TEXAS
WATER
DEVELOPMENT
BOARD

REPORT 53

THE CLIMATE AND PHYSIOGRAPHY OF TEXAS

JULY 1967

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THE CLIMATE AND PHYSIOGRAPHY OF TEXAS

By

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FOREWORD

Individuals interested in the water resources of Texas and the relationship of climate and physiography to these water resources have frequently requested information from State water agencies. This report is intended to provide many more general answers on variations in climate for the professional and non-professional alike. It utilizes meteorological, geological, physiographic and and hydrologic data to assist the reader to a better understanding of the inter-relationships that location and topography have upon the climate of the great area which is Texas. A convenient glossary of terms is included in the interest of a better understanding of the presentation.

Although the report does provide some specific information for the various regions of the State, it is not its intent to provide detailed data for the multitude of localities in the State. Such data can often be secured locally or from the appropriate agencies responsible for obtaining the data.

Texas Water Development Board

John J. Vandertulip

John J. Vandertulip
Chief Engineer

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GLOSSARY OF TERMS

Definitions and abbreviations in this list are intended to explain terms as used in this report. More precise and scientific definitions of most of the terms are contained in "Glossary of Meterology," edited by Ralph E. Huschke and published by American Meteorological Society in 1959.

absolute instability--The state in a column of air when an air parcel that has been displaced vertically will be accelerated in the direction of the displacement.

adiabatic--A thermodynamic change of state of a system in which there is no transfer of heat or mass across the boundaries of the system. In the adiabatic process, compression always results in warming, expansion always results in cooling.

atmospheric pressure--The pressure exerted by the atmosphere as a consequence of gravitational attraction exerted upon the column of air lying directly above the point in question. The weight of a column of air extending upward from the top of a hill will be less than the weight of a column of air extending upward from the valley floor. Therefore, if the air on the valley floor is lifted, the pressure, or weight, exerted from above will decrease and the air will expand.

climatic division or climatic subdivision--As used by the U.S. Weather Bureau, there are 10 climatic divisions in Texas. At any place inside their boundaries, the values of the climatological normals (defined elsewhere) vary within about the same limits.

climatological normals--Typical climate in the sense of lying within limits of common occurrence; the average value of a meteorological element over any fixed period of years that is recognized as standard for the country and elements concerned.

condensation--The physical process by which a vapor becomes a liquid or solid; in general, the opposite of evaporation.

convection--As specialized in meteorology, atmospheric motions that are predominantly vertical, resulting in vertical transport and mixing of atmospheric properties.

convective cloud or convective thunderstorm--A cloud or thunderstorm which owes its vertical development, and possibly its origin, to convection.

convergence--The net flux of mass (air) into a unit volume of a system. If mass convergence is taking place in a plane near the surface of the earth, the incoming air is forced upward. If mass convergence is taking place in a plane that is not near the surface of the earth, the incoming air may either rise or descend.

dew point--The temperature to which a given parcel of air must be cooled at constant pressure and constant water vapor content in order for saturation to occur.

easterly wave--A wave within the broad easterly atmospheric current which moves from east to west. The wave generally moves more slowly than the current in which it is embedded. In Texas, an easterly wave usually brings squally weather along a line moving inland from the Gulf.

expansion--As air is lifted, it expands due to decreases in atmospheric pressure. Expansion is a cooling process, and if the air is sufficiently expanded, hence cooled, the water vapor will be condensed to form clouds. Further cooling will cause further condensation and precipitation.

extra-tropical--In meteorology, this condition is typical of occurrences poleward of the belt of tropical easterlies (easterly trade winds).

hyetography--The study of the annual variation and geographic distribution of precipitation.

isogram, isoline, isopleth--A line, on a given reference surface, drawn through all points where a given quantity has the same numerical value.

isohyetal--A line drawn through geographical points recording equal amounts of precipitation during a given time period or for a particular storm.

physiographic province--The land surface configuration and features within a delineated area (see Figure 1).

physiography--The form and surface configuration of solid earth.

potential evapotranspiration--Generally, the amount of moisture which, if available, would be removed from a given land area by evapotranspiration; one of the processes of evaporating water into the atmosphere.

precipitation--Any or all of the forms of water particles, whether liquid or solid, that fall from the atmosphere and reach the ground.

rainfall or precipitation gradient--The space rate of decrease of rainfall.

relative humidity--The ratio of the actual vapor pressure of the air to the saturation vapor pressure.

scarp or escarpment--A long, high, deep face of rock. Escarpments in Texas do not always have a rock face. The Balcones Escarpment is one example.

trough--In meteorology, an elongated area of relatively low atmospheric pressure either at the surface or aloft. The axis of the trough is a "trough line."

water vapor--Water substance in vapor form; one of the most important of all constituents of the atmosphere.

wave--Very generally, any patterns with some roughly identifiable periodicity in time and space. This applies, in meteorology, to atmospheric waves in the horizontal flow pattern; a disturbance propagated by virtue of periodic motions of the particles of the medium.

THE CLIMATE AND PHYSIOGRAPHY OF TEXAS

INTRODUCTION

A fact well known in the scientific community is that the daily and seasonal weather is strongly influenced by regional physiography everywhere in the world. For convenience, annual climatic averages are often referred to in various reports. These annual climatic averages are a composite of daily and seasonal weather events and are influenced by them. If only the annual climatic averages are considered when evalutating the climate of an area, however, the magnitude of the seasonal, monthly, and day to day fluctuations in rainfall will not be fully appreciated. Day to day and month to month climatic averages are totaled to calculate what are known as "climatological normals," but the tremendous year to year variations in precipitation, which sometime occur in all climatic regions of Texas in unpredictable cycles, are not revealed in these "normals." For instance, it is not at all uncommon in many areas of Texas, particularly west of the 99th meridian, for the precipitation in any year to vary more than 50 percent from the calculated climatological normals.

An understanding of the kinship between the climate and the physiography of Texas will help explain almost all seasonal climatic changes in the various climatic subdivisions of Texas. Some of the reasons why very large amounts of rain sometimes fall in a relatively small area within a climatological subdivision may also be explained when this kinship between weather and physiography is understood.

Purpose and Scope

The primary purposes of this report are to provide technical personnel and the citizens of Texas with a better understanding of the reasons for the sometimes very wide variations in day to day, season to season, and year to year climatic parameters in the various sections of the State; and to emphasize the two most important elements affecting climate--precipitation and temperature.

Physiography and climatic regimes in the various climatological subdivisions of Texas were examined in detail. This was done by analyzing the explanations of the physical properties and processes of the atmosphere as described by the leading climatologists of our time. A simplified explanation of characteristic "summer drought" in East Texas and a simplified explanation of the rainfall gradient along the Texas coast are offered. Also sought is a simplified means of explaining in general terms how and why mountains and scarps trigger the precipitation mechanisms and why plains, valleys, and plateaus do not.

Personnel

This report was prepared in the Texas Water Development Board by John T. Carr, Jr., Hydrometeorologist and Director of Planning Hydrology and Special Studies Division, under the general direction of John J. Vandertulip, Chief Engineer for the Texas Water Development Board. Special thanks are given to Texas State Climatologist Robert B. Orton for his technical advice and the use of his technical library while this report was being prepared.

MOISTURE SOURCES AND TOPOGRAPHIC INFLUENCES

The State of Texas encompasses seacoasts, swamps, prairies, plateaus, valleys, and mountains. Almost the entire range of climate types is scaled along a line from Beaumont to El Paso; from Brownsville to Dalhart; or from Texarkana to Midland. Different physical processes cause rain, or lack of rain, in the various climatic areas of Texas.

Much of Texas is subject to recurrent drought as the great arid areas in the western states expand and contract in reaction to the broad controls of the ocean, the atmospheric circulation, and the sun. At the end of most years, only the eastern sections of Texas have received enough rainfall to offset yearly potential evaporation.

The Gulf of Mexico is the principal moisture source for the precipitation which falls in all areas of Texas, although a less important amount of moisture from the Pacific Ocean does reach the ground in Texas at times. Indeed, much more Gulf of Mexico moisture reaches New Mexico and northern Arizona than does Pacific Ocean mositure reach eastern New Mexico and Texas. For example, almost all summertime precipitation occurs at Grand Canyon National Park, Arizona, when Gulf of Mexico moisture-laden winds have prevailed from the south for several days or weeks.

The distance from the moisture source alone is not an important enough factor to reduce drastically the amount of precipitation falling in a given area. Topography is of prime importance, with its capacity to cool the air forced to rise up mountain slopes, to warm the air descending into valleys, or merely to transport the moisture-laden air across plateaus and prairies. Cooling of the air by expansion, as atmospheric pressure decreases with rises in topography, is a very important "moisture sapping" process.

Fenneman's (1931 and 1938) delineation of physiographic provinces in Texas (Figure 1) discloses a pattern of topography in Texas which methodically and relentlessly "saps" the moisture from the air as it moves westward over the coastal plain and successively reaches the Balcones Escarpment, the Edwards Plateau, the Break in the Plains, and the mountains of the Trans-Pecos. The isohyetal pattern on the precipitation chart for Texas (Figure 2) discloses the locations of these physiographic features. Packing--close spacing--of isohyets characterize breaks in topography, while even and orderly spacings characterize plains and plateaus. Topography and distance are the major reasons why the normal annual precipitation in Texas decreases from a high of more than 56 inches in far East Texas to a low of less than eight inches in far West Texas. Methodical and orderly decreases in precipitation occur as plains and plateaus are crossed and as the distance increases from the Gulf of Mexico. Ragged and

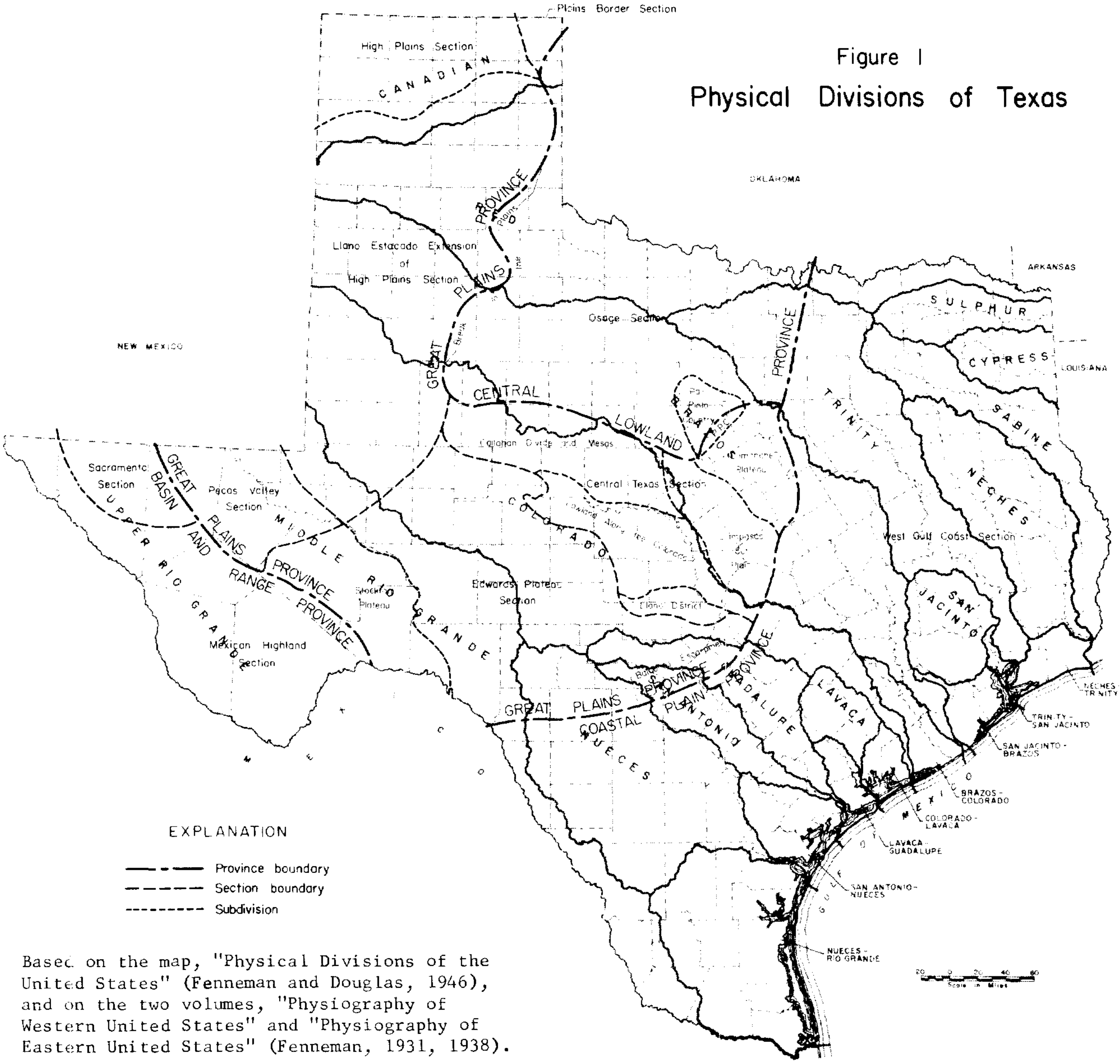
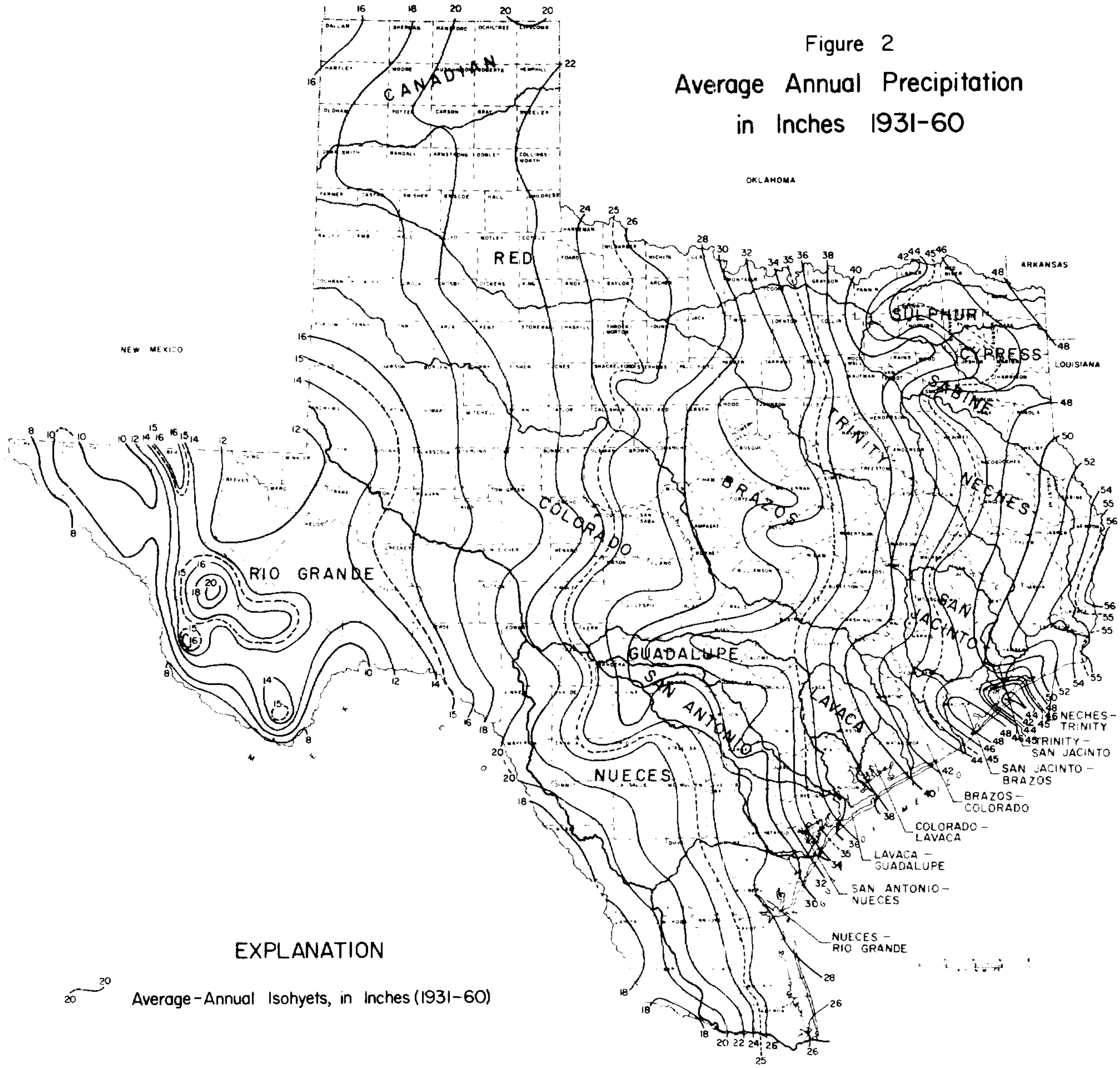


Figure I
Physical Divisions of Texas

Based on the map, "Physical Divisions of the United States" (Fenneman and Douglas, 1946), and on the two volumes, "Physiography of Western United States" and "Physiography of Eastern United States" (Fenneman, 1931, 1938).

Figure 2
Average Annual Precipitation in Inches 1931-60



EXPLANATION

Average-Annual Isohyets, in Inches (1931-60) disorderly decreases in precipitation occur as scarps, breaks in the terrain, and mountains are crossed by the moisture-bearing winds on their westward journey.

CHARACTERISTIC CLIMATIC PATTERNS

The physiographic provinces in Texas do not have the same delineative definitions as the climatic divisions, but the characteristic physiography within each of the provinces so strongly influences the climate that it becomes necessary to assign names and to separately delineate the 10 climatic divisions. The 10 climatic subdivisions of Texas can further be grouped to form these climatic regions. Climatic divisions and climatic regions are shown in Figure 3. The climatic regions are:

(1) The Interior and Lower Coast;

(2) The Upper Coast and Trans-Pecos; and,

(3) East Texas

Figure 4 shows a set of curves depicting the variability of average monthly amounts of rainfall in the 10 climatic divisions of Texas during the 30-year period 1931-60. These 10 climatic divisions are named and the normal monthly rainfall and average monthly temperature for each are shown in Table 1.

Normal Climate

The data used to compute the climatic averages of precipitation and temperature (the "normals" shown in Table 1) include the extremes in either side of the averages, but the sometimes impressive day-to-day, season-to-season, and even year-to-year variations lie completely obscured and embedded in these averages--the "normals." Most impressive are the variations from normal rainfall, normal temperature being more conservative on a seasonal and yearly basis.

Climatic normals change slowly but they do change. We know of the Ice Ages and read that cattle grazed on Greenland during the time of the Vikings. Paleoclimatology, however, is not a concern of this report.

Currently, the climatic normals used by the U.S. Weather Bureau and used in this report are based on the averages for the 30-year period 1931-60. New 30-year averages of rainfall and temperature will be recomputed for the period 1941-70 and at the end of each 10-year period thereafter. In this way the slow evolution of climate will be superimposed on the long-time record, which for some locations in Texas dates backward about a hundred years. For some locations in Europe, Asia, and Africa, the record dates back to and before the advent of the Julian Calendar.

Use of the 30-year normals as currently computed is a more realistic approach than use of long-time averages when describing the climate of an area as we are now experiencing it. Departures from normals are not the same as departures from long-time averages, but for purposes of significance and realism the magnitude of departures from normals are more relevant to the times.

Figure 3

The Ten Climatic Divisions (Blocks of Counties Having Similar Rainfall Amounts) and the Three Climatic Regions in Texas (Blocks of Climatic Divisions Having Common Seasonal Rainfall Characteristics--Summer Maximum, Summer Drought, and May and September Maximum).

Table 1.--Monthly and annual normals of precipitation and temperature in the 10 climatic divisions of Texas (U.S. Weather Bureau data)

Climatic division	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Rainfall													
High Plains	0.66	0.60	0.72	1.36	3.05	2.45	2.41	2.12	1.97	1.83	0.61	0.73	18.51
Low Rolling Plains	.96	1.05	1.05	2.12	4.06	2.72	2.14	1.85	2.40	2.38	1.07	1.19	22.99
North Central	2.18	2.40	2.21	3.69	4.75	3.23	2.22	1.93	2.79	2.84	2.28	2.41	32.93
East Texas	4.22	3.82	3.58	4.56	5.12	3.35	3.42	2.91	2.95	3.15	4.26	4.62	45.96
Trans-Pecos	.68	.41	.46	.56	1.26	1.34	1.80	1.65	1.73	1.18	.40	.56	12.03
Edwards Plateau	1.60	1.59	1.46	2.42	3.54	2.67	2.26	1.98	3.11	2.33	1.28	1.67	25.91
South Central	2.34	2.37	2.10	3.04	3.78	3.13	2.68	2.57	3.61	2.86	2.21	2.56	33.24
Upper Coast	3.62	3.57	2.83	3.35	4.09	3.61	4.70	4.48	4.57	3.65	3.55	4.17	46.19
Southern	1.24	1.17	.95	1.90	3.12	2.55	1.79	2.14	3.13	2.09	.98	1.27	22.33
Lower Valley	1.57	1.19	1.09	1.56	2.72	2.51	1.65	2.56	4.21	2.59	1.16	1.46	24.27
Temperature													
High Plains	38.2	41.9	48.4	58.1	66.8	76.4	79.7	78.7	71.4	60.8	47.3	40.4	59.0
Low Rolling Plains	42.6	46.3	53.2	63.4	71.4	80.5	83.8	83.6	76.0	65.5	52.1	44.7	63.6
North Central	45.4	48.9	55.7	64.8	72.5	80.8	84.5	84.8	77.8	67.8	54.7	47.6	65.4
East Texas	48.7	51.7	57.8	65.8	73.1	80.2	83.0	83.1	77.6	68.4	56.3	50.4	66.3
Trans-Pecos	46.0	50.4	56.3	64.4	72.2	79.8	80.3	79.5	73.9	65.4	53.0	46.9	64.0
Edwards Plateau	48.8	52.5	58.5	66.7	73.9	80.7	83.1	83.1	77.4	68.6	56.4	50.3	66.7
South Central	53.5	56.7	62.3	69.6	76.3	82.3	84.5	84.7	79.9	72.3	61.0	55.4	69.9
Upper Coast	54.4	57.0	61.9	68.9	75.7	81.5	83.3	83.2	79.3	71.9	61.3	56.2	69.6
Southern	55.5	59.2	65.4	72.8	79.1	84.5	86.5	86.4	81.5	73.8	62.6	56.7	72.0
Lower Valley	61.0	63.7	68.4	74.8	79.7	83.4	84.8	85.0	81.8	76.0	67.3	62.3	74.0

The record for the period 1931-60 in the 10 climatic divisions of Texas was studied and, when it was noted that the total annual precipitation varied from normal by the amount of 25 percent or more, the percentage variation was computed as is shown here in Table 2. Annual variations of precipitation up to 20 percent from normal are commonplace in many areas of Texas, particularly in West Texas, therefore these are not shown in the tabulation.

It is evident from the statistics contained in Table 2 that state-wide precipitation varies from 1931-60 normals by ±25 percent more frequently than one out of every three years--112 out of 300 years (30 years x 10 climatic divisions). These variations from normal remain undetected when long-time averages of normal precipitation are the only figures considered. Variations of 20 percent or more from normal precipitation occur so frequently as to be virtually considered "standard deviation" in some climatic divisions.

The 30 years of Texas' total annual precipitation records represented in Table 2 disclose the following significant facts:

1. During only three of these years (1945, 1947, and 1955) did the precipitation fail to vary from normal by 25 percent or more in one or more of the 10 climatic divisions of Texas;

2. The precipitation varied from normal by 25 percent or more the least number of times, seven, in East Texas and the greatest number of times, 14, on the Edwards Plateau;

3. During only one year, 1933, was the sign of the 25 percent or more variation different in one climatic division (positive in the Lower Rio Grande Valley) from the sign in any other climatic division (negative in the High Plains, Trans-Pecos, and Edwards Plateau divisions);

4. During only five years (1931, 1937-38, 1942, and 1959) did the precipitation vary by ±25 percent in just a single climatic division;

5. During the year 1941 only East Texas failed to vary by 25 percent or more, while all other climatic divisions did vary that amount or more (on the plus side)--the High Plains and Trans-Pecos both received more than double normal annual rainfall;

6. During only one year, 1956, did every climatic division have a rainfall deficiency of 25 percent or more;

7. Following the precipitation deficient year of 1956, and for the remainder of the decade ending in 1960, every climatic division in Texas had either a surplus of rainfall, or, whatever deficiencies occurred did not amount to as much as 25 percent below normal; and,

8. The climatic divisions with flat to gently rolling topography (East Texas, Upper Coast, Low Rolling Plains, and North Central) had the fewest number of years when precipitation varied from normal by 25 percent or more. The opposite was true for the climatic divisions having or bordering upon rougher topography, or lying in the path of dry winds descending from the Mexican Plateau (the Edwards Plateau, the Southern Division, and the Trans-Pecos).

Table 2.--Percentage variation in total annual precipitation in excess of ±25 percent of 1931-60 normals in the 10 climatic divisions of Texas. Percentage variations less than 25 percent are not shown.

(U.S. Weather Bureau data were used.)

	High Plains	Low Rolling Plains	North Central	East Texas	Trans-Pecos	Edwards Plateau	South Central	Upper Coast	Southern	Lower Valley
Normal (in.)	18.5	23.0	32.9	46.0	12.0	25.9	33.2	46.2	22.3	24.3
Year		Percent Variation from 1931-60 Normal								
1931									+35	
32	+26	+36	+25		+60	+41				
33	-28				-39	-32				+68
34	-35				-54	-31				
35		+27	+36			+62	+35		+35	+29
36						+39				+28
37									-28	
38										-25
39							-30			-28
1940			+29	+28	+30	+28	+26			
41	+103	+93	+32		+127	+34	+37	+45	-31	+70
42	+36									
43		-25	-27							
44				+32	+29	+31				
45										
46				+34			+41	+53		
47										
48			-27	-26	-38		-27	-33		
49	+36					+27		+38	-30	
1950							-32		-26	-36
51					-39	-47				
52	-32	-34			-27				-44	-30
53	-30				-51	-27				-25
54		-29	-32	-27		-50	-49	-43	-29	
55										
56	-49	-44	-39	-32	-56	-67	-45	-28	-47	-47
57		+45	+46	+32		+47	+37		+33	
58					+42				+53	+54
59								+26		
1960	+37						+37	+25	+29	
Number of entries	10	8	9	7	12	14	11	8	12	11

The Interior and Lower Coast

The late spring (May) and early autumn (September) maximum precipitation periods, coupled with the low winter and low summer precipitation periods, are the climatic patterns of the interior of Texas--the North and South Central Division, Edwards Plateau, Low Rolling Plains, the Southern Division, and to an extent the High Plains. From about Corpus Christi southward along the coastal plains and in the Lower Rio Grande Valley the monthly distribution of precipitation is much the same as for the interior of Texas. The two maximum precipitation periods in May and September are characteristic of the interior, partly because of convective thunderstorm activity and partly because at these two times migrations of cooler air from the north have a good opportunity to encounter well established moisture-laden winds from the Gulf of Mexico (see Figure 5). Also, upper level areas of atmospheric convergence are then moving over Texas from the west and from the east. In September, the coastal regions are experiencing pronounced "easterly wave" action coming in from the Gulf of Mexico and the Caribbean Sea.

In May, the winds have intermittently prevailed from the south for long enough periods of time to have carried great quantities of water vapor from the Gulf of Mexico far into the interior of Texas. The last of the winter season of cold air migrations from Canada and the Great Basin, the first of the warm season air mass thunderstorms, and springtime low pressure troughs aloft in the westerly winds all contribute to causing considerable precipitation and the May maximum.

By September, the first of the autumn-winter season of cold air has begun occasionally to clash with the long established moisture-laden prevailing southerly winds. The last of the summertime convective thunderstorms and the two upper air convergence phenomena, easterly waves and westerly troughs, all act to produce the secondary September maximum precipitation period. Also, in the past, the severest hurricanes to affect Texas have occurred in September.

When the remains of these hurricanes move inland and encounter the scarps and hills, some of the heaviest rainfalls in the State's history have occurred in the interior.

Namias (1960) has shown recently that summer drought in the latitudes spanned by Texas is coincident with the occurrence of a strong warm-core high pressure cell aloft which forms in summer over the Great Plains states. This summertime high pressure cell forms between the Atlantic Ocean and the Pacific Ocean semipermanent high pressure cells. It sometimes first appears as a "bridge" joining the two oceanic high pressure cells. All three cells are thought to be interdependent. The drought-enhancing characteristics of this Great Plains high pressure cell are two tongues of air aloft spiralling inward toward the center of the cell and descending. One is a dry tongue extending southward from the summertime prevailing westerly winds which are at more northerly latitudes in summer; the other is a moist tongue extending northward from the summertime prevailing easterly winds of the low latitudes. Arrows on Figure 6a show the axes of moist and dry tongues. Coded areas beneath the two tongues show on Figure 6b how precipitation varies at the surface below the moist and dry axes.

The dry tongue of air aloft coming from the north sinks as it moves toward the core of the Great Plains high pressure cell, part of which often covers the eastern sections and the interior of Texas. Horizontal divergence results at

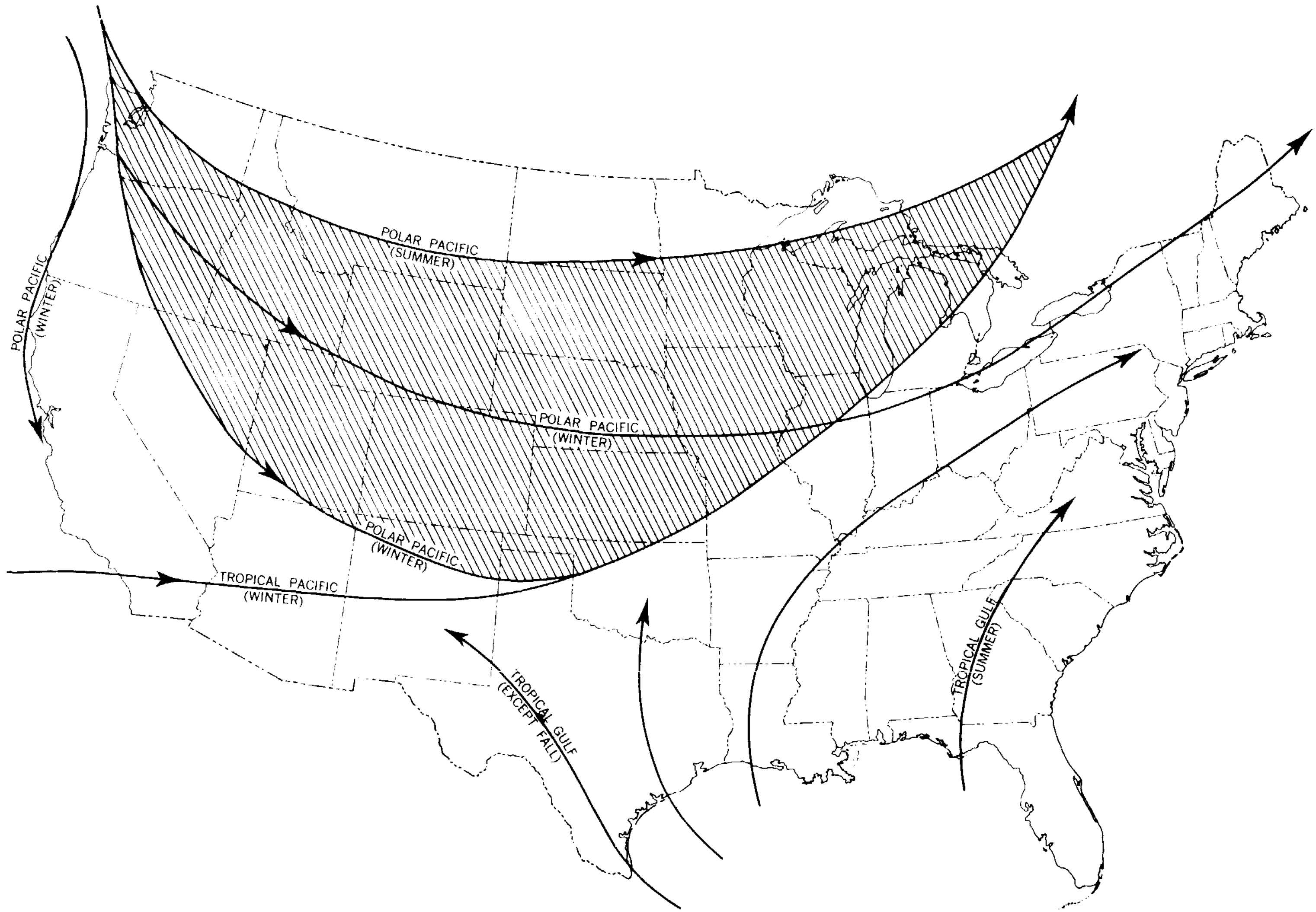
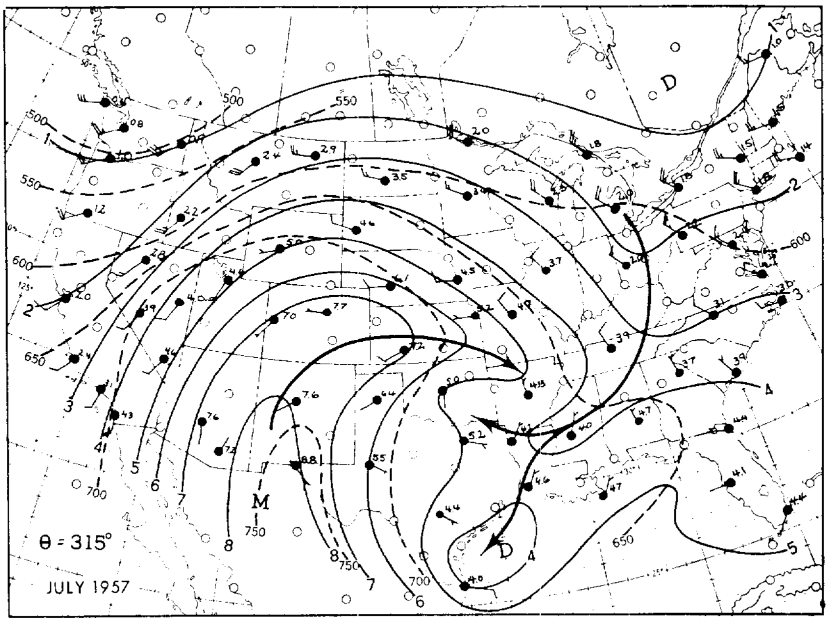


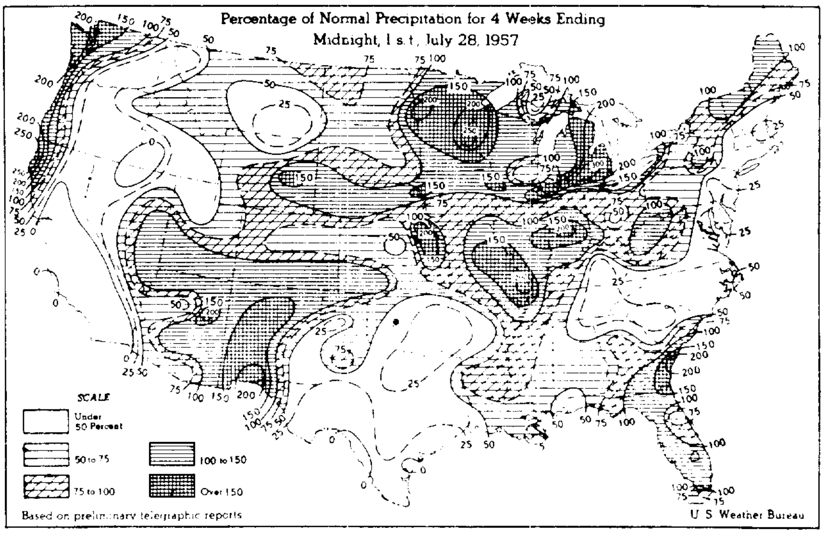
Figure 5

Average Trajectories of Storm Centers in the United States, Excluding Alaska and Hawaii

(Adopted from California Institute of Technology, Department of Meteorology, 1943; reproduced here from Thomas, 1962, p. A-10.)



Isentropic analysis for the potential temperature surface 315° for July 1957. Solid lines are isopleths of mixing ratio in g/kg. Broken lines give the pressure at the isentropic surface. Winds at the isentropic surface are indicated in customary fashion. Arrows depict the axes of moist (M) and dry (D) tongues.



Percentage of normal precipitation for July 1 to 28, 1957.

Figure 6

Isentropic Analysis and Percentage of Normal Precipitation for July 1957

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. 83.

low levels in the atmosphere. Once this high pressure cell is well established, lengthy dry spells result proportional in their severity to the strength and longevity of the high pressure cell. An understanding of horizontal convergence is necessary before the importance of horizontal divergence becomes apparent.

Horizontal convergence in a layer of the atmosphere results when the horizontal flow of air into the layer exceeds the horizontal outflow of air. If the convergent flow is at the surface, as with summertime convective thunderstorms in Texas, upward vertical motion must result. If the convergent flow occurs at any other level in the atmosphere, either upward or downward vertical motion can result. Almost any vertical motion within a layer of air is the result of entrainment of the surrounding air. Horizontal convergence usually produces upward rising air currents which cool by expansion. Precipitation results if the rising air is moist. Horizontal divergence produces the opposite effect: warming, subsiding air, and an increased capability of the air to hold more moisture in the form of invisible vapor without releasing it as clouds or precipitation.

In winter, visitations of cold air from the north may be too frequent for the winds to have had time to shift to the south and begin transporting moisture inland before a new cold visitation arrives. In addition to the time required for northerly winds to shift around to the south, a period of time will be required to transport sufficient Gulf of Mexico moisture deep enough inland to result in significant rains when the Gulf air does clash with the next visitation of cold air. For instance, if the moisture is transported inland by the south wind at a rate of 10 miles per hour, it is evident that about 24 hours would be required to transport the first traces of moisture 240 miles inland, or about as far as Waco.

During the winter, the time required for the north wind to become southerly and transport moisture inland is all too often more time than migrations of cool air are willing to wait. Therein lies an important reason for the low precipitation period in the interior of Texas during late autumn, winter, and early spring. The "northers" are too frequent. The moisture just hasn't had time to be transported inland by the south wind. The coastal areas receive considerable precipitation during the winter, but little finds its way inland. Refer to the Upper Coast (UC) curve in Figure 4.

Upper Coast and Trans-Pecos

The second climatic pattern depicted in Figure 4 is the summer maximum distribution of precipitation illustrated by the Upper Coast (UC) and Trans-Pecos (TP) curves. At first it may seem odd that these two areas, so widely separated geographically and physiographically, should have such similar monthly precipitation distribution curves. But when the causes are examined it becomes apparent that the biggest percentage of precipitation occurring in both areas is due to convective shower and thundershower activity. Potentially unstable air is required to produce convective and air mass thunderstorms.

Unstable air is air out of stratum. It can be defined as lightweight warm air surrounded by or below denser cold air; or, air being heated from below, i.e., cold air passing over a warm surface. The cold dense air wedges in, or settles, forcing the lightweight warm air upward. If the level of free convection is reached and the light air contains moisture, clouds will condense out as the moist air continues to rise freely, expand, and cool as atmospheric pressure decreases. Showers or thunderstorms can result. When warmer air forced upward reaches that level above the earth's surface known as the level of free convection, it will then rise freely until it is cooled by expansion to become about the same temperature as the surrounding air in its new environment. The air then becomes stable again. What starts the potentially unstable air on its way up. The answer is the key to why the Upper Coast and the Trans-Pecos areas can have about the same climatic precipitation patterns.

The Upper Coast

When a potentially unstable air mass occupies the upper Texas coast, latent dynamic forces usually are also present and must manifest themselves if showers are to occur. Acting alone or jointly, these forces eventually will propel the warm, moist air upward to a level where it can ascend freely, expand, cool, and produce showers. Two important dynamic forces which can propel air upward are heat and convergence.

The heat process concerns the fact that land surfaces respond to heat much more rapidly than do water surfaces. Therefore, due only to the rising and setting of the sun, the relative temperature between the Gulf of Mexico water surface and the Upper Coast land surface will reverse to become warm water-cool land at night and cool water-warm land during the day. This will cause a wind shift to become land breeze at night and sea-breeze during the day. A further result is likely to be the forcing aloft of the warm air over waters adjacent to the coast at night as the cooler air is carried out over the water by the land breeze and wedges underneath the warm air. As the land surface radiates heat at night and becomes relatively cooler and cooler, the breeze from land toward water intensifies and forces the warm air aloft over the water at a faster rate. At night when the relative temperatures between the Upper Coast and adjacent Gulf waters are the greatest, thunderstorms can be seen occurring out over the water where the warm air is being forced upward.

After night passes and the sun rises in the morning, the land surface begins to heat up, relative temperatures between land and water begin to equalize, and the wind ceases to blow toward the water. Thunderstorms that have been active over the water at night may now drift over the coast and cause showers until the sun is well up. They do not usually reach maturity, however, until afternoon and after they are carried inland by the sea breeze. The sea breeze has intensified in the meantime due to continued heating of the land by the high sun, causing rising air currents inland. The high sun heats the land more and more as the day progresses, allowing the moist sea breeze air to replace the rising air inland. The tables are now reversed. The Gulf, via its sea breeze, is now supplying relatively cool air to the now warm interior land surface. The cool sea breeze forces the inland warm air aloft at an ever increasing rate. The potentially unstable air is thus forced aloft where it becomes absolutely unstable and continues to rise without further impetus from below. Air mass thunderstorms thus result inland along the Upper Coast due to the heat process.

The convergence process achieves the same end as the heat process, but when this happens, a greater areal expanse of the earth's surface usually receives rain. The convergence process of lifting the air results when waves form aloft in the easterlies (the easterly trade winds of the low latitudes), and when troughs form aloft in the westerlies (the prevailing westerly winds of the mid-latitudes). Both phenomena occur aloft. A wave in the easterlies, commonly called an easterly wave, is an elongated low-pressure trough aloft which forms in the easterly trade winds when the Bermuda high pressure cell is well developed in the Caribbean Sea, as happens in the July-September period.

Easterly waves sometime move on to the Texas coast and travel from the east toward the west at an average rate of about five degrees longitude per 24 hours. The westerly trough is analogous to the easterly wave in that it, too, is an elongated area of low pressure aloft. Westerly troughs form in the prevailing westerly winds and move from the west toward the east.

Low pressure areas in the atmosphere are to the surrounding air as valleys are to mountains. That is, the surrounding air spirals inward toward the low pressure centers and converges much the same as mountain freshets flow into valleys and converge to form rivers. When low level air currents converge in low pressure areas, the result is that the air is forced upward. The air currents cannot go downward into the ground, nor can they advance horizontally against higher atmospheric pressures. They take the course of least resistance, upward. The upward rising air is cooled by expansion and its moisture condenses in the form of clouds and rain. The rainy area sometimes will be as large as the low pressure area. It also moves, causing more widely distributed precipitation than is caused by air mass and orographic thunderstorms which are relatively stationary. The State's most beneficial and widespread precipitation and also some of its worst floods occur as a result of activity when a westerly trough merges with an easterly wave that has moved inland from the Gulf. Easterly waves and westerly troughs meet and merge most commonly along the upper Texas coast in September (Orton, 1964).

Trans-Pecos

Thundershower activity in the Trans-Pecos is the primary contributor of precipitation during the late summer and early autumn months, just as thundershowers provide the upper Texas coast with the greatest monthly percentage of precipitation during the same months. But the reasons for the thundershower activity differ in the two areas. Heat and convergence are the two main forces activating potentially unstable air and causing shower-like rain over the Upper Coast during these months. In the Trans-Pecos, however, both convergence and heat are usually secondary to orography as a lifting and activating agent for the air. The mountains stand ready continuously to deflect any southeasterly winds and their moisture load upward to an altitude high enough to produce sufficient expansion and resultant cooling necessary to form the clouds which produce showers. Indeed, this deflecting action of the mountains is so efficient that, when conditions are otherwise favorable, hail with crop-damaging potential is formed and falls out as the thunderstorms drift away from the mountains and out over the plateaus and valleys where crops are planted.

With an annual rainfall average of only about 12 inches in the Trans-Pecos there is often insufficient rainfall to support dry-land farming. Hence, the Trans-Pecos is necessarily an area of very large stock ranches and smaller irrigated farms. Any significant loss of peak rainfalls during the July-September period could constitute a substantial contribution to the beginning or continuation of drought. Loss of these peak rains is often caused either by unfavorable positioning of the Atlantic or Bermuda high pressure cells, resulting in a low moisture content in the winds arriving by a circuitous route from the Gulf of Mexico; or, by the Pacific Ocean air being forced to pile up the

South and cross the mountains in Mexico--bringing to the Trans-Pecos only west or southwest winds which had their moisture condensed out as they crossed the higher mountains to the west. The latter is often attributed to unfavorable positioning of the Pacific Ocean high pressure cell; i.e., the cell is too far south for the season.

East Texas

The third climatic pattern depicted by the curves on Figure 4 is "summer drought," a characteristic of East Texas (ET) weather. While the East Texas area strictly includes all Texas lands lying north of the coastal strip and east of about the 96th meridian, the portion of East Texas most often affected by summer droughts is the northern three-fourths of the area (see Figure 7). The principle causes of the summer drought in northeast Texas are: (1) the moist and dry tongues of air aloft (see Figure 6) which spiral inward and subside, causing horizontal divergence in the lower levels; and (2) the characteristic failure of cool Canadian air masses to migrate that far south during the summer to wedge the warm air aloft and trigger the precipitation mechanism.

One abnormal climatologic occurrence which would have deleterious effects on East Texas would be the loss in April and May of the generous rainfalls which occur there during these months and again in November and December. These are the two peak rainfall periods before and after the summer-drought months. The loss of peak rainfalls during these months could result in a year-long drought--not merely a summer drought.

The most widespread and lengthy precipitation periods in East Texas during the spring and autumn occur either when cold air from the north moves very slowly through the area, forcing the warmer resident air aloft, or when the leading edges of the cold air masses advance part-way through East Texas and then stop. These remain stationary as a barrier, wedging the impinging warm moist air from the south upward and causing continuous precipitation throughout the area. The dense cold-air barrier forces the overriding moist Gulf air to be deflected upward where it cools and condenses, causing precipitation just as effectively as the Trans-Pecos mountain barrier deflects impinging air aloft and causes rain or thunderstorms there. If the wintertime movements of cold air through East Texas are too rapid, or if the cold-air outbreaks are too frequent and none stop during the season, then East Texas is likely to experience less rain or poorly distributed rain that year.

PRECIPITATION AND TEMPERATURE

For the 30-year period 1931-60, annual temperature and rainfall figures were taken from records published by the U.S. Weather Bureau, the International Boundary and Water Commission, Texas Agricultural Experiment Stations, and from other miscellaneous records on file in the Texas Water Development Board. Additional 30-year average annual rainfall and temperature values were obtained by weighting or adjusting combinations of the foregoing. All 30-year averages thus obtained were then plotted on two U.S. Geological Survey Southwest River Basin base maps.

Isograms were drawn on one map depicting one-degree variations in average annual mean free-air temperature (Figure 8). On the other map, isograms were

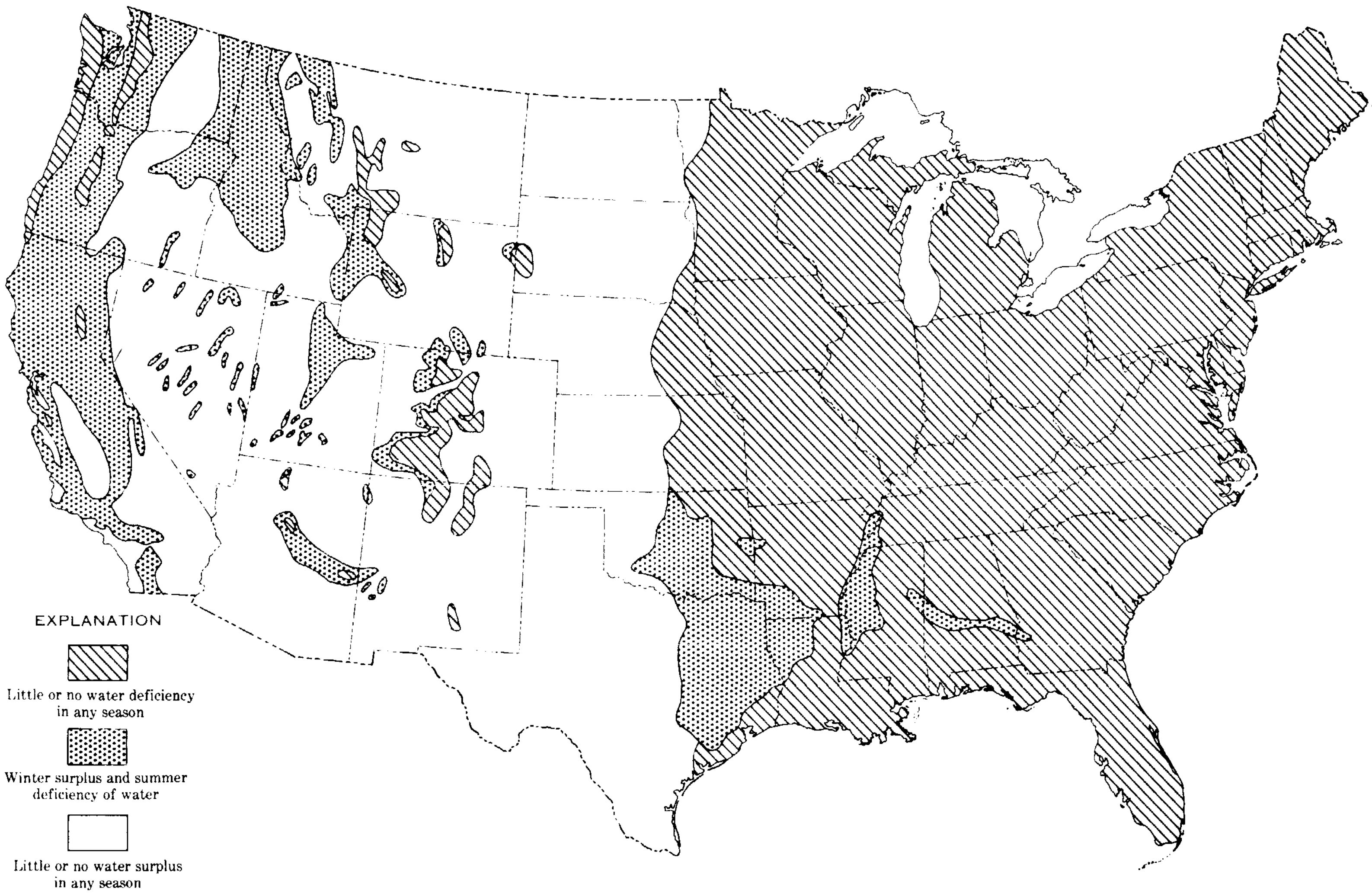


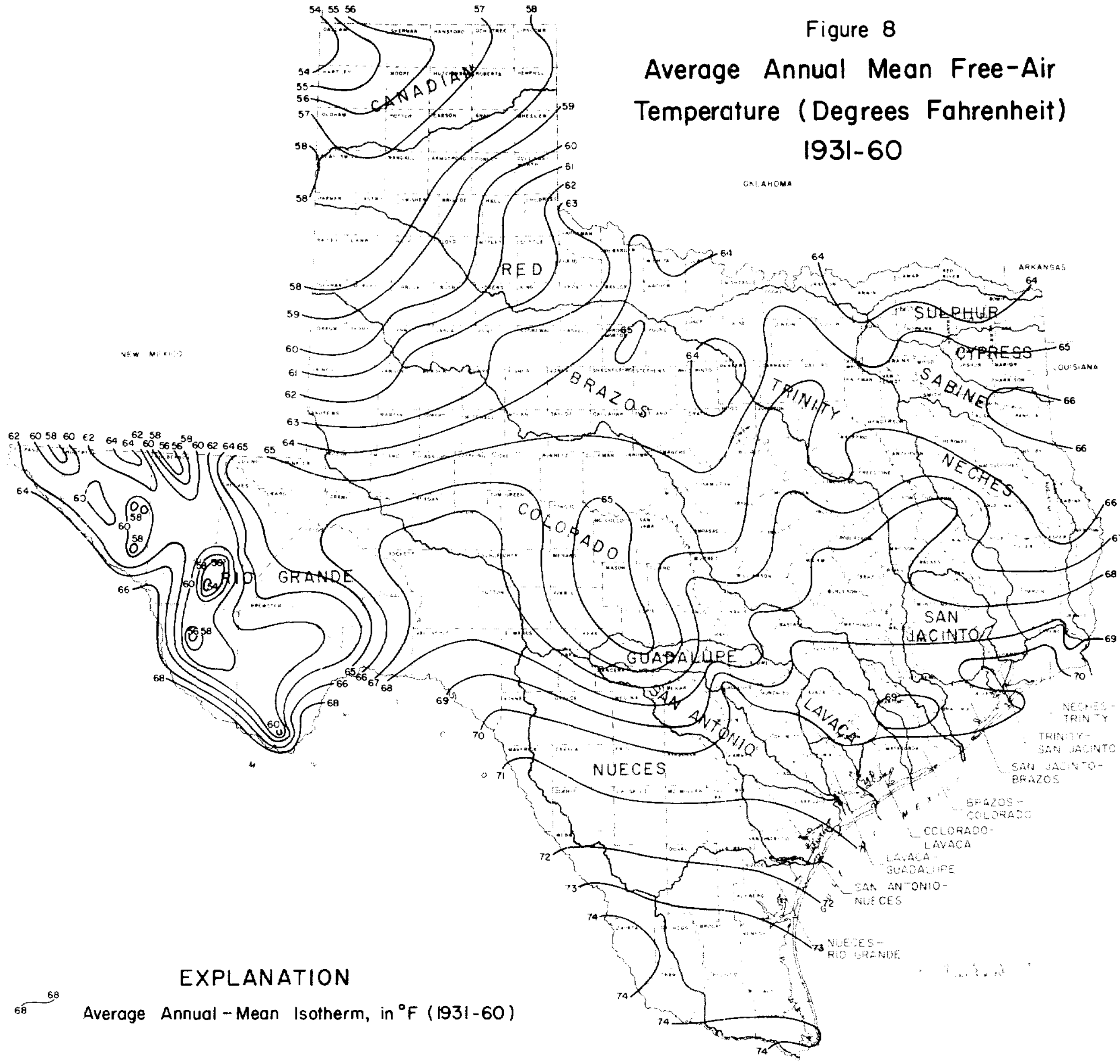
Figure 7

Areas of Dry and Moist Climate in the United States, Excluding Alaska and Hawaii

(Adopted from Thornthwaite, 1948; reproduced here from Thomas, 1962, p. A-4.)

Figure 8

Average Annual Mean Free-Air Temperature (Degrees Fahrenheit) 1931-60



EXPLANATION

68 Average Annual-Mean Isotherm, in °F (1931-60)

drawn depicting two-inch variations in the depth of average annual rainfall. The U.S. Weather Bureau state climatologists for New Mexico, Oklahoma, and Arkansas supplied maps with isograms depicting the average annual rainfall and temperature which occurred in their respective states during the period 1931-60. Isograms crossing Texas' borders were matched to those of the same value on the maps furnished by climatologists in the adjacent states.

After the maps were constructed, it was found that in Texas the rainfall and the temperature isograms were strongly influenced by topography. So much so that in many cases individual physiographic provinces and subdivisions were made easily discernible by the isogram patterns when isograms were drawn to fit the plotted data. The odd configuration of some of the isograms can be explained satisfactorily only when topography is considered.

Ideally, temperature and rainfall reporting stations would have to be checkered about every 10 miles or so throughout Texas, if near accuracy is isogrammatic depiction of these weather elements were a necessity. The impracticability of such a network of reporting stations is obvious. In lieu of such ideal spacing of reporting stations, however, the influence of topography and physiographic features in Texas should be professionally interpreted when average annual rainfall and average annual mean temperature isograms are drawn.

HYETOGRAPHY

It often has been said that the underground water table is just a subdued expression of the topography. Likewise, it logically can be said that an isogrammatic depiction of the rainfall is an accented expression of the topography, so strongly does topography influence rainfall. When a mountain range or prominent fault zone is provided with a moisture-laden prevailing wind, isograms depicting the increase in rainfall with altitude are much the same as stair-steps up a mountain slope. Each time the moisture-laden air is cooled about 10° as it rises up the slope, its capability to hold water vapor is about halved. Assuming a reasonable temperature reduction of 4°F per 1000 feet, it is clear that for every 2500 feet the air is forced upward its ability to hold moisture vapor is reduced by about 50 percent. The water vapor must condense and form clouds as the air cools. Continued cooling (further ascent of the air) will force the clouds to release moisture in the form of precipitation. When mountainous areas and sparse weather data coverage are encountered at the same time, isograms can be logically more closely spaced on the prevailing wind side of the mountains. To do so more accurately depicts the heavier rainfall zone on the windward side of the mountains. As any plateau above is traversed by the then drier air, little or no increase in rainfall occurs and the isograms may be more widely spaced.

Balcones Escarpment and Adjacent Topography

Upon examination of the average annual rainfall chart (Figure 2) it can be seen that near the Red River the 34-inch isogram quite closely follows, almost delineates, the Balcones Escarpment about as far south as San Marcos. The packing of isograms in the vicinity of the 34-inch rainfall line illustrates the physical concept of rapid increases in average annual rainfall as the topography rises. In like fashion, the 32-inch rainfall isogram alternately marks the eastern and then the western limits of the Palo Pinto country, the Comanche

Plateau, the Lampasas Cut Plain, the Llano District, and the Edwards Plateau. It passes onto the Coastal Plain east of San Antonio where it takes its orderly place among the other isograms which are increasing in numerical value toward the east and decreasing in numerical value toward the west. The 26-inch rainfall isogram quite clearly delineates the beginning of the second major rise in the terrain west of the Texas Gulf Coast. About a four-inch difference in average annual rainfall occurs within the narrow margin of this second rise. Immediately west of the 28-inch rainfall isogram (in north-central Texas), the plains of the Osage Section of the Central Lowland Province can be easily located by examining the isogram spacing. The lowlands along the Colorado River in central Texas, the ending of the Llano District, and the beginning of the Edwards Plateau proper in Bandera and Medina counties can just as easily be located in the same manner.

The Tropical Storms Effect

Along the upper Texas coast, from about the mouth of the Colorado River northeastward to the Louisiana border, an erratic isohyetal pattern due to the influence of tropical hurricanes is apparent. This is especially apparent in the vicinity of Galveston. Because hurricanes become extra-tropical and lose intensity rapidly after moving inland, the isograms on the average annual rainfall map show orderly decreases westward from Houston until the influence of the Balcones Escarpment is encountered. The flat to gently rolling terrain of the plateaus above the escarpment contributes little additional reason for the air to further rise, cool, and release moisture. The isohyets are then more evenly spaced and show an orderly decrease in numberical value.

Latitudinal Gradient Along the Texas Coast

In Figure 2, it is apparent that the average annual precipitation increases as latitude increases northward along the Texas coast from Brownsville to about Port Arthur (except for the hurricane influence near Galveston). Because the terrain along the entire Texas Gulf Coast is relatively flat and only a few feet elevation above mean sea level, one must look for causes other than abrupt changes in elevation to fine acceptable meterological explanations for this latitudinal increase in annual rainfall. A partial explanation lies in examination of the monthly humidity and rainfall data for the two cities--Brownsville, in the Lower Rio Grande Valley, and Port Arthur on the Upper Coast. Relevant water vapor data are listed in Table 3.

An enlightening discussion of all known precipitation factors bearing on this latitudinal increase in rainfall is beyond the scope of this report. Two important points will be partially explained here, however. These are the two common expressions of water vapor in the air--dew point and relative humidity. The temperature of the air plays a major role in the determination of both. To a great extent, the temperature of the air controls the maximum amount of moisture the air could contain in vapor form.

The dew point is a good expression of the quantity of water vapor that actually is in the air. The relative humidity is a good expression of how much water vapor the air actually contains compared to how much it could contain under ideal conditions. Relative humidity is expressed in percent. If the relative humidity is 80 percent, this means the air actually contains 80

Table 3.--Expressions of water vapor at Brownsville and Port Arthur, Texas

[Average monthly temperature ($\overline{T_t}$), average monthly dew point ($\overline{T_d}$), the temperature-dew point spread ($\overline{T_t} - \overline{T_d}$), and average monthly relative humidity ($\overline{RH}$). Calculations based on U.S. Weather Bureau data and charts.]

Month	Brownsville				Port Arthur			
	$\overline{T_t}$ (°F)	$\overline{T_d}$ (°F)	$\overline{T_t} - \overline{T_d}$ (°F)	$\overline{RH}$ (Percent)	$\overline{T_t}$ (°F)	$\overline{T_d}$ (°F)	$\overline{T_t} - \overline{T_d}$ (°F)	$\overline{RH}$ (Percent)
January	61	52	9	71	53	47	6	79
February	64	53	11	69	56	49	7	76
March	68	58	10	70	61	53	8	76
April	74	62	12	66	68	59	9	73
May	79	68	11	68	75	66	9	73
June	83	72	11	69	81	71	10	71
July	84	72	12	66	82	73	9	74
August	84	73	11	68	82	74	8	76
September	81	71	10	71	78	69	9	76
October	76	65	11	68	70	61	9	72
November	68	57	11	68	59	53	6	81
December	63	53	10	71	54	47	7	77

percent of the moisture it could contain under ideal conditions. with meteorological parameters other than temperature held constant.

Dew point, on the other hand, is expressed in degrees of temperature. Theoretically at least, if the air temperatue is cooled to the temperature of the dew point the invisible water vapor in the air will condense and become visible in the form of fog, clouds, or precipitation. The temperature-dew point "spread," i.e., the difference in degrees between the temperature and the dew point, denotes how much cooling the air must undergo at the same pressure before the dew point will be reached. Quite obviously, if both Brownsville and Port Arthur have nearly the same dew point, but the spread is greater at one city than at the other, for condensation to occur the city having the greater spread will have to experience more cooling than the city having the lesser spread.

From a cause and effect standpoint, a look first at dew point and relative humidity as effects may lay the groundwork for better understanding of how these expressions are causal factors for precipitation. We know that moisture is in the air along the Texas coast simply becuase the air first passed over the Gulf of Mexico and absorbed evaporated vapors from the water. The temperature of the air, the temperature of the water, the atmospheric pressure, the length of time the air stays over the water, and the path over the water taken by the air, all play major roles in determining the amount of water vapor the air will contain when it reaches the Texas coast. After the moisture gets in the air, what happens to convert the moisture into precipitation is another story.

The major precipitation producing mechanisms along the Texas Coast are (1) fronts, (2) troughs in the westerly winds, (3) waves in the easterly winds, (4) wave action along fronts, (5) tropical storms, and (6) thunderstorms. All of these dynamic mechanisms lift and cool the air to produce precipitation. All have their favored season.

Listed below are five reasons (other than terrain variations) for less rainfall at Brownsville than at Port Arthur:

1. Month-for-month the amount of cooling required to produce precipitation (the temperature-dew point spread) is less at Port Arthur than at Brownsville. Precipitation-producing mechanisms operating with the same efficacy will usually cause more rain at Port Arthur than at Brownsville, even though both cities are under the same influence (as with an <u>easterly wave or westerly trough</u>);

2. Many precipitation producing mechanisms moving down from the north (such as cold fronts) will pass and affect Port Arthur but will stall and never reach Brownsville;

3. Many warm fronts moving toward the north will start their northward movement (or form initially) from a point north of Brownsville but south of Port Arthur, thereby affecting Port Arthur but not Brownsville;

4. Many cold fronts will move to a point south of Port Arthur and a wave will form along them just offshore near Corpus Christi. The wave will induce counter-clockwise winds which produce off-continent (dry) west or northerly winds along the coast south of Corpus Christi. On-continent (moist) southerly winds will occur to the north of Corpus Christi; and,

5. Brownsville is closer to the Mexican Plateau; therefore, much of the time when winds arrive at Brownsville from the west they are not only dry but also have been heated by compression as they descended from the plateau. This causes a wider temperature-dew point spread and lower relative humidity.

Trans-Pecos Mountain Effects

The isohyetal pattern of the Stockton Plateau shows clear indications of an influx of dry Mexican air and a change in the direction of the prevailing wind to more southerly--not directly from the Gulf of Mexico. The drying influence of the Mexican air is also evident in the isohyetal pattern throughout the extent of the Pecos Valley within Texas and southern New Mexico. West of the Stockton Plateau and the Pecos Valley, the Mexican Highland and Sacramento sections of the Basin and Range physiographic province clearly reflect the increased rainfall produced by upslope cooling along the slopes and atop the mountains. Particularly in these mountainous regions of the Mexican Highlands one is made keenly aware of the accented expression of the topography depicted by rainfall isograms.

Plains Effect

The extremely falt terrain of the Llano Estacado extension of the High Plains can be easily picked out by noting the orderly decrease in average annual rainfall from east to west, as the distance from the Gulf moisture source increases. The Break of the Plains delineates the easterly erosion area. With this rather abrupt change in topography, the resultant rainfall produces a packing of the isohyets which is evident along the Great Plains-Central Lowland province border where the Break of the Plains is quite pronounced. Even the High Plains Section, north of the Canadian River and the Pala Duro Canyon, exert, topographic influences on the rainfall. The approximate locations of these features can be picked out by the isogram pattern they produce.

CHARACTERISTIC ANNUAL MEAN TEMPERATURE

Temperature isogram spacing and orientation varies directly as topography varies (other factors being equal) and the isograms in mountainous regions can be drawn with a relatively high degree of confidence even though reporting stations are far apart. This is possible because the temperature is known to change with altitude at a dry adiabatic rate of about 1°C per 100 meters. In mountainous regions such as the Trans-Pecos, which are relatively free of moderating maritime influences, temperature variations are principally attributable to changes in elevation. Except for the influence of transitory weather systems and possible moderating effects of very large bodies of water, 1°C isograms depicting changes in temperature might very well be drawn in mountainous regions as 100-meter elevation contours--the colder ones high and the warmer ones low.

East and South of the Balcones Escarpment

The West Gulf Coast Section of the Coastal Plain physiographic province encompasses all the lands in Texas lying east and south of the Balcones Escarpment. With a few exceptions east and south of the escarpment, normal northerly decreasing latitudinal changes in average temperatures occur and are illustrated by the east-west oriented isograms extending from extreme south Texas to extreme north central Texas.

Western Plateaus

As was the case with rainfall, very few (but progressive and orderly) changes in average annual-mean temperature occur in the plateau regions. The Palo Pinto country, Lampasas Cut Plain, lowlands along the Colorado, and the Edwards and Llano Plateau all clearly illustrate isogram orderliness. Locations of these regions are made apparent by the isogram spacing and configurations on the temperature map. As the terrain west of the Balcones Escarpment gradually rises (about 1500 feet) the isograms of average annual mean temperature align parallel to the escarpment and pack accordingly.

The Great Plains

The Great Plains physiographic province, strictly speaking, includes some of the plateau areas adjacent to and just west of the Balcones Escarpment. The Great Plains province in Texas, however, is generally thought of as including the High Plains, the Llano Estacado extension, and the Edwards Plateau. The High Plains and the Llano Estacado extension are divided by the Canadian River and the Palo Duro Canyon. The eastern border of the Great Plains province in the Texas High Plains generally forms the north-south oriented western border of the Osage Section of the Central Lowlands province. As would be expected in the plains, the isograms depicting temperature changes are quasi-latitudinally oriented and rather evenly spaced. These isograms decrease in magnitude northwestward to the Canadian River-Palo Duro Creek eroded area. There they again characteristically resemble contours of topography. The 58° and 61° average annual mean temperature isograms appear to closely follow portions of the eastern border of the Break in the Plains. Except for the scarcity of reporting stations along the Break in the Plains region, the relationship of these isograms to the Break in the Plains might be more apparent.

West of the Pecos River

Nowhere else in Texas is to be found a better illustration that the average annual mean temperature decreases adiabatically with altitude than in the mountains of the Basin and Range province west of the Pecos River. Without the knowledge that temperature does in fact decrease at a known rate as altitude increases, the analyst would be unable to draw temperature isograms in this extremely mountainous region where reporting stations are widely scattered. When examining the temperature map, care should be taken when interpolating average annual mean temperature values in this mountainous region. All of the temperature isograms shown on the map in the Trans-Pecos region are not based entirely on the adiabatic lapse rate. Sufficient long-record temperature reporting stations are located in the area to show clearly that wide differences of average annual mean temperature do occur in relatively short distances. For example, the Balmorhea Experimental Pan Station on the 31st parallel reliably indicates an average annual mean temperature value of about 65°F, while only a short distance to the southwest (and considerably higher) the station at Mount Locke shows a value of about 57°. Marfa, directly south a few miles, shows about 61°F. Only a few miles east, at Alpine, about 64°F is indicated.

Obviously, the one-degree isograms on the map must be packed closely when drawn between Balmorhea and Mount Locke. Presidio, a scant 60 miles south of Marfa, historically reflecting the hottest temperatures in Texas and often in the nation, has a long-time average annual mean temperature of about 70°; but just north of the 2600-foot high city of Presidio is the 7730-foot high Chinati Peak. Within this 25 or 30 miles there is a difference of about 5000 feet in elevation, which, if such refinement is necessary, must be accounted for with average annual mean temperature lines. At a dry adiabatic cooling rate of 1°C per 100 meters, this means a temperature difference of about 26°F--26 one-degree isograms--if adiabatic cooling alone is to account for the total temperature difference. Air trajectory, passing weather systems, the Gulf of Mexico, and many other forces, however, combine to influence both the long-time averages and the instantaneous temperature values.

CONCLUSIONS

The influence of topography on climatic elements is very strong, but topography alone does not explain all rainfall and temperature variations in Texas. The influence of tropical hurricanes on rainfall, apart entirely from topography, is clearly evident along the upper Texas coast. The decrease in rainfall resulting from a moisture-bearing wind trajectory over the dry land in Mexico is apparent in the Stockton Plateau and Pecos Valley. The influence of topography on rainfall and temperature in Texas is strong enough to force isograms, when drawn on precipitation and temperature maps, to conform in configuration with physiographic features to the extent that these features are sometimes apparent from the isogram patterns they produce.

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