Drought in the Southwest, 1942–56

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UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

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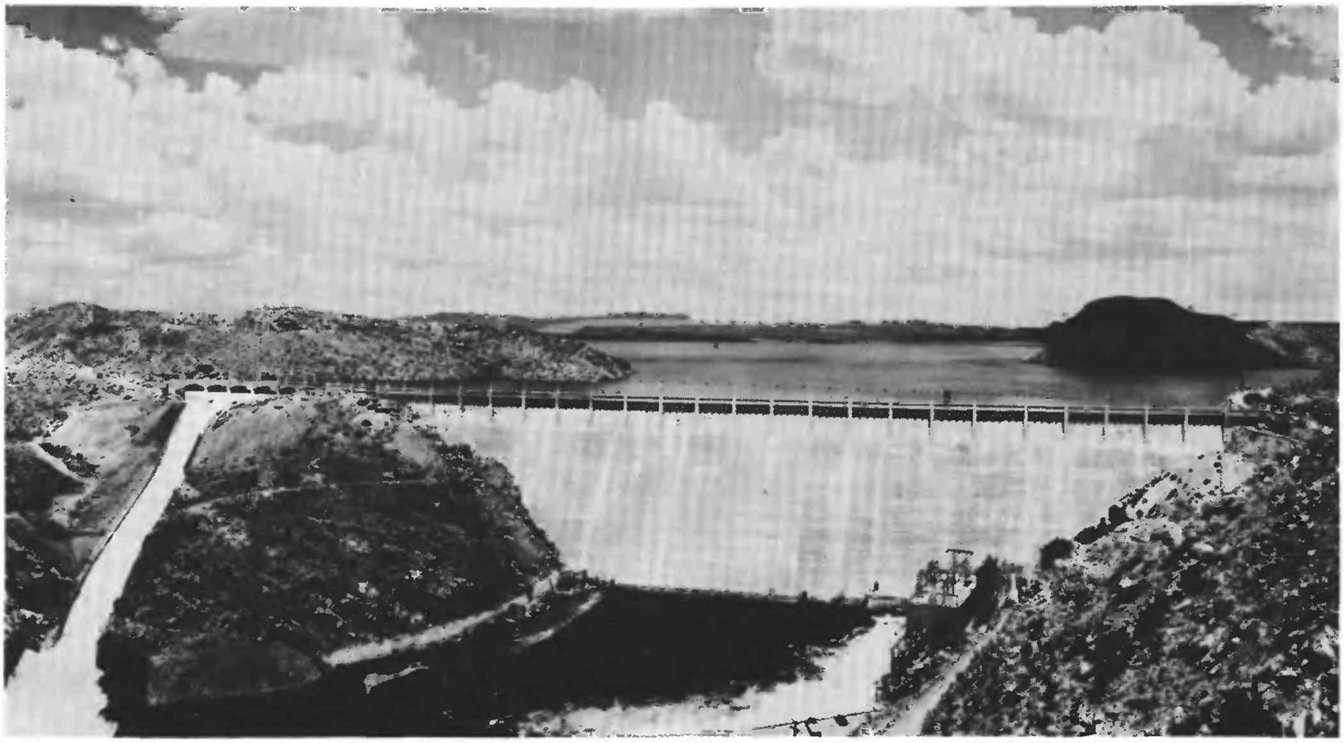
[Letters designate the separate chapters published or in press]



EFFECTS OF WATER SURPLUS AND OF DROUGHT, ELEPHANT BUTTE RESERVOIR, NEW MEXICO

Upper view, reservoir spilling for the first and only time, in the spring of 1942. Lower view, reservoir on September 4, 1951. High-water mark of 1942 is faint line above most conspicuous white watermark.

The Meteorologic Phenomenon of Drought in the Southwest

By H. E. THOMAS

DROUGHT IN THE SOUTHWEST, 1942–56

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PREFACE

One prerequisite for this study is a definition of "drought" that is applicable to conditions in the Southwest, and yet not out of line with the general though varied usage of the term in other regions. Chapter A defines drought as a meteorologic phenomenon, and presents some of the published and recorded conclusions and ideas concerning the basic meteorologic factors that influence the patterns of precipitation in the Southwest. It also considers the characteristics of drought as indicated by meteorologic records. Another chapter will give a general discussion of the effects of the Southwest drought as shown by hydrologic data. Subsequent chapters will provide more detailed evaluations of the effects of drought in individual river basins and specific localities. The effects of drought are discriminated from water shortages due to other causes wherever possible.

Because "drought" is a comparative term, a study of drought requires analysis of the longest records available, whether of precipitation, temperature, wind, streamflow, reservoir storage, use of water, or fluctuations of water levels in wells—with special attention to the drought period to see how it differs from other periods of record. Despite this special emphasis, a study of drought must be almost as broad in scope as general studies of the interrelations of the several phases of the hydrologic cycle, such as the studies of rainfall and runoff in the United States by W. G. Hoyt and others (1936).

In many comprehensive studies of water resources, an important product has been a hydrologic equation, in which the volume of mean precipitation has been calculated, and its disposal accounted for in ground-water recharge, discharge, and changes in storage; in surface runoff and changes in storage; and in evapotranspiration or other consumptive use. In all such studies, emphasis has been on average conditions, and standard procedures have been developed, or at least suggested, for calculation of such items as mean or median runoff, duty of water, consumptive use, safe yield, and the like. By contrast, in a study of drought the emphasis has necessarily been on nature's failure to achieve the average, and the evaluation of that deviation. The methods of study for this report have been of the old-fashioned qualitative type—peering at graphs and noting similarities and contrasts—and include very little statistical analysis of the rather meager data available.

The wet year 1941 provided an excellent starting point for the drought in most of the Southwest, but as year followed year it became evident that drought visited some part of the Southwest practically every year, the only exceptions being wet years like 1941—and history indicates that very few of those occur in a century. The studies leading to this report cover especially the years 1942 to 1956, inclusive. The report includes maps showing the boundary of the area where drought was recorded in the 15 years 1942–56, but the boundary is primarily for the purpose of defining the limits of study and has been determined empirically. Areas outside that boundary have recorded severe droughts during some of these years.

Personnel of the Geological Survey who were assigned specifically to analysis of data and preparation of this report on "Drought in the Southwest" include Joseph S. Gatewood and Alfonso Wilson of the Surface Water Branch; John D. Hem and subsequently Lester R. Kister of the Quality of Water Branch; Harold E. Thomas and George D. Scudder of the Ground Water Branch. Mr. Thomas was designated coordinator of the studies for the Water Resources Division. Other projects of the Water Resources Division throughout the Southwest have been a major source of data and analyses pertinent to the drought. Credit for much of this work is shown in the body of the report, by quotations and references, and by authorship of certain sections. The supervisors of the Geological Survey district offices in the seven southwestern States have also contributed much to this report, in technical assistance whenever it was requested, and in basic data in files of those offices. These district supervisors include Francis M. Bell, Revoe C. Briggs, John H. Gardiner, Berkeley Johnson, Douglas Lewis, Stanley Lord, Wallace Miller, Trigg Twichell, Jack M. Terry, and Milton T. Wilson of the Surface Water Branch; Clyde S. Conover, William E. Hale, John W. Harshbarger, Omar J. Loeltz, Thad G. McLaughlin, Joseph F. Poland, Ray W. Sundstrom, Herbert A. Waite, and George F. Worts of the Ground Water Branch; Eugene F. Brown, John G. Connor, Burdge Irelan, Jay Stow, and Ishmael W. Walling of the Quality of Water Branch.

Other important sources of data pertaining to drought have included the offices of the following State officials: Robert Ernst, and subsequently Obed Lassen, State Land and Water Commissioner of Arizona; Harvey Banks, Director of the California Department of Water Resources; Jean S. Whitten, State Engineer of Colorado, and Ivan C. Crawford, Director of Colorado Water Conservation Board; Hugh A. Shamberger, State Engineer of Nevada and since 1958 Director of the Nevada Department of Conservation and Natural Resources; John Erickson, and subsequently Stephen Reynolds, State Engineer of New Mexico; R. M. Dixon, and subsequently Durwood Manford, Chairman of the Texas Board of Water Engineers; Joseph M. Tracy, and subsequently Wayne D. Criddle, State Engineer of Utah.

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THE METEOROLOGIC PHENOMENON OF DROUGHT IN THE SOUTHWEST

By H. E. Thomas

ABSTRACT

The recent drought is one of several which have been recorded in the arid Southwest in the past century. In regions where precipitation comes chiefly from a single source, as in California and the Great Plains, prevailingly dry periods have alternated with wetter periods, each lasting 10 to 15 years. In the intervening area that includes the basins of the Colorado River and Rio Grande and numerous basins of interior drainage, a deficiency from one source may be ameliorated in some localities by precipitation from another source; in other areas all sources have failed and the drought has continued for a quarter of a century. Earlier droughts of similar duration, and some of longer period, are indicated by historic records and by studies of tree rings, lake levels, and archeologic data.

GENERAL INTRODUCTION

In one of the earliest and most outstanding reports on the arid region of the United States, John Wesley Powell (1879, p. 3–5) points out both the prevailing moisture deficiency and the marked variations in water supply from time to time:[1]

The Arid Region is the great Rocky Mountain Region of the United States, and it embraces something more than four-tenths of the whole country, excluding Alaska. In all this region the mean annual rainfall is insufficient for agriculture, but in certain seasons some localities, now here, now there, receive more than their average supply. Under such conditions crops will mature without irrigation. As such seasons are more or less infrequent even in the more favored localities, and as the agriculturist cannot determine in advance when such seasons may occur, the opportunities afforded by excessive rainfall cannot be improved.

The limit of successful agriculture without irrigation has been set at 20 inches, that the extent of the Arid Region should by no means be exaggerated; but at 20 inches agriculture will not be uniformly successful from season to season. Many droughts will occur; many seasons in a long series will be fruitless; and it may be doubted whether, on the whole, agriculture will prove remunerative. On this point it is impossible to speak with certainty. A larger experience than the history of agriculture in the western portion of the United States affords is necessary to a final determination of the question.

In fact, a broad belt separates the Arid Region of the west from the Humid Region of the east. Extending from the one hundredth meridian eastward to about the isohyetal line of 28 inches, the district of country thus embraced will be subject more or less to disastrous droughts, the frequency of which will diminish from west to east. For convenience let this be called the Sub-Humid Region.

Statistics and statisticians have been multiplying in the decades since Powell made this observation, and they confirm his judgment in all essentials. In the 80-year sample of climate that has now been recorded in the West, there has been a central tendency toward semiaridity in the Great Plains and extensive areas farther west, and toward even greater dryness in many lowland areas of the West. In most of the western half of the United States the mean precipitation is less than the potential evapotranspiration. (See p. A–3.)

Countless plants and animals of the West are adapted to the varying degrees of dryness: for example, grasses thrive in the Great Plains where average precipitation is less than 25 inches; and cactus, creosote bush, yucca, and other xerophytes persist in deserts where the average annual rainfall is less than 10 inches. So far as the people are concerned, whether comparisons are made with the more humid eastern half of the United States or considering the water needs of ourselves and the aggregations of plants and animals that serve us, the western half of the country is recognized as one of prevailing water deficiency. It would probably not be too difficult to adapt ourselves to these climatic conditions if only the "average" climate at each locality were the climate actually experienced. But in most of the West there is a marked variation in precipitation from year to year. For example in the Great Plains, there

[1] Concerning Powell's report, Stegner (1954, p. 212) makes the following analysis: "Embodied in the scant two hundred pages of his manuscript—actually in the first two chapters of it—was a complete revolution in the system of land surveys, land policy, land tenure, and farming methods in the West, and a denial of almost every cherished fantasy and myth associated with the Westward migration and the American dream of the Garden of the World. Powell was not only challenging political forces who used popular myths for a screen, he was challenging the myths themselves, and they were as rooted as the beliefs of religion. He was using bear language in a bull market, 'deficiency terminology' in the midst of a chronic national optimism well recovered from the panic of 1873."

is a central tendency toward semiaridity but the rainfall in one year may be as great as the average for Iowa, and in another as little as the average for southern Arizona. It is the deviation from average conditions that leads to difficulty in many parts of the West. This report is concerned primarily with these deviations from the averages as developed from available records, rather than with the averages. Specifically, we are concerned with the deviations in the southern part of the area west of the 100th meridian that have been below the average in recent years.

Drought was a matter of great concern in the Southwest in 1951. Although there were several localities where the total precipitation that year was less than 50 percent of the long-term average, the concern was caused chiefly by the fact that so many of the years preceding 1951 had also passed with less than average precipitation. The cumulative deficiencies of these years over extensive areas of the Southwest evidently had a pronounced effect on the water supply in many localities.

"The Drought in Southwestern United States as of October 1951" was the subject of a report by the U.S. Department of the Interior (1951), based on data collected and compiled by those bureaus within the department which are concerned in one way or another with the water resources of the region: the Geological Survey, Bureau of Reclamation, Bureau of Land Management, Bureau of Indian Affairs, and Fish and Wildlife Service. The report pointed out that the drought was considered to have begun in 1942 in Arizona, 1943 in New Mexico, 1945 in southern California, and 1947 or later in Texas; also that the drought as of 1951 was one of the eight most severe droughts that had occurred in the region since the 13th century. The contribution by the Geological Survey to that 1951 report was the basic hydrologic data on the drought (p. 11-29). Although those data were hurriedly assembled and analyzed, they gave some insight into the hydrologic phenomenon of drought; more important, they gave promise that a more comprehensive analysis of available data might provide valuable information concerning drought, its causes and effects.

After 1951, drought and the study of drought in the Southwest continued with varying diligence, both as to time and place. Southern California enjoyed a relatively wet year in 1952, sufficient to terminate the drought of the preceding 7 years; that drought has been described by Troxell (1957). However, 1953 was a year of somewhat less than average precipitation in southern California, and so were 1955 and 1956. For the remainder of the Southwest, each of the years 1952 to 1956 brought subnormal precipitation over extensive areas, and the drought shifted from one area to another within the 7 southwestern States. Furthermore, it extended beyond the borders of those States in several years, notably into the northern Great Plains, where serious drought began in 1952 or earlier.

This report summarizes existing information concerning drought in the Southwest, and especially the effects of drought upon the ground- and surface-water resources, based on studies chiefly during 1955 through 1957. Although the report is primarily concerned with drought subsequent to 1941 in the States of California, Nevada, Arizona, Utah, New Mexico, Colorado, and Texas, the characteristics of drought during these years are developed largely by comparison with other "dry" periods, and by contrast with intervening "wet" periods.

DROUGHTS IN GENERAL

"Drought," and its alternative spelling "drouth," trace their etymologies to the Anglo-Saxon "drūgath," meaning "to dry." The words are characteristically associated with the undesirable aspects of being without water. Dictionaries indicate a widespread and somewhat varied use of the word "drought": (a) Dry weather, especially when so long continued as to cause vegetation to wither; want of rain or water; aridity. (b) Dryness of the throat and mouth for want of water; thirst. (c) Figuratively, scarcity of any necessity; dearth. (d) Dryness; also a desert.

Drought is also discussed, or at least mentioned, in numerous scientific and technical writings pertaining to climate or to aspects of water supply. In these references, of course, drought is always indicative of dryness rather than wetness, but that is about as far as one can go toward a universal definition. Reflecting the inexactitude of popular definitions of the word, drought may indicate a moisture deficiency at a certain place over a period of time, or it may describe the conditions in one region as contrasted with another. The U.S. Weather Bureau (1953), after pointing out that drought conditions occur in one or more sections of the country nearly every year, states:

> A drought is usually defined as a "period of dry weather sufficient in length and severity to cause at least partial crop failure." But rainfall, while an important criterion, does not give the complete picture, and a period of scanty rainfall that would be fatal to crops in one region might be sufficient for growth in another. Factors besides rainfall that intensify or mitigate drought effects are temperature, wind, evaporation, sunshine, character and conditions of soil, stage of crop development, etc.

Although the term "drought" is used most widely with respect to precipitation and soil moisture, it is applied also to deficiencies in other water supplies. And because drought also means "want of rain or water," many writers consider adverse effects upon man or his activities as a necessary condition of drought. Thus technical definitions of drought vary rather considerably, depending upon the technologist's hydrologic environment and special field of interest. In particular, the concepts of drought developed in humid regions differ in many respects from those developed in arid regions.

As stated by Thornthwaite (1948, p. 55–56, 75):

> We cannot tell whether a climate is moist or dry by knowing the precipitation alone. We must know whether precipitation is greater or less than the water needed for evaporation and transpiration * * *.
>
> The vegetation of the desert is sparse and uses little water because water is deficient. If more water were available, the vegetation would be less sparse and would use more water. There is a distinction, then, between the amount of water that actually transpires and evaporates and that which would transpire and evaporate if it were available. When water supply increases, as in a desert irrigation project, evapotranspiration rises to a maximum that depends only on the climate. This we may call "potential evapotranspiration," as distinct from actual evapotranspiration * * *.
>
> Where precipitation is exactly the same as potential evapotranspiration all the time and water is available just as needed, there is neither water deficiency nor water excess, and the climate is neither moist nor dry. As water deficiency becomes larger with respect to potential evapotranspiration, the climate becomes arid; as water surplus becomes larger, the climate becomes more humid.

Thornthwaite's areas of moist and dry climates are delineated on figure 1, which shows also the areas of moist climate in which there is a seasonal (summer) water deficiency; the map is based on long-term average precipitation and temperature at more than 3,000 Weather Bureau stations.

DROUGHT IN A HUMID REGION

Several scientists define drought in a humid region on the basis of deficiencies in soil moisture. As stated by J. C. Hoyt (1938, p. 1):

> When in an area that is ordinarily classed as humid, natural vegetation becomes desiccated or defoliates unseasonably and crops fail to mature owing to lack of precipitation, or when precipitation is insufficient to meet the needs of established human activities, drought conditions may be said to prevail.

This is elaborated by Thornthwaite (1947, p. 88):

> Drought is most accurately described as a condition in which the amount of water needed for transpiration and direct evaporation exceeds the amount available in the soil. It results from too little rain. Soil moisture is used up, and plants then suffer from lack of water * * *. It is evident that we cannot define drought as a shortage in rainfall alone. Such a definition would fail to take into account the amount of water needed. Furthermore, the effect of a shortage of rainfall depends on whether the soil is moist or dry at the beginning of the period. Shantz (1927) explained that drought in its proper sense is related to soil moisture and that it begins when the available soil moisture is diminished so that the vegetation can no longer absorb water from the soil rapidly enough to replace that lost to the air by transpiration. Drought does not begin when rain ceases but rather only when plant roots can no longer obtain soil moisture. As early as 1906, Henry pointed out that the intensity of drought could not be measured as a departure of rainfall from the normal, "since a deficiency of 50 percent in a region of abundant rainfall is not so serious as the same deficit in a region where the average precipitation is barely sufficient for the needs of staple crops."

Accurate identification of drought conditions under these definitions requires a detailed water budget such as Thornthwaite (1953) maintained at Seabrook, N.J. This detailed work shows that hidden drought, which brings about a borderline soil-moisture deficiency, oftentimes holds crop yields to as little as a third of the potential.

Because of the difficulty of similarly keeping water accounts for extensive areas, drought is usually defined as a period of consecutive days without rainfall. According to Henry (1930), a drought exists whenever the rainfall for a period of 21 days or longer is but 30 percent of the average for the time and place, and this is approximately the definition used by the Tennessee Valley Authority. The British Rainfall Organization defines a "partial drought" as a period of more than 28 days with a very small rainfall per day, and an "absolute drought" as a period of at least 15 consecutive days to none of which is credited as much as 0.01 inch of rain.

In previous studies of droughts in the United States by the Geological Survey, it has been customary to identify the areas of drought on the basis of meteorologic records, as stated by J. C. Hoyt (1938, p. 2):

> Although deficiency in precipitation is the prime cause of drought, it is not possible to set for any region an exact limit of the total annual precipitation above which a drought does not exist and below which a drought may prevail. In general, however, in the humid and semiarid States there are no serious drought effects unless the annual precipitation is as low as 85 percent of the mean—that is, unless there is an annual deficiency of 15 percent or more. This limit is used in the present report as a measure of a drought year and may serve in many drought studies.

However, annual precipitation is not a sufficient criterion for all droughts. A severe drought may develop because of deficient precipitation during the growing season, even though precipitation in other months may be enough to bring the annual total up to average. Conversely, even though the annual precipitation is well below average, drought may not be recognized if rainfall in the growing season is average or above, because the evapotranspiration is so little in the rest of the year that precipitation less than average may still exceed the need. Thus the distribution of precipi-

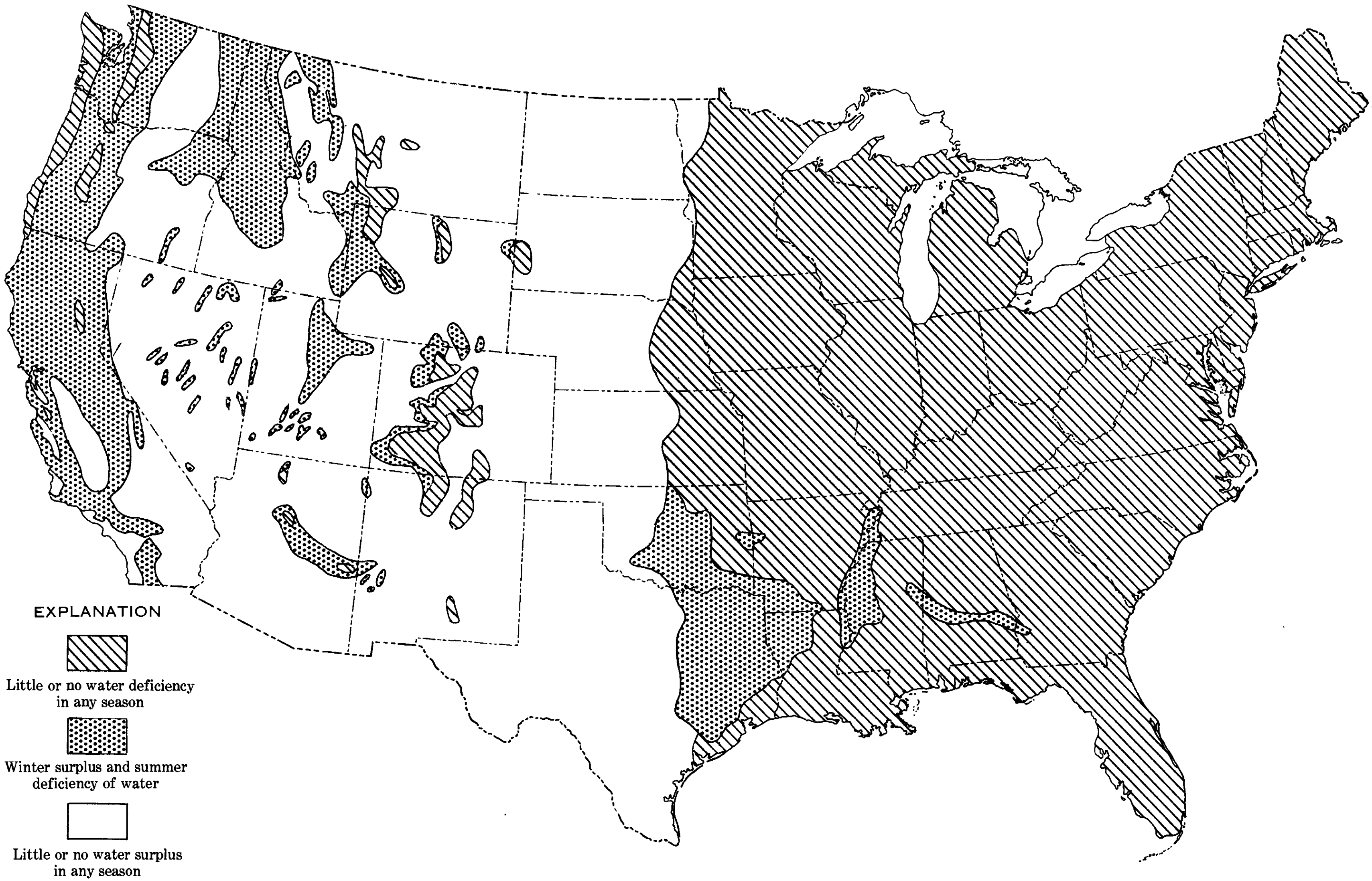

FIGURE 1. Areas of dry and moist climate in the United States excluding Alaska and Hawaii. Adopted from Thornthwaite, 1948

tation in the year may also be a determining factor in drought.

Most reported droughts in humid regions affect mankind chiefly during the growing season of a single year; the resulting soil-moisture deficiencies are replenished by the precipitation of the following winter, and the drought receives a designation such as "drought of 1936," or "drought of 1930." A drought in the northeastern States in 1949 was exceptional among droughts in humid regions because it extended beyond the growing season. No rain was recorded in New York City in the 22 days beginning May 27, and the total rain during June was only 0.16 inch, or 5 percent of the long-term average for the month. This deficiency affected the crops that depended upon rainfall for maintenance of their soil-moisture requirements, a typical feature of drought in the region. But the precipitation continued to be less than usual: in the 8 months ended January 1950 it was less than 65 percent of the long-term average for those months. Discharge from springs and streamflow diminished, with marked effect upon numerous municipal and industrial water supplies, including especially New York City's Croton and Catskill reservoirs. Although this drought was of lesser intensity than several earlier droughts, it caused more trouble to the people of the metropolitan area. (See p. A–7.)

One may surmise at this point that the emphasis on soil-moisture deficiency in the growing season, as a prime measure of drought in a humid region, is to be expected wherever surface- and ground-water resources are habitually more than sufficient for man's domestic and industrial needs. But as man increases his development and utilization of water resources, he will become progressively more concerned with deviations below the average, regardless of the season or the source of supply.

DROUGHT IN AN ARID REGION

An arid region year after year receives precipitation insufficient for the requirements of most crops, and those crops therefore require irrigation. From the viewpoint of a humid region, this is "perennial" or "permanent" drought. From the viewpoint of the arid region, however, it may be questioned whether the term "drought" is applicable when the dearth of precipitation is usual, or "normal," for this dearth is embraced in the definition of aridity that characterizes the region. The native vegetation is well adapted to the climatic norm—the plants in the driest areas subsist on very little water and may remain dormant for months and even years without water. Man, too, can adapt himself and his culture to the climatic norm by irrigation of crops to supply their water requirements throughout the growing season. If "want of water" were the basic criterion of drought, irrigated lands might well be drought-free, even though the entire growing season were rainless.

Nevertheless, the inhabitants of the arid regions are cognizant of drought. At first glance it would appear that their concept of drought must be vastly different from that of the inhabitants of humid regions, for in recognition of the characteristic inadequacy of precipitation upon their lands, they have made themselves independent of it by irrigation. But the water needed for irrigation, as well as that required for domestic, municipal, and industrial use, is also derived ultimately from precipitation somewhere, and variations from the average in precipitation and temperature are of critical importance to all water users. Such variations are as evident in arid as in humid regions, and may be far greater percentagewise.

PRECIPITATION AS A BASIC FACTOR IN DROUGHT

The arid and humid regions depicted on figure 1 have much in common. In both regions, precipitation constitutes the ultimate source of the fresh-water supplies that are useful to man. Except for the water that evaporates at the surface, the soil has top priority upon the water that falls as precipitation. Overland runoff does not occur unless or until the precipitation exceeds the capacity of that surface layer to absorb water. The soil holds water until its field capacity is reached, and any additional water absorbed by the soil moves downward by gravity. In the intervals between storms soil moisture may be depleted by evaporation and transpiration, and this depletion must be made up during subsequent storms before there can be additional downward percolation. The water that percolates downward through the soil enters ground-water reservoirs, and water moves in them by gravity to be discharged ultimately into lakes or streams or oceans, or at the land surface by springs or by evapotranspiration. Streams have the lowest priority on the water that falls as precipitation, for water enters a stream only if it falls directly into the channel, or if it cannot get into the ground by infiltraton, or if it is subsequently discharged from subsurface sources. Even after water has reached a stream it may be lost by evapotranspiration or it may disappear by seepage into underlying ground-water reservoirs.

The great differences in soil-moisture resources, ground-water resources, and streamflow characteristics in various parts of the country are traceable not only to variations in precipitation and other climatic factors, but also to differences in the soil and underlying materials through which water may pass. From any single source—whether it be stream, reservoir, lake, well, spring, seep, infiltration gallery, cistern, or soil—variations in available supply are generally caused by variations in precipitation, unless the natural storage facilities for water are changed by man. Droughts resulting from less than average precipitation, if continued long enough, will ultimately affect all these sources of water, and as Thornthwaite has pointed out, there is no need to classify droughts as climatic, biologic (or agricultural) and hydrologic (or water-supply).

In the eastern half of the country (fig. 1) precipitation generally exceeds evapotranspiration and thus provides a surplus that moves toward the ocean in streams or underground. By contrast, the western half of the country is prevailingly a region (unshaded part of fig. 1) where there is little or no water surplus in any season. This region, of course, includes a wide variation in moisture conditions—from hardly any precipitation at all to sufficient precipitation for certain grasses and grains, for native vegetation suitable for forage, and for dry farming. Of major importance to the region, however, are the small isolated areas (shaded areas within the unshaded part of fig. 1) that produce water surpluses seasonally or throughout the year. These are the humid islands—or highlands—to which the inhabitants of the arid region look for water to meet their requirements.

The western United States, then, is not a uniformly arid region, but a composite of arid and semiarid lowlands and humid and subhumid mountains and plateaus. The mountains and plateaus are sparsely inhabited because of ruggedness, poverty of soil, or short growing season, but the precipitation upon them may be enough for a forest cover and a thick snow cover in the winter. The inhabitants of the fertile but arid lowlands look to these highlands for most of the water they use for irrigation as well as for municipal and industrial supplies. Because of the water flowing from these highlands both in streams and underground, the lowlands may have a relatively large perennial water supply, even though the lowland precipitation may be nil during the growing season, and in places very little at any time of the year.

"WANT OF WATER" AS A FACTOR IN DROUGHT

The definitions of drought quoted on page A–2 suggest that the water needs for established human activities are an essential criterion for drought conditions. W. G. Hoyt (1942, p. 580) states:

> In connection with present-day activities of a highly-organized civilization, it is therefore increasingly difficult to define and delineate droughts on the basis of a study of meteorological and hydrological conditions alone.

In descriptions of droughts as thus defined, the meteorologic phenomenon may play only a secondary role, and the existence of drought depends chiefly upon man's activities. Thus Troxell (1957, p. 7, 29) says:

> To the city dweller, as well as to the agriculturist, a drought exists whenever he is required to reduce his water uses. In light of the foregoing definitions, the frequency of a drought will depend largely on the amount of the water reserves in relation to the region's annual water requirements. If these reserves are large in terms of the water requirements, then many a period of deficient precipitation may pass without any curtailment of the water requirements, and the droughts may go unnoticed as meteorological phenomena. However, there are many less fortunate areas where the reserves are small in terms of the water requirements. In these areas each such period of deficient precipitation is recognized as a drought.
>
> * * * as man's water requirements increase, the adverse effect of the drought on his economy also increases. And frequently these economic features form the principal index of the drought's magnitude in the mind of the public.

Some droughts are described as resulting entirely from causes other than meteorologic, as is brought out by Brooks (1949, p. 169) in reporting the desiccation of South Africa:

> In the past fifty years the country has been suffering increasingly from drought, but the conclusion from expert evidence is that this is not due to an actual decrease in the amount of rainfall, but to a change in the nature of the soil and vegetation. When South Africa was first settled, the country was covered by a rich vegetation, the rainfall was steady and persistent, and a large proportion of it was absorbed. The effect of over-pasturage has been to destroy much of the protective vegetation, and the soil has been washed away or trampled hard. The temperature contrasts have been increased owing to the heating effect of the sun on the patches of bare ground, and the rain now falls largely in heavy "instability" showers, including destructive thunderstorms. The run-off is proportionally greater, owing to the more torrential nature of the fall and the loss of the vegetation, so that with nearly the same rainfall the amount of water available for use has decreased.

Drought would be of little interest to a man if it had no bearing upon his activities, and it becomes of progressively greater concern as it cuts into the water supplies needed by him. Obviously "want of water"—or water requirement—is overwhelmingly important, for it is a basic reason for man's interest in any aspect of water resources. However, from a brief outline of the water situation in the arid parts of the United States (p. A–5) the difficulty of defining drought in terms of water "deficiency" is apparent. Such a definition might be possible in terms of a single crop covering a small area, but in any sizable area, even within a radius of a few miles, water deficiencies might be very pronounced at one place, not apparent at another, and overcome at a third.

The chief difficulty in using water requirement as a factor in the measure of drought is that it easily becomes paramount in the minds of men, and a water shortage may be labeled a "drought" regardless of its cause and, in particular, regardless of the meteorologic background. In terms of water requirements, precipitation alone is never satisfactory for man, beast, or plant: precipitation everywhere is intermittent and irregular and the water must be stored somehow if it is to meet the needs of any form of life. Therefore, any definition of drought based on water requirements must embrace an evaluation of these storage facilities—in soils, aquifers, lakes, reservoirs, and streams—facilities which may be modified by man's activities and in any case are problems separate and distinct from the basic meteorologic factors in drought. Thus, the city of New York would not have been affected by drought in 1949 if the storage facilities then under construction in the headwaters of the Delaware River had been in operation. Lesser demand or greater storage facilities would not have altered the basic meteorologic factors responsible for the drought, but would have made a considerable difference in the effect of the drought upon the city of New York. As another example, the Imperial Valley of southern California is within the southwestern drought area as described in subsequent sections of this report, a broad area in which precipitation has been substantially below the long-term mean for several years. However, Imperial Valley is dependent not upon local precipitation but upon the Colorado River for its water, and since Hoover Dam was completed the storage facilities have been ample to meet the valley's requirements. Thus Imperial Valley feels no effects of the drought that engulfs it.

DEFINITIONS USED IN THIS REPORT

Summarizing the preceding sections, the term "drought" has been commonly applied, rather inconsistently, to three major forms of dryness: (a) a natural condition caused by less than average precipitation over a certain period of time; (b) a natural condition where the average precipitation is low; and (c) Nature's failure to fulfill the wants or to meet the developed requirements of man.

The first of these definitions is used in this report—that is, drought is a meteorologic phenomenon and occurs during a period when precipitation is less than the long-term average, and when this deficiency is great enough and continues long enough to hurt mankind. Drought is thus measured in terms of the duration and magnitude of the departure from the average climate in the area under consideration. Human bias cannot be eliminated from the physical phenomenon, for the records that delineate the physical conditions are available because of the interest of mankind—as shown for instance by the fact that we have no basis for evaluating or studying drought in the Antarctic, where there is no one to be affected. Studies of drought are justified chiefly because of man's interest in the phenomenon in relation to his "want of water."

The dryness of a region with a very low average precipitation is termed "aridity." Drought occurs in arid regions, as it does in regions with a higher average precipitation, only when the precipitation is significantly less than the long-term average. "Water shortage" describes the conditions where the water requirements of man or his crops or industries are greater than the available supplies. Drought may be a contributing factor, or even a predominant factor, in shortage of water supplies, but some shortages can be credited entirely to man.

The effects of drought are measured in the various sources of water—soils, lakes, streams, and surface and underground reservoirs—upon which man depends for his supplies. Depending upon the extent to which a drought reduces these supplies with respect to the developed demand, the effects of drought may be mild, moderate, or severe. By first considering the meteorologic phenomenon without regard to the effects of drought, it is possible to evaluate and compare climatic trends without introducing complications that reflect the varying degree of water-resources development in various localities. Inasmuch as full development of the water resources in a drainage basin is planned on the basis of the long-term average precipitation and streamflow and ground-water recharge, comprehensive analysis of climatic fluctuations, independent of factors related to the stage of development, is an important element in planning.

On the basis of a great variety of data it is possible to identify, or at least infer, climatic fluctuations with great ranges in both duration and magnitude (p. A–17 to A–40). Of the drier periods that are shown by these records, some are measured in days, others in months, seasons, years, decades, centuries, millennia, and even geologic epochs. Not all these dry periods, however, can be called droughts, if the term "drought" is limited to the periods when the precipitation deficiency is great enough and continues long enough to hurt mankind.

In humid regions, a rainless period of several consecutive days is significant for crops dependent entirely upon soil moisture, and is logically termed a drought (p. A–3 to A–5); in a study of such droughts, therefore, the focus is upon climatic fluctuations measured in days or weeks. Throughout the West, however, the development of ground- and surface-water resources has created independence from day-to-day fluctuations in precipitation; instead the focus is especially upon the annual and longer climatic fluctuations that affect those ground- and surface-water resources.

There is a clue from prevailing usage that the term "drought" reflects the relative insecurity of mankind in the face of a natural phenomenon that he does not understand thoroughly and for which, therefore, he has not devised adequate protective measures. A Westerner does not call a rainless month a "drought," and a Californian does not use the term even for an entire growing season that is devoid of rain, because these are usual occurrences and the developed water economy is well bolstered against them. Similarly, a dry period lasting several years, or even several decades, would not qualify as a drought if it caused no hardship among water users. At present, however, we do not understand these long-term fluctuations or their causes sufficiently to anticipate them, and our corrective measures have generally not yet accomplished a perennially stable water economy. Dry periods of several years' duration, therefore, still create a feeling of insecurity, and are properly designated "droughts."

This report is concerned chiefly with dry periods of several years' duration, which are the ones that affect markedly the resources of surface water and ground water. Dry periods measured in centuries are also of scientific interest in the Southwest, but most of the available records are not long enough to cover periods of such length. Here it is necessary to make some ground rules for this report, because the term "drought" as defined is dependent not only upon climatic factors but also upon the population, its requirements for water, and its capabilities in regulating and utilizing the water resources. In the discussions of specific regions, and of the numerous components of those regions (subsequent chapters) the effects of climatic fluctuations upon the established civilization can be recognized, and drought can then be described quantitatively. However, regional comparisons throughout the Southwest, and comparisons of the most recent drought with earlier droughts, are based upon the evidence of climatic fluctuations and their effect upon the water resources.

PATTERNS OF PRECIPITATION IN THE SOUTHWEST

If drought is defined as a meteorologic phenomenon, some understanding of basic meteorology is necessary before droughts can be discussed intelligently, although adequate treatment of this subject is quite beyond the scope of this report. The following sections provide merely a brief summary, with numerous references to more detailed discussions. In particular, the reader is referred to Tannehill (1947), for a comprehensive and very readable exposition of the causes of drought.

MAJOR AIR MASS MOVEMENTS

As pointed out by Tannehill (1947, p. 54):

> The sun heats the continents more in summer than in winter. The oceans change temperature more slowly than the continents. There is nearly always a powerful temperature contrast between the hemispheres, between the oceans and continents, and between the tropics and poles. This keeps the atmosphere in motion and brings moisture to the interior of the continents.

The contrast between solar heating in the tropics and at the poles has a global effect upon atmospheric circulation, to which we can attribute some of the aridity that characterizes southwestern United States. The heating in the tropics causes expansion, decreasing density, and rising of air—most pronounced north of the equator in July, and south of the equator in January. The air tends to pile up at the horse latitudes (30° N. and S.) with resulting high pressure and generally descending winds, but temperature contrasts and air circulation between continents and oceans break up these high-pressure belts in many places. From the high-pressure areas along the belt at 30° N. latitude, part of the air flows back toward the equator, deflected to the right by the earth's rotation to form the northeast trade winds; part continues north, also deflected to the right, and constitutes the prevailing westerlies that are dominant in most of the United States.

The contrasting temperatures of oceans and continents are a dominant factor in the circulation of air over the United States. The Pacific Ocean in particular, because of its size and the prevailing west-to-east direction of air movement identified by Tannehill (1947, p. 78-87) as "The Monster in the Backyard," controls especially the weather throughout western United States but probably exerts considerable influence also farther east. The temperature contrast between ocean and continent results from the fact that the water temperatures change very little from winter to summer in comparison with the land temperatures. The contrast either in summer or in winter is greater in Canada than in the United States. In winter, because of the cooling of the northern part of the continent and the resulting greater density of air in comparison with that over the ocean, there is rapid eastward movement of air from the ocean. The air moving on eastward over the Atlantic becomes warmer and piles up at high levels, so that the eastward outflow of upper atmosphere from the continent is less than the inflow from the Pacific. As the pressure builds up over Canada, cold air is forced southward into the United States, obstructing the flow of warm air from the south. In summer, when the continent is warmer, conditions are reversed: air moves slowly into the continent from the Pacific and more rapidly out of the continent to the northeast. The resulting decrease in pressure over Canada induces northward movement of warm air across the United States from the Gulf of Mexico.

The temperature contrasts between equator and poles, and between oceans and continents, would cause movements in the atmosphere regardless of its composition, so long as it is a gaseous envelope around the earth. So far as precipitation is concerned, however, the important item in the atmosphere is the water vapor, even though the other gases make up 96 to 99.98 percent of the total. The degree of saturation of the air near the land surface indicates whether the atmosphere can absorb more water (if available) by evaporation, or drop some by condensation or precipitation.

The requirements for precipitation include the presence of condensation nuclei and the cooling of an air mass sufficiently to change some of the water vapor into liquid or solid. Clouds may form as a result of the cooling of rising air, and local showers may result if there is sufficient condensation. In the larger airmass movements mentioned earlier, the cold air that descends and becomes warmer at latitudes about 34° N. and S. does not cause precipitation; most of the world's deserts, including those in southwestern United States, occur in these belts. In winter the cold air flowing southward from Canada obstructs the warm moist air flowing northward from the Gulf of Mexico; the resulting movement of the warm air up and over the cold air causes rain or snow in the United States. In summer, also, the warm moist air moving from the Gulf of Mexico is an important source of precipitation as it moves northward toward cooler latitudes.

Mountains form barriers to air circulation; they force the air to rise and become colder, and thus they may be major factors in producing precipitation. In particular, the mountain chains, which extend north-south in the western part of North America, wring the moisture from the air moving eastward from the Pacific Ocean, and thus they receive heavy precipitation on their western slopes. For this reason the air accumulating over Canada in winter is generally dry (Tannehill, 1947, p. 89–96).

The Great Basin and Colorado Plateaus, which include Nevada and Utah and parts of Colorado, New Mexico, Arizona, California, Oregon, and Idaho, are arid or semiarid because of mountain barriers formed by the Sierra Nevada and the Cascade Mountains on the west, the Mogollon Rim on the south, and the Rocky Mountains on the east. Particularly in the autumn and winter when the land is cooling, cold dry air accumulates in this basin to form a persistent high-pressure area, which feeds dry air into the Southwest (Tannehill, 1947, p. 97–106).

Water vapor is itself a dynamic factor in air circulation. Because of its lower density, it has less weight than an equivalent volume of air. Thus, the greatest concentrations of water vapor form areas of low pressure. Other air moves toward these low-pressure areas, for pressure gradients are important factors in air movements.

AIRMASS TYPES IN THE SOUTHWEST

From the brief discussion above of major air mass movements, it is possible to deduce the principal source regions of air contributing to the climate of the Southwest. Thornthwaite and others (1942, p. 4) list the following types of airmasses: (a) Cool moist Polar Pacific, from the northern Pacific Ocean; (b) warm moist Tropical Pacific, from the southern Pacific Ocean; (c) warm moist Tropical Gulf, from the Gulf of Mexico; (d) cold dry Polar Continental, from Canada; (e) hot dry Tropical Continental, from Mexico. The weather at any given place may be influenced in many ways by these masses, but some types of movement predominate in certain seasons. The following descriptions of the predominant movements of these masses into the Southwest are based largely upon studies by the California Institute of Technology, Department of Meteorology (1943).

The Polar Pacific type (fig. 2) brings moisture to the southern half of the United States chiefly in winter, when there is strong southward movement of cold dry air in western Canada. Typically, low-pressure areas are generated along the coast of British Columbia, move southward either along the coast or inland across Oregon, Nevada, and Utah, or perhaps as far south as northern Arizona and New Mexico, before trending eastward across the Great Plains and northeastward over the Great Lakes. By summer the average trajectories of low centers migrate northward to the northern tier of States.

The Tropical Pacific type invades the Southwest infrequently, but when it does it may result in very heavy precipitation. The type is generated between Hawaii and southern California, commonly moves eastward across southern California, Arizona, New Mexico, and north Texas, and continues northeastward. In most winters not more than one or two major storms are identified as of the Tropical Pacific type, but there were eight of them in 1941, which was one of the wettest years on record in the Southwest.

The Tropical Gulf type brings moist air from the Gulf of Mexico into the Southwest, especially into the Great Plains east of the Rocky Mountains and also into western New Mexico and Arizona. These masses are the principal source of precipitation throughout the

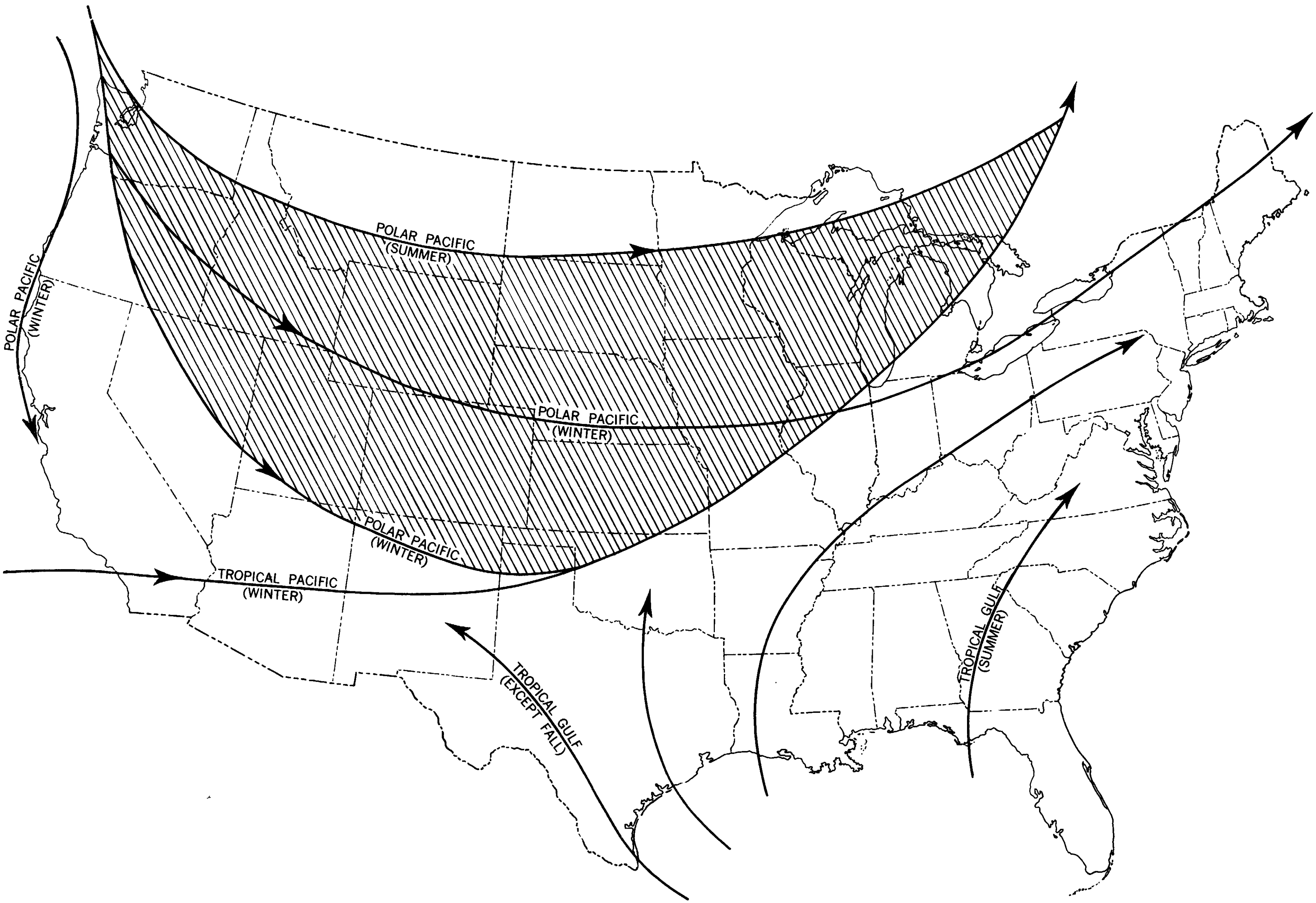

FIGURE 2.—Average trajectories of storm centers in the United States, excluding Alaska and Hawaii. Adopted from California Institute of Technology, Department of Meteorology, 1943.

year in much of the Great Plains, as well as in other parts of New Mexico. In the summer these airmasses are the chief sources of precipitation in most of the Southwest.

Dry Polar Continental air may invade the Southwest from the north or northeast during the winter. Such invasions produce a persistent high-pressure area and sustained periods of cold weather in the Great Basin. The remaining airmass type, the Tropical Continental, is also dry, but hot; it is particularly prevalent in Arizona and New Mexico during late spring and early summer.

A study by Horn, Bryson, and Lowry (1957), which utilizes the Fourier analysis for the description of the annual march of precipitation over the United States, outlines the situation in the Southwest as one of transition between broad regimes. The Pacific winter rains extend eastward in diminishing relative importance across Arizona and New Mexico. The Gulf summer rains sweep northwestward rather suddenly around July 1 to cover Arizona and New Mexico, but diminish northward in relative importance and fail to reach westward to coastal California. Over Arizona, southern Utah, and southern Nevada those two regimes are of similar importance and result in a dominant semiannual variation of rainfall, somewhat more in winter in most of Utah, Nevada, and western Colorado, somewhat more in summer south of a line through Elgin, Nev., Cedar City, Utah, and Gunnison, Colo. Subsequently, Bryson (1957) made a more detailed analysis of the annual march of precipitation in Arizona, New Mexico, and northwestern Mexico, and concluded that:

> an area consisting largely of the Sierra Madre Occidental in northwestern Mexico, and the portion of Arizona southeast of Tucson constitute a single rainfall province with a strong summer maximum of rainfall. This province also has a winter maximum but only in Arizona does the semiannual term exceed the annual in amplitude. Within the United States the Gila and Rio Grande valleys constitute rainfall provinces of internally similar annual march, while the upland areas tend to resemble the Pacific coastal pattern to the west.

Recent studies by Eugene Peck of the U.S. Weather Bureau show that in southern Utah also the annual march of precipitation in upland areas is different from that in adjacent lowlands.

OROGRAPHIC INFLUENCE

The average annual precipitation at Weather Bureau stations has been the basis for various maps showing mean precipitation by isohyets (lines connecting places having equal precipitation) or by zones such as 0–10 inches and 10–20 inches. For the country as a whole the most recent map of mean precipitation was published by the U.S. Weather Bureau (1957), based on the 30-year period 1921–50. Figure 3, adapted from this map, shows the close relation of precipitation to topography in the Southwest: the highest average precipitation occurs on the high mountain ranges, and precipitation is least in the lowlands.

In recent years the precipitation pattern has been studied in greater detail in several areas in the seven southwestern States, notably by Spreen (1947) in western Colorado, Hiatt (1953) in northern Arizona, Troxell and others (1954) in southern California, and Peck (1956) in northern Utah. Troxell and others found that the lines of equal average precipitation increase in altitude with increasing distance from the ocean and are notably higher on the lee slopes than on the windward (western) slopes of mountain ranges. Hiatt found altitude to be the most important topographic factor in precipitation in northern Arizona, although the degree of rise and direction of rise were also significant.

The mean annual precipitation necessarily includes precipitation from both Pacific and Gulf sources. It is well recognized that the prevalence, directional movement, and characteristics of airmasses follow no single defined standard pattern during winter or summer: Polar Pacific air may sweep across the Southwest at any time, and Tropical Gulf masses may cause precipitation during winter as well as summer. Nevertheless there is a seasonal predominance of each that may influence the average weather, or climate, at any given location. The relative proportion from Gulf and Pacific sources is therefore suggested by comparison of precipitation during the summer (April–September) and winter (October–March). Dorroh (1946, fig. 2) shows that the average summer precipitation is more than 75 percent of the annual total in the Great Plains, and slightly less than 50 percent in western Arizona and Utah. By contrast, the April–September precipitation in southern California is a very small proportion of the annual total.

SUBDIVISIONS OF THE SOUTHWEST

In his analysis of precipitation data for Arizona, Hiatt (1953, p. 191) found it necessary to use the parameter of "Zone"—

> * * * an area contained within logical topographic boundaries which separate the stations into sizable groups exhibiting a consistent relationship between station precipitation and the parameters used. The Zone parameter, in particular, is also a catch-all which serves to separate the data into groups containing unaccountable but consistent variations in precipitation.

Early in the studies for the present report it became apparent that the broad region of the Southwest is not a homogeneous meteorologic unit, and that it includes several subdivisions of contrasting precipitation pat-

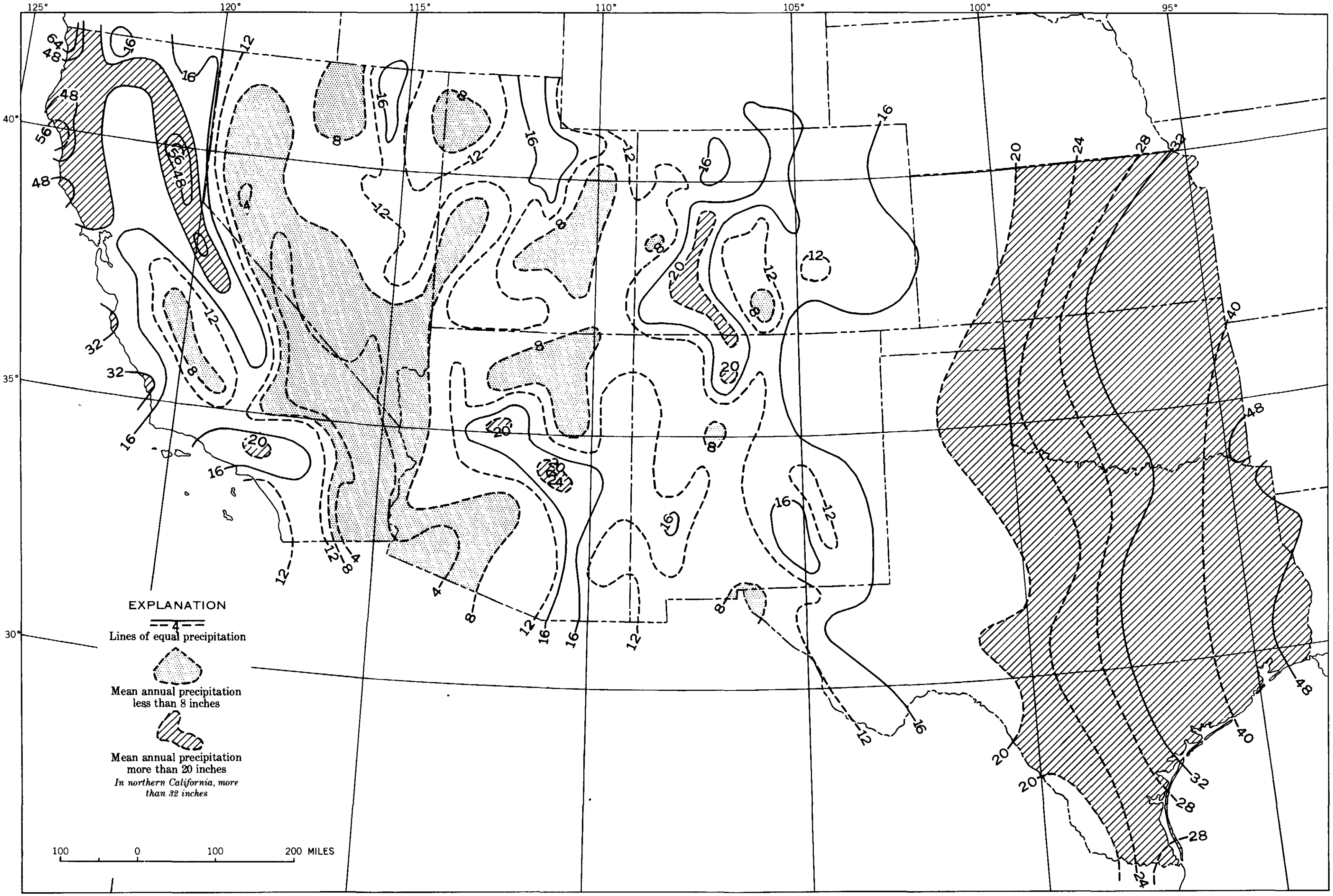

Figure 3.—Mean annual precipitation in the Southwest. Based on 30-year normals, 1921–50, supplemented by long-term averages in mountain areas.

terns within each of which there is some degree of consistency among the records from individual localities. This is to be expected from the various airmasses that cause the precipitation, and from the indicated effects of topographic barriers upon that precipitation. In part the subdivisions suggested below and outlined on figure 4 are extensions of the zones outlined by Hiatt in Arizona.

The Pacific Border includes the part of California west and south of the Sierra Nevada and the high ranges of southern California—that is, the coastal valleys and ranges and the San Joaquin Valley—where most of the precipitation originates from Polar Pacific or Tropical Pacific airmasses, and falls during the six months October through March.

The Sonoran Border adjoins the Pacific Border to the southeast, and lies generally south of the Mogollon Rim and other highlands as far east as the middle Rio Grande Valley in New Mexico. It includes the Mojave and Colorado deserts in California and the Sonoran desert of Arizona, which border the Mexican State of Sonora. Here too the Pacific Ocean is the source of precipitation during the winter, but the amount is considerably less than that received along the Pacific Border, because the deserts of southern California are in the rain shadow of high ranges, and southern Arizona and New Mexico are far inland. The California deserts receive no more precipitation in the summer (April through September) than does the Pacific Border subdivision, but summer precipitation constitutes a larger proportion of the annual total. Farther east, in Arizona and New Mexico, most of the annual precipitation occurs during the summer, during the "Sonoran summer monsoon" (Bryson, 1957). This Sonoran Border includes the most arid region in North America, which receives very little precipitation from any source. A feature of the zone is the hot dry Tropical Continental airmasses originating in Mexico, especially in late spring and early summer.

The Great Basin–Colorado Plateaus subdivision is east of the Sierra Nevada, north of the Mogollon Rim, and west of the Rocky Mountains, and thus includes the

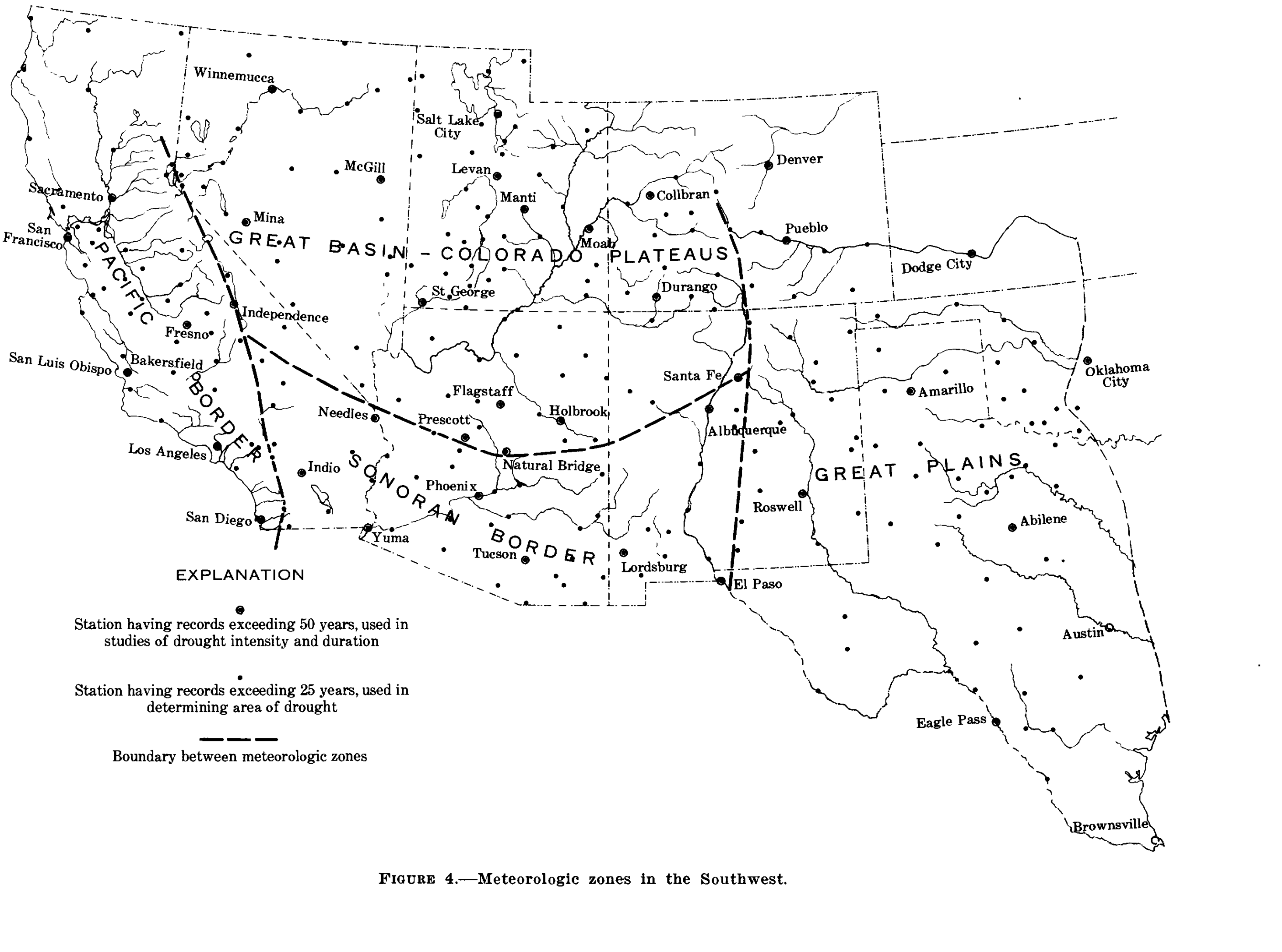

FIGURE 4.—Meteorologic zones in the Southwest.

Great Basin of Nevada and western Utah and the Colorado Plateaus farther east. The western part of this area is in the rain shadow of the Sierra Nevada. The Ruby and Snake Ranges in eastern Nevada and the Wasatch Range in northern Utah are the most significant orographic features within this subdivision. The area receives precipitation from both Polar Pacific and Tropical Gulf airmasses, and in winter it also receives dry Polar Continental air from the north, which may develop persistent high-pressure areas within the Great Basin.

The Great Plains subdivision includes the part of the drought area lying east of the Rocky Mountains in eastern Colorado, eastern New Mexico, and Texas. Much of this subdivision is in the rain shadow of the Rockies insofar as moisture of Pacific origin is concerned, and a large part of its precipitation occurs during the six months April through September.

DEVIATIONS FROM AVERAGE PRECIPITATION

The precipitation patterns of the Southwest, and the airmass movements involved, have been summarized in preceding sections in terms of average conditions: in the case of precipitation, the computed mean at each locality, based on the period of record; in the case of airmass movements and storm tracks, the average of observations of many individual storms as they progressed into and across the region.

These averages are important elements in the description of the climate of a region; in some parts of the earth the climate, at least seasonally, is sufficiently uniform that such averages indicate the normal or usual climate. This is not true of the Southwest, where in most places the averages of annual precipitation are based upon a great range in yearly totals; as an outstanding example, the maximum annual precipitation at Indio, Calif., (in 1939) was 89 times the minimum (in 1894). Thus, although in common parlance and in Weather Bureau publications prior to 1955 [2] "normal" is used as synonymous with "mean," the mean precipitation in southwestern localities is not normal in the sense of being usual or most common. At six cities having precipitation records covering 63 to 103 years (p. A–15), the yearly precipitation during more than half of the years has been either less than 85 percent of the record mean or more than 120 percent of that mean.

[2] In January 1955 the Weather Bureau issued the following definitions: Normal: a mean based on the 30-year period, 1921–50, if necessary adjusted to the most recent location, and revised at the close of every decade by dropping the first 10 years of data and adding the 10 most recent years (according to the World Meteorological Organization regulations). Record mean: mean for the entire period of record without adjustments. Mean: mean for any specific period of record, other than normal or record mean.

Many of the irregularities of individual storms are obviously caused by detailed physical aspects of the earth's surface as the airmasses pass over it. As Namias (1955, p. 205) points out:

> To name only a few pertinent factors, one might cite the differing effect of various surfaces (snow cover, open water, bare land, etc.) upon incoming radiation from the sun, the impact upon various air flows of mountain chains, and the net result of the latent heat of condensation released when precipitation falls. These factors presumably operate differently depending upon the initial state of the general circulation. In this sense subsequent anomalous patterns are viewed as a natural evolution from preceding patterns which are themselves anomalous. In other words, the circulation changes, whether treated on the scale of a day, a week, a month, a season or more, are self-evolving and are guided by an ever-changing radiational balance incident to changing season.

CHARACTERISTICS OF RECORDED DROUGHTS IN THE SOUTHWEST

This section considers drought in the Southwest solely as a meteorologic phenomenon—a deficiency of precipitation in comparison with the long-term average—and disregards the question of its significance or seriousness to mankind. Drought during the years 1942–56 is considered with respect to geographic area and the annual variations, frequency of dry years, and persistence of drought within that area. Comparisons of this drought with earlier droughts and with intervening periods of more abundant water supply are based upon data from a variety of sources which document the climatic fluctuations in the Southwest.

The most abundant and detailed records pertaining to climatic fluctuations are those from the U.S. Weather Bureau's network of precipitation stations, which provide the only direct and quantitative measurements of the gross water supply that falls as precipitation. Although each station provides only a sample of the rainfall in a broad area, a sufficient number of records reasonably consistent with each other provides a sound basis for conclusions as to regional climate and fluctuations in that climate. Hence these records are given especial attention. In the Southwest hundreds of these records cover more than 50 years, and about half a dozen extend back for a century.

Climatic fluctuations prior to 1850 are indicated by data from tree rings, lakes in closed basins, historic records, and archeologic and geologic studies. Based on these data, inferences may be drawn concerning climatic fluctuations in the past several thousand years.

AREA OF DROUGHT IN 1942–56

For a first approximation in delineation of the area of the recent drought in the Southwest, it was assumed that there are no serious drought effects unless the annual precipitation is less than 85 percent of the record mean as computed by the Weather Bureau. J. C. Hoyt uses this criterion for State averages of precipitation in identifying drought in humid and semiarid States, but points out also that in arid regions it might be misleading because of the wide range of precipitation; he shows (1936, p. 65–66) that in the Southwest the State average precipitation was less than 85 percent of the long-term mean in 12 to 19 out of 54 years, and less than 70 percent of that mean in 3 to 7 of those years. It has long been recognized that relative variability of precipitation varies inversely with mean total precipitation; a recent confirmation of this principle is contained in a report by McDonald (1956), who points out that the coefficient of variability (the dimensionless quotient of the standard deviation of precipitation divided by the mean) is generally higher for Arizona localities than for more humid regions.

Plate 1 shows the areas in the Southwest where precipitation was less than 85 percent of the record mean as of 1941 in each of the calendar years 1942 to 1956, inclusive. These areas are outlined on the basis of data from more than 300 precipitation stations (locations shown by dots on the maps) where records cover more than 25 years. The area of precipitation deficiency changed markedly in size and position from year to year but every year it was large enough to extend into at least four States, and in most years it covered parts of all seven States, California, Nevada, Arizona, Utah, Colorado, New Mexico, and Texas. In some years, notably in 1956 and to a lesser extent in 1950 and 1952 to 1954, inclusive, drought conditions enveloped a large part of the United States (U.S. Weather Bureau, 1953, 1957). In these years the area of precipitation deficiency extended beyond the arid and semiarid Southwest and into more humid regions farther east, where the chief effects of drought are deficiencies in soil moisture during the growing season.

The dashed line forming the eastern boundary on each of the maps of plate 1 (extending from central Kansas south to the Gulf of Mexico) represents the boundary between areas of normally moist and dry climates, as delineated by Thornthwaite (see fig. 1). East of this line the mean precipitation exceeds the potential evapotranspiration and provides a surplus for surface or underground flow. West of the line (except in numerous but isolated mountainous areas) the average precipitation is insufficient for the evapotranspiration demand, and the climate is arid or semiarid.

It is a general rule that dry years—when precipitation is less than average—are more frequent that wet years. In other words, the median rainfall—the amount that is exceeded in 50 percent of the years—is significantly less than the mean, or long-term average. The graphs of figure 5 show the frequency of annual precipitation at six cities in the Southwest. In this group the annual precipitation has been less than the mean during 52 to 65 percent of the time, and has been less than 85 percent of the mean in one-third to one-half of the years of record. The "scatter" of individual years from the central tendency is indicated by the standard deviation. Statistics of these six records are summarized in the table below.

Precipitation in every part of the Southwest has been less than 85 percent of the record mean in at least 3 of the years 1942–56, and in some areas as much as 13 of those years. If annual precipitation less than 85 percent of the mean is to be expected at least one-third of the time, as suggested by the records from several stations (fig. 5), then drought or exceptional dryness occurs only when and where such a precipitation deficiency exceeds this frequency.

The areas where precipitation was less than 85 percent of the mean in more than half of the years 1942 to 1956, inclusive, are bounded by heavy lines on figure 6. This boundary defines the southwestern drought area as discussed in this report; it includes nearly all of Arizona and New Mexico, substantial parts of California and Texas, and some of Nevada, Utah, and Colorado.

Annual precipitation, in inches, at six cities in the Southwest

Station (see fig. 5)	Length of record in 1954 (years)	1	2	3	4	5	6
		Median	Record mean	Observed maximum	Observed minimum	Standard deviation	Coefficient of variability [1]
Indio, Calif	75	3. 07	3. 56	12. 47	0. 36	1. 92	0. 54
El Paso, Tex	74	8. 26	8. 67	17. 46	2. 40	3. 43	. 40
St. George, Utah	63	8. 29	8. 45	20. 11	3. 01	2. 81	. 33
San Diego, Calif	103	9. 63	10. 05	26. 09	3. 63	3. 48	. 35
Tucson, Ariz	85	10. 80	11. 19	20. 90	4. 73	3. 26	. 29
Santa Fe, N. Mex	103	13. 73	14. 18	26. 75	7. 31	4. 25	. 30

[1] Ratio of standard deviation to mean.

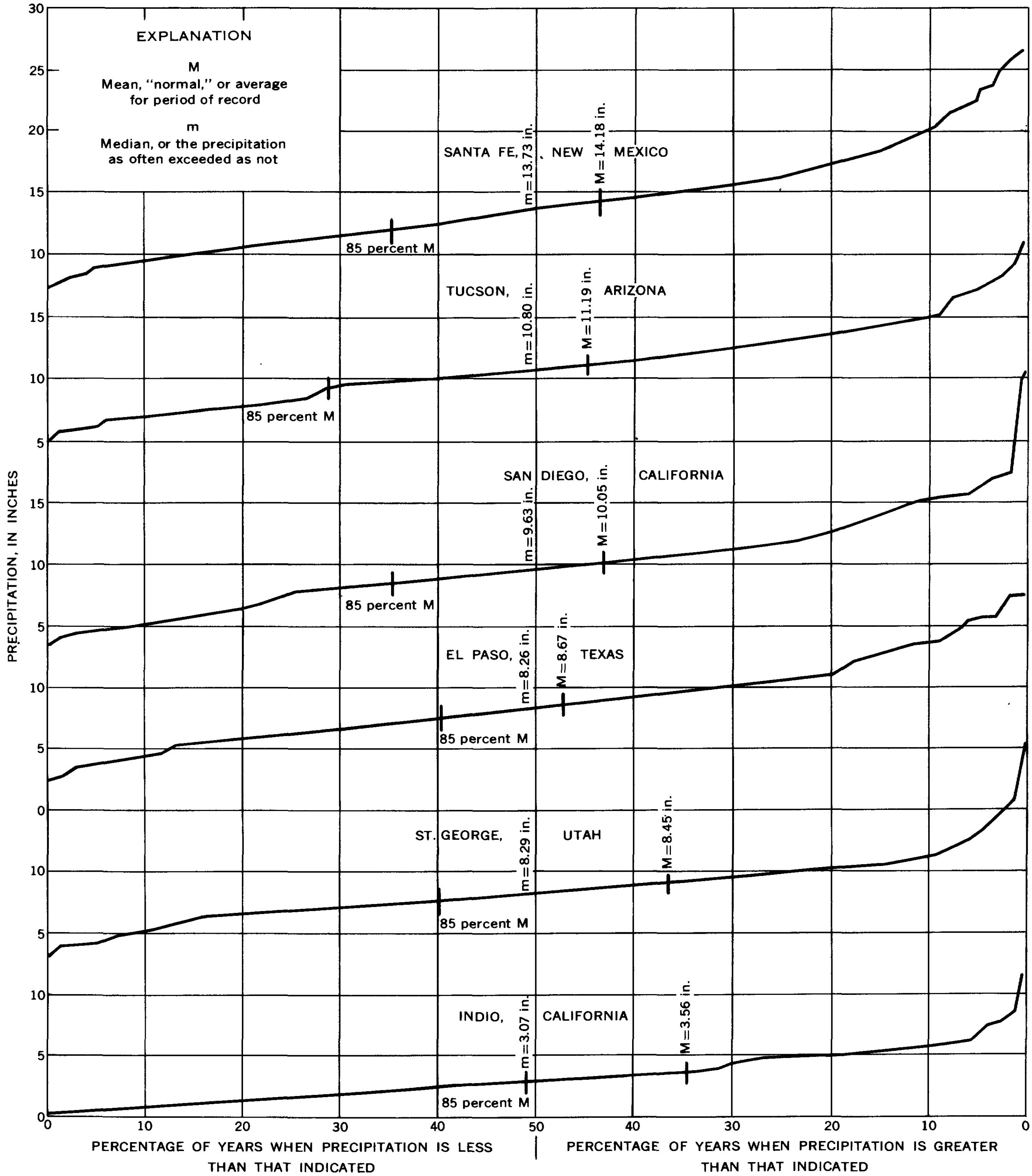

FIGURE 5.—Frequency of annual precipitation at six cities.

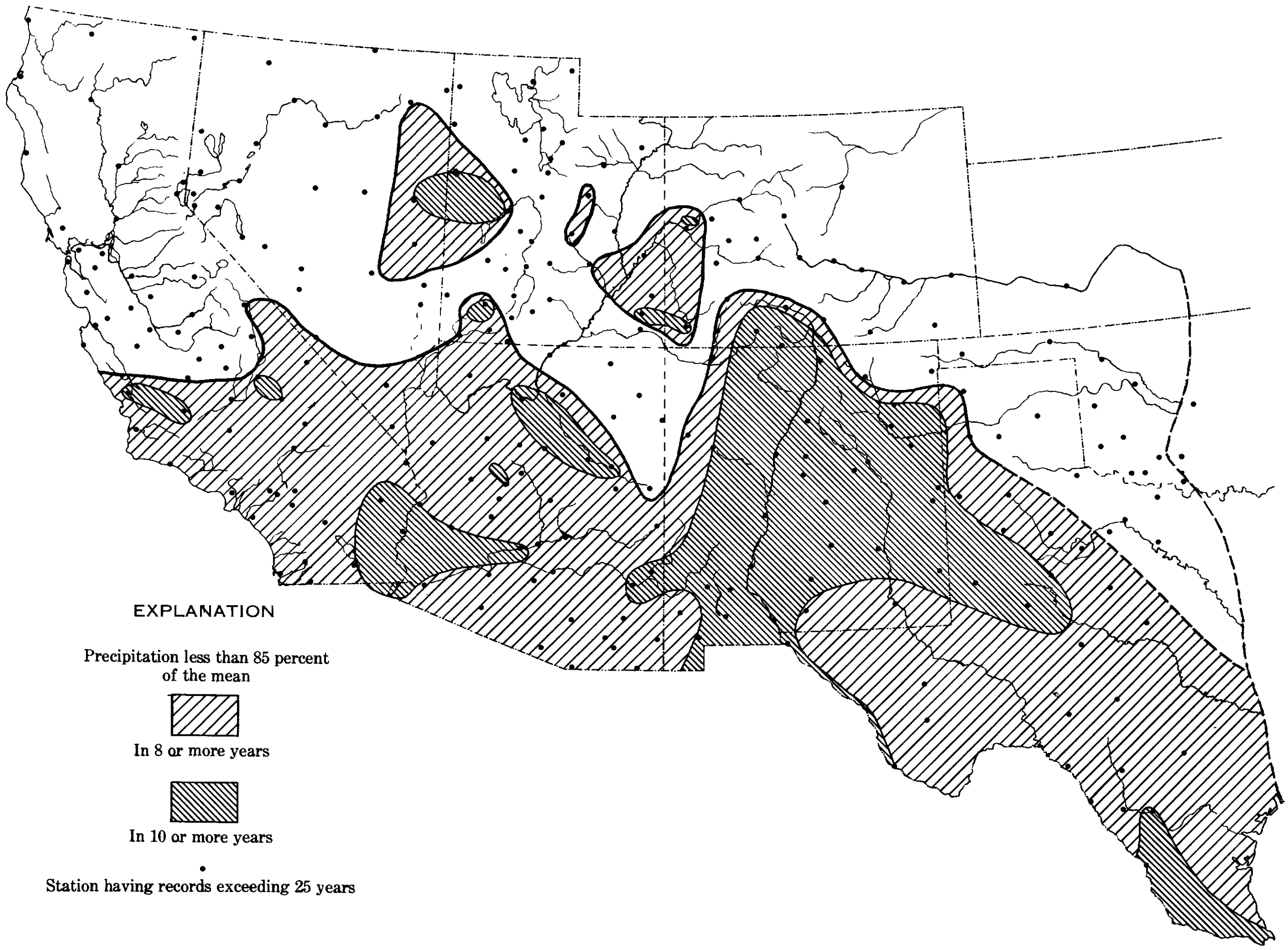

FIGURE 6.—Area of drought in the Southwest, 1942–56.

CLIMATIC FLUCTUATIONS SHOWN BY WEATHER RECORDS

ANALYSIS OF RECORDS

Our studies of climatic fluctuations during the past century, and especially the comparisons of the recent drought with earlier droughts and with periods of more abundant precipitation, are based chiefly upon records at 40 localities in the southwest quarter of the country. These localities are indicated on figure 4, and 31 of them are within the drought area outlined on figure 6. Eight of the records were begun prior to 1870, 17 by 1880, 30 by 1890, and all 40 by 1900. At most of these cities and towns the locations of the rain gage has been changed one or more times during the period of record—perhaps from ground level to the top of a building or vice versa, or from the center of town to an airport, or from valley to ridge or ridge to plain.

CONSISTENCY OF OBSERVED DATA

Generally for the discussion and graphs in this report, the records have been accepted as published, because comprehensive adjustment of the observed data is beyond the scope of this report. It is recognized, however, that several of the records may include some inconsistencies resulting in part from the method of sampling. For ascertaining the consistency of precipitation data over a long period of record, a method frequently used is double-mass analysis, developed by Merriam (1937) and recommended by Kohler (1949) for testing the consistency of meteorologic records. This method is based on determining the mean precipitation for each year of common record at a group of stations within a certain region, and plotting cumulatively the annual precipitation at one station against the accumulated group mean. A straight line indicates a consistent year-by-year relation, and it is then pre-

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sumed that the single station has recorded the same natural fluctuations as are indicated by the group. A change in relation is shown by a change in slope, and the point of change may coincide with the date of a change in location of the station (Hiatt, 1953; McDonald, 1956, p. 19). For study of records extending back for 50 years or more, the method has the limitation that the stations are generally so widely spaced that natural consistency among them cannot be assumed.

The San Francisco Bay area in California, however, provides an excellent opportunity to compare records from three stations—San Francisco, Oakland, and San Jose—all within 50 miles of each other, and all operated continuously since 1875. From preliminary analysis of the records, Piper (1959) states that the three stations sample a relatively homogeneous meteorologic environment, and that the major inconsistencies in records of measured yearly rainfall were due to changes in station locations, of which there have been 5 at San Francisco, 3 at Oakland, and 7 at San Jose during the 83-year period of common record. On the basis of double-mass analysis, he concludes that for consistency among the three stations, adjustments to the San Francisco record would range from +1 to −5 percent in 68 of the years, but would be near +30 percent in one 15-year period; the Oakland record requires little adjustment after 1917, but an increase of 12 to 15 percent in earlier years; and the indicated adjustments for San Jose range from −20 to +11 percent. "Sampling errors," including those resulting from changes in location of the gage, may thus be of sufficient magnitude and duration to simulate a marked fluctuation in climate, whether a drought or a wet period.

CENTRAL TENDENCY IN PRECIPITATION

Concerning precipitation in arid regions in general, and in Arizona in particular, McDonald (1956, p. 2) points out that the "overall variability of a given station's precipitation series may be regarded, in first approximation, as composed of two parts—the variability contributed by secular trends or oscillation about the long-term mean, and the variability contributed by shorter period (as, yearly or seasonal) 'random' fluctuations about the secular trend."

He then (1956, p. 81) summarizes his studies to date as follows:

> Computation of the ninety-five percent confidence half-widths of seasonal and annual precipitation means has made clear how large an uncertainty must be recognized as existing even in the means of stations that have many decades of past records. Roughly, these half-widths amount to fully ten percent of the mean themselves for the sampled long-record stations.
>
> * * * Secular trends in Arizona precipitation, studied through the use of 10-year moving-average plots, revealed a widespread pattern of general decline of precipitation since about the 1920's, but also revealed differences between stations that demand further careful study. Resolution of total variance into components associated with secular trend and with year-to-year fluctuations indicated that the latter is definitely the dominating component, yet the decadal means have clearly varied through amplitudes of very great ecologic and economic significance.

In studies involving the use of records from numerous localities, many scientists have found it necessary to reduce the tabulated precipitation values to means for a standard period of records. "Otherwise," states Hiatt (1953, p. 187), "we would be dealing not only with averages based on various lengths of record but with averages based on an unknown assortment of predominantly dry, wet, or normal periods." Piper (1953, p. 12) compares the precipitation records from numerous cities in the United States on the basis of the 1901–50 mean but concludes that this period is too short to measure a firm long-term average. In Los Angeles where there are indications of cyclic fluctuations in precipitation, Stafford and Troxell (1953) developed means based upon the records for one or more complete cycles of wet and dry periods, rather than for half-centuries or other periods convenient to man but irrelevant in nature.

The mean precipitation can be derived and utilized effectively in studies of the climate of areas where the research is detailed enough to develop the major patterns of climatic fluctuations (Stafford and Troxell, 1953), or where a standard period of record can be applied to homogeneous climatic zones (Hiatt, 1953). In the broad area of the Southwest drought, however, such detailed study is beyond the scope of this report. The term "mean" therefore is used with qualifiers that state the period for which it applies, and no inference is intended as to the true mean of precipitation at the locality.

GRAPHIC PRESENTATION OF DATA

A common method of representing the time changes in precipitation is a bar graph showing monthly or annual precipitation. Figure 7 shows the fluctuations in water-year [3] precipitation at five localities in the Southwest. As shown by these graphs, the range in annual precipitation, expressed in inches, is generally greatest in localities of high average precipitation, but the variation from the mean, expressed in percent, is highest in those arid regions where the average precipitation is only a few inches a year. The graphs show also that both the yearly precipitation and the average precipitation differ considerably from place to place in the

[3] The "water year," ending September 30 of the year indicated, is commonly used in hydrologic studies. Particularly in the North and West, where precipitation accumulates as snow during the winter and contributes to runoff in the following spring, the water year has obvious advantages over the calendar year.

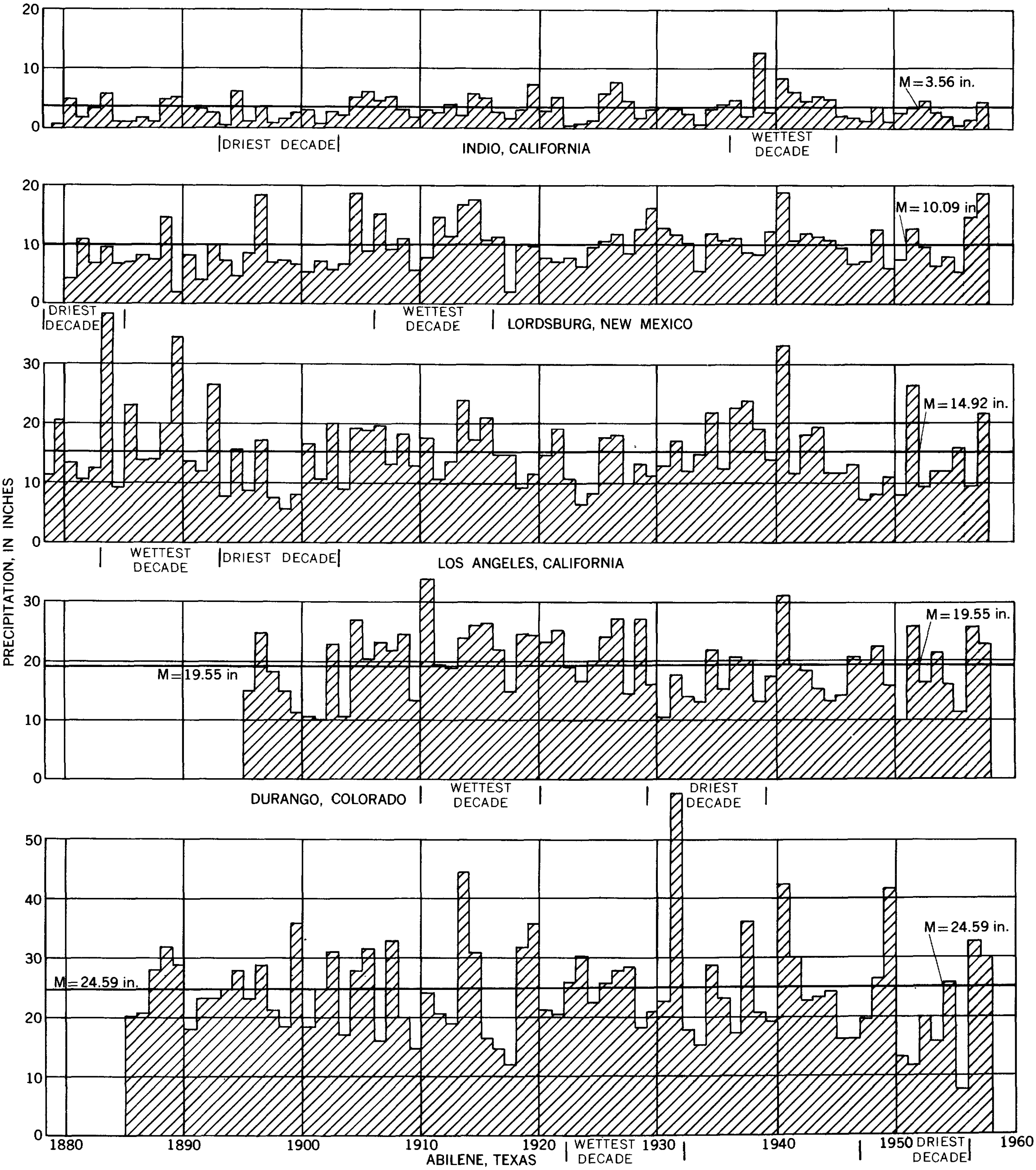

FIGURE 7.—Water-year precipitation at five cities in the Southwest. Means (M) are for period 1901–1950.

Southwest. Annual variations at each locality are so great as to make it difficult to draw conclusions as to precipitation trends, but certainly the recent period of drought does not stand out as unique in dryness. Great variations in precipitation patterns in the Southwest are quite evident: No two of the five stations had the greatest rainfall or the least rainfall in the same year, nor have the wettest decades or the driest decades coin-

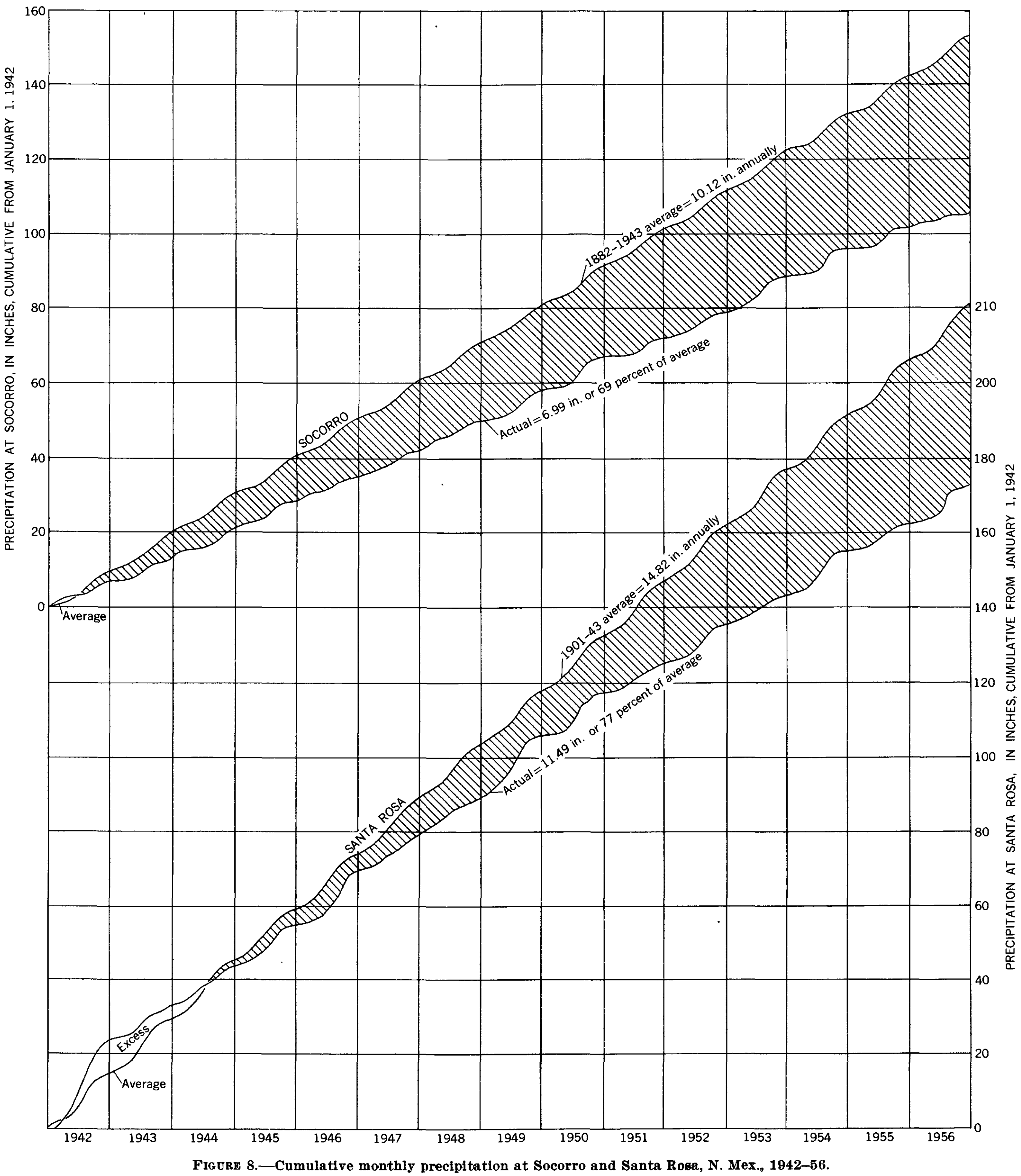

FIGURE 8.—Cumulative monthly precipitation at Socorro and Santa Rosa, N. Mex., 1942–56.

cided. On the other hand, some climatic phenomena extend over most of the Southwest; for example, 1941 was one of the three wettest years at all five stations.

Another form of presentation is by graphs of the accumulated actual and normal precipitation during a designated period. Figure 8 shows the cumulative total of precipitation by months from January 1942 to December 1956 at two localities in New Mexico. At both

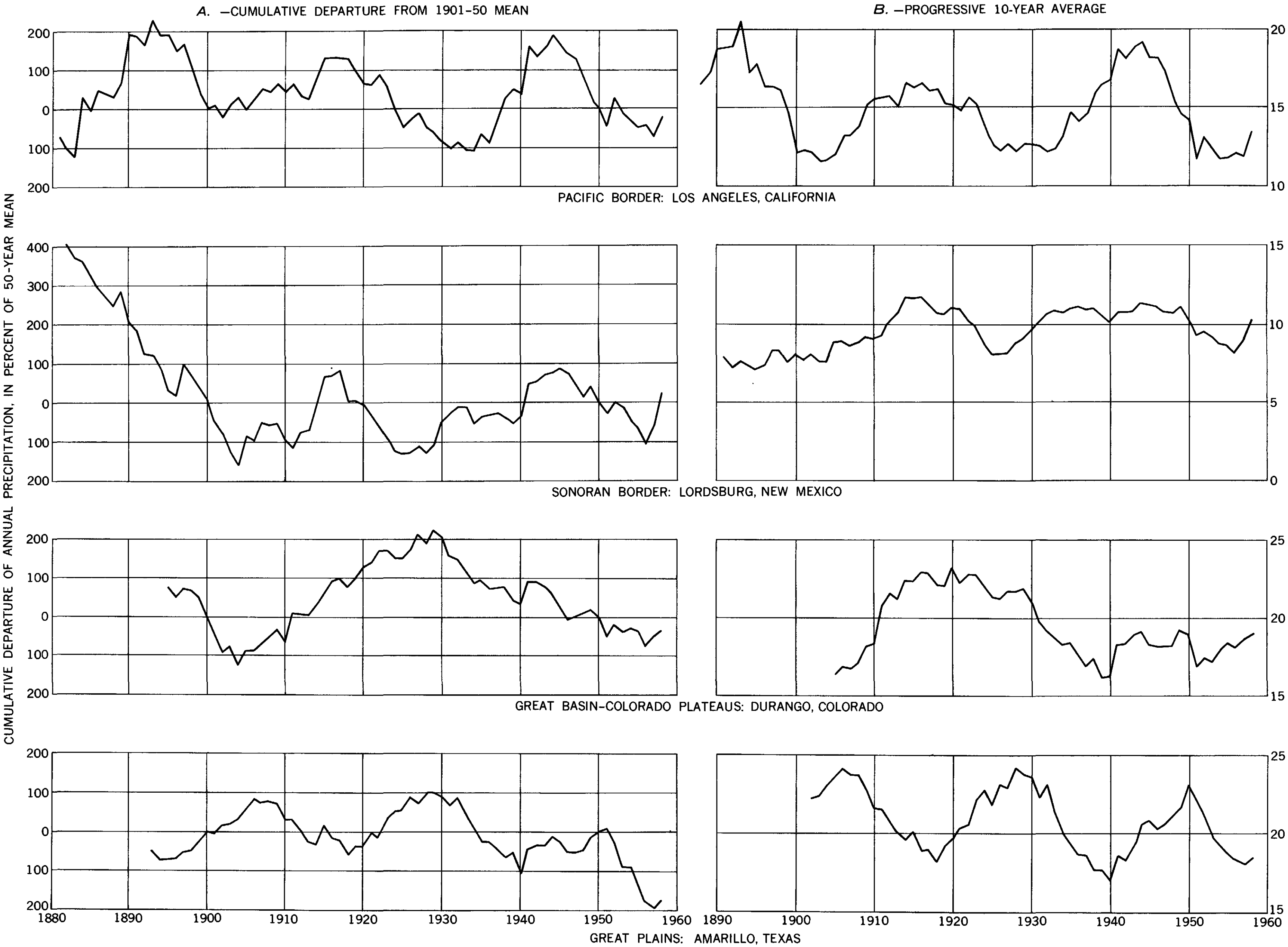

FIGURE 9.—Comparative graphs of water-year precipitation at four cities in the Southwest.

stations the seasonal cycle, with heaviest rainfall in summer, is noticeable even in dry years, although summer precipitation was below average in most years.

In order to show major trends in precipitation, and thus compare the intensity and duration of recorded dry periods, it is necessary to suppress, or smooth, the great fluctuations in precipitation at individual localities. Graphs of cumulative departure from mean precipitation, and graphs of progressive or moving averages of precipitation have both been widely used to indicate general trends; each form of graph has its advantages and disadvantages. Both types of graphs, showing precipitation at four localities, are presented in figure 9.

For the graphs of cumulative departure, the mean water-year precipitation has been computed for the base period 1901–50, and yearly deficiencies or surpluses with respect to this mean have been added progressively. Each graph crosses the line of origin in 1900 and 1950, and is extended back to the beginning of record for each station, and also forward to include water-year 1958. For better comparison of localities with markedly different mean precipitation, the cumulative departure in figure 9 is expressed in percentage of the 1901–50 mean. On a cumulative-departure graph the wettest years are shown not by a peak, but by the most steeply rising parts of the graph, and conversely the driest years are indicated by the steepest descents. Progressively decreasing precipitation throughout the base period is shown by a convex-upward curve on a cumulative-departure graph, and progressively increasing precipitation is indicated by a concave-upward curve. Alternating wet and dry periods are faithfully depicted on a cumulative-departure graph, but if the record begins with a wet period the entire graph may be above the line of origin and if it begins with a dry period the graph is generally below the base line.

Progressive averages have been used by several students of long-term trends, notably by Kincer (1933) for temperature, by W. G. Hoyt and others (1936) for precipitation and runoff, and by McDonald (1956) to show secular trends in seasonal precipitation. All three used averages for 10-year periods: in their graphs each plotted point represents the "mean" that would have been computed had the record been initiated ten years earlier. Progressive-average curves have several advantages over cumulative-departure curves: they depict not only long-term cyclic fluctuations, but also any long-term trends that persist throughout the period of record; and they permit direct comparison of stations having great differences in length of record. However, there are the disadvantages that cyclic fluctuations may be obscured or amplified, depending upon the method and time interval chosen for "smoothing"; and a single year of outstandingly excessive or deficient precipitation creates a plateau or trough whose significance is to be discounted.

ANNUAL PRECIPITATION

Figure 9, which provides comparisons of graphs showing cumulative departures and progressive averages of annual precipitation, also presents graphs for a city in each of the four meteorologic subdivisions of the Southwest described on pages A–11 to A–14. The pairs of graphs for each city are similar in that they show upward trends and downward trends during the same general periods. Each graph trends downward and thus indicates a preponderance of dry years during the period 1942–56, but the dry years within that period vary from one city to another. Earlier droughts are indicated by similar downward trends in each graph—and these also vary considerably in the four cities represented. There are very few years in the past 75 when at least one of the four cities represented on figure 9 was not undergoing extended drought. However, although many droughts occurred in the Southwest in the past century, these droughts characteristically did not engulf the entire region.

The graphs for Los Angeles, Calif., show an alternation of wet and dry periods, generally of 10 to 13 years' duration. Dry periods occurred in 1894–1904, 1917–32, and 1945–56; the intervening periods were comparatively wet. This alternation is typical of the Pacific Border zone, where precipitation originates almost entirely in moist Pacific airmasses, and occurs during the winter. The graphs for Amarillo, Tex., also exhibit an alternation of wet and dry periods, similarly of 10 to 13 years' duration, but the dry periods do not correspond to those in the Pacific Border zone. Instead, the dry periods occurred in 1907–18, 1929–40, and 1950–56. These dry periods have been recorded at many other places in the Great Plains, where most of the precipitation comes from the Gulf of Mexico and occurs during the summer.

The other graphs on figure 9 represent localities in the Great Basin–Colorado Plateaus zone—which receives precipitation from both Pacific and Gulf air masses—and the Sonoran Border zone, which similarly depends upon both sources but receives little from either. The droughts shown at these cities occur in part during the dry years recorded in the Pacific Border, and in part during the dry years recorded in the Great Plains. Because the annual precipitation in this broad region is derived from two major types of air masses, each producing cyclic alternations but in opposite phases, the trends in precipitation show an interesting variety. Notable examples are a quarter century of predominantly wet years at Durango, Colo., and a dry period of corresponding length at Lordsburg, N. Mex.

Because of the contrasting precipitation trends at these four cities representing the principal meteorologic zones in the Southwest, it is desirable to explore in greater detail the trends in precipitation within each zone.

DROUGHT IN THE PACIFIC BORDER ZONE

The graphs assembled in figure 10 represent three cities near the Pacific coast and two in the Central Valley of California. All graphs show declining trends during the years 1945–56, similar to that in Los Angeles (fig. 9). All graphs likewise indicate the dry periods shown at Los Angeles in 1894–1904 and 1917–32, although in several cities those dry periods extended somewhat beyond the periods indicated. The longest records also indicate a drought in the years 1870–79. The four drought periods are shaded on figure 10.

In San Diego and San Luis Obispo the steepest declines, indicative of the most severe droughts, were in 1894–1904 and 1945–56. In the Central Valley (Fresno and Sacramento) the wettest period (1935–44) of the past century was followed by a drought (1945–51) that was short and intense in comparison with earlier periods when precipitation was prevailingly less than the long-term average; in both localities the precipitation deficiency in 1894–1904 was less than in the cities farther south.

The graph based on measured rainfall at San Francisco shows trends similar to those indicated by the records for San Luis Obispo, Los Angeles and San Diego. However, when this record is adjusted on the basis of contemporaneous records for nearby Oakland and San Jose (Piper, 1959), the indication of drought during the decade 1891–1900 disappears. Instead, the adjusted graph has trends similar to those shown for Sacramento, which is less than 100 miles northeast of San Francisco. The official San Francisco rain gage has been moved 10 times during the past century, and the largest indicated correction was during the period 1892–1906. San Francisco is not within the area of Southwest droughts as defined in this report; it is brought in to suggest that sampling errors may be of considerable magnitude, particularly in the longest records.

The uppermost graph of figure 10 shows the annual relative sunspot number, as developed at Zurich Observatory by Wolf; as shown by Ellison (1955, p. 31–54) this graph is similar in form to a graph of mean area of sunspots based on daily photographs, as recorded by the Greenwich Royal Observatory. Most of the dry periods in the Pacific Border apparently began during years of maximum sunspot activity, and have continued through several years of declining activity, and sometimes until a subsequent and lower maximum was recorded.

DROUGHT IN THE GREAT PLAINS ZONE

Precipitation in the Great Plains, reaching a maximum in the summer, commonly occurs during convectional storms that may be quite localized. The graphs of figure 11 represent eight cities in the Great Plains area, from Denver, Colo., which is farthest north and farthest from the Gulf of Mexico, to Brownsville, Tex., which is farthest south and borders the Gulf. On this graph, single years when precipitation was more than 50 percent above the average for 1901–50 are shown by heavy lines. Commonly these years include storms of high intensity but local or irregular distribution.

The alternating wet and dry periods shown so clearly by the record for Amarillo, Tex., (fig. 9) appear also on most of the graphs of figure 11, but not in the graph for Brownsville, Tex. The graphs for Denver and Pueblo, Colo., indicate some alternation of wet and dry periods, but the periods are not synchronous with those recorded at cities farther south. In the last 50 years the major trends shown on the Denver graph are counter to those shown at Brownsville, and suggest that when Brownsville is receiving more than average rain, there is less available for the remoter parts of the Great Plains as represented by Denver. Tannehill (1947, p. 109, 119) points out that such differences in precipitation trends are evident not only between the northern and southern Great Plains, but between the northern and southern parts of the continental interior.

Comparison of these graphs with the graph of relative sunspot numbers indicates that many of the droughts in the Great Plains, like those in the Pacific Border, begin in years of maximum sunspot activity; these droughts, however (as distinguished from those in the Pacific Border), begin during the lower maximum of the double sunspot cycle.

CYCLIC FLUCTUATIONS

To summarize the fluctuations that appear on figures 10 and 11: the wet and dry periods noted in the Pacific Border and Great Plains are generally of 10 to 13 years' duration, but are almost opposite in phase, so that when one zone is drier than average the other is wetter than average; northern localities in each zone exhibit different trends from those farther south; cyclic fluctuations are more pronounced at some localities than at others in each zone, and are not clearly discernible

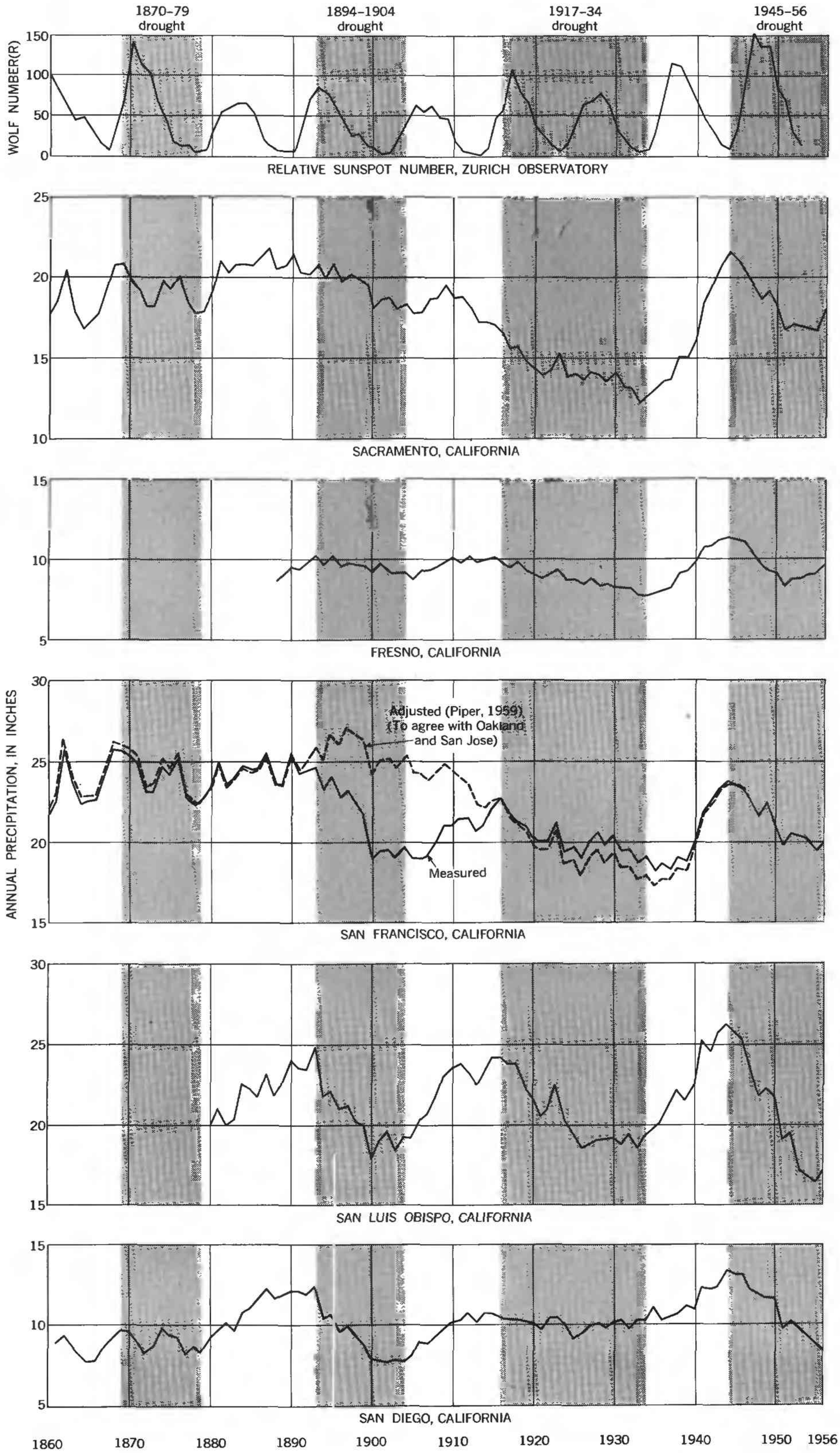

FIGURE 10.—Fluctuations of annual precipitation at five cities in Pacific Border zone. Progressive 10-year average.

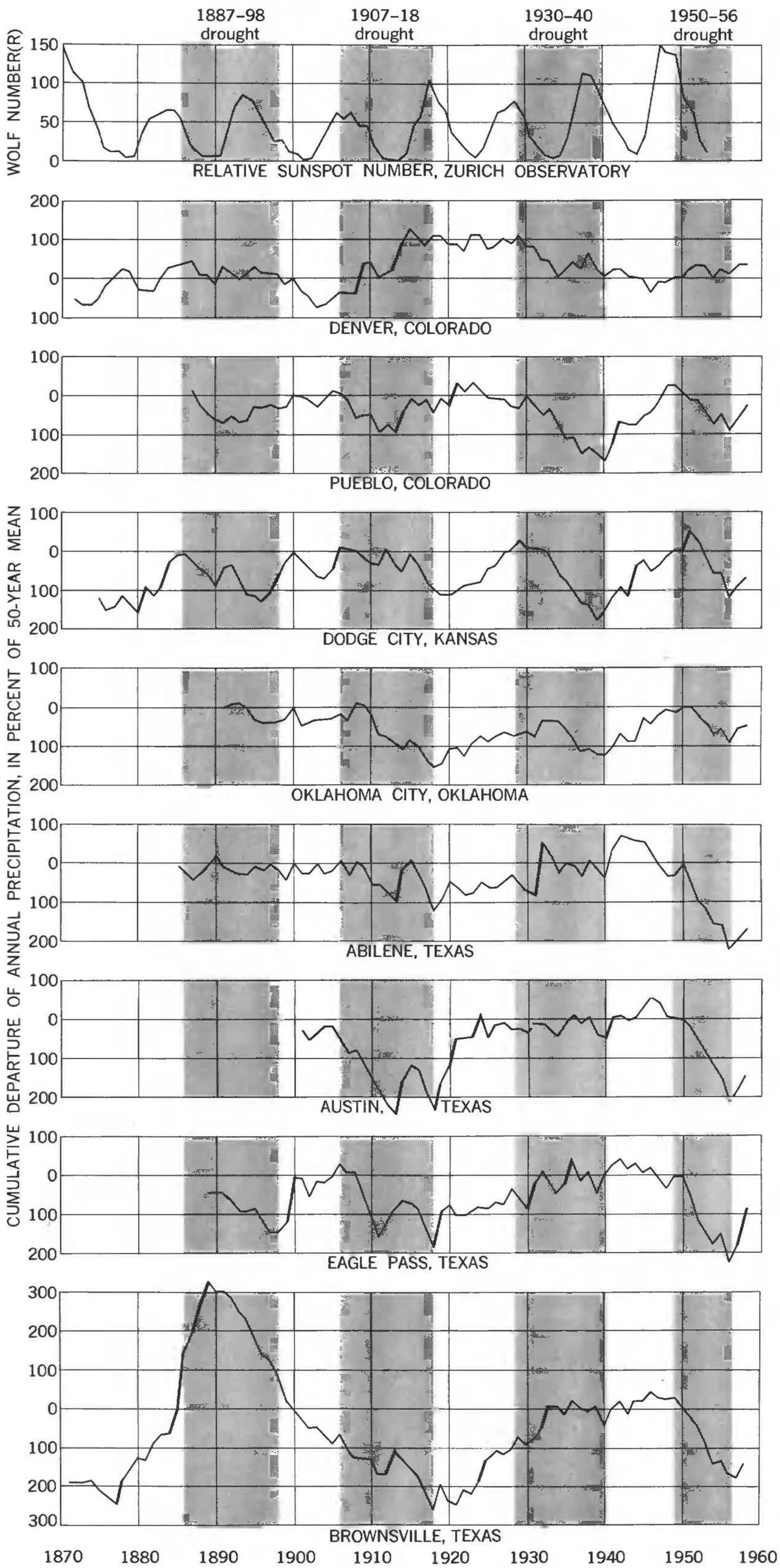

FIGURE 11.—Fluctuations of annual precipitation at eight cities in the Great Plains zone.

in the records for some localities. As to possible causes of these fluctuations, Tannehill (1947, p. 135–144) states:

During periods of deficient rainfall in the United States we frequently hear that droughts come in cycles. The most frequent claim is that they come in some fraction or multiple of the sunspot period of about 11 years. There is much evidence that rainfall varies in a cycle of about 11 years, and also there are some indications of variations in periods of 22 or 23 years, and in the so-called Bruckner cycle which is roughly three times the sunspot period * * *. In the long run, the sun's heat is responsible for all changes in the weather, as the sun rises and sets and goes north and south with the seasons. The diurnal effects, and especially the seasonal effects, will afford some clues as to what happens when the sun's radiation changes in a period of eleven years, or whatever it may be.

In spring and summer a high percentage of the year's rainfall is carried into the interior of the continent. The sun is high and the continent warm, and the oceans are relatively cool. In autumn and winter a greater percentage of the year's rainfall occurs in coastal areas or nearer to the coasts than in spring and early summer. When the sun is low, the continent is cold and the oceans are relatively warm. Therefore, if the sun gets progressively colder from year to year there should be an increasingly lower percentage of rainfall in the interior, and vice versa. There will be many local variations, of course, and the lag of ocean temperature changes will have to be taken into account; but the broad effects should be fairly clear if the sun's radiation changes in an eleven-year, as we believe it does * * *.

[From study of the differences between the national rainfall in the first and second halves of the calendar year] we see that in general when there were numerous sunspots there was more rain in the first half of the year and when there were few sunspots there was more rain in the second half of the year * * *.

The temperature differences which carry rainfall into the interior of the United States in late winter, spring, and early summer are owing to (1) the sun's heat and (2) the lag of ocean temperatures. The temperatures of the Pacific rise in the spring and fall in the autumn at a much slower rate than the temperatures of the continent in the same latitudes. In the same way, the temperatures of the Atlantic and Gulf also rise and fall at a slower rate than the continent. The Atlantic and Gulf, especially the latter, are smaller than the Pacific and consequently their temperatures change more rapidly than the Pacific but less rapidly than the continent. Furthermore, there is a variation in temperature between the eastern and western parts of the oceans. These varying temperature differences between the two oceans (and the Gulf of Mexico) introduce a secondary effect which is evident chiefly in changes in the seasonal distribution of the rainfall in the area east of the Rockies * * *.

When sunspots are numerous, more of the rainfall tends to go to the interior, including the Great Plains * * *. At high sunspottedness, the Southern Great Plains get relatively more rain [than the Gulf Coast]. The difference is very important, with a range of nearly 10 inches per year. There are definite indications that when the increase in the sun's heat is unusually great, or when the oceans are relatively colder than usual at time of maximum sunspots, the rainfall is diverted still farther into the interior * * *.

The varying rates of response of the continents and oceans give us rainfall variations that do not follow exactly the sunspot cycles; but the rainfall curves of the United States, if analyzed properly, seem to fit the broad pattern. Perhaps we can watch the sunspots and predict what our rainfall will be. It may be possible when we know more about it. In the past we have been as badly confused about sunspots as on the drought question * * *. Galileo published his paper on sunspots in 1613. Later it was found that the numbers of these sunspots vary in a cycle of about eleven years. After more observations were made, the period was found to average slightly more than eleven years. Actually, the period varies, going as long as seven years or as high as fifteen years. The discovery of the sunspot cycle brought forth the idea that the temperatures on the earth should vary with the number of spots, and many scientists enthusiastically assembled temperature records to prove it. There was great hope that it would be possible to predict the weather far in advance. The investigators expected to find that at maximum sunspots, when the sun is hottest, the atmosphere would be warmed. With few spots and a cool sun, the atmosphere was expected to be cooler. To their astonishment, they found that the opposite was true. At the surface of the earth, where we have all our long weather records, more sunspots bring lower temperatures and fewer spots bring higher temperatures. This fact is fully supported by records in the tropics, where there are fewer violent changes in the weather than in the latitude of the United States. A hot sun makes a cool earth, and vice versa * * *.

Sunspots represent only one activity in the sun. There are other evidences of solar activity, such as prominences, magnetic activity, faculae, and the corona. Records of sunspots are available for a long period of time. The other evidences of solar variation seem to follow the same course, but the records are by no means so extensive.

DROUGHT IN THE GREAT BASIN AND SONORAN BORDER ZONES

The cumulative-departure graphs of annual precipitation at several cities in the Great Basin and Sonoran Border zones (fig. 12) show a considerable variety in precipitation trends, and a significant lack of uniformity in the region during the period 1942–56, as well as during earlier droughts. In this broad region the annual precipitation is contributed from both Pacific and Gulf sources, one source predominating in the winter, the other in the summer. For evidence of cyclic fluctuations, or of fluctuations synchronous with those observed in the Pacific Border and Great Plains, it is therefore desirable to analyze the precipitation trends in this intermediate region by seasons.

SEASONAL PRECIPITATION

A comprehensive analysis of precipitation in the Southwest on the basis of major sources of that precipitation would require the study of individual storms, but for the purpose of this report it is considered sufficient to work with periods during which the precipitation is predominantly from one source. On this basis, annual totals have been used for analysis of precipitation in the Pacific Border, where precipitation comes predominantly from Pacific airmasses, and in the Great Plains, where precipitation comes chiefly from the Gulf of Mexico.

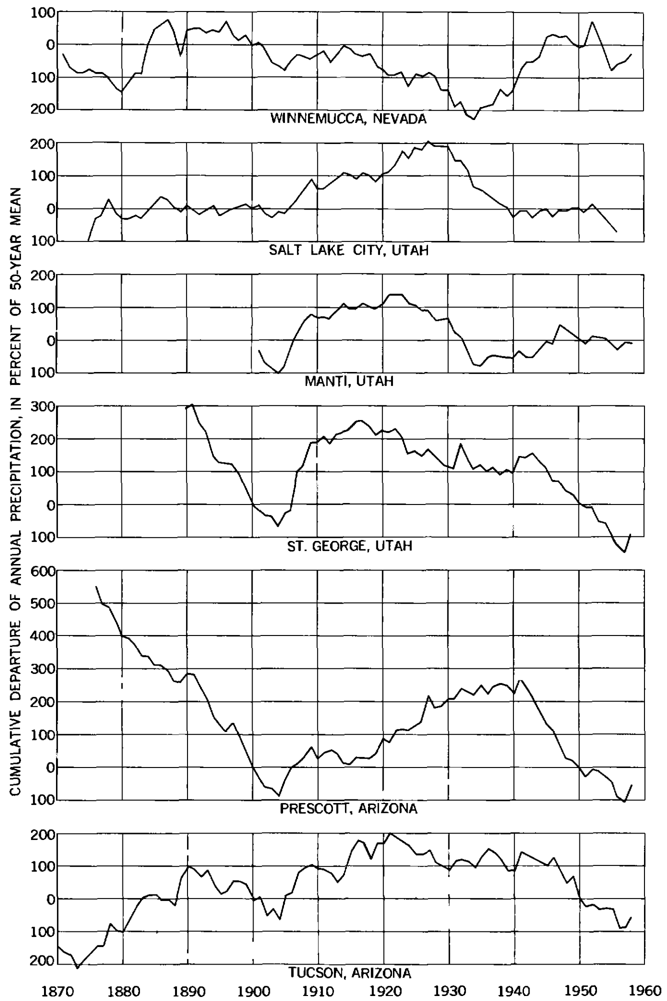

Figure 12.—Fluctuations of annual precipitation at six cities in the Great Basin and Sonoran Border zones.

In the Great Basin, Colorado Plateaus, and Sonoran Border the precipitation during the winter (starting in October or November and continuing until April or May) comes chiefly from the Pacific Ocean. Gulf sources are dominant in the summer, notably in July, August, and September, and to a lesser extent in earlier and later months. On the basis of storm genesis no regular dividing dates can be set between the "winter" and "summer" seasons. Indeed there may be a considerable overlap in some years when the region is the recipient of storms from one source and then another; and in other years there may be an interval when very little precipitation is received from either source (June is ordinarily the driest month of the year in many communities, evidently too late for general winter storms and too early for the summer convectional storms). For convenience, however, the water year (ending September 30) can be subdivided into halves: a winter season from October through March, and a summer season from April through September. These are the seasonal subdivisions considered in the following discussion.

Graphs showing progressive average seasonal precipitation at six cities are presented in figure 13. All these places except Salt Lake City are in the area of Southwest drought (fig. 6). Salt Lake City and St. George, Utah, and Durango, Colo., usually receive most of their precipitation during the six winter months, October through March. At the other three cities, located farther south, most of the yearly precipitation occurs during the months April through September.

On the chart for winter (October–March), the periods that have been prevailingly dry in the Pacific Border (fig. 10) are shown by shading. Winter precipitation is less than average during these periods at several of the cities represented in figure 13, notably at Tucson and Prescott, Ariz., and St. George, Utah, but to some extent even at Roswell, N. Mex., which is in the Great Plains zone.

On the chart indicating summer (April–September) precipitation, shading indicates the periods that have been prevailingly dry in the Great Plains. Precipitation has trended downward during these periods at several of the cities represented by the graphs of figure 13, including Roswell as well as localities in the Sonoran Border and the Great Basin-Colorado Plateaus zones.

A graph of the yearly sunspot numbers (fig. 13) for the years 1870–1955 shows a cyclic fluctuation, with a minimum (ordinarily less than 10) every 10 to 13 years. The maximums alternate between "higher highs" that approach or exceed 100 (in 1870, 1893, 1917, and 1938) and "lower highs" in the range of 60 to 75 (in 1883, 1907, and 1928).

The graphs of figure 13 indicate that the dry periods in Pacific winter precipitation commonly begin within a year or two of the higher maximums of the sunspot double cycle; they may continue until the next (lower) maximum, and even longer in the instance of the 1917–34 dry period. The dry periods in Gulf summer precipitation appear to begin at about the time of the lower sunspot maximums, but they too ordinarily continue for about a decade.

This suggestion of correlation between drought periods and sunspot cycles may merit considerable skepticism, because the precipitation trends indicated on figure 13 may well be created by other factors, including for instance sampling errors at individual precipitation stations, the vagaries of distribution during individual storms, the method of smoothing the observed data, and the empirical though convenient subdivision of the year into two seasons of equal length. On the other hand, these same factors might also explain why

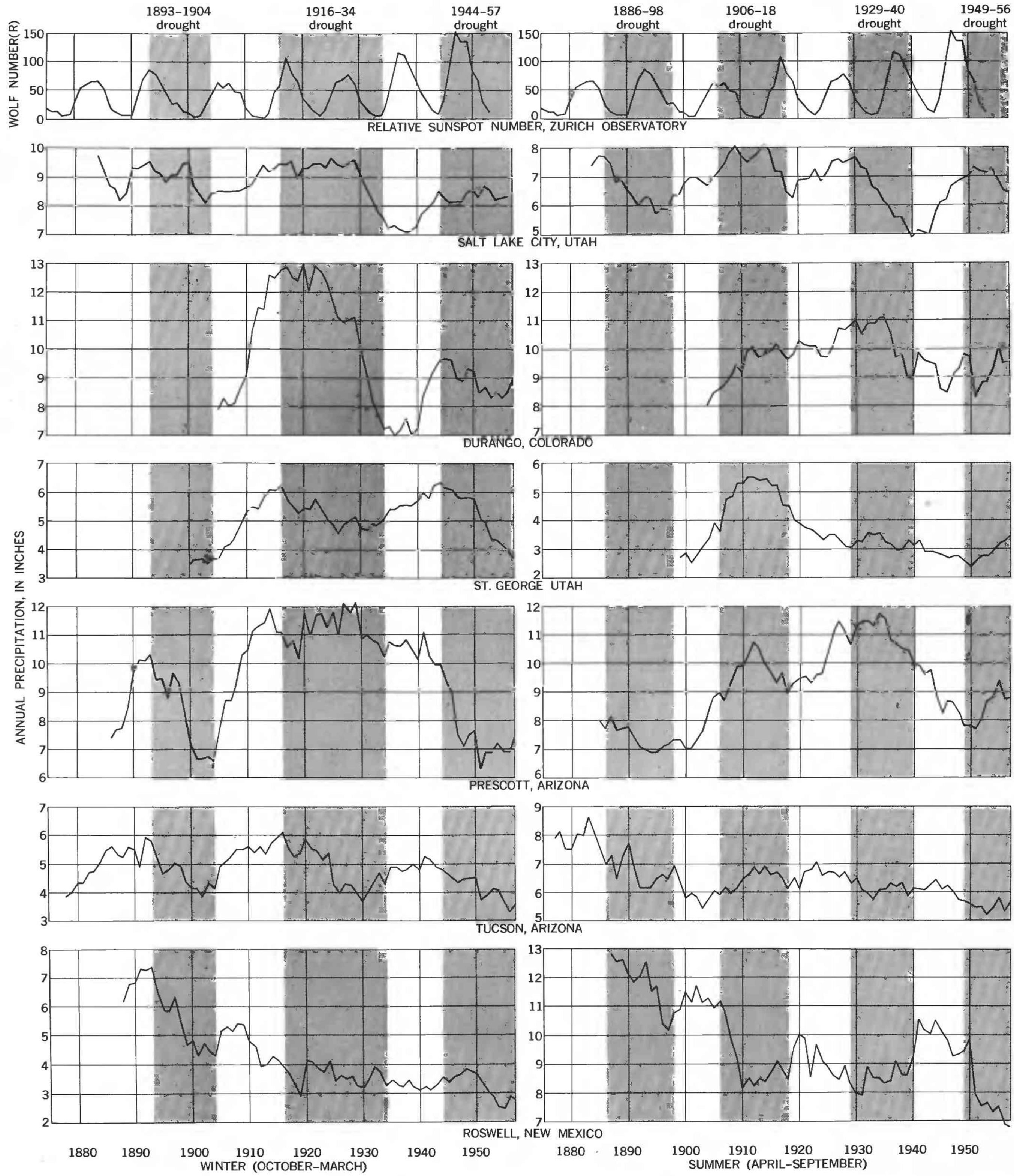

FIGURE 13.—Fluctuations of seasonal precipitation at six cities in the Southwest. Progressive 10-year average.

all the graphs on figure 13 do not show regular and uniform cyclic fluctuations.

TEMPERATURE

In the preparation of this report, studies of long-term fluctuations of temperature have been limited to the records of San Francisco and San Diego, as representative of the northern and southern parts of the Pacific Border zone; Salt Lake City and Phoenix, in the Great Basin and Sonoran Border zones; and Dodge City, Kans., El Paso and Abilene, Tex., in the Great Plains zone. Graphs of progressive 10-year average temperatures at these seven cities in October to March are shown in figure 14, and in April to September in figure 15.

Both winter and summer temperatures at San Francisco show a downward trend in the 1890's, an upward trend for about the first four decades of this century, and downward since the mid-1940's. These trends may reflect changes in temperatures of the Pacific Ocean in midlatitudes. The temperature graphs for San Diego are generally similar in trend to those for San Francisco, except that winter temperatures rose in comparison with San Francisco during the dry periods 1894–1904 and 1945–51. The trends observed in the Pacific Border are also evident as far inland as Salt Lake City and Phoenix in the summer, but not in the winter. The temperature trends in the Great Plains appear to be quite independent of those observed farther west, and in many instances independent of each other. There is some similarity among the graphs of winter temperature at Dodge City, El Paso, and Abilene, but marked divergences in summer trends at these three places.

At practically all seven cities both summer and winter temperatures reached the maximum for the period of record in the early 1940's; thus one common characteristic of the graphs is an increase in temperature during the first four decades of the century and at some places ever since the beginning of the record, and a decline in subsequent years. Similar trends have been observed in many parts of the world (p. A–35).

No general rule can be stated concerning the trends of temperature during dry periods. The steepest rise in summer temperature shown on any graph is that at Dodge City during the drought of the 1930's, and summer temperatures trended upward at all cities during those years. But temperatures did not rise at Dodge City during an earlier dry period (1907–18). Of the seven localities, only Abilene has recorded a rising trend in temperature during each of the dry periods 1907–18, 1930–40, and 1950–56. Winter temperatures declined during the dry period 1945–51 in the Pacific Border, but rose at most places during the dry period 1917–34. Thus if there is any relation between drought and temperature, it is obscure and not consistent.

OROGRAPHIC EFFECT UPON PRECIPITATION

The mountains in the Southwest have a marked effect upon precipitation, and precipitation in the mountainous areas as a rule is greater than that in adjacent lowlands. The distribution of precipitation during individual storms may vary markedly from the pattern shown by long-term averages, and such variations may characterize most of the storms in an entire season. For example, along the Wasatch Range in Utah at altitudes lower than 8,000 feet, the snowfall in 1952 was so far above the usual proportion at those altitudes that damaging floods developed in several creeks having low headwaters. Thus, precipitation-altitude relations during individual storms or seasons may range widely from the established long-term mean.

In regions where the dominant source of precipitation varies seasonally, it is to be expected that the precipitation-altitude relation also will vary from season to season. Along the Wasatch Range, where winter storms originate chiefly in the North Pacific, and summer storms may come from South Pacific or Gulf sources, Peck (1956) has found significant differences from winter to summer in the precipitation-altitude relation.

A question for which we ourself could find no published answer is whether the variations from the long-term mean relation of precipitation to altitude are entirely random in character, or whether there are evidences of time trends in those variations, as there appear to be in the records of precipitation at individual localities. The problem could well be important in a study of the effects of drought, because precipitation records are collected chiefly in lowland areas, and unless the fluctuations shown by them are representative also of fluctuations in the highlands, the conclusions concerning the water supplies contributed by the high mountain ranges must be inconclusive.

For preliminary study of this question we selected the records of snow-survey courses in the Kings River basin in California, extending from Fresno northeastward to the crest of the Sierra Nevada. This area receives precipitation chiefly from Pacific sources and chiefly during the winter. Because many of the snow-survey courses were not established until 1930, and because it is standard practice on them to measure the water content as of April 1 each year, the study was limited to the October to March precipitation in the period 1930–56, inclusive. This 27-year period includes several years of the prevailingly dry period 1924–34, the entire wet period 1935–44, and the prevailingly dry period 1945–51.

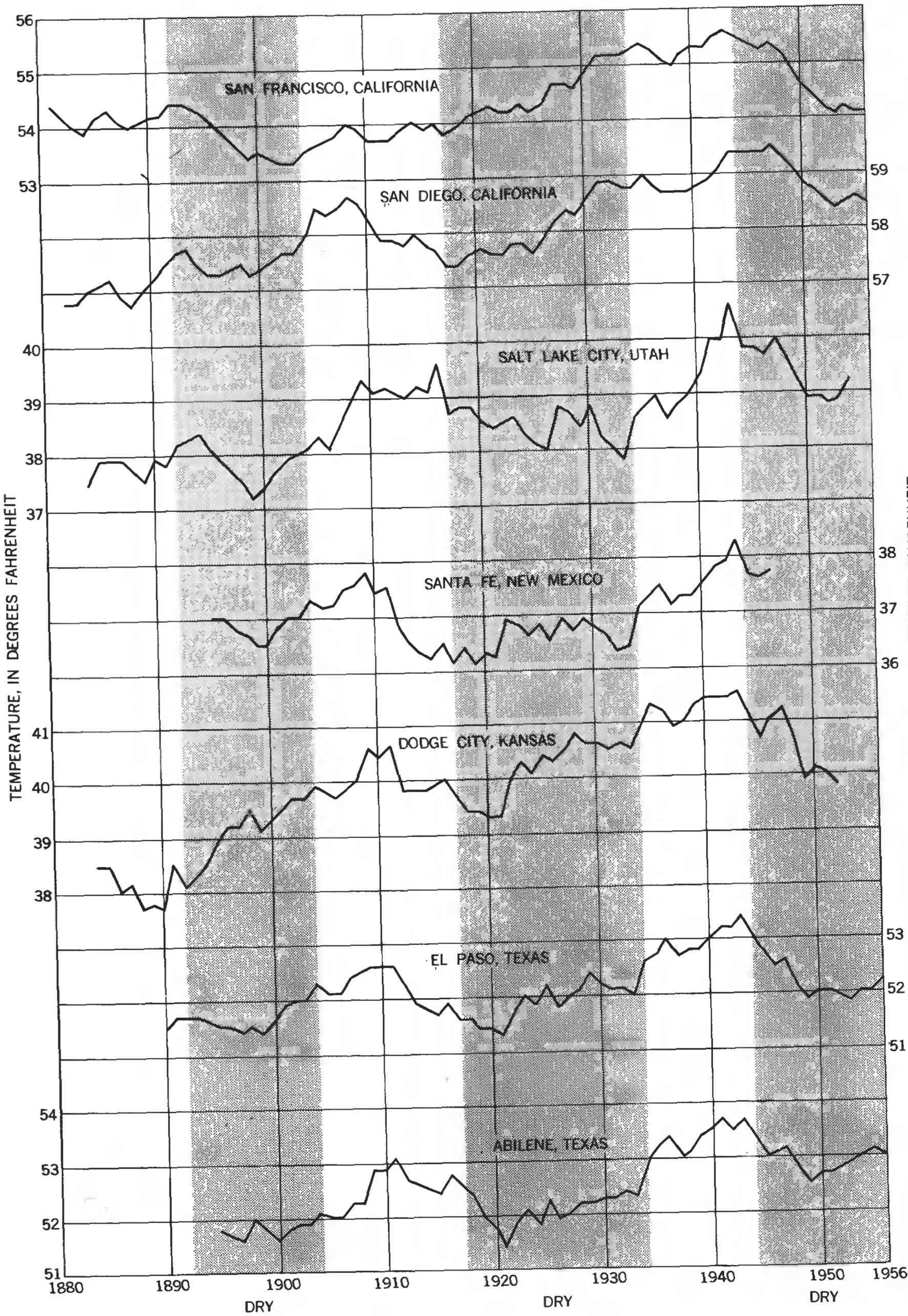

FIGURE 14.—Progressive 10-year average October–March temperature at seven cities in the Southwest.

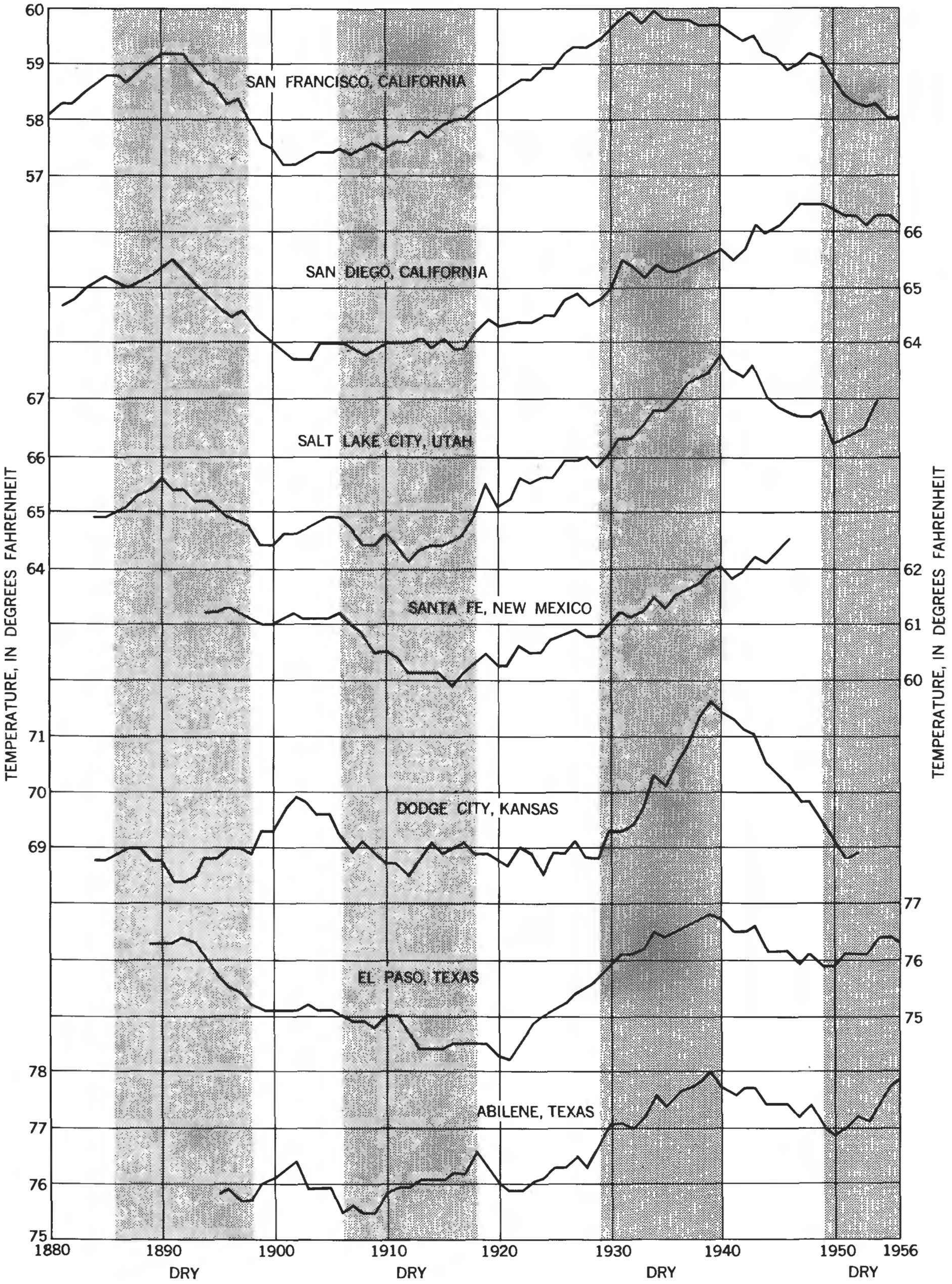

FIGURE 15.—Progressive 10-year average April–September temperature at seven cities in the Southwest.

At each of eight snow courses, ranging in altitude from 5,500 to 10,800 feet above sea level, the snow accumulation in each year was computed in percentage of the average for the course in the 20-year period 1930-49. These percentages for each year were then plotted against altitude of the courses. The resulting graphs indicate that in most years the snow accumulation, in percent of the mean, does not vary greatly with altitude; but in some years there is a far greater proportion of snow at low altitudes than at high, and in other years the reverse is true. Graphs representing several selected years are assembled in figure 16. Although there are obvious variations from year to year, these variations appear to be random, whether comparisons are made between wet and dry years or between years in prevailingly wet or dry periods. Thus in 1952

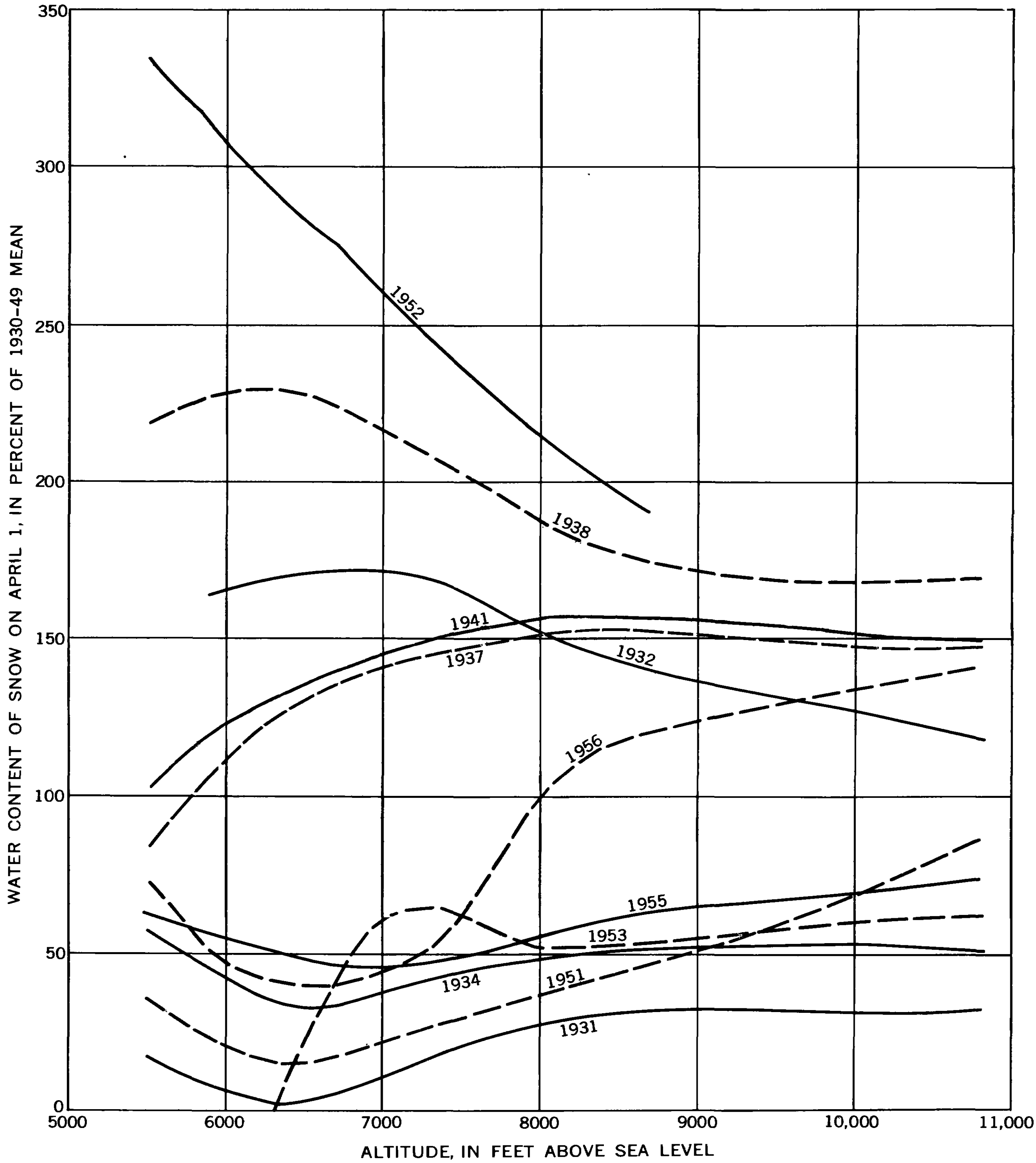

FIGURE 16.—Snow accumulation in relation to altitude in selected years, southern Sierra Nevada.

and 1932—wet years in prevailingly dry periods—there was a greater proportion of snow at low altitudes. The same is true of 1938—a wet year in a prevailingly wet period (see fig. 10)—but not of 1937 and 1941, which were other wet years in the same period. As a rule the variations in the relation of snow accumulation to altitude have a less regular pattern below 8,000 feet altitude, which are caused at least in part by melting and therefore reflect differences in temperature rather than precipitation. This was the case in December 1955, for example, when rains melted some of the accumulated snow and caused floods in several Sierra streams; the graph for April 1956 shows greater than average snow accumulation above 8,000 feet, but far less than average at lower altitudes. It is concluded that if the observed inconsistencies in relation of precipitation to altitude are not random, at least we can see no regular pattern to them.

The graphs of figure 17 represent another attempt to ascertain whether there are time trends in the relation of precipitation to altitude. The graphs shown by dashed lines are based upon the April 1 accumulation, in percent of the 20-year mean, at snow courses at altitudes 10,800 and 8,500 feet in the Kings River basin; and the solid lines are based on the recorded October–March precipitation, in percent of the same 20-year mean, at Weather Bureau stations at altitudes 7,000, 4,900, 2,100, and 300 feet, within that basin. All graphs represent moving 5-year averages of the percentage deviations from the mean, and all are plotted to a common scale, although the order and spacing of the graphs are more or less in accordance with the altitudes of the respective snow courses and precipitation stations. The curves for the four Weather Bureau stations are remarkably similar to each other and to the curves for the snow courses, suggesting that there is no significant difference in the climatic fluctuations as recorded at high and low altitudes.

From this very brief analysis of records from an area which appears to be an excellent one for study of variations in orographic effects upon precipitation, the tentative conclusions are that there are indeed variations from year to year in the long-term mean relation of precipitation to altitude, but these variations appear to be random in character and have no apparent relation to the major climatic fluctuations which have been observed at all altitudes.

CLIMATIC FLUCTUATIONS SHOWN BY OTHER DATA

According to Willett (1953, p. 55)—

> There is continually in progress an entire spectrum of cyclical fluctuations of climate, cycles of shorter period and smaller amplitude being superposed on those of longer period and larger amplitude. These cycles include one whose half period, at least in Europe, extends from the Climatic Optimum at about 3000 B.C. to the peak glaciation from A.D. 1600 to 1900, a second cycle of smaller amplitude and a period of some 2000 years, cool-wet from 500 B.C. to A.D. 100, warm-dry from A.D. 400 to 1000, and cool-wet from the thirteenth century to the present, and shorter and smaller cycles, from a few centuries in period to the 80-year, the double sunspot, and the single sunspot cycles observed during the past two centuries.

The longest records of the U.S. Weather Bureau, extending back about a century, are not long enough to give evidence for or against the longer cycles mentioned by Willett. For this evidence we must look to climatologic records from other parts of the world, and to other types of data in the Southwest and elsewhere.

Evidence of climatic fluctuations of assorted periods and amplitudes, such as those mentioned by Willett, comes from climatologic, historic, archeologic, biologic, glaciologic, limnologic, oceanographic, and geologic data. As we probe farther into the past, all these forms of data become less complete and less definitive, and require more shoring up by inferences. Major climatic fluctuations—or more properly climatic variations, since they represent changes maintained over periods measured in tens of thousands of years—are clearly shown by the geologic record of the Pleistocene continental glaciations and interglacial epochs. Numerous climatic fluctuations have been identified in the period of 10,000 years since the last advance of continental glaciers (about 8000 B.C.). Generally these reported fluctuations are reckoned in millennia for the first 8,000 years (B.C.), in centuries during most of the Christian era, and in years only since about A.D. 1700—because of the increasing detail of the available records in recent years.

Summaries by Sears (1958) and Deevey and Flint (1957) form the basis for the graphs assembled in figure 18, which suggest the following broad postglacial sequence:

8000–7000 B.C.:
: Recession of continental glaciers, leaving tundra; preponderance of spruce in pollen record. Climate cold and moist.

7000–5000 B.C.:
: Beginning with climate "similar to today," then progressive increase in temperature and decrease in precipitation. Abundance of oak, beech, and hemlock in pollen record. Also includes Cochrane glacial advance.

5000–2500B.C.:
: Climate generally warmer and drier than today, so that period has been designated "climatic optimum," "altithermal," "megathermal," "thermal maximum," and "xerothermic." Abundance of oak and hickory in pollen record. Drying up

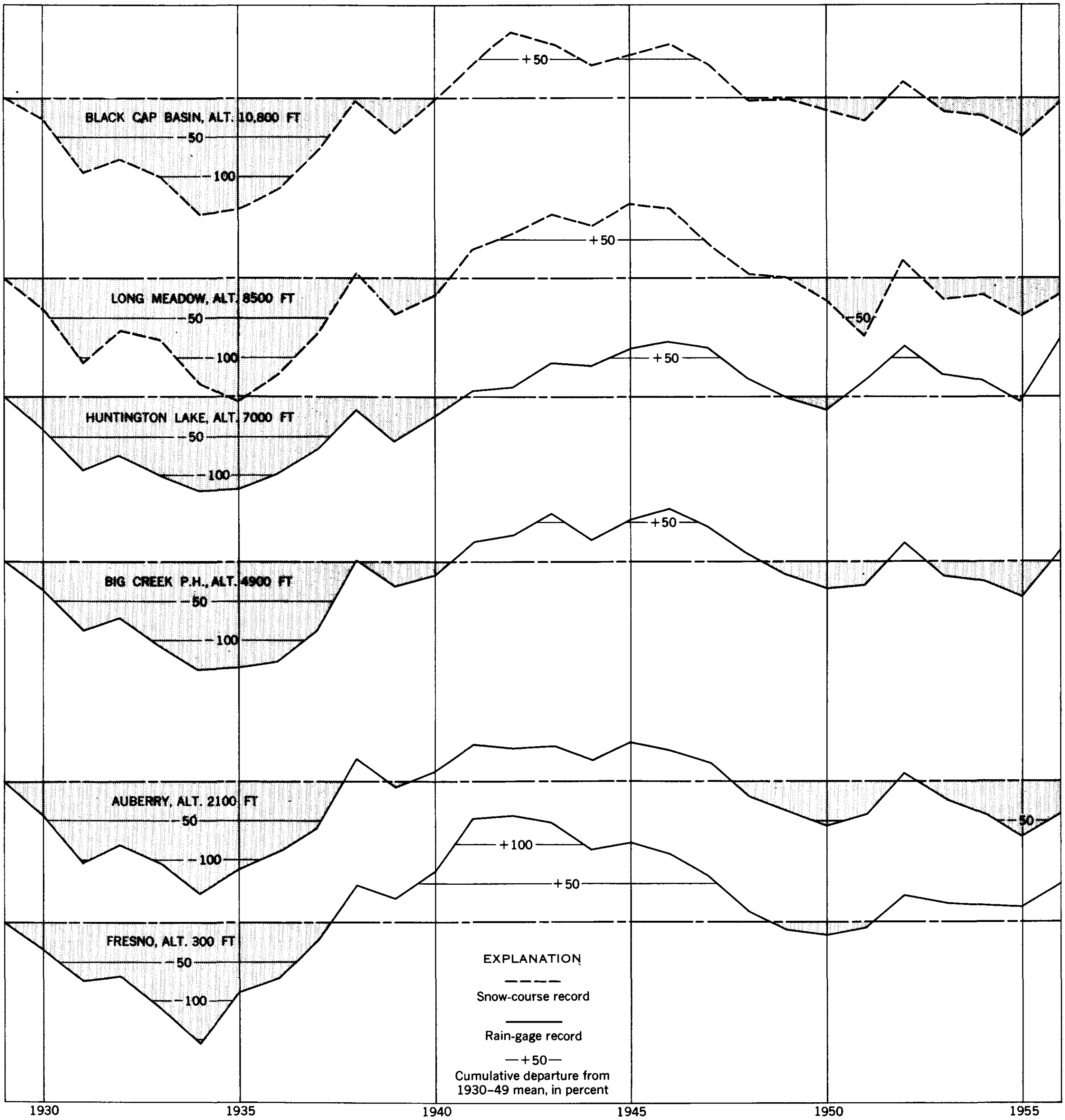

FIGURE 17.—Cumulative departure of winter precipitation from 1930–49 mean, southern Sierra Nevada.

of lakes and glaciers, 30-foot rise in sea level during period.

2500–600 B.C.:
Gradual decrease in temperature, with probable rebirth of some lakes and glaciers. Some marked glacial advances. For sedimentary sequence in the period 7000 to 600 B.C. Deevey and Flint have proposed the term "hypsithermal."

600 B.C.–A.D. 1300:
A period providing gradually increasing detail concerning climatic fluctuations, as summarized by Brooks (1950, p. 113) for countries bordering

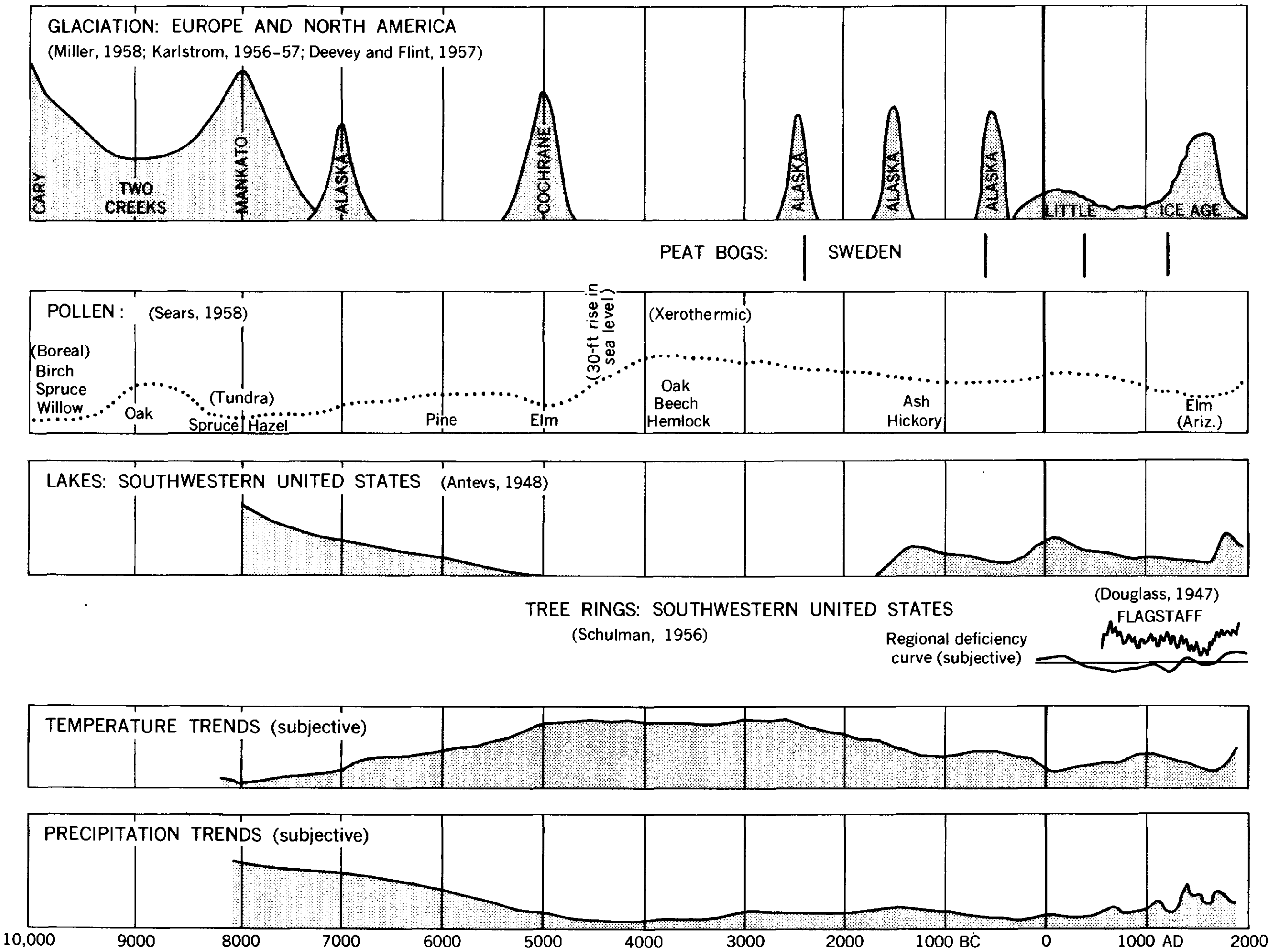

FIGURE 18.—Summary of findings pertaining to post-Pleistocene climates.

the North Atlantic and Arctic Oceans, and by Co-Ching Chu (1926) for China. Generally the rainfall was near or below present averages, with some periods of marked drought; the temperature was probably somewhat higher than today, judging by the history of Iceland and Greenland. However, some glacial advances in Alaska.

A.D. 1300–1850:

"Little Ice Age," marked by increasing rainfall and storminess, advancing glaciers, abandonment of northern outposts of civilization, rising lake levels toward end.

A.D. 1850–1940:

The lines of evidence concerning the "present climatic fluctuation" as summarized by Ahlmann (1949) include climatologic records from several places in the Northern Hemisphere, the longest of which began in Holland in A.D. 1706. These records indicate generally increasing temperatures beginning about 1850 in many parts of the world, but as Ahlmann points out they are not distributed quite widely enough to allow us to characterize the temperature fluctuations as world wide, because of the dearth of information concerning the Southern Hemisphere, and particularly the Antarctic.

The fluctuation in the past century is indicated also by the recession of glaciers in practically every glacial region in the world, by warming of ocean currents in far northern latitudes, by rising ocean levels with the melting of ice stored on the continents, and, in the Northern Hemisphere, by northward migration of the zones most suitable for certain species of fish and of vegetation. Ahlmann concludes (1949, p. 190):

If we find in the Antarctic similar evidence of the present climatic fluctuation as has been found in other parts of the world, we shall be justified in concluding that the present fluctuation is a world-wide phenomenon and probably the result of variations in solar activity which, slow as they may be to take effect, are actually resulting in an improvement[4] in the climate of our world.

The accumulated evidence concerning climatic fluctuations of various lengths is far from complete, and becomes more sketchy as one probes further into the remote past. However, there is considerable evidence that the rising temperature trends in the last century have not persisted since the ice recessions of the last glacial epoch some 9,000 years ago. Instead, those 9,000 years have included centuries that were warmer, centuries that were colder, centuries that were wetter, and centuries that were drier than the one we know best.

The general world conditions as outlined above are based in part upon studies in the Southwest. Many of the findings in that region fit in nicely with the broad summary, and some conclusions serve to amplify or modify the general picture. The results of specific studies pertaining to long-term climatic fluctuations in the Southwest are summarized in the following sections.

HISTORIC DATA

The diaries and notes of the Spanish missionaries in southern California have been the basis for estimates by Lynch (1931, 1948) of the annual rainfall in the Los Angeles area since 1769, a full century before the beginning of official precipitation records. His cumulative-departure graph (fig. 19) indicates dry periods in 1793–1809, 1822–32, and 1843–59 comparable in magnitude and duration to those shown (fig. 9) by Weather Bureau records in 1870–83, 1894–1904, 1917–34, and 1945–57. The apparent overall downward trend in this graph results partly from the fact that the graph begins with a wet period.

LAKE LEVELS

Fluctuations in level of the enclosed lakes of the Southwest reflect the water-supply conditions on their drainage areas, for the water accumulated represents the difference between the sum of all elements of inflow and the total discharge. With sufficient records and interpretive study it is possible to discriminate the effects of such factors as precipitation upon the lake, evaporation from the lake, ground-water and surface-water inflow; and more indirectly, the effects of precipitation and of evapotranspiration or other consumptive use of water in the part of the drainage basin not occupied by the lake. Without such detailed records it is still possible to draw broad conclusions concerning climatic fluctuations: the lake level will ordinarily rise if precipitation increases or evapotranspiration decreases, or both, within the drainage basin; and it will decline if precipitation decreases or evapotranspiration increases. The rate of evapotranspiration commonly rises with increasing temperature, decreasing humidity, and increasing wind movement. Thus lake levels indicate the resultant effects of several meteorologic factors that determine climate. Several enclosed basins in the Southwest were filled to overflowing during parts of the Pleistocene, and several have been evaporated to dryness in subsequent warmer or drier times.

Antevs (1948, p. 178) uses data from Abert and Summer Lakes in Oregon and Owens Lake in California as evidence of a warmer and drier climate in the Southwest during the period of the "Climatic Optimum":

> These lakes lacked outlets in postpluvial times, but nevertheless have only a low salinity, a salinity so low in fact that they cannot be remains of the pluvial lakes in the same basins. The pluvial lakes must have dried, and the accumulated salts must have been removed by wind or have become buried, before the modern lakes came into existence. The amount of salts in the waters of these lakes in 1887 to 1912, the salt contents of their main feeder streams, and the rate of evaporation suggest that the accumulation of the salts may have required some 4,000 years. This means that the modern lakes were reborn 4,000 years ago and that their basins were dry for long ages before 2000 B.C.

Actual records of lake levels in the Southwest began in 1840 or later, but indirect evidence of low stages prior to 1850 has been obtained from trees growing around the margins of some of the lakes. Harding (1935, p. 90) has summarized this evidence at Eagle Lake, Mono Lake, and Lake Tahoe in California, and at Great Salt Lake in Utah: "(1) For 100 years prior to 1850 these lakes were continuously lower than they have been at any time since 1850; and (2) the high stages reached about 1915 are higher than any reached for from 250 to 300 years." Thus for one or more centuries prior to 1850, the Southwest appears to have had a hotter, drier, or hotter-drier climate than that since 1850.

In some drainage basins the hydrologic records are sufficient to permit computation of the natural runoff (lake inflow) of the drainage basin. This is the case in the Truckee River drainage basin, which includes Lake Tahoe in its headwaters and Pyramid and Winnemucca Lakes in its lowest parts. From records of

[4] In using the word "improvement," Ahlmann speaks especially from the viewpoint of those in Sweden, England, and far northern latitudes generally. In the Southwest, which already includes the hottest and driest parts of the country, an upward trend in temperature and resultant increase in evapotranspiration would not be called an improvement, because it would reduce the net supplies of surface and ground water, unless there were also a general increase in precipitation that might tend to offset the increased rates of evapotranspiration.

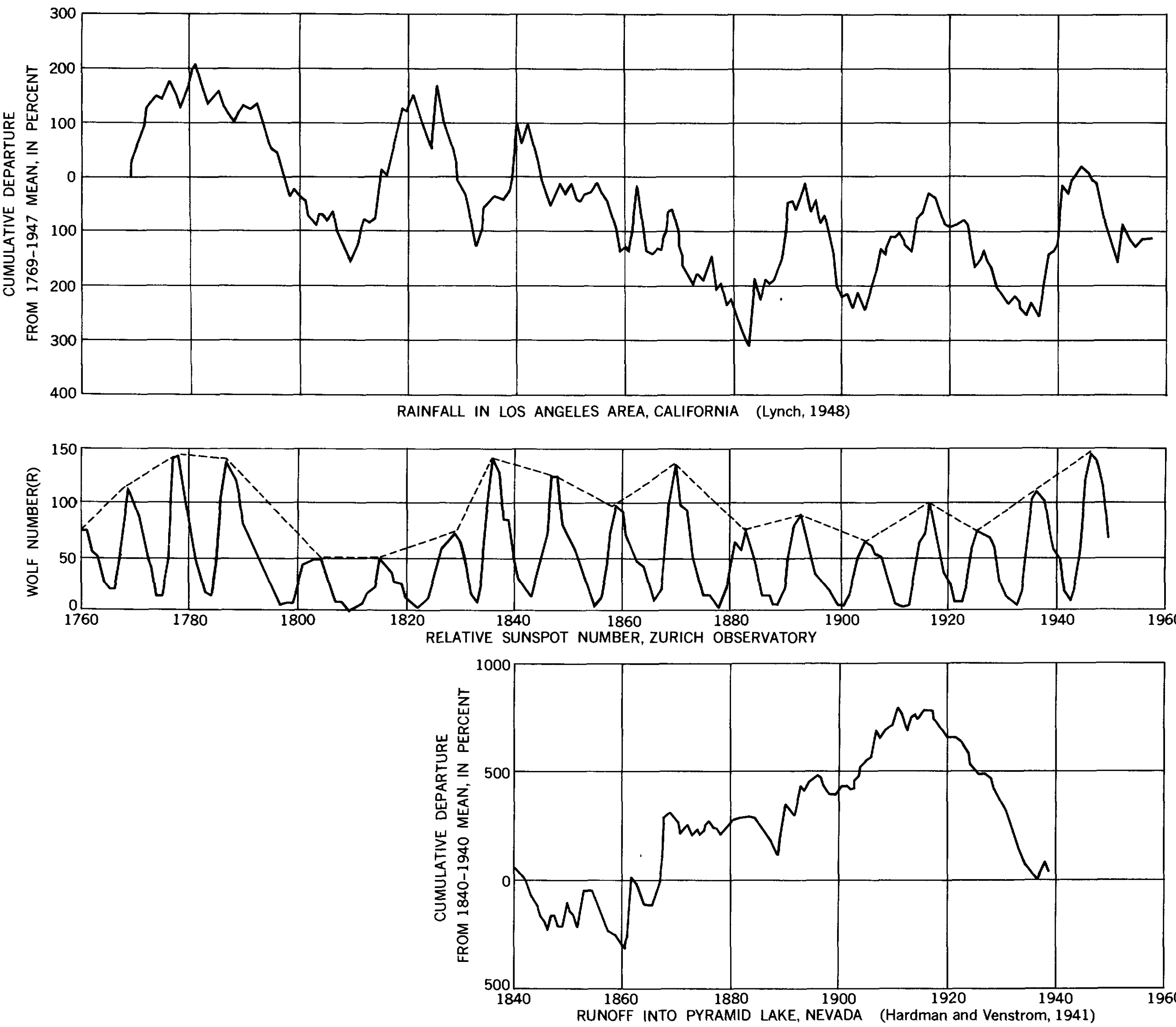

FIGURE 19.—Fluctuations in precipitation and runoff deduced from historic records.

fluctuations of levels in these lakes, runoff and diversions of the Truckee River, and consumptive use within the basin, Hardman and Venstrom (1941) estimated the annual natural runoff of the Truckee River in percentage of the 1840–1939 mean. The trends in cumulative departures from this mean are similar to those shown by Lynch's estimates of rainfall in Los Angeles, especially after 1900 (fig. 19). Hardman and Venstrom's general conclusions as to the 19th century history of the drainage basin are similar to those by Harding concerning Eagle and Mono Lakes: drought conditions prevailed for many years prior to 1840; a period of generally increased precipitation began about 1860 which, although broken by minor drought periods, lasted until about 1917.

Graphs showing the fluctuations in level of Mono Lake, Eagle Lake, and Tulare Lake in California, and of Great Salt Lake, in Utah, are presented in figure 20. The levels of all these lakes have been affected by man-made diversions—Mono Lake since 1940, Eagle Lake since 1924, and Tulare Lake since 1879: Great Salt Lake levels have doubtless been affected by progressively increasing diversions from its tributaries during the last century and according to Harding (1935, p. 89), "general computations of the effect of this diversion indicate that the lake would have been as high from 1923 to 1927 as it was from 1868 to 1878 if irrigation had not increased between these two periods. It is also probable that the lake would not have been as low in 1934 [to 1940] as it was [in 1904–1907] had it not been for the same effect." Harding also notes that Great Salt Lake does not fluctuate in harmony with all the variations of the lakes in the western part of the Great Basin, but does tend to follow their major movements.

FLUCTUATIONS IN TREE GROWTH

Tree-ring analysis has provided information concerning climatic fluctuations in the Southwest far better than any other source of information for the period prior to the beginning of Weather Bureau records. Douglass (1914), reporting on studies begun in 1901, noted that in properly located trees in the Southwest the relation between annual tree growth and rainfall is close. For climatologic studies it is desirable to obtain tree-ring sequences free from the effects of pests, fire, and other environmental or structural factors that are more or less nonclimatic, and therefore it has been necessary to develop a considerable set of principles of selection, reduction, and interpretation of specimens. Then, to show climatic history of a region, concurrent and homogeneous sequences of annual ring-widths of trees are merged, and may be plotted as a mean growth curve. Most of the local variations are eliminated in averages of 5 to 10 well-selected cores.

The results of dendrochronologic studies in the semiarid regions of North America during the past half century have recently been summarized by Schulman (1956, p. 68-69):

> Based on about one-third million annual rings in selected, drought-sensitive trees from semiarid sites, regional indices have been derived which are believed to represent, to a fair approximation, fluctuations in rainfall in the upper basins of all the major streams of the western United States. In most areas, where the tree growth may be closely correlated with runoff, the indices provide information about that variable also. Almost all indices are statistically well-based for about 500 years; the Colorado and Missouri indices are well documented for about 800 years. Three series of maximum length are: Colorado, 2,009 years, including the extension in archaeological beams; Snake, 1,494 years; Missouri, 973 years.
>
> A major element in the construction of these indices was the discovery and extensive sampling of a category of drought-recording, stunted conifers growing with extreme slowness on the most adverse sites and attaining ages twice or more the normal for the species on optimum growth sites. The oldest tree thus far discovered in each of the principal species is: limber pine, 1,700 years; bristlecone pine, 1,500 years [recent collections have extended these maximum ages as follows: limber pine, 2,000 years; bristlecone pine, 4,100 years]; piñon pine, 980 years; Rocky Mountain Douglas fir, 890 years; ponderosa pine 860 years. The 3,200-year Sequoia chronologies developed by Douglass and Huntington for the relatively moist southern Sierra Nevada have been reexamined in light of the highly sensitive southern California and Colorado River Basin chronologies. Some of the Sequoia series show a fairly good relation to these chronologies and thus perhaps can be taken to provide a fair first approximation to southern Sierra rainfall for the past 1,500 to 2,000 years. Too few good records in earlier years of the Douglass series and cumulative errors in the Huntington series lead to the conclusion that at least the 1,300 years of Sequoia chronology in B.C. have at present very limited climatic value.
>
> Despite limitations in amount of material and uncertainties inherent in the data of this report, some conclusions of fair reliability may be drawn regarding long-term rainfall variations in the West.
>
> Evidence is strong for the existence of a great 200-year wave in rainfall and runoff in the Colorado River Basin, the 1200's extraordinarily dry, the 1300's extraordinarily wet (more precisely, perhaps, 1215-1299 and 1300-1396). The droughts of the first interval and the floods of the second appear to have far exceeded in duration and intensity those recorded by modern gages.
>
> Noteworthy among other climatic events is the pronounced and extensive drought of 1573-1593, which seems to have been as severe in southwestern Montana as it was in the southern Rocky Mountains and southern California, though it apparently did not extend into Alberta. The total flow of the Colorado River during the two years 1584-85 may not have exceeded the record for low runoff recorded in 1934.
>
> Some of the indices suggest the possibility of a peculiar change in the characteristic march of rainfall some three centuries ago. In southern California the tendency for long-term swings to one side of the growth-mean or the other, which had been typical for some centuries preceding the mid-1600's, gave way to swings of much shorter average duration. This tendency is very pronounced in the Colorado River Basin. On the other hand a reverse tendency seems to be indicated in the Missouri River Basin indices, in which shorter variations are more characteristic preceding 1650. It is perhaps no more than a coincidence that about 1645 to 1715 occurred the well-known great dearth in sunspots, for some of the representative growth indices in this report, from regions other than those just noted, apparently do not record such a change.
>
> Comparison of growth fluctuations in recent decades with those for the past several centuries suggests that in many areas of the West the interval since 1870 or so has been one of decidely abnormal climate. The present climatic fluctuation has taken the form of a major drought in recent decades over much of the West; it is pronounced in the Colorado River basin and particularly in southern Arizona. In the latter region the drought began in 1921, has been broken in very few years, and appears to be the most severe one since the late 1200's.
>
> The evidence is very strong that the present fluctuation represents, in terms of centuries-long dendroclimatic data, a major disturbance in the general circulation, at least over western North America. It remains to be determined whether this presages a fundamental change in type of climatic fluctuation such as seems to have occurred in some areas in the 1600's. More light on this will probably come when more extensive, significant dendroclimatic histories have been developed.

In an appendix Schulman (1956, p. 70-123) presents graphs showing growth curves for groups of trees in several western drainage basins. Climatic fluctuations with lengths ranging from a few years to several decades are indicated in all these records, as well as in other areas where tree-ring chronologies have been developed. Seeking evidence of cyclic recurrence of climatic phenomena, Schulman analyzed the data for

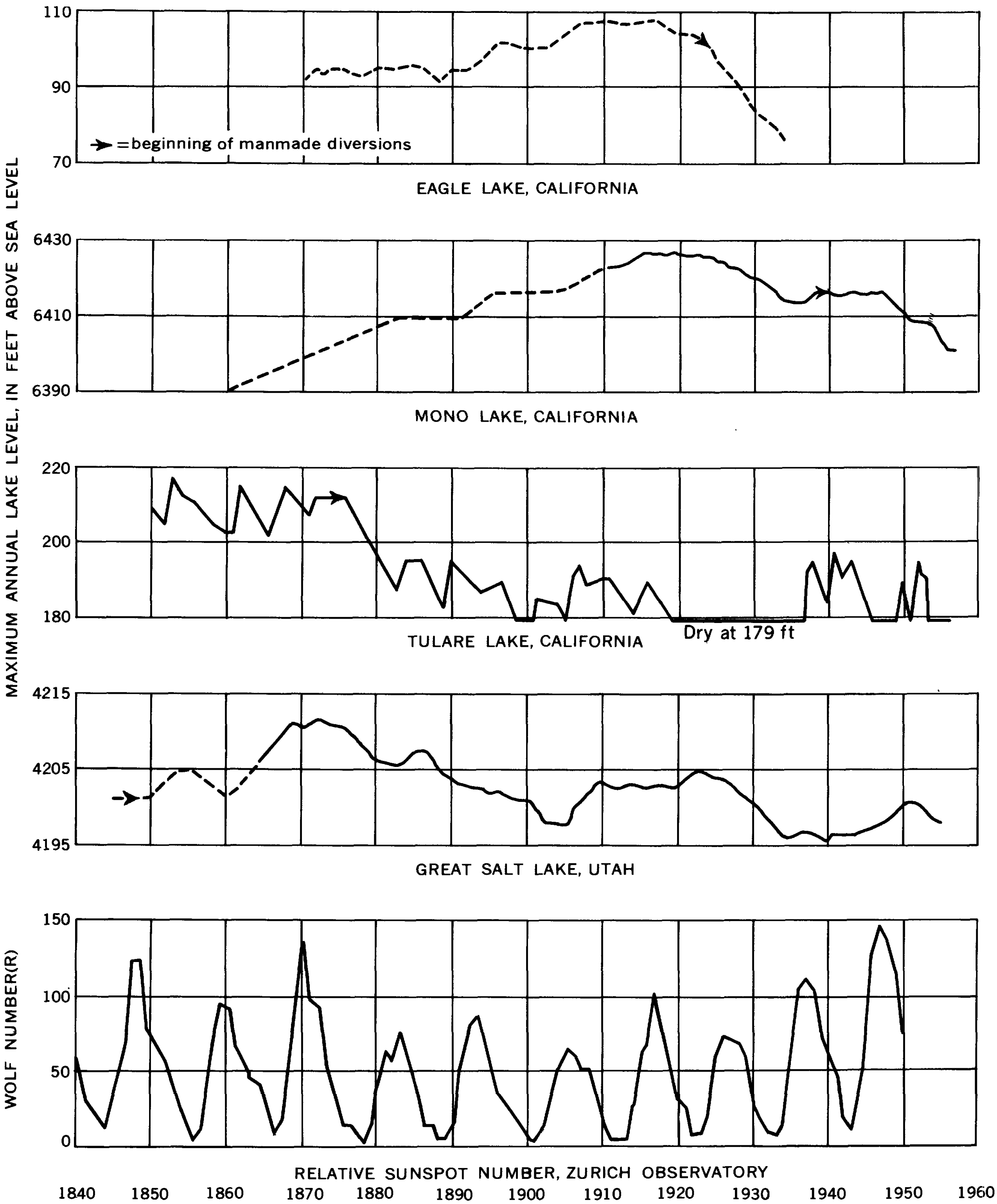

FIGURE 20.—Fluctuations of level in several lakes of the Southwest. Dashed lines are inferred.

cycle-lengths in the range 15 to 100 years. Cycles of 20 to 24 years (approximately the length of the double sunspot cycle) were noted in data from several regions in the West, and cycles up to a century in length were identified in some records. However, Schulman (1956, p. 63) points out that "in no extensive data were cyclic tendencies found of such regularity and strength as to suggest physical reality," and concludes that none of the apparent cycles are systematic enough to permit long-range synoptic forecasting after the fashion of the daily forecasting of weather.

SUMMARY OF DROUGHT CHARACTERISTICS

In an arid or semiarid region, because it is a "have-not" region so far as precipitation is concerned, every storm is important and every dry period of whatever length is significant to someone. Dry farmers, from Hopi Indians to wheat ranchers, greet each successive rainless day with a sadder shake of the head, and welcome each rain with a smile. To them, a drought is measured in days and weeks, for their needs are similar to those of farmers in more humid regions, although they have generally learned to get along with less. Stock ranchers are similarly dependent upon soil moisture, but they may avoid the pinch of short-term droughts if they are allotted sufficient rangeland—particularly if the rangeland extends into highlands with their habitually greater precipitation.

The majority of people of the Southwest can ignore a deficiency in precipitation extending over several months, and many are not affected adversely by a complete lack of precipitation throughout the growing season. To these people, dry periods measured in days, months, or whole seasons are not serious. When the precipitation deficiency extends over several years or decades, however, with resulting curtailment in stream or ground-water supplies, that dry period is serious, and is properly termed a drought. This report is concerned especially with the effects of such dry periods upon the net supplies of surface and ground water, and the emphasis therefore is upon droughts lasting at least several years. These droughts cover periods of various length and various magnitudes of precipitation deficiency; each of them aggravates the water deficiency that characterizes the average climate.

A considerable variety of data shows that the climatic history of the Southwest is comprised of a long succession of alternating wetter and drier periods; other data indicate that there have also been alternating warmer and cooler periods which have influenced the water-supply conditions in the region. The recorded fluctuations include many that may be cyclic and of fairly regular recurrence interval. Indeed a cycle enthusiast can find so many cycles, ranging widely in period and amplitude, that he ends up with the same conclusion as the cycle skeptic: the causative factors are too little understood and the resultant precipitation too irregular to serve as an adequate basis for long-range forecasting of the climate. Nevertheless, some climatic fluctuations appear to have recurrence intervals sufficiently regular, and amplitudes sufficiently great, that they may be important considerations in long-range planning for water-resource development and utilization.

The droughts best shown by the available data are those having average durations of 10 to 13 years. The evidence for these droughts is especially in the Weather Bureau precipitation records covering most of the past century, in tree-ring records covering as much as 2,000 years, and in other less specific supporting data. These droughts are products of climatic fluctuations that have durations comparable to the double sunspot cycle, which varies considerably in length but has a recurrence interval averaging 22 to 23 years.

The droughts with average durations of 10 to 13 years and recurrence intervals of slightly less than a quarter of a century do not by any means span the entire Southwest. Characteristically they are most prominent in regions where the precipitation is chiefly from a single source: in the Pacific Border where moisture comes from the Pacific Ocean, and in the Great Plains where moist airmasses come chiefly from the Gulf of Mexico. In both these regions the precipitation deficiency during a 10- to 13-year drought period may be equivalent to as much as three times the mean annual precipitation. Within these regions recurrent drought periods are very pronounced in some localities, fairly clear at others, and not clearly recognized at still other places.

In the intervening region, which includes the Great Basin, Colorado Plateaus, and Sonoran Border zones, droughts are less regular in duration, recurrence interval, and magnitude. This intervening region receives its annual precipitation from several sources, but in various parts of the region one source is likely to be dominant in certain seasons, and another source dominant in other seasons. By analysis of precipitation by seasons, therefore, it is possible, at least in some localities, to discriminate drought periods with recurrence intervals similar to those observed in the Pacific and Great Plains zones.

Long-term trends are shown in records of temperature, and for several decades prior to 1940 these trends were generally upward throughout the Southwest. Records from other parts of the Northern Hemisphere indicate that similar temperature trends are very widespread and possibly worldwide in distribution. The trend toward increasing warmth throughout the Northern Hemisphere—and in the Southern Hemisphere wherever records are available—continued for about a century, and seems now to be changed.

Records of tree growth indicate that during the past 2,000 years there have been droughts of exceptional magnitude in various parts of the Southwest, such as those that are shown by analysis of tree rings in the central Pueblo area of northern New Mexico and Arizona to have occurred in about A.D. 700–720, 1070–1100, 1275–1300, and 1570–1600. Exceptional droughts at various times are also inferred from historic, archeologic, and other data, but those data provide no basis for comparison with the conditions of recent years. These exceptional droughts may be the products of centuries-long climatic fluctuations, augmented by the shorter-period fluctuations noted in the records for the last century. However, Schulman points out that even in highly sensitive trees the sequences may contain centuries-long swings which are not necessarily representative of a general climatic fluctuation, and he concludes (1956, p. 56) that no decisive conclusion may yet be drawn regarding the existence of a long-term trend in Southwestern rainfall in postglacial times on the basis of ring growth. Individual trees having ages approaching 4,000 years, of which several have recently been found in California, are likely to provide much additional information concerning climatic fluctuations having lengths of several centuries.

The area of Southwest drought in 1942–56, depicted on figure 6, achieves insignificance in the light of these conclusions concerning the climatic fluctuations that are responsible for drought. The map is correct for the specific 15-year period, but it does not by any means delineate an area that is especially vulnerable to drought. The 15-year period is significant because it is slightly longer than the average duration of the droughts of greatest magnitude in the past century. Because these droughts are caused by fluctuations that are almost opposite in phase in the Pacific and Great Plains subdivisions of the Southwest, a map for any 15-year period is likely to show extensive areas in the Southwest where precipitation has been significantly less than average. But, as suggested by plate 1, these areas shift from year to year.

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