Hydrology of Floods and Droughts

Climate and Floods

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INTRODUCTION

The climate of the United States is characterized by a diversity of climatic regimes—humid coastal plains and arid desert basins, temperate woodlands and semiarid grasslands, tropical islands and subarctic interiors, and the complex microenvironments present throughout the major mountain ranges of the Nation. Yet, within these diverse climatic regimes, each of the 50 States is subject to flooding on a periodic basis. This article summarizes the role of climate in the occurrence of floods throughout the United States.

Floods are caused by weather phenomena and events that deliver more precipitation to a drainage basin than can be readily absorbed or stored within the basin. The kinds of weather phenomena and events that cause floods include intense convective thunderstorms, tropical storms and hurricanes, extratropical cyclones and frontal passages, and rapid snowmelt. These individual meteorological processes are part of a larger climatic framework that determines (1) the seasonal availability and large-scale delivery pathways of atmospheric moisture, (2) the seasonal frequency, typical locations, and degree of persistence of the weather phenomena that release the delivered moisture, and (3) the seasonal variation of climate-related, land-surface conditions that affect flood runoff, such as antecedent soil moisture or snow cover.

MOISTURE IN THE ATMOSPHERE

The oceans are the primary source for the atmospheric moisture that eventually falls as precipitation to cause a flood. The atmosphere, a temporary reservoir and delivery system for this moisture, evaporates the moisture from the ocean surface and transports it to the continents in the form of precipitable water vapor through the large-scale motions of the general circulation of the atmosphere. Warm air has a greater capacity for retaining water vapor than does cold air; hence, air masses that originate over the warm, tropical parts of oceans evaporate and transport more precipitable water vapor than do air masses that originate over the cold, polar parts of oceans. The average annual precipitable water vapor of the lower atmosphere over the conterminous United States, measured from the land surface to 6 miles above sea level, is shown in figure 22*A*. Also shown in figure 22*A* is the water content at middle altitudes only, between 2 and 6 miles above sea level. Most precipitable water vapor is contained in the lower, warmer parts of the atmosphere. The maximum values of precipitable water vapor are measured near warm oceanic moisture sources, and the minimum values are measured in the mountainous regions of the western conterminous United States.

The greatest influx of precipitable water vapor across the entire conterminous United States occurs in July (fig. 22*B*). During July, the maximum available precipitable water vapor is present in the atmosphere over the southeastern United States, especially over the Gulf Coast States. Even at altitudes higher than 2 miles, the precipitable water vapor in the atmosphere is greatest in July, and at these altitudes, a northward influx of moisture into the western United States is evident. Only at altitudes between 2 and 6 miles above sea level over the Far Northern and Western States does the atmosphere contain less than 0.4 inch of precipitable water vapor during July.

Large-Scale, Moisture-Delivery Pathways

The primary large-scale, moisture-delivery pathways along which low-level precipitable water vapor enters the conterminous United States are determined by the direction of average surface winds at different times during the year. These pathways can be depicted for each season by using simplified streamlines of the average surface winds over North America (fig. 23). In figure 23, generalized pathways are shaded to reflect the average precipitable water vapor in the lower atmosphere over different areas of the continent during each season. At any given time, the dominant pathways over the conterminous United States originate from three distinct air-mass source regions—the Pacific Ocean, the Atlantic Ocean and Gulf of Mexico, and the Arctic region (Bryson and Hare, 1974; Wendland and Bryson, 1981). In addition, in fall and winter, some pathways originate from air masses located over the north-central and eastern United States (Bryson and Hare, 1974; Wendland and Bryson, 1981).

Regionally, the dominant air masses and moisture-delivery pathways shift as the seasons progress. These shifts are important controls of the seasonality of average monthly precipitation and streamflow in the conterminous United States. These shifts also determine the regional flooding regimes of rivers by affecting the timing and magnitude of large influxes of precipitable water vapor that are necessary for intense or prolonged storms.

Moisture Delivery from the Pacific Ocean

A belt of strong westerly winds delivers moisture-laden air from the Pacific Ocean into North America along several pathways that shift with the seasons—as far north as about 60° N. latitude in summer and as far south as about 35° N. latitude in

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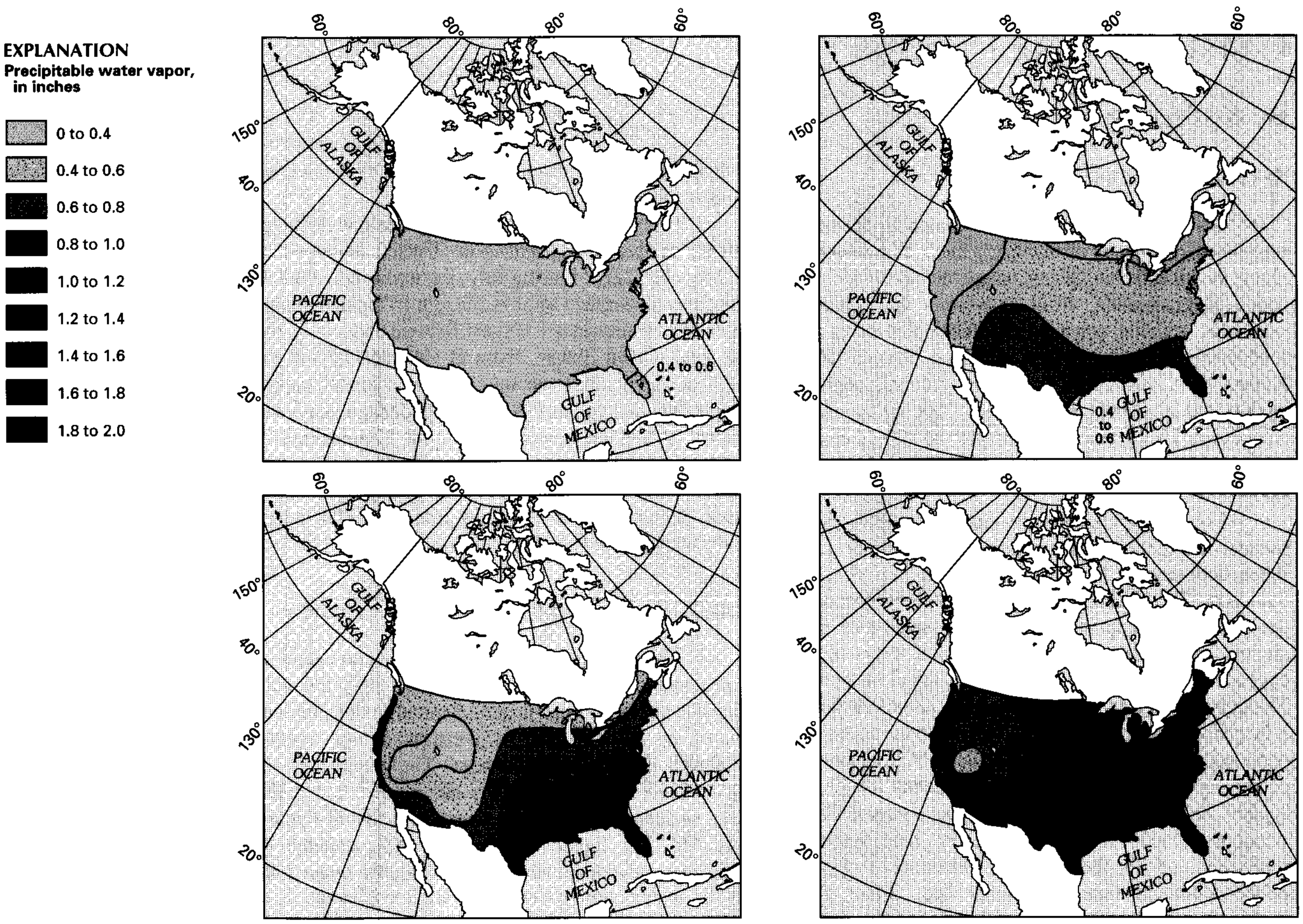


A. **AVERAGE ANNUAL**
Upper map: middle altitudes only, from 2 to 6 miles above sea level
Lower map: lower atmosphere, from land surface to 6 miles above sea level

B. **AVERAGE JULY**
Upper map: middle altitudes only, from 2 to 6 miles above sea level
Lower map: lower atmosphere, from land surface to 6 miles above sea level

Figure 22. Precipitable water vapor in the atmosphere over the conterminous United States. *A*, Average annual. *B*, Average July. (Source: Data from Reitan, 1960.)

winter (fig. 23). Penetration of this Pacific air into the interior of the continent by the westerly winds is impeded at lower atmospheric levels by the mountain ranges along the west coast of the continent. Entry into the interior is possible where the westerly winds are strongest, between about 45° and 50° N. latitude, and where elevations of the mountain ranges are low (Bryson and Hare, 1974). Although air from the Pacific Ocean generally contains substantial precipitable water vapor before the air penetrates deep into the interior, the moisture in the air in the southern pathways, which affects much of the west coast of the United States, is not released abundantly as precipitation due to the proximity of the North Pacific subtropical anticyclone and the stabilizing effect of the cold California Current. These conditions are especially true in summer, which tends to be a dry season along the far West Coast. In the interior southwestern part of the continent, however, localized intense precipitation and flooding can occur during the summer when moisture from the warm, tropical parts of the Pacific Ocean is conveyed northward along the west coast of Mexico into parts of southern California and Arizona. In the middle latitudes of the Far West, major occurrences of intense precipitation and flooding take place in winter, when well-developed, extratropical, cyclonic storms and fronts are conveyed into the region by strong westerly winds that have shifted to more southerly pathways. In the northern latitudes of the West Coast and in Alaska, moisture delivery by pathways from the Pacific Ocean is most effective in late summer and fall.

Air from the Pacific Ocean that crosses the western mountain ranges and enters the north-central and eastern parts of the continent loses much of its precipitable water vapor and has a modified character that contrasts with the cold, dry air from the Arctic and the warm, moist subtropical air from the Atlantic Ocean and Gulf of Mexico. This modified air from the Pacific Ocean has a drying effect when it dominates during the fall, thereby decreasing the likelihood of flooding. During the winter, however, modified air from the Pacific Ocean occasionally can be the source of unseasonably warm temperatures and dry air, which

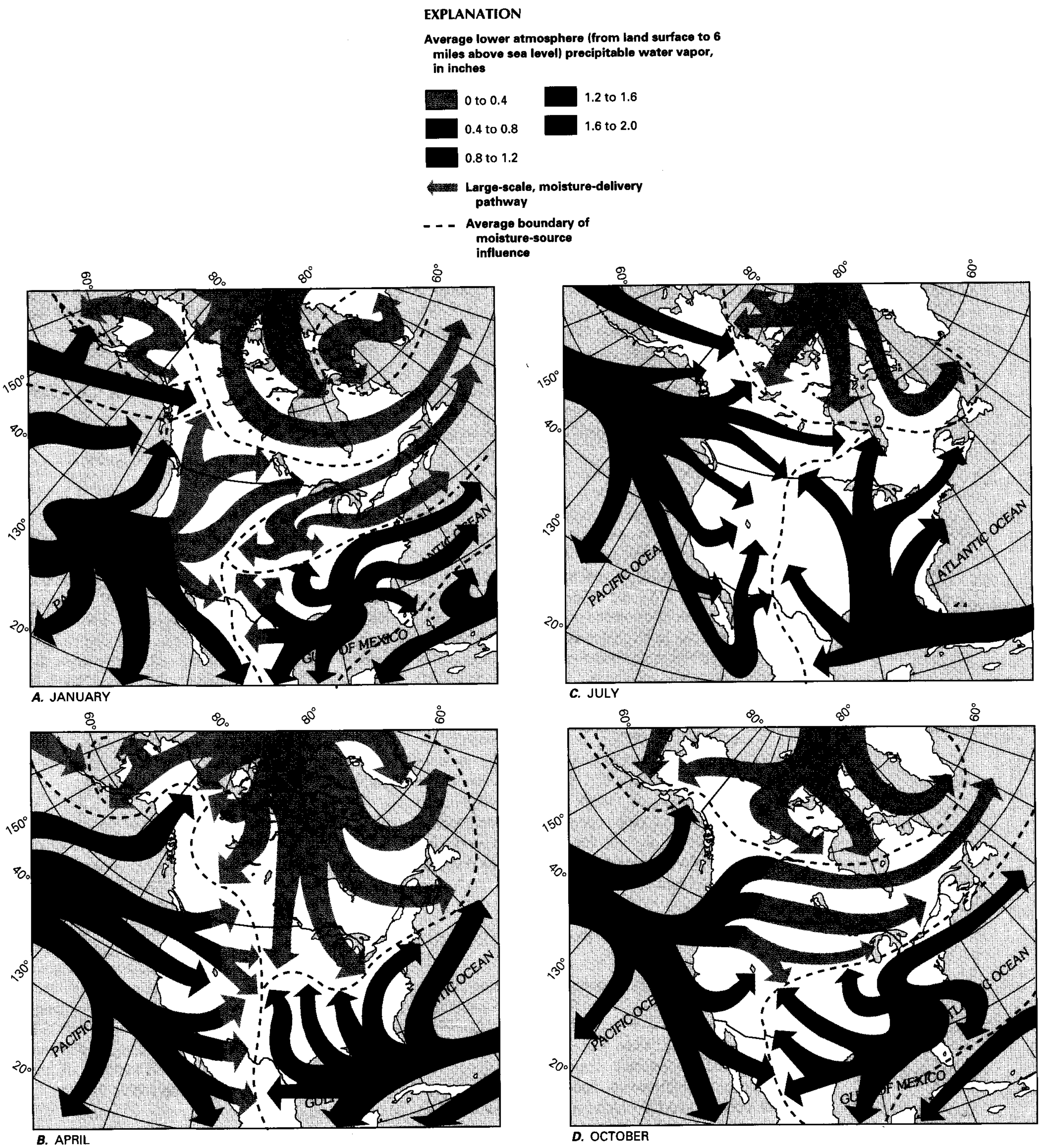


Figure 23. Large-scale, moisture-delivery pathways over North America in four midseason months. *A*, January. *B*, April. *C*, July. *D*, October. (Sources: Pathways data from Bryson and Hare, 1974; precipitable water vapor data from Reitan, 1960.)

result in a temporary thaw that produces significant snowmelt flooding in the Northern States.

Air that is conveyed across the tropical part of the Pacific Ocean by the northeasterly trade winds has a continuous effect on Hawaii. This State receives abundant precipitable water vapor in all months of the year, but most of it is concentrated at low levels in the atmosphere, below 5,000 to 8,000 feet above sea level. Above this altitude, the upper trade winds and high pressure from the North Pacific subtropical anticyclone typically produce an inversion that has a stable layer of dry air above. Light to moderate rain showers are common under these conditions, but occasionally extreme rainfall intensities and subsequent flooding can occur, especially during periods of frontal passage and storm activity in the winter and tropical cyclone activity in the summer and fall.

Moisture Delivery from the Atlantic Ocean and Gulf of Mexico

Moisture-delivery pathways originating in the Atlantic Ocean and Gulf of Mexico are predominant in the eastern and central United States, especially during the spring and summer (fig. 23). These pathways penetrate farthest into the interior of the United States and Canada when the North Atlantic oceanic cell of subtropical high pressure shifts north and slightly west during the warm season and causes warm, humid, and unstable maritime tropical air masses to move onto the continent. The widespread availability of precipitable water vapor from the Atlantic Ocean over most of the Central and Eastern States during the spring and summer can result in large volumes of intense precipitation and subsequent flooding. Occasionally, in summer, pathways originating over the warm waters of the Gulf of Mexico convey moisture-laden air into the Southwestern States, although some of the precipitable water vapor in this air is lost as it crosses the mountain ranges in eastern Mexico and the western United States. During the fall and winter, the influx of air from the Atlantic Ocean and Gulf of Mexico is limited to the Gulf Coast region, and the flood potential is decreased for areas to the north, except during periods of late-season tropical cyclone activity that may occur in September or October.

Moisture Delivery from the Arctic Region

Moisture-delivery pathways that originate in the Arctic region convey cold air that contains minimal precipitable water vapor to the south (fig. 23). When this air converges with warmer and moister air from the Pacific or Atlantic Ocean or the Gulf of Mexico along frontal boundaries, density contrasts between the air masses produce instability and can result in major, extratropical, cyclonic-storm activity and widespread frontal precipitation. During the winter or spring in the Northern States, this precipitation may be in the form of snow that accumulates during the cold season, until warmer air from the Pacific or Atlantic Ocean or the Gulf of Mexico causes the snow to melt. In the Central and Southern States, storm activity along frontal boundaries between air masses of Arctic and non-Arctic origin is a major source of widespread winter rainfall and subsequent flooding.

Modified Air Masses

During the fall and winter, much of the eastern and southeastern United States is dominated by air of Pacific Ocean or Arctic origin that has been extensively modified. This air flows away from a high-pressure area that generally is located over the eastern interior of the continent in fall and the southeastern part of the continent in winter (fig. 23*A*, *D*). Modified air masses that originated in the Pacific Ocean or the Arctic also affect the northern interior of the continent during the fall and winter (fig. 23*A*, *D*) in the belt of strongest westerly winds. The continental modification of this air results in less precipitable water vapor; hence, in the absence of direct northerly and southerly pathway convergence, the interior of the continent remains dry during the fall and winter. In fact, with the exception of areas affected by tropical cyclone activity, fall tends to be the season least prone to widespread precipitation and flooding throughout the conterminous United States.

ATMOSPHERIC PROCESSES THAT RELEASE MOISTURE

Once large volumes of precipitable water vapor are delivered into a region, the release of this moisture from the atmosphere is dependent on the existence of an uplift mechanism that will cool and condense layers of moist air so that cloud development, precipitation, and eventual flooding might result. This uplift can occur through any combination of (1) thermal convection in moist, unstable air, (2) large-scale frontal convergence of contrasting air masses such that a warmer, moister air mass will be forced to rise over a cooler, drier air mass, (3) forced vertical motion in response to perturbations in the upper atmosphere, and (4) orographic lifting, that is, the forced rising of moist air up the slopes of hills and mountains.

Convectional processes tend to have limited areal extent but cause intense precipitation that results in flash floods in small drainage basins. Frontal-convergence processes affect extensive areas, and the resulting precipitation is the predominant cause of floods in large drainage basins. Upper atmosphere perturbations can have a local or widespread effect on precipitation and flooding, depending on the small-scale or large-scale nature of the perturbation. Orographic uplifting also can have a local or widespread effect on precipitation and flooding, depending on the extent and orientation of the topography with respect to prevailing wind directions and the type of precipitation associated with the orographic uplift.

Convectional Processes

Convectional processes that are capable of releasing enough precipitation to cause floods include thermally induced thunderstorms, mesoscale convective systems, and tropical cyclones. In addition, convectional processes also can occur in conjunction with frontal convergence and orographic lifting. The characteristic feature of a strong convectional process is the towering thunderstorm cloud from which exceedingly intense precipitation of short duration can fall.

Extreme precipitation intensities of as much as 1.26 inches in 1 minute (Maryland), 3.9 inches in 14 minutes (Texas), 7 inches in 30 minutes (Ohio), and 12 inches in 42 minutes (Missouri) have been recorded in the United States in association with summer convectional processes (Costa, 1987). Precipitation of such great intensity is delivered at a rate faster than the rate at which it infiltrates the soil; hence, it contributes to surface runoff almost immediately, and commonly results in urban street flooding and flash flooding within small drainage basins. Most thunderstorm cells are of limited areal extent [4 to 40 mi^2 (square miles)], whereas large, convectively induced and maintained thunderstorm clusters, called mesoscale convective complexes, can have areas of 30,000 to 80,000 mi^2. The convectional processes associated with tropical storms and hurricanes can affect areas as large as 400,000 mi^2. The seasonality and geographic distribution of each of these types of convectional processes are discussed in more detail in the following sections.

Thunderstorm Activity

Intense precipitation from thunderstorms is the major cause of flash floods in small drainage basins and is an important component of many instances of widespread, severe flooding. Thunderstorms occur in all 50 States, but their frequency and spatial distribution vary from season to season. The major requirements for severe-thunderstorm development are warm, moist, unstable air and an atmospheric environment that supports low-elevation cloud bases and instability aloft so that clouds can form to great heights. Thunderstorms can develop in homogeneous warm, moist air masses or along fronts. In the former, instability is initiated by local heating, topographic effects, or upper atmosphere perturbations, whereas in the latter, instability is initiated by marked density contrasts between warm and cold air masses.

The average number of days during which thunderstorms develop in the United States varies from season to season (fig. 24), and there is a general relation between the number and geographic distribution of these days and the volume of precipitable water vapor in the lower atmosphere (figs. 22 and 23). Areas where there is an exception to this relation are along the west coast of the conterminous United States and Hawaii, where thunderstorms are infrequent despite an abundance of moist air from the Pacific Ocean. Along the West Coast, the cold California Current and the North Pacific subtropical anticyclone have a stabilizing effect on the atmosphere, whereas in Hawaii, an inversion in the trade winds having a stable, dry layer aloft suppresses thunderstorm development. Nevertheless, when thunderstorms do develop in these areas, the intense precipitation from these storms can cause major flooding, especially when atmospheric uplift and instability are enhanced by orographic effects.

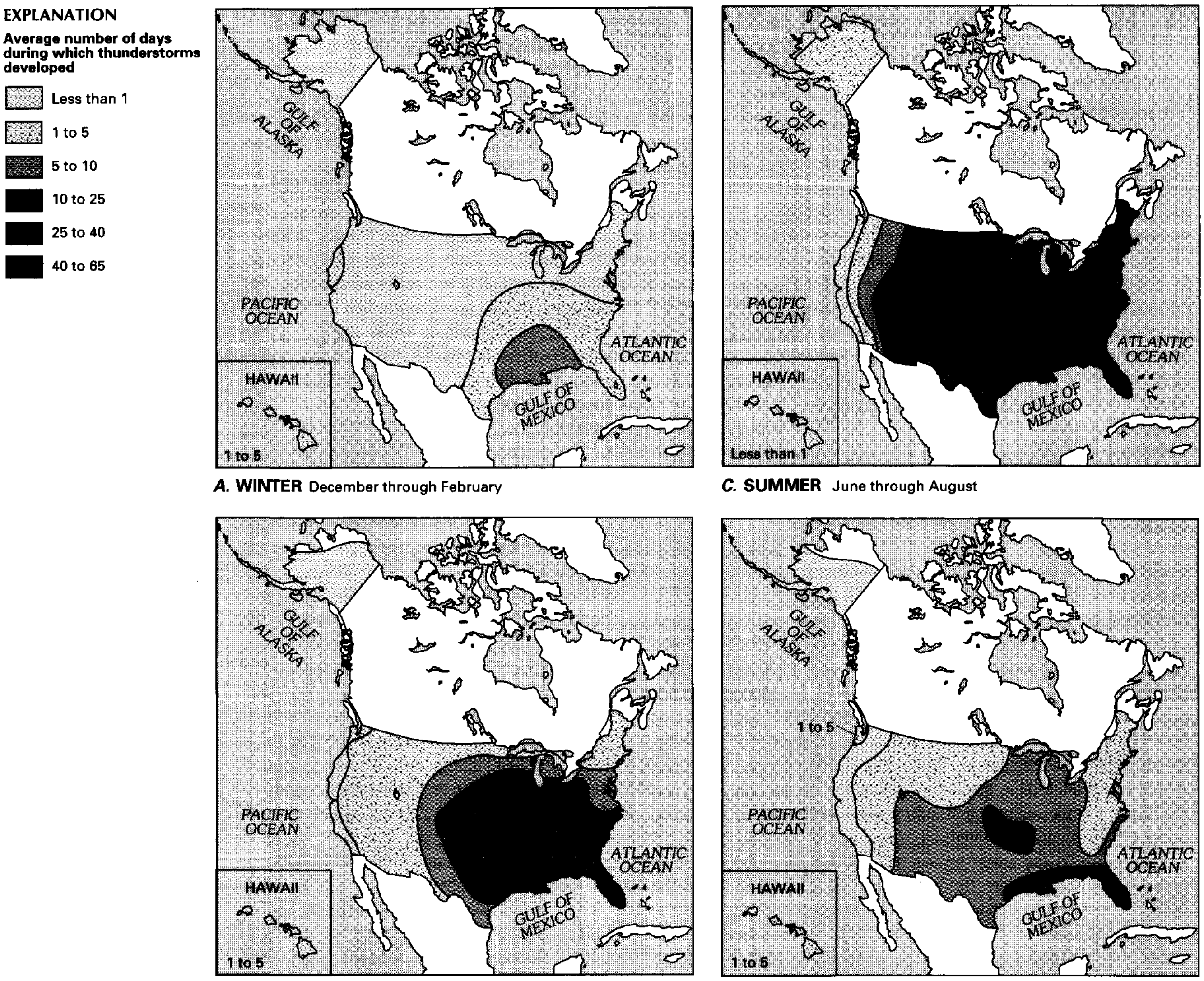
Elsewhere in the United States, the number and geographic distribution of days during which thunderstorms develop varies from a minimum number of days during the winter, when thunderstorm activity is limited to the Gulf Coast region, to a maximum number of days during the summer, when thunderstorm activity occurs throughout most of the country (fig. 24*A*, *C*). The regions most prone to thunderstorm development are the Gulf Coast (all seasons), the Great Plains and the eastern slopes of the mountains just to the west of the Great Plains (spring, fall, and especially summer), and the southwestern deserts and mountains (summer). The winter concentration of thunderstorms in the Gulf Coast region primarily represents squall-line activity associated with fronts, rather than thermally induced thunderstorms that are more typical of summer. Annually, Florida has more days during which thunderstorms develop than does any other State. Thunderstorm development in the summer is especially enhanced along the Florida peninsula when land-surface heating causes sea breezes to move toward the peninsula so that convergence of air from the two coasts is possible. The large number of days during which thunderstorms develop in the Great Plains region is related to a variety of mechanisms, including frontal convergence, upper atmosphere perturbations, and mesoscale convective systems (discussed in the next section). In the mountainous parts of the western and southwestern regions, the forced up-slope movement of moist air during the summer greatly enhances thunderstorm development.

Despite their propensity for producing intense precipitation, most typical thunderstorms do not yield sufficient precipitation to cause major floods. A single storm usually is small, of short duration, and is characterized by several convective cells that develop and decay during an hour or so. Floods are most likely to be caused by precipitation from severe, long-duration thunderstorms that develop to great heights—at times penetrating through an inversion layer to do so. These thunderstorms must have an internal structure that can withstand the dispersing effect of strong winds in the upper atmosphere. Development to the severe stage can be in the form of a single "supercell" thunderstorm, a row of thunderstorms that forms a squall line, or a multicell cluster of developing and decaying thunderstorms (Eagleman, 1983). Due to the limited areal extent of precipitation from single, supercell thunderstorms or small, multicell thunderstorms, flooding caused by the precipitation is localized, but it can be extreme. This condition is especially true when the thunderstorm remains quasi-stationary and is centered directly over a drainage basin or its headwaters or when a slow-moving thunderstorm moves along a path from the headwaters area to the discharge area of a linear drainage basin, thus allowing intense precipitation and resulting runoff to become superimposed on flood waters coming from upstream. On September 14, 1944, in a small drainage basin in Nevada (22.9 mi^2), the latter situation resulted in one of the largest known flash floods for a drainage basin of this size (Glancy and Harmsen, 1975; Costa, 1987). In this instance, and in numerous other instances of major localized flooding in the United States that results from precipitation from thunderstorms, orographic lifting of warm, moist air has been an important component contributing to the severity of the thunderstorms.

Mesoscale Convective Complexes and Systems

Floods also are caused by precipitation from larger scale convective systems known as mesoscale convective complexes (MCC's) and mesoscale convective systems (MCS's). MCC's are huge, highly organized, multiple celled, and convectively induced and maintained thunderstorm systems that are defined on the basis of enhanced-infrared satellite imagery (Maddox, 1980, 1983; Ray, 1986). On this imagery, an MCC appears as a large, circular or oval-shaped region composed of high clouds that gradually become colder and higher toward the center of the system. MCC's are capable of producing substantial flood-causing precipitation because of their large areal extent, equal to or greater than 40,000 mi²; their long duration, 6 to 36 hours; and the severe nature of their weather, which is characterized by multiple and supercell thunderstorms, locally intense precipitation, tornadoes, and lightning. MCC's can be components of larger MCS's. An MCS is any multicell storm or group of interacting storms that is characterized by organized features such as a squall line or thunderstorm cluster (Chappell, 1986). MCC's and MCS's produce widespread and locally intense precipitation that can cause major flash floods, especially if either are slow moving or become quasi-stationary at some time during their duration.

The seasonal and geographic distribution of a 7-year record of MCC's is shown in figure 25. Of the 284 MCC's plotted in figure 25, one-third of them were reported to have produced sufficient precipitation to cause flooding. MCC's are most common during the spring and summer and are concentrated in the Great Plains and Midwestern States. The thunderstorm activity associated with MCC's probably is an important contributor to the large number of days during which thunderstorms develop in the Central States during the spring and summer (fig. 24). The geographic



A. **WINTER** December through February

B. **SPRING** March through May

C. **SUMMER** June through August

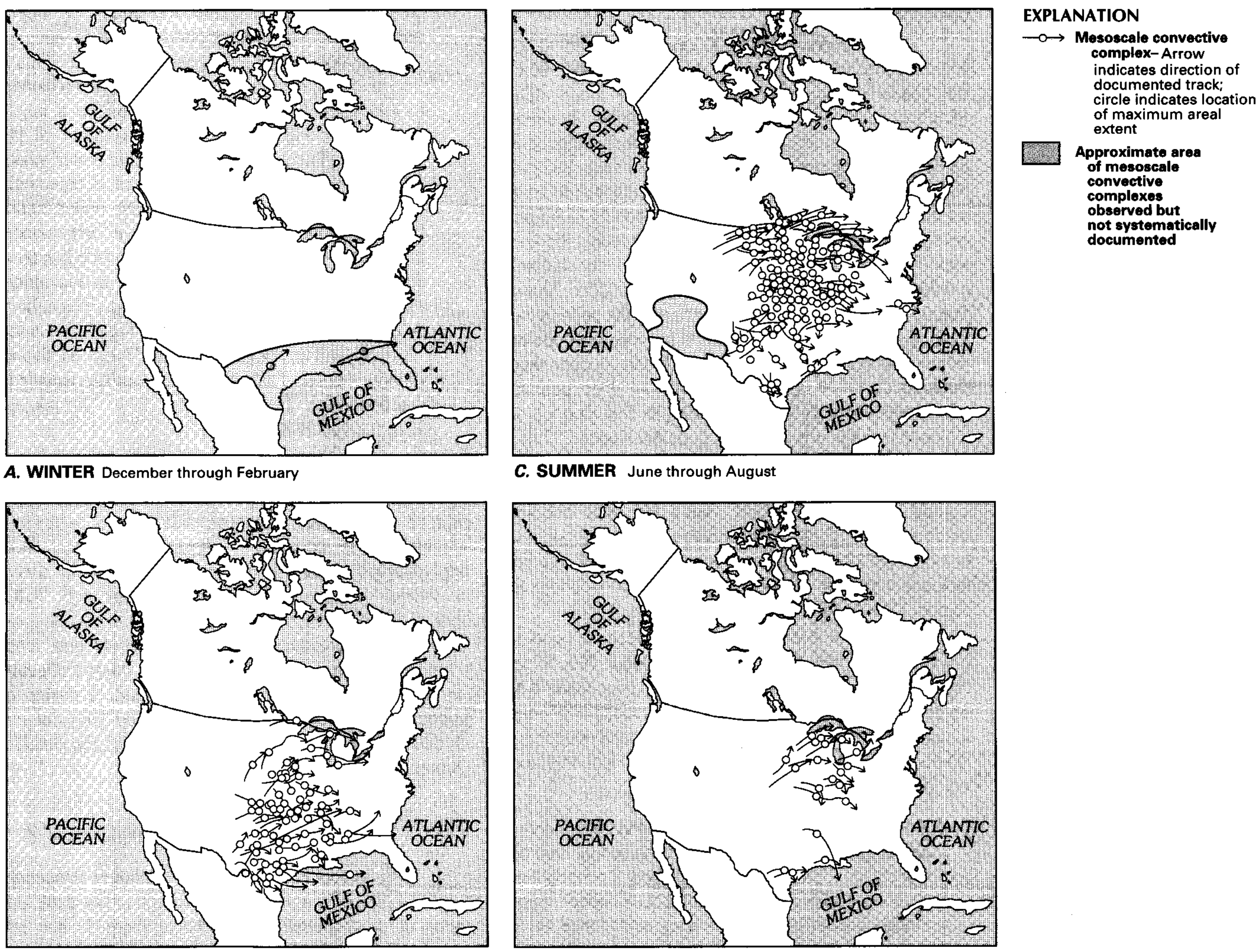
D. **FALL** September through November

Figure 24. Average number of days per season during which thunderstorms developed in the United States, 1951–75. *A*, Winter. *B*, Spring. *C*, Summer. *D*, Fall. (Source: Modified from Court and Griffiths, 1983.)

distribution of MCC's also reflects the seasonal pattern of thunderstorm frequency by having a similar northward progression during the spring and summer. Because of their geographic concentration in the Central and Midwestern States, MCC's do not appear to be dependent principally on orographic effects for their generation or enhancement; however, about one-fourth of the MCC's documented between 1978 and 1986 had their origins in thunderstorm activity that began over the mountains or their eastern slopes just to the west of the Great Plains (Maddox and others, 1986).

MCC's also have been documented during the summer in eastern Mexico (R.A. Maddox, National Oceanic and Atmospheric Administration, oral commun., 1990) and western Mexico (Douglas and others, 1987) and have been observed in the southwestern United States—parts of Arizona, California, Nevada, New Mexico, and Utah (fig. 25)—although there has been no systematic documentation of MCC's on an annual basis for this part of the country (R.A. Maddox, National Oceanic and Atmospheric Administration, oral commun., 1989). MCC's, along with other types of mesoscale convective systems, such as tropical squall lines, produce sufficient precipitation to cause flash flooding during the summer in the deserts of the Southwestern States (Smith and Gall, 1989).

MCS's are not as well defined as are MCC's, yet these large convective systems are equally capable of producing sufficient precipitation to cause flooding in many parts of the United States. Quasi-stationary MCS's, in particular, have been known to produce substantial precipitation that has caused some of the most severe localized flooding known, such as the destructive flood of July 31–August 1, 1976, in the foothills of north-central Colorado (McCain and others, 1979); the flood of June 9-10, 1972, in western South Dakota (Schwarz and others, 1975); and the floods of July 1977 in western Pennsylvania (Hoxit and others, 1982; Chappell, 1986).



***A.* WINTER** December through February

***B.* SPRING** March through May

***C.* SUMMER** June through August

***D.* FALL** September through November

Figure 25. Documented and observed mesoscale convective complexes in North America, by season, during 1978, 1981-82, and 1984-87. *A*, Winter. *B*, Spring. *C*, Summer. *D*, Fall. (Sources: Data from Maddox, 1980; Maddox and others, 1982; Rodgers and Howard, 1983; Augustine and Howard, 1988; R.A. Maddox, National Oceanic and Atmospheric Administration, written commun., 1989.)

Tropical Cyclones

Tropical cyclones are the largest atmospheric features that are induced and maintained primarily by convectional processes. Precipitation from these tropical low-pressure systems, which have diameters of 60 to 600 miles when fully developed, can cause major floods. Easterly waves, tropical depressions, tropical storms, and hurricanes each represent different stages of disturbed tropical weather associated with tropical cyclones. Those tropical cyclones that affect the conterminous United States originate in the western part of the North Atlantic Ocean, the Gulf of Mexico and Caribbean Sea, and the eastern part of the North Pacific Ocean (fig. 26). The point of initial genesis of these cyclones and their season of occurrence are affected principally by the presence of sea-surface temperatures of about 79 degrees Fahrenheit or warmer (Gray, 1979). The official tropical-cyclone season extends from June through October, but the greatest frequency of these cyclones is in late summer and early fall, when sea-surface temperatures tend to be warmest.

The effects of tropical cyclones on local and regional precipitation totals can be substantial. Along the coasts of the Atlantic Ocean and the Gulf of Mexico, precipitation from tropical cyclones contributed as much as 15 percent of the total precipitation from June through October during 1931–60 (Cry, 1967). Most of this precipitation occurred in the months of August and September, when 25 to 45 percent of the total monthly precipitation along the Gulf and Atlantic Coasts was contributed by tropical cyclones (Cry, 1967). In the southwestern United States, tropical cyclones originating in the eastern part of the North Pacific Ocean tend to have an even greater relative affect on precipitation totals during June through October because normal summer and fall precipitation totals are much less in this part of the country, which is more arid than the eastern United States. Several of the greatest precipitation totals ever recorded for individual storms in the southwestern United States have been associated with tropical cyclones, and these precipitation totals have helped to establish all-time records of total monthly precipitation at a number of stations scattered throughout the region (Smith, 1986).

Although floods caused by precipitation from tropical cyclones are infrequent, these floods can represent the largest recorded peaks in a flood time series; hence, these floods are important contributors to estimates of the 100-year and probable-maximum floods. Tropical cyclones can have an effect on flooding in three different ways:

1. As a cyclone approaches land, storm-surge waves and high water levels produced by strong onshore winds can cause severe coastal flooding and shoreline erosion. Extremely damaging coastal floods caused by such waves and water levels occurred during Hurricane Camille in August 1969, when storm surges of 15 to 22 feet above normal sea level were recorded at various locations along the Gulf Coast of Louisiana and Mississippi (Wilson and Hudson, 1969; U.S. Army Corps of Engineers, 1970).
2. After a cyclone has reached land, individual thunderstorms embedded within spiraling cloud bands of the cyclone can produce intense, localized precipitation that causes flash flooding in urban areas and small drainage basins. At the same time, widespread, intense precipitation that is generated by atmospheric instability throughout the extent of the cyclone can cause major riverine flooding in large drainage basins that are located along the path of the cyclone—especially if the cyclone is slow moving, becomes stalled, or reverses direction. The devastating floods during Hurricane Agnes that affected drainage basins throughout the Mid-Atlantic States in late June and early July 1972 were of this type (Bailey and others, 1975).
3. Regardless of whether or not a cyclone reaches land, residual moisture fluxes from any stage of a cyclone—including the dissipating stage—can introduce abnormally large volumes of precipitable water vapor into areas where substantial surface heating, orographic lifting, or upper atmospheric instability can produce intense precipitation sufficient to cause flooding. This is one of the most common ways in which a distant or dissipating tropical cyclone can be a major factor affecting flooding in the interior of the continent. The residual precipitable water vapor from a dissipating tropical cyclone is especially likely to cause flooding when this water vapor is incorporated with that in a preexisting atmospheric disturbance that moves into the area, such as a cutoff low, a front, or an extratropical cyclone. The record-breaking floods in southern Arizona in September 1970 (Tropical Storm Norma) and in October 1983 (Tropical Storm Octave) were of this type, as were the floods in southwestern Texas in June 1954 (Hurricane Alice) (fig. 26*B*).

On the basis of the tracks of previous tropical cyclones, most of the southwestern, south-central, and eastern parts of the conterminous United States are susceptible to occasional extreme flooding from precipitation or storm surges produced by the direct or indirect effects of a tropical cyclone (fig. 26*B*). Hawaii also is vulnerable to severe coastal and riverine flooding by precipitation and storm surges from tropical cyclones originating in the Pacific Ocean; however, Hawaii is not located in a source region of tropical cyclones, and fully developed tropical cyclones are not common in this part of the Pacific Ocean.

LARGE-SCALE ATMOSPHERIC CONVERGENCE

In contrast to thermal-convectional processes within a single homogeneous air mass, the development of widespread precipitation from fronts and extratropical cyclones is dependent on the convergence of air masses of marked density contrast. Precipitation resulting from large-scale atmospheric convergence tends to have a greater geographic extent, less intensity, and a longer duration than does that resulting from thermal-convectional processes. The

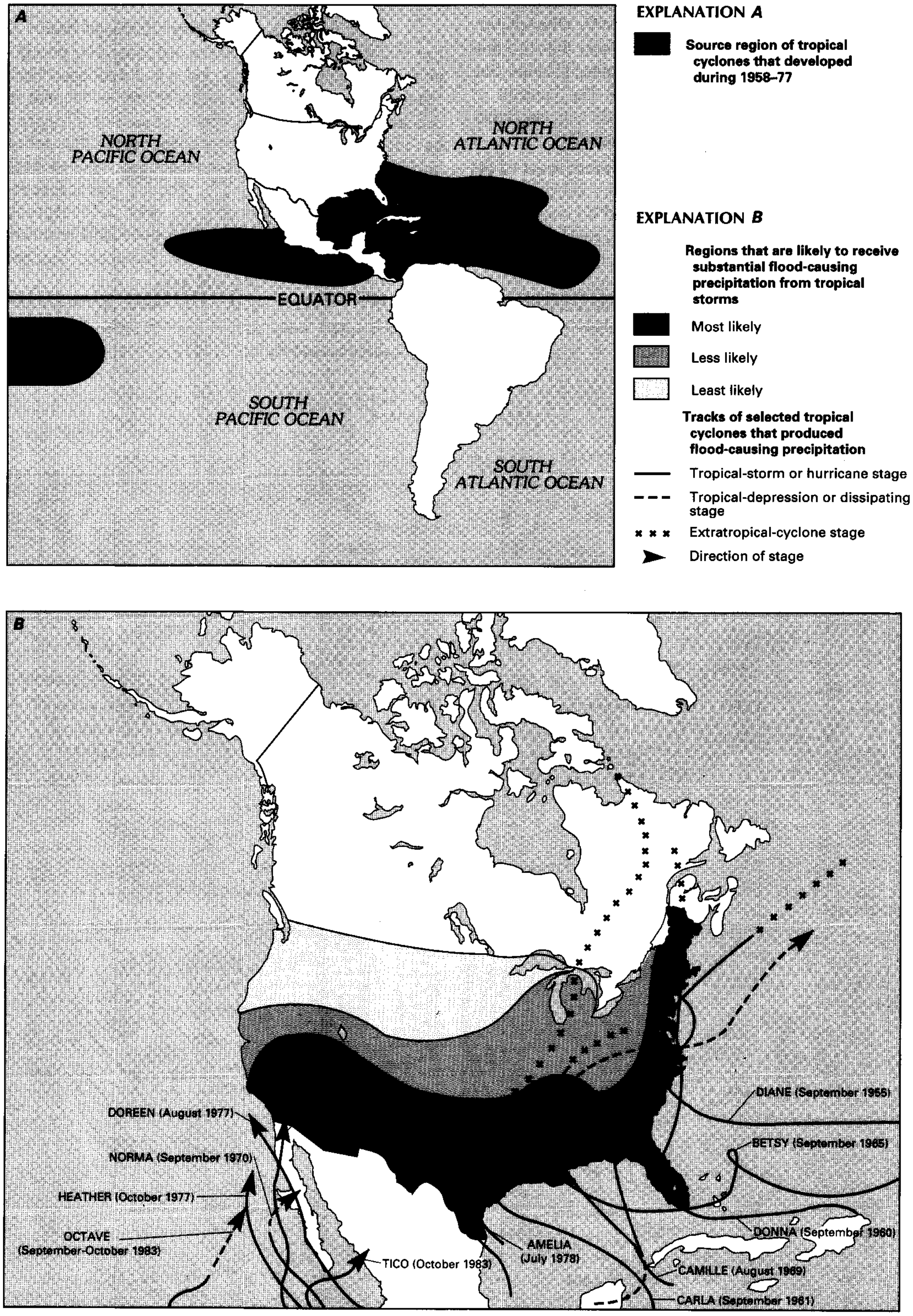


Figure 26. **Tropical cyclones and their effect on flooding in the conterminous United States.** *A*, Source regions of tropical cyclones. *B*, Tracks of selected tropical cyclones that produced flood-causing precipitation or storm surges and regions affected by precipitation from tropical cyclones. (Sources: *A*, Modified from Gray, 1979; *B*, Modified from Cry and others, 1981 (tracks in eastern part of map); Smith, 1986 (tracks in western part of map); Cry, 1967 (darker regions in eastern part of map); Smith, 1986 (darker regions in western part of map); Cry and others, 1981 (lighter regions in eastern part of map); Court, 1980 (lighter regions in western part of map).)

presence of converging air masses, however, can enhance atmospheric instability that induces localized thermal-convectional processes; hence, it is common for frontal activity to be characterized by widespread, moderate precipitation due to large-scale atmospheric convergence and localized, intense precipitation due to thunderstorms or squall lines in the vicinity of the front. When this occurs, large-scale riverine flooding and local flash flooding are possible.

Due to its middle-latitude location, most of the conterminous United States underlies zones of convergence between polar and tropical air masses; the location of these zones varies from season to season (fig. 23). Specific flood-causing processes that are associated with large-scale atmospheric convergence are extratropical cyclones and their associated fronts and wind patterns in the upper atmosphere that enhance convergence and instability near the land surface.

Extratropical Cyclones and Their Associated Fronts

Most major floods in large drainage basins in the conterminous United States are caused by precipitation from extratropical cyclones and their associated fronts. Systematic observations of the movement of extratropical cyclones and fronts across North America have identified a series of preferred tracks that define regions most susceptible to repeated passages of these cyclones and fronts (fig. 27). These preferred extratropical cyclone tracks shift to their southernmost trajectories in the winter and to their northernmost trajectories in the summer and have intermediate trajectories in the spring and fall.

In the winter, virtually all States in the conterminous United States are, at least in part, susceptible to flooding caused by precipitation from extratropical

EXPLANATION

Area in which fronts associated with extratropical cyclones occur more than 50 percent of the time during the winter (December through February) and the summer (June through August)

Primary track of extratropical cyclones—x indicates center of cyclone genesis. Arrow indicates direction

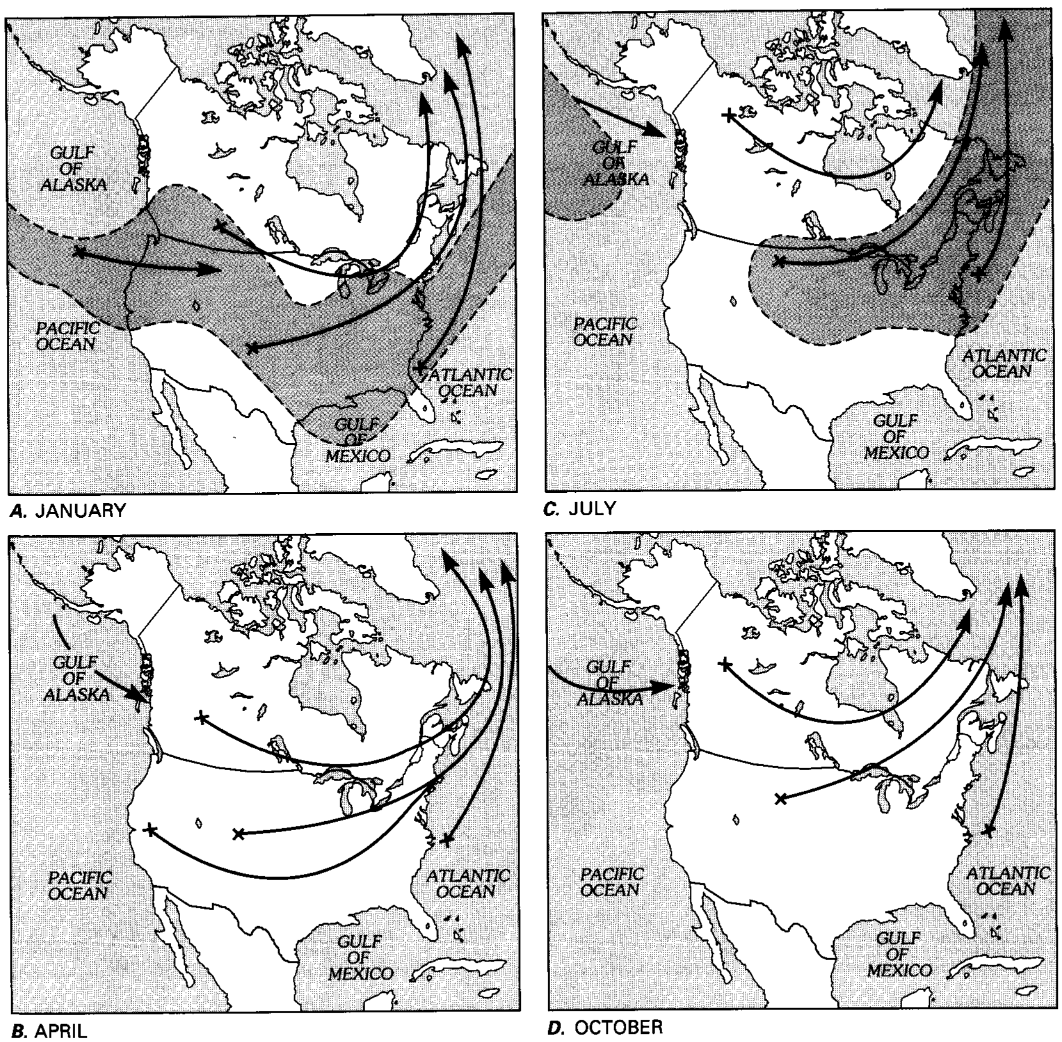


Figure 27. Primary tracks of extratropical cyclones in North America for four midseason months based on frequency of extratropical cyclones during 1951–70. *A*, January. *B*, April. *C*, July. *D*, October. (Sources: Modified from Reitan, 1974 (primary tracks of extratropical cyclones) and Reed, 1960 (areas of fronts).)

cyclones and their associated fronts (fig. 27*A*). Extratropical cyclones from the Pacific Ocean associated with the Aleutian Low storm track successively enter the Northwestern States and bring rain to lower elevations and snow to higher elevations—some of which can contribute to snowmelt flooding during thaws. In the Northeastern States, substantial winter precipitation results from extratropical cyclones that originate in Alberta and Colorado. In the higher elevations of the Northeastern States, deep snow can accumulate, due in part to snow squalls generated by the thermal effects of the Great Lakes. This snow accumulation can result in flooding during thaws or periods of warmer rainfall. In the winter, East Coast States from Georgia to Maine are susceptible to flooding from intense precipitation and coastal storm surges produced by extratropical cyclones that track northeastward along the Atlantic seaboard. Also in the winter, Gulf Coast States experience flooding due to the frequent presence of fronts in the region. In this region, cold fronts in the winter commonly are accompanied by thunderstorms that can produce intense precipitation in the form of rain. In addition, stationary fronts tend to be alined with the Gulf Coast and commonly produce widespread, persistent rain that saturates the soil and increases the likelihood of flooding.

In the spring, extratropical cyclones are quite active, and their trajectories shift slightly northward (fig. 27*B*). Extratropical cyclones that traverse the Southwestern and South-Central States become numerous in late winter and early spring, and frontal passages associated with these cyclones can produce substantial rainfall or late-season snowfall from the mountainous regions of the West all the way to the Northeast Coast. The other extratropical-cyclone tracks of spring are similar to those of winter but are shifted slightly to the north. The density contrasts between converging air masses are much greater in the spring, however, and greater volumes of precipitable water vapor are available in spring than in winter. These factors combine with the presence of saturated soil, frozen ground, and rapid snowmelt to make spring the season that has the greatest flooding potential in many areas of the conterminous United States.

During the summer, most extratropical cyclonic activity shifts to the Northern States and Canada and to the northeastern seaboard (fig. 27*C*). Intense precipitation from convective thunderstorms associated with these cyclones and fronts can cause floods, especially when the precipitable water-vapor content of the atmosphere is unusually large and when fronts or low-pressure centers move slowly or become stalled.

In the fall, extratropical-cyclone tracks are similar to those of summer but are shifted slightly to the south (fig. 27*D*). Northern-latitude extratropical cyclones are quite active during this season, but because the moisture content of the atmosphere is less than in the summer and soil-moisture storage has been depleted, flooding is less common than in the summer. An exception occurs in the far Northwestern States and Alaska, where extratropical cyclonic activity in the Gulf of Alaska is at a maximum. Here, strong extratropical cyclones from the North Pacific Ocean can produce widespread precipitation that may become locally intensified through orographic effects. Storm surges also can cause flooding along low-lying areas of the Alaskan coast.

Precipitation-Enhancing, Upper Atmospheric Air Patterns

The development and movement of extratropical cyclones and their associated fronts are related to large-scale convergence and divergence of strong winds in the overlying upper atmosphere. These strong winds have circulation patterns that vary in response to pressure and temperature gradients in the atmosphere. The fastest upper atmospheric winds, called jet streams, tend to overlie marked atmospheric temperature and density discontinuities near the surface of the Earth, especially those discontinuities that occur along frontal boundaries. The general direction of movement over North America is from west to east, but a sinuous movement pattern is typical, characterized by wave-like southerly and northerly components of wind direction. This sinuous movement of air in the upper atmosphere forms troughs of low pressure and ridges of high pressure that normally progress eastward from day to day. When this progression is stalled or blocked, the trough-and-ridge positions can remain quasi-stationary for several days and cause extratropical cyclones and associated fronts near the surface of the Earth to also become similarly quasi-stationary (fig. 28*A*). Under these conditions, the potential for severe flooding, such as occurred in April 1983 in Louisiana (fig. 28*A*), is great because prolonged precipitation is possible along the stalled front and because intense convective showers can develop repeatedly along squall lines in the unstable air in the vicinity of the front. A related situation that is likely to cause floods is the frequent recurrence of precipitation resulting from the repeated development of a trough-and-ridge pattern in approximately the same location during an extended period of several weeks or months. The precipitation that caused the severe spring floods of 1973 in the Mississippi River basin was a result of these conditions (Chin and others, 1975).

Another upper atmospheric air pattern that can produce flood-causing precipitation is the cutoff low (fig. 28*B*). This low is an upper atmospheric low-pressure system that originates as part of a trough but then becomes displaced to the south and is cut off from the main west-to-east component of wind direction. Cutoff lows may persist for several days in approximately the same location, especially if they are flanked by blocking ridges of high pressure to the west or east. When stalled in this manner, cutoff lows can induce atmospheric instability and precipitation near the surface of the Earth and can slow the eastward progression of fronts. The cutoff low shown in figure 28*B* was associated with flooding in east-central Colorado.

Pulses of intense precipitation caused by the movement of small-scale, short-wave troughs of low pressure through the large-scale, upper atmospheric troughs or ridges also are potential producers of flood-causing precipitation (fig. 28*C*). Many severe flash floods in the Western and Central States have been associated with these short-wave troughs, including

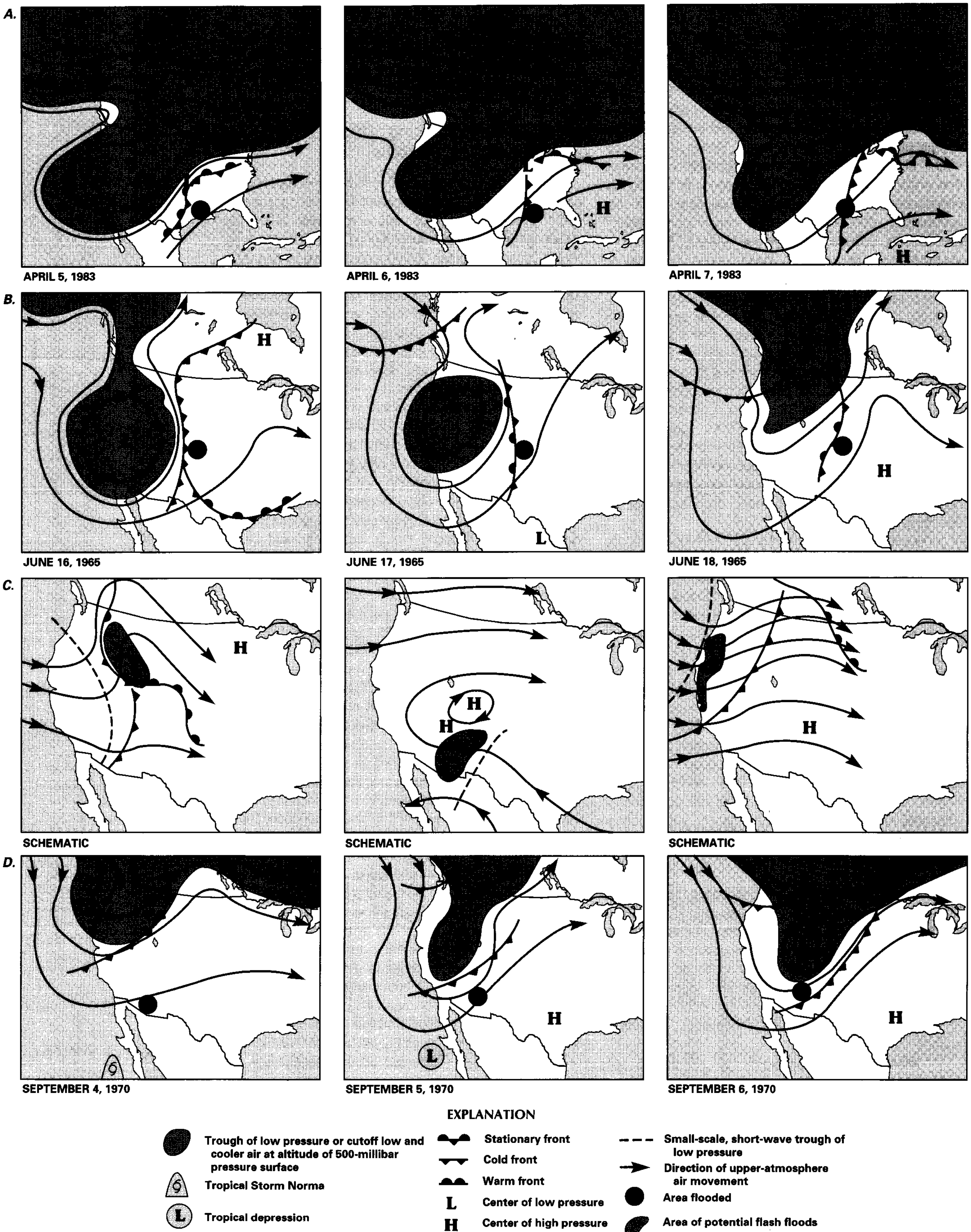


Figure 28. (see caption on facing page)

several of the largest rainfall-runoff floods ever recorded in the United States (Maddox and others, 1979, 1980; Hirschboeck, 1987a).

Commonly, a precipitation-enhancing upper-atmospheric air pattern will occur in conjunction with other precipitation-producing meteorological features, and an extreme or catastrophic flood will ensue. Several such floods have occurred in the Southwestern States when moisture from dissipating tropical cyclones, which originated in the Pacific Ocean, became incorporated into cutoff lows, small-scale, short-wave troughs of low pressure, or slow-moving fronts near the surface of the Earth (fig. 28*D*). During the 3 days shown in figure 28*D*, moisture from dissipating Tropical Storm Norma interacted with an upper atmospheric cutoff low and a cold front to produce substantial precipitation that caused flooding in central Arizona. In the Central and Eastern States, floods caused by precipitation from the interaction of similar, multiple meteorological features have occurred, such as the floods of August 1978 in central Texas that were initiated by precipitation from remnants of Tropical Storm Amelia and compounded by precipitation caused by other lower and upper atmospheric meteorological factors (Schroeder and others, 1987). Another multiple-feature interaction that is typical of the eastern United States is the merging of a tropical cyclone with an upper atmospheric trough of low pressure and its subsequent transformation into an extratropical cyclone. This occurred during Hurricanes Agnes, Carla, and Betsy (fig. 26*B*).

OROGRAPHIC LIFTING

In mountainous and hilly terrain, the release of moisture from the atmosphere by localized thermal convection, large-scale frontal convergence, or upper-air perturbations can be augmented by the process of orographic lifting. Orographic lifting is the forced ascent of an air current caused by its passage up and over a topographic barrier. Moist air that is lifted in this manner can cool sufficiently so that clouds will form and release some of the moisture as precipitation. Precipitation usually is greater at high elevations than on lowlands because of this process. Clouds and precipitation resulting from orographic lifting tend to be concentrated on the windward slopes of topographic barriers, so that windward slopes often are wet whereas the lee sides of slopes often are quite dry. Precipitation from orographic lifting can be locally intense, but it usually takes the form of moderate rain or snow that occurs regularly and persistently over specified areas and often yields extremely high totals of annual precipitation. When orographic lifting occurs in combination with other processes that release moisture in the atmosphere, substantial precipitation can result to produce a flood.

Orographically enhanced precipitation can occur wherever there are mountains or irregular terrain but is most common in regions where mountain ranges lie perpendicular to the direction of prevailing winds that transport moisture-laden air. In the eastern part of the conterminous United States, a moderate orographic effect occurs when air from the Atlantic Ocean or Gulf of Mexico is forced up the foothills and slopes of the mountainous terrain that extends from Tennessee to Maine. In the western part of the conterminous United States, the greatest orographic enhancement of precipitation occurs in the mountain ranges that parallel the west coasts of Washington, Oregon, and northern California and that lie in the path of westerly winds from the Pacific Ocean. In Alaska, orographically enhanced precipitation occurs where air currents from the Pacific Ocean move onshore and up the slopes of coastal mountain ranges, especially along the southern coast and in the southeastern panhandle region of the State. In Hawaii, steep, windward slopes that are perpendicular to the prevailing northeasterly trade winds receive abundant precipitation, whereas the lee sides of these slopes are often quite dry.

Orographic lifting can be a factor in the occurrence of floods in several ways. Local flash floods are often the result of convective precipitation that has been orographically enhanced. The ascent of warm, moist, unstable air up the slopes of hills and mountains supports and enhances the development of severe thunderstorm cells that can yield substantial rainfall. Steep-sided valleys that are open to the inflow of moisture-laden winds can funnel moist air up the valley to the headwater area of a drainage basin. This topographically forced atmospheric convergence enhances instability in the air and promotes the development of clouds and heavy precipitation over the headwater area. In these instances, the terrain sometimes has an anchoring effect on a developing severe storm and causes the storm to remain quasi-stationary, while one thunderstorm cell after another is generated in roughly the same location. Precipitation from such a storm can be excessive and lead to severe flooding in small drainage basins. The destructive flash floods of June 9-10, 1972, in southwestern South Dakota (Schwarz and others, 1975) and July 31- August 1, 1976, in central Colorado (McCain and others, 1979) were floods caused by intense precipitation that was enhanced by orographic lifting.

Orographic lifting can be an important factor in the occurrence of floods even in regions that do not have major mountain ranges. When abundant moisture is present in the air and other flood-causing meteorological processes are active, orographic lifting over hilly terrain often combines with these processes and enhances the development of thunderstorms that produce excessive precipitation. The floods of August 1978 in central Texas were of this type (Schroeder and others, 1987).

Orographic lifting also has an influence on widespread, regional flooding. The persistence and regularity of orographically enhanced precipitation in certain areas can make these areas more susceptible

Figure 28. Precipitation-enhancing, upper atmospheric air patterns over various parts of North America. *A*, Quasi-stationary trough-and-ridge patterns. *B*, Development and dissipation of a cutoff low. *C*, Movement of small-scale, short-wave troughs of low pressure through large-scale, upper atmospheric air patterns. *D*, Multiple meteorologic features interacting with upper atmospheric air patterns. (Sources: *A*, Muller and Faiers, 1984. *B*, Hansen and others, 1988. *C*, Maddox and others, 1980. *D*, Hansen and Schwarz, 1981.)

to flooding because soils are more likely to stay close to saturation in such regions. Furthermore, many areas dominated by orographic lifting lie in the path of persistent storm tracks. In these regions, the passage of extratropical cyclones and their associated fronts can deliver widespread precipitation which, when locally enhanced and intensified by orographic lifting, can cause flooding in many drainage basins over a large area. The floods of December 1964–January 1965 in northern California were of this type (Waananen and others, 1971). Finally, winter precipitation in mountainous regions where orographic lifting is active usually results in the accumulation of extremely great snow depths at high altitudes. Spring snowmelt runoff from these areas can cause widespread flooding, especially during periods of rapid warming and when rain falling on snow accelerates the snowmelt process.

ANTECEDENT LAND-SURFACE CONDITIONS

Even the most intense precipitation produced by some of the processes described above might or might not cause a flood, depending on the antecedent conditions of the land surface that affect the infiltration of the precipitation. Extensively urbanized areas flood easily because of the decreased infiltration capacity of the land surface resulting from buildings, paved streets and parking lots, and sidewalks. Furthermore, areas that have steep slopes, sparse vegetation, thin or almost impermeable soils, or any combination of these characteristics have enhanced runoff because of limited infiltration. Climate also is a factor in determining the flood potential of a given area because climate controls the seasonal soil-moisture cycle and the presence of snow cover and frozen ground.

Soil Moisture

When a soil has a substantial infiltration capacity, it can absorb all but the most prolonged or intense precipitation, thereby limiting excessive surface runoff. Once the soil is saturated, however, even light to moderate precipitation will become surface runoff, and the potential for flooding increases. The volume of moisture held in a soil at any given time is controlled climatically by the difference between precipitation that infiltrates the soil and evapotranspiration that removes moisture from the soil. The relation between these two processes varies geographically and seasonally. Precipitation varies in response to the moisture-delivery pathways and meteorological processes discussed earlier. Evapotranspiration varies in response to available solar and heat energy and is greatest during the summer, when days are longest and temperatures are highest. Evapotranspiration is least during the winter, especially at northern latitudes, where days are short and temperatures are low.

In most areas of the United States, the volume of stored soil moisture is greatest during the late winter and early spring, at the end of the period of least evapotranspiration (fig. 29). Conversely, due to substantial evapotranspiration in the summer, moisture stored in the soil is least during the late summer and early fall throughout much of the Nation. This relation is true even in regions that have substantial precipitation in the summer. [For additional information on evapotranspiration, see article "Evapotranspiration and Droughts" in this volume.]

These seasonal fluctuations in soil-moisture storage determine the susceptibility of an area to flooding at different times during the year (fig. 29). In most parts of the United States, the flooding potential from a storm of a given magnitude is greatest in the late winter and early spring and least in the late summer and early fall.

Snow Cover, Frozen Ground, and Snowmelt

Other antecedent land-surface conditions that strongly affect the susceptibility of an area to flooding are the presence of frozen ground (fig. 30*A*), the depth of snow accumulated on the ground (fig. 30*B*), and the water equivalent of the snow. Climatic conditions that contribute to the likelihood of flooding due to snowmelt are a long winter season during which frequent and substantial snowfalls accumulate; severely low winter temperatures that freeze the ground and, thus, inhibit infiltration; the occurrence of rapid midwinter or spring thaws; and periods of rain falling on snow that accelerate the snowmelt process.

The average annual snow depths in the conterminous United States (fig. 30*B*) are greatest in the North-Central States, the Northeastern States, and the high mountainous areas of the Western States—especially in the far Northwestern States, where the maximum single-season snowfall ever recorded in North America (1,120 inches) was recorded on Mt. Ranier, Wash., during the winter of 1971–72. In Alaska, average annual snow depths are greatest in the mountains of the southeastern panhandle and the south-central part of the State.

Snowpacks vary in density, crystalline structure, and liquid-water equivalent, but predictions of snowmelt runoff are possible, and statistical relations have been developed to provide estimates of the maximum water equivalent of snow cover in the north-central conterminous United States (U.S. Weather Bureau, 1964). This region contributes substantial runoff to the annual peak flows of the upper Mississippi River basin and its northern tributaries. In the mountainous Western States, prediction of flooding due to snowmelt is more complex due to altitudinal variations in precipitation and redistribution of snow by wind and avalanches (Meier, 1986).

Rain falling on snow is a critical factor affecting flood development and can produce some of the largest snowmelt-related floods. These floods are especially common in the coastal mountain regions of the Northwestern States, where substantial rain from intense cyclonic storms frequently falls on shallow snow accumulations during the fall months (Church, 1988). In other parts of the country that are covered with snow for long periods, these floods commonly occur in the spring or during midwinter thaws, when frozen ground may exacerbate the problem.

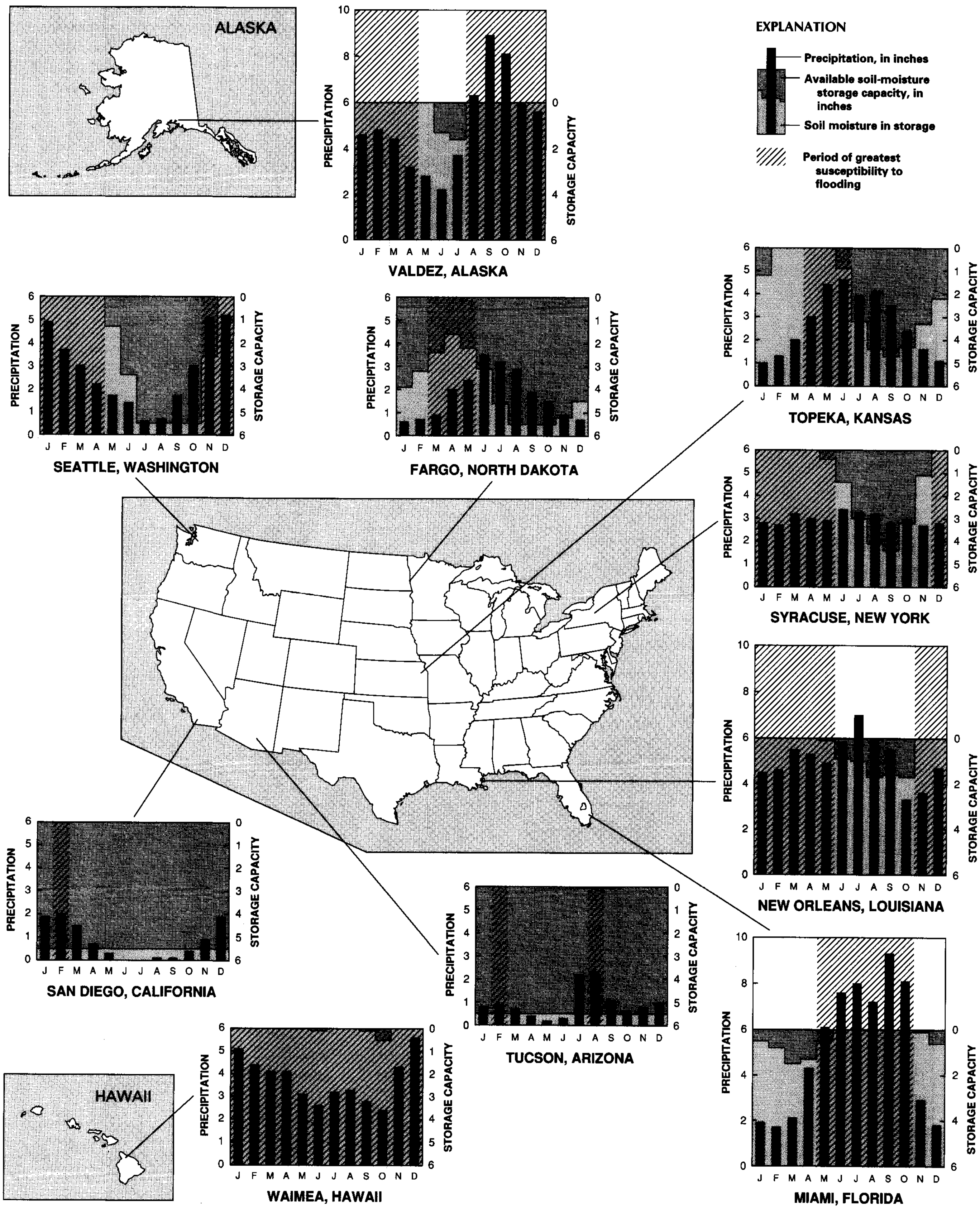


Figure 29. Effects of average monthly precipitation and soil moisture on susceptibility to flooding at selected locations in the United States. (Source: Data from Mather, 1964.)

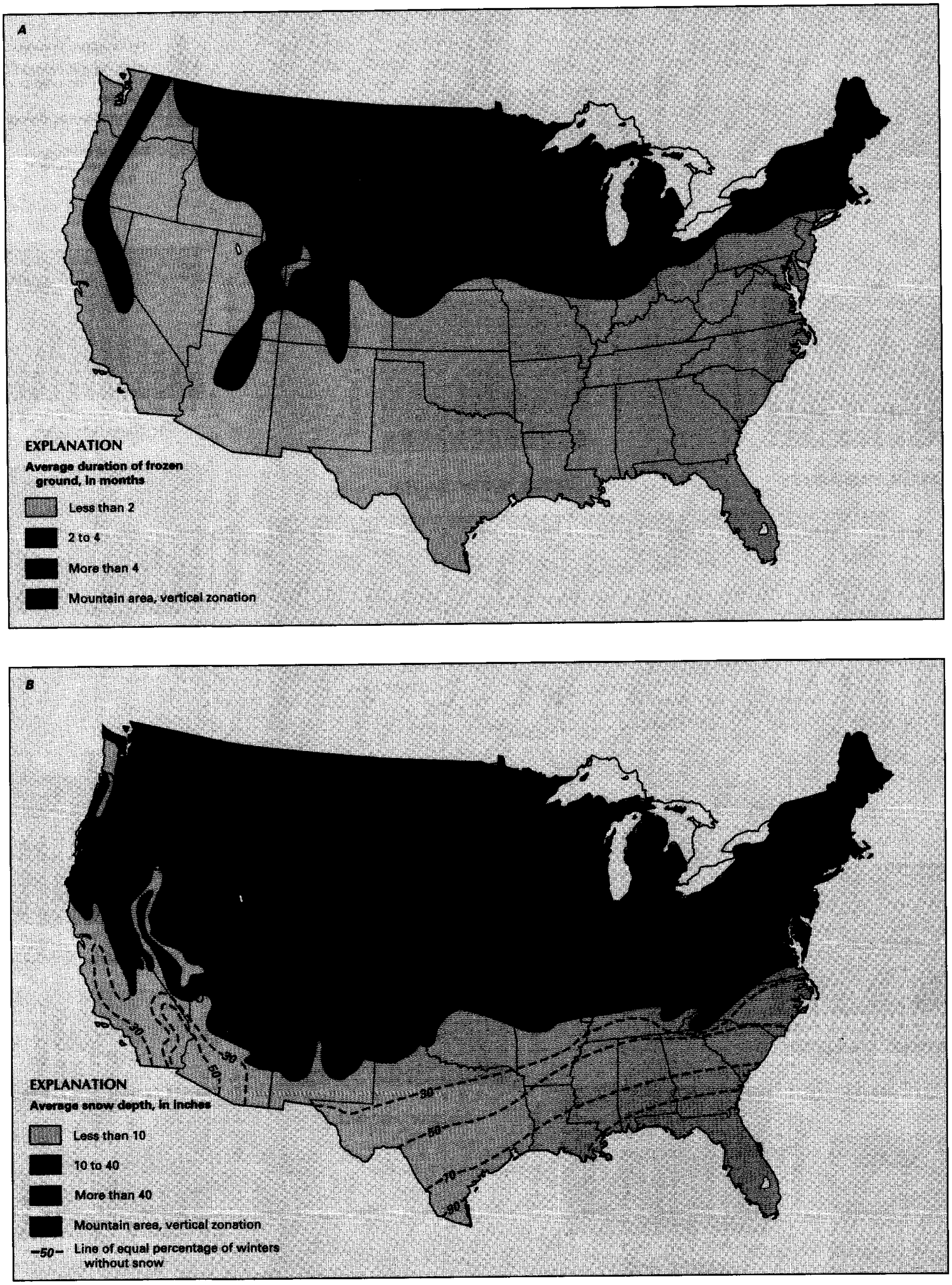


Figure 30. Average duration of frozen ground (*A*) and average snow depth (*B*) in the conterminous United States. (Source: Data from Rabenhorst, 1981.)

An abrupt warming after a long period of cold weather commonly is the trigger that induces a snowmelt flood. Conversely, a gradual warming slows the melting process and distributes runoff throughout a much longer period, thus lowering the flood peak. Rapid warmings or thaws occur most often when upper atmospheric troughs and ridges are subject to abrupt east-west shifts.

The climate also affects another form of cold-season flooding—that due to river damming caused by ice when the ice begins to break up during a thaw. Persistent fair weather and a gradual warming during the spring will decrease the likelihood of a major ice jam on a large river because the ice becomes weakened and breaks up easily without jamming when major runoff from upstream reaches the ice-covered part of the river. In contrast, a rapid warming, combined with rain, increases the likelihood of creating a serious ice jam when large volumes of runoff from upstream encounter relatively strong ice (Church, 1988).

MIXED POPULATIONS OF FLOODS

The previous sections of this article have illustrated the variety of climatic processes that cause floods in the United States. An important reason for understanding these processes is that a better knowledge of the processes may improve predictions of future flooding.

Floods caused by distinctly different climatic processes commonly have distinctly different magnitude and frequency relations. A variety of studies have examined the nature of these differences by separating flood data for a station into two or more populations on the basis of the climatic causes of the floods (U.S. Army Corps of Engineers, 1958; Elliott and others, 1982; Jarrett and Costa, 1982; Waylen and Woo, 1982; Hirschboeck, 1987b). Results of these studies for different regions have indicated that floods caused only by snowmelt, by rain on snow, and only by rain form distinct populations; floods caused by rain on snow or only by rain tend to have larger magnitudes than do floods caused only by snowmelt. In parts of the arid Southwest, floods caused by precipitation from frontal passages in the winter tend to be larger than floods caused by precipitation from convectional storms in the summer. In the Southwest and Northeast, floods caused by precipitation from tropical cyclones tend to have a greater magnitude than do floods caused by precipitation from storms other than tropical cyclones. Floods caused by precipitation from tropical cyclones commonly include the peak flow of record. By defining regions where climatically separated flood populations are distinct, and by effectively applying appropriate statistical procedures to compute flood probabilities from mixed populations, hydrologists generally can determine more accurate estimates of the 10-, 50-, or 100-year floods.

NATIONAL OVERVIEW OF FLOODING

A generalized national overview of the geographic distribution and seasonality of the various flood-causing mechanisms discussed in this article is presented in figure 31. A selection of individual floods that had different climatic origins and represent various parts of the country is listed in table 3. Floods can occur in any season, but the annual peak flood in most of the large drainage basins in the Nation has a tendency to occur in spring, when soil-moisture storage is maximum, snowmelt is rapid, and extratropical-cyclone activity is vigorous (fig. 31*A*). Exceptions to this general rule are parts of Arizona (annual peak flood in midsummer or fall); California, Oregon, and Washington (annual peak flood in winter); parts of Alaska (annual peak flood in summer or fall); and parts of Florida (annual peak flood in fall). In small drainage basins, the annual peak flood may be caused by rapid snowmelt and rain on snow in the spring or by orographically enhanced precipitation, intense precipitation from thunderstorms, or prolonged precipitation from mesoscale convective systems in other seasons.

The flood-climate regions shown by season in figure 31*B* represent a synthesis of the information contained in figures 22 through 30 and are based on the seasonal and geographic distributions of thunderstorm frequency, tropical-cyclone tracks and effects, frontal frequency, extratropical-cyclone tracks and effects, and snow depths. As shown in figure 31*B*, the country is divided into general regions that are dominated by different flood-causing precipitation processes in each season. Overlap among the regions is expected because of the widespread distribution of some sources of flood-causing precipitation, such as thunderstorms and fronts, in certain seasons. In addition, boundaries in mountain regions probably are far more complex than those indicated, due to orographic effects.

The location of the representative floods listed in table 3 has been plotted in figure 31*B*; there is good agreement between the climatic origins of specific floods and the generalized seasonal flood-climate regions. The boundaries of the regions also show general agreement with the classification of flood climates by Hayden (1988), which was derived on a more theoretical basis for a global scale.

CONCLUSIONS

Floods are caused by meteorological processes that deliver more precipitation or runoff to a drainage basin than can be absorbed readily or stored within the basin. The most important sources of flood-causing precipitation and runoff in the United States are extratropical cyclones and their associated fronts; convective thunderstorms, especially when they occur in mesoscale convective systems; and tropical cyclones. Extratropical cyclones and their associated fronts are important sources of flood-causing precipitation in all seasons, although they predominate in the winter and spring, when the effects of their flood-causing precipitation are enhanced by saturated soil and melting snow. In the summer and fall, convective storms—thunderstorms and tropical cyclones—caused by warmer temperatures and enhanced by large influxes of precipitable water vapor increase in frequency and become more important as sources of flood-causing precipitation because the extremely intense precipitation of convective storms can produce substantial runoff, despite seasonally small values of soil-moisture storage. Precipitation occurring from any of the above

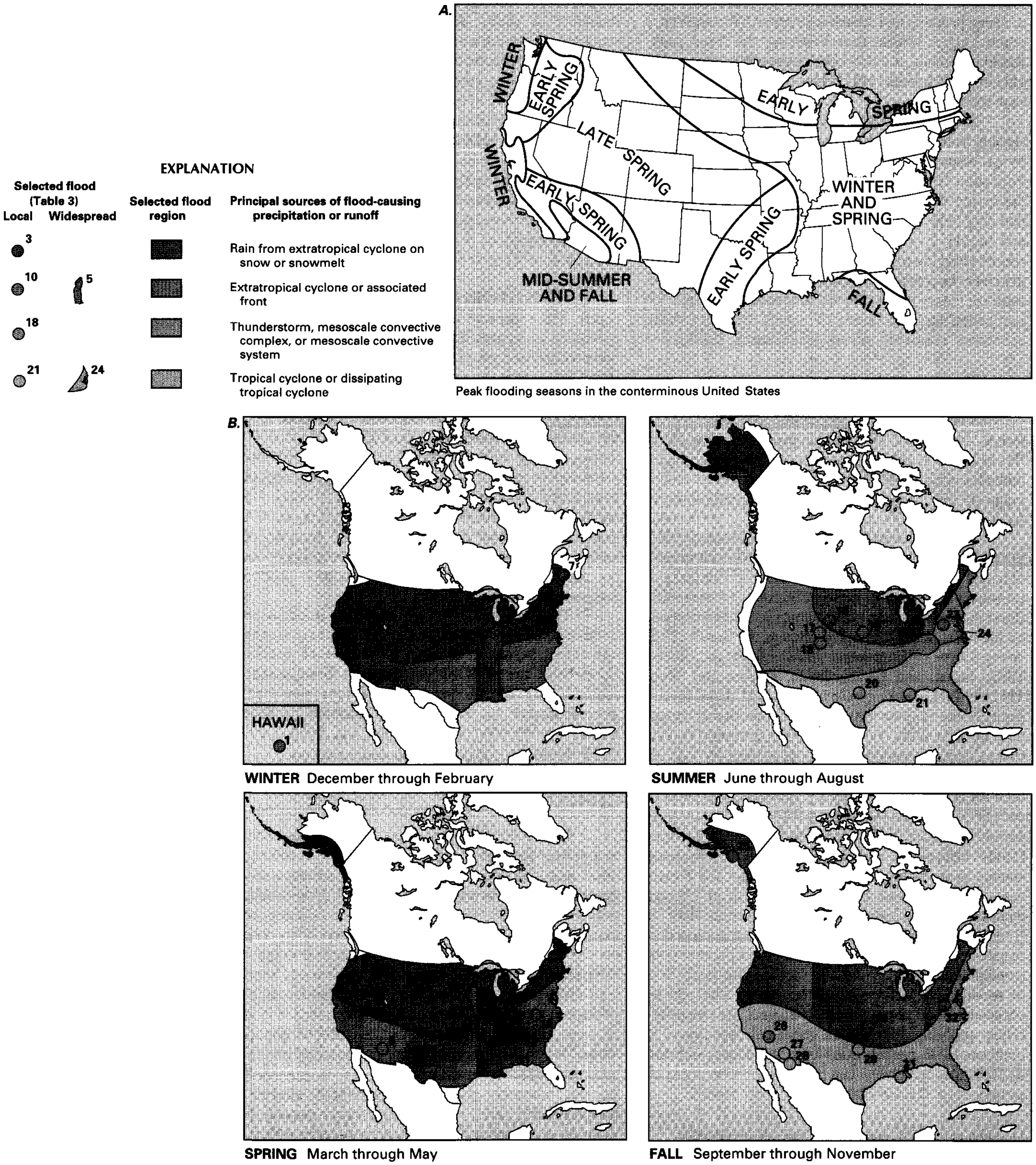


Figure 31. Seasonal summary of flooding and seasonal flood-climate regions in the United States. *A*, Typical seasons during which the largest flood peak of the year occurs in different parts of the conterminous United States. *B*, Seasonal flood-climate regions in the United States and selected examples of floods caused by different sources of precipitation or runoff. (Sources: *A*, Modified from Baldwin and McGuinness, 1963. *B*, Information presented in this article.)

Table 3. Selected floods and their source of precipitation or runoff in the United States, by season, 1964–87
[Source of data given in reference column]

Site (fig. 31*B*)	Flood		Source of precipitation or runoff	Reference
	Area	Date		
		WINTER		
1	Island of Hawaii.	February 20, 1979	Cyclonic storm.	Harris and Nakahara, 1980.
2	Northern California.	December 1964–January 1965	Snowmelt, frontal passage, and orographic uplift.	Waananen and others, 1971.
3	Northeastern Nevada.	February 1962	Rapid snowmelt, frozen ground, and rain on snow.	Thomas and Lamke, 1962.
4	Gila River basin, southern Arizona.	November 1965–January 1966	Repeated frontal passages.	Aldridge, 1970.
5	Central and southern Mississippi River basin.	December 1982–January 1983	Quasi-stationary trough and frontal passage.	Sauer and Fulford, 1983.
6	Northern New York State.	December 1984–January 1985	Rain on snow.	Lumia and others, 1987.
7	Maine coast.	February 2, 1976	Extratropical cyclone and storm surge.	Morrill and others, 1979.
		SPRING		
8	Central Arizona.	March 1978	Repeated frontal passages.	Aldridge and Eychaner, 1982.
9	Southeast Montana and northeast Wyoming.	May 1978	Rain on snow and quasi-stationary front.	Parrett and others, 1984.
10	Mississippi River basin.	Spring 1973	Repeated development of trough and frontal passages.	Chin and others, 1975.
11	Southeastern States.	March–April 1973	Quasi-stationary cold front.	Edelen and Miller, 1976.
12	Mississippi, Alabama, and Georgia.	April 1979	Extratropical cyclones and frontal passages.	Edelen and others, 1986.
13	Appalachian region.	April 1977	Frontal passage and small-scale short-wave low-pressure trough.	Runner and Chin, 1980.
14	Indiana, Michigan, and Ohio.	March 1982	Precipitation and snowmelt.	Glatfelter and others, 1984.
15	Maine, Massachusetts, and New Hampshire.	April 1987	Precipitation and snowmelt.	Fontaine, 1987.
		SUMMER		
16	Rapid City, South Dakota.	June 9–10, 1972	Quasi-stationary thunderstorms in mesoscale convective system and orographic uplift.	Schwarz and others, 1975.
17	Cheyenne, Wyoming.	August 1, 1985	Quasi-stationary multicell thunder-storm.	Lowham and Druse, 1986.
18	Big Thompson River, Colorado.	July 31–August 1, 1976	Quasi-stationary thunderstorms in mesoscale convective system and orographic uplift.	McCain and others, 1979.
19	Missouri River and tributaries.	June 1984	Succession of extra-tropical cy-clones and frontal passages.	Burmeister, 1985.
20	Central Texas.	August 1–4, 1978	Moisture from dissipating Tropical Storm Amelia, orographic uplift, and other atmospheric features.	Schroeder and others,1987.
21	Mississippi and Louisiana coasts.	August 1969	Storm surge from Hurricane Camille.	Wilson and Hudson, 1969.
22	Northwestern Ohio.	June 13–15, 1981	Intense precipitation associated with frontal passage.	Webber, 1982.
23	Johnstown, western Pennsylvania.	July 19–20, 1977	Quasi-stationary thunderstorms in mesoscale convective system.	Hoxit and others, 1982.
24	Mid-Atlantic States.	June–July 1972	Precipitation from Hurricane Agnes.	Bailey and others, 1975.
		FALL		
25	South-central Alaska.	October 10–12, 1986	Quasi-stationary front.	Lamke and Bigelow, 1987.
26	Eldorado Canyon, Nevada.	September 14, 1974	Thunderstorm, small-scale, short-wave low-pressure trough, and orographic uplift.	Glancy and Harmsen, 1975.
27	Central Arizona.	September 4–6, 1970	Moisture from dissipating Tropical Storm Norma, frontal passage, and cutoff low.	Hansen and Schwarz, 1981.
28	Tucson, Arizona.	September 28-October 3, 1983	Moisture from dissipating Tropical Storm Octave.	Saarinen and others, 1984.
29	Central and southwestern Oklahoma.	October 17–23, 1983	Residual moisture from Hurricane Tico.	Hauth, 1985.
30	Kansas City, Missouri and Kansas.	September 12–13, 1977	Extratropical cyclone and frontal passage.	Hauth and others, 1981.
31	Louisiana coast.	September 8–11, 1965	Storm surge from Hurricane Betsy.	U.S. Army Corps of Engineers, 1966.
32	West Virginia and Virginia.	November 4–5, 1985	Extratropical cyclone and remnants of Hurricane Juan.	Clark and others, 1987.

processes can be enhanced by orographic lifting to cause flooding in regions that have mountainous or hilly terrain.

The meteorological processes that produce flood-causing precipitation and runoff in the United States occur within a much larger climatic context that is global in extent. The seasonal and geographic distributions of flood-causing precipitation and runoff are related to the large-scale, general circulation of the atmosphere, which determines the seasonal availability and large-scale delivery pathways of atmospheric moisture. Within a given season, the frequency, typical locations, and degree of persistence of the meteorological processes that release the delivered moisture to cause a flood are influenced by large-scale, atmospheric circulation patterns that develop over areas that are much larger than the flood-affected region. Furthermore, the large-scale climatic framework that influences the occurrence of floods can have a continuity that is much longer than the period of flooding. This occurs when the climate-related, land-surface conditions that affect flood runoff—such as saturated soils or extensive snow cover—develop over a period of several weeks or months.

The role of climate in the occurrence of floods varies from region to region in the United States. Some regions are dominated by several different sources of flood-causing precipitation during the year, whereas others regions are dominated by only one or two. Floods caused by distinctly different climatic processes have distinctly different magnitude and frequency relations. Continued investigation into the effects of multiple sources of flood-producing precipitation will provide hydrologists with more accurate flood estimates, in addition to a better understanding of the flooding process itself.

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