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FLOOD CLIMATES

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INTRODUCTION

An examination of the literature reveals neither a global classification of flooding nor a regionalization or map of flood climate types on a global basis. Our goal here is to generate such a classification and a map of the resulting flood climate types and to detail the basis for its construction.

A coherent global climatology of flooding is not easily constructed from stream discharge frequency and magnitude statistics. The difficulty arises, in part, because the frequency and magnitude of floods vary between and within drainage networks because of variability in basin characteristics. This variability is further complicated by the diversity of weather systems that may give rise to flooding, each with its own characteristic return interval spectrum. Although the variability in basin characteristics prohibits regionalization on a global basis, the meteorological causes and potential for flooding can be classified and regionalized. In this chapter flood climate regions are delineated on the basis of meteorological causation. Subregionalizations based on basin characteristics might then prove possible.

PRIMARY RESERVOIR OF FLOODWATERS

The primary reservoir of floodwaters is the atmosphere. The water stored on the land as snow and ice is the secondary reservoir. The potential for flooding depends on the content of these reservoirs and on the rates and duration of discharges. The regionalization scheme proposed here focuses first on the content of the reservoirs and then on the meteorological mechanisms responsible for discharge from the reservoirs.

The atmosphere contains about 1.4×10^4 km^3 of water. This is only a small fraction (10^{-5}) of the total water inventory of the earth (Lamb, 1972). On a global average basis there is only about 23 mm of water in the air. In contrast, global precipitation averages about 1000 mm/yr. Evaporation effectively replenishes the total atmospheric water about 40 times per year. Total annual evaporation is approximately equal to the water that resides in lakes and streams at any time (0.3×10^6 km^3) (Lamb, 1972).

Most of the water in the atmosphere is contained within the troposphere. Within this layer of the atmosphere the processes that give rise to precipitation take place. The troposphere in tropical latitudes extends from the surface to a height of 17 km, and in polar latitudes to about 11 km. The actual volume of the atmospheric reservoir thus declines with latitude. Average tropospheric temperatures also decline with latitude. Therefore the atmosphere's capacity to hold water vapor also declines, because the saturation vapor pressure of the air increases as air temperature increases. Warm air can hold more moisture than can cold air. In addition, evaporation is a temperature-dependent process, so the primary areas of atmospheric recharge occur in the low latitudes where temperatures are high. More then 60% of the water evaporated into the atmosphere occurs between 30°N and 30°S (Lamb, 1972). In contrast, only about 5% of the total evaporation takes place poleward of the 50th parallel. This latitudinal inequality is complicated by the distribution of land and sea. More than 60% of the evaporation occurs over the oceans. Vigorous circulation of the atmosphere reduces the equator-to-pole and ocean-to-land contrasts in the total water content of the atmosphere but does not eliminate them.

Geographic variations in available water within the atmospheric reservoir can be assessed using the parameter total water content. The total water content of the atmosphere is that depth of water that would result if the water content of a column of the atmosphere extending to the top of the troposphere were condensed to liquid. In polar continental regions in winter this depth may be as little as 5 mm, whereas in tropical maritime areas values around 50 mm are common all year. Clearly if air were not advected, converged, and uplifted, rain in amounts sufficient to directly cause flooding would never occur.

Barotropic and Baroclinic Atmospheres

Earth's troposphere may be divided into two broad classes: baroclinic and barotropic. The distinction is somewhat complex but involves the root cause of rotational circulation. It is thus important to detail the difference. The atmosphere is said to be baroclinic when solenoids are present. Solenoids arise when gradients of pressure and temperature intersect. A simple example of a solenoid would be a saucepan filled with water but heated only on the bottom outer rim. Temperature declines both toward the center of the pan and upward toward the surface of the water in the pan. On the other hand, pressure just declines upward as dictated by the hydrostatic relationship. Temperature gradients and pressure gradients intersect. When such intersections are present, a circulation is initiated. In the pan water rises around the side walls of the pan: it flows toward the center, sinks to the bottom, and then flows toward the heated rim. The baroclinic condition of solenoidal circulation is largely absent in the barotropic atmosphere. Temperature and pressure gradients are weak and nearly parallel. Solenoidal circulations are poorly developed. Alternative means of generating circulations are needed.

A barotropic atmosphere is more typical of tropical low-latitude regions, and a baroclinic atmosphere is typical of higher latitudes with contrasting air masses. In a barotropic atmosphere pressure is constant on constant-density surfaces. This condition prevails where horizontal thermal gradients are small. A consequence of small horizontal thermal gradients is the absence of large changes in wind speed with height. So, the barotropic atmosphere is characterized both by little horizontal temperature contrast and also by little vertical wind shear. Once upward motions are started due to surface heating or airstream convergence, or by orographic effects, it is the release of latent heat that drives convection, vertical motions, and precipitation in the barotropic atmosphere.

Vertical motions give rise to condensation and upward-growing clouds in both the barotropic and baroclinic atmospheres. However, with the absence of significant wind shear with height in the barotropic atmosphere, the upward motions are nearly vertical. These convective clouds grow as great vertical chimneys as the clouds are not sheared off by strong winds aloft. Convection through a deep layer of the atmosphere is possible, and high rainfall rates can be generated.

The warm moist air typical of the low-latitude barotropic atmosphere tends to be unstable or nearly unstable. Upward motions give rise to a temperature decline, condensation, and the release of latent heat. The rising parcel of air becomes less dense, lighter than the surrounding air, and thus more buoyant than its surroundings. Upward motion therefore induces further upward motion. It is this autoconvective process that sustains the vertical motions and upward cloud growth that typifies the barotropic atmosphere of the low latitudes. Small vertical motions in the surface layer can give rise to the towering cumulonimbus clouds and the deep convection that characterizes the tropical atmosphere. This cumulus cloud scale convective chimney is the fundamental rainmaking element of the barotropic atmosphere. Even great tropical hurricanes can be viewed as an organized structure, a vortex, of convective cloud elements.

In a baroclinic atmosphere, typical of the higher latitudes, pressure is not constant on surfaces of constant density. Accordingly, horizontal thermal contrasts are often sharp, and wind speeds increase with height in proportion to the strength of the horizontal thermal contrast. The intersections of pressure and temperature surfaces give rise to solenoidal circulations in the horizontal plane. Convergences in the horizontal circulation in turn give rise to vertical motions, cooling, condensation, and precipitation. The middle- and high-latitude baroclinic atmosphere is driven by the hydrodynamics of horizontal flows, which in turn sustain the vertical motions that give rise to precipitation. However, rainfall rates are modest compared to those generated by the deep convective processes of the barotropical atmosphere. This difference is in part counteracted by the longevity of baroclinic weather systems and thus the longer durations of baroclinic rainfall.

In a general sense the earth's atmosphere may be divided into low-latitude barotropic and high-latitude baroclinic portions. The boundary between the two varies on both seasonal and synoptic time scales but is roughly the northern limit of tropical air masses. For our purposes the 25-mm contour of total atmospheric water content marks this transition and separates the atmosphere into two parts with fundamentally different driving forces in the precipitation process. It is of importance to note that this division also delimits those regions where high rainfall rates of short duration are the norm from those areas with modest rainfall rates but longer durations. Discharges from the atmospheric reservoir are fundamentally different in the barotropic and baroclinic atmospheres.

Figure 1 shows the January and July 25-mm contours of atmospheric water content. The position of the line follows that of Lamb (1972) except in the area of North Africa where barotropic conditions are found but water

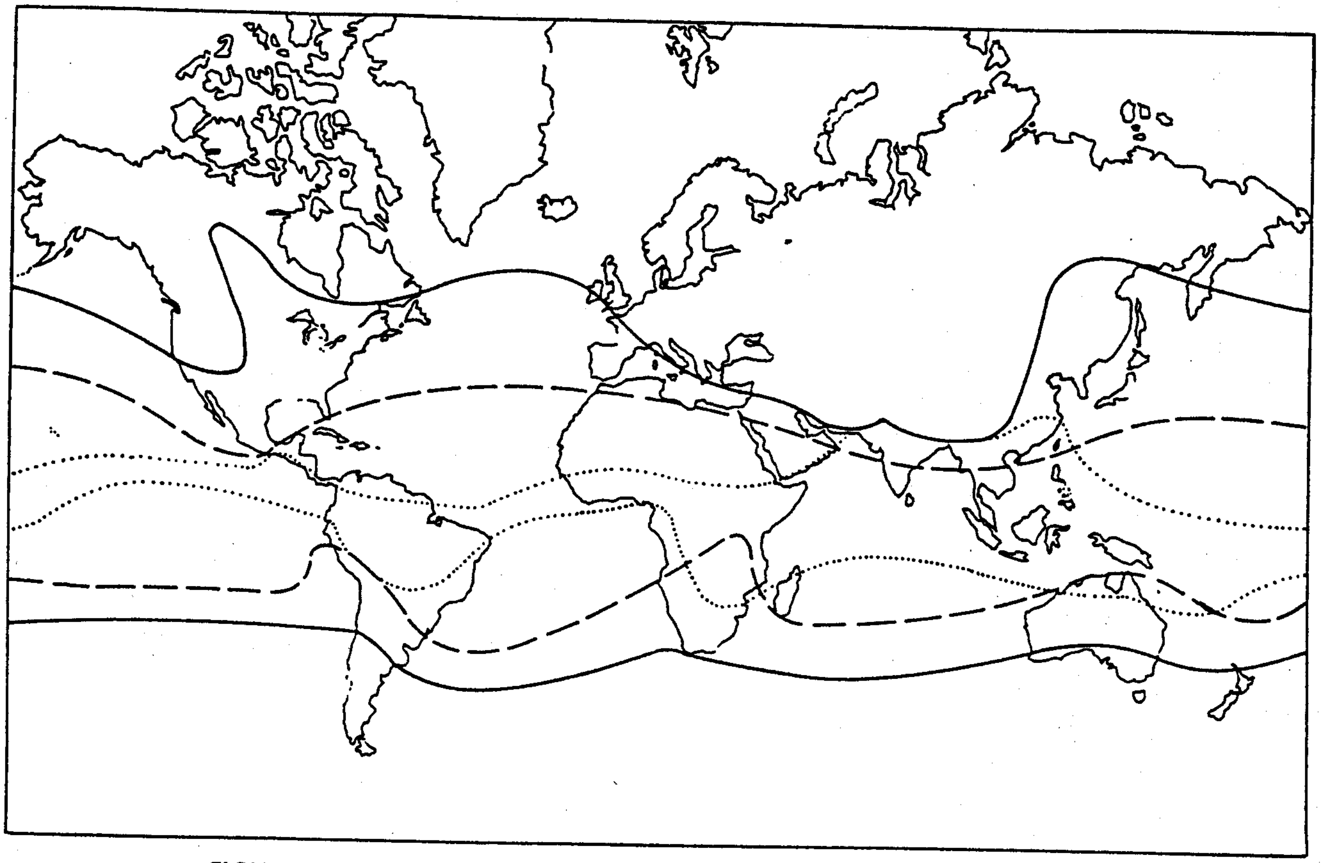

FIGURE 1. The mean winter (dashed line) and summer (solid line) boundaries between the low-latitude barotropic and high-latitude baroclinic atmospheres. The four lines are after Lamb (1972) and represent the 25-mm atmospheric water content contours in January and July. The dotted lines are the July (upper dotted line) and January (lower dotted line) positions of the ITCZ (after Atkinson and Sadler, 1970).

contents fall below 25 mm. The contour is adjusted in this region to reflect the distribution of barotropic conditions. Also shown in Figure 1 are the January and July positions of the convergences of the trade winds from the two hemispheres. This circumequatorial band of convergence and cloudiness is known as the Intertropical Convergence Zone (ITCZ), discussed in a subsequent section. The winter and summer 25-mm contours of atmospheric water taken separately define three broad zones. In the high latitudes, where mean water content is generally less than 25 mm all year, we have the perennially baroclinic zone. In the low latitudes water contents exceed 25 mm all year, and we have the perennial barotropic zone. In the middle latitudes barotropic and baroclinic conditions alternate on seasonal and synoptic time scales. The 25-mm contour in July also clearly indicates the monsoon invasion of moist air in eastern Asia and in the Northern Hemisphere summer as well as the midsummer penetration of maritime tropical air and barotropic conditions into the high plains of North America.

In the north of Africa the poleward limit in January of barotropic conditions is not well delineated by the 25-mm contour. The air over North Africa, while usually barotropic, has less than 25 mm of water in it. The dashed line in Figure 1 along the coast of North Africa represents the mean winter poleward limit of barotropic conditions. This then is a departure from the 25-mm contour of Lamb (1972). The air over arid North Africa as well as that over the Outback of Australia and the Rajastan desert of northwest India is then sufficiently moist to support considerable rainfall and flooding. However, the rainfall is not often realized because of the absence of the meteorological mechanisms to initiate, support, and sustain the vertical motions needed for condensation and precipitation.

Weather Systems of the Barotropic Atmosphere

The horizontal convergence and heating in the surface layer of the barotropic atmosphere gives rise to the vertical motions needed to support condensation and precipitation.

The convective cloud is the basic element of rain production in the barotropic atmosphere. Figure 2 shows the global distribution of thunderstorms, fully matured convective systems, by broad frequency classes: more than 100, between 50 and 100, between 20 and 50, and less than 20 thunderstorms per year. Frequent thunderstorms on an average annual basis are typical of both the perennial and the seasonal barotropic conditions. Populations of thunderstorms are, however, often organized into larger weather systems, and it is these larger scale assemblages of convective elements that are of greatest importance where other than highly localized flooding is concerned. The dominant rain-producing organized weather systems of the barotropic low latitudes are: (1) the convergence of the trade wind streams between the two hemispheres (the ITCZ) (2) cyclonic curvatures of the pressure field (tropical storms and easterly waves), and (3) orographic uplift as airstreams rise over the relief of the land. Barotropic regions where these weather systems are infrequent or weak, such as North Africa, tend to be arid in spite of the barotropic conditions of the atmosphere.

The Intertropical Convergence Zone. The Intertropical Convergence Zone (ITCZ), sometimes referred to as the meteorological equator and the doldrums, marks the convergence of wind streams from the two hemispheres. The convergence and rising air results in a circumequatorial band of cloudiness. This band is clearly evident in satellite photographs (Fig. 3). The zone of intertropical convergence and the belt of raininess that results goes through an orderly annual north–south excursion. The day-to-day position and movement of the ITCZ are difficult to forecast with precision. It is in its most northward position during the Northern Hemisphere summer and is farthest southward during the Southern Hemisphere summer. Because of this latitudinal variation in the ITCZ, a pronounced seasonality in rainfall results over much of the intertropics. The generic term *monsoon* is often associated with this summer rainy season. The specific term *Monsoon* is generally reserved for the pronounced Asian monsoon. Figure 1 shows the January and July limits of the ITCZ. The intertropics defined by the seasonal swings of the ITCZ encompass most of what is commonly known as the moist tropics. However, in some regions such as eastern Africa and the southern coast of the Arabian peninsula, the strength of the convergence is often weak, upward motions small, and rainfall slight. Where there are highlands present within this intertropical zone, uplift may be enhanced by orographic pro-

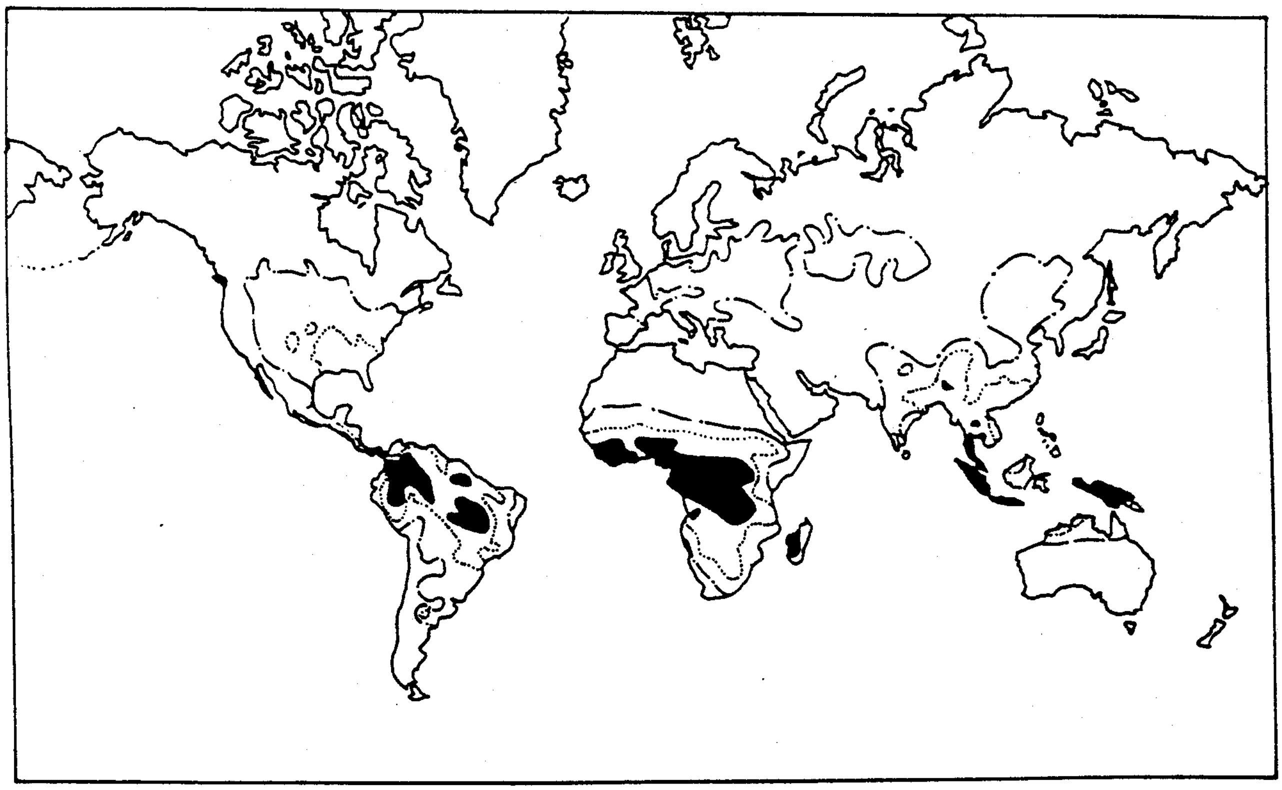

FIGURE 2. Annual thunderstorms by frequency classes. Regions with 100 or more thunderstorms per year are black. The dotted line encompasses regions with more than 50 thunderstorms per year and the dashed-dotted line encompasses regions with at least 20 thunderstorms per year (Lamb, 1972).

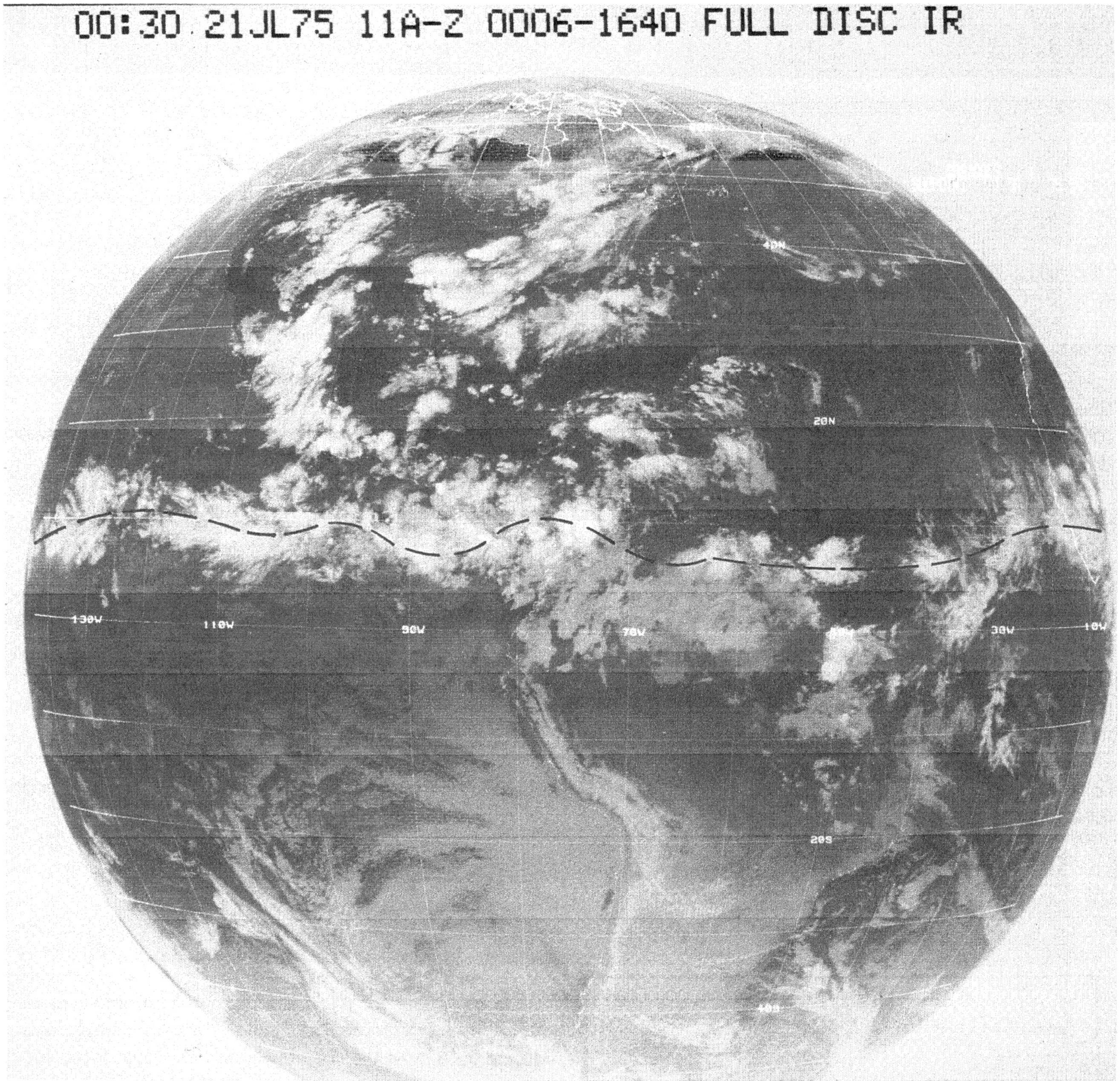

FIGURE 3. The ITCZ on 21 July 1975. The dashed line follows the axis of brightest cloud masses. The photograph is an infrared image and the tallest and coldest cloud tops are the brightest areas. Regions of greatest convection are clearly seen.

cesses, and great quantities of rain may result. At Cherrapunji, India (in June 1876) 2500 mm (100 in.) of rain fell in about 100 hr. Most of the rains that give rise to Nile flooding fall on the Ethiopian highlands as the ITCZ passes northward during the Northern Hemisphere summer. In years when the convergence is weak or fails to penetrate that far north, drought occurs. The great drought and famine of 1981–1985 marks an episode in the erratic, unreliable history of the ITCZ in this region.

Off the west coast of South America the normal seasonal excursions of the ITCZ encompass only a few degrees of latitude and are largely confined to Colombia and Equador. However, in years of the El Niño, warm tropical waters extend southward along the coast as does the ITCZ. Heavy convective rains may then come to the extremely arid Peruvian coast. In years of the El Niño, floods are common in Peru.

Cyclonic Motions. On occasion, large-scale cyclonic curvatures of the wind streams occur within the perennially barotropic atmosphere of the lower latitudes. The most common weather system of this type is the easterly wave (Fig. 4). The easterly wave is a wavelike or sinusoid deformation in the trade wind flow pattern. Convective clouds (thunderstorms) become organized at the scale of the easterly wave and may give rise to intense prolonged periods of rainfall. These easterly waves tend to move from east to west within the trade wind zone, and the greatest rainfalls occur when the easterly wave passes over islands or continental margins. Here the heated land surfaces and the roughness of the landscape enhance upward motions, and the convective elements intensify.

The most important type of cyclonic motion in the barotropic atmosphere is the tropical cyclone. Tropical cyclones frequently arise from the organized system of convective elements of an easterly wave. It is not known why a few of the easterly waves intensify into tropical storms nor why most do not. Those tropical cyclones that intensify to the level where winds of 116 km/hr (72 mph) or greater are generated are known as hurricanes. This is the name generally applied to those tropical storms of great intensity in the North American sector. Over most of the Pacific Ocean basin they are referred to as typhoons. In the Indian Ocean area they are called cyclones. In general these storms do not form adjacent to the equator where the Coriolis parameter is small and closed circulation systems uncommon. The genesis of tropical storms requires an ample supply of latent energy, and thus the region of genesis is restricted to the subtropical oceans where sea surface temperatures exceed 27°C. An additional constraint is that the atmosphere be largely free of vertical wind shear. Although the barotropic atmosphere in general tends to have little shear, this is not true everywhere. The south Atlantic Ocean region in the subtropics tends to have a wind shear in the vertical, and tropical storms are essentially unknown there.

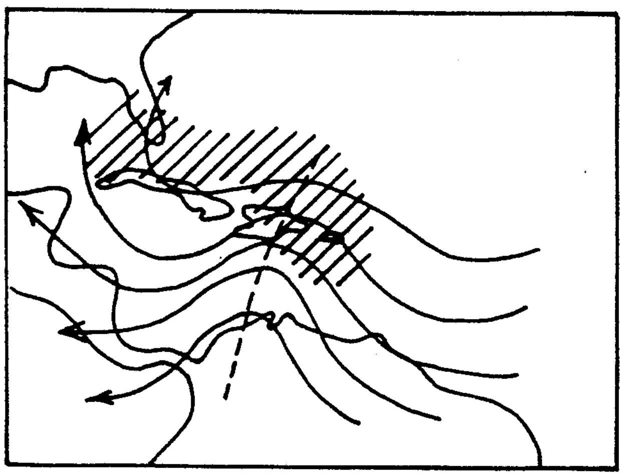

FIGURE 4. An easterly wave centered over the Dominican Republic on August 13, 1969. The dashed line indicates the axis of the easterly wave trough. The arrows indicate the prevailing airstreams and the cross-hatched area is the region of cloud masses.

The absence of shear permits deep convection. The hurricane is a spiral-form organization of hundreds of convective elements (Fig. 5). Strong upward motions and the release of latent heat support the vigorous horizontal cyclonic motions of the tropical storm. Should the top of the convective chimneys of the thunderstorms be "blown off" because of increasing velocities aloft, the hurricane would tend to dissipate quickly.

Once formed, tropical cyclones tend to move westward within the trade wind belt, then northward and eastward into baroclinic regions. Here tropical cyclones may interact with midlatitude frontal systems and benefit from the hydrodynamics of the baroclinic atmosphere. While some of its characteristics as a tropical system may then disappear, great quantities of rain may result. Hurricane Camille in 1969 and Agnes in 1972 did just this and resulted in 250–500 mm of rain on the Atlantic Coastal Plain. The highest rainfall totals from both storms occurred when the most baroclinic portion of the atmosphere intersected the remnants of the tropical storm. Similar conditions are also common in southeastern China. Figure 6 shows the distribution of the trade winds where easterly waves occur and the major tropical cyclone tracks.

Some otherwise arid areas, such as Arizona, only rarely experience tropical storms. Thus these landscapes are not "equilibrated" to the copious rainfalls that result from even modest tropical storms. Modest tropical storms may result in record floods in such areas. Such circumstances occur in Arizona where tropical storms may give rise to extensive flooding. Chapter 2 (on flood hydroclimatology) is particularly instructive. The distribution of tropical storms shown in Figure 6 must thus be viewed in two ways. First, there are those regions that because of the high frequency of tropical cyclones may well experience the most intense tropical storms and are prone to frequent hurricane flooding. Second, there are those regions that only rarely experience the effects of tropical storms, but when a storm track on occasion enters the region, major flooding occurs.

Orographic Uplift. Upward motions and strong convective activity are often directly coupled to the terrain over which airstreams must flow. In the barotropic atmosphere these upward motions are accompanied by condensation and the release of latent heat, and the air becomes more unstable. Rising air becomes less dense than the surrounding air, and further upward motions follow. This autoconvectivity is enhanced over highlands as solar heating of the land

FIGURE 5. Tropical storm Blanch off the Carolina coast on July 27, 1975. Although storms at this stage are not classed as a full hurricane, the spiral bands of convective clouds are clearly evident.

and, in turn, the air further increases the upward motions and the chances of rain. Orographic rainfall often has a strong diurnal component, with rainfall maxima following the period of strongest solar heating. Orographic rainfalls are regionally organized where north–south land masses, mountain chains, and archipelagos intersect the persistent east-to-west trade winds of the subtropical latitudes.

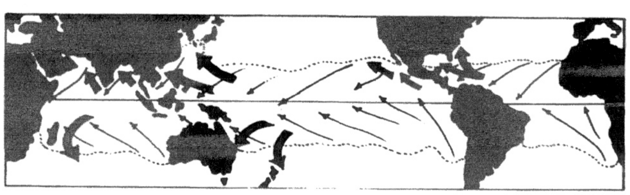

FIGURE 6. The zone of easterly waves and trade wind disturbances. The thin arrows indicate the general direction of the trade winds (after Crowe, 1949) and the large black arrows the major hurricane tracks (after Simpson and Riehl, 1981).

In the middle latitudes the atmosphere tends to be barotropic in the summer half of the year. Convective precipitation is often associated with thunderstorms. Usually, serious flooding from individual thunderstorms is restricted to arid regions. However, in regions where orographic effects may be present, thunderstorms may merge to form what is now called mesoscale convective clusters. Rainfall rates from these merged thunderstorms are like those of the deep barotropic atmosphere of the tropics and occur because of the dynamic interaction of the storm and the terrain. The mesoscale convective cluster may be stationary for a long time. The Rapid City, South Dakota, flood of

1972 and the Johnstown, Pennsylvania, flood of 1979 were devastating floods of this type. The mesoscale convective cluster is typical of areas where barotropic and baroclinic conditions alternate on seasonal and synoptic time scales. While little is known about these newly recognized atmospheric phenomena, they are easily detected from satellite images, and we are sure to learn more about their climatology in the years ahead.

Although the inclusion of every element of relief on a map of flood climate regions would seem advantageous, the map quickly becomes filled with details inappropriate to a global map. Accordingly only the major terrain elements will be shown, and then only in a stylized fashion. The detail of terrain relative to the flood climate classification is left to the reader to deal with on a region by region basis. However, it is essential that a map of the climatology of flooding include the major elements of relief of the landscape.

Weather Systems of the Baroclinic Atmosphere

In a baroclinic atmosphere wind shears in the horizontal and vertical planes arise from strong thermal contrasts and the solenoidal fields associated with intersecting temperature and pressure surfaces. Convergences and divergences at various levels in the atmosphere give rise to vertical motions, condensation, and precipitation. This is not to say that the release of latent heat is an unimportant process in the baroclinic atmosphere, but rather that the initiating forces are more hydrodynamic than thermodynamic in nature.

Strong horizontal thermal contrasts in the baroclinic part of the earth's atmosphere tend to be associated with fronts. At these fronts masses of air from different source regions converge. The polar front exhibits the strongest temperature contrast. The polar front usually separates the barotropic tropical atmosphere from the high-latitude baroclinic atmosphere. In the region of the polar front, north–south thermal contrasts are greatest, and the westerly winds increase rapidly with height. Aloft there is usually a jet stream associated with the polar front. The polar front marks a region of great hydrodynamic instability. It is in this region the frontal cyclones commonly develop.

These polar front storms have access to tropical barotropic air to the south and the latent energy available from that moist air. Storms along the polar front may reach great intensity and size. The strong upward motions, sustained by convergence toward the storm center at the surface and divergence at the top of the storm supported by the jet stream aloft, may result in heavy precipitation.

These frontal storms vary in size from several hundred kilometers to more than a thousand kilometers in diameter. They tend to move from west to east and/or southwest to northeast. The "footprint" of precipitation that results is of the same size class as the large drainage basins of the middle latitudes. Precipitation from these storms and their associated frontal zones generally has durations of 12–36 hr. It is significant that frontal storms tend not to be solitary, but rather several storms form along the frontal zone at separation distances of several hundreds of kilometers. Figure 7 illustrates such a family of frontal cyclones. This is significant for flooding in the middle latitudes because sequences of storms and rainfall are common. The first may saturate the ground and subsequent storms result in flooding. In the middle latitudes storms within a family tend to pass a given region about every 3.5 days. It is common, however, for every other storm to be more vigorous in rain production. As a result a weekly cycle of precipitation is observed. Namias (1966) referred to this weekly cycle as a quasi-periodic phenomenon. A more general term of the regular recurrence is the *synoptic cycle*. It is not uncommon for rain to occur for 10–15 consecutive Tuesdays. It seems, however, that 10–15 consecutive weekends of rain are more common, but this is the result of our memory of dashed plans for our leisure time. Over the long term there is no day of preference within the week, that is, the phase angle of this quasi-periodic phenomenon varies from year to year.

Polar front cyclones are largely restricted to the zone of the seasonally baroclinic atmosphere (see Fig. 1). However, even a casual examination of a weather map for the Northern Hemisphere will reveal other fronts north of the polar front. Like the polar front, these other fronts separate masses of air from different source regions and thus air masses with differing thermodynamic properties. Unlike the storms of the polar front, when over continental areas, the frontal cyclones of these other fronts rarely have access to masses of air with sufficient moisture to result in heavy rainfall and flooding. However, if there is orographic enhancement of condensation and precipitation, heavier rains may result. For flooding to occur, the relatively modest precipitation from these frontal cyclones must be stored on the land as snow and ice, accumulated from storm to storm during the winter season. In short, to the north of the zone of seasonally baroclinic conditions, that is, the zone of polar front storms, flooding is usually a spring and early summer phenomenon. In polar regions the atmosphere is sometimes barotropic, that is, temperature and density contours intersect; however, the Coriolis parameter is extreme and horizontal circulations of a dynamic rather than a thermodynamic nature dominate. In addition the air in polar regions has low water content and cannot support heavy precipitation.

THE SECONDARY RESERVOIR OF FLOODWATERS

The secondary reservoir of floodwaters is the accumulated snow and ice on the land surface. Flooding from this

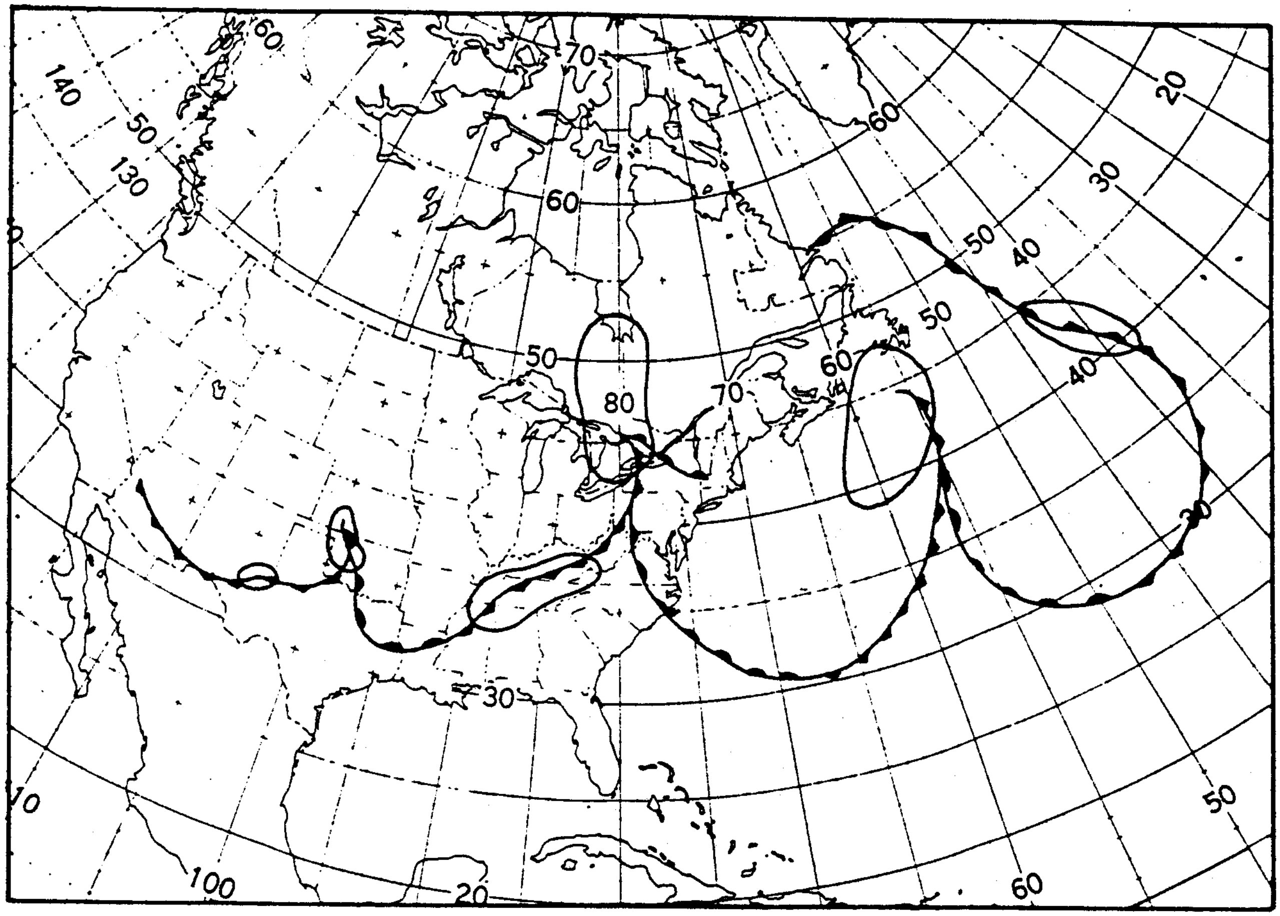

FIGURE 7. A family of cyclones on the polar front. The centers of low pressure (cyclones) are indicated by circles (closed isobars). In regions where the air of tropical origin is moving poleward, a warm front (half circles on the front) is indicated. where air of higher latitude origin is moving southward, a cold front (triangles on the front) is indicated. The family of cyclones progresses from west to east.

reservoir is dependent on the amount of snow cover and the rate and frequency of meltwater discharge. In some regions, such as Greenland and the Antarctic, the snow and ice cover is perennial, and discharges during the summer ablation season are inadequate to cause flooding. In addition there are regions with a winter snow cover and a spring melt that do not flood because there is inadequate snow cover. Extensive areas of the Canadian and Asian Arctic fall in this category. However, many other high-latitude land areas have sufficient snow cover and a spring melt that result in an annual flooding. In the zone we called the seasonally baroclinic, snow cover, while often substantial, is ephemeral. Furthermore, melting is often associated with rainstorms following snowstorms, resulting in rapid and large discharges. Within winter and spring flooding is common in this region.

Flooding for those regions that are perennially baroclinic or seasonally barotropic is often associated with discharges from the secondary reservoir of floodwaters. The several regions discussed above are classified here with the following criteria: (1) perennial ice cover, (2) winter snow cover less than 50 cm with durations that exceed 50 days, (3) winter snow cover of more than 50 cm with durations that exceed 50 days, and (4) those regions with any snow cover duration between 10 and 50 days. Figure 8 shows the geographic extent of each of the four classes. Details of ice and snow cover associated with mountains and islands are omitted.

FLOOD CLIMATE REGIONS

The flood climate regions discussed here are derived from the union of Figures 1, 2, 6, and 8. The composite and the resulting flood climate regions are shown in Figure 9. Sixteen types are delineated. The figure caption gives the definitions of the boundaries between regions, and the legends on the map are keys to the symbolic nomenclature.

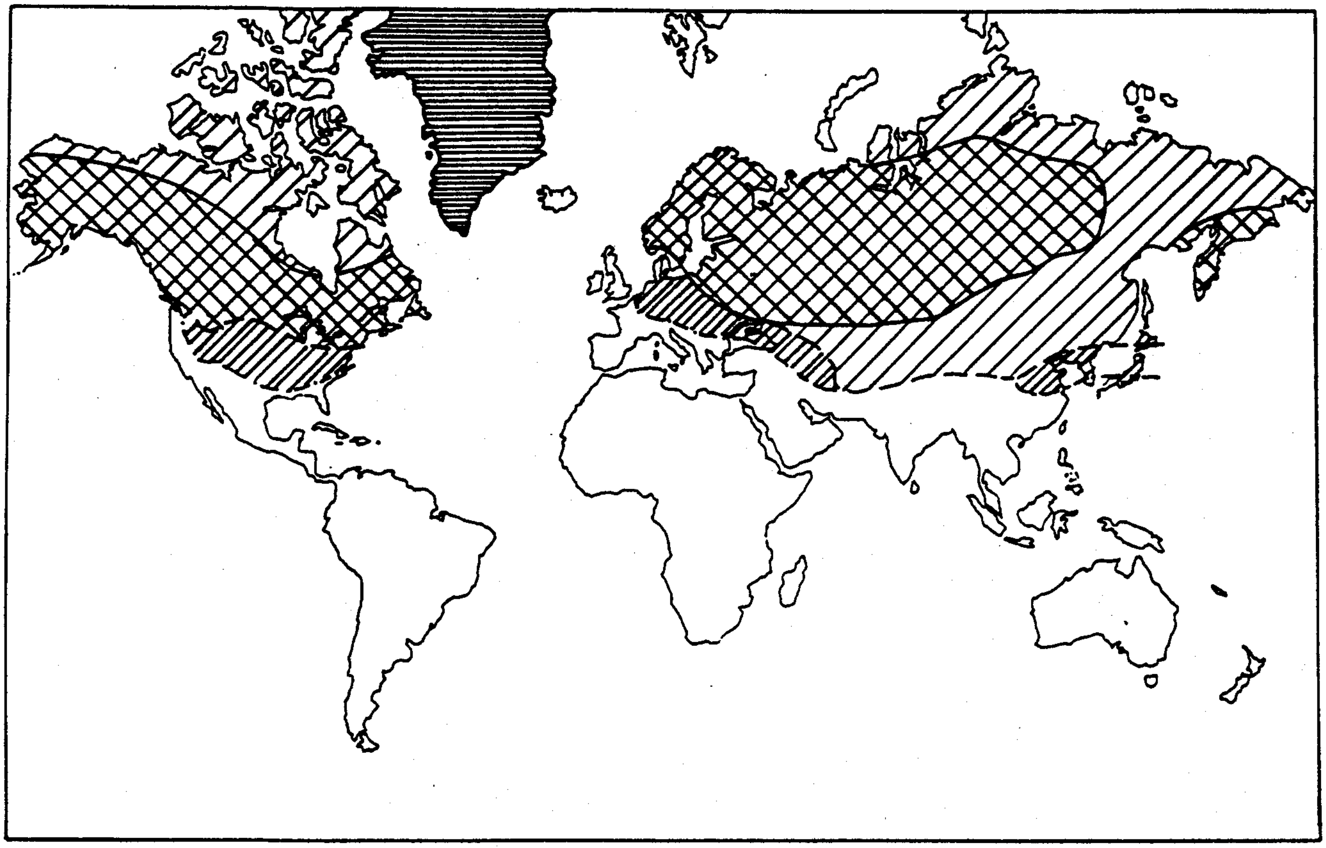

FIGURE 8. The secondary reservoir for floodwaters. The horizontal hatched area is glacial. The cross-hatched area has at least 50 days of seasonal snow cover and at least 50 cm total snowfall. The wide-spaced, diagonal-shaded area has at least 50 days of seasonal snow cover but less than 50 cm total snowfall. The narrow diagonal-shaded areas have less than 50 days of seasonal snow cover and more than 10 cm of snowfall. Data from Lamb (1972). Snowfall and snow cover in mountainous areas are ignored.

The primary reservoir may be characterized either by atmospheric barotropy (T) or baroclinicity (C). These states may be present in all months, that is, perennial (p) or only present on a seasonal basis (s). When barotropic conditions are present, discharge from the reservoir may be due to the intertropical convergence zone (z), organized convective activity at the synoptic scale (o) or unorganized convective activity (u) as in the case of individual thunderstorms. In the baroclinic atmosphere discharge from the atmospheric reservoir of water results from cyclones and fronts. These systems may be present in all seasons (p) or for only part of the year (s). In the high latitudes where rainfall intensity and totals are modest, accumulation of snow on the surface (S) and subsequent discharge is the main mechanism of flooding. When snow accumulates over the winter season and then melts in the spring, the subscript (s) is used and indicates seasonal snowmelt and flooding. When the accumulated snow is discharged within the winter season on a periodic basis, the subscript (e) is used and indicates the ephemeral nature of the snow cover in this reservoir. The potential for flooding at the end of the winter snow accumulation season is dependent on the depth of snow cover. Areas with sufficient snow cover (50 cm or more) are indicated by double asterisks (**) and areas with less than 50 cm snow cover by single asterisk (*).

DESCRIPTION OF FLOOD CLIMATE REGIONS

The letter notations used in this section to designate different regions are shown in Figure 9.

Tpz. —In this region perennially barotropic conditions prevail, and the intertropical convergence zone provides the upward motions needed to initiate the precipitation. The ITCZ undergoes a north–south movement, and so there is usually a rainy season and a drier season. The exception to this seasonality occurs along the west coast of South America in Colombia. Here the north–south excursions of the ITCZ are small and it is rainy in all months of the year. While the zone is circumglobal, there are strong longitudinal variations in the amount of precipitation realized as the ITCZ is not equally vigorous at all longitudes.

Tsz. —In Tsz the seasonality of precipitation is twofold. The ITCZ is present for part of the year as it reaches its extreme southern position in January and with it the rainy season. Six months later the ITCZ is far to the north, and the condition of barotropy, as defined by atmospheric water contents in excess of 25 mm, disappears. During this dry season even individual convective thunderstorms are uncommon. Tsz occurs only in southern Africa, and unlike similar areas elsewhere on earth, it is distant from the trade wind zone and organized disturbances like easterly waves and tropical storms.

Tszo. —Like Tsz this region has a pronounced seasonality in discharge from the atmospheric reservoir of water. Conditions are seasonally barotropic as tropospheric water content falls below 25 mm in winter, and the Tszo regions are poleward of the winter positions of the excursions of the ITCZ. However, unlike the Tsz region of southern or south central Africa, the Tszo region also gets heavy rainfalls from organized convective systems, that is, easterly waves in the trade wind streams and tropical storms. Tszo regions occur in Southeast Asia, the subcontinent of India, and northern Australia.

Tpo. —Tpo regions are barotropic all year and are poleward of the seasonal limits of the ITCZ. Flood-producing rainfalls arise from organized systems of convective elements, that is, easterly waves in the trade wind streams and tropical storms. Tpo regions are within the trade wind

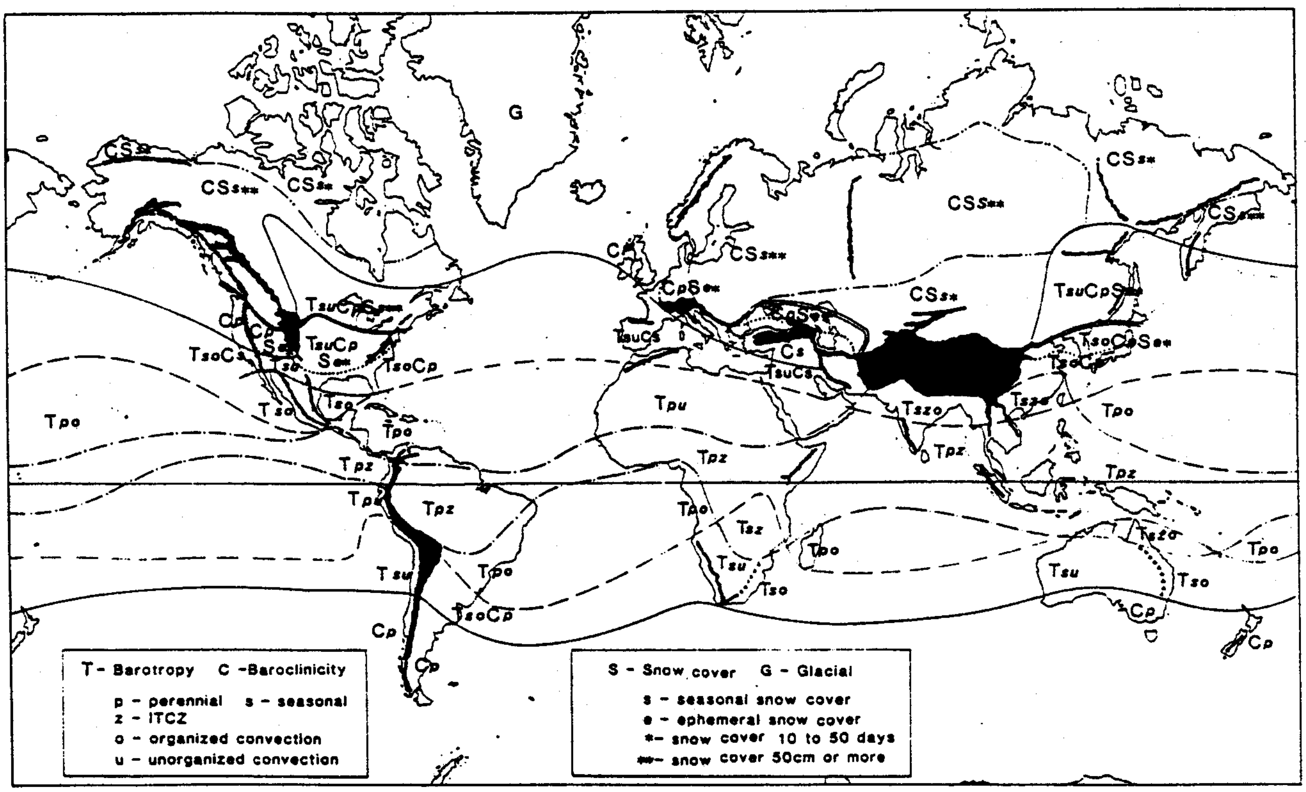

FIGURE 9. Flood climate regions of the world. The legends give the meanings of the letters in the symbolic notation. The solid lines indicate the poleward limits of barotropic conditions in summer and the dashed lines the same limit in winter. The dash-dot lines are the January and July positions of the ITCZ. The dotted line marks the equatorward limit of winter snow cover durations of 10 days or more. The double solid line indicates the equatorward limit of snow cover durations of 50 days or more. The dash-dot-dot line indicates regions with more than 50 days of seasonal snow cover and more then 50 cm of snow. The cross-hatched solid line marks the equatorward limit of frontal cyclones in the North American sector. Solid areas indicate major mountainous regions

zone, and precipitation enhancement of upward motions by orography and heated land surfaces are important in the initiation of precipitation and in flooding. Many islands in oceanic areas fall within Tpo regions. These regions tend to have a strong diurnal cycle in rainfall as daily solar heating is an important forcing process. Rainfalls are most common in the late afternoon and just after sunset.

Tpu. —Tpu regions are also barotropic in all months, but unlike the Tpo areas easterly waves and tropical storms are uncommon or absent. Convective elements are usually discrete or individual thunderstorms. These regions are generally semi-arid or arid and streams frequently ephemeral. Orography is, however, an important aspect where mountains occur in Tpu regions. Unusual conditions may produce flooding in these regions. The Tpu region along coastal Peru may go for decades without sufficient rain to cause flooding and then experience extensive flooding as the ITCZ moves unusually far to the south. This is most likely to occur in El Niño years when warm waters and the ITCZ extend southward along the Peruvian coast. The Tpu region that covers much of North Africa and the southern portion of Saudi Arabia may on infrequent occasions get rains from an unusual northward excursion of the ITCZ in summer or a frontal cyclone in winter. When these rare events occur, significant flooding may occur as the landscape is not adjusted to such precipitation.

Tso. —Tso regions are seasonally barotropic and seasonally baroclinic. During the barotropic part of the year, easterly waves and tropical storms are the most likely discharge mechanism that result in flooding. During the baroclinic part of the year frontal cyclones are the usual source of precipitation for flooding. Tso areas are generally arid or semi-arid and not well adjusted to the copious rainfalls that can arise from tropical storms. The Gulf of California and the central east coast of Australia are two examples of the Tso flood climate type.

Tsu. —Tsu regions like Tso areas are seasonally barotropic (summer) and seasonally baroclinic (winter). During the barotropic part of the year, rain from individual thunderstorms, sometimes orographically enhanced, is the main source of precipitation. During the winter baroclinic period, only modest rainfalls result from fronts and cyclones. The regions are arid and thunderstorms are the main agent of flooding. Thunderstorms in these regions are initiated over the heated surface and along fronts that pass through the region. Central Australia and portions of coastal Chile and Peru are flood climate regions of this type.

TsoCp. —This type of region is predominantly barotropic in the summer season, but fronts and frontal cyclones are present in all months of the year. Tropical storms are common in these regions. The piedmont and coastal plain of the eastern United States is an example. Summer barotropic thunderstorms are often associated with the frontal systems. Mesoscale convective clusters, merged thunderstorms, and severe hail and tornado-producing storms are frequent in this zone. Frontal cyclones in this region may result in heavy rains as they usually involve moist air of tropical origin. Rainfall rates may be high and storms often occur in sequences. Floods occur in all seasons of the year.

TsoCs. —An example of this region is restricted to southern California and northern Baja, Mexico. Barotropic conditions prevail in the summer, and this coastal region is affected by tropical storms. Summer floods of great magnitude, while uncommon, may result from these tropical storms. Otherwise flooding is restricted to the winter when cyclones from the Pacific are common along the California coast. Were it not for the presence of tropical storms this area would classify as TsuCs like the Mediterranean region and southwestern coastal Australia.

*TsoCpSe**. —This region has all the properties of the adjacent TsoCp region but also has winter snow accumulations that are generally short-lived and can result in winter flooding. Tropical storms are common and give rise to heavy flooding in this region. The upper piedmont east of the Blue Ridge Mountains would fall into this category, but the resulting region is small relative to the other regions mapped. Careful inspection of Figure 9 reveals an area between the dotted line and the mountains of New Jersey, Pennsylvania, Maryland, Virginia, and North Carolina. This thin strip would classify as TsoCpSe*.

*TsuCpSe**. —This region is similar to TsoCpSe* except that tropical storms are rare or absent. An example of this type region is the central United States east of the Rocky Mountains and includes the grasslands and much of the deciduous forest of the eastern United States. Like TsoCpSe* there is a diversity of weather systems that may give rise to flooding. It is possible for remnants of dissipated hurricanes to enter these regions and become associated with fronts, but they will differ little from frontal cyclones in these regions that have access to moist air from the south. Flooding occurs in all seasons. Flooding may occur during winter as the snows from earlier storms melt as new rains fall.

*TsuCpSs**. —This region is like TsoCpSe* except that the winter snows usually do not melt and cause midwinter flooding, but there is the potential for an annual flooding at the end of the winter season. The regional example is found in eastern China. The spring flooding is modest because the snow cover is not great. Moist barotropic air masses from the low latitudes provide the moisture for summer thunderstorms that can give rise to local flooding and also provide the moisture for greater precipitation from summertime frontal cyclones.

*TsuCpSs***. —Here winter snow cover is great enough to result in significant spring flooding. Fronts and cyclones occur all year. Barotropic conditions and severe convective thunderstorms occur from time to time during the summer. This type is restricted to North America where warm moist maritime tropical air penetrates far into Canada.

Cp. —In these regions baroclinic conditions prevail all year and flooding arises from frontal cyclone precipitation. Although there may be a seasonality in the frequency of these storms, which are most frequent in winter, they occur in all months of the year. These regions are found in the upper middle latitudes on the western margins of the continents and have access to relatively moist air from the cool oceanic areas. Most of these regions also have mountain ranges, and orographic enhancement of precipitation is important in generating sufficient rainwater for flooding or snowfall accumulation in the mountains. Because these areas are in close proximity to the temperate ocean, the climate is moderate even in winter and snowfalls, except in the mountains, are rare and quickly melt.

*CpSe**. —These areas, like Cp regions, are baroclinic all year, and precipitation arises from frontal cyclones. Unlike Cp regions, CpSe* areas are considerably colder in winter and have snowfalls that may give rise to within-winter flooding as these snows melt. Where elevations are high in CpSe* regions, snows may accumulate throughout the winter season and, springtime flooding from the highlands is common.

*CSs***. —This is a perennial baroclinic region, but rainfall rates and durations from frontal cyclones are usually modest. This low productivity of precipitation is due largely to the inadequate supply of atmospheric moisture. Moist air from barotropic regions is rare. Rainfall from cyclones is generally modest and rarely results in flooding. In these regions the effect of many cyclones must be aggregated by snowfall accumulations. Snowfall is substantial and the snow cover season is long. Flooding is associated with the spring snow melting.

*CSs**. —Like CSs**, conditions are perennially baroclinic but cyclones do not produce enough rainfall to give rise to flooding without accumulations from one snowfall to the next. However, in CSs* regions total snowfalls are modest. In regions of this type in the high latitudes where evaporation is small the spring snowmelt may result in standing water on the tundra but little stream flooding. The CSs* region in central Asia has but a modest spring snowmelt. This region is arid, and, although thunderstorms are infrequent as are well-developed cyclones, these systems are the primary agents of flooding. Ephemeral streams are common in this area of central Asia.

RELATIONSHIPS TO OTHER CLASSIFICATIONS

The flood climate regions delineated in this chapter bear considerable similarity to charts of the vegetation cover classes based on climatic relationships (see Emanuel et al., 1985) as well as to the more standard classifications of vegetation cover such as that of Udvardy (1975). It is not surprising that this correspondence occurs. Vegetation cover is in part a function of rainfall, temperature, snow cover, and the seasonality of these parameters. The correspondence, however, is not exact. Ideally the vegetation cover reflects the mean of conditions of recent centuries and millennia.

Similarities with the more traditional climate classifications of Koppen and Trewartha are apparent in a comparison of Figure 9 with Köppen (1936) and Trewartha's (1968) maps. In their classifications temperature plays a major role. In the flood climate classifiation presented here barotropic and baroclinic conditions of the atmosphere are an "unintended" proxy of temperature.

Similarities of the present classification to classifications of climates based on the circulation are especially encouraging. The reader is encouraged to compare the present flood climate classifiction with Dietrich's (1963) classification of the climate of the ocean; the classification of coastal and marine regions of the world by Hayden et al (1984); and, Bryson's (1966) classification of North American climates based on air masses and streamlines. These classifications and the one generated for this chapter all had the goal of deriving a classification based on atmospheric dynamics.

MEAN VERSUS EXTREME CONDITIONS

Like most climatologies and climate classifications the one proposed here is based on mean conditions. Flooding, by its very nature, is a significant departure from mean conditions. The classification of flood climate regions might well have the term *potential* appended in front. The flood climate regions delineated should have similar potential for flooding. Clearly there will be variations within the delineated regions in the realization of flooding. Basin morphologies, soils, and vegetation cover all vary within regions.

The boundaries between the flood climate regions proposed here reflect the presence or absence of weather systems and their movement as well as the circulation of the atmosphere. The mapped boundaries are mean boundary positions. The actual positions vary from day to day. We have accounted for the seasonal variations in mean positions of the boundaries but have not included the year-to-year differences in the mean boundary positions. The boundaries are not fixed entities. When the ITCZ, for example, moves further northward across North Africa, rain is delivered to the Sahel and the southern margins of the Sahara Desert. Flooding at the times of these extreme movements of the boundaries is especially likely. Tropical storms only rarely penetrate deep into Arizona from the Gulf of California, but, if they do, extreme flooding can result. These landscapes are just not adjusted to such high rainfall rates or totals.

IMPLICATIONS TO PALEOHYDROLOGY AND PALEOGEOMORPHOLOGY

On longer time scales we should also expect to see modifications of the boundaries between flood climate regions. Records of the Holocene and the Pleistocene clearly indicate different hydrologic regimes than those we experience today. During glacial times baroclinic conditions would have extended further equatorward than at present. Tropical cyclone frequencies were probably lower than today (Wendland, 1977) and the extent and duration of winter snow cover were markedly different.

Based on charts published by Joussaume et al (1984), rainwater from the ITCZ has a O−18 isotopic content of about −2 parts per thousand; the rainwater from Tpo regions between −2 and −3 or −4 parts per thousand. In general rainwater taken from north of the polar front zone in winter has O−18 contents that exceed −8 parts per thousand and may reach −28 parts per thousand. Fossil water O−18 may well provide a marker diagnostic of flood climate conditions and as such may help in deciphering the record of Holocene hydrology and geomorphology. Preliminary comparisons of atmospheric vapor O−18 contents using atmospheric general circulation models compare most favorably with observed O−18 contents of rainwater (Joussaume et al., 1984). It may thus be possible to link general circulation model outputs of Holocene climates to the flood climate regions proposed here. Proxies of paleoflood frequencies may in turn help in verifying reconstructions of past climates.

CONCLUSION

The flood climate regions are based on the potential available floodwater in the atmosphere and on the land and on the weather systems that result in the discharge from the atmospheric reservoir and the recharging of the reservoir of snow and ice on the land. The presence of mountains that orographically enhance precipitation and tend to have winter storage of snows complicate the latitudinal and longitudinal symmetry of the distribution of the flood climate regions. Nonetheless, the resulting regions should be internally homogeneous in terms of the kinds of flood-generating events, moisture availability, and other aspects of the water resources of the regions defined.

The goal of this work was to develop a globally consistent overview of the flooding. In this regard it should stand as a valuable addition to the often used charts of global climate, vegetation, soils, and fluvial geomorphologic features.

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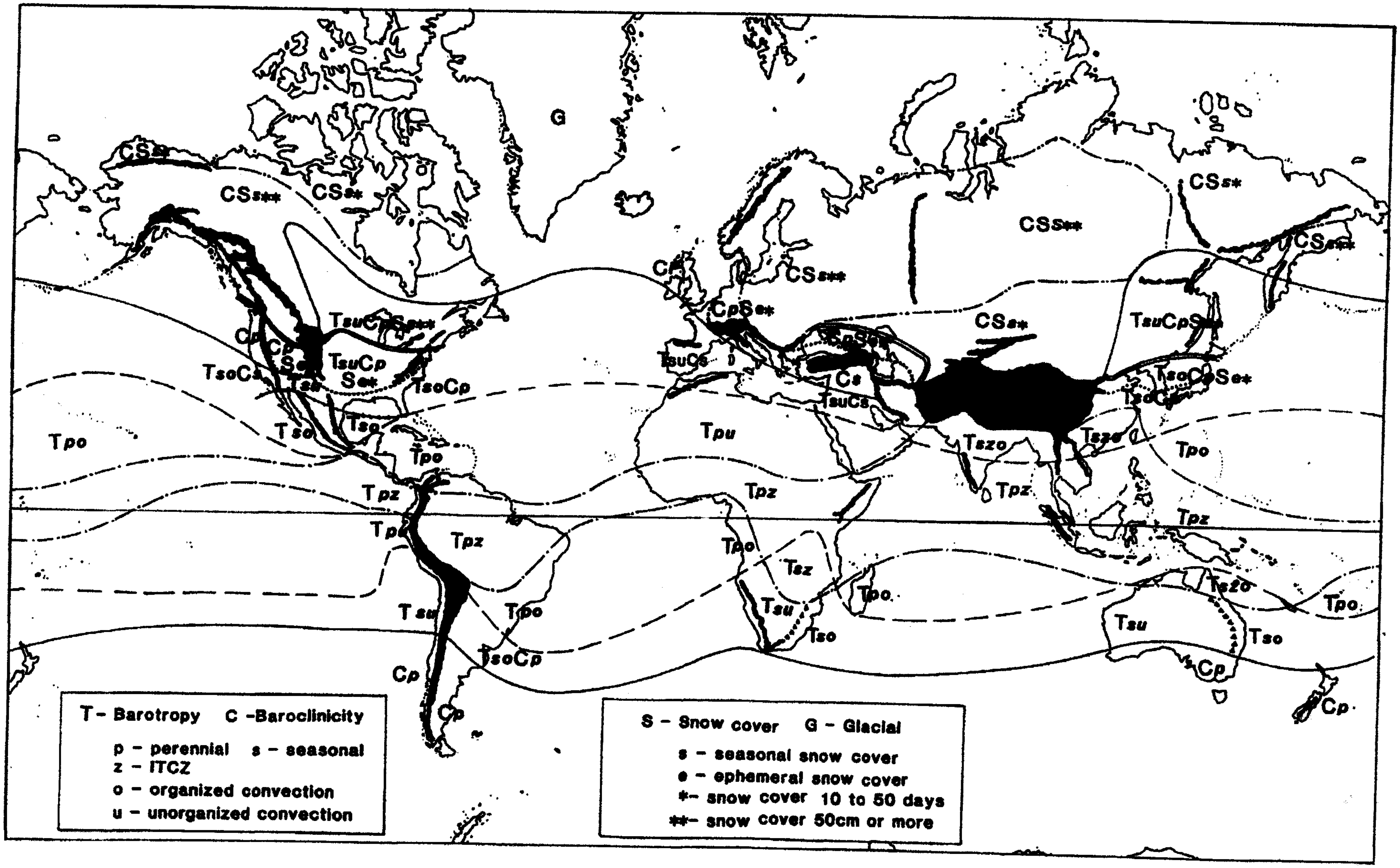
T - Barotropy C -Baroclinicity
p - perennial s - seasonal
z - ITCZ
o - organized convection
u - unorganized convection
S - Snow cover G - Glacial
s - seasonal snow cover
e - ephemeral snow cover
*- snow cover 10 to 50 days
**- snow cover 50cm or more
G
CSs**
CSs*
CSe*
TsuCp
TsoCp
TsoCs
Tso
Tpo
Tpz
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Tsz
Tszo
Cp
CpSe*
TsuCs
Cs
TsuCpSe*
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