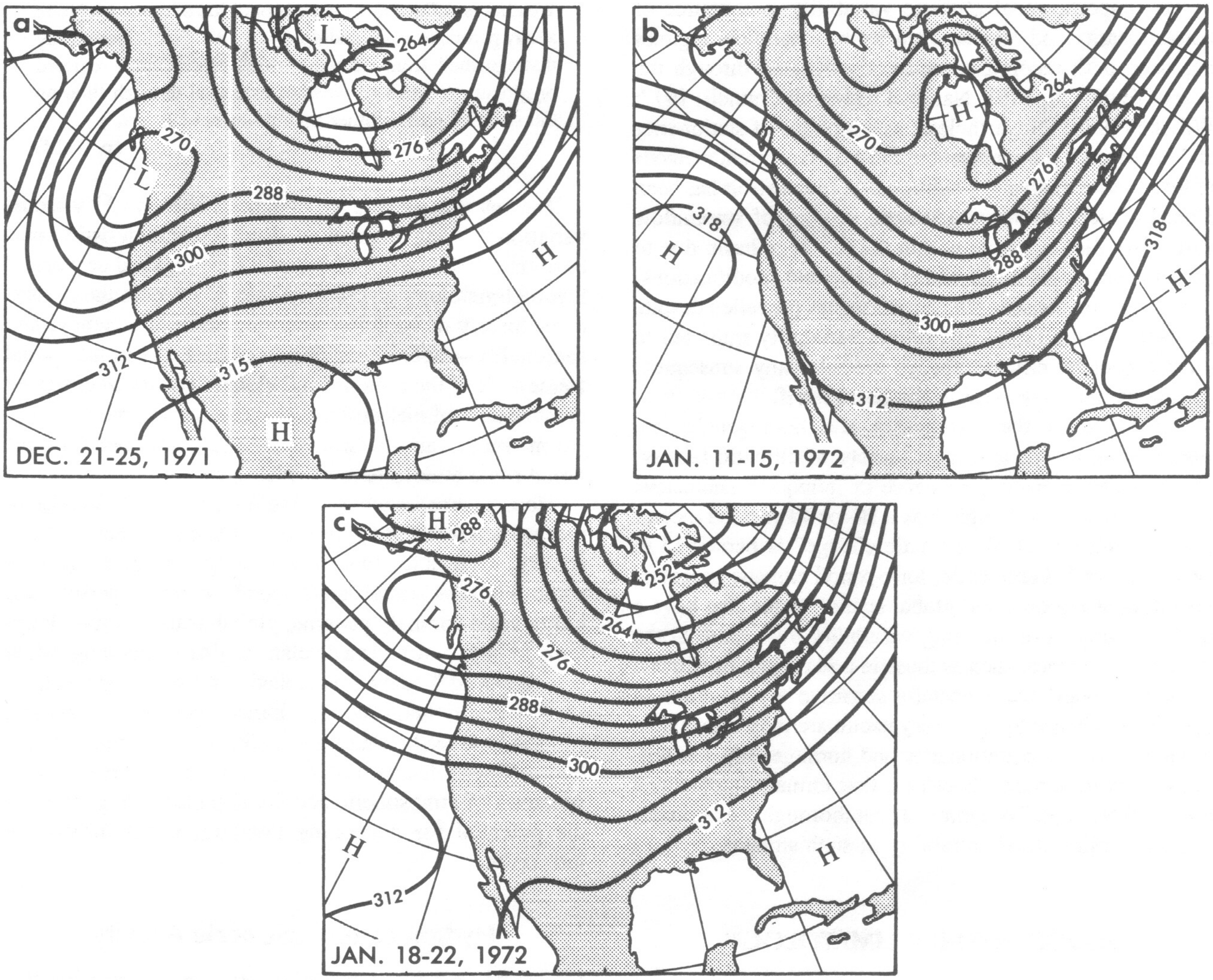


FIGURE 2. Three types of large-scale upper-air patterns that occurred during the winter of 1971–1972. The contoured values are heights (in dekameters) of the 700-mb pressure surface averaged for weekly periods. The wave pattern, defined by the steepest gradient in the contours, tends to separate cold polar air masses from warmer tropical air masses. Upper-air winds and steering currents, such as the jet stream, flow parallel to the contours. (*a*) High-amplitude meridional wave pattern over western United States. A deep trough of upper-air low pressure is situated over the West Coast. Synoptic studies have demonstrated that associated surface low-pressure systems are most likely to develop under the eastern sides of upper-air troughs. (*b*) A slightly lower-amplitude meridional wave pattern. The broad ridge of upper-air high pressure off the West Coast and broad trough over eastern United States is a preferred pattern in winter. The ridge tends to develop frequently over western North America in winter due to a combination of factors including sea surface temperatures, the presence of a blocking high-pressure system in the North Pacific, and the anchoring effect of the western Cordillera mountain system. (*c*) A zonal (west–east) wave pattern interrupted slightly by a shallow trough over Texas and Oklahoma.

matology, oceanography, and statistics, and to expand and develop the approach to hydrologic problems that is already found in the cross-discipline of hydrometeorology.

Kilmartin's emphasis was not on floods but on long-period events in hydrology, for he was specifically concerned with past and future climatic changes and their effects on long-term reservoir storage and water supply. The term *hydroclimatology*, however, can be equally applied to the analysis of short-period events, such as those in an annual or partial duration flood series, by examining how these events vary temporally and spatially in response to longer term climatic variations.

The importance of climatic variability as a source of nonstationarity and nonhomogeneity in streamflow regimes has been both recognized and hotly debated through the years (Yevjevich, 1968; National Research Council, 1977; Willeke, 1980). Nevertheless, assumptions of stationarity and homogeneity are inherent in most of the current methods of flood series analysis. Traditionally, much effort has been placed on identifying nonclimatic sources of streamflow variability that originate within the drainage basin due to such factors as land-use changes, channel modifications, or complex responses. This emphasis has prevailed despite the fact that the initial hydrologic variability imparted to a catchment by climate always precedes any subsequent variations that may arise in the basin itself.

Violations of the stationarity and homogeneity assumptions may occur from a variety of climatic factors. Decadal-scale climatic persistence or infrequent anomalous extreme events can strongly bias a 30- or 40-yr flood record, even though no actual "climatic change" is perceived to have transpired. Large-scale, long-period climatic processes operating at regional and global spatial scales also have a profound impact on flooding variability over time. Some streamflow regimes, such as those in arid regions or climatic transition zones, are especially sensitive to variations in climate, and hence by their very nature are most susceptible to violations of the stationarity and homogeneity assumptions. It is important, therefore, that climate fluctuations not be "filtered out" or removed, but thoroughly examined, when modeling flood variability in such streams.

FLOOD HYDROCLIMATOLOGY

The cross-disciplines of both hydrometeorology and hydroclimatology are essential for understanding the interactions between the atmosphere and the hydrosphere. Hydrometeorology has more traditionally been applied to the analysis of floods, but the broader perspective of hydroclimatology provides new insights into flood variability by synthesizing and integrating information emerging from hydrometeorologic studies. The subtle differences between a hydroclimatic and a hydrometeorolgic approach to the analysis of floods can be explained in part by a comparison of *climate* and *weather*. Fairbridge (1967) presents the following definitions:

> Climatology is that branch of atmospheric science which deals with the climate, i.e., the statistical synthesis of all weather events taking place in a given area in a long interval of time. It is customary to describe the climate by the seasonal variation of various meteorological elements and their characteristic combinations.
>
> —(pp. 217–218)

> Weather is defined as a state or condition of the atmosphere at any particular place and time. . . . Weather is specifically distinguished from climate, which represents a regional or global synthesis of weather extended through time on the scale of years, rather than minutes or hours.
>
> —(p. 1114)

The key phrases here are "synthesis of events," "seasonal variation," "long interval of time," "characteristic combinations, " "frequency of events," and "regional or global." Hydroclimatology places a hydrologic event in the context of its history of variation—in magnitude, frequency, and seasonality—over a long period of time and in the spatial framework of the regional and global network of changing combinations of meteorologic elements such as precipitation, storm tracks, air masses, and other components of the broad-scale atmospheric circulation.

Flood hydroclimatology, therefore, has as its foundation the detailed focus of hydrometeorologic-scale atmospheric activity, while at the same time seeking to place this activity within a broader spatial and temporal, "climatic" perspective. Large-scale anomaly patterns, global-scale controls, long-term trends, and regional relationships in flooding might be overlooked if analysis is limited to the hydrometeorologic space–time domain alone, whereas these same patterns, controls, and relationships are readily detected at the broader hydroclimatic domains of analysis. In effect, the complete spectrum of atmospheric activity depicted in Figure 1 has the potential for generating flooding, either directly or indirectly.

Hydrometeorologic-scale Activity

Microscale and small mesoscale atmospheric activity such as convectional showers, isolated or small thunderstorms, and squall line disturbances tend to have a localized or limited regional areal extent of influence of less than 1–1000 km^2 and a storm life of a few minutes to one or two hours. These events are most likely to produce local flash flooding of small areal extent (Fig. 3).

Larger mesoscale features such as severe thunderstorms, multiple squall lines, extensive moist and unstable layers in the atmosphere, and shortwave troughs have the capabilities of producing major precipitation events of great intensity over relatively large areas. Atmospheric activity at this scale has been responsible for many catastrophic flash floods, such as the Johnstown, Pennsylvania, flood of July 1977 (Fig. 4).

Macroscale (synoptic) features such as major fronts, tropical storms, and extratropical cyclones affect much larger areas of 1000 to 1,000,000 km^2 during their longer life spans of several hours to several days. These features at times are associated with flash flooding when they provide the necessary synoptic situation for locally intense meso-

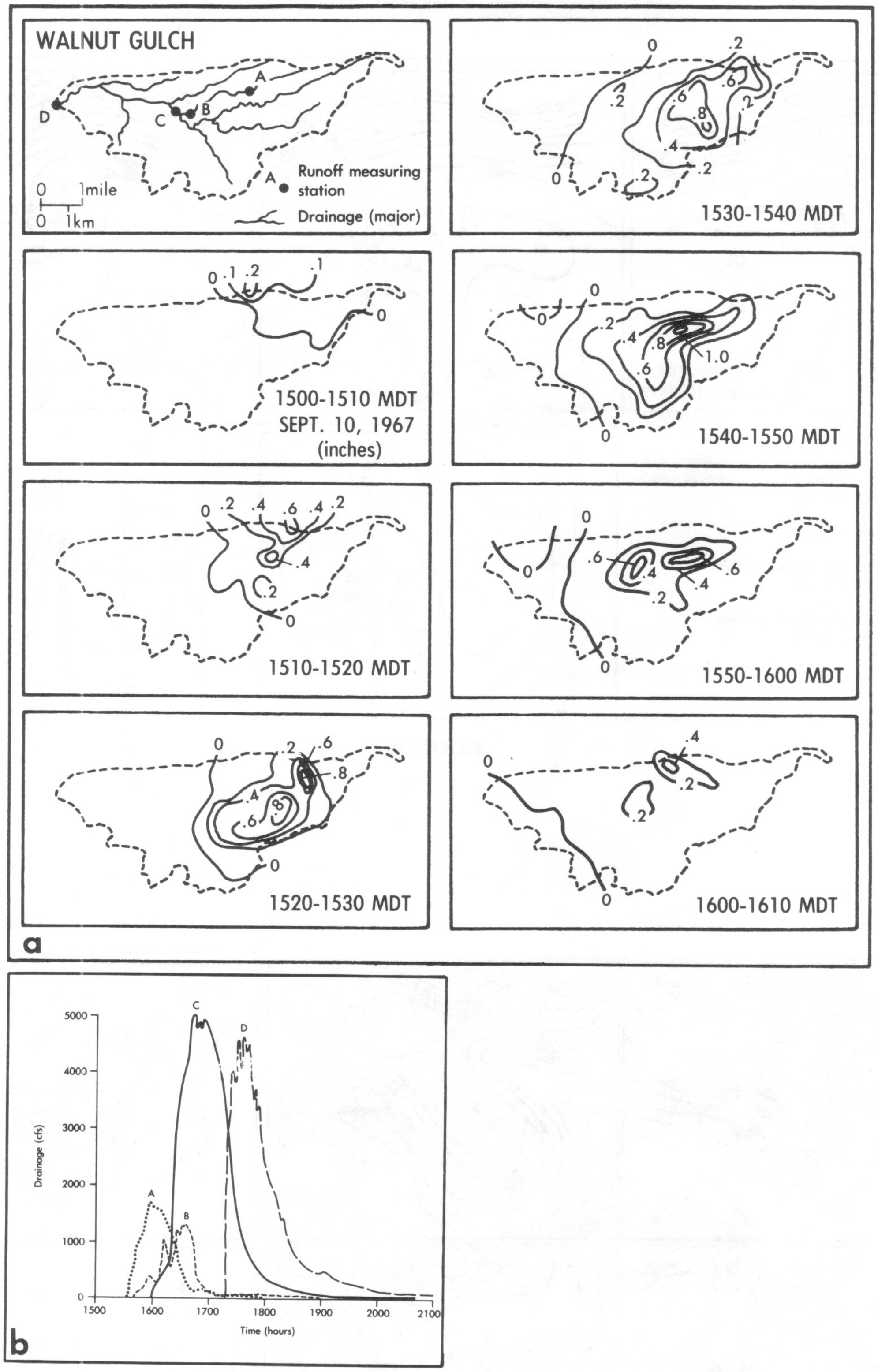
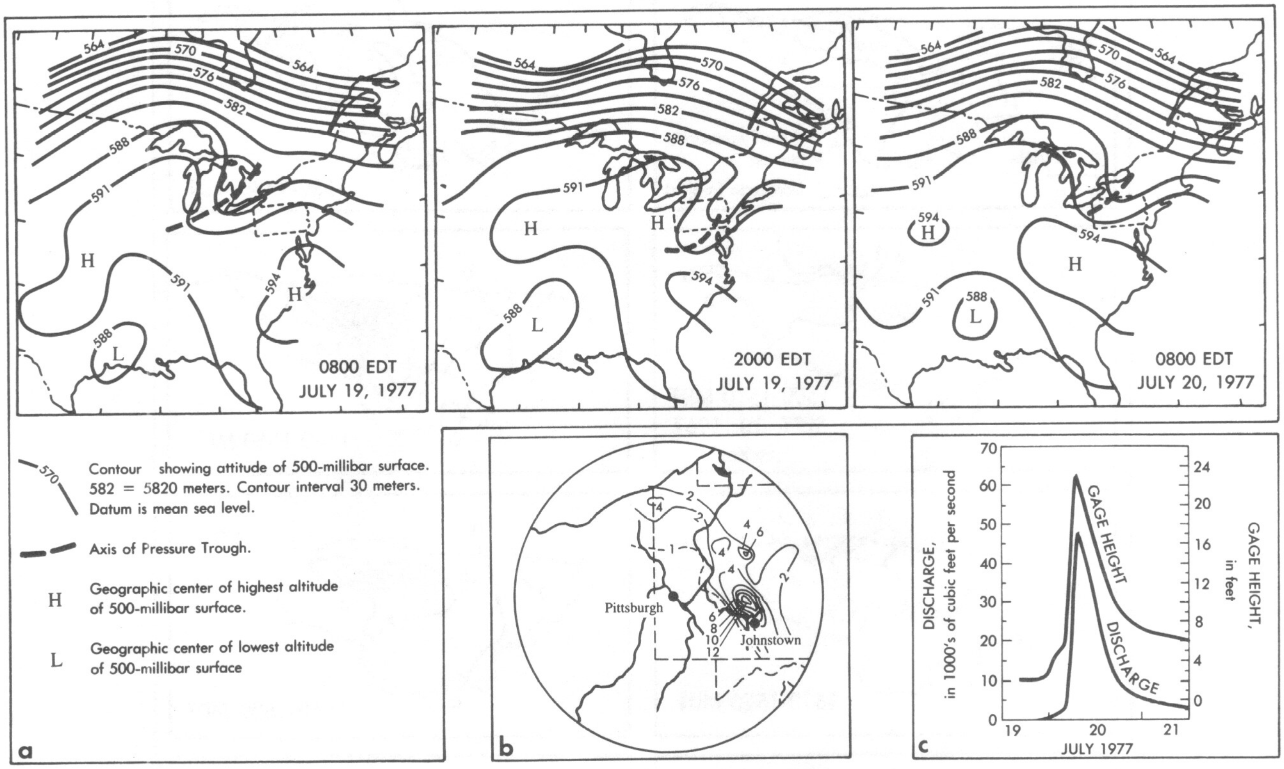


FIGURE 3. Example of small mesoscale atmospheric activity and resulting flood hydrographs. (*a*) Isohyetal maps (in inches) for 10-min intervals showing the movement of a thunderstorm across the Walnut Gulch watershed (93 km^2) near Tombstone, Arizona, from 15:00 to 16:10 MDT on September 10, 1967. Several localized cells of high-intensity rainfall developed and dissipated during the course of the storm, which lasted a little over an hour. (*b*) Discharge hydrographs resulting from the September 10th storm for four subwatersheds within the Walnut Gulch catchment. Over 80% of the total annual 1967 runoff was generated by this one storm (Source: Osborn and Renard, 1969).



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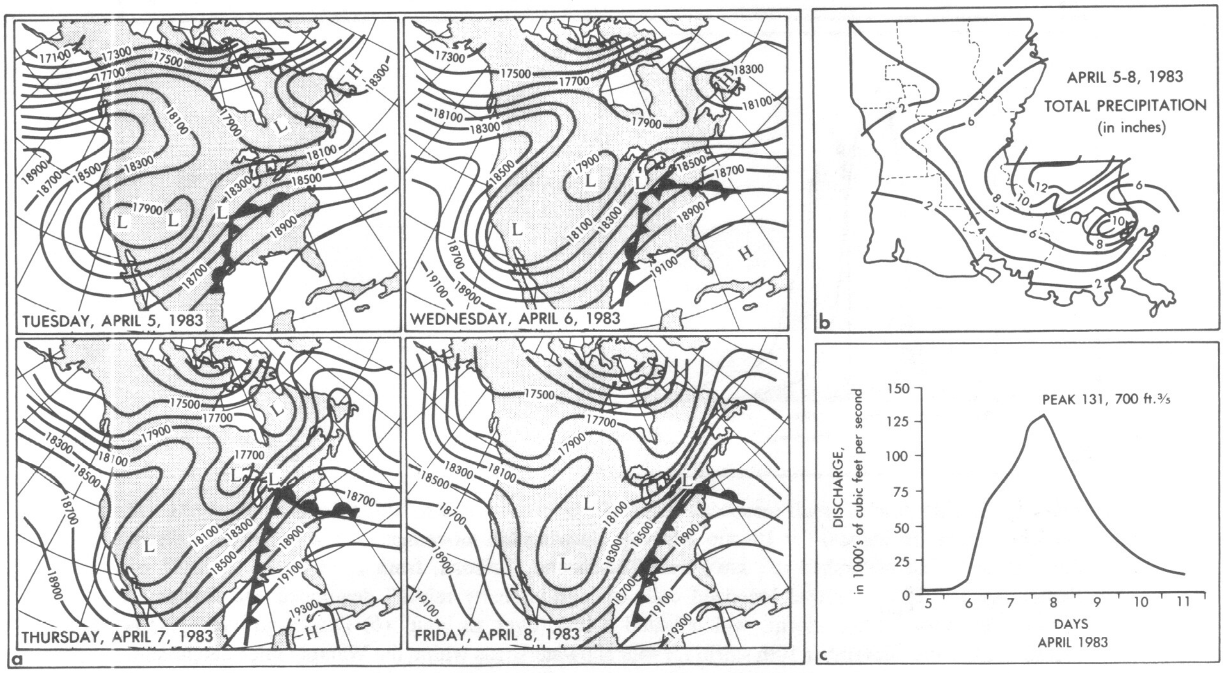


FIGURE 5.

scale activity to develop (Maddox et al., 1979, 1980; Huff, 1978). However, in addition to flash flooding, synoptic-scale events also have the ability to produce long-duration, widespread flooding throughout a large drainage basin or in several basins across a region. Precipitation generated by macroscale systems is characterized by alternating periods of high and low rainfall intensities, persisting either continuously or intermittently for several hours or days. The widespread nature of these storms, coupled with their complex intensity–duration properties leads to an overall tendency for flood hydrographs with slower rise times and longer periods with streamflow at flood stage, than are found in the smaller-scale, flashier events (Fig. 5).

Larger Scale Hydroclimatic Activity

Although less obvious, larger scale and longer duration climatic events that take place beyond the space–time domain of most hydrometeorologic activity also have a significant impact on flooding. The most widely recognized of these is the seasonal accumulation and melting of winter snow, a process that may contribute to runoff volumes for several days or weeks and be generated from an area as large as the entire upper Mississippi River basin. Spatially, snowmelt flooding can occur in any sized drainage basin, but in large basins the area affected by snowmelt may be extensive because the snowmelt process has the capability to induce flooding at downstream reaches of a basin that are far removed from the area that directly received the original precipitation input. Temporally, the runoff resulting from snowmelt reflects the cumulative climatic events of several weeks or months prior to the runoff event itself, even though the actual snowmelt may occur rapidly over a 1- or 2-day period. Furthermore, the rate of snowmelt is a function of climatic factors other than the amount of snow itself, such as air temperature, solar radiation, cloud cover, and rainwater falling on the snow surface. Because of the space–time domain of the processes that contribute to snowmelt floods, they are most appropriately analyzed from a larger scale, longer duration, climatic perspective (Fig. 6).

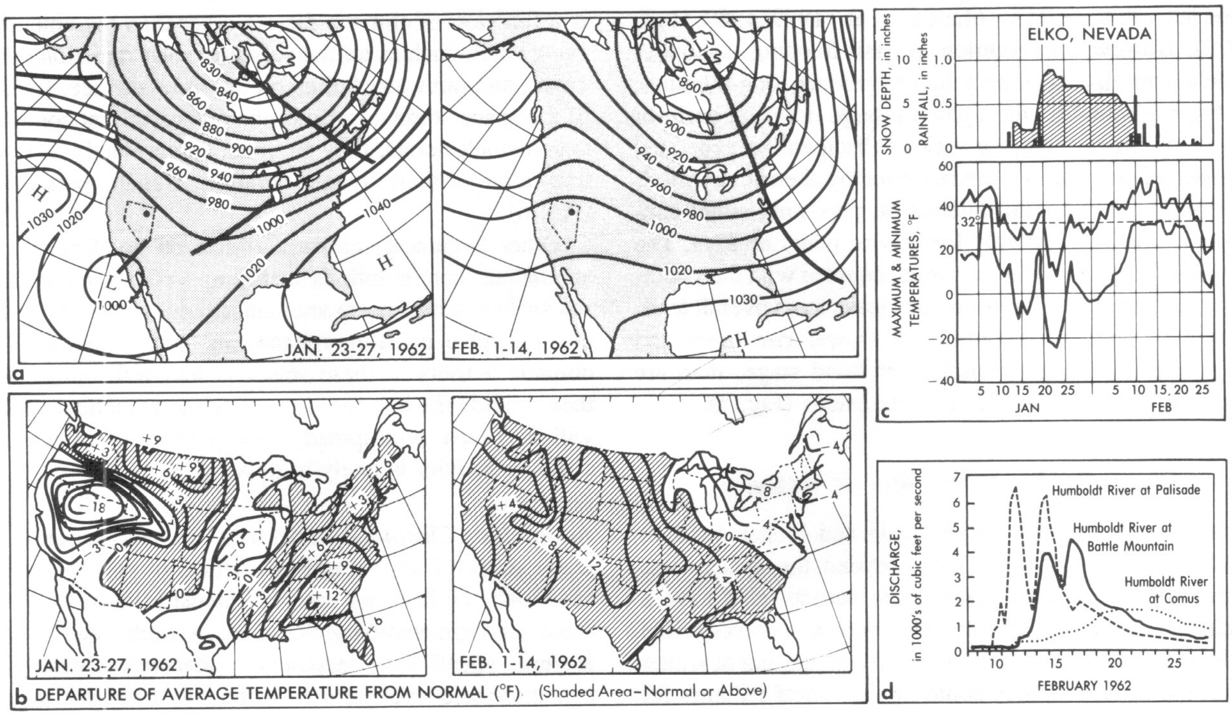
Other large-scale climatic effects on flooding include anomalous configurations in the upper-level circulation, sea surface temperature anomalies, and decadal-scale circulation episodes. Although the direct link to flooding from climatic activity at these scales is less well understood, they provide the key for identifying the climatic scenarios within which widespread flood-generating hydrometeorologic activity is likely to develop.

Anomalous Circulation Patterns. In many cases floods result simply from excessive amounts of precipitation or snowmelt, or from an unusual intensity in an otherwise typical hydrometeorologic circulation mechanism, such as a front, squall line, mesoscale convective complex, or synoptic-scale cyclone. Occasionally, however, certain floods are associated with very atypical patterns in the atmospheric circulation. These anomalies can be in the form of (1) an unusual combination of several common mechanisms occurring together, (2) an unusual location or unseasonal occurrence of an otherwise typical circulation mechanism, (3) the unusual persistence of a specific circulation pattern, or (4) a rare configuration in the upper-air pattern itself.

Figure 7 depicts an example of the first type of anomaly—an unusual combination of circulation features—that resulted in widespread flooding throughout central and southern Arizona. During September 4–6, 1970, several

FIGURE 4. Example of large mesoscale atmospheric activity and resulting flood hydrograph. (*a*) 500-mb charts for July 19–20, 1977, showing the movement of a short-wave trough over western Pennsylvania. The mesoscale trough triggered widespread thunderstorms across Pennsylvania and was associated with two major squall lines that moved across the state. (*b*) Total observed rainfall (in inches) over western Pennsylvania from 0800 EDT July 19–0800 EDT July 20, 1977. (*c*) Discharge hydrograph for Stony Creek at Ferndale, Pennsylvania (726 km^2), about 2 km upstream from the Johnstown city limits. Many deaths and extensive property damage resulted from this event, estimated at a recurrence interval of 100 yr (from Hoxit et al., 1982).

FIGURE 5. Example of macroscale atmospheric activity and resulting flood hydrograph. (*a*) 500-mb charts for April 5–8, 1983, showing the position of major surface fronts. Widespread flooding across southeastern Louisiana and southern Mississippi was associated with the stationary front. High pressure over southeastern United States prevented the upper-air trough to the west and its associated surface front from moving eastward, causing the system to remain in the Gulf Coast area for several days. (*b*) Total precipitation (in inches) over Louisiana for the April 5–8 storm event (Source: Muller and Faiers, 1984). (*c*) Discharge hydrograph from Bogue Chitto near Bush, in southeastern Louisiana (1952 km^2). The peak discharge of this event was more than twice the previous maximum and was estimated at a recurrence interval of greater than 100 yr (Source: Carlson and Firda, 1983).



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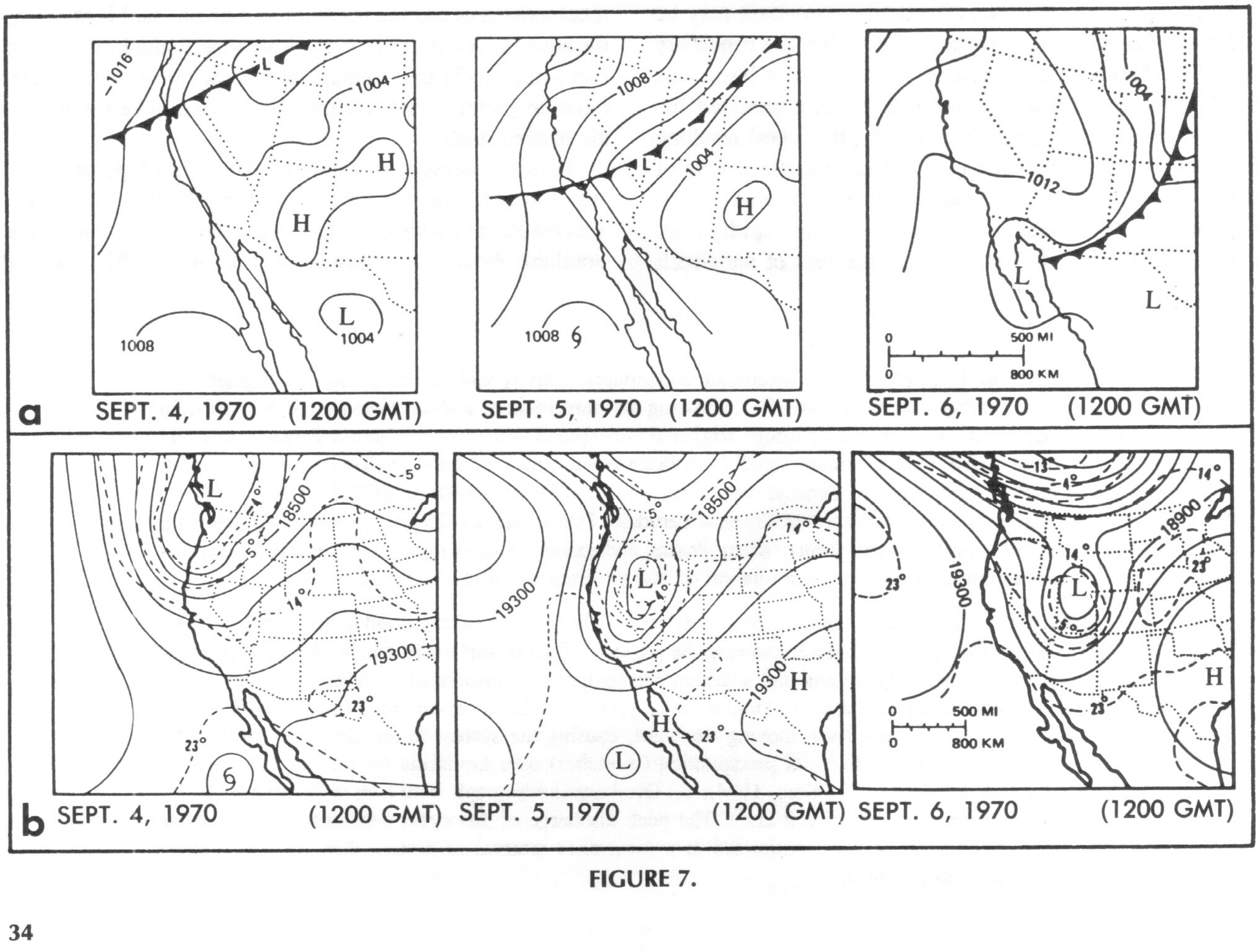

FIGURE 7.

major synoptic features occurred simultaneously and introduced excessive amounts of precipitable water vapor into the Southwest. At the same time they provided the necessary uplift triggering mechanisms to release this moisture. The features included a deep upper-air trough, an incipient cutoff low circulation, a surface cold front, and a tropical storm off the Baja California coast (Fig. 7). This unusual coincidence of synoptic-scale events generated severe flash flooding in small mountain watersheds throughout southern Arizona as well as widespread flooding in many larger drainage basins, with some gauges recording the highest annual flood of record. Each of the synoptic-scale operating mechanisms alone had the potential for generating a flood. However, none of them was particularly anomalous in itself. It was the combination of several mechanisms operating simultaneously that produced an anomalous circulation pattern that resulted in a major flooding episode.

An example of the second type of circulation anomaly—unseasonal atmospheric conditions—occurred in northern California during February 11–19, 1986. A movement of the ridge off the western North American coast (see Fig. 2*b*) produced a high-latitude blocking effect in the eastern North Pacific ocean and shifted the main branch of the winter jet stream to a more southerly location for over a week, a situation that is unusual for February. These events allowed massive low-pressure systems to develop and redevelop over the ocean and fed a succession of devastating storms into California over a 9-day period. The result was extensive flooding, loss of lives, forced evacuation of thousands of residents, and millions of dollars of damage.

Severe flooding in the Mississippi River basin during the spring of 1973 had its origin in the third type of circulation anomaly—the unusual persistence of a specific upper-air pattern over an extended period of time (Fig. 8). Throughout March and April the repeated development of a trough over the southern United States produced frequent and persistent episodes of southerly wind flow. As this southerly flow moved through the eastern side of the trough, it introduced moist maritime gulf air masses into the lower Mississippi valley. In addition, the strong surface convergence and divergence aloft, typically associated with the eastern sides of troughs, provided the necessary mechanisms for frontal formation, storm development, uplift, and release of the excess moisture. This extended hydroclimatic episode resulted in new records for consecutive days above flood stage for many of the main-stem Mississippi River gauging stations from southern Iowa to Louisiana (Chin et al., 1975).

Finally, some of the most unusual flood-producing conditions are those that result from the fourth type of circulation anomaly, a rare configuration in the upper-air pattern itself. In June 1972, Hurricane Agnes produced flooding that devastated the East Coast of the United States in what was called at the time, "the greatest natural disaster ever to befall the Nation" (U.S. Department of Commerce, 1973, p. 1). Although not an unusual storm in the beginning, 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 deep Tropics. However, it was the influence of a highly abnormal configuration in the large-scale circulation pattern over the North Atlantic ocean that affected Agnes' unusual path

FIGURE 6. Example of large-scale climatic activity and its affect on snowmelt flooding. (*a*) Contrast between mean 700-mb charts for the weeks of January 23–27 and February 1–14, 1962. During the last week of January a deep trough of very cold air was situated over most of the far west as a surface arctic high-pressure system settled over the Great Basin, however, by the end of the second week of February, a strong ridge of warmer air had replaced the trough in the west. (*b*) Corresponding temperature departure maps for each week showing the departure of average surface temperature from the 1931–1960 normal (in °F). In late January subfreezing temperatures in the Idaho–Nevada area froze the ground to depths of as much as 3 ft under a cover of light snow. (*c*) Antecedent climatic conditions and rainfall at Elko in northeastern Nevada. (*d*) Discharge hydrographs for three stations in the Humboldt River basin in northeastern Nevada. The February 10th–15th flooding resulted from the combination of several days of low-intensity rain falling on moderate amounts of snow that had accumulated during January. The snow melted rapidly in response to the warmer temperatures and light rain, but due to the severity of the previous cold spell, the ground beneath remained frozen and exacerbated the flooding. The resulting complex hydrographs show the contributions of individual upstream tributaries and the downstream progression of the flood wave. Floods estimated at recurrence intervals of greater than 50 to over 100 yr occurred throughout northeastern Nevada and southern Idaho during this unusual hydroclimatic episode [Source for (*a*) and (*b*): Stark, 1962; Andrews, 1962; source for (*c*) and (*d*): Thomas and Lamke, 1962].

FIGURE 7. A flood-producing circulation anomaly that resulted from the simultaneous occurrence of several synoptic-scale events. (*a*) Surface charts for September 4–6, 1970. (*b*) Corresponding 500-mb charts [Source for (*a*) and (*b*): Hansen and Schwarz, 1981].

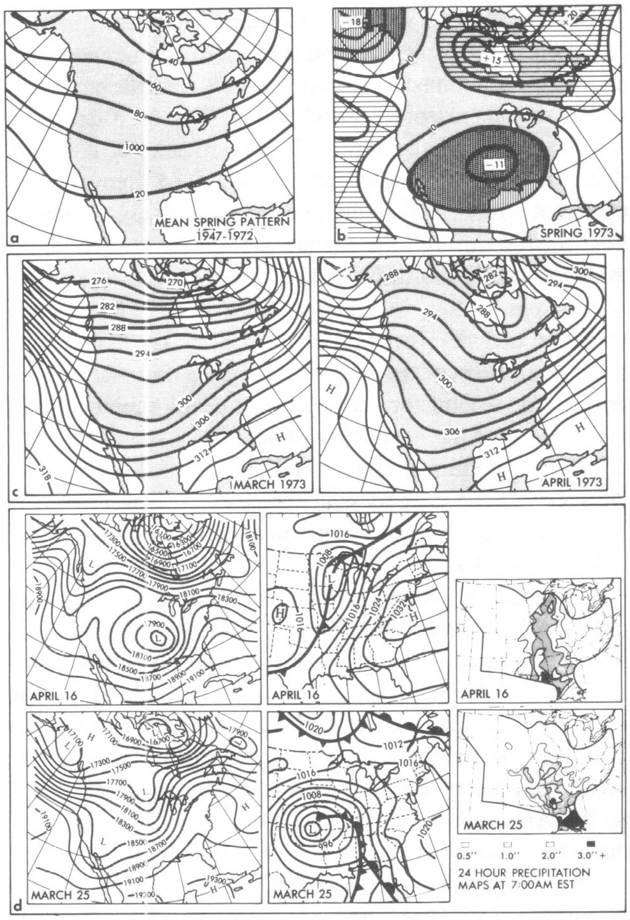

FIGURE 8. A flood-producing circulation anomaly that resulted from the repeated development of a trough-to-ridge configuration over the Mississippi River basin and the unusual persistence of this pattern for 2 months. (*a*) Mean spring 700-mb height pattern in tens of feet (based on March–May over the period 1947–1972). (*b*) Spring 1973 departure pattern from the 26-yr mean in tens of feet. Contour interval 50 ft [Source for (*a*) and (*b*): Namias, 1979]. (*c*) Mean monthly 700-mb height patterns for March and April, 1973 in dekameters. (*d*) Selected daily 500-mb and surface charts showing the position of the trough in relation to the Mississippi basin and the resultant pattern of precipitation in the basin (24-hr totals over 0.5 in.). Similarly positioned troughs were present on about 60% of the days in March and April. The associated surface low-pressure centers and fronts brought persistent heavy rainfall over the basin in March and April and set new monthly records for many stations [Source for (*c*) and (*d*): Chin et al., 1975).

and fed large amounts of moisture into the storm during its latter stages, resulting in phenomenal rains and record-breaking floods in Virginia and Pennsylvania (Fig. 9).

Sea Surface Temperature Anomalies. The June 1972 circulation anomaly associated with Agnes and its attendant anomalously warm Atlantic sea surface temperatures were the culmination of global-scale events that had actually been developing over a much longer span of time. According to Namias (1973), the June anomaly pattern that influenced the track of Agnes began to establish itself as early as February or March, due in part to the external forcing of abnormally warm sea surface temperatures (SSTs) and positive feedback effects between the ocean and the atmosphere. Such air–sea interactions—along with the tendency for major pressure centers in the global circulation to exhibit intercorrelations or "teleconnections"—form the basis for many long-range forecasting techniques. They also present an argument for possible long-term, large-scale hydroclimatic controls on major flooding episodes around the world.

El Niño, the anomalous warming of sea surface temperatures from coastal Peru westward along the equator, and the Southern Oscillation, a related atmospheric pressure shift in the western South Pacific ocean, are the most frequently cited large-scale SST factors to be linked to flood events at diverse locations across the globe such as Peru, Bolivia, and Ecuador in South America, the Pacific coast of North America from Oregon to Baja California, the Colorado River basin, and coastal areas of the Gulf of Mexico (Quiroz, 1983; Rasmusson, 1985). In other parts of the world, however, the El Niño/Southern Oscillation phenomenon has been associated with the occurrence of droughts. Continued research is needed to better understand the global-scale atmospheric teleconnections and air–sea interactions that indirectly affect flooding over such vast spatial scales, especially in terms of how they interface with local mesoscale and macroscale processes that have a more proximate flood-generating impact.

Long-Period Circulation Episodes. Episodic tendencies in the overall pattern of the circumpolar upper-air waves constitute the largest spatial and longest temporal scales to have a potential hydroclimatic impact on flooding. Although the ridges and troughs that form the upper-air wave pattern may adjust into high- and low-amplitude patterns on a daily, weekly, monthly, or seasonal basis, over the last 100 years extended intervals of time characterized by more zonal circulation patterns have alternated with periods characterized by more meridional patterns. These circulation episodes, often several decades in length, have been documented in a variety of ways by researchers who have used both subjective and objective means to classify large-scale patterns and adjustments in the atmosphere over time (Dzerdzeevskii, 1963, 1969; Kutzbach, 1970; Kalnicky, 1974; Knox et al., 1975; Lamb, 1977; see also Barry and Perry, 1973, pp. 365–377). Circulation adjustments at these decadal scales have their greatest hydroclimatic impact in generating trends and variations in flood series over time (Fig. 10).

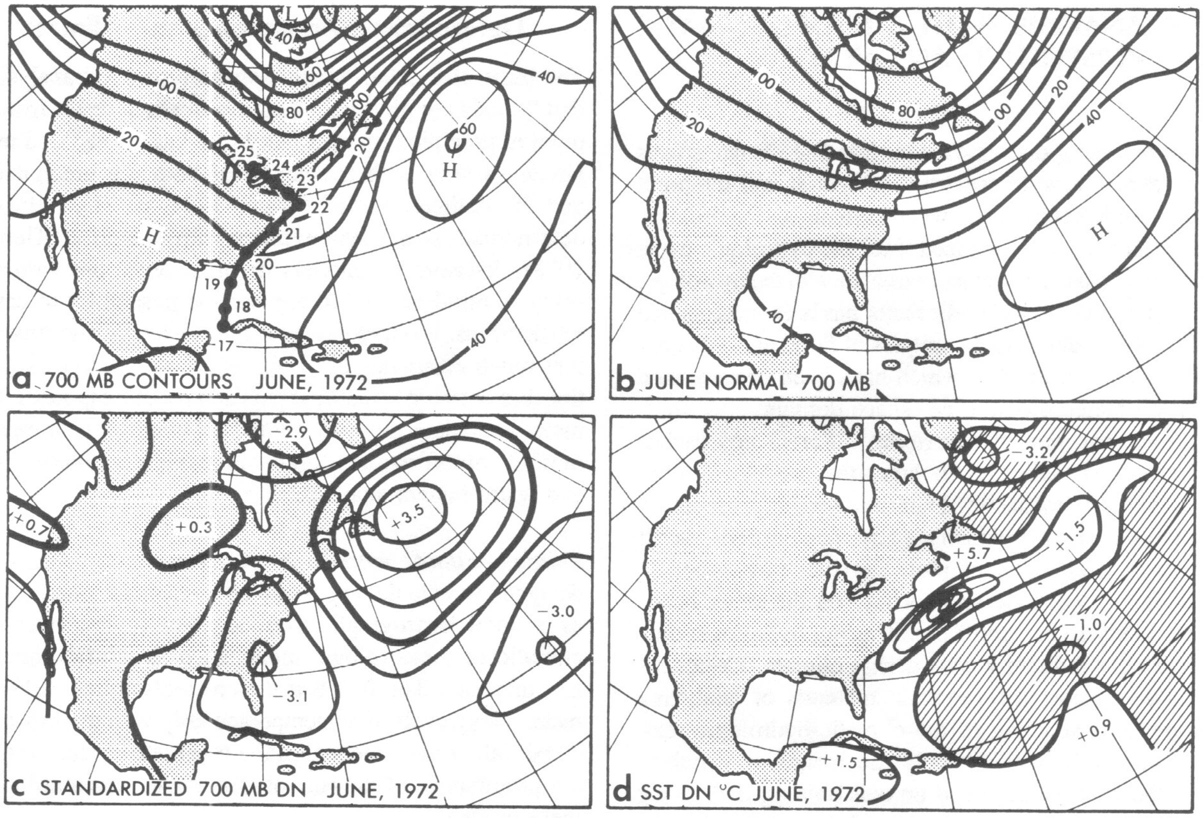

FIGURE 9. A flood-producing circulation anomaly due to a rare configuration in the upper-air pattern. (*a*) June 1972 700-mb height pattern showing path of Agnes and a deeply developed trough and ridge pattern in the western North Atlantic Ocean. (Contours are labeled in tens of feet with hundreds omitted. Path of Agnes from June 17–25 is shown with a solid line.) (*b*) Normal June pattern based on the mean of Junes from 1947–1963. (*c*) Deviations of the June, 1972, 700-mb height pattern from the normal pattern. (Isopleths are in standard deviations with a contour interval of 1.) The unusual ridge (blocking high) in the far North Atlantic helped to steer the path of Agnes due north. (*d*) Sea surface temperature departures from normal for June 1–26. Air masses feeding into Agnes moved over these anomalously warm waters and picked up excessive amounts of moisture (Source: Namias, 1973).

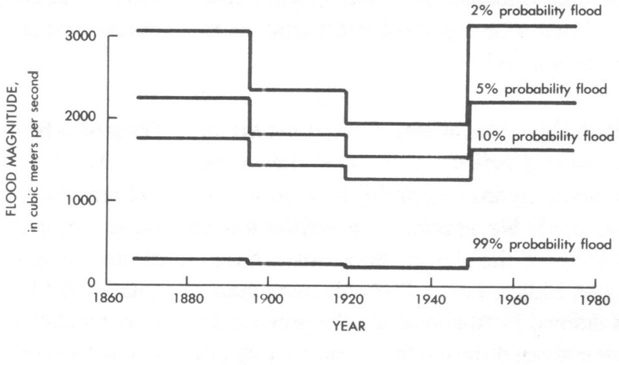

FIGURE 10. Affect of decadal-scale circulation episodes on the partial duration flood series of the Mississippi River at St. Paul. Separate estimates of flood probability were computed for different sections of the record using the standard log-Pearson Type III method. The boundaries defining the subperiods are not arbitrary, but have a distinct physical basis because they represent significant dates of change in prevailing global circulation patterns. Meridional circulation patterns were more frequent before about 1895 and since 1950, but zonal circulation patterns were more common between 1895 and 1950 (Source: Knox, 1983).

FLOOD ANALYSIS WITH A HYDROCLIMATIC PERSPECTIVE: AN OVERVIEW

From the preceding discussion it is clear that climate affects flooding across a wide spectrum of spatial and temporal scales. These interactions between climatic and hydrologic processes have been recognized since the hydrologic cycle was first conceptualized; yet an examination of the hydrologic literature shows that the climatic factor has been incorporated into standard models and techniques of flood analysis only in limited degrees, most of which have been concentrated in the hydrometeorologic time–space domain.

A convenient way of describing different approaches to hydrologic modeling is to label the model as either deterministic or stochastic. Deterministic approaches to flood analysis, many of which are based on rainfall–runoff relationships, frequently employ climatic information in their models. Stochastic approaches, on the other hand, are more likely to be runoff based, using hydrologic data alone and only indirectly considering climate. Criticisms often raised against deterministic methods of analyzing floods are that modeling of the climatic-hydrologic relationship generally involves only the means of variables and that the models are based on constraining underlying assumptions about the environment that oversimplify the processes operating in the real world and neglect the large number of random factors that can affect the responses of natural hydrologic systems (Yevjevich, 1974). Conversely, stochastic approaches to flood analysis tend to be constrained at the opposite end of the spectrum by having as their basis the underlying assumption that all hydrologic processes should be viewed as "random numbers of random variables." Although the randomness assumption allows hydrologic processes to be modeled and described on the basis of probability density functions, in practice the assumption has tended to somewhat limit the scope of certain schools of stochastic hydrology by focusing analyses on the hydrologic time series itself and appearing to eliminate the need to examine hydrologic events from any sort of physically based viewpoint, especially in terms of the climatic origins of the events. In recent years the distinction between deterministic and stochastic approaches has become blurred since many models contain elements of both. Physically based stochastic models of rainfall and runoff, in particular, have ushered in a new direction in hydrology by effectively combining stochastic and deterministic methodologies (e.g., Eagleson, 1972, 1978; Chan and Bras, 1979; Waymire et al., 1984).

The following sections present an overview of the various ways in which climate has been incorporated into deterministic, stochastic, and physically based approaches to flood analysis.

Deterministic Approaches and Climate

The basis of a deterministic approach to flood analysis is that "floods are physical phenomena which result from an input of precipitation into a drainage basin, the flood magnitude varying with the nature of both the precipitation and the drainage basin" (Ward, 1978, p. 71). Although determinism is not synonymous with causality (Klemeš, 1978), deterministic models are often developed with causality in mind or used to explore the possibility of causal relationships. It is therefore within the deterministic approach that much effort has been placed on examining the relationship between climatic inputs and runoff responses. Climate-based deterministic methods of flood analysis include rainfall–runoff models, probable maximum precipitation, and water budget analysis.

Rainfall–Runoff Models. Most deterministic methods are designed to calculate or predict a hydrologic output, such as a flood hydrograph, from a given or predetermined climatic or meteorologic input, such as rainfall duration and intensity. The fact that the cross-discipline of hydrometeorology evolved contemporaneously with the expansion of rainfall–runoff models in the twentieth century reflects the prominence of the role of climate and meteorology in these models.

Comparative discussions of the many deterministic models that have been developed for runoff analysis have been presented in several recent review papers. An overview of rainfall–runoff models is given by Linsley (1982), deterministic surface water routing models are described by Dawdy (1982), physically based and process-oriented models are discussed by Woolhiser (1982) and Dunne (1982), and some deterministic models that specifically focus on the analysis of peak flows are reviewed by Feldman (1980). The common thread among most of these approaches—from the earliest simple mathematical calculations of peak discharge using the "rational formula" to the sophisticated modeling of runoff by solving partial differential equations for three-dimensional, time-varying flow—is the inclusion of climatic or meteorologic variables as important inputs in the analysis.

Probable Maximum Precipitation and Hydrometeorologic Studies. A method that exemplifies the deterministic hydrometeorologic approach to flood analysis is the *probable maximum precipitation* technique, used to determine the design flood for a river basin (see Myers, 1969; Miller, 1973). Probable maximum precipitation (PMP) is defined as "theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year" (Interagency Advisory Committee on Water Data, 1985, p. 124). The methodology was developed in the United States in the mid-1930s and remains in use today, particularly as a guide for the design specifications of large dams. In the PMP approach information obtained from extensive meteorological analyses of major storms and atmospheric conditions known to have produced flooding is used to develop regional maps depicting precipitation depth estimates for storms of different duration. The PMP estimates are then converted to estimates of the probable maximum flood for a particular drainage basin through a deterministic model such as the unit hydrograph.

The PMP method has aroused a great deal of controversy between the deterministic and stochastic schools of thought. The crux of the argument against PMP by some stochastic hydrologists is that the method is not based on any concept of probability or statistics (despite its name) and that it implies that there are definable upper limits to the meteorologic processes operating in an area (Yevjevich, 1968; Benson, 1973; discussion in Schulz et al., 1973, pp. 95–113). Proponents of PMP have responded that the method provides a useful bench mark for determination of the design flood for a dam, especially when existing records are inadequate for using statistical flood frequency methods to estimate extreme floods (discussion in Schulz et al., 1973, pp. 95–113). E. M. Laurenson, commenting during a discussion session on PMP, summed up the controversy as follows:

> The argument that has gone on over the past twenty years between determinists and probabilists on the question of PMP has been most destructive, because it has forced people into opposing camps and into positions they feel they must maintain. . . .
>
> The only hope for advancement in the area of estimation of extreme floods is in a combination of the deterministic approach to those aspects of the precipitation and runoff processes where we have physical knowledge and the probabilistic approach to those aspects which cannot be described in terms of cause and effect.
>
> —(E. M. Laurenson in discussion in Schulz et al., 1973, p. 105)

As Laurenson suggests, deterministic hydrometeorologic studies of runoff phenomena have greatly increased our understanding of the physical processes that produce floods. In the arid, semi-arid, and mountainous West, the complexities of the storm–flood relationship are especially difficult to analyze. Several studies have contributed in this area, notably National Weather Service Hydrometeorological Report No. 50 by Hansen and Schwarz (1981) on the meteorology of important rainstorms in the Colorado River and Great Basin drainages, and the National Oceanic and Atmospheric Administration (NOAA) studies of R. A. Maddox and his colleagues (Maddox and Chappell, 1978; Maddox et al., 1979, 1980) on meteorological characteristics of flash floods in the western United States.

Water Budget Analysis. Studies of flooding from a meteorological perspective have advanced our knowledge of the physical causes of individual flood events. However, the deterministic hydrometeorologic approach is usually not directed toward synthesizing this information over sufficiently large spatial or sufficiently long temporal scales to present a picture over time of the *variability* of occurrence of the hydrometeorologic phenomena. Here lies the strength of hydroclimatic methods for analyzing floods. One such technique is water budget analysis, an environmental systems approach to the hydrologic cycle that studies the income, outgo, and storage of water at the surface of the earth (Muller, 1976; Mather, 1978). The water budget can be computed at various spatial scales and over daily, monthly, seasonal, or yearly time scales, depending on the needs of the analysis. The approach is especially useful for distinguishing climatic from nonclimatic sources of runoff variability because it can compute expected runoff solely on the basis of surpluses in the climatically derived water budget and thereby assess the amount of streamflow variability that is related to climatic variability (Fig. 11).

Stochastic Approaches and Climate

The stochastic approach in hydrology has been defined as "the manipulation of statistical characteristics of hydrologic variables to solve hydrologic problems, on the basis of the stochastic properties of the variables. A stochastic variable is defined as a *chance* variable or one whose value is determined by a probability function" (Committee on Surface-Water Hydrology, 1965, p. 77). Some hydrologists make a distinction between the terms *stochastic* and *probabilistic*, the former referring to the treatment of variates as time dependent and the latter as time independent (Chow, 1964). Most, however, avoid this distinction and refer to a stochastic process as one that "evolves, entirely or in part, according to a random mechanism" (Kisiel, 1969a, p. 15), and use the terms *stochastic*, *probabilistic*, and *random* interchangeably as synonyms for any process that is governed by the laws of chance (Yevjevich, 1974). According to Klemeš (1983), although the usage of the term *stochastic* is not uniform among hydrologists, "the prevailing view is that whenever some variables or parameters in mathematical formulations of hydrologic processes or relationships are defined as variates (random variables), the formulations belong under the label of stochastic hydrology" (p. 695).

Since the basis of a stochastic approach is the modeling of a process according to the laws of chance, climate—

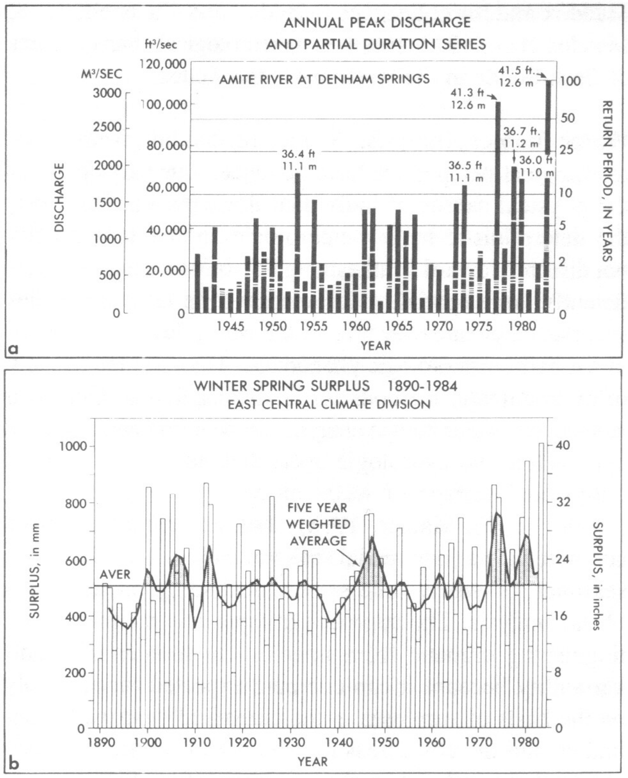

FIGURE 11. Use of the water budget for interpreting streamflow variability. (*a*) Annual and partial flood series for the Amite River in eastern Louisiana. Partial series peaks are shown with white horizontal bars. Most of the annual floods occur in spring. A trend toward larger floods is evident in recent years. Nonclimatic factors, such as land-use changes or measurement error, are often proposed as explanations for trends like this one in a flood series. (*b*) Time series of the winter–spring surplus available for runoff in east-central Louisiana, computed from climatic data. The plot shows that the 11-yr period between 1973 and 1983 was extremely wet in winter and spring and generated some of the largest seasonal moisture surpluses in the entire 96-yr record. This additional hydroclimatic information lends support to a climatic explanation for the recent trend toward increasing flood peaks (Source: Muller and McLaughlin, 1987).

when viewed as a deterministic component—is generally not involved in most stochastic analyses of hydrologic processes. Furthermore, in some cases, when the effects of a climatic control may be influencing a hydrologic series by producing a trend or a jump in the record, this deterministic component of the series is often removed (see Yevjevich, 1972). In general, climatic information enters into most stochastic analyses of hydrologic processes mainly by offering either support or reservations concerning the underlying assumptions of stationarity and homogeneity in the hydrologic data. The climatic basis for these assumptions is important in both probabilistic flood frequency analyses and in stochastic time series analyses of long-term hydrologic variability.

Flood Frequency Analysis. Stochastic approaches to flood analysis were formally introduced in 1914 by Fuller when he presented a discussion of flood frequencies and used the return period as a measure of the probability of recurrence of floods of different magnitudes (Fuller, 1914). This concept soon expanded into the use of theoretical probability distribution functions to describe the actual frequency distribution of the floods (Foster, 1924; Hazen, 1930; Gumbel, 1941) and is still in active use today in what might be referred to as standard probabilistic flood frequency analysis (U.S. Water Resources Council, 1981).

Numerous methods for calculating the best estimates of flood frequency have evolved over the past 70 years and are reviewed by Jarvis and others (1936), Benson (1962), and Reich (1976). In 1968 Benson reported on a study by a federal interagency group that compared the most commonly used methods of flood frequency analysis (Benson, 1968). This group recommended that all U.S. government agencies adopt the log-Pearson Type III distribution as their base method in order to achieve a uniform procedure for computing flood estimates. Although the recommendation set off a major controversy (Kisiel, 1969b; Benson, 1969; Reich, 1977), it did result in a standard procedure for flood analysis in the United States, first outlined by the U.S. Water Resources Council in 1967, revised in 1976, and revised again as Bulletin 17B in 1981. The recommendation also set off a flurry of reactivated interest in methods of flood frequency analysis that persists to the present day. [For overviews of some of these more recent approaches, see Greis (1983), Cunnane (1987), Stedinger and Cohn (1986), and Tasker (1987).] Despite the continued interest in improving flood frequency estimates, climatic information has not often been utilized in this area except as a factor in the underlying assumptions of the analysis. Bulletin 17B addresses the role of climate and climatic variability in terms of the conditions necessary for a valid statistical procedure. These assumptions are "that the array of flood information is a reliable and representative time sample of random homogeneous events" (U.S. Water Resources Council, 1981, p. 6). Possible violations of these conditions that are related to climate are subsequently elaborated in the bulletin:

> ***Climatic Trends***
>
> There is much speculation about climatic changes. Available evidence indicates that major changes occur in time scales involving thousands of years. In hydrologic analysis it is conventional to assume flood flows are not affected by climatic trends or cycles. Climatic time invariance was assumed when developing this guide.
>
> —(p. 6)
>
> ***Mixed Populations***
>
> At some locations flooding is created by different types of events. For example, flooding in some watersheds is

> created by snowmelt, rainstorms, or by combinations of both snowmelt and rainstorms. Such a record may not be homogeneous and may require special treatment.
>
> —(p. 7)

The integration of flood hydroclimatology with traditional flood frequency analysis can effectively address these possible violations by examining the physical causes of flood events and the nature of climatic anomalies that produce unusual "outliers," mixed populations, or trends in flood series. For example, the space–time domains of various kinds of hydroclimatic activity (Fig. 1) can be used to explore Bulletin 17B's assumption of "climatic time invariance" by examining the sensitivity of hydrologic systems to climatic variations at different time scales.

Time-dependent Stochastic Approaches. While the probabilistic methods of flood frequency analysis were being refined, compared, and promulgated in the 1960s and 1970s, the techniques of time-dependent stochastic analysis of hydrologic processes were also receiving attention (e.g., Yevjevich, 1963, 1972; Fiering, 1967; Mandlebrot and Wallis, 1968; Kisiel, 1969a). These time series methods were developed to analyze or synthesize hydrologic processes on long time scales. However, the impact of climatic variability on hydrologic time series was often not appreciated:

> In the analysis of the longest series of annual values of precipitation and runoff, no statistically significant climatic changes could be detected. There is, however, a possibility that some slow changes of yet unidentified characteristics may be taking place, mainly because of man-made factors. . . . These new factors are bound to change the climate and also to affect some hydrologic phenomena along the water cycle. However, an overemphasis on these changes has given them a distorted importance. The consequence has been to retard investigation of the basic structure of hydrologic time series by proper techniques. The "warming up" and "cooling off" periods over some areas, or the advance or retreat of glaciers, may be only part of a random fluctuation in the time series of temperature and volume of ice in glaciers. The "climatic change complex" . . . has diverted the efforts of hydrologic investigations to less productive scientific areas.
>
> —(Yevjevich, 1968, pp. 228–229)

These comments are symbolic of a bias among some stochastic hydrologists against any approach to the analysis of a sequence of hydrologic data that is dominated by a "ruling hypothesis" that seeks to deterministically explain all hydrologic variability as a function of climatic changes and therefore essentially denies the basis of the stochastic approach: that a hydrologic process is a random or stochastic process. Given the history of a rash of hydrologic determinists in search of hidden periodicities and cycles in the early 1900s, which culminated in what has been described as "the largest historic failure in the analysis of hydrologic processes" (Yevjevich, 1974, p. 229), the wariness of some stochastic hydrologists toward climatic change explanations for hydrologic variability is understandable.

In recent years the relationship between climatic variability and hydrologic series has been more responsibly explored by using various time series analysis techniques (e.g., Schaake and Kaczmarek, 1979; Lettenmaier and Burges, 1978; Meko and Stockton, 1984). Much of this work has been done in the realm of water resources systems analysis for the purpose of providing better estimates of long-term storage and water availability, given the possibility or reality of climatic changes or long-term climatic fluctuations. Of great interest in this area is the potential for modeling two types of phenomena that have been observed in hydrologic time series and have been linked to climate: the *Joseph* and *Noah* effects, so named by Mandelbrot and Wallis (1968).

Joseph Effects. The phenomenon described as a *Joseph effect* is the occurrence, on occasion, of very long periods of low flows (or precipitation), or very long periods of high flows (or precipitation). The term was inspired by the biblical story of Joseph, whose Egyptian reign included seven years of plenty followed by seven years of famine. Models that can account for or describe the extended wet and dry episodes often seen in hydrologic series are considered to be in the Joseph realm and have been used to explore the relationship of droughts and long-term persistence to the statistical properties of time series.

Kilmartin (1980) saw a great need for the application of a hydroclimatologic approach to the analysis of Joseph effects because "the 'Joseph event' is not merely a within-basin process, it is a basin response to a major anomaly in the atmospheric circulation, an anomaly that is often near hemispherical in areal magnitude" (p.161). Indeed, the most active current research on the relationship between climatic variability and hydrologic variability is largely concentrated in the Joseph realm of time series analysis of long-term climatic and hydrologic fluctuations and the consequences of these fluctuations for future water supplies.

Noah Effects. In contrast with the long-period Joseph effects, the term *Noah effect* refers to the short-term rare occurrences in nature of extremely high flows (or precipitation) and, of course, was inspired by the biblical story of Noah and the great flood. Time series modeling of the Noah effect has posed problems of a different nature than the Joseph effect.

Statistically, the phenomenon has usually been analyzed by using extreme value theory or other probabilistic methods for modeling outlier behavior in the tails of highly skewed distributions (see, e.g., Kottegoda, 1984). The huge recurrence interval that should, in theory, be attached to a true Noah event renders most time series techniques that use available hydrologic records useless for examining the phenomenon. Dendrochronologic reconstructions of annual or seasonal runoff—particularly effective for studying Joseph events (Stockton, 1975; Stockton and Boggess, 1980)—are generally not sufficiently sensitive to the extremes in a series to be of major use in the study of Noah events. However, some success has been achieved in evaluating the recurrence intervals of extremely large floods by using both historical and paleoflood data (e.g., Costa, 1978; Baker, 1982; Stedinger and Cohn, 1986).

Kilmartin (1980) indicates that the study of extremely large flows has traditionally fallen within the (more deterministic) realm of hydrometeorology, especially in the probable maximum flood approach. However, a hydroclimatic approach to the analysis of Noah events, outliers, or the extremes of a flood probability distribution can contribute important information about the synoptic circulation anomalies and characteristic climatic patterns that affect the recurrence intervals and probabilities of such unusual events.

Physically Based Approaches and Climate

Apart from some of the studies mentioned above, most stochastic hydrologists who analyze floods have not focused on incorporating climate or climatic variability into their models. Recently, however, a new outlook has emerged among hydrologists who are calling for a more physically based stochastic hydrologic analysis (Klemeš, 1978, 1982). The physically based approach has proceeded along two closely related avenues of inquiry: detailed conceptual rainfall–runoff modeling of the dynamic hydrologic physical system (hydrodynamical models) and attempts at arriving at a conceptual basis for the probability laws and distribution functions that emerge from the physical properties and interactions of hydrologic variables.

Hydrodynamic Models. One type of physically based approach to flood analysis can be found in the so-called hydrodynamic models (Eagleson, 1972, 1978). The underlying purpose of such models is to derive the probability distribution of peak streamflows, not on the basis of extreme value theory (Gumbel, 1941), but by conceputalizing the streamflow process as a sequence of kinematic waves that originate from a given joint probability distribution of rainfall intensity and duration, and are transformed into streamflow waves through a modeled catchment process. The model effectively integrates several of the deterministic and stochastic approaches previously discussed in this overview by aiming to describe the continuum from rainfall to flood with a set of differential equations, culminating in a derivation of the probability distribution of the resulting flood peaks. Another model with a similar physically based, combined deterministic-stochastic approach can be found in the "geomorphoclimatic" model of Rodriguez-Iturbe (1982) that seeks to "couple" the geomorphic parameters of a drainage basin with rainfall intensity and duration to arrive at an instantaneous unit hydrograph that is conceived as a stochastic response function dependent on both climate and geomorphology.

This kind of comprehensive modeling represents an exciting turn of events in hydrology and holds out the possibility of an ever-deepening understanding of hydrologic processes as they occur in nature:

> The hydrodynamical model, which aims at describing the prototype by a set of differential equations, is often viewed as an ideal of perfection and rigor, the final goal of conceptual hydrologic modeling. It is argued that such a model would have a general applicability since, by being able to describe the streamflow process in terms of the basic equations of mechanics, it would readily facilitate the derivation of all the commonly used coarser representations such as the series of mean daily, monthly, and annual flows, as well as any specific properties like those of maximum and minimum flows, drought periods, and flood volumes.
>
> —(Klemeš, 1978, p. 302)

The difficulties in developing such models, however, often lead to simplification or lumping of input parameters, estimation of critical parameters for which no actual measurements are available, and assumptions for ease of analysis that may or may not hold up in the real world. As Klemeš (1983) states, the hydrodynamic approach

> . . . faces formidable difficulties of at least two kinds. The first is the constraint of mathematical tractability which may enforce simplifications and approximations whose physical plausibility is in doubt. The second is the incompleteness of our knowledge of phenomena at the starting level which brings about the necessity of filling gaps with unverified assumptions whose effect can distort the plausibility of the final product.
>
> —(Klemeš, 1983, p. 7)

Given these factors, and the complexity and expense of developing such rigorous models, their greatest value is their immense contribution to the conceptualization of fundamental hydrologic processes, rather than their practical usefulness in providing computed end products.

Physically Based Distribution Functions. Another way in which stochastic hydrologists have attempted to incorporate more deterministic aspects of the physical world, such as climate, into their models is by probing the possibility of a physical basis for the particular shape of the various probability distribution functions (PDFs) that describe streamflow behavior. These studies have directed most of their attention to the timing of floods in relation to each other and the resulting PDFs that represent this process (Todorovic and Zelenhasic, 1970; Denny et al., 1974; Gupta et al., 1976; Todorovic, 1978). Interest in the timing of large floods has nurtured a further interest in the climatic factors that influence hydrologic variability, especially in terms of the seasonality of flows. A good example of this sensitivity toward climate in a stochastic analysis of flows can be found in Denny et al. (1974) where, by incorporating observations on the nature and timing of climatic inputs to streamflow, the authors developed the underlying assumptions for a Markov analysis of stream behavior and imparted a physical basis to their model.

Mixed Distributions. One of the most frequently cited areas of potential hydroclimatic flood research using physically based distribution functions is the problem of mixed distributions or multiple populations in hydrologic time series. Although homogeneity in the flood series is a basic underlying assumption for the probabilistic determination of flood magnitudes and frequencies, wherever this assumption is stated in the literature, it is often followed by a disclaimer. A typical example, found in Bulletin 17B, states that due to differences in the climatic processes involved in the generation of floods—rainfall, snowmelt, tropical storms, and so on—multiple populations or mixed distributions may be present in the data.

Despite the almost universal recognition that some observed flood samples may not be drawn from a single, climatically homogeneous population, only a handful of researchers have seriously devoted their efforts to the analysis of this problem. Potter (1958) was one of the first to discuss the evidence for two or more distinct populations of peak runoff (as seen in dogleg flood frequency curves), and he proposed possible climatic causes for the multiple populations. Singh (1968, 1974) presented a methodology for mathematically simulating mixed distributions in hydrologic samples, but although he referred to climate as a probable cause of multiple populations, his approach was to objectively search the streamflow data alone to define a mixture of distributions, rather than to decompose the data on the basis of additional climatic information. Other studies have attempted to identify mixed distributions in streamflow series by separating the flood record into seasonal subpopulations (Guillot 1973; Browzin et al., 1973).

Klemeš (1974) discussed mixed distributions and emphasized that the concept is meaningful "only if physically justified and if the component subsamples can be separated on physical grounds" (p. 6). Accordingly, Jarrett and Costa (1982), Elliott et al. (1982), and Waylen and Woo (1982) moved beyond the simple seasonal division of a flood series and looked at the differences between rainfall- and snowmelt-generated floods to examine the problem of mixed distributions in hydrologic data. By detailed examination of both streamflow and weather records, these researchers were able to subdivide flood series into rainfall and snowmelt "populations" so that separate flood frequency curves could be developed from each subset of data.

The analysis of mixed distributions can be taken a step further by using flood hydroclimatology to identify the various synoptic atmospheric circulation mechanisms and patterns that generate each flood event in a series (Fig. 12). When events in a flood series are separated into climatically homogeneous subgroups, the shape of the sample frequency distribution can be interpreted in terms of the physical processes that generated the sample. This is especially appropriate in climatically sensitive regions or in climatic transition zones where floods evolve from a variety of different processes that may be exhibited in complex frequency functions. For example, Figure 12 shows that the largest annual floods on the Salt River in central Arizona are associated with winter frontal passages and tropical storm/cutoff low circulations, while snowmelt floods and summer monsoon floods are of less importance in shaping the upper tail of the sample distribution. In the Santa Cruz River to the south, floods generated by summer monsoon circulation patterns control the basic shape of the sample distribution; however, infrequent but extreme floods generated by winter frontal passages and tropical storm/cutoff low circulations maintain an important influence on the upper tail. This new hydroclimatic information, applied to a mixed distribution, holds the promise of both enhancing our understanding of the flooding process and potentially improving flood frequency estimates by determining the physical basis for events in the upper tails.

HYDROCLIMATIC INTERPRETATION OF THE FLOOD TIME SERIES MODEL

The preceding sections have described the spatial and temporal scales at which flooding and climate interact and the various ways in which climatic information has been integrated into the analysis of floods. Climate can also be applied to the theoretical interpretation of flood series models. One way to interpret an annual flood series is to consider each peak to be an independent observation, without considering the time sequence of the flood events. Many flood frequency analysis techniques proceed under this assumption, and the role of climate is presumed to be time invariant.

However, there is another type of flood series model that seeks to describe, either conceptually or mathematically, the underlying process that determines how floods vary *over time*. This standard time series model is based on the concept of a time-dependent stochastic process and is usually assumed to be a stationary model. The dynamic nature of hydroclimatic activity, operating at long- and short-term

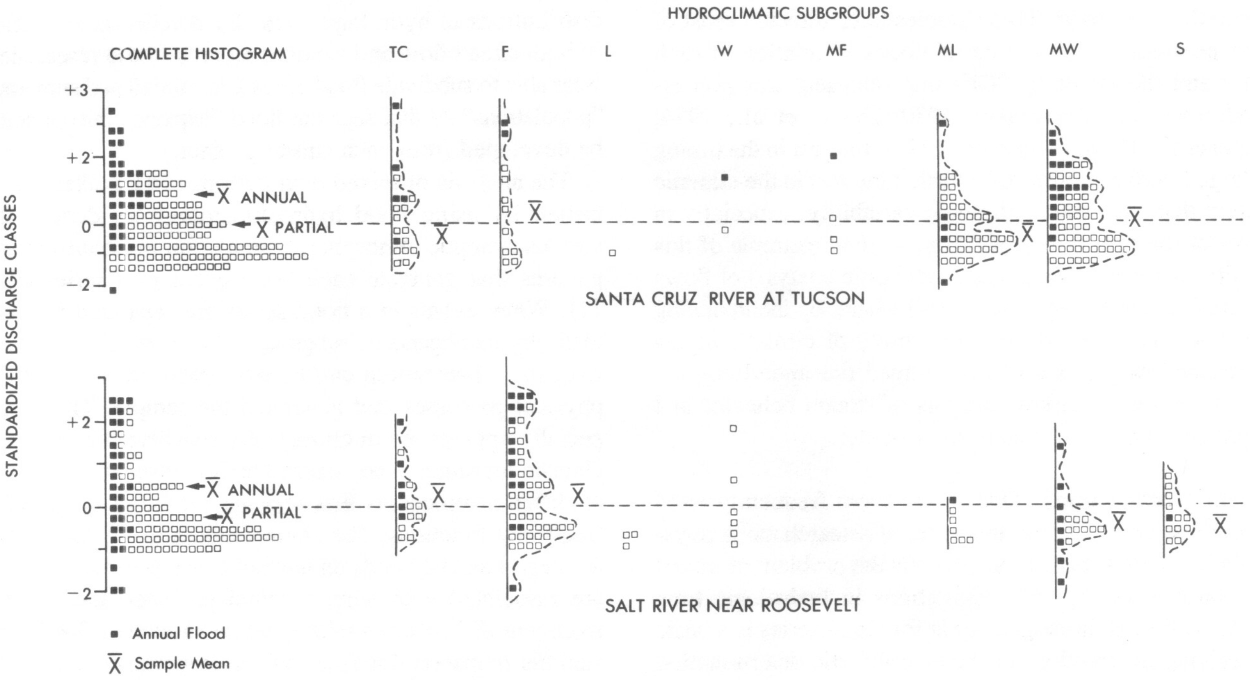

FIGURE 12. Decomposition of two partial-duration flood series into hydroclimatic subgroups to define mixed distributions in the record. The floods were separated into groups on the basis of the atmospheric mechanism that generated each flood: (TC) tropical storm/cutoff low event, (F) frontal passage, (L) local cool season precipitation, (W) widespread nonfrontal cool season precipitation, (MF), (ML), and (MW) "monsoon season" frontal, local, and widespread precipitation, respectively, (S) snowmelt. The flood discharges are in the form of standardized dimensionless z scores. (Source: Hirschboeck, 1987).

time scales, implies that the stationarity assumption may not always be valid. Hence flood time series should also be viewed from the perspective of alternative, nonstationary models that have a hydroclimatic basis.

Standard Flood Time Series Model

When modeling flood time series, the observed record of peak discharges measured at a gauging station over a finite period of time is generally viewed as a sample drawn from the population of all possible floods occurring during an undefinable length of total time (T), which theoretically goes to infinity. The standard model for a time-dependent process is depicted in Figure 13 and is described stochastically as follows:

> Mathematically speaking, a *stochastic process* is a family of random variables $X(t)$ which is a function of time (or other parameters) and whose variate x_t is running along in time t within a range T. Quantitatively, the stochastic process, which may be discrete or continuous, can be sampled continuously or at discrete or uniform intervals of $t = 1, 2, \ldots$, and the values of the sample form a sequence of $x_1, x_2, \ldots$, starting from a certain time and extending for a period of T. This sequence of sampled values is known as a time series. . . .
>
> The random variable $X(t)$ has a certain probability distribution. If this distribution remains constant throughout the

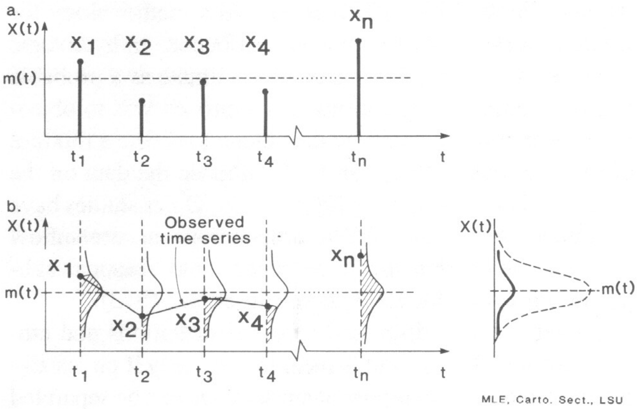

FIGURE 13. The standard stationary stochastic process model for a flood series. (*a*) Generalized version of an observed flood series. (*b*) Conceptual representation of the stationary stochastic process with time invariant mean and variance (modified from Kisiel, 1969a).

> process, the process and the time series are said to be *stationary*. Otherwise they are *nonstationary*. For example, a virgin flow with no significant change in river-basin characteristics or climatic conditions for the period of record is considered as a stationary time series. If it is affected by man's activities in the river basin or nature's large accidental or slow modifications of the rainfall and runoff conditions, the recorded or historical flow is a nonstationary time series. Since a nonstationary process is very complicated mathematically, hydrologic processes are generally treated as stationary.
>
> —(Chow, 1964, p. 8–9)

For the stationary stochastic process in Figure 13 to be valid in a hydroclimatic sense, the overall climatic environment from which floods are generated must remain essentially the same over time so that the probability distributions for the random variable $X(t)$ at each successive t will remain constant. If stationarity holds, interpretation of Figure 13*b* suggests that at certain times, t_n, for example, the observed flood value represents an extremely rare event because it falls well within the uppermost tail of the theoretical distribution of all possible floods at time t_n. Other floods, such as x_2, are much smaller than would be expected on the basis of the theoretical distribution and would be considered unusually low for peak events at time t_2.

Alternative Hydroclimatic Interpretations

Despite the elegance and pervasive use of the stationary stochastic model, when flood events are interpreted hydroclimatically, the validity of the stationarity assumption must be seriously questioned due to the history of variation of regional and global networks of changing meteorological features and circulation patterns. Within the framework of the space–time domain of hydroclimatic activity, three alternative flood series models are likely to be better representations of the actual flooding process over time (Fig. 14). In these nonstationary processes it is clear that the statistical properties of the random variable $X(t)$ differ from one realization of $X(t)$ in time to another. For example, in the time-varying mean model (Fig. 14*a*), flood event x_n, which was previously interpreted as being so rare because of its upper tail location (Fig. 13*b*), must now be interpreted as an event with a high likelihood of being equaled or exceeded, given the new position of the theoretical distribution at time t_n. In the time-varying variance model (Fig. 14*b*), the large x_n and the small x_2 events are no longer located in the extremes of the upper and lower tails of their respective populations as they were in Figure 13*b*. In the model depicting both time-varying mean and variance (Fig. 14*c*), floods x_2 and x_n lie close to the means of their respective populations. Conversely, flood x_4 now reflects an extreme in the lower tail of its theoretical distribution.

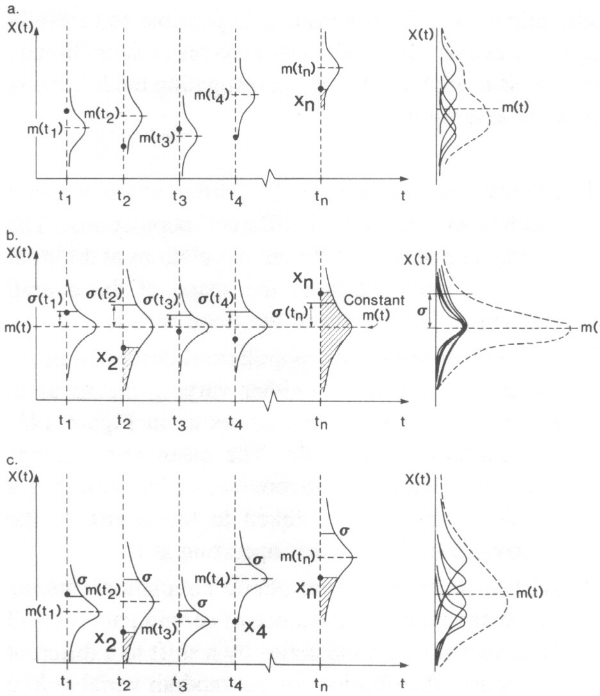

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FIGURE 14. Alternative nonstationary stochastic process models for a flood series. (*a*) Time-varying mean. (*b*) Time-varying variance. (*c*) Time-varying mean and variance. The composite distribution at the right of each time series represents the theoretical distribution for the complete flood series. Although the distributions at each *t* are depicted as normal, skewed distributions could also be substituted into the model (modified from Kisiel, 1969a).

Although not depicted in Figure 14, another aspect of variation in a time series is the tendency for a specific feature, such as the mean, variance, or distribution shape, to persist for a certain time, and then change. In this case the intervals between changes and the times of change themselves become important variables (e.g., Fig. 10).

It is interesting to note that of the four models proposed for a flood series the models in Figure 14*a* and especially Figure 14*c* depict theoretical distributions for the overall flood series that look most like the typical positively skewed flood frequency distributions of many arid, semi-arid, and humid streams. Therefore, although the standard stationary model in Figure 13 is the most easily analyzed, it may not be the best model for studying flood processes in the real world. In fact many stochastic hydrologists concede that, in the physical world, most hydrologic time series are nonstationary with a mean and variance that tend to vary with time (Kisiel, 1969a).

In traditional flood series analyses, because the actual distributions of the random variable $X(t)$ over time are unknown, stationarity and homogeneity have been the most convenient assumptions to make and have eased the mathematics involved in analyzing time series. In a flood hydroclimatic approach, however, it is possible to carefully analyze the events in a flood series in terms of their climatic origins so as to evaluate $X(t)$ by investigating the following alternative assumptions:

1. Floods occurring as a result of different atmospheric mechanisms belong to different populations. The dominance of these different populations at different times, t, will determine the shape of the overall frequency distribution of the flood series.
2. Differences among the populations described in assumption 1 are due to either varying means as in Figure 14*a*, changing variances as in Figure 14*b*, or both as in Figure 14*c*. The mean and variance associated with each theoretical distribution has a physical basis that is linked to the nature of the atmospheric mechanisms operating at t.
3. A shift in general atmospheric circulation patterns or the anomalous persistence of certain patterns will be reflected in a flood series by a shift to a different theoretical distribution for the random variable $X(t)$ in the series.

Although research along these lines is at its early stages, two previously mentioned studies have demonstrated the usefulness of viewing the flood series model from a hydroclimatic perspective to explore the assumptions outlined above.

Assumptions 1 and 2 were examined by grouping flood events generated by similar hydroclimatic mechanisms into climatically homogeneous subsets (Hirschboeck, 1985, 1987). It was found that mixed distributions could be hydroclimatically defined in a flood series and that the shapes of the frequency distributions of different hydroclimatic subgroups had a physical basis that could be linked to the nature of the flood-generating mechanism.

Knox (1983) used dates marking episodic adjustments in large-scale atmospheric circulation patterns to subdivide a flood series into meaningful hydroclimatic episodes. His results, depicted in Figure 10, bear a resemblance to the nonstationary models in Figure 14 and lend support to assumption 3.

Other Applications of Flood Hydroclimatology

Numerous other applications of flood hydroclimatology can be envisioned to analyze flood time series and evaluate basic assumptions on how floods vary over time and space. In standard flood frequency analysis the hydroclimatic approach has potential for examining outliers and determining the usefulness of short flood records for representing long-term flood variability. In regional analysis (Tasker, 1987) hydroclimatology provides an effective means for grouping streams and gauging stations that covary spatially in their response to various climatic inputs.

In the development of physically based stochastic models, hydroclimatology can contribute to an understanding of how the atmosphere and hydrosphere interact at various spatial and temporal scales. Some research along these lines is already in progress; (e.g., see Waymire et al., 1984, who incorporated information on the dynamics of extratropical cyclones into a physically realistic stochastic model of mesoscale rainfall intensity).

Finally, because flood hydroclimatology encompasses long-period climatic variations as well as short-period hydrometeorological events, it provides a climatic framework for meshing paleoflood studies and other aspects of flood geomorphology with the relatively short time scales of gauged flood records. For example, knowledge of the types of circulation features that currently generate floods at a given station (Fig. 12) can be applied to paleoflood data collected for the same station. With the aid of circulation models and climatic reconstructions, the paleoflood event can be linked to the most probable flood-generating mechanism and evaluated on the basis of the modern sample frequency distribution of all floods produced by that mechanism.

CONCLUSION

Flood hydroclimatology analyzes floods as real-world physical events occurring within the context of time-varying climatic conditions and within a spatial framework of local, regional, and global networks of changing atmospheric circulation patterns. Although climate has been incorporated into flood analyses in a variety of ways, given the broad space–time domain of hydroclimatic activity, there is a great need to re-evaluate certain assumptions about how floods vary over time in relation to climate and to reexamine other current issues in flood hydrology from a new hydroclimatic perspective.

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