TEXAS WATER DEVELOPMENT BOARD

REPORT 30

TEXAS DROUGHTS

Causes, Classification
and Prediction

By

John T. Carr, Jr.

November 1966

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INTRODUCTION

There is little doubt but what prolonged drought can be equated with plague. All within the animal and vegetable kingdoms of the affected areas must suffer and endure, die, or seek tolerable environments. Time and again history documents the devastating effects of drought, and history points out the vast areas droughts have laid to waste for many years afterward--some lands never to be reclaimed again for cultivation or permanent habitation within known history. However, this report makes no attempt to chronicle or document historical droughts. Rather, a presentation is made of the results of a comprehensive search of the literature for drought causes, drought classification, and drought prediction.

While a wealth of literature is available on drought causes and classification, there is a dearth of information on drought prediction. Most who delve seriously into the matter seem unwilling to record their forecasts of the beginning and ending of droughts, although there is general agreement that drought conditions are cyclic in an inexplicable way and that drought will return time and again to regions historically susceptible to drought.

Two schools of thought emerge. Some believe drought to be a random thing, brought about by the chance occurrence of the right combination of drought-producing terrestrial conditions coming together spatially and temporally. Others believe that droughts occur in definite cycles and are caused by extraterrestrial influences. Fluctuations in insolation receive the most attention and comment.

The literature discloses fairly general agreement among the authors that: Sun is the principal source of Earth's heat, and other sources of heat such as the interior of the earth are insignificant; fluctuations in the amount of heat received by the earth from the sun are a matter of historical record; heat fluctuations produce more air movement; and more air movement, or circulation, produces more precipitation. Beyond these general agreements, scientists go their separate ways.

Purpose and Scope

The principal purposes of this applied research were to provide a basis for determining the feasibility of including drought prediction as a criterion in the Texas Water Development Board's water-resources planning effort; to draw attention to the meteorological phenomenon, drought, as it affects Texas' water resources and development and the users dependent thereon; and to summarize views on the causes, classification, and predictability of the various types of drought as of 1965.

In this report the several classifications of drought are examined, some of the causes and effects of drought are described, and some of the drought predictions reviewed are verified insofar as technically feasible. All predictions of drought found in the literature receive attention in the text.

A sizable cross section of the literature on droughts was examined, evaluated, and partially abstracted for this report. Readers desiring more detailed understanding of the drought phenomenon are referred to the investigations of the many authors listed as references.

Personnel

This report was prepared in Engineering Services of the then (prior to September 1, 1965) Texas Water Commission, by John T. Carr, Jr., Research Hydrometeorologist, under the direct supervision of Louis L. McDaniels, Reseach Program Coordinator, and under the general supervision of John J. Vandertulip, Chief Engineer.

Louis L. McDaniels is especially acknowledged for making himself constantly available for consultation and advice on the hydrologic and agricultural ramifications of meteorologic drought.

Special thanks are given to Texas State Climatologist Robert B. Orton for his technical review and criticism of the original manuscript.

DROUGHT DEFINITIONS

Definitions of drought vary with the author and his area of interest. Palmer (1965, p. 3), when writing about meteorological drought, defined a drought period as "...an interval of time, generally on the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply." Palmer explained further that the severity of drought may be considered as being a function of both the duration and magnitude of the moisture deficiency.

The U.S. Weather Bureau (1953) calls attention to the fact that droughts of some severity occur almost yearly in one or several regions of the United States, and further states that a drought is usually defined as a:

> "...period of dry weather of sufficient length and severity to cause at least partial crop failure."

and further:

> "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."

When considering agricultural drought, Thornthwaite (1947, p. 88) said:

> "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...."

The work of Thornthwaite points up one fallacy in defining drought as a shortage in rainfall alone: neglecting to take into account the antecedent soil-moisture conditions renders incomplete any computations made to determine the amount of water needed.

Thomas (1962, p. 7), after reviewing most of the foregoing and many other definitions of drought, chose the following definition as best fitting his needs when authoring U.S. Geological Survey Professional Paper 372-A, "The Meteorologic Phenomenon of Drought in the Southwest":

> "Drought is a meteorologic phenomenon and occurs during a period when precipitation is less than the long-term average [See Figure 1], and when this deficiency is great enough and continues long enough to hurt mankind."

Drought, according to Thomas, then, is measured in terms of the duration and magnitude of departure from the average climate in the area under consideration. This is somewhat of a departure from Hoyt's (1938, p. 2) definition of drought used in some of the previous U.S. Geological Survey studies of droughts in the United States:

> "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."

Thomas (1962, p. 5) further states:

> "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."

A. J. Henry pointed out in the Monthly Weather Review (v. 58), when writing of the great drought of 1930 in the United States, that 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. Thomas (1962) points out that Henry's definition of a drought roughly parallels the drought definition used by the Tennessee Valley Authority.

Some of the other definitions of drought encountered in this study include: (1) The British Rainfall Organization says that a <u>partial</u> drought is a period

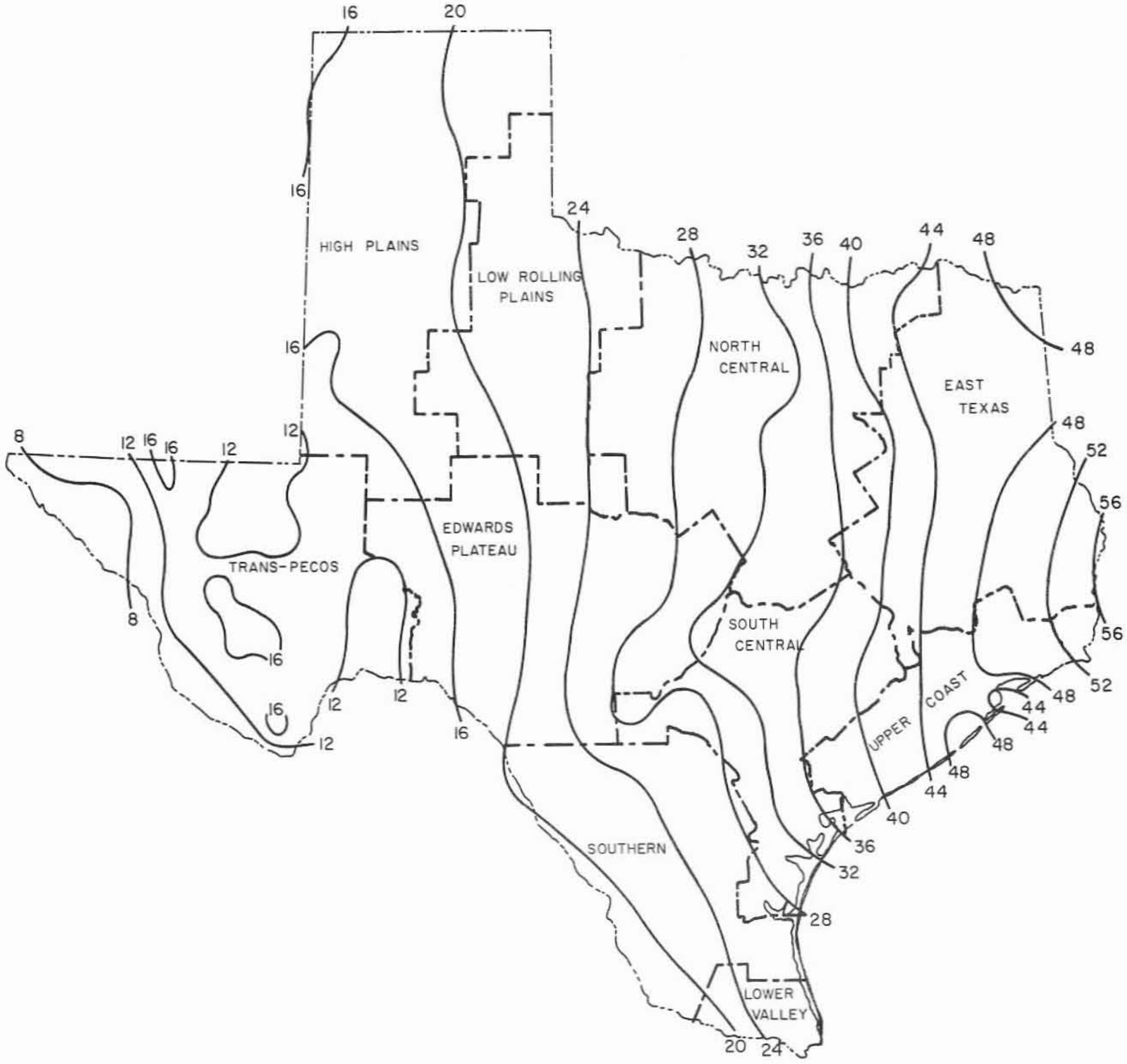


Figure 1

Normal Annual Precipitation (Inches) and Climatic Divisions in Texas Based on the Period 1931-60

Courtesy U.S. Weather Bureau

of more than 28 days with a very small rainfall per day, and an absolute drought is a period of at least 15 consecutive days to none of which is credited as much as 0.01 inch of rain; (2) Tannehill (1947, p. 37) notes that in European Russia a drought was defined as a period of 10 days with a total rainfall not exceeding a fifth of an inch; and (3) Friedman (1957, p. 8) in his paper on drought in south and southwest Texas chooses to use Havens (1954) definition of drought:

> "...a lack of rainfall so great and long continued as to affect injuriously the plant and water supplies both for domestic purposes and for the operation of powerplants, especially in those regions where rainfall is normally sufficient for such purposes." (See Figure 2.)

Ad infinitum, dependent only on the works of how many authors and on how many viewpoints one has the time or need to research.

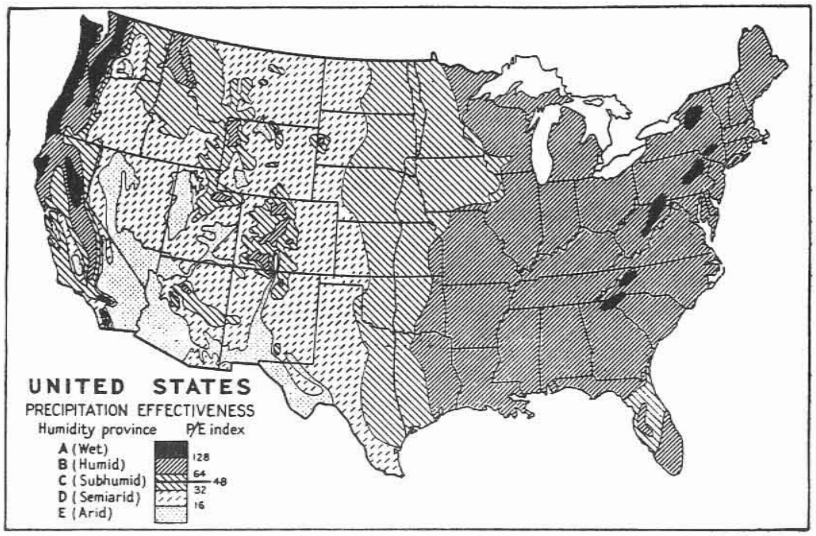


Figure 2

Normal Climatic Regimen of the United States

After C. W. Thornthwaite, 1931, the climate of North America according to a new classification: © Geographical Review, v. 21, p. 642.

Some considerations found to be common in most definitions of drought are:

1. Rainfall--the meteorologic parameter most used to determine when a drought is in progress.

2. Duration and magnitude of rainfall deficiency--the key to soil-moisture deficiency, which is in turn the key to the severity of agricultural drought.

3. Purpose of the technical paper, report, or study--strongly influences

the definition of drought given by the author; each author chooses an existing definition or coins a new one which best suits his needs at the time.

Provoking thought, Tannehill (1947, p. 15) asks:

> "What is drought? In the United States drought brings to mind withering crops, parched fields, dusty roads, and failing water supplies. In its extremes in some other countries it means hunger, famine, starvation, human emaciation and death, skeletons of animals, and mass migration of peoples. Sometimes it has led to war.
>
> "But we have no good definition of drought. We may say truthfully that we scarcely know a drought when we see one. We welcome the first clear day after a rainy spell. Rainless days continue for a time and we are pleased to have a long spell of such fine weather. It keeps on and we are a little worried. A few days more and we are really in trouble. The first rainless day in a spell of fine weather contributes as much to the drought as the last, but no one knows precisely how serious it will be until the last dry day is gone and the rains have come again. We ask if this was just a chance combination of dry days, or were we, even from the first, in the grip of some powerful force which might have been recognized?"

DROUGHT CLASSIFICATION

Considering drought classification separately from drought definition and drought severity, the following broad classifications were selected for discussion:

1. Meteorologic drought,

2. Hydrologic drought, and

3. Agricultural drought.

Meteorologic Drought

Broadly, as death results when the heart ceases to beat for a period of time, drought results when no precipitation falls for a long period of time. Thus, simply, drought is caused by lack of rain. Drought may occur in a very small area, affecting only a few farmers or a small community, but generally a drought hurts many people and affects the economy severely before receiving enough attention for study, classification, and documentation in the record books. Thus, a meteorologic drought is a significant decrease from the climatologically expected and seasonally normal precipitation over a wide area.

Palmer (1964a, 1965) developed a numerical drought index and a method of computing an index number designating the severity of meteorologic drought. Palmer's drought classifications and numerical values are tabulated on next page.

Index	Description
0	Normal (for place being analyzed)
-0.50 to -0.99	Incipient drought
-1.00 to -1.99	Mild drought
-2.00 to -2.99	Moderate drought
-3.00 to -3.99	Severe drought
≤ -4.00	Extreme drought

At Austin, Texas, during the 360-month period 1931-60, using the Palmer analytical technique of classifying drought, it was determined there were 160 dry months--44 percent of the total of 360 months--in which Austin suffered drought conditions of some severity ranging from incipient to extreme. This may not be actually as bad as it seems. Palmer treats drought as a meteorological phenomenon and defines drought as a prolonged abnormal moisture deficiency. By that definition drought severity is a function of moisture demand as well as moisture supply. It depends on climate because drought is a relative condition, and it depends on current as well as antecedent weather. Although the computations were made for Austin, they can just as well be made for other locations having a sufficiently long precipitation record. Figure 4 shows a breakdown of the results of applying Palmer's analytical technique to the Austin rainfall data. Figure 3 is an example of how the Palmer drought index for an area can be depicted by computing the same data for many stations just as the data were computed for Austin and shown on Figure 4.

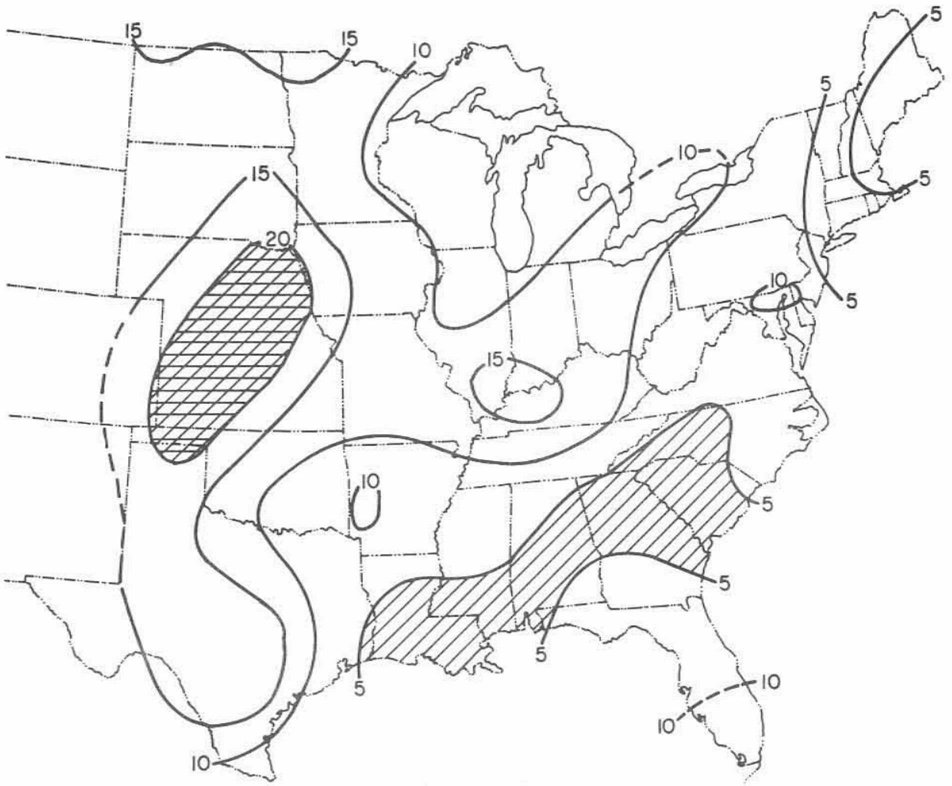
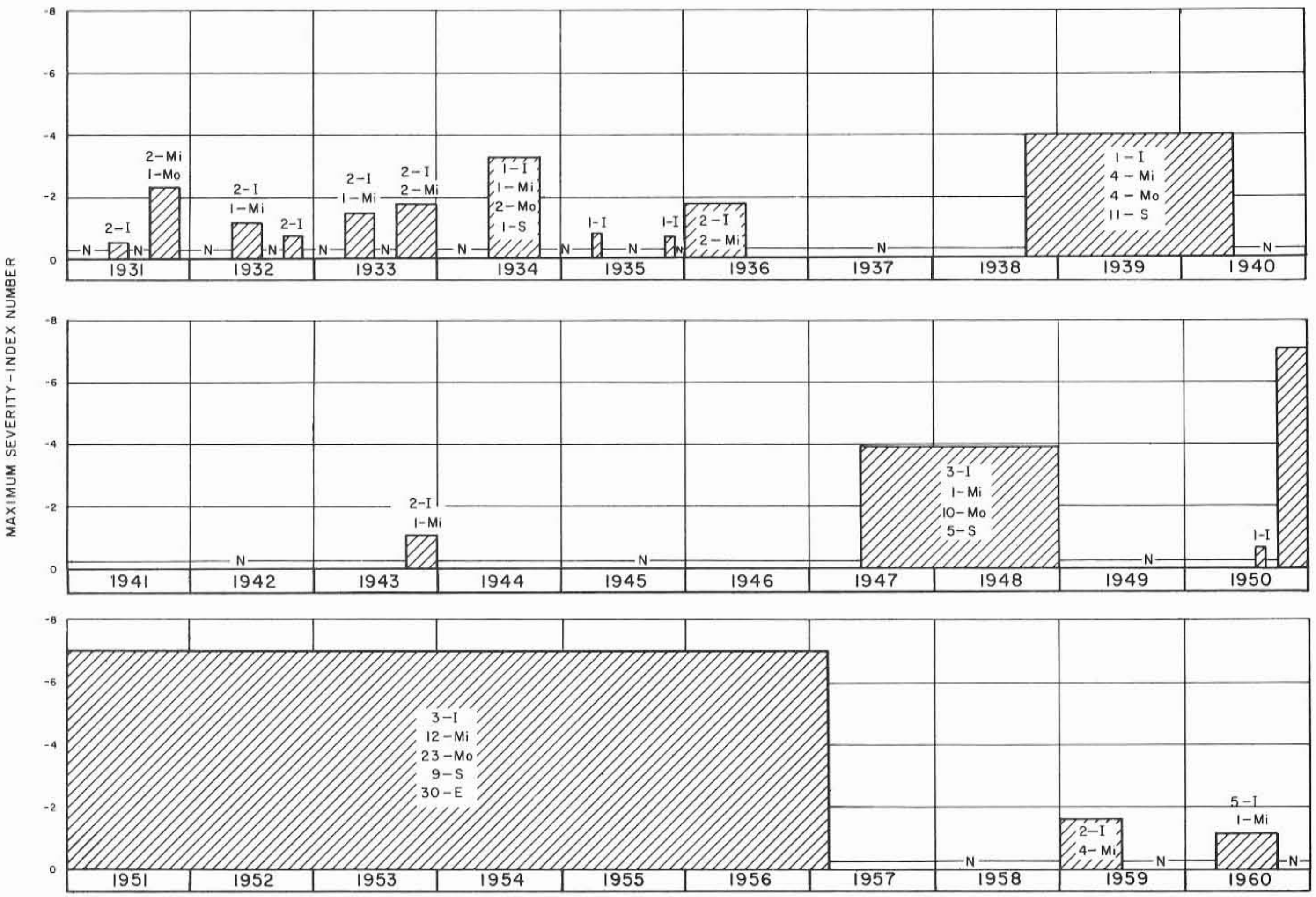


Figure 3

Percent of Months, 1931-60, with Severe or Extreme Drought

After W. C. Palmer, 1964, Moisture variability and drought severity: Presented at 13th Ann. Mtg., Agr. Research Inst., Oct. 12-13, 1964, Washington, Natl. Acad. Sci., Natl. Research Council.



EXPLANATION

Description	Index Number	Description	Index Number
N=Normal	0 to -0.50	Mo=Moderate drought	-2.00 to -2.99
I =Incipient drought	-0.50 to -0.99	S=Severe drought	-3.00 to -3.99
Mi=Mild drought	-1.00 to -1.99	E=Extreme drought	-4.00 and less

Example: 4-Mi indicates 4 months of mild drought.
Shading indicates period of drought and maximum severity during the period.

Figure 4

The Palmer Analytical Technique Applied to Austin, Texas, 1931-60

Hydrologic Drought

Hydrologic drought is a step further than meteorologic drought, usually lasting for several years and being reflected in the climatological normals of rainfall and temperature where it occurs. Meteorologic drought may cause crop destruction, but if continued long enough, hydrologic drought will be marked by skrinkage and drying up of streams and rivers, depletion of water stored in surface reservoirs and lakes, cessation of spring flows, and decline of groundwater levels (Figure 5).

Hydrologic drought is more far-reaching than meteorologic drought, affecting industry as well as agriculture. Chemical plants and factories that depend on a plenitude of water may be force to curtail or cease operations. Hydroelectric power generation may be similarly affected, and there will be insufficient water to serve all irrigation needs. Clearly, if hydrologic drought continues long enough factories may be forced to relocate and irrigable lands may have to be abandoned. More rain is required to end a hydrologic drought than any other type of drought. Most of the prolonged droughts in Texas can be classified as hydrologic droughts, their severity depending on the magnitude of water use and the water in storage when the drought begins.

Agricultural Drought

Agricultural drought occurs when soil moisture and rainfall are inadequate during the growing season to support healthy crop growth to maturity and to prevent extreme crop stress and wilt.

An agricultural drought may very well exist even though a meteorologic drought does not. That is, soil moisture may be deficient for agricultural needs when the records show that the total rainfall exceeded the total agricultural needs during the period. When the rain falls is of prime importance to agricultural production. Too much rain during the planting or harvesting seasons can cause crop failure; growing crops may wilt because of excess rain, or matured crops may ruin in too wet fields before they can be harvested. On the other hand, a good rain or two during critical growth periods may result in good crop yields even when the total rainfall for the year is low.

Hurricane Effect

Annual rainfalls are not dependably indicative of agricultural drought, but particularly this is true in areas of hurricane influence along the Texas Upper Coast. During a "wet" year, a late summer or early autumn hurricane or a series of easterly waves (tropical storms) may bring rainfall in abundance and meteorologically no drought occurs for the year. However, couple these events with significant rainfall shortages during the spring and early summer crop-growing season, and the results can contradictorily add up to normal or excessive rainfall for a year in which there was agricultural drought.

Yearly rainfall normals are calculated by determining the 30-year arithmetic mean decennially, which of course includes all the excessive rainfall from all the hurricanes during the last 30 years (Figure 6). Thus, the so-called "normal" rainfall figure can be misleadingly high.

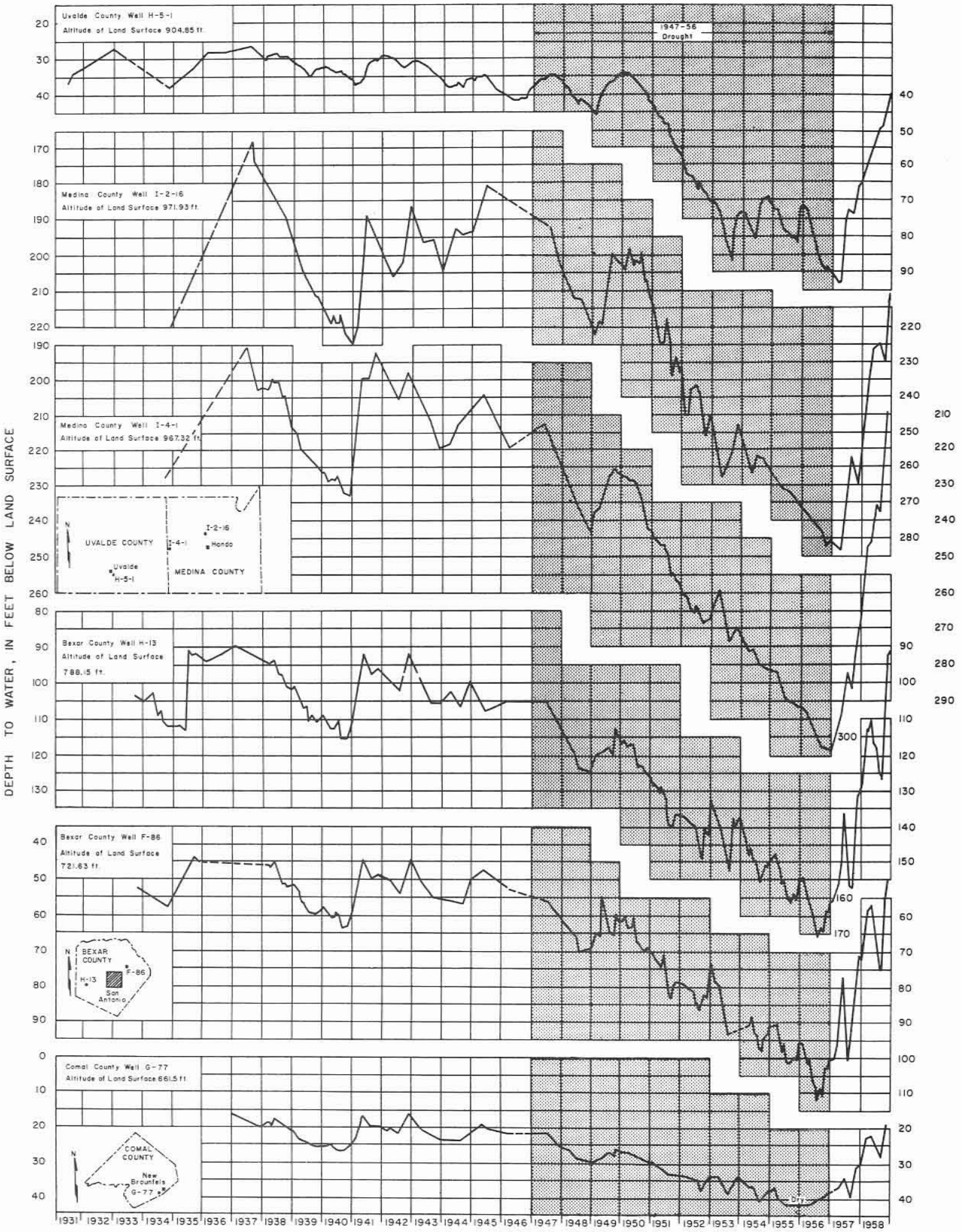


Figure 5

Hydrographs of Six Wells in the Balcones Fault Zone

After H. E. Thomas and others, 1963, Effects of drought in Central and South Texas: U.S. Geol. Survey Prof. Paper 372-C, pl. 4.

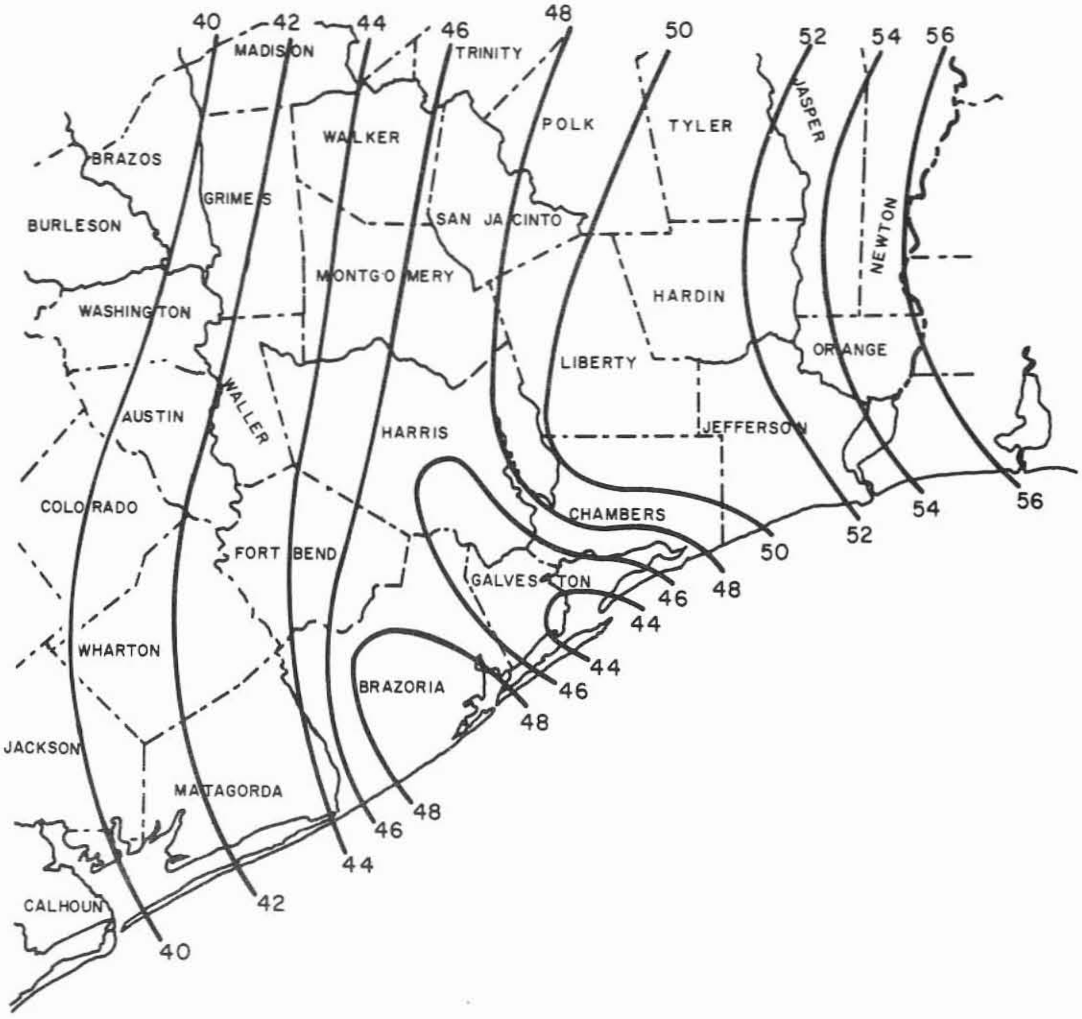


Figure 6

Normal Precipitation Isograms (Inches) Along the Texas Upper Coast, Showing Irregular Pattern Due to Hurricanes

Isograms honor U.S. Weather Bureau Decennial Census rainfall figures based on the standard period 1931-60.

Evapotranspiration Effect

According to Thornthwaite and Mather (1955, p. 15), potential evapotranspiration is the amount of water that will be lost from a surface completely covered with vegetation if there is sufficient water in the soil at all times for the use of the vegetation. In all but East Texas and along the Upper Coast, the average annual potential evapotranspiration, as computed by Thornthwaite (1948) and pictured in Figure 7, exceeds the "normal" precipitation. This seems to suggest that perhaps most of South and West Texas, being on the edge of the arid western interior of the United States, is not the best suited for dryland farming. However, this reasoning does not take into account the greater importance of adequate rains that can be climatologically counted on during critical growth periods. Although not a direct cause of drought, high potential evapotranspiration rates can threaten damage to crops as soon as rainfall begins to become inadequate.

DROUGHT CAUSES

The Arid West

The arid western interior of the United States, still shown as the Great American Desert on some maps, includes parts of the Texas High Plains and Trans-Pecos areas. The "border areas" near the world's great deserts are most likely to be stricken repeatedly with severe drought. If the deserts expand, and contract from time to time, as many climatologists believe (see Figure 8), then much of Texas will forever be subject to recurring drought. But is not drought a near-normal condition in these desert-border areas? Has not life and the economy in these areas long ago adjusted to "drought as the normal thing"? For the most part, yes. But progressively outward from the desert areas, life and the economies have grown less and less accustomed to drought, hence are not prepared for a "long dry spell." It is in these unprepared areas that severe drought is a calamity--areas to where the desert expands during only the most severe droughts. Much of Texas is in such an area.

Variations in Solar Radiation

Beyond a shortage of precipitation, the causes of droughts, or expanding deserts, have been attributed variously to both terrestrial and extraterrestrial influences. One characteristic most theories have in common is that no matter what else the cause, solar radiation is behind it all, and the sun's energy is at least indirectly responsible for all changes in climate.

North American "Sinks"

Tannehill (1947) has a widely publicized explanation of how variations in insolation (incoming solar radiation, or heat) can cause precipitation to abandon one large area of North America for extended periods in favor of another large area far removed, thereby causing meteorologic drought. Using easily understood physical concepts, Tannehill explains how the sun's heat causes great quantities of air from the Pacific semipermanent high-pressure cell to pour into the Canadian sink and the Great Basin sink. These great quantities

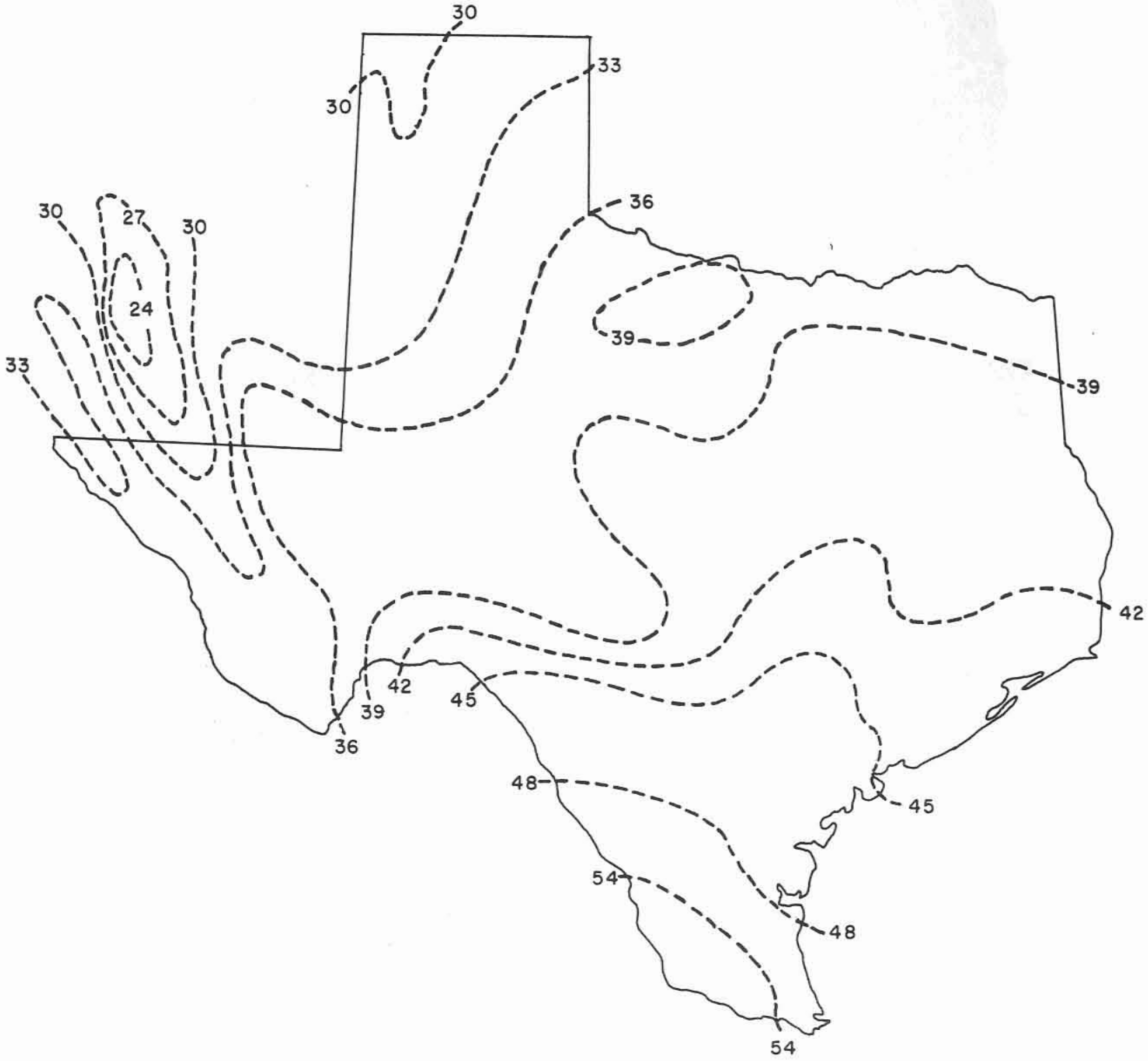
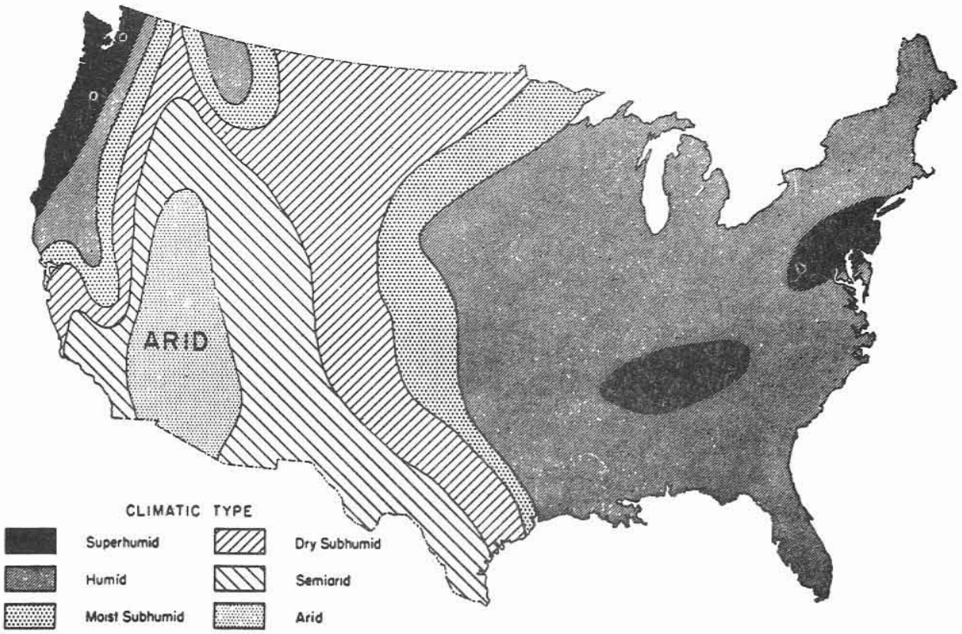


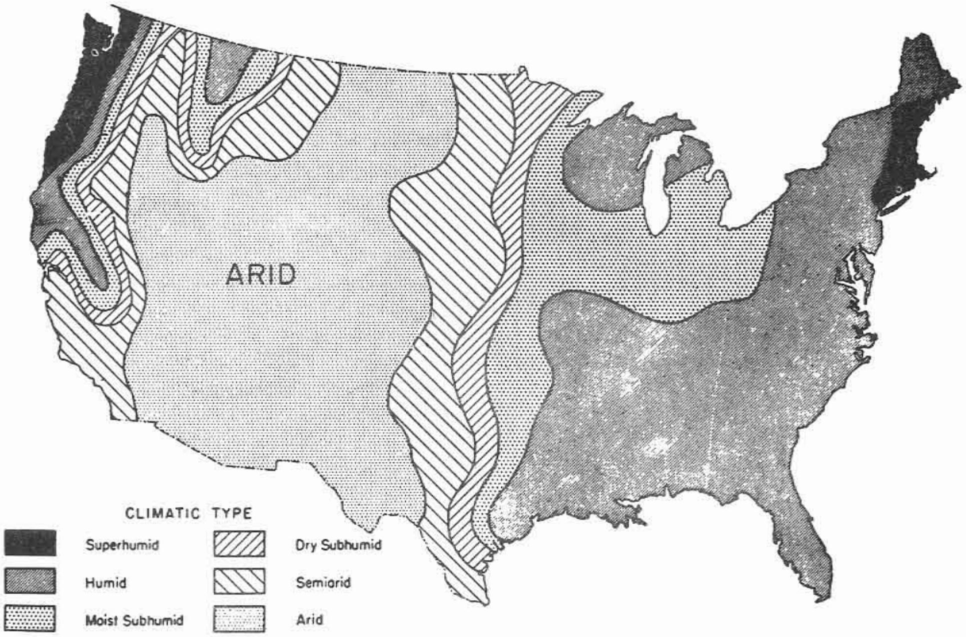
Figure 7

Average Annual Potential Evapotranspiration (Inches) in Texas Computed by Thornthwaite

After D. G. Friedman, 1957, The prediction of long-continuing drought in South and Southwest Texas: The Travelers Insurance Co. Weather Research Center, Occasional Papers in Meteorology, no. 1, p. 33.



A. Wet year of 1915. Note the comparatively small arid area.



B. Dry year of 1934. Note that the arid area has expanded when compared with the wet year of 1915.

Figure 8

Generalized Distribution of Climatic Types in the United States in a Wet Year and in a Dry Year

After C. W. Thornthwaite, 1941, Atlas of climatic types in the United States, 1900-1939: U.S. Soil Conservation Service Misc. Pub. 421, p. 5.

of Pacific air after a period of time assume the temperature characteristics of the Canadian and Great Basin ground surfaces and, as cold masses of air, move eastward or southward to invade the area east of the Rocky Mountains.

The Great Basin sink is in the several-state area between the Rocky Mountain range and the Sierra Nevada and Cascade ranges, inland from the Pacific coast. The Canadian sink is in that portion of Alberta and bordering Canadian provinces which lie east of the Canadian Rockies and north of the Canada-United States border. In addition, a sink over Alaska at times contributes to infrequent invasions of masses of Arctic air deep into the United States.

The term "sink" refers to the relative thickness of the mass of air compared with adjacent masses of air. The thickness of a mass of air is the vertical distance from the bottom to the top, and because warm air is lighter, somewhat expanded, a layer of warm air is thicker vertically than a layer of cold air of the same weight. Examine the top of any layer, or accumulation of layers, of air within adjacent masses of warm and cold air, and layer for layer the warm layer will be thicker than the cold. The air in the thicker (taller) warm mass will flow to the colder (less thick) mass of air, the "sink" (Figure 9).

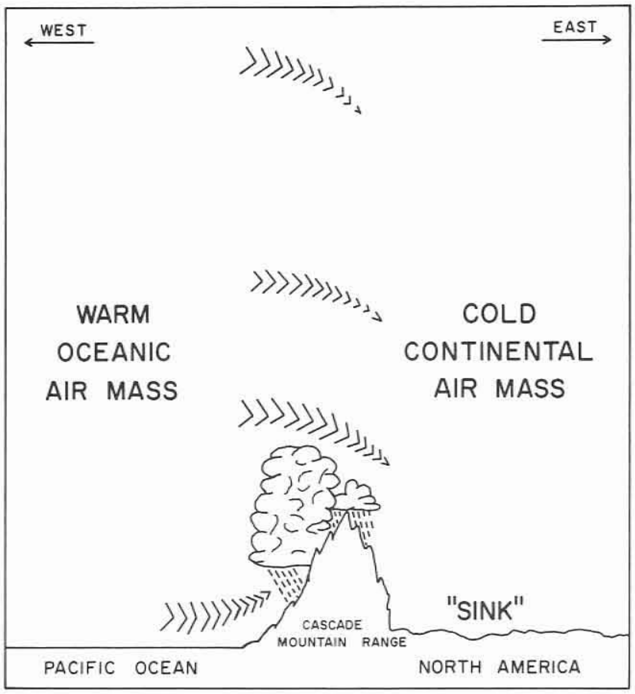


Figure 9

Cold "Sink" Schematic

Relatively warm Pacific Ocean air moving eastward onto the West Coast is at first lifted and cooled by expansion and its moisture is condensed out as the mountain barrier is encountered. Thus, as this air descends the downwind slopes of the mountains it is much dryer than when it ascended on the windward side. The air is then warmed by compression as it descends, but in the "sink" it stagnates and soon loses its heat to the colder, often snow-covered, land surface. At higher altitudes the relatively warmer and expanded Pacific Ocean air flows downward into the "sink" created by the colder air below, which is becoming denser and more and more compacted as it loses its heat more and more to the cold land surface. Arrows indicate normal direction of air movement from the Pacific Ocean to North America at mid-latitudes.

The semipermanent cell of high pressure over the Pacific Ocean is the warm, or thick, mass of air and the less thick mass is the sink located over Alaska, Alberta, or the Great Basin. Aren't they always there, and what does this have to do with drought? They're always there, but the magnitude of temperature contrast between the two is not always the same and the position and size of the Pacific high-pressure cell is not always the same, and this has to do with drought (See Figure 10).

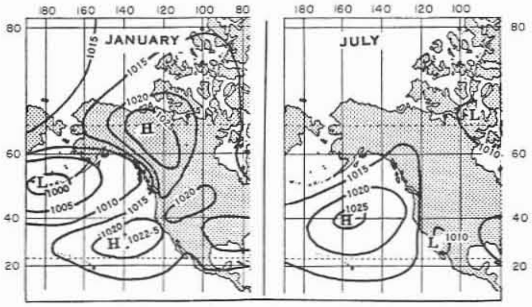


Figure 10

The Pacific High in January and July

After I. R. Tannehill, 1947, Drought, its causes and effects: © Princeton Univ. Press, p. 75.

Pressure in millibars. In January the high (H) is small and there is a low over the Aleutians (L) and another high (H) over the interior of Canada. In July the Pacific high (H) is expanded and located farther to the northwest.

Changes in the location and strength of the Pacific high-pressure cell are brought about in part by variations in the amount of heat the earth receives from the sun. When, because of these variations in heat, the water surface of the North Pacific Ocean is relatively warm compared with a cold land surface on the continent, the North Pacific high-pressure cell expands, grows thicker vertically, and causes more air to flow into the sinks, piling up. As air flows into the sinks, pressure builds up. By the time pressures build sufficiently to start the mass of air migrating southeastward, the new air which flowed from the Pacific into the sink has had enough time to assume the temperature characteristics of the cold, perhaps snow- or ice-covered, land surface. Therefore, when the mass of air migrates southeastward it is very cold and dry. It pushes ahead of it a front, and precipitation occurs along the front whereever warm moist air from the Gulf of Mexico or Atlantic Ocean is encountered and forced upward.

Air moving southeastward out of the continental sinks is both cold and dry. Cold, because the once-warm air settled and paused for a while over a cold land surface. But why dry, when its origin is over water where it should have acquired moist conditions? This is because the warm moist air from the Pacific Ocean had to travel over a mountain range to get into the sinks. By far most of the moisture in the atmosphere is in the lowest levels. The moisture-laden warm Pacific Ocean air, as it crossed the mountains, was lifted and cooled, and therefore forced to release its moisture as precipitation (See Figure 9, the Cascades). The once-moist Pacific air must arrive much dryer in the sinks on the downwind side of the mountain ranges. This forced release of moisture in the form of precipitation, as the Pacific Ocean air crosses the mountain ranges along the western edge of the North American Continent, is the major reason that rainfall maps show the greatest rainfall on the Continent to be along the upwind, seaward slopes of these mountain ranges (Figure 2).

The Cold Air Migrates

The cold and dry air that moves southeastward out of the sinks is also heavy and dense, and thus hugs the ground, wedging underneath and forcing aloft all warm air in its path. If the warm air that is wedged aloft is moist, its moisture is condensed and precipitated as the air rises and cools. This is the same method by which the Pacific Ocean air was made dry as it rose over the mountains en route to the sinks. The major difference between the two methods is that the "mountain barrier" is stationary but the "frontal barrier," the wedge, is moving and distributes precipitation over thousands of square miles.

Where the precipitation falls in the vast areas east of the Rocky Mountain Range is governed by where on its southeastward journey the cold air encounters the warm moist Gulf of Mexico or Atlantic Ocean air. If warm moist air is not encountered by the wedge of cold air as it migrates southward, no precipitation occurs. When warm moist air stays away from a given area long enough, or when cold wedges of air cease to migrate southeastward, rainfall becomes deficient, surface-layer soil moisture is depleted by evapotranspiration, and subsurface soil moisture either percolates downward or travels upward to the surface-soil layers by capillary action to be lost--the result can be drought.

Physical Processes Involved

How long will the drought caused by this effect last? Simply stated, as long as the adjacent Pacific Ocean remains seasonally cool compared with the North American Continent, causing the "sink factories" to lie dormant. But that is not the whole story. Table 1 shows in one column some major contributors to Texas droughts, and in the other column some deterrents.

Table 1.--Drought contributors and deterrents in Texas

Contributors	Deterrents
1. Relatively cold Pacific Ocean near the North American Continent	1. Relatively cold continent
2. Diminished large-scale air circulation	2. Increased circulation caused by increased heat from the sun
3. Minimal or too frequent southward migration of cold air	3. Functioning "sink factories"
4. High rates of evaporation	4. Wintertime cold air masses
5. Low sunspot activity in spring	5. Relatively low atmospheric pressures in the South, east of the Rocky Mountains
6. A trend of prevailing winds from the west or southwest	6. Favorable positioning of Atlantic high-pressure cells for maximum transport and distribution of the moisture in the air

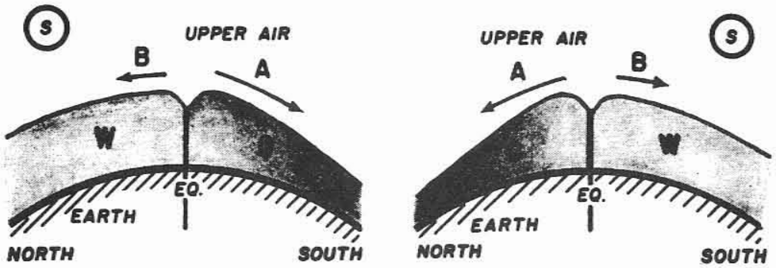
Broad Climatic Controls

Alone, none of the contributors to drought shown in Table 1 could be expected to produce serious or widespread drought unless the contributor persists for a long period of time. Even then, nature probably would react to damp out the abnormality. For instance, should the heat from the sun increase or decrease over a long period of time, three likely results would be: (1) the oceans would adjust to the new temperature, and further abnormal behavior of the sun would then be required--because relative temperature differences between the ocean and continent are the driving forces in operating (or failing to operate) the North American "sink factory"; (2) land surfaces would continue to respond readily to heat fluctuations while ocean surfaces would continue to resist; and (3) moisture necessary for precipitation would still have to be transported by the winds around the outer peripheries of the Atlantic high-pressure cells.

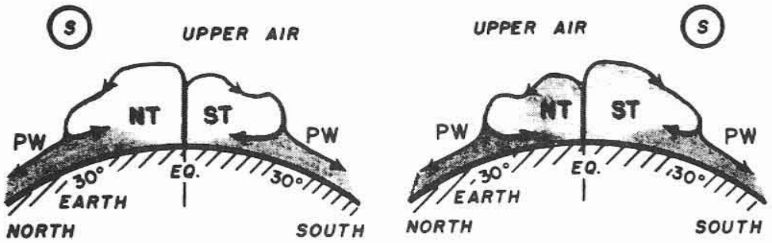
According to Tannehill (1947, p. 224-226),

> "The processes by which solar variations are translated into rainfall variations may be summarized as follows: An increase in heat from the sun, either seasonally or in longer periods, tends to bring rain farther into the interior of the continent; a decrease causes more of the national rainfall to go to coastal areas. An increase or decrease in solar radiation, if sufficiently large, causes a considerable increase in the circulation of the atmosphere; this is greatest at the times when the sun's heat is normally increasing or decreasing. The increased circulation of the atmosphere in turn causes changes in the distribution of ocean temperatures. First, there is a cooling due to mixing of the waters; second, there is the effect of oceanic circulation. Therefore, when solar radiation increases or diminishes, the ocean temperatures lag behind and are relatively high or relatively low compared with continental temperatures. This causes changes in the amount and distribution of rainfall."

There are national "wet" years and national "dry" years, that is, years when the national rainfall average is above the climatological normal, and vice versa. Drought occurs somewhere in the United States almost every year, but each area within the United States must be examined separately to determine the cause of the drought there. Each area obtains a major portion of its yearly rainfall in a different way. On the Pacific Coast most of the rain occurs during winter and is caused by warm moist Pacific Ocean air being lifted and cooled as it travels up the seaward slopes of the mountain ranges. On the Florida Peninsula most of the yearly rainfall comes from convective thunderstorms. In the north-central states most of the yearly rainfall is caused by clashes between cold air masses from Canada and warm air masses from the Gulf of Mexico. It follows that since all rainfall is not caused in the same manner, there cannot be a single cause for lack of rain, or of drought. The right unfortunate combination of deleterious atmospheric circulation patterns, absence of ample contrast between cold and warm air masses, low sunspot activity, and a host of other adverse factors may be necessary to produce prolonged drought. The timing in the reactions of the oceans, which lag behind continents in their response to temperature changes; the variations in radiant heat from the sun; the exchange of atmosphere between the two hemispheres (Figure 11); and the movement of warm and cold ocean currents: all act to control the broad weather pattern.



A. At left, in summer (sun at S) in the Northern Hemisphere, warm atmosphere (W) is expanded and cold atmosphere (C) in Southern Hemisphere is dense and lies nearer to the earth; air goes more rapidly (A) from equator (Eq.) down the steeper slope toward the South Pole than (B) from equator toward North Pole. At right, in northern winter, air moves more rapidly (A) down steeper slope into Northern Hemisphere than (B) into Southern Hemisphere. By this expansion at the equator and excess flow toward the cold hemisphere, there is a vast exchange of air across the equator.



B. Same as above, but these diagrams shown how earth rotation causes the overflow from the equator to accumulate in regions of high pressure at about 30° latitude from where the northeast trades (NT) and the southeast trades (ST) blow toward the equator at the surface of the earth while in higher latitudes the prevailing westerlies (PW) blow from the west and incline toward the polar regions.

Figure 11

Air Exchange Between Northern and Southern Hemispheres

After I. R. Tannehill, 1947, Drought, its causes and effects: ©Princeton Univ. Press, p. 129, 130.

Much of Texas is destined to suffer periodic drought as the arid areas in the western states expand and contract in reaction to the broad controls of the ocean, the atmospheric circulation, and the sun. Most years, only the eastern sections of Texas can at years' end expect to have received enough rainfall to offset potential evapotranspiration (Figure 7).

THE INGREDIENTS OF DROUGHT

The major causes of drought in Texas can be enumerated, but the forces behind the causes are more difficult to pin down. It seems clear that a combination of forces, actions, and interactions, terrestrial and possibly extraterrestrial, broadly control our weather patterns. Although any single meteorological element may be the cause of no rain, a combination of these elements acting over a substantial period of time is required before drought can become well established.

A seasonally cool Pacific Ocean in relation to the key sink areas of the Great Basin, Canada, and Alaska does seem to be the principal culprit in causing our arid west to expand its borders, march eastward, and at times spread over half or more of Texas. The Pacific Ocean may be relatively cool in its own right, or if the continent does not cool enough seasonally the layer of air over the continent may be too warm and too thick vertically to permit formation of well developed sinks (see Figure 9). Either of these causes for failure of the Pacific Ocean to be warm in relation to the sink areas is reason enough for poorly developed or ill-timed seasonal migrations of cold air southeastward, resulting in poor activation of precipitation mechanisms. Next examined will be some of the most widely accepted reasons for a relatively cool Pacific Ocean.

How Oceans Become Relatively Cool

Volcanic Dust

Humphreys (1939) and other investigators have introduced evidence that volcanic activity and dust in the atmosphere are responsible for historical downward trends in world mean temperatures. In Humphreys' hypothesis, sunspots play a minor role and are relied upon only to explain some of the temperature variations which cannot be explained by resident dust in the air and by volcanic dust. World temperatures are shown to be lower during and in the years following great historical volcanic eruptions (Figure 12). In the year 1816, Mount Tamboro, Dutch East Indies, erupted killing more than 50,000 persons and spreading enough dust in the atmosphere to cause darkness for 3 days over many thousands of square miles of land and water surface. When Krakatoa erupted in 1883, the atmosphere was filled with great quantities of dust. Cold years followed the Krakatoa eruption (Figure 12).

Dust in the atmosphere is known to reflect and scatter solar radiation, shielding the earth. Humphreys and many other investigators believe sufficient radiant heat from the sun has been diffused and reflected away from the earth by volcanic dust to account for not only the downward trends in temperature during historical times but also during previous geologic times. Humphreys points out that the volcanic mountain-building periods during the geologic past were also the periods of glaciation. Brooks (1949) postulated that the glacial epochs began because of temperature changes that are well within the range of probability of temperature fluctuations recorded during the immediate past. For instance, Tannehill (1947, p. 195) shows that in North Dakota the average February temperature during the years 1889-91 was 14°F colder than December, but during the years 1925-27 February averaged 10.5°F warmer than December--a

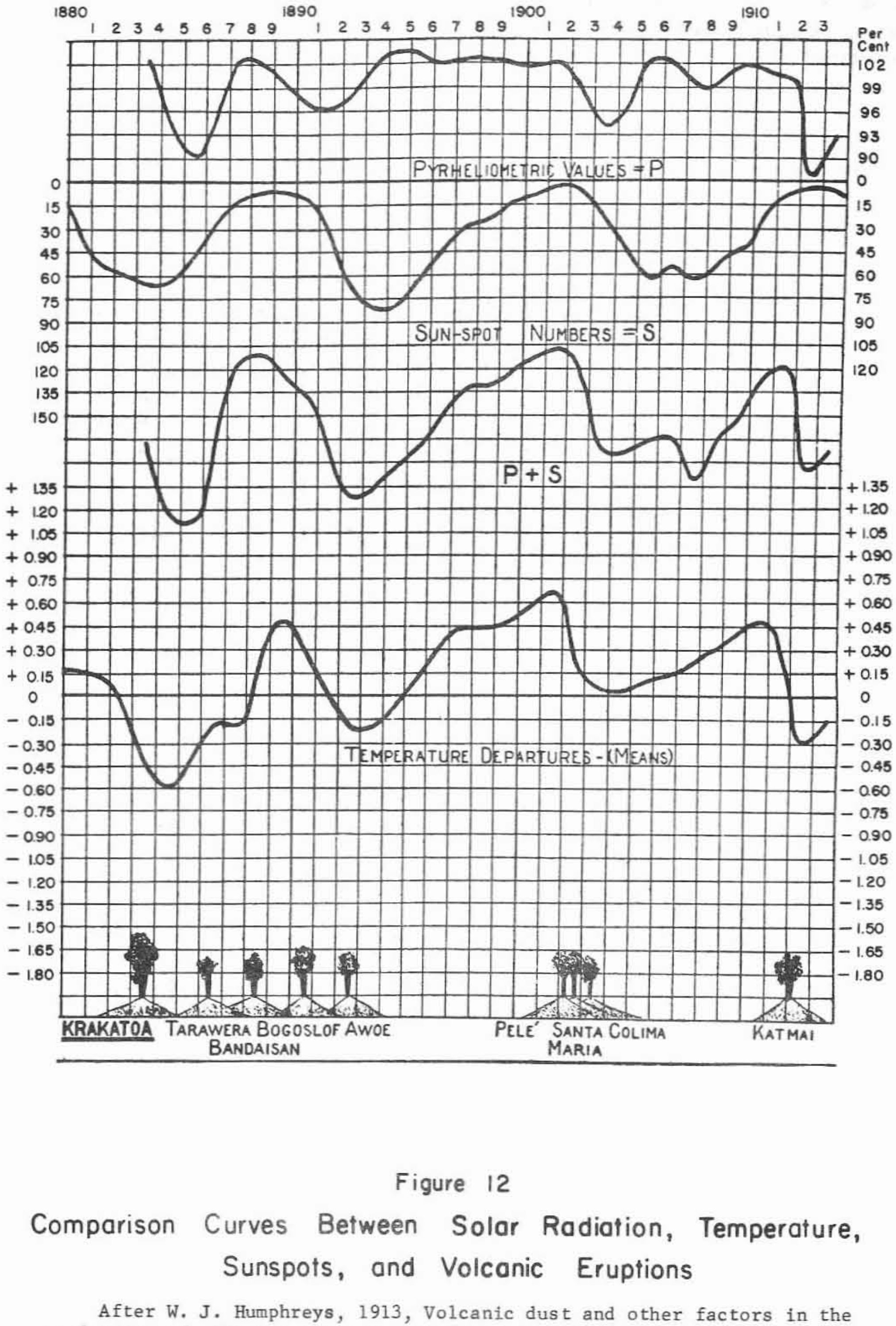


Figure 12

Comparison Curves Between Solar Radiation, Temperature, Sunspots, and Volcanic Eruptions

After W. J. Humphreys, 1913, Volcanic dust and other factors in the production of climatic changes, and their possible relation to ice ages: Bull. Mount Weather Observatory.

total difference of 24.5°F in mean monthly temperatures between the two periods in winter. Figure 13 illustrates this phenomenon for the entire United States.

A popular view among meteorologists is that the right chain of circumstances, which could begin any year, 1966 for instance, is all that is necessary to launch another ice age. Assume that the polar ice caps begin to expand a little due to temperature changes that are well within the range of current probabilities--the 24-degree range which occurred in North Dakota may be enough: the expanding north-polar ice cap could intensify the Canadian sink and cause more precipitation to fall in the United States, the belt of increased precipitation could move northward toward the expanding ice cap during times of sunspot maxima, the rain would be replaced with snow near the edges of the ice cap, and the ice cap would expand rapidly due to failure of the snow to melt, if the sunspot cold suboscillations should begin to phase with or closely follow snow accumulations near the ice cap. Any increase in the yearly cold and wet periods would decrease the length of warm and dry periods, thereby further contributing to growth of the ice cap. So, we may have another glacial epoch in the making. But one must wonder, what reversals of the trend could melt the ice cap and return the climate to normal? The answer to that question is much more complicated, is not fully or satisfactorily explained in any literature examined by the author, and will not be undertaken in this report.

If a long period of volcanic eruptions associated with mountain building could produce enough dust to partly shield the earth from the sun and cause an ice age, then a few volcanic eruptions could surely produce enough dust to reduce the world mean temperature sufficiently to cool the oceans and result in poor transfer of Pacific Ocean air over the mountains and onto the Continent.

Sunspots

Although known to exist for centuries--they are mentioned in early Chinese records--sunspots are not yet fully understood. The Englishman, Harriot, is officially credited with their discovery in 1610. Galileo published a paper on sunspots in 1613. We have today a record of monthly sunspot occurrences since at least 1750. Figure 14 shows a graph of the 12-month sunspot averages for the 200-year period 1755-1955.

It is known that the temperature of the spot is lower than the temperature of the surrounding surface of the sun. The spot itself is about 4,700°C; the surrounding area of the sun is about 5,940°C. Sunspots have been the solar phenomena most widely used by investigators to attempt explanation of apparent cyclic weather variations on the earth, but although the most commonly used, sunspots are not the only cause of fluctuations in solar radiation. Solar activity also includes corona, faculae, magnetic activities, and prominences.

Many cycles, oscillations, and suboscillations exist in the sunspot records, and many more can be discovered by curve smoothing, moving averages, and other manipulation of the data. The reader can probably discover a few for himself by perusing Figure 14 in detail. A complete listing of investigators and the cycles discovered by them through the years is not necessary or justified in this report; however, some of the sunspot cycles cited most often in the literature are listed on page 25:

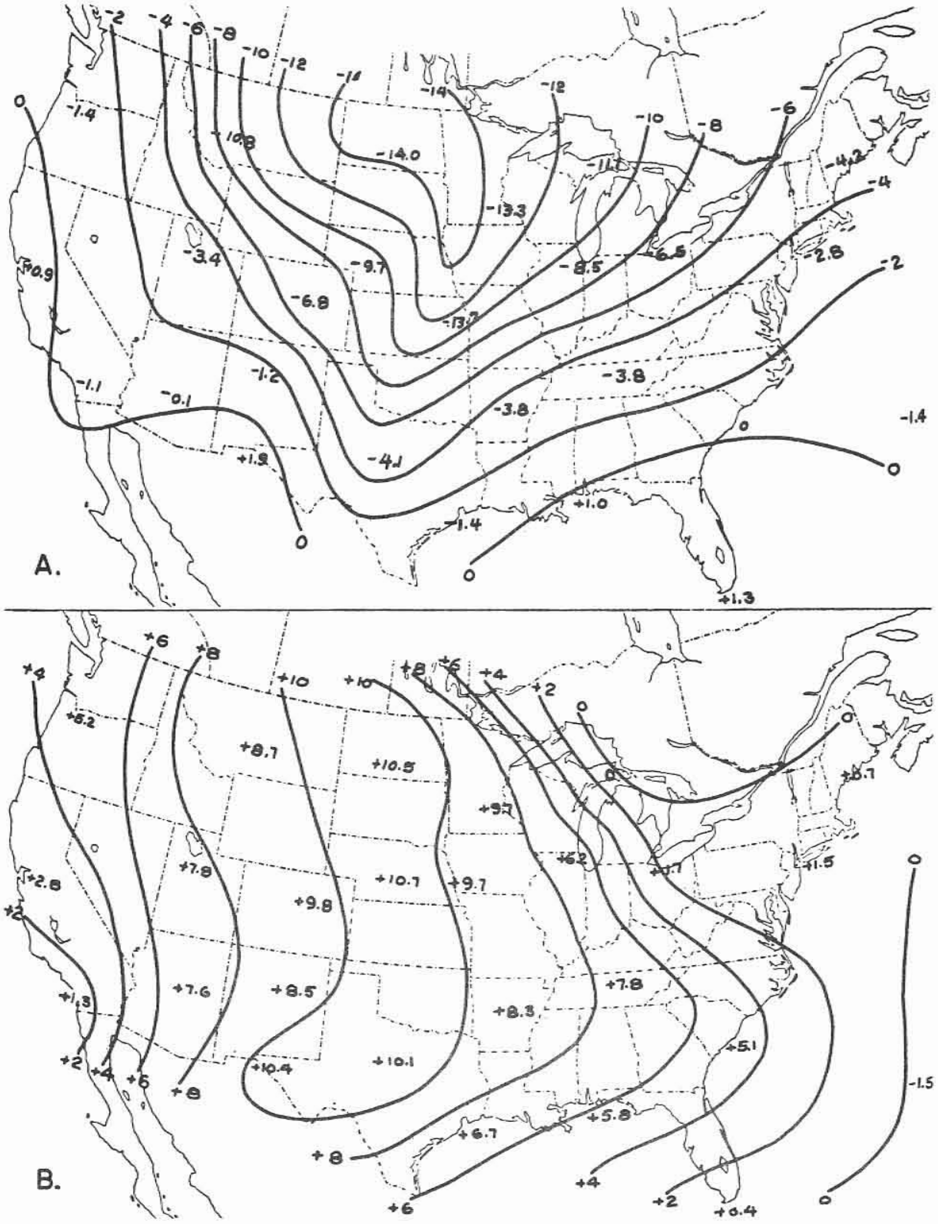


Figure 13

Excess or Deficiency of February Temperatures Compared with December Temperatures. A. Average for years 1889, 1890, and 1891. B. Average for years 1925, 1926, and 1927.

After I. R. Tannehill, 1947, Drought, its causes and effects: © Princeton Univ. Press, p. 195.

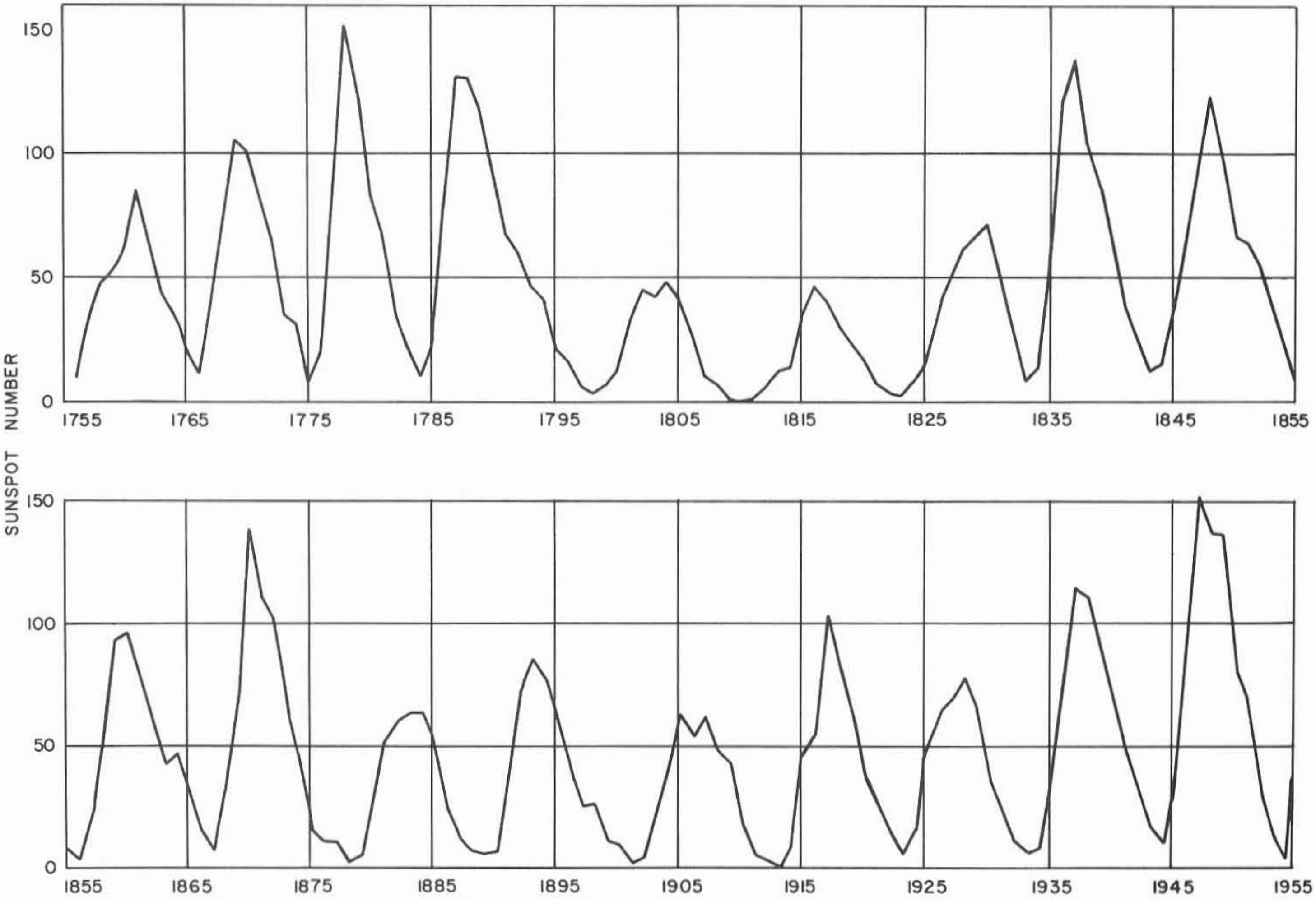


Figure 14

Sunspot Numbers for 1755-1955

After D. G. Friedman, 1957, The prediction of long-continuing drought in South and Southwest Texas: The Travelers Insurance Co. Weather Research Center, Occasional Papers in Meteorology, no. 1, p. 130; based on a tabulation by E. H. Munro.

1. An 11-year cycle;
2. The Bruckner cycle--about three times the sunspot period of 11 years;
3. A 5½-year cycle;
4. A 90.4-year cycle;
5. "Warm" and "cold" suboscillations;
6. "Double" and "single" periodicities; and
7. The Brooks double sunspot cycle (Brooks, 1928).

Nearly all of these sunspot cycles were discovered by investigators seeking an answer to the weather cycle riddle by studying historical sunspot data amassed over the centuries. These cycles have often been offered as proof that certain weather fluctuations correlate with sunspot fluctuations. With as many cycles as have been discovered in the sunspot data, it was inevitable that certain sunspot cycles could be fitted to certain weather occurrences over the years. Who is to say which correlations are fact and which are fancy? There is very strong evidence that heat from the sun is at the bottom of the whole matter, because most investigators agree that heat from within the earth and from the planets and stars is insignificant in producing weather fluctuations. It seems that nothing short of time--eons of time--will tell. Weather patterns that now appear to correlate so well with historical sunspot cycles may not correlate at all with future sunspot cycles.

The occurrence of cycles of sunspot maxima and minima can be forecasted quite reliably, but the magnitudes of these maxima and minima are extremely difficult to predict. Perhaps therein lies the key; if the magnitude of sunspot cycles could be accurately forecasted, then perhaps climatic trends--droughts--could be reliably forecasted. Again, only time and more cycle hunting will tell.

Look again at Figure 14. Who would not be willing to predict that a sunspot activity maxima is likely to occur about 1957 or 1958, and a minima about 1964 or 1965? But few readers would be willing to say that the 1965 minima will be at the bottom of a curve segment looking exactly like any other curve segment on the 200-year sunspot graph. Perhaps a totally reliable 2,000-year continuous record of sunspot activity would disclose enough true cycles to reveal a pattern by which the occurrence of droughts could be accurately forecasted, but not a 200-year record.

To illustrate how misleading curve smoothing, moving averages, and such like can be in the cycle-hunting game, Cole (1957) determined the average hourly metabolic rate of a unicorn, a fictitious, legendary animal having a single horn. Cole proceeded by drawing 120 numbers from a table of random numbers, to represent 24 hourly observations of the metabolic activity of the unicorn during a 5-day period. The corresponding hourly data were then averaged for the 5-day period. The "lunar rhythm" effects were removed from the data by advancing 1 hour forward on successive days to allow for changes in moonrise, the moon having been determined to effect the unicorn's metabolic rate. The data were smoothed by using moving averages and the results plotted on graph paper (Figure 15). The definite conclusion could then be drawn that the unicorn is most active in the morning and has a tendency toward lethargy around 3:00 p.m.

As can be seen, fictitious cycles might be generated by misuse or misunderstanding of the data. Fictitious weather cycles could be "detected" while examining the long sunspot record, or for that matter while examining any other very long climatic record. The author does not wish to imply that weather cycles do not exist. The point is that by enough manipulation of the data it is possible to "prove" the existence of imaginary weather cycles just as the metabolic rate of the fictitious unicorn was "proved." Again, time and many, many years of continously recorded data will be required to establish the existence of true cooling-trend cycles of sufficient magnitude and duration to cause the Pacific Ocean to develop a trend of becoming relatively cooler than the North American Continent, thereby upsetting the "sink factory," and causing or prolonging drought in Texas.

Atmospheric Circulation

Variations in solar radiation meet with resistance from the oceans, which are slow to respond, but the continents react quickly. Warm or cold air does not make a warm or cold ocean, but rather, the continental air which blows out over the ocean soon takes on the temperature of the ocean surface. Warm air flowing out over a cold ocean soon becomes cool and settles, whereas cold air blowing out over a warm ocean is soon heated and is forced upward by more of the colder air blowing off the continent and wedging underneath.

Although the temperature of air blowing over the ocean has very little effect on the temperature of the ocean surface, if the air circulation is strong, considerable mixing of the ocean's waters will result. Mixing distributes the warm surface waters to a considerable depth, resulting in upwelling and cooler surface waters than would exist under calmer wind conditions. Also, cold ocean currents coming from northern waters as a result of steady north winds (in the Northern Hemisphere) will cause cooler ocean surface temperatures. Figure 16 shows by arrows the major cold ocean currents in the Atlantic and Pacific Oceans. Combine cool ocean currents with strong air circulation over the ocean, and the result is likely to be a Pacific Ocean surface cool enough, comparatively, to slow the flow of Pacific Ocean air over the Cascades and into the continental sinks. This retards the migration of cold air southward over the United States, thereby contributing to drought conditions.

DROUGHT PREDICTION

General

The word "drought" seems to be studiously avoided by most who are willing to leave a record of their long-range precipitation forecasts. This hesitancy on the part of authors to forecast the occurrence, continuation, or ending of drought stems in part, no doubt, from the extreme difficulty in even defining drought. What means drought to one may not mean drought to another. What may in fact be drought at one location may not even be a climatological abnormality at another location. Accordingly, in this report much more must be said about

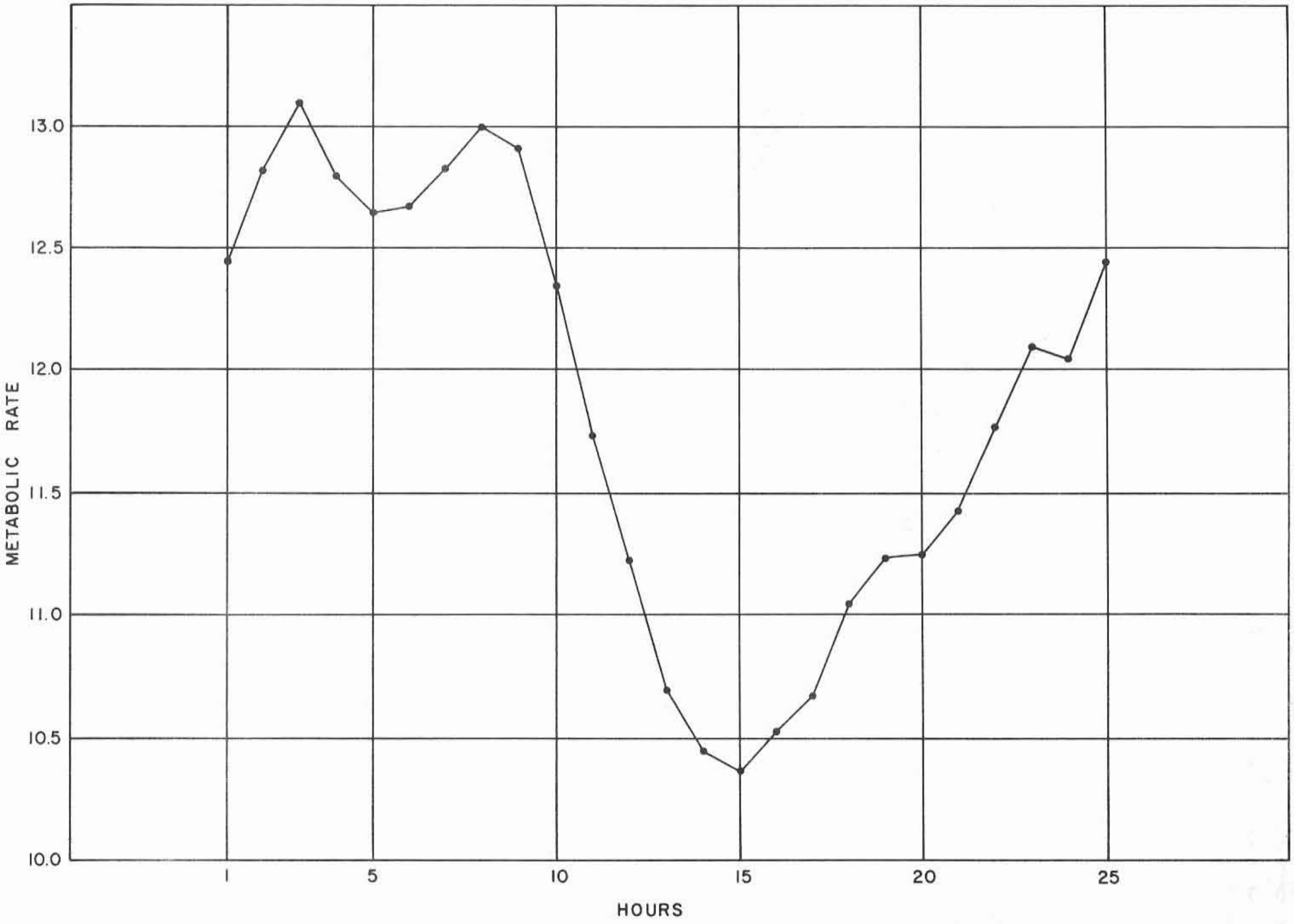


Figure 15

Average Hourly Metabolic Rate of the Fictitious Unicorn

After L. C. Cole, 1957, Biological clock of the Unicorn: ©Science, v. 125, no. 3253, p. 874.

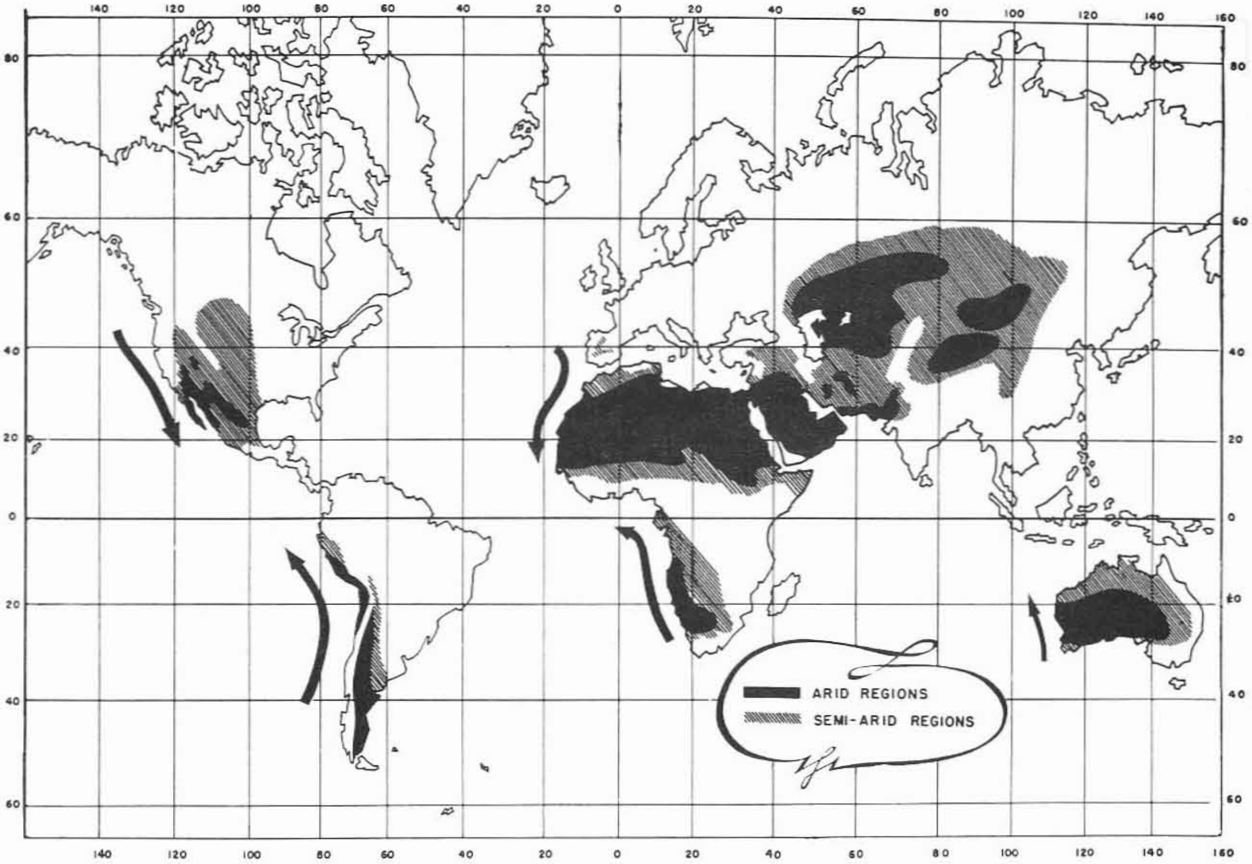


Figure 16
The Relationship of Arid (Desert) and Semiarid
Regions of the World to Cold Ocean Currents

After I. R. Tannehill, 1947, Drought, its causes and effects: ©Princeton Univ. Press, p. 14.

long-range precipitation and climatological-trend forecasts than can be said about drought forecasts. Such forecasts fall mainly in three catagories: probability forecasts, projections of past trends into the future, and forecasts linking precipitation, or lack of it, with extraterrestrial influences. Also, there is some evidence of seasonal persistency in climate.

Tannehill (1947, p. 231) maintains: "Droughts are not mere chance occurrences; they are part of a physical process which can be measured and studied and predicted with increasing precision as our observations of the sun and the upper air and the oceans continue to accumulate." Tannehill (1955, p. 86) also wrote, "We have yet no generally accepted method of predicting solar variations so that the resultant weather changes can be foreseen in any detail." Abbot (1960, p. 1) states that a hidden family of harmonic regular periods exists in weather, that periodic members of this family persist for scores of years, and that by proper use of these harmonics, successful forecasts may be made for years in the future.

Discussing the atmospheric circulation relationships between the Atlantic and Pacific Ocean high-pressure cells and a drought-enhancing interdependent Central and Southern Plains high-pressure cell, Namias (1957, p. 12) states:

> "There is not agreement among meteorologists on how these mutually supporting circulations are generated. Some believe that they are responses to certain abnormalities in ocean temperatures; others that they are caused by certain changes in the radiation received from the sun and thus may be related to sunspots. Still other theories exist, but to date no one has developed these theories to the point where reliable predictions of drought for as long as a season or a year ahead are possible. Such predictions must await clearer understanding of the ultimate causes--one of nature's most complex problems to which many research groups over the world are not addressing themselves."

After applying various statistical tests to precipitation records spanning the last half-century at nine cities in South and Southwest Texas, Friedman (1957) concluded that there is little statistical evidence of trends, cycles, or even year-to-year persistence in annual rainfall in South Texas. Further, he found that very little information is inherent in the time series of annual rainfall in South Texas that can be extrapolated into the future, and that because of the relationship between annual rainfall and drought-producing conditions, it is not possible to predict categorically the occurrence of years with large drought potential one or more years into the future.

It appears, then, that scientists are no more in accord about the predictability of drought than about its definition. Actually, meteorology and climatology are not exact sciences, the parameters of which can be proved quantitatively every time. Let us now turn our attention to some long-range precipitation and climatological-trend forecasts.

Probability Forecasts

Friedman (1957, p. 70-90), not satisfied that a "best" test of randomness existed, applied three well-known statistical tests to sample time series of precipitation records at stations in and near South Texas. These were the "ranking" test, the "runs" test, and the "persistence" test. The tests were applied to a drought index to examine three questions, which are presented below with the conclusions he reached:

> "Question 1: Is the climate of South and Southwest Texas becoming progressively drier [climatic trend]?"
>
> Conclusion: On the basis of the results of statistical tests applied to 66 years of past records, "...there is no general indication that the climate of South Texas is getting drier. However, an indication of lower annual rainfall at El Paso and Roswell requires more study before any final conclusions can be drawn."
>
> "Question 2: Are there regularly recurring cycles of wet or dry periods in Texas climate [climatic cycles]?"

> Conclusion: On the basis of the application of two "runs" tests to a 42-year sample, "...there is no general evidence of regularly recurring cycles in the annual rainfall data of South Texas that cannot be explained by random fluctuations."
>
> "Queston 3: Is there any year to year persistence in the wet and dry spells (climatic persistence from year to year)?"
>
> Conclusion: Evidence was found for persistence between successive values of annual rainfall at Brownsville, one of 10 stations sampled in and near South and Southwest Texas. The other 9 stations were El Paso, Fort Davis, Roswell, Amarillo, San Angelo, Del Rio, San Antonio, Laredo, and Corpus Christi (Figure 17). For the purpose at hand, the practical significance of evidence of persistence at the one station, Brownsville, was considered to be negligible inasmuch as none of the other nine stations showed evidence of statistical significance in the test for persistence.

After determining that annual rainfall in South and Southwest Texas is a random phenomenon and that no categorical predictions of annual rainfall or drought potential conditions seem possible, Friedman (1957, p. 90-125) developed a set of maps of Texas depicting probabilities of occurrence of annual rainfall equal to or less than amounts indicated for periods of time ranging from 1-out-of-10 years to 9-out-of-10 years. Isograms labeled with inches of precipitation were overprinted on maps of Texas (Figure 18).

Figure 18 used in conjunction with Figure 17, average annual rainfall, can aid in evaluating for a given year the probabilities of a small annual rainfall and hence the possibility of long-term drought conditions.

Giving an illustration of the use of his probability charts, Friedman (1957, p. 119-120) explains for Laredo:

> "The average annual rainfall is a little over nineteen inches [Figure 17]. However, in one year out of ten [probability of 0.1 on Figure 18], the annual rainfall will be less than ten inches. This is only one-half of the normal rainfall. In two years out of ten [Figure 18, probability of 0.2], the rainfall is sixty percent or less of normal. In three out of ten years, the annual rainfall is less than three-fourths of normal while in four years out of ten, the annual rainfall is eight-tenths or less of the average annual rainfall. The drought potential of these drier than normal years cannot be evaluated directly because of other factors such as rainfall timing. However, these probabilities should be of assistance in giving a first approximation to the chances of drought conditions in a particular year in the future."

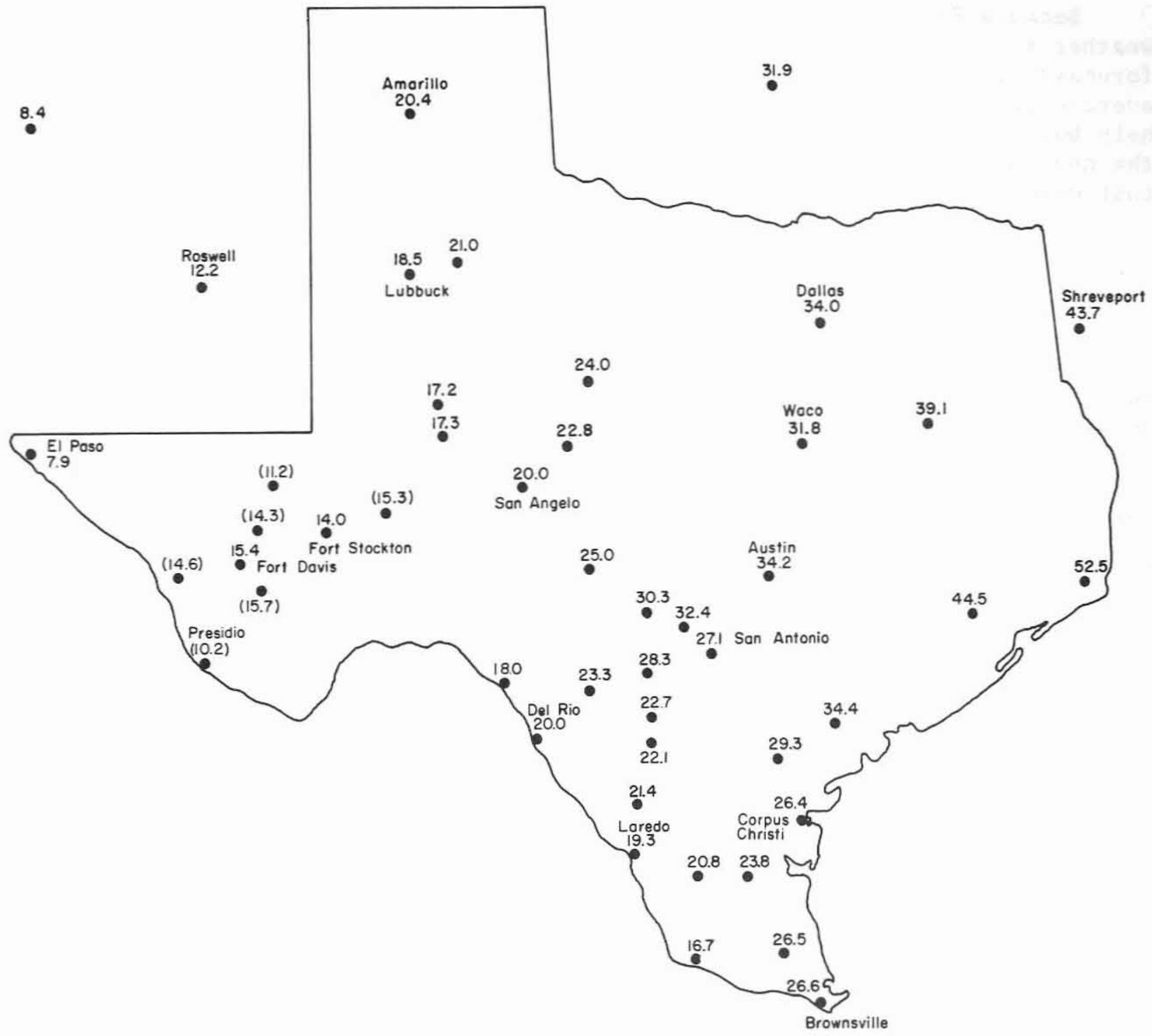


Figure 17

Average Annual Rainfall in Texas (Inches) Based on the 42-Year Period 1914-55. Averages shown in parentheses are based on shorter periods.

After D. G. Friedman, 1957, The prediction of long-continuing drought in South and Southwest Texas: The Travelers Insurance Co. Weather Research Center, Occasional Papers in Meteorology, no. 1, p. 109.

Because Friedman's probability forecasts are based on sample time-series weather statistics of the past, complete verification of the accuracy of his forecasts (Figure 18) must await the passage of enough time to alter the average-annual precipitation values he used. His probability forecasts cannot help but verify if, as he stated he expected, the climatic characteristics of the next half-century are not drastically different from climatic conditions that were experienced in the last half-century.

Seasonal Persistency

Namias (1960) published Tables 2, 3, 4, and 5 which show that historically the summer climate with respect to normal temperature and precipitation is apt to be much like the climate which occurred during the spring, and the climate next summer is apt to resemble the climate this summer. This persistence feature of summer climate is related to the upper-air circulation patterns during the spring. These upper-air circulation patterns are governed by the high- and low-pressure areas aloft. For every altitude there is a mean atmospheric pressure. When departures from the mean pressure are significantly on the plus side in the spring of the year, the circulation pattern is more conducive to spring and summer rainfall deficiencies. Figure 19 illustrates these points.

Table 2

Summer temperature classes following differing springs over the western Great Plains of United States

		Summer Temperature		
		Cold	Normal	Warm
Spring Temperature	Cold	101	70	40
	Normal	53	74	81
	Warm	57	65	87

"Thus a cold spring in the Great Plains is much more apt to be followed by a cold summer than a warm one, in the ratio 101 to 40, while a warm summer is more apt to follow a warm spring (ratio 87 to 57). In another tabulation [Table 3] both temperature and precipitation were combined to indicate summer temperature." (After Namias, 1960, p. 90.)

Table 3

Summer temperature classes over the western Great Plains following different combinations of spring temperatures and precipitation (totals in italics)

		Summer Temp.			
Spring Temp.	Precipitation	Cold	Normal	Warm	Total
Cold		*101*	*70*	*40*	
	Light	29	21	10	*60*
	Moderate	31	18	19	*67*
	Heavy	41	31	11	*83*
Normal		*53*	*74*	*81*	
	Light	12	18	34	*64*
	Moderate	18	33	27	*78*
	Heavy	23	23	19	*65*
Warm		*57*	*65*	*87*	
	Light	9	27	50	*86*
	Moderate	18	22	22	*62*
	Heavy	30	16	16	*62*

(After Namias, 1960, p. 90.)

Table 4

Summer precipitation as related to temperature and precipitation of the preceding spring over the Plains of the United States (totals in italics)

Spring Temp.	Precipitation	Summer Precip.		
		Light	Moderate	Heavy
Cold		*53*	*73*	*85*
	Light	12	18	30
	Moderate	19	24	25
	Heavy	22	31	30
Normal		*70*	*73*	*65*
	Light	28	17	20
	Moderate	27	26	26
	Heavy	15	30	19
Warm		*87*	*63*	*58*
	Light	49	22	14
	Moderate	24	16	22
	Heavy	14	25	22

(After Namias, 1960, p. 91.)

Table 5

Summer temperature over the Great Plains related to temperature and precipitation of the preceding summer (totals in italics)

Summer		Following Summer Temp.			
Temp.	Precip.	cold	normal	warm	Total
Cold		*86*	*79*	*46*	*211*
	Light	11	13	7	31
	Moderate	30	17	22	69
	Heavy	45	49	17	111
Normal		*73*	*69*	*62*	*204*
	Light	16	18	23	57
	Moderate	30	30	18	78
	Heavy	27	21	21	69
Warm		*42*	*58*	*91*	*191*
	Light	18	33	59	110
	Moderate	16	19	23	58
	Heavy	8	6	9	23

(After Namias, 1960, p. 93.)

Forecasts Based on Trends

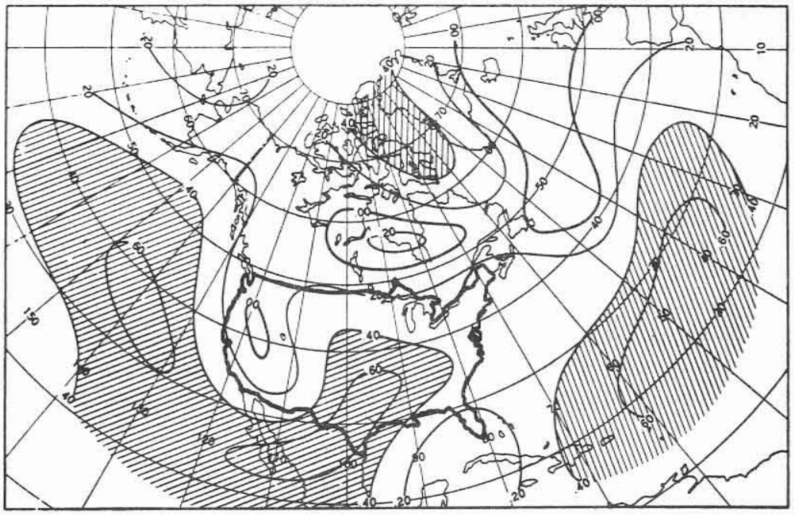
C. G. Abbot, a Research Associate of the Smithsonian Institution, was for many years a leading proponent of the feasibility of extrapolating past weather trends into the future. Abbot (1960) offered evidence that: (1) a hidden family of harmonic regular periods exists in weather; (2) the sun's radiation is variable by as many as 60 regular periodic pulses ranging from 1 month or less to 273 months and all submultiples of 273, such as 91, 39, and 7 months, having a range in amplitude from 1/50 to 1/4 percent, all going on simultaneously; (3) as many as 30 of these exact periods (of the 60 regular periodic pulsations of the sun) have been found in monthly weather records which have been kept from 1870 and earlier; (4) the variation of the sun is the real cause of the variation of the weather; and (5) the variations of the sun and of the weather have exactly the same periods, but are not always in phase due to variable lag affects depending on place, time, and the state of the atmosphere.

Abbot explained that his forecasts were made by adding the effects of 27 regular periodic cycles in precipitation which he discovered and which he felt were integrally related to a fundamental cycle of 273 months. Table 6 is a list of the 27 harmonics used by Abbot for forecasting.

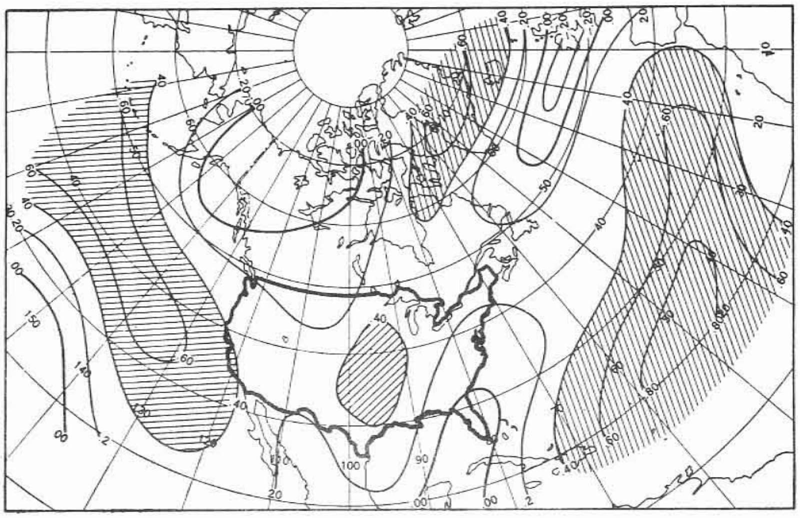
Table 6.--Periods used by Abbot (1960, p. 7) for forecasting

Fraction	Months	Fraction	Months	Fraction	Months
1/3	91	1/12	22-3/4	1/27	10-1/9
1/4	68-1/4	1/14	19-1/2	1/28	9-3/4
1/5	54-3/5	1/15	18-1/5	1/30	9-1/10
1/6	45-1/2	1/18	15-1/6	1/33	8-3/11
1/7	39	1/20	13-13/20	1/36	7-7/12
1/8	34-1/8	1/21	13	1/39	7
1/9	30-1/3	1/22	12-9/22	1/45	6-1/15
1/10	27-3/10	1/24	11-3/8	1/54	5-1/18
1/11	24-9/11	1/26	10-1/2	1/63	4-1/3

Although Abbot discovered this harmonic family of weather cycles by studying more than 30 years of daily solar-constant observations of the Smithsonian Astrophysical Observatory, his forecasts were not dependent on observations of any kind--it was only necessary to employ a long record of monthly mean values of precipitation, or temperature, to make long-range predictions. The periods of the harmonics used by Abbot are invariable, both in sun and weather. Their phases are invariable in solar radiation, but shift in weather depending on atmospheric influences.



A. Correlation between spring and summer



B. Correlation between successive summers

Figure 19

Isopleths of Lag Correlations of Seasonal Mean 700-Millibar Height, (A) Between Spring and Summer, and (B) Between Successive Summers (Period 1933-58)

Shaded areas show where correlations exceed the 5 percent level of significance.

After Jerome Namias, 1960, Factors in the initiation, perpetuation, and termination of drought: © Internat. Assoc. Scientific Hydrology [Gentbrugge, Belgium], Comm. Surface Waters Pub. 51, p. 89, 92.

Because monthly values of precipitation varied too widely to be useful, Abbot smoothed the record by 3-month consecutive means. He found considerable differences in "normal" monthly precipitation values if computed separately for periods of high and low sunspot frequencies; therefore, he computed separate monthly normals for years above and below an average of 20 Wolf numbers in sunspot frequency[1]. From these normals he tabulated the percentages of normal precipitation. His forecasts for the United States, expressed in percentage departure from normal, in 4-month increments for the years 1959-67, are shown on Figure 20. For the two Texas stations (Abilene and El Paso), comparison of the forecasts with observed precipitation is given in Table 7 for the years 1959-63. Space is provided on Table 7 to enable the reader to further verify Abbot's forecasts for Abilene and El Paso when the data for the years 1964-67 become available. Note that Wolf sunspot number and precipitation data for the 4-month period being verified must both be available for Abilene and El Paso before a technically accurate verification can be made. Remember, Abbot computed two precipitation "normals" for each station, because he found a difference when normals were computed for periods having more than 20 Wolf sunspot numbers and when normals were computed for periods having less than 20 Wolf sunspot numbers.

Palmer (1965) developed a drought measurement and classification system tractable to high-speed computed programming which involves the use of some 30-odd equations. Processing is adaptable to weekly or monthly periods. Solving Palmer's equation 28 (1965, p. 29) results in determining the amount of precipitation required to end an existing drought in one month, and the percentage probability that an existing drought has ended. Because of the scope of Palmer's paper, no attempt will be made here to explain his system. Rather, the reader seeking details of the system is referred to Palmer's U.S. Weather Bureau Research Paper 45, "Meteorological Drought." Basically, a drought has to be in progress and classified according to Palmer's system before a prognosis of its having ended is possible.

The Palmer system of drought measurement and classification (and probability of ending) should be inaugurated the next time it can be determined that a drought exists in Texas. Some measurement of the validity of his method of probability forecast and drought classification system might then be under taken.

---

[1] Sunspot Numbers.--As a measure of the frequency of sunspots, R. Wolf of Zurich introduced his "sunspot number" defined by Kiepenheuer (1953) as follows:

If there are on the solar disc f individual spots which are collected into g groups, the Wolf number R is

$$R = K\ (10\ g + f).$$

The factor K depends on the observer, the instrument used, and the method of of observation (eyepiece, projection screen, photograph).

Wolf set K = 1.0 based on his instrument. Efforts to keep the scale homogeneous have resulted in values of K from 0.91 to 0.64 at various observatories. This footnote is adapted from Morgan (1958).

Monthly means of Wolf sunspot numbers, based on observations made at Zurich Observatory, Zurich, Switzerland, are published in the first issue each month of the Journal of Geophysical Research, as Geomagnetic and Solar Data.

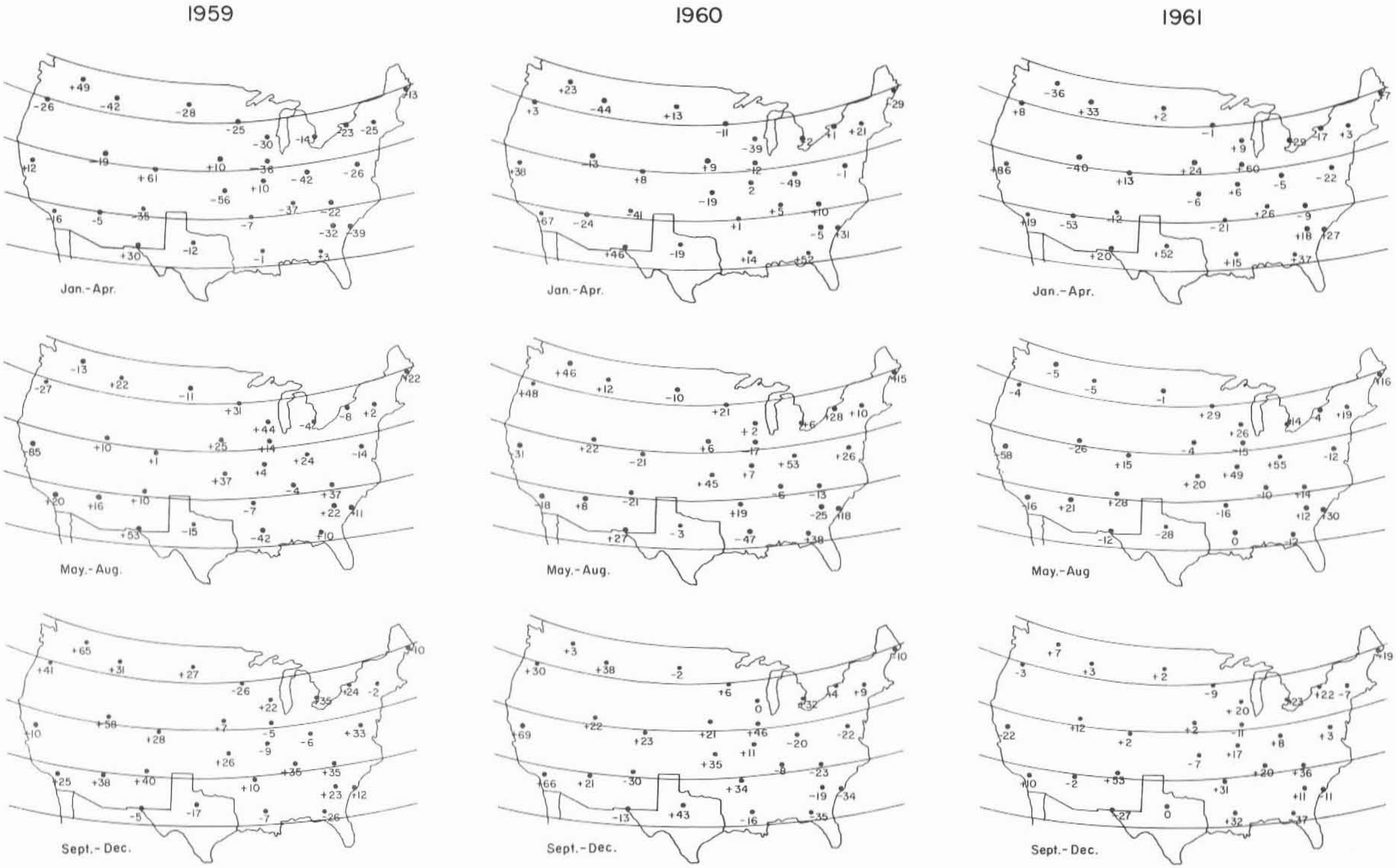


Figure 20

Precipitation Forecasts, in Percentage Departure from Normal

After C. G. Abbot, 1960, a long-range forecast of United States precipitation: Washington, Smithsonian Misc. Colln., v. 139, no. 9, p. 70-78.

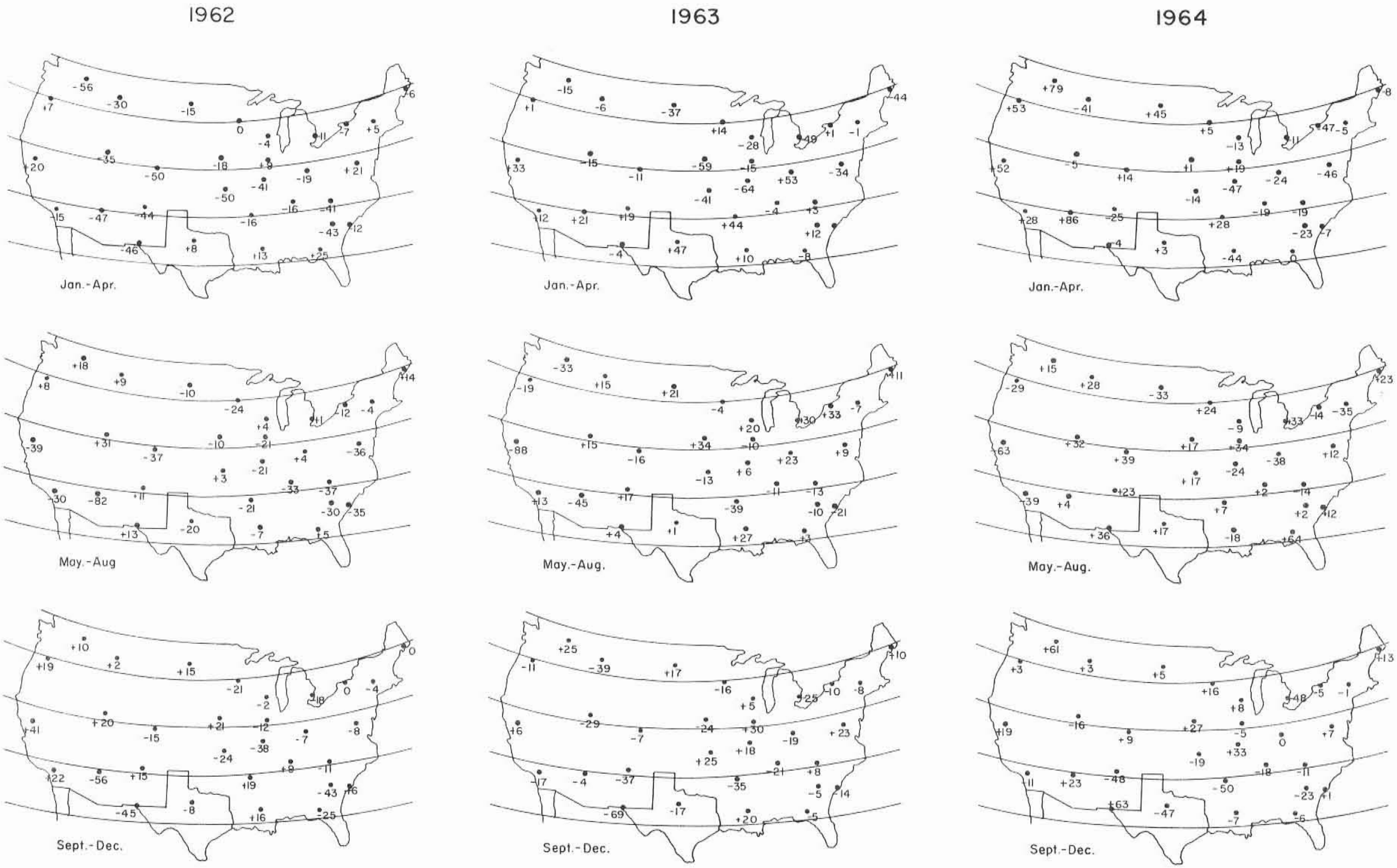


Figure 20--Continued

Precipitation Forecasts, in Percentage Departure from Normal

After C. G. Abbot, 1960, a long-range forecast of United States precipitation: Washington, Smithsonian Misc. Colln., v. 139, no. 9, p. 70-78.

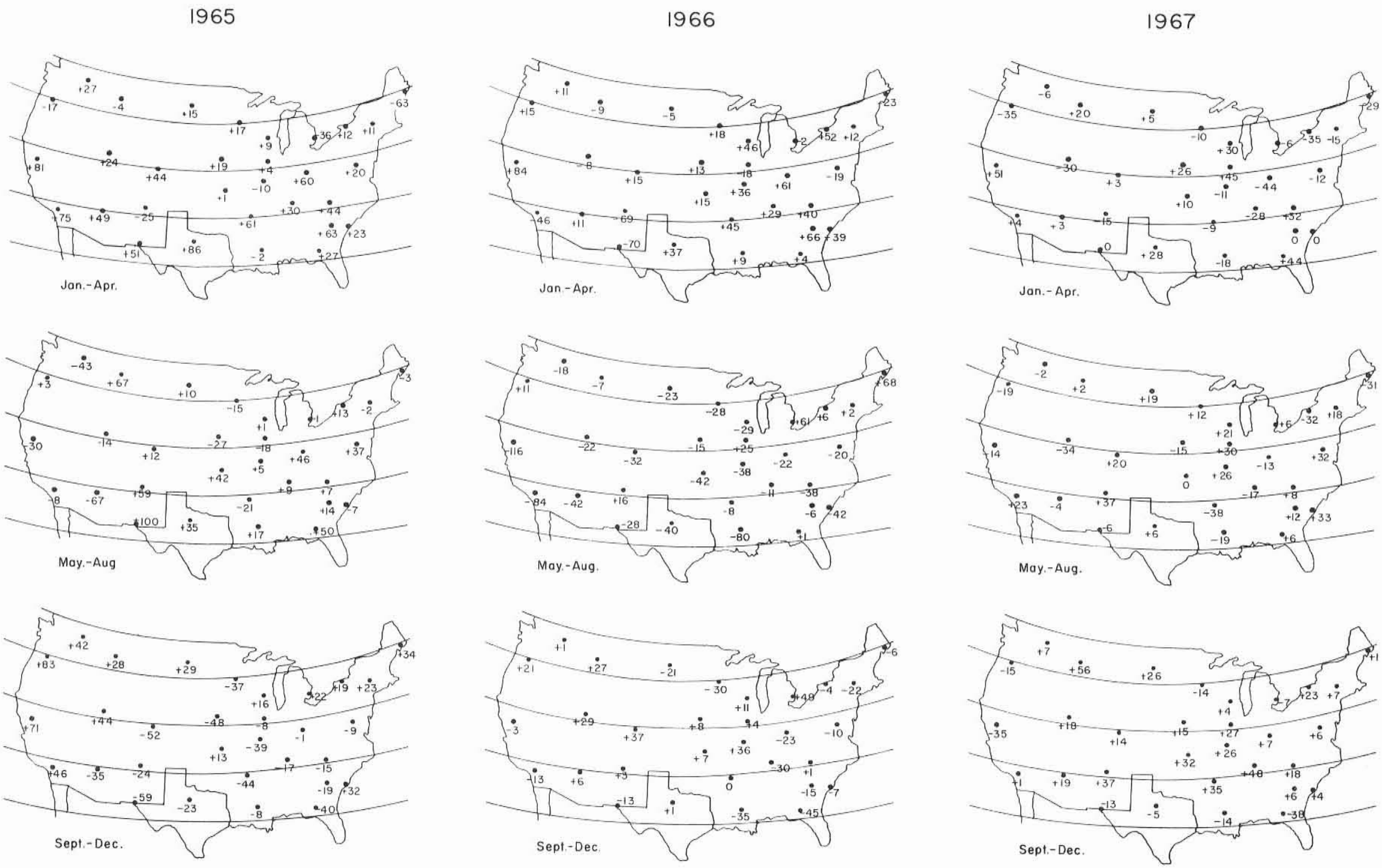


Figure 20--Continued

Precipitation Forecasts, in Percentage Departure from Normal

After C. G. Abbot, 1960, a long-range forecast of United States precipitation: Washington, Smithsonian Misc. Colln., v. 139, no. 9, p. 70-78.

Table 7.--Verification of Abbot's precipitation forecasts for Abilene and El Paso*

Period		Abilene precipitation in inches			El Paso precipitation in inches		
		Forecasted		Observed	Forecasted		Observed
1959	Jan. - Apr.	4.8		3.1	0.9		0.4
	May - Aug.	10.4		15.2	6.1		3.6
	Sept. - Dec.	6.5		9.0	2.6		1.0
	Total	21.7		27.3	9.6		5.0
1960	Jan. - Apr.	4.6		5.8	1.9		1.3
	May - Aug.	11.7		11.1	5.1		5.2
	Sept. - Dec.	10.5		8.3	2.3		2.6
	Total	26.8		25.2	9.3		9.1
1961	Jan. - Apr.	8.2		6.2	1.6		0.7
	May - Aug.	9.0		16.6	3.5		3.8
	Sept. - Dec.	7.6		12.7	2.0		3.1
	Total	24.8		35.5	7.1		7.6
1962	Jan. - Apr.	6.0		2.7	0.7		1.9
	May - Aug.	9.8		15.2	4.5		1.8
	Sept. - Dec.	7.1		9.2	1.5		4.6
	Total	22.9		27.1	6.7		8.3
1963	Jan. - Apr.	8.0		1.9	1.2		0.7
	May - Aug.	12.1		11.7	4.1		2.3
	Sept. - Dec.	6.5		4.2	0.9		1.8
	Total	26.6		17.8	6.2		4.8
		Col. A	Col. B		Col. A	Col. B	
1964	Jan. - Apr.	6.4	5.8		1.1	1.3	
	May - Aug.	11.7	13.5		5.4	5.4	
	Sept. - Dec.	4.9	4.4		4.1	4.4	
1965	Jan. - Apr.	7.6	6.9		1.8	2.0	
	May - Aug.	13.7	15.7		8.0	8.0	
	Sept. - Dec.	6.7	5.2		1.0	1.1	
1966	Jan. - Apr.	8.3	7.4		0.4	0.4	
	May - Aug.	6.7	7.7		2.9	2.9	
	Sept. - Dec.	8.5	7.7		2.2	2.3	
1967	Jan. - Apr.	7.8	7.0		1.2	1.3	
	May - Aug.	11.0	12.6		3.8	3.8	
	Sept. - Dec.	8.0	7.3		2.2	2.3	

* Beginning with 1964, the precipitation forecasts shown under Columns A are for periods when Wolf sunspot numbers are less than 20, and those under Columns B are for periods when Wolf sunspot numbers are greater than 20. For the years 1964-67, space is provided for the reader to further verify the forecasts as data become available.

Friedman (1957) has analyzed tree-ring growth evidence with a view to developing a drought index based on these data. Figure 21 shows a tree-ring index based on the annual growth of 15 old trees in the Big Bend area of Texas for the 300-year period 1645-1945. Sifting the evidence, Friedman concluded that the available tree-ring indices were not adequate quantitative measures of drought potential for the following reasons:

1. Variation in the distribution of rainfall during the season has an effect on growth even though the total annual rainfall amount may be the same during two different years;

2. Varying influence of temperature and other meteorological elements on growth;

3. Other factors which affect the rainfall runoff conditions;

4. Tree-ring indices provide only a relative, rather than an absolute, measure of annual rainfall;

5. Ring thickness depends on the age of the tree, the species, and many other non-meteorological factors such as damage by forest fire; and

6. Only a small percentage of the total variability of many tree-ring indices can be attributed to variations in rainfall.

Palmer (1964a) cities evidence of the periodic recurrence of extreme drought in western Kansas at intervals of approximately 20 years. Analyzing meterological records beginning in 1887, Palmer found a "surprising degree of regularity"; really serious drought occurred there in 1894 and adjacent years, 1913, 1934 and adjacent years, and in 1954 and adjacent years. Historical accounts mention exceptional drought occurrences there in the early 1870's and in the early 1850's. Palmer's paper continues (1964a, p. 174),

> "This apparent regularity leads one to speculate concerning the possibility that a drought of extreme severity will again occur in western Kansas sometime around the mid-1970's. Understanding of basic atmospheric actions and interactions is entirely inadequate to permit one to formulate any physical method for estimating the probability of such an occurrence. But, on the basis of past history the <u>early or mid-1970's may be years one might well anticipate.</u>" [emphasis added.]

Analyzing climatic data for St. Louis, the longest continuous meteorological record in the middle United States (from 1838), Palmer found that peaks of maximum drought severity appeared in St. Louis data in 1838, 1845, 1872, 1895, 1914, 1931, and 1955. Palmer points out that the St. Louis record cannot be considered to be entirely independent evidence, and finds (1964a, p. 174), "The only justifiable conclusion at this point is that there is <u>some</u> statistical evidence for suspecting that serious drought tends to occur about every 20 years in the central United States and that the subject requires looking into in much greater detail with more powerful methods and techniques."

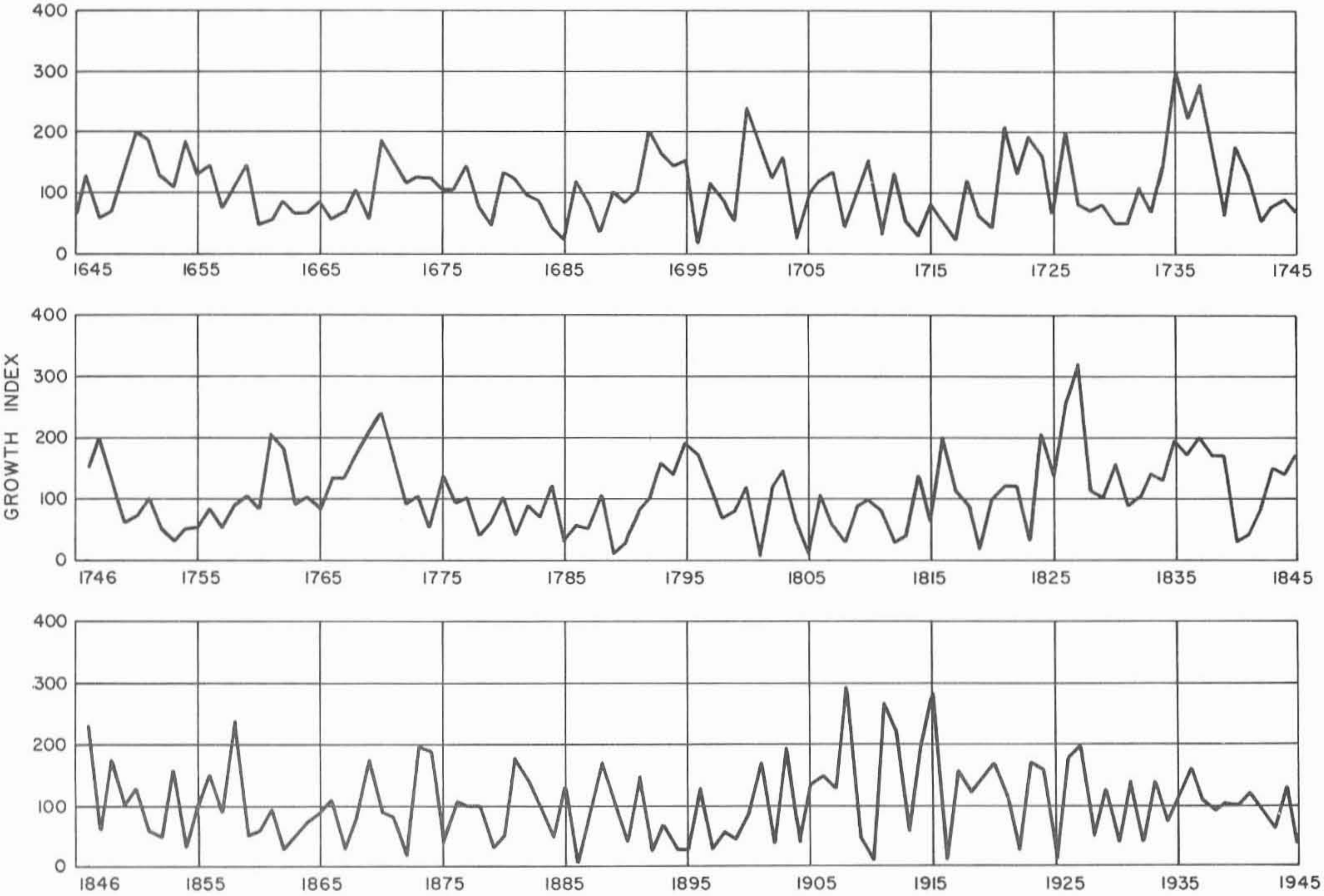


Figure 21

Tree-Ring Index Based on Annual Growth of 15 Old Trees in the Mountains of Southwest Texas (Big Bend Area) for the 300-Year Period 1645-1945

After D. G. Friedman, 1957, The prediction of long-continuing drought in South and Southwest Texas: The Travelers Insurance Co. Weather Research Center, Occasional Papers in Meteorology, no. 1, p. 23.

Forecasts Based on Extraterrestrial Influences

Lunar Effects

Unlike Abbot's forecasts of specific amounts of precipitation for specific locations and times, based on long-time trends, most investigators who are willing to record their views about extraterrestrial influences on weather write mainly in generalities and express negative views. Most present the data, their method of processing the data, what the data do not prove, and leave it up to the reader to draw whatever conclusions he chooses regarding use of the data for drought prediction. The following paragraphs summarize what was uncovered in the literature in the way of correlations between extraterrestrial influences and surface weather. A number of figures are offered for use by readers wishing to indulge in cycle-hunting games on their own.

Brier and Bradley (1964) report the discovery of a precipitation cycle of 14.765 days (one-half the lunar synodic month) while studying the dates of maximum 24-hour precipitation amounts for 1,544 weather stations in the continental United States over the 50-year period 1900-49. Twelve dates were listed for each station, one for each calendar month. A total of 16,057 entries representing 6,710 individual dates were used. Each of the 18,262 days of the 50-year period was characterized by a number, ranging from zero to about 40, indicating the number of stations reporting a maximum rainfall on that day.

During the period 1900-24 there were 7,856 maximum precipitation records, and these data were tabulated according to the 100 synodic decimal classes. The results are shown by the solid upper curve in Figure 22-A; the lower curve shows the results of a similar analysis for the period 1925-49. Figure 22-B shows the results of a study of possible modification of the lunar effect by variable solar radiation--the data were divided into two sets of 25 years according to whether the annual sunspot number was above or below the median for the 50 years.

Figure 22-C shows the curves for the 91-year period 1871-1961 for Boston, Toronto, New York City, and Washington, which can be compared with the "national curve" shown in Figure 22-D for the 50-year period 1900-49; and finally, Figure 22-E, a summary of 63 years of United States precipitation data, shows the results of these data in terms of inches of rainfall, and indicates that the average rainfall was about 10 percent higher a few days after the full moon than a few days before the full moon.

The 14.765-day lunar-influenced precipitation cycle demonstrated by Brier and Bradley can be of little practical significance in drought forecasting, as "dry spells" of 2 weeks duration are common in many places in Texas every year. However, the mass of data used in this demonstration and the programming techniques developed for use with high-speed electronic computers open the door to the possibility that real precipitation cycles of longer duration might exist that can be defined with skilled use of equipment and data. It might well be as Tannehill (1947, p. 231) said:

> "In the future, farmers will not have to gaze despairingly into a clear sky, wondering if a few clear days will continue into a disasterous drought. Even if we are never able to control the climate, much will be gained by knowing

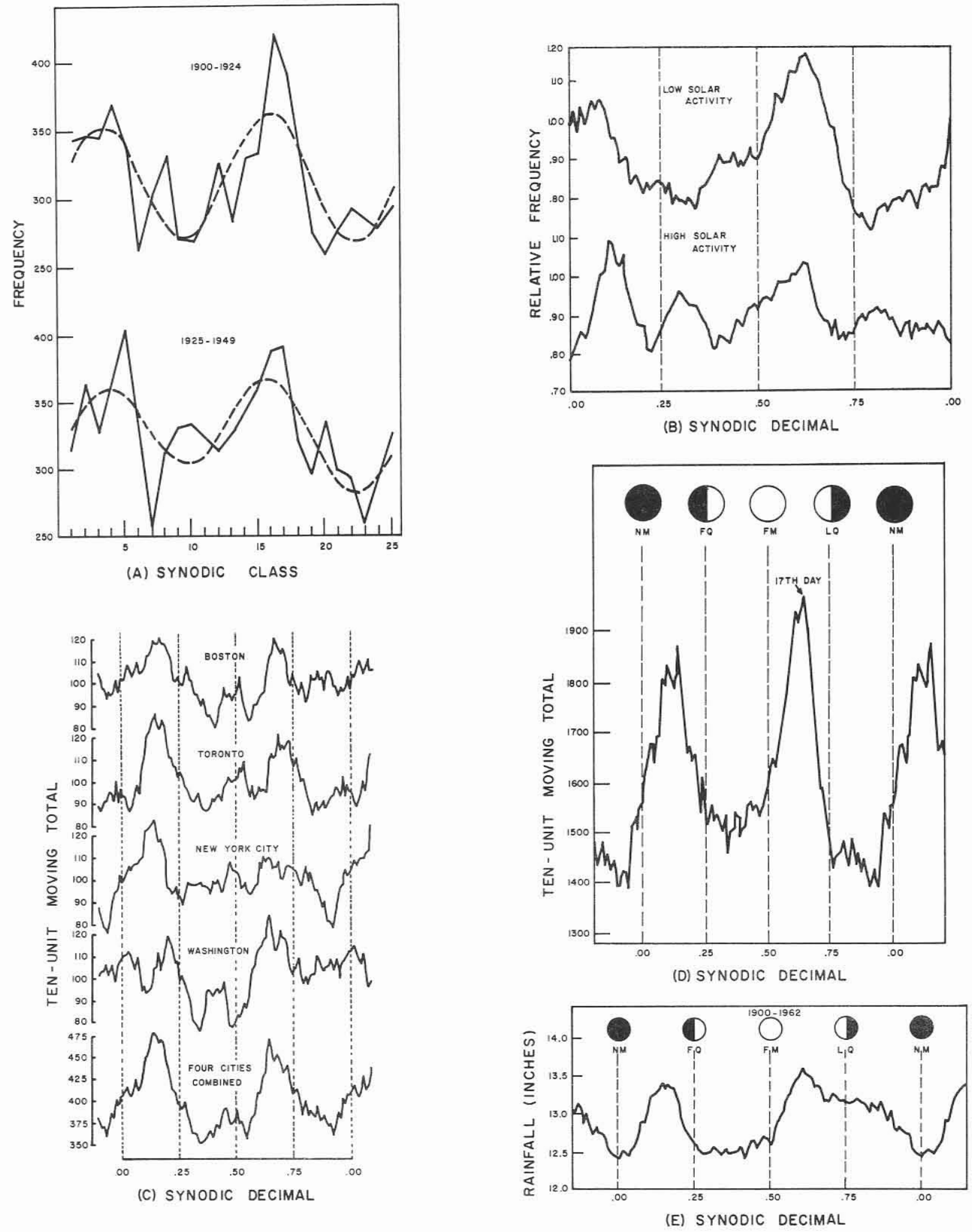


Figure 22

Lunar Effects on Precipitation

After G. W. Brier and D. A. Bradley, 1964, The lunar synodical period and precipitation in the United States: U.S. Weather Bur. manuscript.

what to expect. Droughts are not mere chance occurrences; they are part of a physical process which can be measured and studied and predicted with increasing precision as our observations of the sun and the upper air and the oceans continue to accumulate."

Sunspot Effects

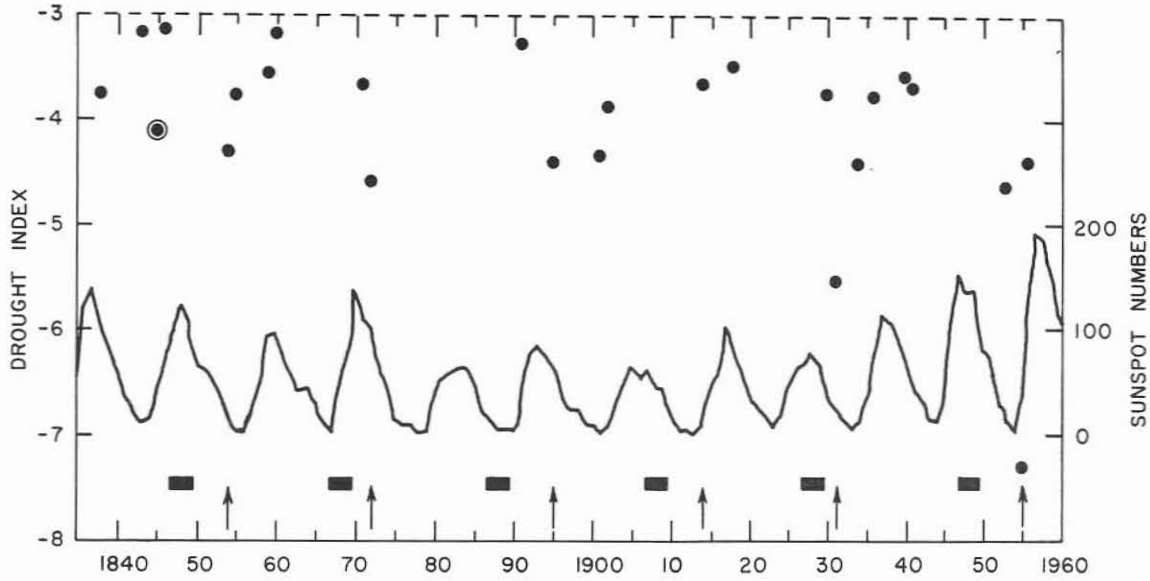
Mitchell (1964) agrees to the existence of two periodicities in climate and the possible existence of another. He used electronic computers for a power spectrum analysis (otherwise known as "generalized harmonic" analysis), which is based on the idea that a time series is not necessarily made up of a finite number of oscillations, each having a discrete wavelength, but rather a large number of small oscillations having a continuous distribution of wavelengths. Mitchell confirmed: (1) a suspected biennial oscillation in stratospheric wind and temperatures above equatorial regions, and (2) Brier and Bradley's semi-synodic lunar cycle in precipitation, discussed above. He commented that neither of these two cycles evidently accounts for enough variance in surface climate to be worth incorporation into routine procedures of prediction. However, Mitchell acknowledged the possibility of an appreciable variation in climate over periods of 80 or 90 years, and perhaps over longer periods, corresponding to similar periods of variation in solar activity (sunspots). If such long cycles can be verified, they may be of some value for predicting average climate, or climate variability, on the order of decades in advance.

Illustrating a negative correlation of sunspot cycles with drought, Palmer (1964a) points to the absence of serious drought during the last third of every other decade at St. Louis, Missouri, as represented by the short horizontal bars below the sunspot curve shown on Figure 23-A. Historical drought periods in Texas since 1900, obtained from Lowry (1959), are plotted along the sunspot curve on Figure 23-B. Lowry classified the Texas droughts according to a severity scale measured in 10-inch increments (accumulative rainfall deficiency) and ranging upward to 60 inches during drought periods of one or more years duration during the years 1891-1956. Table 8 lists these droughts in order of their severity in the four sections of Texas: Western, Mid-West, Mid-East, and Eastern.

Table 8.--Order of severity of historical droughts in the four sections of Texas, as indicated by deficiencies of rainfall in percentage of the mean annual rainfall

Order of severity	Western	Mid-West	Mid-East	Eastern
1 (most severe)	1953	1953	1901	1954-56
2	1933-34	1916-18	1954-56	1916-18
3	1954-56	1954-56	1909-12	1901
4	1909-12	1933-34	1916-18	1924-25
5	1891-93	1950-52	1924-25	1909-12
6	1916-18	1909-12	1950-52	1896-99
7	1937-39	1901	1933-34	1950-52
8	1950-52	1891-93	1891-93	1937-39
9	1896-99	1937-39	1937-39	1891-93
10	1901	1924-25	1953	1933-34
11	1924-25	1896-99	1896-99	1953

(After Lowry, 1959, p. 23.)



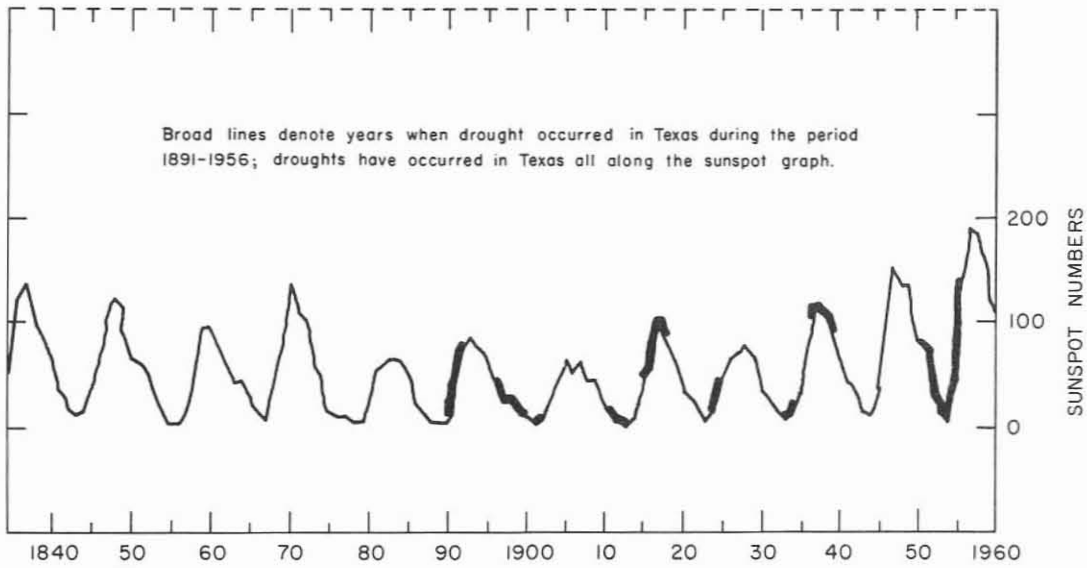
A. Years of Severe and Extreme Drought at St. Louis

● - Denotes drought year of indicated severity

▬ - Denotes year when no drought occurred

Arrows mark peaks of maximum drought severity

After W. C. Palmer, 1964, Climatic variability and crop production, in Weather and our food supply: Iowa State Univ., Center Agr. and Econ. Devel. Rept. 20, p. 185.



Broad lines denote years when drought occurred in Texas during the period 1891-1956; droughts have occurred in Texas all along the sunspot graph.

B. Drought Years in Texas

Sunspot graph as above. Drought periods after R. L. Lowry, Jr., 1959, A study of droughts in Texas: Texas Board Water Engineers Bull. 5914.

Figure 23

Sunspot Graph Compared with Drought Years at St. Louis and in Texas

Figure 24 affords comparisons between sunspots (Palmer, 1964a), approximate 5-year incremental rainfall averages for Texas (computed by Noriega[2]), and temperature and precipitation departures from normal for the United States (Kincer, 1937).

Noriega's rainfall averages are for the State of Texas as a whole. Each average represents a period of approximately 5 years. Single rainfall figures were calculated to represent the entire approximate 5-year periods and are shown as lines in Figure 24-B. Noriega's formula for weighting each yearly rainfall figure is:

$$C = \frac{a + 4b + 6c + 4d + e}{16},$$

Where C is the rainfall figure to be plotted for the year in question, a and b are the two years preceding C, and d and e are the two years following C.

Solution of the equation for each year plotted will yield figures which actually are weighted yearly 5-year running averages of rainfall for the State of Texas as a whole[3]. A rainfall curve was plotted from these yearly yields by Noriega and then was divided into approximate 5-year periods. The five yearly figures in each approximate 5-year period were then averaged, and one figure was calculated to represent each approximate 5-year period (Figure 24-B).

The broken-line curves on the left half of the page in Figure 24 (A and B) are the same as the solid-line curves on the right half of the page; they have been shifted to the left to illustrate Noriega's finding that the rainfall curve for the 34-year period 1927-60 appears when presented in this manner to be much the same as the rainfall curve for the 34-year period 1890-1923. There seems to be correlation in the sign and magnitude of change in the rainfall curve. There seems to be no clear-cut correlation between the sunspot curve and the rainfall curve. However, the 34-year period 1927-60 averaged about two inches drier, that is, experienced less rainfall, than the 34-year period 1890-1923. This tends to support Kincer's (1937) illustration (Figure 24-C), which shows that precipitation in the United States decreased during the period from about 1910 to about 1934 while the temperature increased.

To preclude misunderstandings about temperature trends since about 1934, parts of Mitchell's (1961) paper, "Recent Secular Changes of Global Temperature," have been reproduced in Figures 25 and Table 9. Figure 25 indicates a possible link between the low temperatures just preceding the turn of the 20th Century and the numerous volcanic eruptions of the time. Further comparison shows a possible connection between the lower temperature trend which started during the 1950's, the two Northern Hemisphere volcanic eruptions during the 1950's, and the rather spectacular rise in Zurich relative sunspot numbers during the latter part of the same period.

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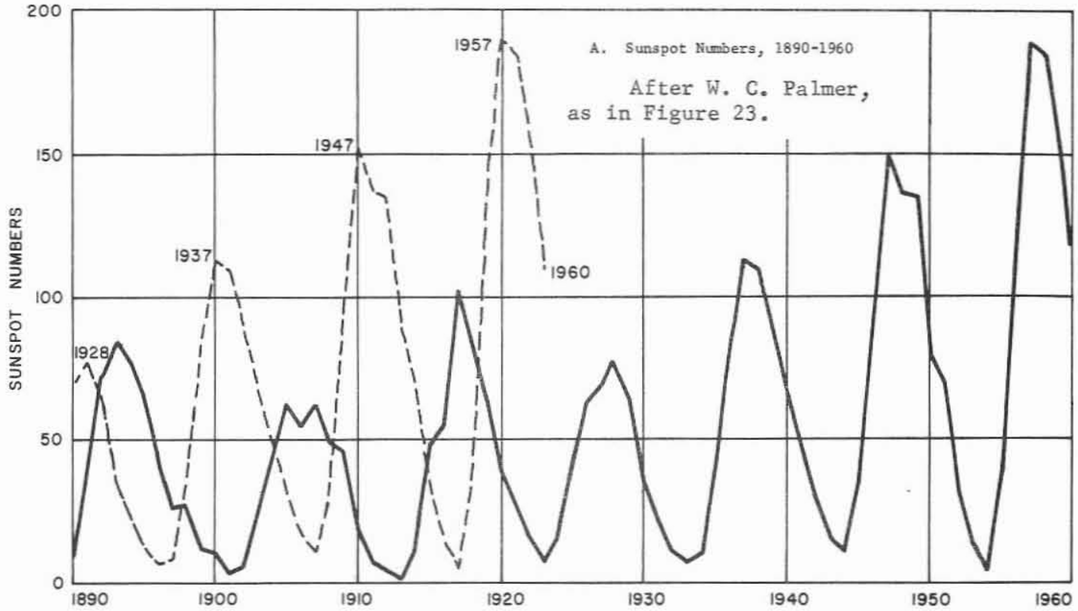
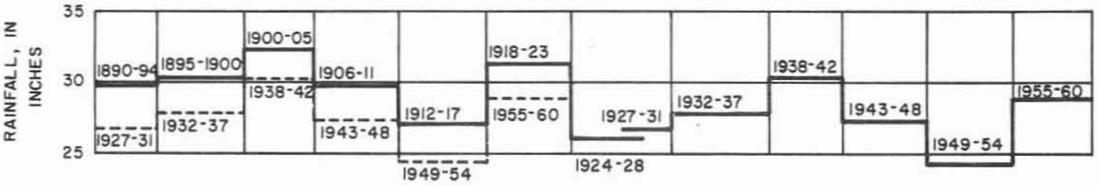
[2] Written communication of J. S. Noriega to Commissioner H. A. Beckwith, Texas Water Commission, Austin, Texas, Sept. 15, 1964.

[3] Use of statewide average precipitation amounts determined by averaging Climatic Division in Texas may yield slightly different values.



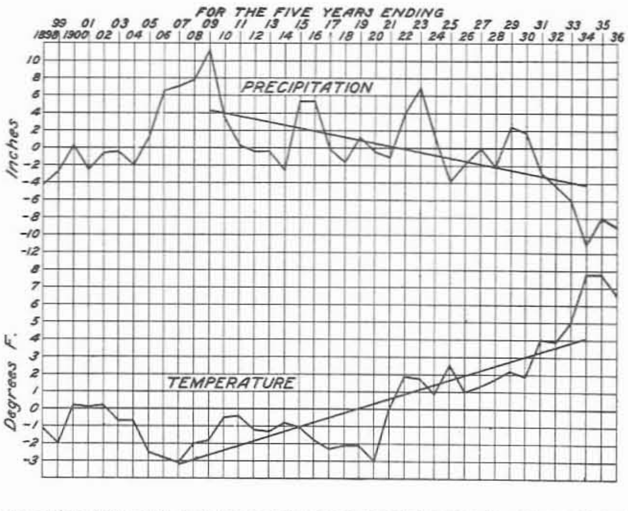
A. Sunspot Numbers, 1890-1960

After W. C. Palmer, as in Figure 23.



B. Incremental Averages of Rainfall in Texas, 1890-1960

Based on computations by J. S. Noriega. Explanation and formula are in the main text.



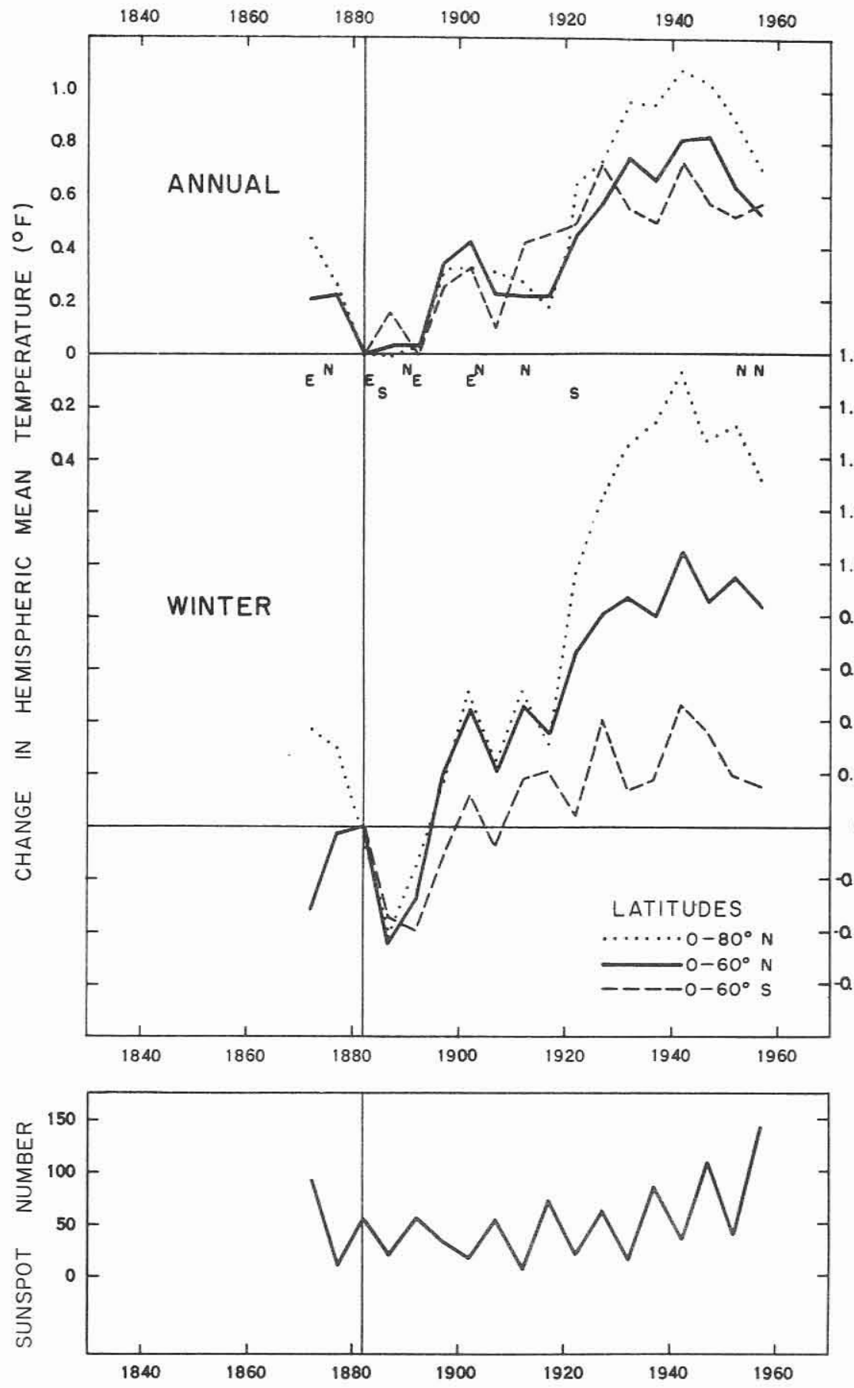
C. Progressive 5-Year Sums of Temperature and Precipitation Departures From Normal for the United States, 1898-1936

After J. B. Kincer, 1937, Is our climate changing: Illinois Farmers' Inst. duplicated rept., p. 25.

Figure 24

Comparison of Sunspots with Rainfall and Temperature Trends

(Broken-line curves in the upper charts are the same as the solid-line curves but are shifted to the left for comparison.)



All temperature curves are area-weighted averages of 10°-latitude band data. Dates of major volcanic eruptions shown by E (for equatorial), N (for Northern Hemispheric), or S (for Southern Hemispheric).

Figure 25

Comparison of Hemispheric Mean Temperature Trends with Volcanic Eruptions and Zurich Relative Sunspot Numbers (Successive 5-Year Averages)

After J. M. Mitchell, Jr., 1961, Recent secular changes of global temperature: © The New York Academy of Sciences, Annals, v. 95, art. 1, p. 239, 241.

Table 9.--Major volcanic eruptions since 1855 and ensuing changes of hemispheric mean temperature

		Did world cool?	
		Annual	Winter
Tropical			
1855-6	*Cotopaxi, Ecuador†	yes?	yes?
1872	Merapi, Java†	no?	yes?
1883	Krakatoa, Java-Sumatra	yes	yes
1892	Awoe, Indonesia	yes	no
1902-3	Mont Pelée, Martinique and others	yes	yes
		Did eruption hemisphere cool? (Cool relative to other?)	
		Annual	Winter
Northern			
1875	Vatna Jökull, Iceland†	yes? (?)	no? (?)
1890	*Bogoslof, Aleutians	yes (yes)	yes (no)
1912	Katmai, Alaska	yes (yes)	yes (yes)
1953	Mt. Spurr, Alaska and *Hibok-Hibok Philippines	yes (yes)	yes (yes)
Southern			
1886	Tarawera, New Zealand	no (yes)	yes (yes)
1921	*Southern Andes	no (no)	yes (yes)
1932	Quizapú, Chile	yes (yes)	yes (yes)

* Denotes eruption of doubtful intensity.
† Data for Southern Hemisphere lacking.
(After Mitchell, 1961, p. 245)

In Table 9, known major eruptions since 1885 are listed along with indication of temperature changes in the 5-year period following each eruption. The results show a tendency for eruptions to be followed by lower 5-year average temperatures in the eruption hemisphere. Mitchell points out that some subjectivity was applied in deciding which pentads to compare.

What have temperature statistics to do with drought prediction? It is the consensus of most meteorologists that, as shown in Figure 24-C and as pointed out from time to time in the preceding pages, higher temperatures go hand in hand with lower precipitation totals. One wonders but what a capability to accurately forecast temperature trends, by predicting sunspot trends or whatever, may be the eventual key to forecasting drought periods many years in advance of their occurrence.

Thomas (1962), in his paper, "The Meteorologic Phenomenon of Drought in the Southwest," has shown that four long periods of deficient rainfall have affected the Great Plains cities since about 1890; respectively, the periods were 1887-98, 1907-18, 1930-40, and 1950-56. Cities that he selected for illustrative purposes were Brownsville, Eagle Pass, Austin, and Abilene, Texas; Oklahoma City, Oklahoma; Dodge City, Kansas; and Pueblo and Denver, Colorado. On Figure 26, which is from Thomas (1962), the rainfall deficient periods (shaded) may be compared with relative sunspot numbers measured at the Zurich Observatory. To facilitate comparison, the author has added a broken line to the uppermost plot to indicate the approximate sunspot trace since 1953.

Similar alternating wet and dry periods are indicated on Figure 26 for all the cities studied except Brownsville, where in the last 50 years the alternating wet and dry periods are counter to those further inland at Denver. This suggests that when Brownsville is receiving more than average rain, there is less available for the more inland parts of the Great Plains as represented by Denver. Also, the graphs show that many of the Great Plains droughts begin in years of maximum sunspot activity during the lower maximum of the double sunspot cycle.

Regarding sunspots, the sunspot cycle averages approximately 11.3 years, but has been as short as 7 years and as long as 17 years. For climatic oscillations within historical times the evidence points to two probable causes: the effect of dust thrown into the atmosphere by volcanic eruptions and the effect of the sun's radiation. Only the latter is generally considered to be cyclical in nature. Illustrating a possible connection between the cyclical nature of sunspots and climatic oscillations, three of Tannehill's (1955) figures have been combined here as Figure 27.

Remarking about cycle hunting, after illustrating some of the various means by which apparent cycles and periodicities in weather may be statistically checked out, Mitchell (1964, p. 195) said:

> "From the historical viewpoint, if all cycle hunters had checked their results by these means, very few of their publications would ever have been written. Hasty and uncritical acceptance of the reality of evidence of cycles in climate has evidently been the source of more wasted effort in meteorology than any other kind of scientific misjudgement. Beyond a doubt, meteorology has not been alone in this experience either."

CONCLUSIONS

No single definition of drought fits all needs. If existing definitions do not fit the needs of a particular drought investigation the investigator will fashion a new one--hence the great number of drought definitions to be found in the literature.

Droughts are classified according to severity by use of descriptive words and by use of index numbers. The use of words alone to describe the severity of droughts leaves room for individual interpretation of descriptive terms. A numerical classification system with descriptive terms defining the index numbers is the most easily understood and most meaningful system.

The sun is the principal source of heat at the earth's surface. Heat received from the sun contributes to large-scale atmospheric circulation, thereby encouraging cold air from polar regions to migrate southward where it

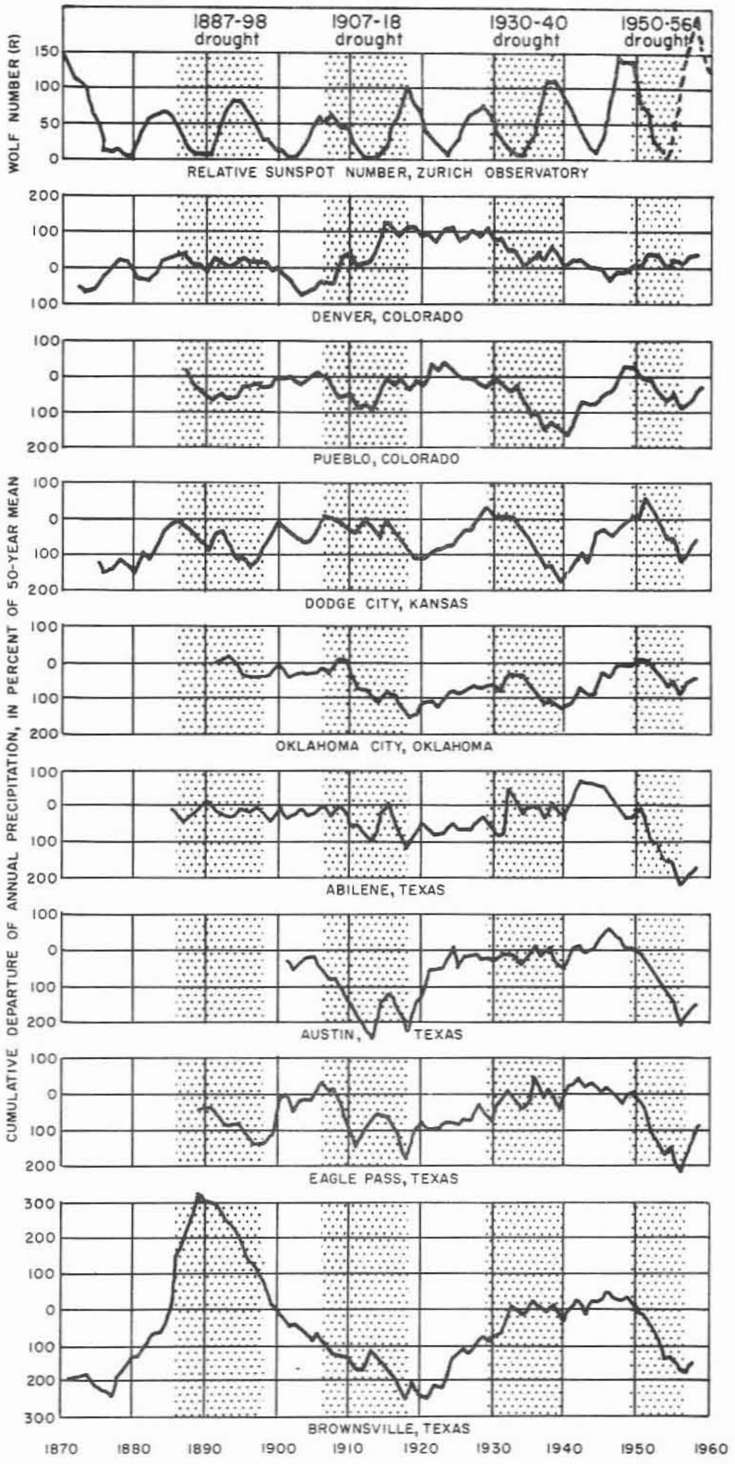
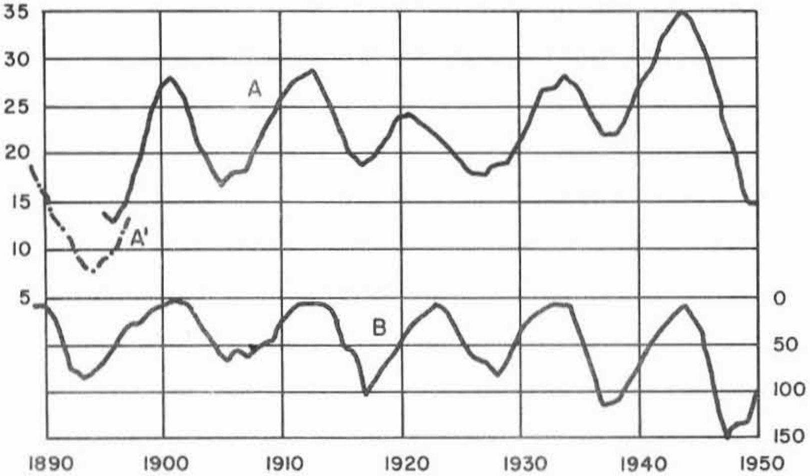


Figure 26

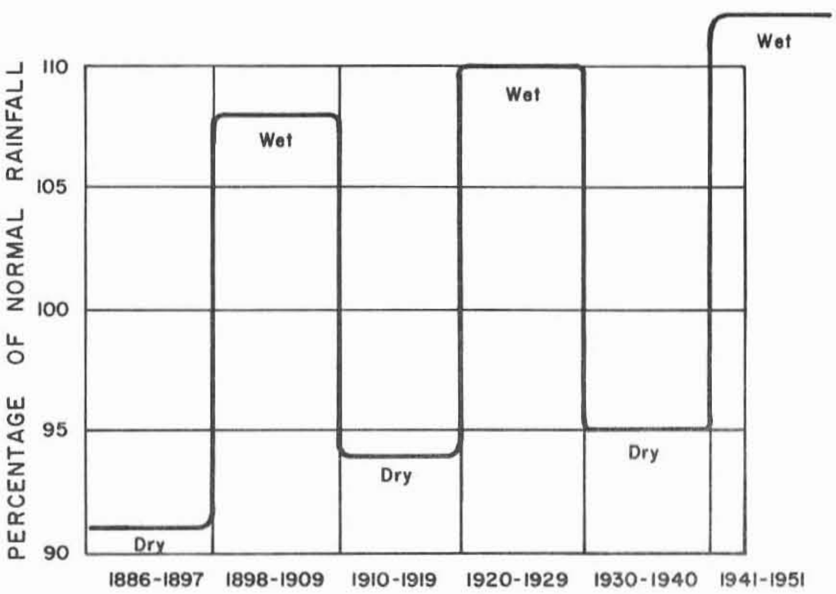
Fluctuations of Annual Precipitation at Eight Cities in the Great Plains Zones

After H. E. Thomas, 1962, The meteorologic phenomenon of drought in the southwest: U.S. Geol. Survey Prof. Paper 372-A, p. 25.

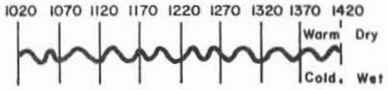


A, Differences in yearly rainfall between Galveston and Amarillo, Texas (smoothed); A', Abilene rainfall is used for years prior to beginning of Amarillo record. Scale at left shows excess of Galveston rainfall over Amarillo's in whole inches. B, Annual sunspot numbers inverted by scale at lower right. This cycle shows migration of rainfall from coast to interior and back again.

Cycle of Dry and Wet Years, 1886-1951



B. Cyclical pattern in Oklahoma rainfall. The total rainfall for each group of years given with the diagram is shown in percentage of normal. Each group of years begins 3 years before sunspot minimum.



C. Eduard Brückner's weather cycle for the years from 1020 A.D. to 1420 A.D. It is based mostly on records of the severity of European winters. (After Gregory.)

Figure 27

Examples of Cycles in Weather

After I. R. Tannehill, 1955, Is weather subject to cycles?, in The yearbook of agriculture, 1955: U.S. Dept. Agriculture, p. 86, 88, 90.

can clash with warm moist maritime air and cause precipitation. Failure of cold air to migrate southward seasonally will contribute to beginning or prolonging a drought in Texas. Warm moist Gulf of Mexico or Atlantic Ocean air is transported from the south and east by the winds around the outer periphery of the Atlantic and Gulf high-pressure cells. Unfavorable positioning or poor definition of the centers of these high-pressure cells will result in changes in their peripheries, which will in turn shift the belts of incoming moisture, denying some areas and favoring others, thereby contributing to or prolonging a drought in various sections of Texas.

Droughts in Texas may result when invasions of cold air from the north and west are either nonexistent or are too frequent in the colder half of the year to allow enough time for the southerly winds to transport Gulf of Mexico moisture inland to where it is needed. They also may result when deep easterly trade winds do not develop in the Gulf of Mexico to bring easterly waves to Texas in late summer and early autumn, as climatologically expected. And droughts may result when the areal extent of subsidence produced by an upper level Great Plains high-pressure cell does not remain confined to East Texas as climatologically expected each summer, but instead the subsidence spreads over most of Texas, it begins earlier in the year, and it persists after the summer has passed; even though during this time there may be considerable moisture in the air at lower levels, there can be no mechanism for initiating precipitation as long as this subsidence persists.

Drought is a word having many definitions, and many classifications and intensities of drought are defined in the literature. But investigators are generally most unwilling to forecast the beginning, duration, or end of a drought period as such. The phrase "drought forecasting" is shied away from and rightly so, because the literature reviewed reflects no method by which droughts have been consistently forecast in the past. No significant precipitation cycles have been proved beyond reasonable doubt, and it seems fair to conclude after reviewing the literature that no scientifically sound method has been found to forecast the long-range behavior of such climate-controlling factors as: development and movement of major semipermanent high-pressure systems, ocean-surface temperature changes, variations in solar radiation, and the major volcanic eruptions which throw great quantities of dust into the atmosphere to reflect the sun's heat away from the earth.

One long-range precipitation departure-from-normal forecast for El Paso and for Abilene proved to be inconclusive for the period verified. One isogrammed set of nine precipitation probability maps of Texas, based on the precipitation statistics of at least the 42-year period 1914-55, must await the passage of time for unqualified verification. Some cyclic-appearing drought curves were found, showing regular temporal amplitudes at specific localities, but no conclusive ones were found which could be applied to any large area on the order of thousands of square miles.

A regularly occurring and seemingly forecastable cycle, which may be a major factor in future drought forecasting techniques, is the sunspot cycle. Even though several hundred years of sunspot records are available, no exactly matching series of cycles of any significant length have yet been detected. The period of the cycle is forecasted with more confidence than the amplitude. The unforecastable and upsetting effects of volcanic dust clouds on insolation add significantly to the problem of determining to what degree variations in radiation from the sun may have affected world climate.

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