TEXAS WATER DEVELOPMENT BOARD

REPORT 111

AN INVESTIGATION OF CLOUDS AND PRECIPITATION FOR THE TEXAS HIGH PLAINS

By

Donald R. Haragan

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FOREWORD

The Texas Water Development Board has interests in the field of weather modification which derive both from its statutory responsibility for administering the Weather Modification Act of 1967, and from its primary function of planning for an adequate water supply for the entire state. Because of these interests, the Board encourages and provides financial support when possible to basic research in this field.

In planning any attempt to modify the weather through cloud seeding, a knowledge of the statistical distribution both in space and time of suitable cloud types is important. This Report provides such information for the High Plains of Texas.

This report is being published by the Texas Water Development Board because it represents an original contribution to climatology, and as such it will be of interest not only to the scientific community but to all citizens having an interest in the climatology of the Texas High Plains.

Texas Water Development Board

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ABSTRACT

A study of the relationship among cloudiness, precipitable water vapor, water vapor flux, stability and precipitation is presented for the Texas High Plains. A cloud census, based on data from three first-order United States Weather Bureau stations, gives the annual and diurnal variations of cloud types and amounts in the area. The census reveals that the most common cloud types are altocumulus and cirrus. Total cloud cover is greatest during winter and least during the fall. A study of clouds during periods of above normal rainfall indicates that precipitation during late fall and winter is associated with stratiform clouds which develop in conjunction with cyclonic activity. Spring and summer precipitation is most highly correlated with cumuliform clouds characteristic of convective activity. As expected, periods of above normal precipitation in the plains area are associated with above normal cloud amounts, while dry periods are generally lacking in clouds. An exception is summer cumulus which occurs with surprising regularity during both dry and wet periods.

Investigation of other macro-scale atmospheric features indicates that wet periods are further characterized by atmospheric instability and above normal values of precipitable water vapor and water vapor transport. Dry periods are associated with atmospheric circulation patterns which either serve to cut off the supply of low-level moisture, produce subsidence and consequent atmospheric stability, or both. These conditions, which are unfavorable for the formation of precipitating clouds, often lead to extended periods with very few clouds. The success of attempts at artificial precipitation production would depend in these cases upon the initiation of cloud development. Occasionally, however, sufficient clouds are present during dry periods in conjunction with adequate supplies of precipitable water and the absence of upper level stability. It is these situations which may hold promise for artificial cloud modification experiments.

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I. INTRODUCTION

The problem of providing an adequate water supply in the Texas plains emphasizes the importance of a more comprehensive knowledge of clouds and precipitation characteristic of this area. Ground water is being depleted at an alarming rate. The low water table has brought about the realization that other water sources must be found and utilized.

The Texas Water Development Board (1968) has published a water plan for Texas suggesting that surface water from adjacent areas be pumped in to alleviate the water shortage problems in West Texas. It is certain that the implementation of this program must overcome many engineering, political, and financial obstacles. At the present, however, it appears to be a feasible approach to a problem that is fast becoming acute.

It is obvious that a much cheaper and more direct approach would be to tap the water resources of the atmosphere. The problem here is that cloud modification techniques are not sufficiently reliable, and there is no assurance that this reliability will increase significantly before the ground water supply in many areas has been largely depleted.

Nevertheless, it is imperative that large-scale studies be initiated in an attempt to better understand the distribution of precipitation in space and time and its causes. The economic future of the Texas plains is dependent to a large extent on the solution of hydrologic problems related to the occurrence of precipitation. The design of hydrologic structures is also dependent on this type of information.

The present investigation has been initiated as part of a general program to obtain greater understanding and knowledge of the precipitation process and its behavior in the Texas plains. In particular, the objectives are as follows:

1. to investigate the distribution of cloud types and amounts in the area and to relate these to precipitation.
2. to study in detail characteristically dry and characteristically wet months in an attempt to explain some of the factors which control the amount of clouds and/or precipitation.
3. to investigate in particular, dry period cloudiness and the potential of artificial modification techniques during such periods.

It is generally recognized that one is not able to produce general rain in the midst of a meteorological drought. In many instances there are no clouds present on which to focus our modification efforts. The question is not "How suitable is a typical drought day for cloud seeding", but "How frequently during an extended drought do seeding opportunities present themselves?" It may be that several periods during a typical drought are suitable for cloud seeding when the natural precipitation mechanism almost reaches the stage of rain but does not quite get there. Then the aim becomes to relieve the intensity of the drought condition rather than actually to "break the drought".

It is not the purpose of this research to evaluate cloud seeding techniques themselves, but rather to investigate the natural occurrences of clouds and precipitation in an effort to determine if modification efforts are feasible, especially during dry periods.

Section II, which follows, is devoted to a 10-year cloud census investigation of the Texas High Plains. Since different types of clouds react in different ways to cloud seeding attempts, any progress in the field of cloud modification is dependent upon the types of clouds characteristic of the area. It has been demonstrated that the seeding of warm active cumulus clouds, for example, may result in rain, whereas the same type of seeding when applied to warm layer clouds and small inactive cumuli often leads to dissipation (Carr, 1965). The internal structure of supercooled clouds, those containing liquid water droplets at temperatures below freezing, are almost invariably modified to some extent when artificial freezing nuclei or dry ice are introduced into them.

Section III is a discussion of the relationship of clouds and precipitation observed in the plains area. The natural occurrence of precipitation is described as it relates to synoptic precipitation-producing systems. Cloud occurrences during periods of excessive precipitation are described. In addition, a rank correlation study between cloud type and precipitation amount is presented.

Section IV describes some characteristically dry and wet monthly periods in the plains. Comparisons of cloud types and amounts are included along with a discussion of precipitable water, water vapor flux and atmospheric disturbances as they relate to precipitation.

Section V is an investigation of dry periods. A dry period is defined for this study as a period of at least five days duration during which no more than a trace of precipitation is recorded within a 60 mile radius of the primary station. The two primary stations used for this study are Amarillo and Midland. Once again the macro-scale features of particular interest are cloudiness, precipitable water, water vapor flux, and stability.

Section VI is a summary of results and some comments regarding the potential for artificial cloud modification in the Texas High Plains. Conditions believed necessary for successful seeding operations from a physical point of view are discussed.

II. THE CLOUD CENSUS

The cloud census is based on ten years (1952-1961) of three-hourly cloud data from Amarillo (AMA), Lubbock (LBB), and Midland (MAF). The locations of these stations are shown in Figure 1. The selection of this particular ten-year period was based on its inclusion of periods of both above and below-normal precipitation for the area. This is illustrated in Figure 2 which shows yearly departures from the 40-year (1926-1965) average precipitation as a function of time. Note that the period from 1952 to 1956 was relatively dry, while precipitation during the latter five years was, for the most part, well above normal. A brief climatic summary for each of the stations is given in Appendix I. The results of the cloud census for Amarillo and Lubbock are based on the entire ten-year period. Cloud <u>type</u> observations were not made at Midland during 1952 and 1953, thus the results for this station are based on only eight years of data (1954-1961). Cloud amounts for Midland are based on the entire ten-year period.

A. Definition of Cloud Types

From the macrophysical point of view, a cloud is the result of cooling moist air to a temperature below its dewpoint. In the atmosphere, this cooling is almost always brought about by lifting of the air, which cools during expansion as the pressure falls. A comparison of the temperature lapse rate in cloud-forming ascent with the temperature structure of the environment determines whether or not the ascending mass will be buoyant.

During buoyant ascent, when the surrounding temperature is lower than the cloudy updraft, upward acceleration is enhanced, thus favoring the formation of clouds with large vertical extent. The term "penetrative convection" is used to convey the idea that a small volume of cloud air penetrates vertically through a region of relatively stable air. Clouds formed in this manner are called <u>cumulus</u> clouds. In some cases only small cumulus clouds form. As the clouds grow to higher altitudes, clear, dry air mixes into the clouds and causes them to be chilled by evaporation of the cloud droplets. When this occurs, the cloud stops growing and evaporates. Small cumulus clouds normally last only about five to fifteen minutes (Mason, 1957). On the other hand, if the atmosphere is very moist and unstable, the rising air may be accelerated as it moves to higher altitudes. Updrafts exceeding

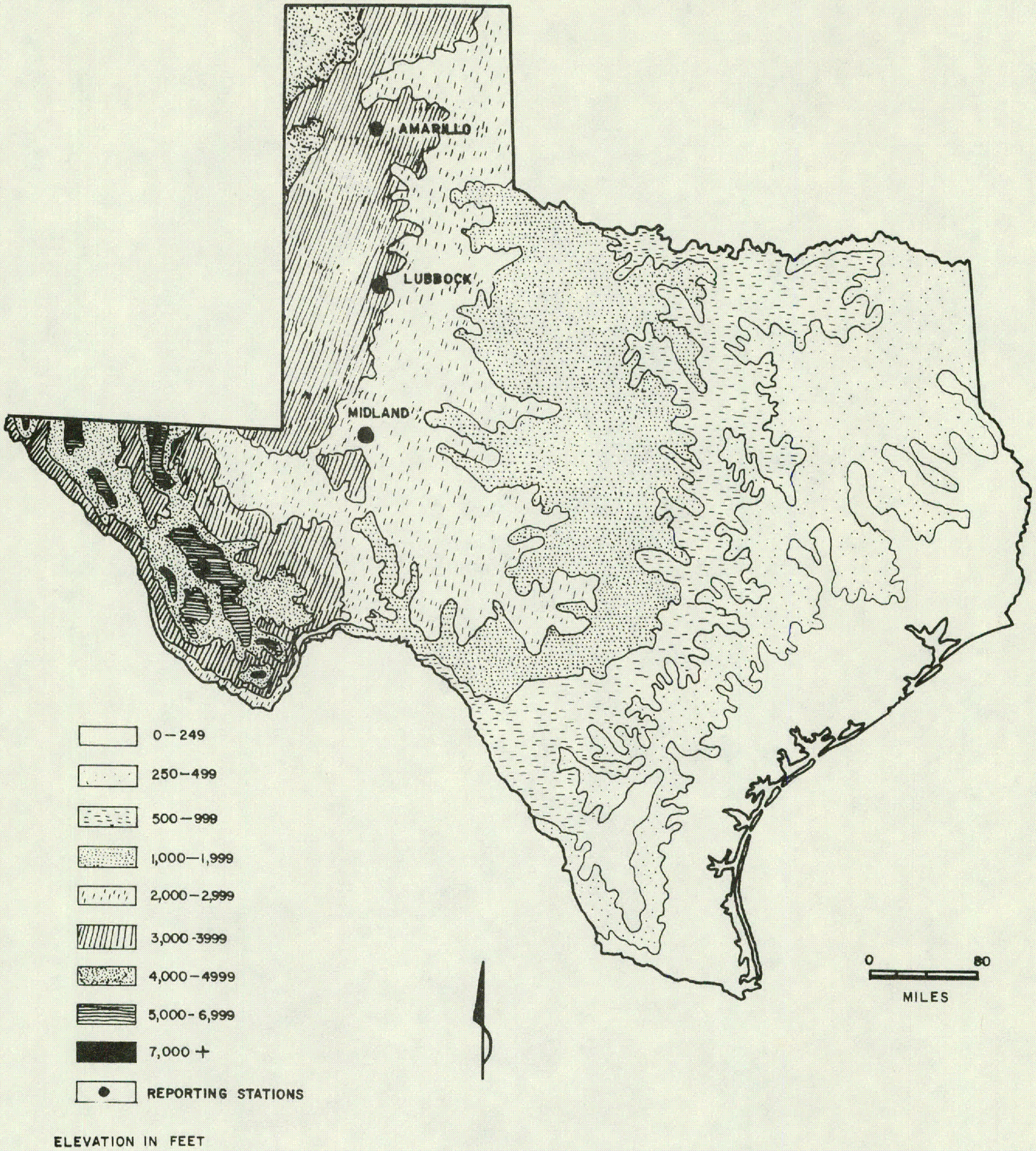


Fig. 1 Station Locations

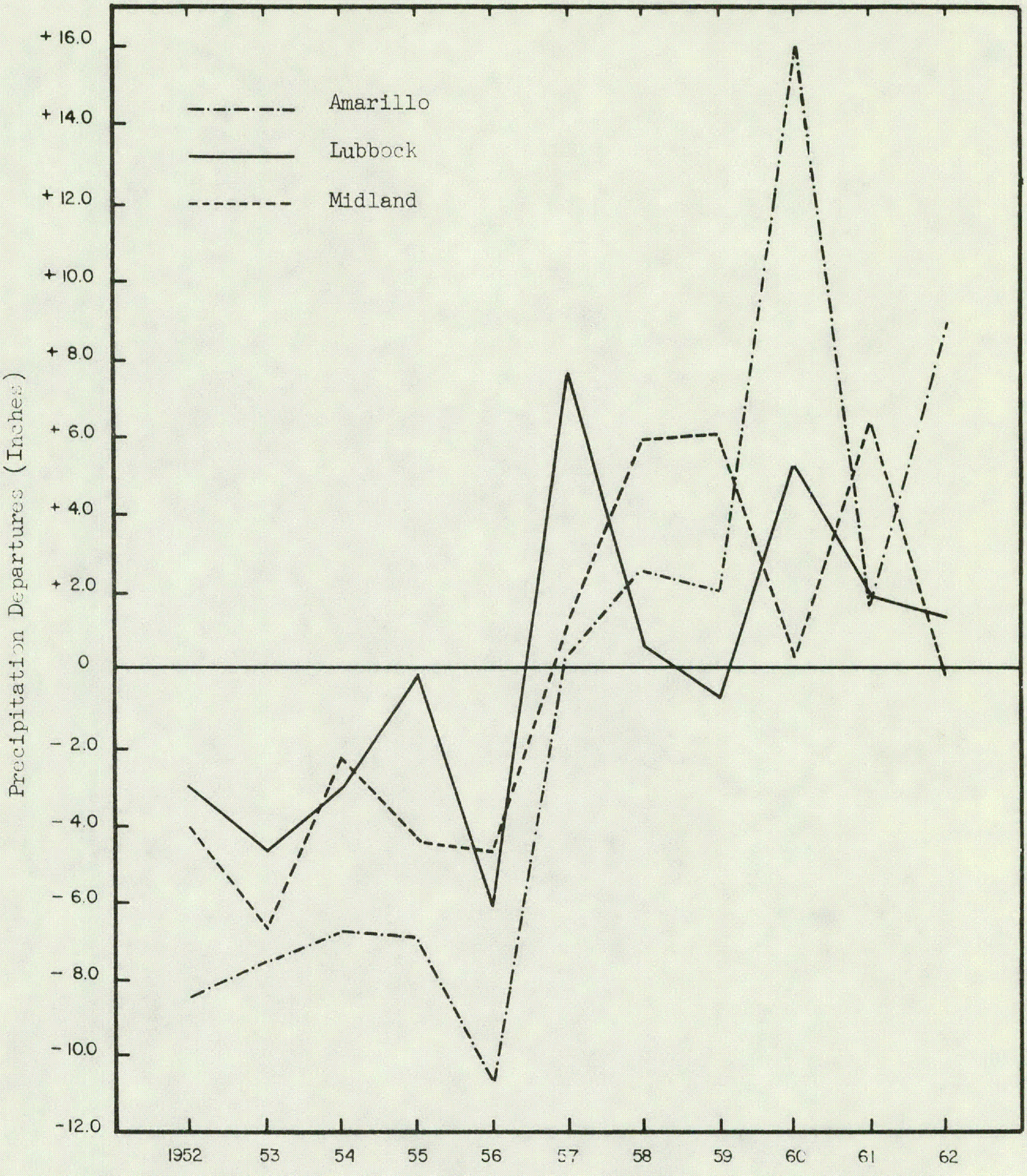


Fig. 2 Annual Precipitation Departures from Normal (1926-1965)

two meters per second can develop. The cloud can grow into the stratosphere to altitudes of more than 18 km. Clouds which develop in this manner are called cumulonimbus clouds and often produce torrential rains, hail, lightning and thunder. Since the lower part of the stratosphere is composed of very stable air, it acts as a deterrent to further cloud growth. It often causes the cloud tops to spread out and leads to the development of anvil clouds.

Despite the release of latent heat of condensation, it is possible for temperature to decrease upward more quickly in a cloudy updraft than in the surrounding clear air. Under such circumstances, a cloud should not grow or even persist. Nevertheless, cloud growth often occurs because other factors, mainly large-scale mass flow toward a cyclone center, will force the ascent of air by horizontal convergence (Willet, 1944). Such forced ascent leads to the formation of cloud sheets spread over a large area horizontally compared to their depth. These clouds, which appear as thin stratified layers are called stratus.

Although stratus and cumulus are the basic cloud forms, there is an infinite variety of cloud patterns which renders complete cloud classification difficult. Nevertheless, different observers can usually agree on some outstanding features of clouds. A cloud composed entirely of ice crystals is called a cirrus. Cirrus clouds form at high altitudes and generally have a hairlike and silken appearance.

When cirrus are so abundant as to fuse into a layer, it is called cirrostratus. A low-level cloud which is broken up into a wavy pattern is called stratocumulus, unless it is higher, delicate and associated with cirrus, when it is cirrocumulus. Similar clouds at intermediate levels (2 km to 6 km) are called altocumulus and a stratified layer of cloud at these levels is altostratus. Finally, a dark widespread layer from which prolonged rain or snow falls is a nimbostratus.

Fifteen cloud types are reported routinely by each of the first-order Weather Bureau stations. These are fog, stratus, stratocumulus, cumulus, cumulonimbus, fractostratus, cirrus, cirrocumulus, cirrostratus, altocumulus, fractocumulus, altostratus, nimbostratus, altocumulus castellatus, and cumulonimbus mammatus. A brief description of each of these clouds is given in Appendix II. These definitions are taken from the International Cloud Atlas (World Meteorological Organization, 1956).

After considering the frequency of occurrence of each type of cloud, it was decided to combine some of the types, which occur infrequently, with similar forms. For this reason, nimbostratus has been included with altostratus, cirrocumulus with cirrostratus, fractostratus with stratus, fractocumulus with cumulus, and cumulonimbus mammatus with cumulonimbus.

B. Data and Data Limitations

The cloud data were acquired on IBM punched cards from the National Weather Records Center, Ashville, North Carolina. More than 87,000 cards containing three-hourly cloud data were processed during this investigation.

The data include the number of cloud layers, the cloud types in each layer, cloud type amounts in each layer and the total sky cover. Detailed instructions for making and recording these observations are given in WBAN Circular N (Anon, 1956).

From one to four layers of clouds and obscuring phenomena can be recorded at each observation. The clouds whose bases are at approximately the same level are regarded as a single layer. The layer may be continuous or composed of detached elements. It is not necessary that there be space between layers or that the clouds composing each layer be of the same type. Cumuliform clouds may develop vertically such that they extend both below and above other cloud layers. Also, horizontal development may cause swelling cumulus or cumulonimbus to form stratocumulus, altocumulus, or cirrus clouds. When clouds are formed in this manner and attached to a parent cloud, they are regarded as a separate layer only if their bases appear horizontal and at a different level from the parent cloud.

Cloud amounts are reported in terms of fractional portions of the sky that is covered by the cloud. Amounts are reported for each of the four layers as well as for the sky as a whole. The total of the layer amounts does not necessarily equal the total sky cover since the layers may overlap. Thus, the cloud amount in each layer is independent of the other layers.

Cloud types are reported for each of the layers. If more than one type appears in a layer, only the predominating type is reported. This can be very misleading for two reasons. First, some clouds may be present and are not reported. Secondly, the predominant type is assigned the total amount of sky coverage of all types in the layer. As an example, 0.2 altostratus and

0.4 altocumulus is reported as 0.6 altocumulus. In some instances the most significant, rather than the predominant, cloud type is reported. Thus, cumulonimbus may be reported even though another type of less significance may be predominant. This recording procedure makes it extremely difficult to determine the true individual cloud frequencies or amounts. Only the frequency with which a cloud type is a predominating type in its layer can be determined. In addition to these data limitations, there are several others worth noting (Changnon, 1957; DesJardins, 1958; Sellers, 1958):

1. Cloud identification at night: It is obvious that visual cloud observations are severely limited by darkness. In many instances, cloud types and amounts at upper levels may be difficult to detect and thus go unreported. Cirriform clouds are especially difficult to detect at night, even when they are the only cloud type present. A sharp rise in the frequency of occurrence of cirrus in the early morning may be due simply to the fact that the sun has risen and observation is possible. A study by Braham (1955) in Arizona indicates the number of reports of cirriform clouds increased directly with the lunar altitude. Cloud amounts in all layers are subject to error under conditions of darkness.
2. Obscuration by lower layers: In some instances, low-level clouds may serve to obscure clouds at upper levels. Smoke and haze also contribute to the obscuration problem. This probably causes middle and high clouds to be underestimated.
3. Observer error: Even though the observations are made by trained observers, there is an error introduced in the recording of types by different observers. A particular cloud type may have a variable appearance and may be difficult to differentiate from another type under certain conditions.

All of these limitations should be kept in mind when reviewing the results of this census.

No attempt has been made to differentiate between the four layers reported. A particular cloud type is recorded and tabulated without regard to the layer in which it occurred. Once a cloud type has been recorded at a particular observation time, it will not be counted again, even though it may be reported at more than one level. Thus no cloud may occur with a frequency greater than one at a particular observation time. Central Standard Time is used throughout this report. Detailed tabulations of the cloud census are included in a recent report by this author (Haragan, 1969).

C. Analysis of Total Cloud Amount

Figure 3 illustrates the annual variation in mean monthly cloud cover. The values were obtained by averaging each of the eight daily observations for a one-month period; thus, each point in the figure represents approximately 240 single observations.

Generally, cloud cover has a maximum in the winter, decreasing to a sharp minimum in September at each of the three stations. During most of the year, the cloud cover at Amarillo is greater than that at either of the other stations. During the late winter and spring this difference is accounted for primarily by stratus in association with frontal passages and overrunning patterns set up by stationary fronts south of the station. Many late winter fronts which affect the Amarillo area dissipate or become stationary soon thereafter and have little or no effect on stations farther south. The summer difference is accounted for by cumulonimbus in association with more intense convective activity at Amarillo.

In each case, the maximum winter cloudiness is due to frontal activity. Since cloudiness is not widespread in time with the passage of an individual front, cloud types such as stratus, altostratus and nimbostratus are not dominant on the average. Nevertheless, when they do occur with the passage of a front, they tend to be dominant in the sky for several days at a time. Figures 4, 5 and 6 are representations of clear and overcast sky frequency as a function of the time of year and the time of day. The contours in these figures represent the total number of clear or overcast sky observations for the entire data sample. Thus, Figures 4 and 5 are based on a 10-year period, while Figure 6 is based on only eight years. As an example in interpreting the charts consider that the maximum number of clear sky observations which could be made during January at 1800 LST is 310 for Amarillo and Lubbock. The number actually reported in this case for Amarillo was between 100 and 120. Note that the maximum number of clear sky observations occurs in the fall.

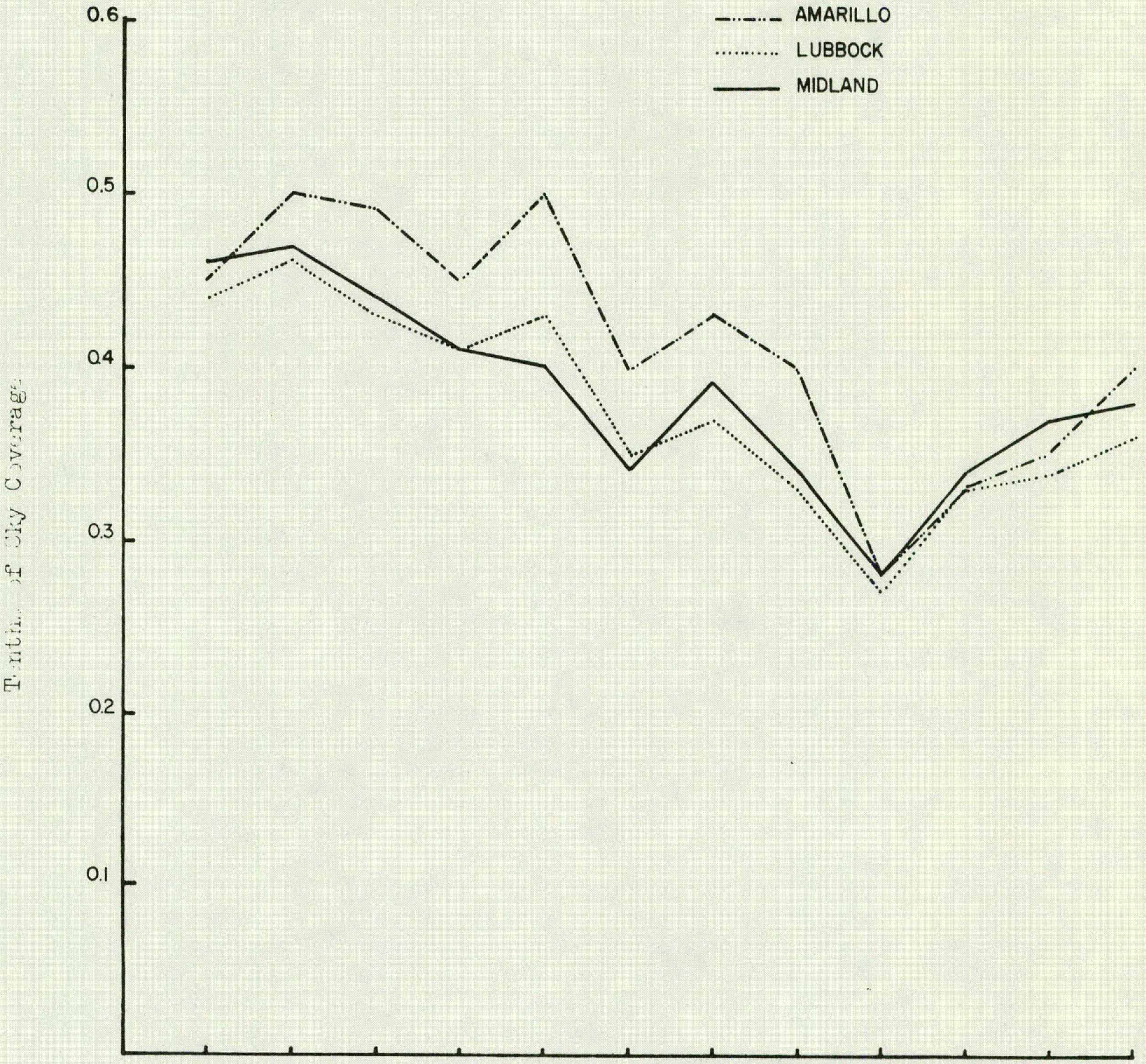


Fig. 3 Annual Variation in Total Cloud Amount

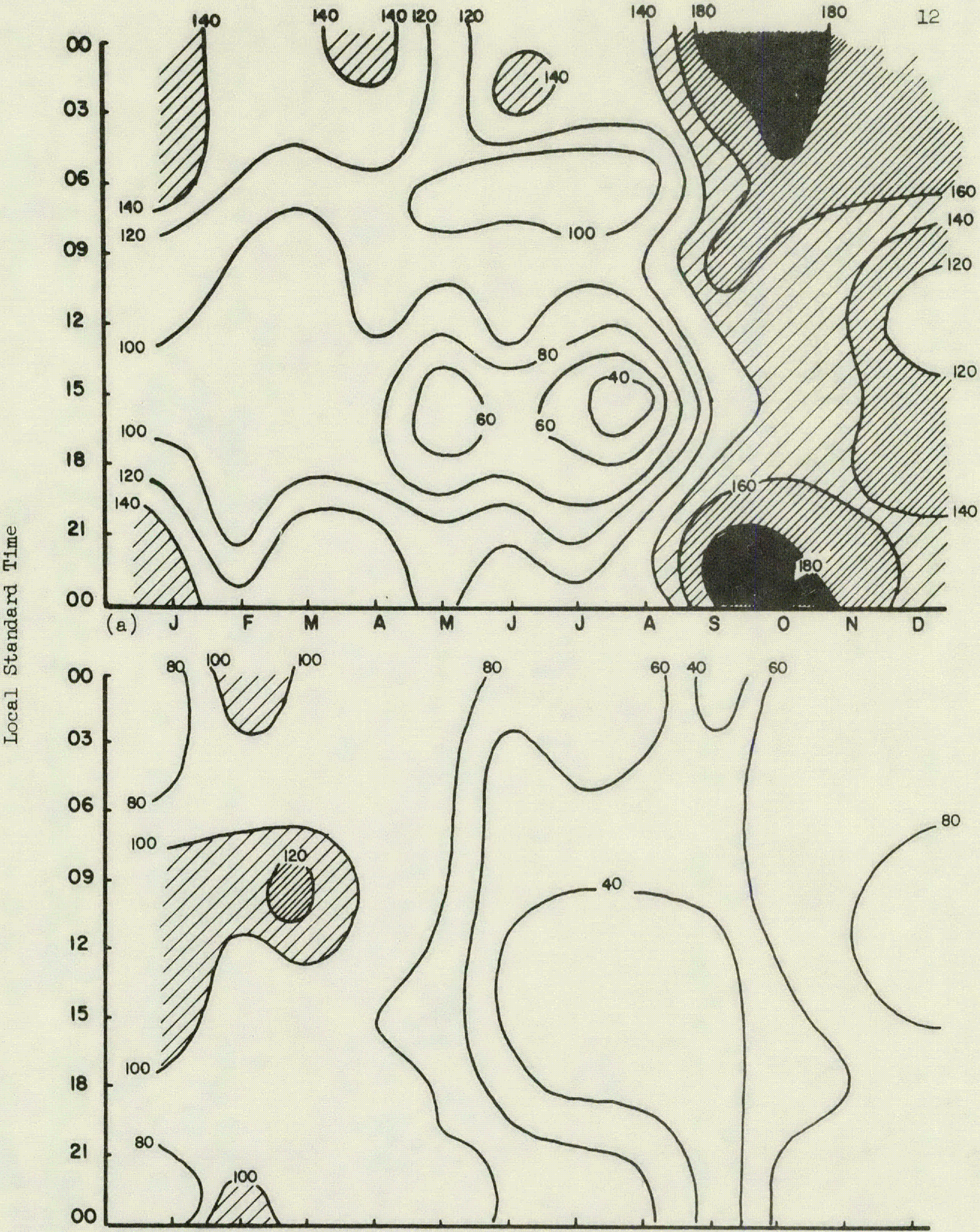


Fig. 4 Frequency of Occurrence of (a) Clear and (b) Overcast Skies
Amarillo 1952-1961

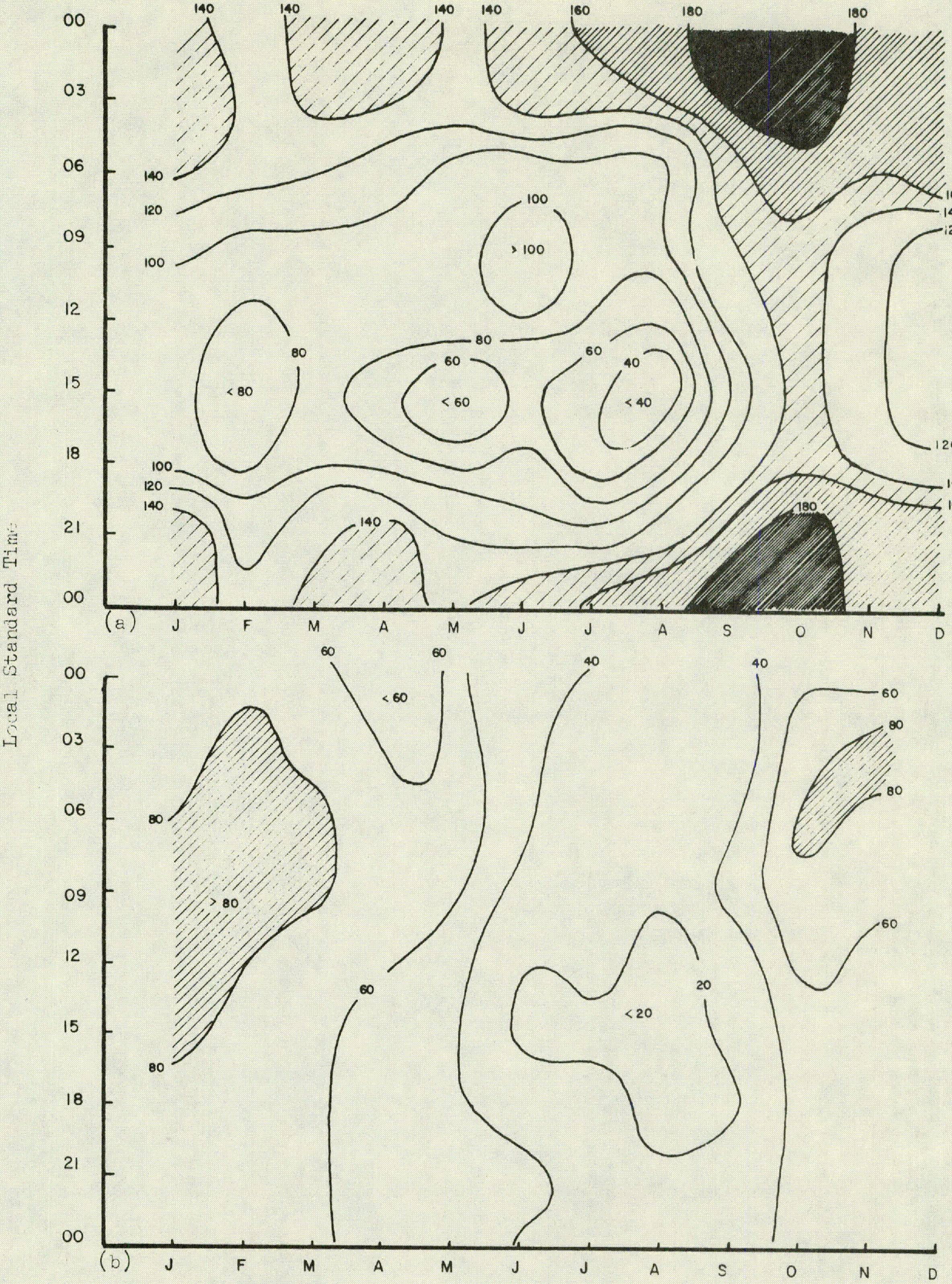


Fig. 5 Frequency of Occurrence of (a) Clear and (b) Overcast Skies
Lubbock 1952-1961

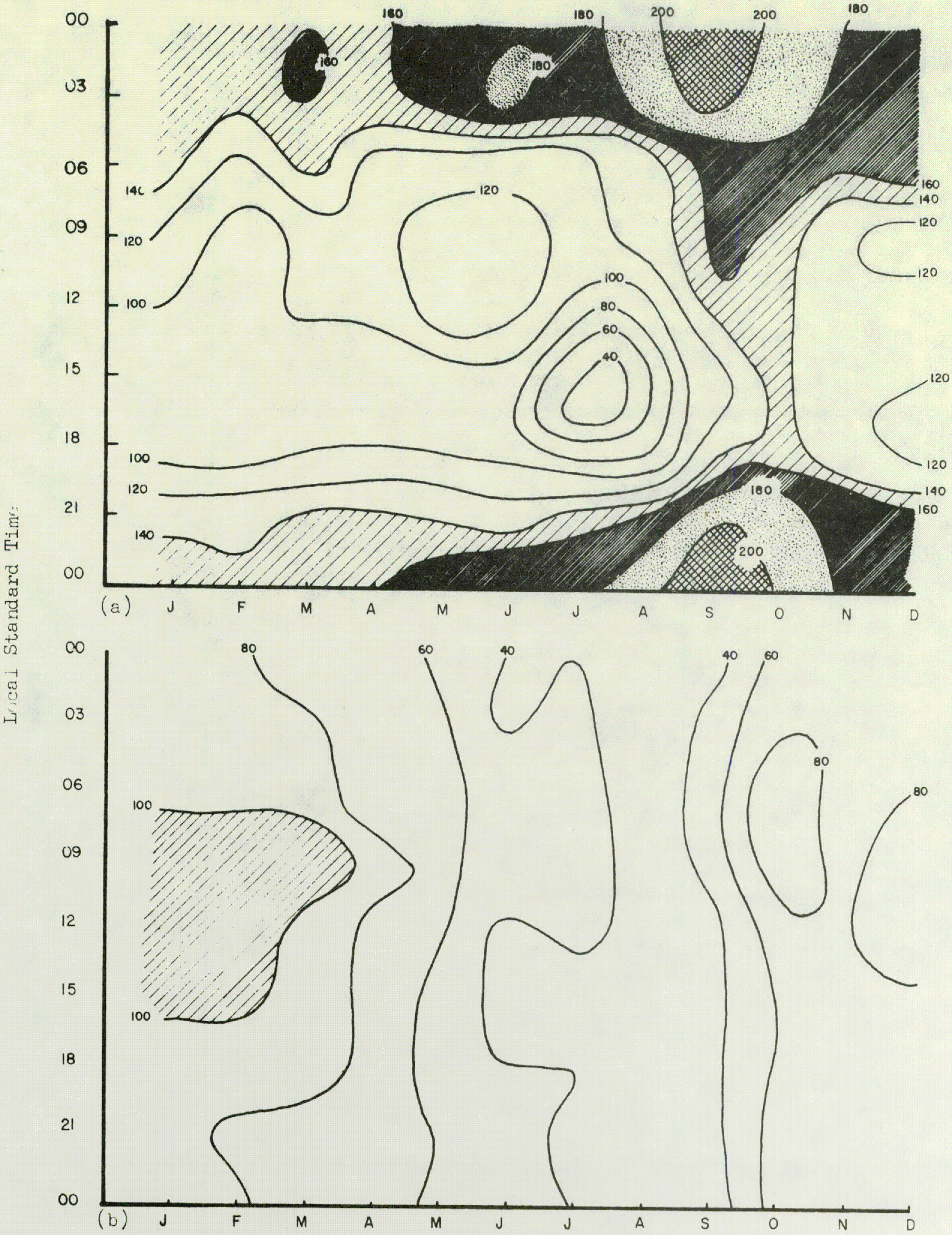


Fig. 6 Frequency of Occurrence of (a) Clear and (b) Overcast Skies

Midland 1954-1961

This reflects the winter maximum and fall minimum in sky cover shown in Figure 3.

Spring is a transition season which includes clouds due to late winter frontal activity in addition to clouds due to convective activity which is being inititated during this season. The secondary maximum in May, shown in Figure 3, is mainly a result of violent convective activity in association with squall lines characteristic of this time of year (Staley, 1959). Summer sky cover is almost entirely due to convective activity. It is the season with the minimum number of both clear and overcast skies; the frequency of cumulus and cumulonimbus clouds is quite high during the summer, but rarely do they cover the entire sky.

The highest frequency of clear skies occurs at each of the stations during the fall. This is a season of transition between the summer convective activity and the frontal disturbances which dominate cloud production during the winter. Clouds which do occur are generally stratocumulus formed by the merging of slightly developed cumulus clouds, sometimes in association with weak frontal passages of stratus or altostratus clouds resulting from warm moist maritime tropical air from the Gulf of Mexico overrunning cooler continental air at the ground. In the late fall, the cold air often invades the plains region so repeatedly that there is little opportunity for return flow of Gulf moisture; these frontal systems are usually called "dry northers". Even under these conditions, however, clouds may form by upslope motion in the cold air.

Average diurnal variations in cloud amount for the ten-year period are shown for each month of the year at each station in Figures 7a and 7b. Note that January, February, March, and April are all characterized by broad daytime maxima and nighttime minima in cloud cover. The amplitude of the curves is probably magnified somewhat by the difficulty in observing high clouds during darkness. During February, March and April, the cloud cover at Amarillo is greater than at Lubbock or Midland. This is accounted for in large part by a higher frequency of occurrence for early morning stratus resulting from nighttime cooling of moist air. The higher moisture content at Amarillo is also responsible for the higher incidence of afternoon convective activity which is reflected in the curves. This peak is noted to a lesser extent at

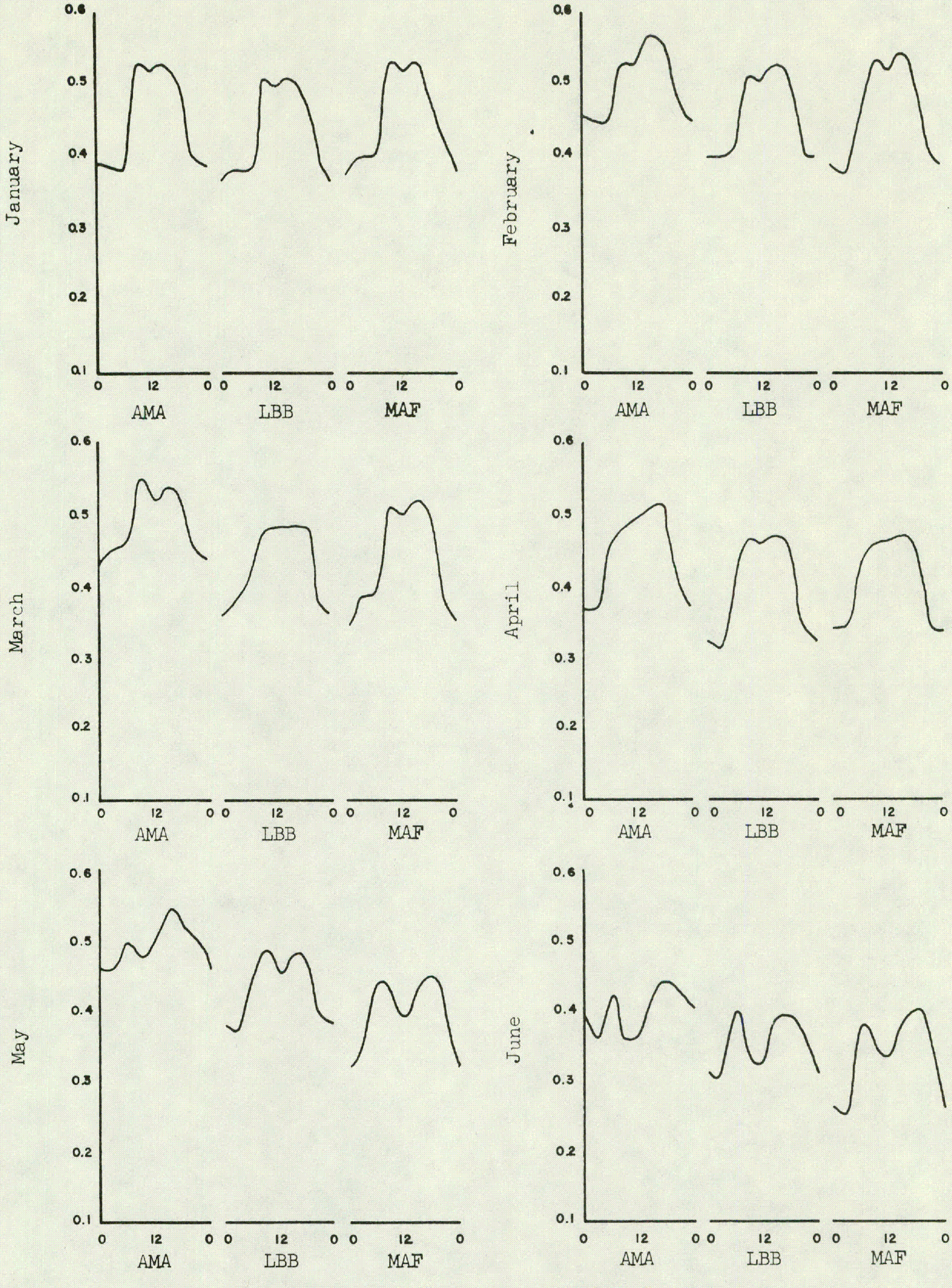


Fig. 7a Diurnal Variation of Total Cloud Amount

Ordinate is Average Cloud Cover in Tenths

Abcissa is Time in Hours

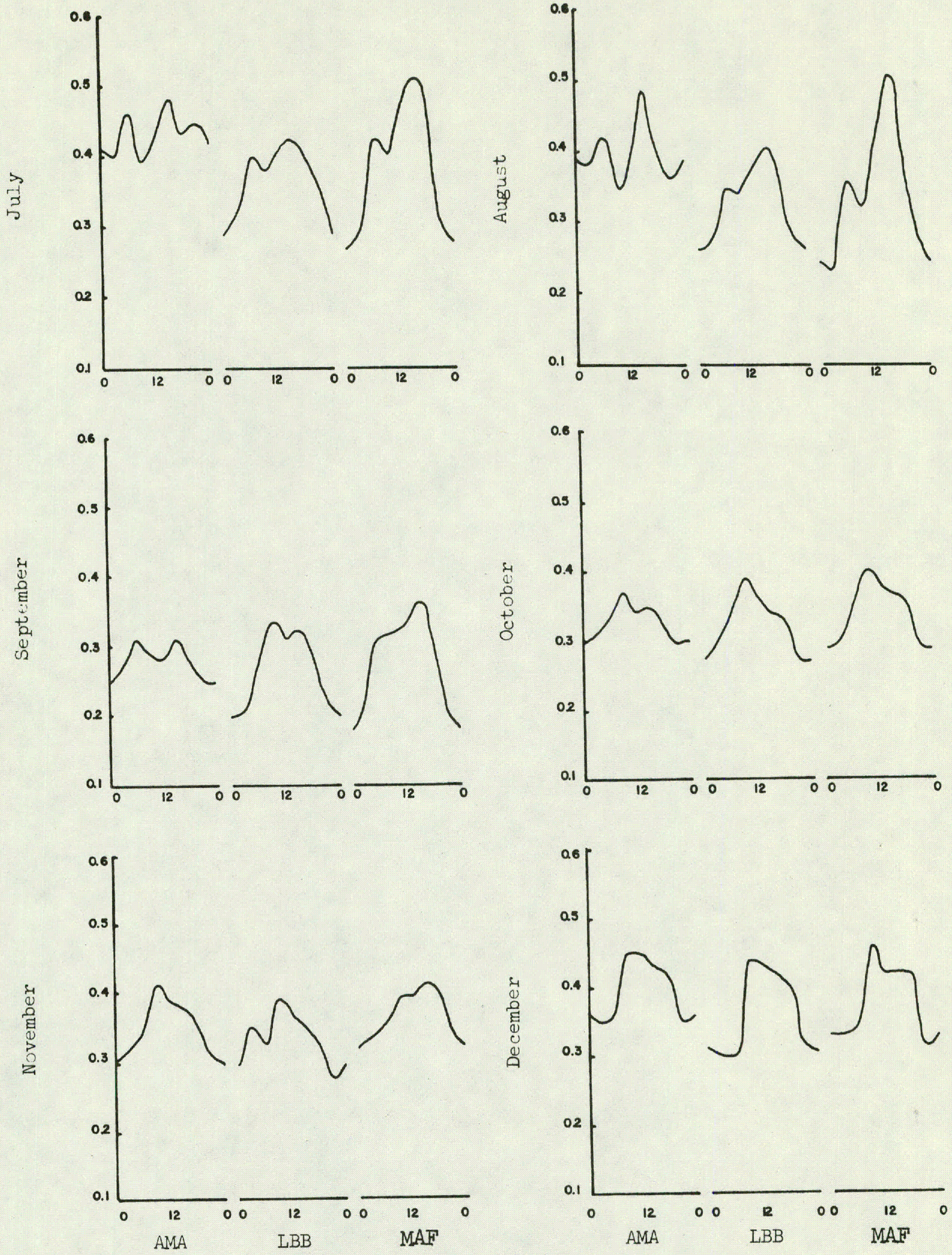


Fig. 7b Diurnal Variation of Total Cloud Amount

Ordinate is Average Cloud Cover in Tenths

Abcissa is Time in Hours

the other stations and becomes pronounced at all three stations during the late spring and summer.

During April, May and June, there is a continuous decrease in cloud cover toward the south. The distributions are becoming definitely bi-modal with peaks in the early morning and mid-afternoon. The higher cloud amounts at Amarillo are accounted for primarily by stratiform clouds at all levels. This is probably due to the higher frequency of cyclonic activity in the northern portions of the study area during the spring months.

The first striking difference among the three stations occurs in July. The diurnal range in sky coverage at Amarillo is quite small compared to the other stations. This reduced amplitude at Amarillo is also characteristic to a somewhat lesser degree of August and September. The difference is accounted for by a higher occurrence of early morning cloudiness associated with greater amounts of moisture at Amarillo.

The greatest diurnal range for the months of June through September is found at Midland. During July, August and September, Midland has the highest mean cloud cover in the afternoon and the lowest at night. In October, the curves for the three stations begin to look more alike. The range at Amarillo is still somewhat smaller, however, and the maximum afternoon cloud cover increases from north to south.

Other changes can be noted in November, when the amplitude of the Amarillo curve becomes comparable to that at the other stations. A single mid-morning peak is apparent at Amarillo, while at Midland the primary peak is in the mid-afternoon. The Lubbock curve shows the mid-morning peak that is present at Amarillo in addition to a secondary peak during the early morning hours.

Cloud cover increases at all stations in December with Midland exhibiting a mid-morning peak which was characteristic of Amarillo and Lubbock during November. Further discussion of the diurnal variation of different cloud types is contained in the following section.

D. Analysis of Cloud Types

Figures 8a and 8b illustrate the mean monthly frequency of occurrence for the different cloud types at each of the three stations. The frequencies were computed by adding the number of times a particular cloud type was reported

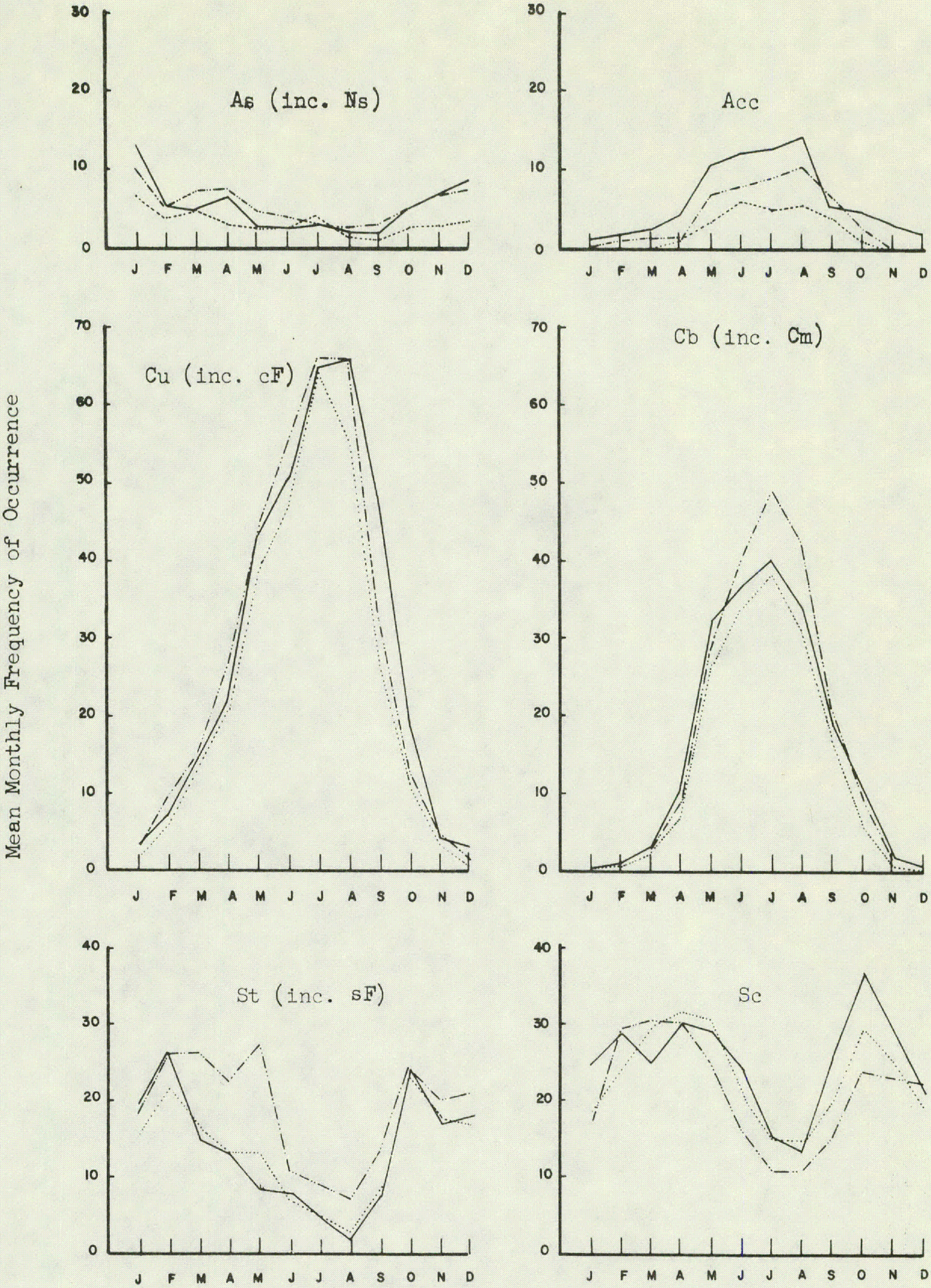


Fig. 8a Annual Variation of Cloud Types

Amarillo - .. - Lubbock ---- Midland ——

1952-1961

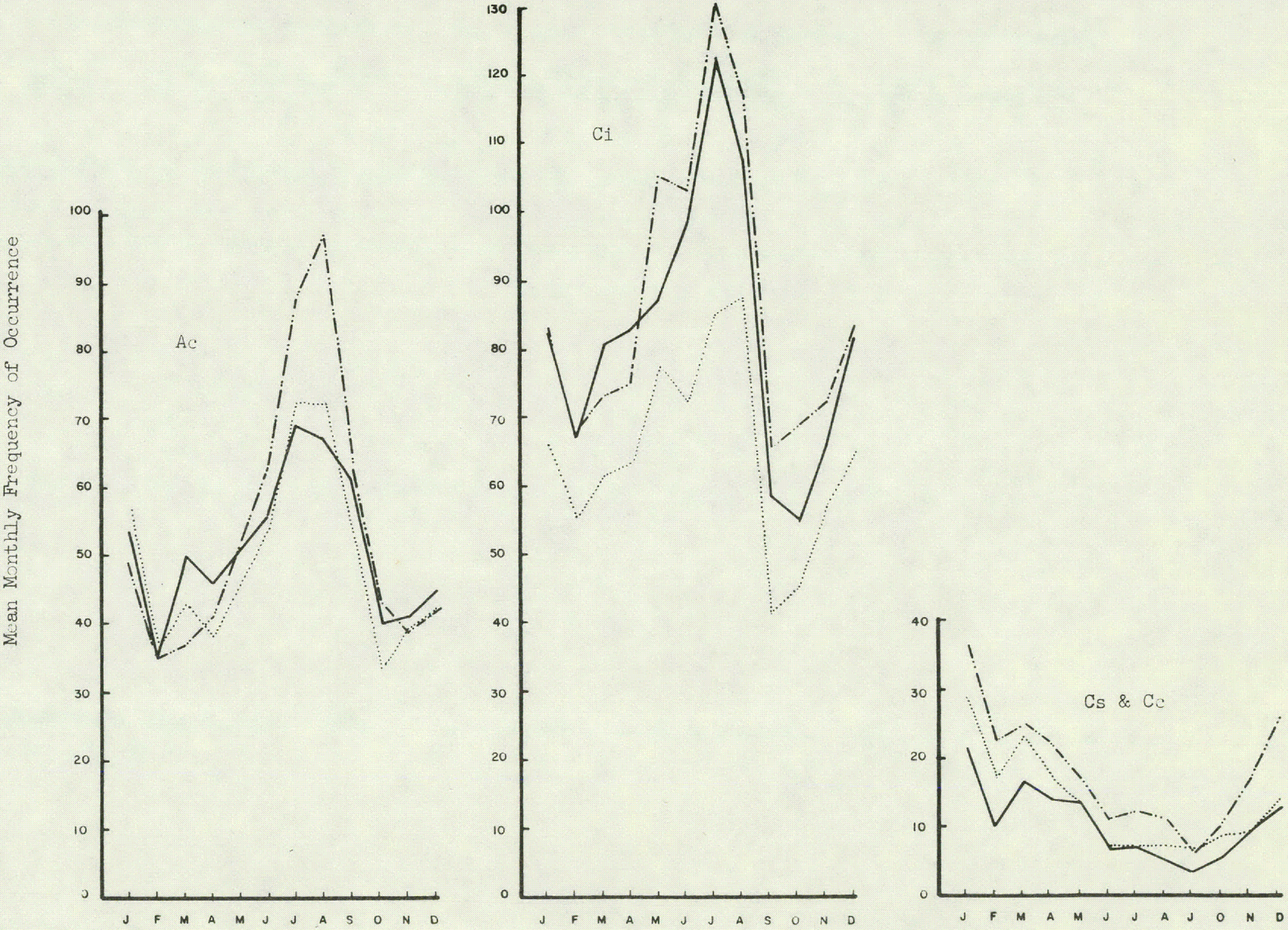


Fig. 8b Annual Variation of Cloud Types

Amarillo - .. - Lubbock ---- Midland ——•

1952-1961

during each month over the entire study period and dividing by the number of months in the series. Thus, in the case of Amarillo and Lubbock, the total was divided by ten, while in the case of Midland the divisor was eight.

The frequency curves for stratus (St) occurrence are bi-modal for Lubbock and Midland. Maxima occur in February in association with the maximum in frontal activity and in October as a result mainly of nocturnal cooling and overrunning in association with early-season cyclonic activity. At Amarillo, the winter maximum is considerably broadened to include the entire spring season. This is probably due in part to the higher frequency of occurrence of frontal passages in the late winter and early spring at Amarillo. The high frequency in May can be accounted for in large partby a relatively high number of stratus observations during May 1954 and May 1957. The minimum at all three stations is in August.

Stratocumulus (Sc) is characterized by maxima in the fall and spring with the minimum occurring during the middle and late summer. The stratocumulus curves have much the same shape as those for stratus. One apparent difference is that thereis a broad late winter and spring maximum at all three stations. The minimum is once again in August, followed by another peak in October. The higher frequency at Midland in the fall may be due to the fact that the Midland data are weighted by more wet than dry years.

Cumulus (Cu) is obviously associated with the warmer half of the year, the peak frequency occurring in July and August at each of the stations. The annual variation in cumulus frequency is considerably higher than any of the other cloud types with the exception of cirrus, which exhibits an annual variation almost as large.

Cumulonimbus (Cb) is typically a late spring and summer cloud type. Early and mid-summer rainfall depends upon the development of these clouds thru daytime heating, low-level moisture and the absence of subsidence aloft. Dry summers are characterized by an extension of the Atlantic anticyclone westward which brings upper level stability and inhibits vertical development in any but isolated cases.

Altostratus (As) and Nimbostratus (Ns) are not dominant cloud types at any of the stations. The distribution is fairly uniform throughout most of the year with a maximum in mid-winter during the time of maximum cyclonic disturbances.

Altocumulus (Ac) is one of the two dominant cloud types in the area. It is present at each station in sizable amounts throughout the year. The maximum is associated with the intense convective activity of summer and is usually due to the merging of slightly developed cumulus clouds at middle levels. Altocumulus clouds are not usually associated with significant amounts of precipitation.

Altocumulus castellatus (Acc) is observed frequently in the spring and summer but is practically non-existent during the remainder of the year.

Cirrus (Ci) is the other dominant cloud type in the area, occurring in significant amounts during each month of the year. The maximum occurrence during summer is related to the anvils of cumulonimbus clouds. The space distribution of cumulonimbus is such that its occurrence may not be reported at a station even though the cirrus from distant cumulonimbus may be.

Cirrostratus (Cs) and Cirrocumulus (Cc) have been combined due to their low frequency of occurrence in the area. The combination is dominated by cirrostratus, cirrocumulus having the lowest frequency of occurrence among those clouds considered in this investigation. Since cirrostratus is associated with the frontal activity of winter, the combination shows a mid-winter maximum and a pronounced minimum during late summer and early fall. The cirrocumulus which is reported is associated with summer convective activity.

The diurnal variation of seven of the most common cloud types is shown in Figures 9a, 9b, 9c, and 9d. Mean monthly frequency of occurrence is plotted against the time of day for each month of the year. Thus, the maximum frequency at any particular three-hour interval is 30. Midland is not included in the figures due to its shorter period of record for cloud-type observations. The statistics for Amarillo and Lubbock are based once again on 10 years of data.

Cirrus is the dominant cloud type during January, occurring nearly 15 times per month during the daylight hours and falling off to a minimum frequency of about 5 or 6 times per month in the early pre-dawn hours. This nighttime decrease is probably exaggerated somewhat due to observational difficulties during darkness. The second most prevalent cloud type is altocumulus. It also has a daytime maximum with peaks at 9 a.m. and 6 p.m. LST. Weak convective activity is probably producing some late afternoon cumulus. Stratus, which occurs only 2 or 3 times per month appears to be slightly more

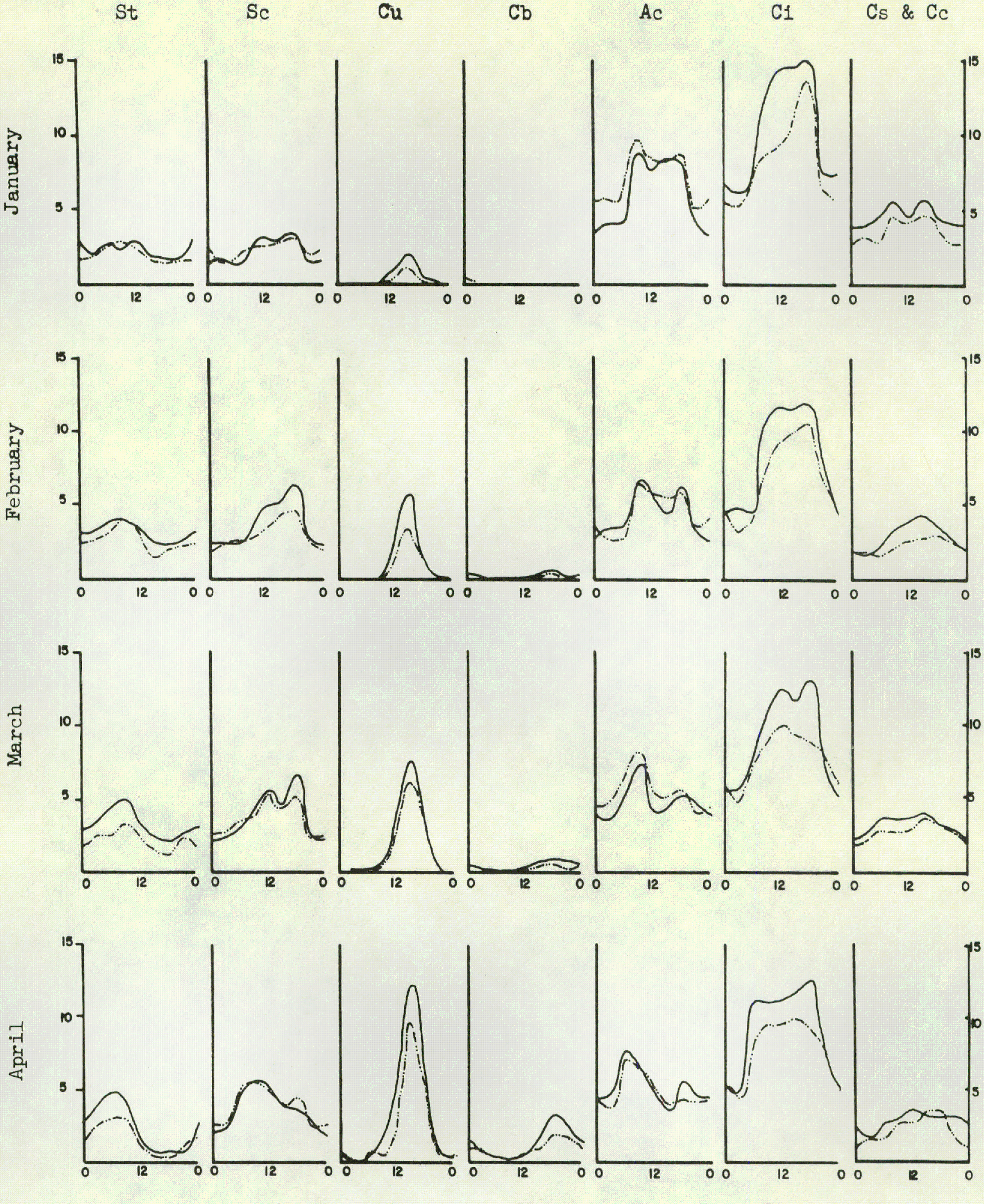


Fig. 9a Diurnal Distribution of Cloud Types

Ordinate is Mean Monthly Frequency of Occurrence

Amarillo ——— Lubbock - .. -

1952-1961

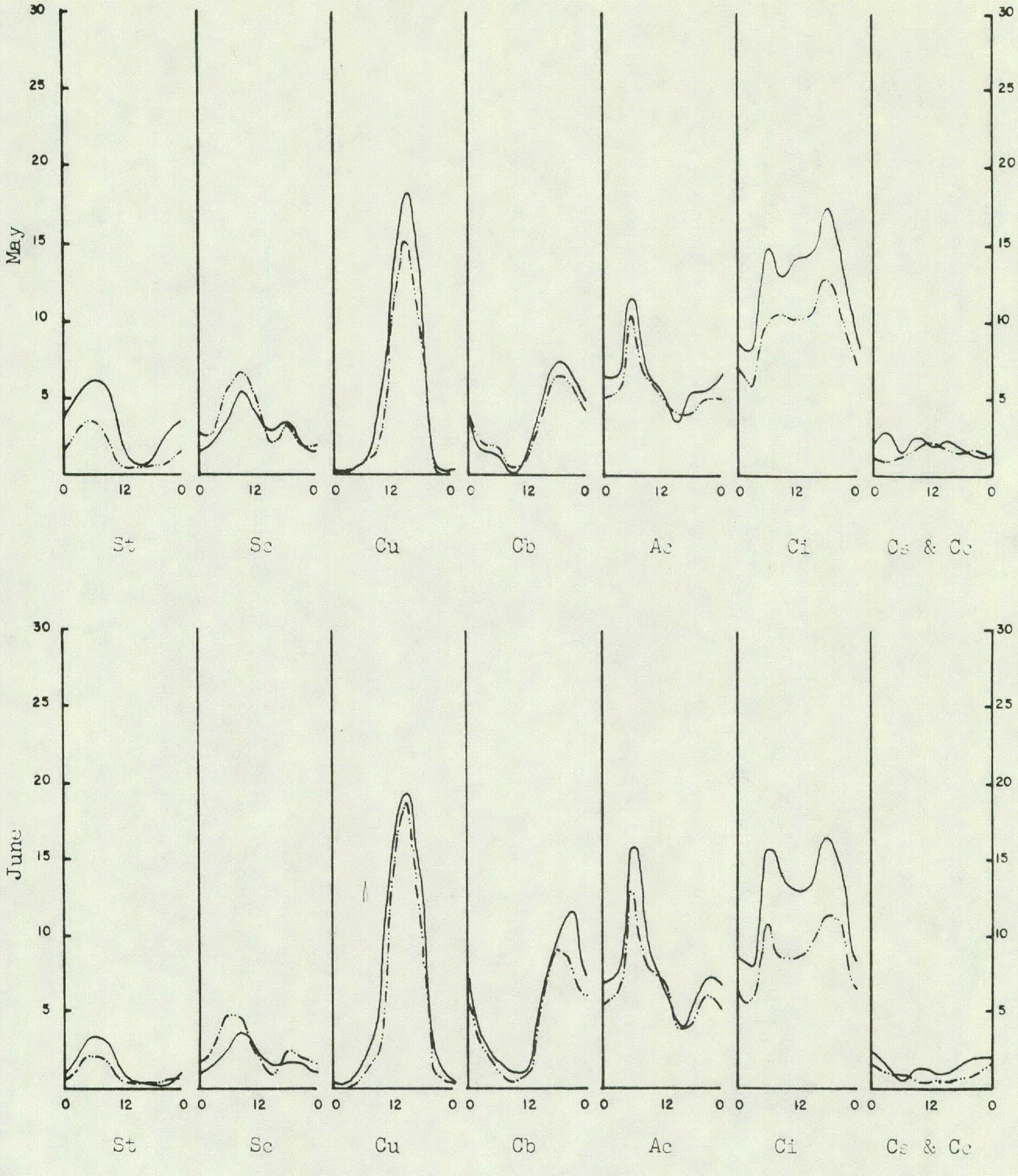


Fig. 9b Diurnal Distribution of Cloud Types

Ordinate is Mean Monthly Frequency of Occurrence

Amarillo —— Lubbock - .. -

1952-1961

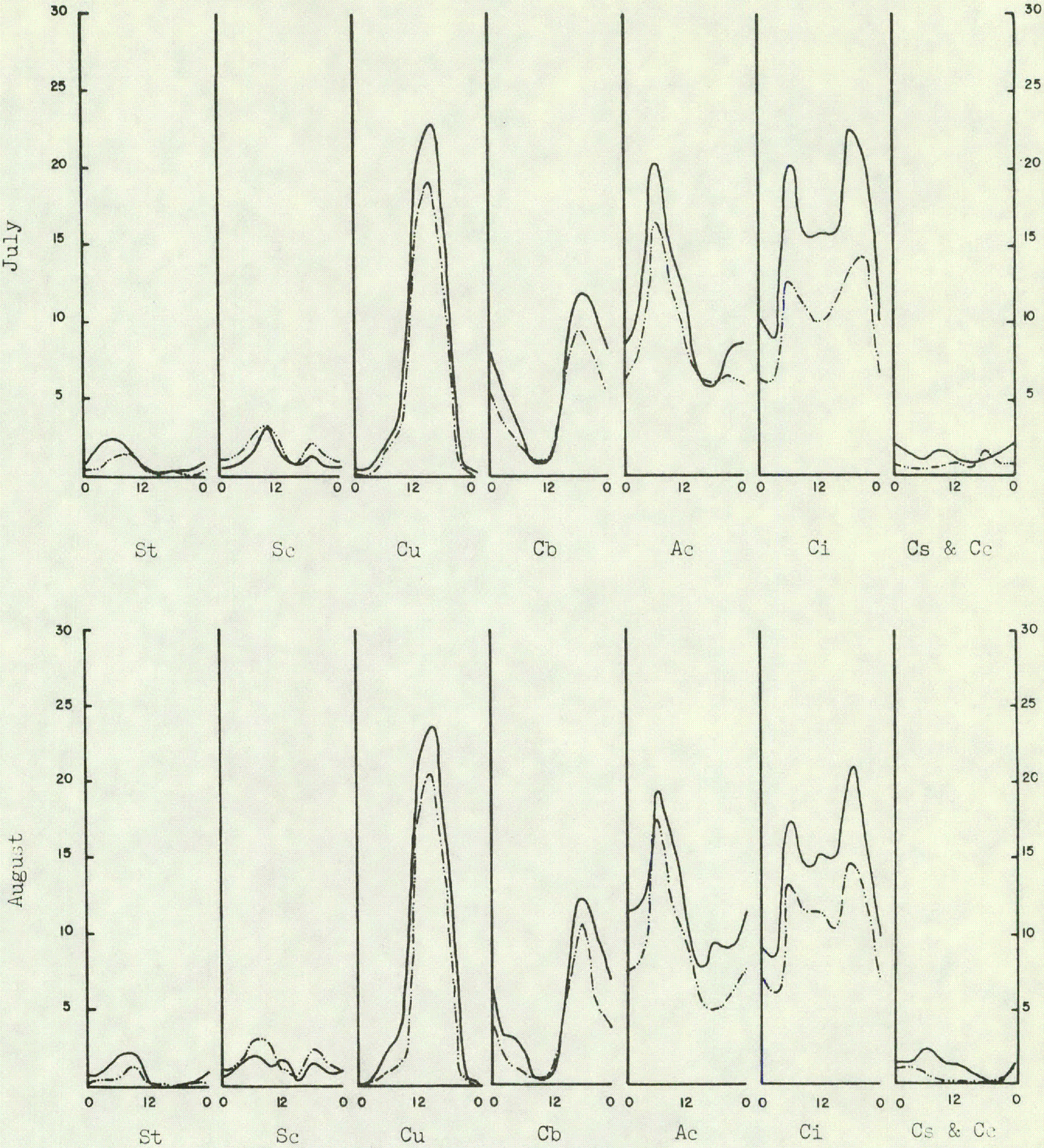


Fig. 9c Diurnal Distribution of Cloud Types

Ordinate is Mean Monthly Frequency of Occurrence

Amarillo ——— Lubbock - .. -

1952-1961

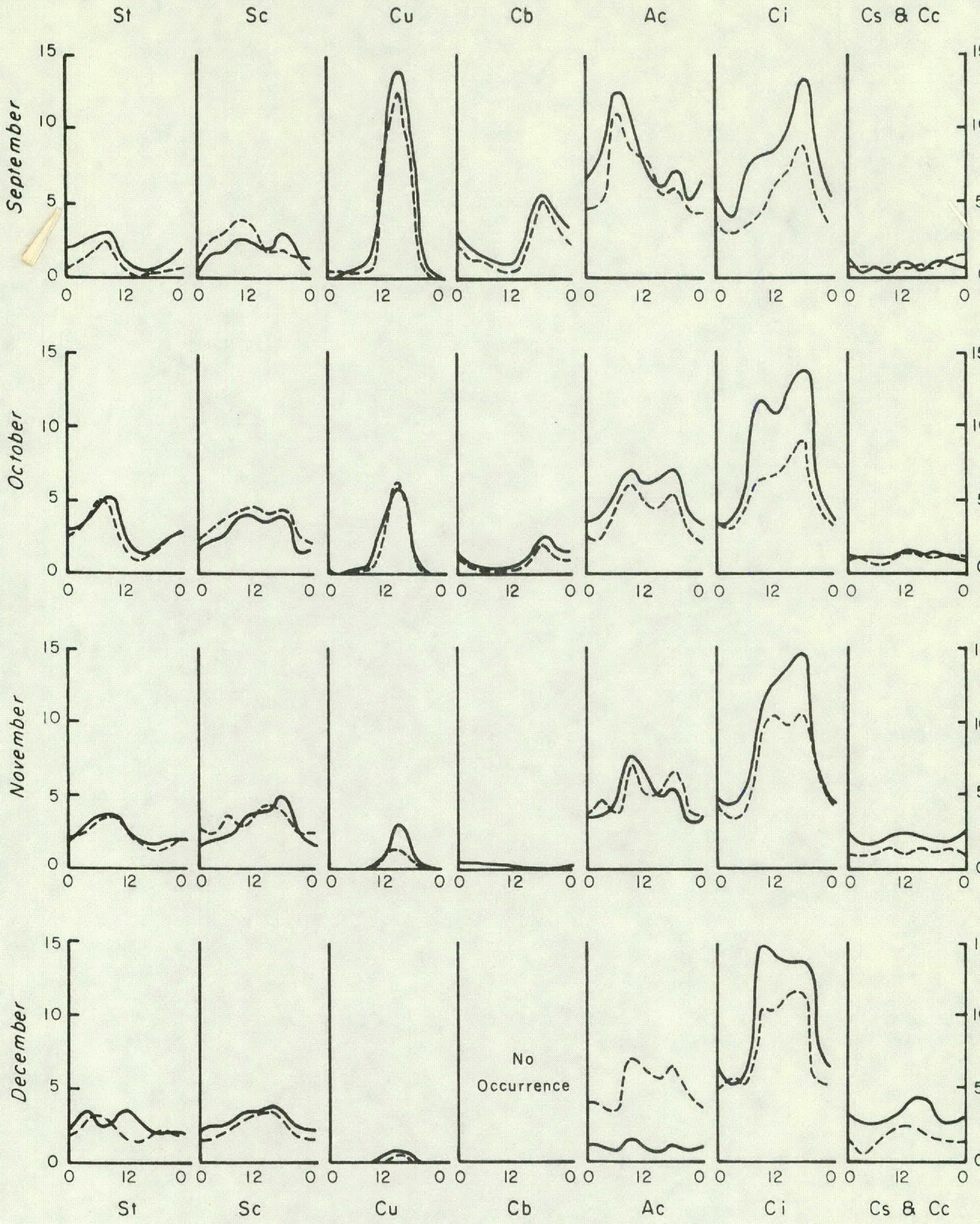


Fig. 9d Diurnal Distribution of Cloud Types

Ordinate is Mean Monthly Frequency of Occurrence

Amarillo —— Lubbock - .. -

1952-1961

prevalent in the daylight hours preceding noon and reaches a minimum in the early evening. Stratocumulus is most common during the afternoon hours. Cirrostratus and cirrocumulus shows a daytime maximum while cumulonimbus is practically non-existent.

Cirrus and altocumulus continue to be the most common cloud types during February. The diurnal variation in each case is identical to January with the exception that the frequency at all hours is reduced. An increase in convective activity is indicated by the increased frequency of afternoon cumulus. Stratus is slightly more prevalent than in January with a maximum during the morning hours, while stratocumulus shows a pronounced 6 p.m. LST maximum at both Amarillo and Lubbock.

Cumulus activity continues to increase during March; however, cirrus and altocumulus remain the most common cloud types. Cirrus has increased slightly while altocumulus has increased during the morning hours and decreased during the afternoon. It must be kept in mind that as low-level cloud frequencies increase, the possibility of not observing the occurrence of upper-level clouds also increases. It should also be noted that the occurrence of cirrus, which during the winter months was due primarily to frontal activity, becomes increasingly related to convective activity during the spring and summer months. Stratus and stratocumulus are much the same as in February.

During April, cumulus overtakes altocumulus as a dominant afternoon cloud type. The pronounced cumulus maximum at 3 p.m. is equal to the cirrus frequency at this hour. Cumulonimbus, which has been practically non-existent during the previous months is beginning to make an appearance with a maximum at 6 p.m. at both stations. The maximum in the cirrus frequency at 6 p.m. is probably due in part to the increased cumulonimbus activity at this hour. It should be remembered, however, that the decrease in cirrus at sunset may also be related to the difficulty in observing cirrus during darkness. The low frequency of morning stratus remains about the same in April while afternoon stratus occurrence has decreased to a mean frequency of less than one per month. The maximum stratocumulus frequency has also shifted from afternoon to morning.

Cumulus and cirrus are the dominant cloud types during May. Cumulus reaches a 3 p.m. maximum of greater than 15 times per month at both stations, falling off to practically zero at midnight. The cirrus distribution is becoming increasingly bi-modal with a primary maximum at 6 p.m. and a secondary maximum at 6 a.m. As mentioned previously, the afternoon maximum in cirrus is probably related to cumulonimbus development. The increase in cirrus at dawn may be due to the difficulty in cirrus observation at night. Altocumulus is becoming less and less prevalent as a daytime cloud type. The maximum in altocumulus frequency has shifted to 6 a.m. during May and falls off rapidly thereafter to a minimum in mid-afternoon. Stratocumulus exhibits the same variation to a lesser degree. It reaches a 9 p.m. maximum and decreases to a minimum at midnight. The small secondary maximum at 6 p.m. is probably due to the merging of afternoon cumulus. The occurrence of cirrostratus and cirrocumulus has become insignificant. Cumulonimbus has become considerably more frequent during May with a pronounced maximum at 6 p.m. and a minimum at 9 a.m.

With the exception of their amplitudes, the frequency curves for June are almost identical to the May curves. Increased frequencies are noted for cumulus, cumulonimbus and altocumulus, while decreases characterize stratus, stratocumulus, and the combination of cirrostratus and cirrocumulus. Cirrus occurrence remains about the same with the exception that the 6 a.m. maximum is nearly equal to the 6 p.m. value.

July is characterized by further decreases in stratus, stratocumulus and cirrostratus, so that the only cloud types of significance are cumulus, cumulonimbus, altocumulus, and cirrus. Morning altocumulus is increased over its June value and cirrus frequency has undergone an overall increase. No significant change is noted in the frequency of cumulonimbus.

The curves for August are almost identical to those for July. Cirrus and altocumulus are dominant in the morning and during the night, while cirrus and cumulus are most prevalent in the afternoon. The frequency of cumulonimbus remains about the same for the entire summer period.

The general sequence of cloudiness during a summer day might be the following: The sun rises on a broken deck of altocumulus with scattered cirrus or a broken cirrus deck above. By mid-morning cumulus activity has begun, altocumulus has reached a maximum and cirrus is decreasing. Cumulus dominates the sky by noon as the altocumulus activity generally dies out and the cirrus frequency continues to decrease. By mid-afternoon, cumulus has reached a maximum and cumulonimbus activity begins to be prevalent. As the cumulonimbus frequency increases, cirrus also increases so that by 6 p.m. there is cumulus and cumulonimbus, each thunderhead being surmounted by an associated veil of cirrus. As the sun approaches the horizon the cumulus clouds begin either to dissipate or to flatten out and become altocumuli, which as a result, increase slightly. As the sun sets, all convective activity, except for a few scattered cumulonimbus, ceases, and the cloudiness is mostly due to altocumulus and cirrus. This pattern is maintained throughout the rest of the night.

The description above is identical to the sequence of cloudiness reported by Sellers (1958) for a typical Arizona station during a mid-summer day. In making generalizations of this sort, several factors, especially as regards the distribution of cirrus and cumulonimbus must be considered. As mentioned previously, there is a space distribution of cumulonimbus such that its occurrence may not be reported at a station even though the cirrus from distant cumulonimbus may be. Also, cumulonimbus is not readily seen at night, although lightning and thunder may be reported in present weather. Under these circumstances, cumulonimbus clouds would not be reported.

All cloud types, with the exception of stratus and stratocumulus are reported less frequently in September than in August. The lessening of convective activity has caused a sharp decrease in the occurrence of cumulus and cumulonimbus. It should be noticed also that the bi-modal character of the cirrus distribution has practically disappeared and cirrus exhibits only one maximum at 6 p.m.

October is characterized by a further decrease in cumulus, cumulonimbus, and altocumulus and a slight increase in stratus, stratocumulus, and cirrus. Cirrus is the dominant cloud type, followed by altocumulus and cumulus. Morning cirrus is increasing so that there is once again a secondary peak during the morning hours. In general, October is characterized by decreasing cloudiness.

With the exception of cirriform clouds, frequencies continue to decrease during November. Cumulonimbus clouds have essentially disappeared and the cumulus frequency is down to 2 or 3 per month. Cirrus continues to be the dominant cloud type, and is beginning to exhibit a broad maximum during the daylight hours. Altocumulus continues to be the second most abundant type followed by stratocumulus and stratus in that order.

Cirrus continues to be the dominant cloud type in December. Altocumulus remains the second most abundant type at Lubbock but has become insignificant at Amarillo. Very little change is noted in stratus and stratocumulus, while cirrostratus and cirrocumulus have increased slightly over their November occurrences. No cumulonimbus clouds are reported.

Figures 10, 11 and 12 show the annual (abcissa) and diurnal (ordinate) variations of cloud types on the same diagram for Amarillo, Lubbock, and Midland respectively. The contours represent isolines of total frequency of occurrence for the entire period under investigation (ten years for Amarillo and Lubbock; eight years for Midland).

Note that stratus occurrence is a maximum during the early morning hours of fall and spring and reaches a minimum during the summer season. This early morning stratus is probably due in large part to nocturnal cooling of low-level moisture. Stratocumulus is a maximum during the daylight hours of spring and fall and is a minimum during the summer.

Cumulus has a maximum frequency during the summer afternoon hours. The cumulus frequency reaches a minimum during the morning and nighttime hours of winter, when convective activity is at a minimum. The maximum frequency of cumulonimbus occurs also in the summer during the late afternoon and early evening. Cumulonimbus cloud frequency is a minimum during the late fall, winter, and early spring.

Altostratus are generally most abundant in the winter and least abundant in the fall. No consistent diurnal trend is obvious. Altocumulus is prevalent throughout the year with a maximum during the early morning hours of summer. The minimum frequency occurs during the nighttime hours of fall, winter, and spring.

Cirrus is also abundant throughout the year. It reaches a maximum during the summer between the hours of 6 a.m. and 9 p.m. and a minimum during the early morning hours of autumn and winter. Cirrostratus has a maximum in the winter and a minimum in the summer and early fall.

Inspection of the cloud regimes at each of the stations indicates that the similarities are sufficient to warrant the construction of frequency ogives based on the combined total data sample. After deriving frequency curves for each month individually, it was discovered that many curves were almost identical.

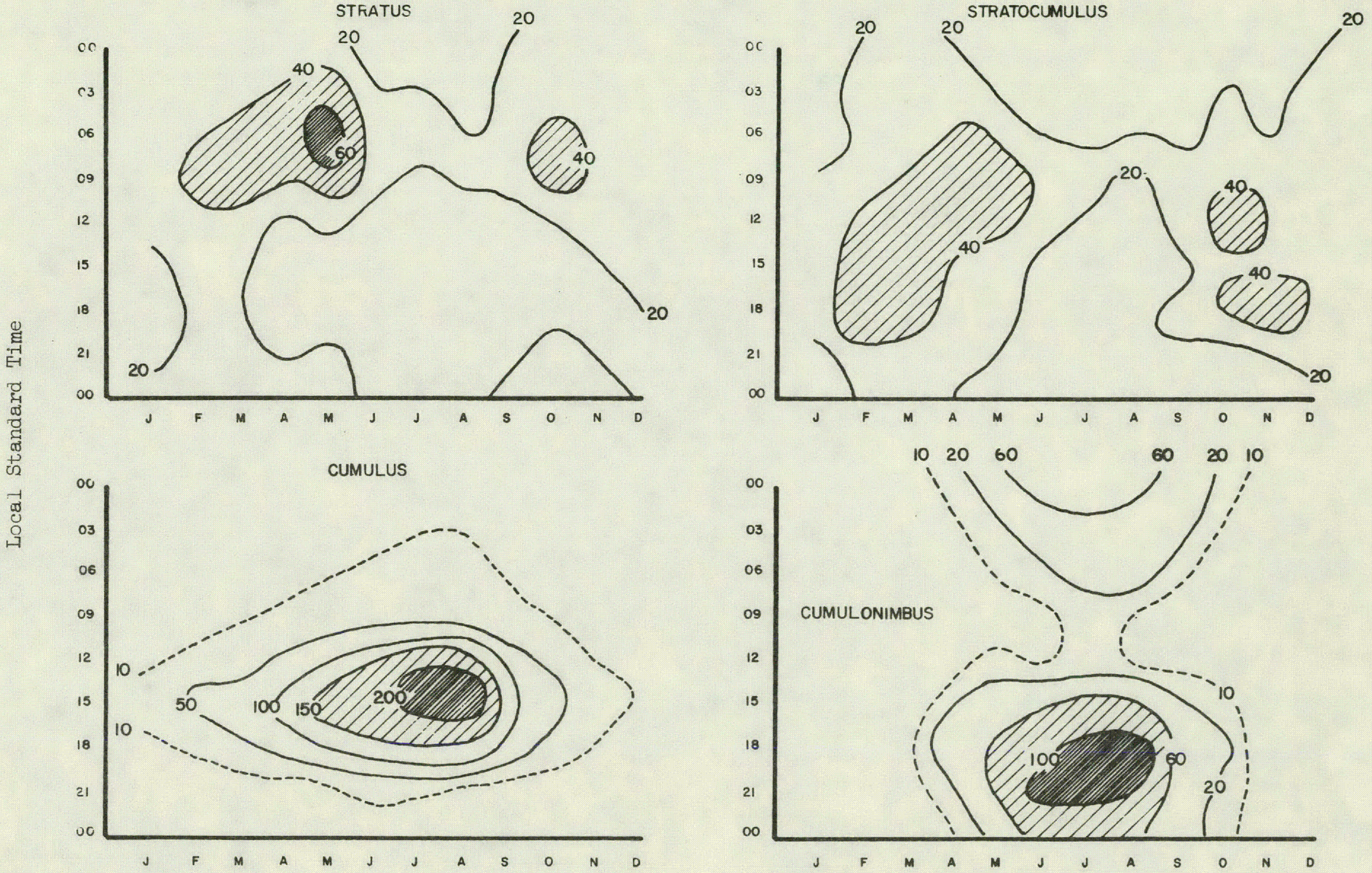


Fig. 10a Total Frequency of Occurrence of Cloud Types

Amarillo 1952-1961

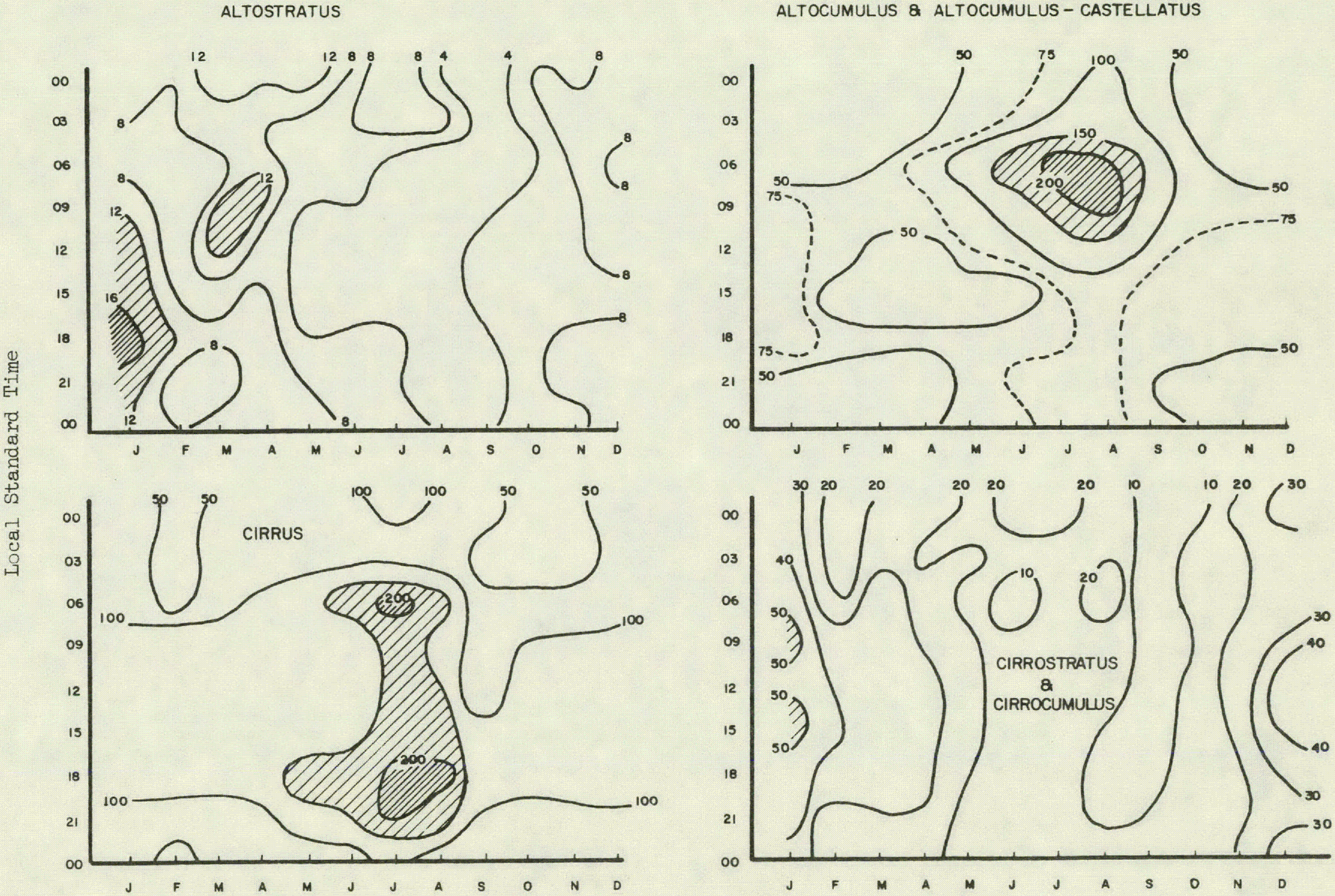


Fig. 10b Total Frequency of Occurrence of Cloud Types

Amarillo 1952-1961

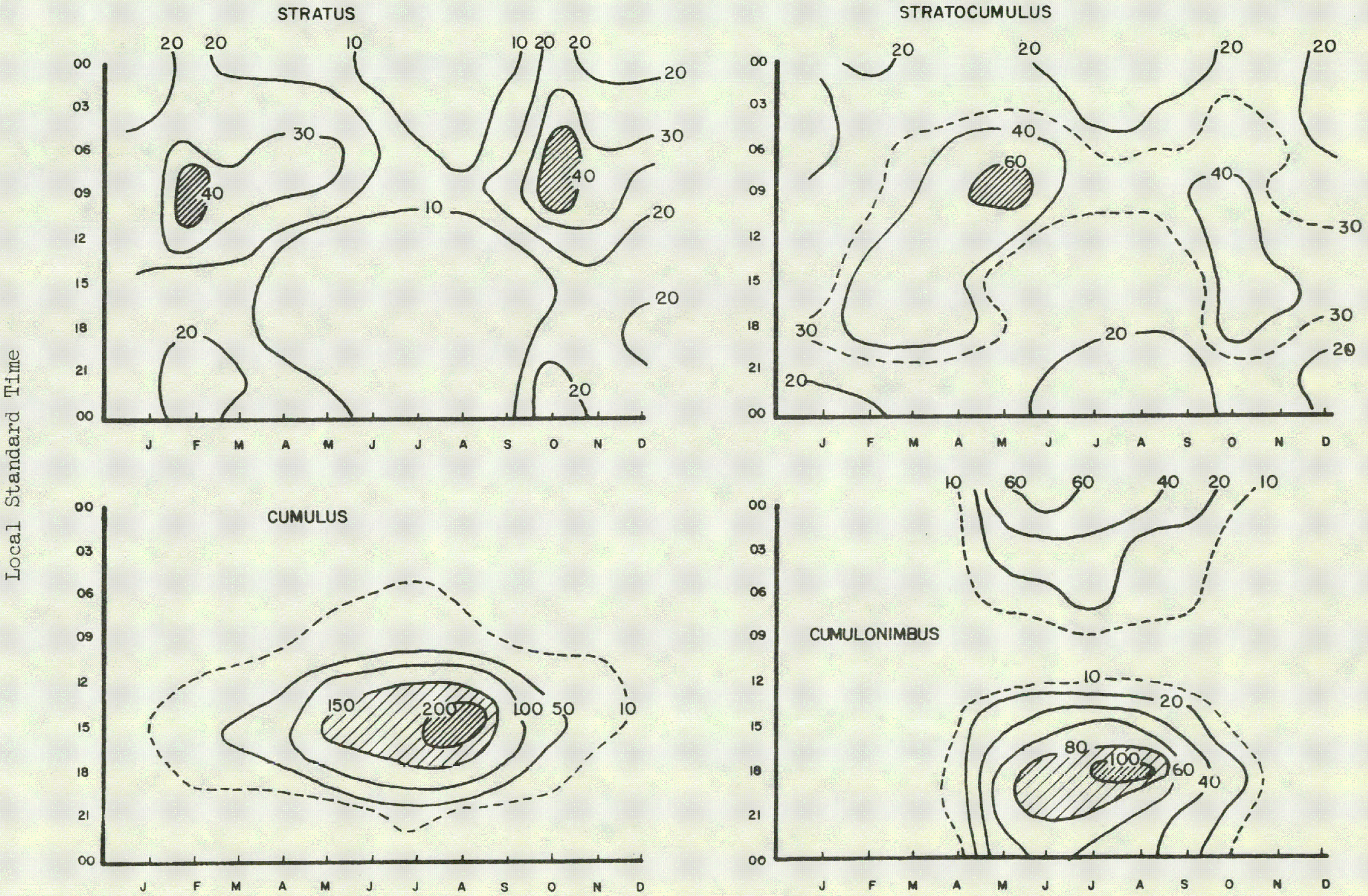


Fig. 11a Total Frequency of Occurrence of Cloud Types

Lubbock 1952-1961

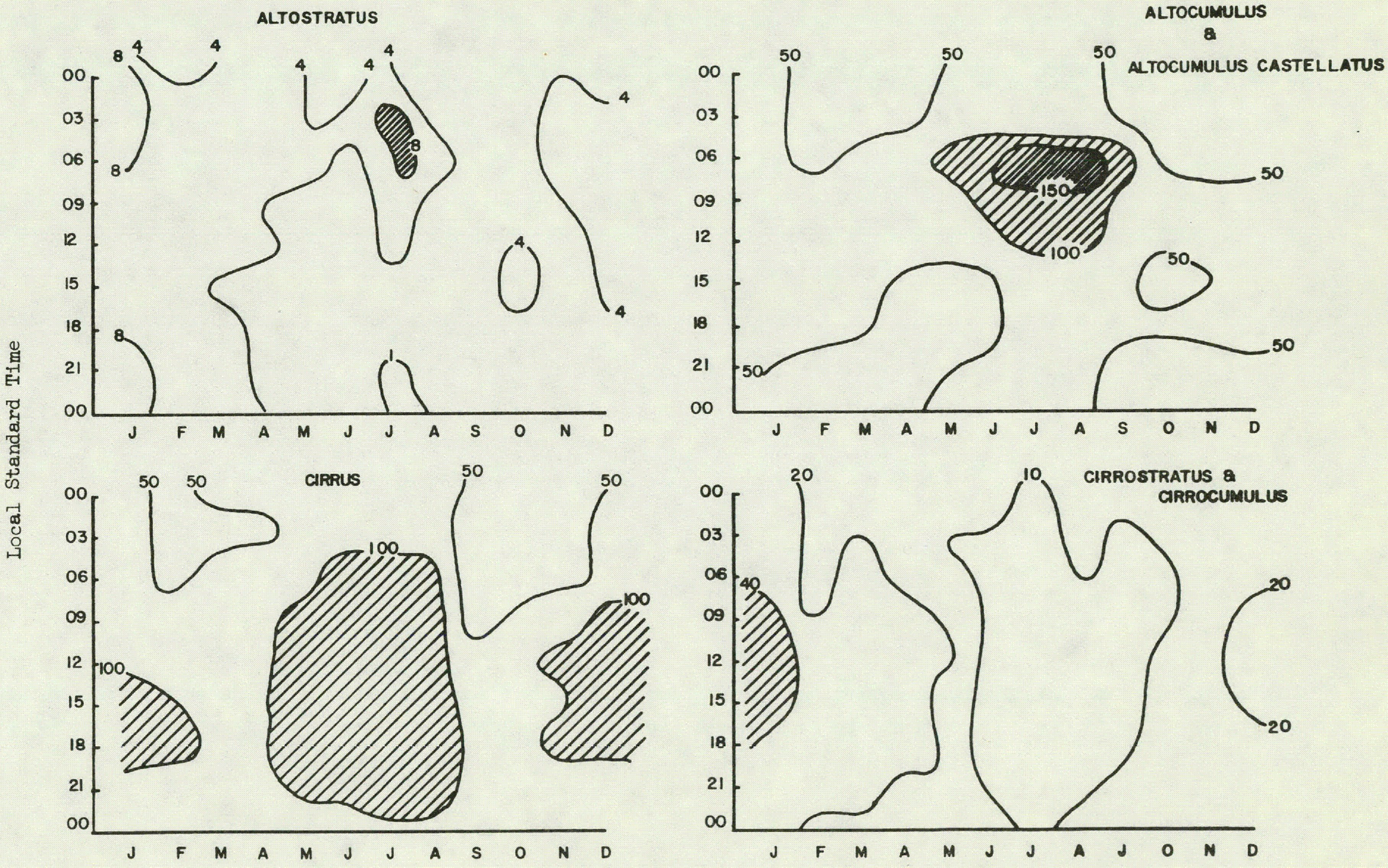


Fig. 11b Total Frequency of Occurrence of Cloud Types

Lubbock 1952-1961

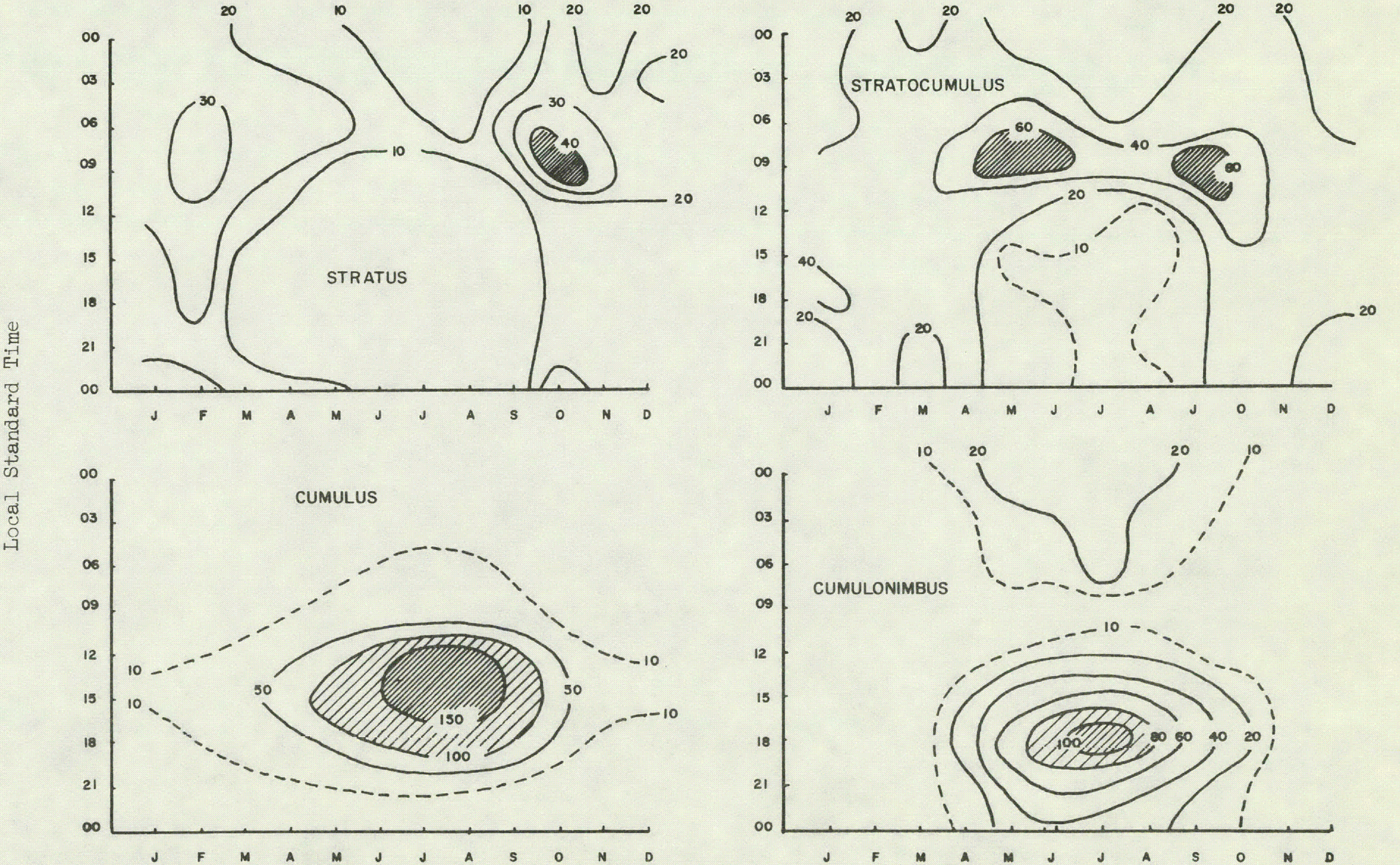


Fig. 12a Total Frequency of Occurrence of Cloud Types

Midland 1954-1961

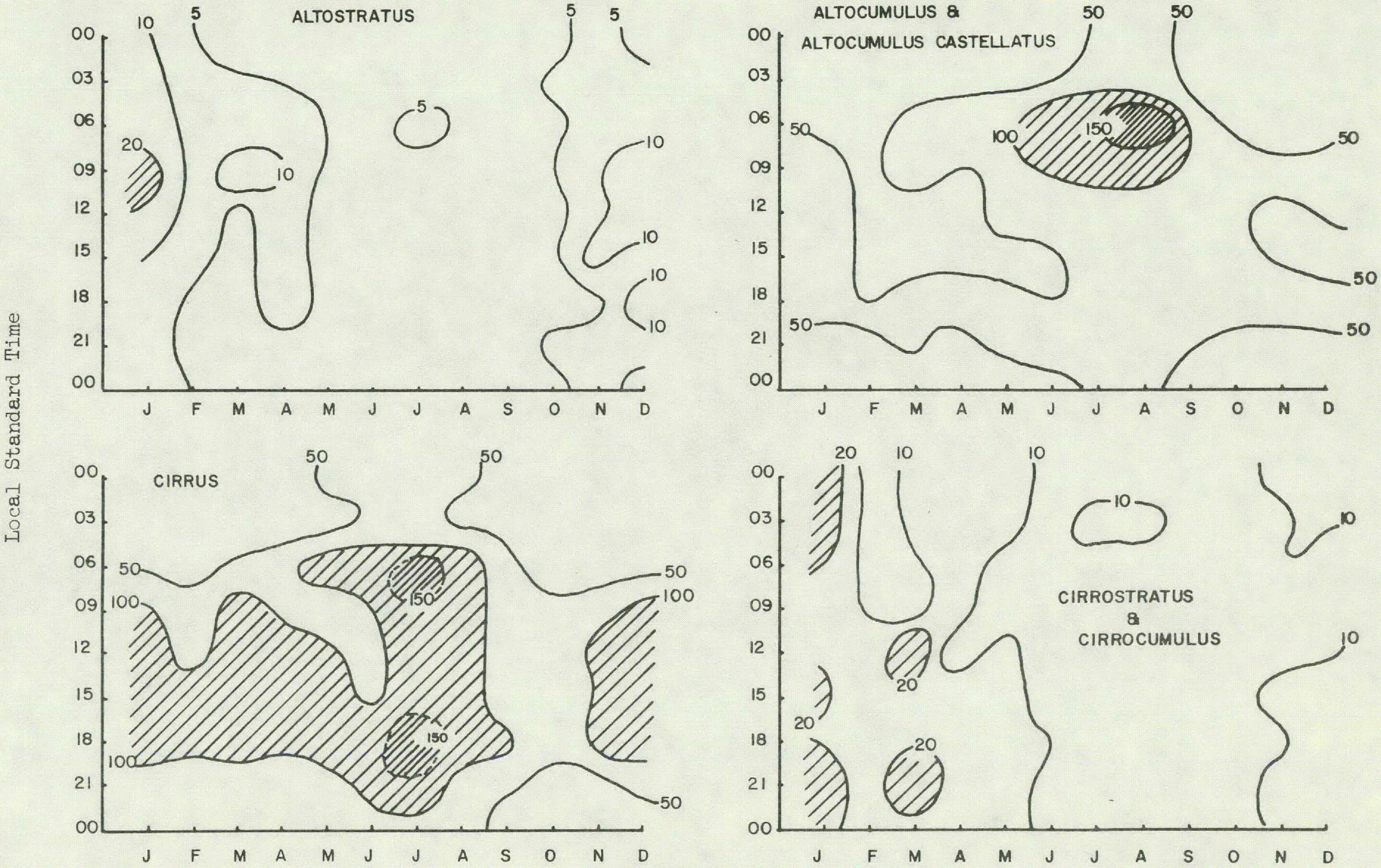


Fig. 12b Total Frequency of Occurrence of Cloud Types

Midland 1954-1961

Thus, individual months were grouped into "cloud seasons" according to similarities in their distributions. In some instances the clouds could reasonably be separated into two groups while in other cases, three or four groups were necessary. The groups for each cloud type are as follows:

Cirrus: Group I - May thru August
II - September thru April

Stratus: Group I - June thru September
II - October thru February
III - March thru May

Cumulus: Group I - November thru February
II - March thru April, October
III - May, September
IV - June thru August

Cumulonimbus: Group I - April, September, October
II - May thru August
III - November thru March (not plotted due to extremely low frequency)

Altocumulus: Group I - October thru May
II - June thru September

Stratocumulus: Group I - February thru May, October, November
II - June thru September
III - December, January

Figure 13 shows cumulative percentage ogives derived from the frequency histograms. The abcissae in these diagrams are the number of occurrences of a particular cloud type while the ordinates represent cumulative percentage frequency. Thus, for Group I cumulus, the curve indicates that a frequency of greater than 10 per month is observed 10% of the time. For Group II cumulus a frequency of greater than 10 per month is observed 82% of the time.

E. Amounts of Different Cloud Types

Figures 14a and 14b show the amount of different cloud types as a function of the time of year. It is immediately obvious that these curves very closely resemble those in Figures 8a and 8b for cloud frequency. This indicates that clouds tend to occur in greater amounts during the time of year that they are most frequently observed.

The curves for stratus are once again bi-modal, with maxima in October and February. The spring maximum at Amarillo is once again prominent. The

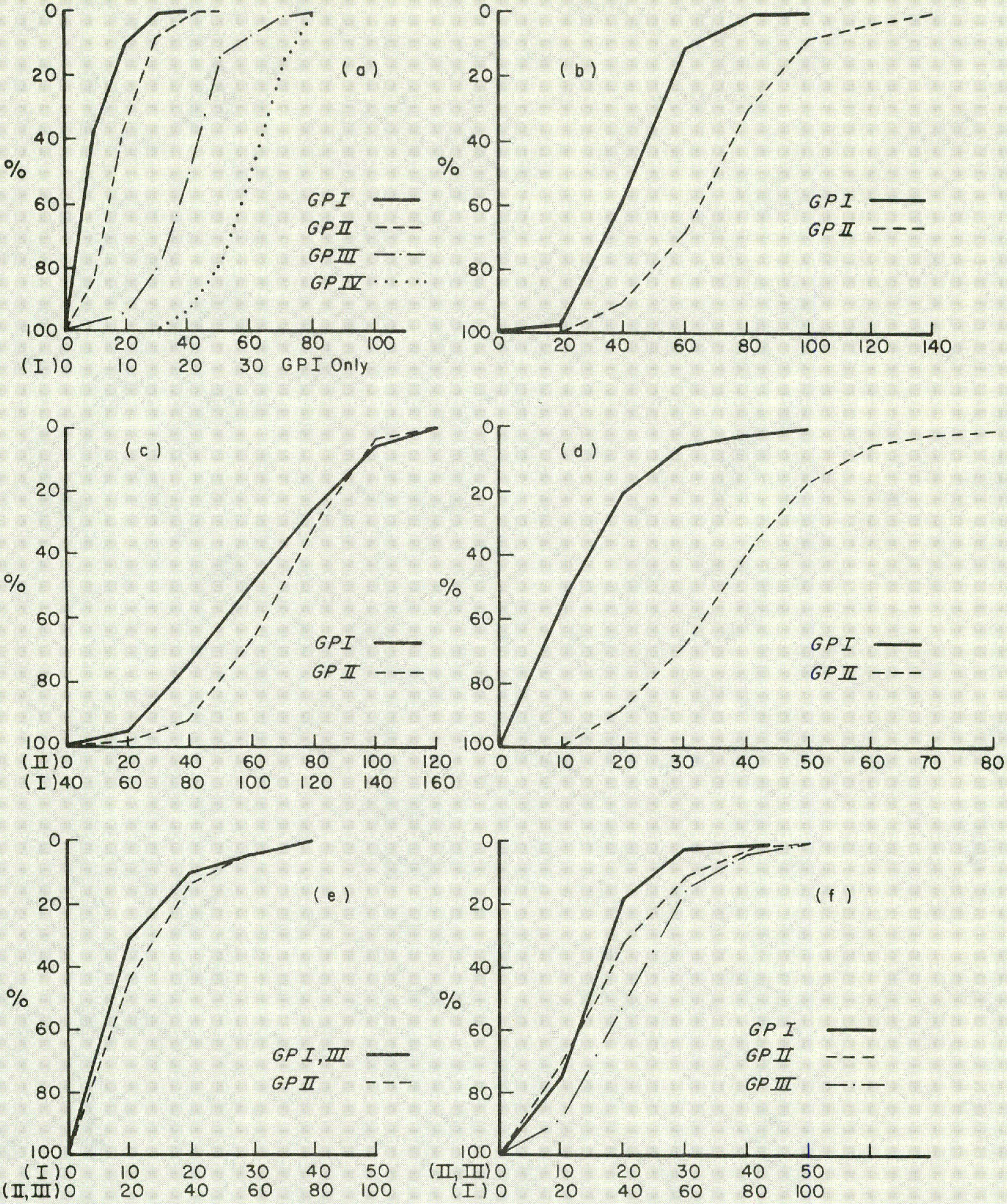


Fig. 13 Cloud Frequency Cumulative Percentage Ogives

(a) Cumulus (b) Altocumulus (c) Cirruc

(d) Cumulonimbus (e) Stratus (f) Stratocumulus

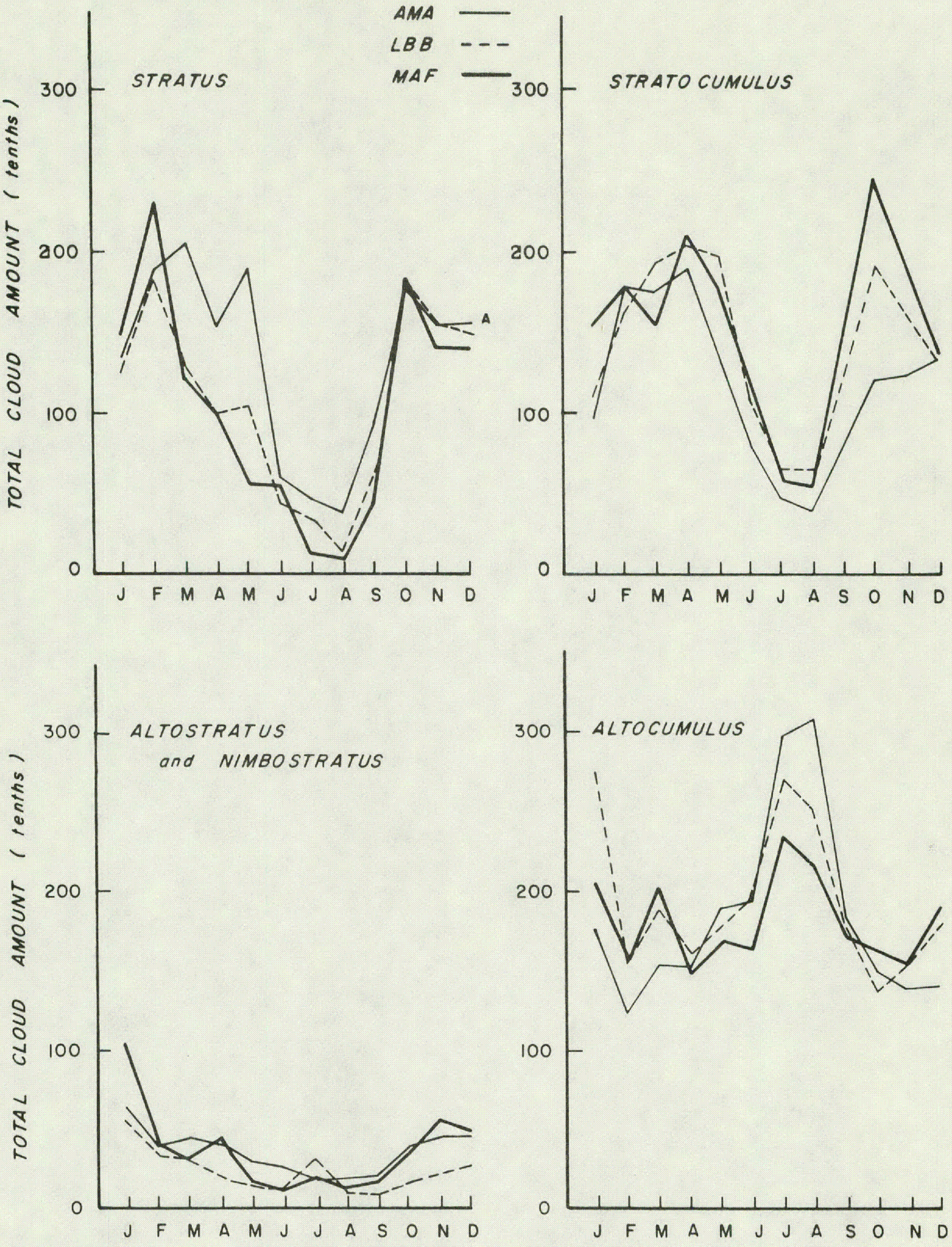


Fig. 14a Annual Variation in Cloud Amount

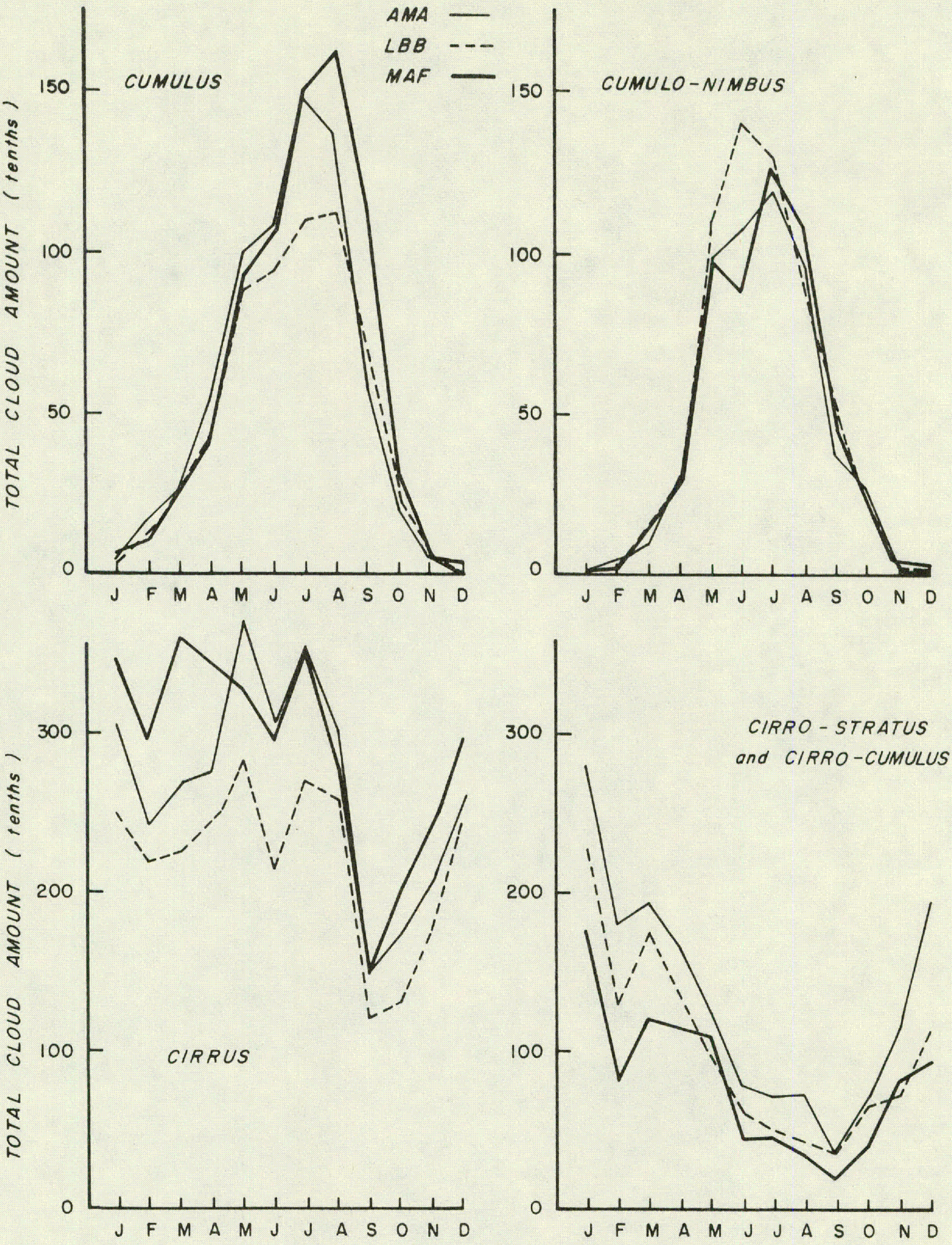


Fig. 14b Annual Variation in Cloud Amount

stratocumulus variation is almost identical to that for cloud frequency. This is true also in the cases of altostratus and altocumulus. For cumulus, the shape of the curves corresponds to those in Figures 8a and 8b, but there appears to be a greater separation during the time of maximum occurrence (summer). Note that while the frequency of cumulus occurrences at Midland and Amarillo is about the same during August (Fig. 8a), the amount of cumulus is greater at Midland during this period. This would seem to indicate that while cumulus clouds are dominant in the sky the same percentage of time at the two stations, they occur in greater amounts at Midland. Note, however, that the reverse of this situation is evident in the case of cumulonimbus. The amounts are nearly the same, but the frequency of occurrence is significantly greater at Amarillo during August. This may indicate that a greater percentage of cumulus clouds develop into cumulonimbus at Amarillo during the summer season.

The curves for cirrus seem to indicate a significant difference in cloud amount between Amarillo and Midland which is not evident in Figure 8b. It is important to recognize that this may simply be due to the difficulty in observing cirrus (especially the amount) at night or in the presence of lower level clouds.

III. CLOUDS AND PRECIPITATION

The search for an adequate physical explanation of the formation of precipitation elements has been an area of intense investigation for many years. Bergeron (1935) concludes that of several competing mechanisms, none is adequate to account for the release of precipitation. He postulated that the only factor that could explain the growth of precipitation-size drops was the appearance of a few ice crystals among a large population of supercooled droplets in those parts of the cloud where the temperature was below -10°C. In this region, there would exist a supersaturation with respect to ice so that the ice crystals would tend to grow rapidly. Condensation would take place continually on the ice, while at the same time liquid water would evaporate from the droplets. This process would continue until the liquid phase was entirely consumed. Thus, Bergeron postulated that every raindrop ($d>0.5$ mm) originates as an ice particle which grows in this way and therefore all rain clouds must extend well above the level of the 0°C isotherm.

The Bergeron theory, with support from Findeisen, came to be generally accepted during the following decade. However, it was obvious to most meteorologists that, in tropical regions, showers often fell from clouds whose tops did not reach the freezing level. Suggestions that rain could be produced by wholly liquid clouds began to become more prominent. In recent years, careful visual and radar observations have accumulated which show beyond all doubt that heavy rain may fall from clouds which are entirely beneath the level of the 0°C isotherm.

Thus it appears that droplet growth to precipitation size can be due to either or both of two mechanisms:

1. the Bergeron process for clouds extending well above the freezing level, and,

2. pure coalescence for clouds not extending above the freezing level.

In most instances it appears that a combination of the above mechanisms is operative. It may, therefore, be a difficult task to decide which of the two possible mechanisms is responsible for the initiation of the precipitation process. During the rainy seasons in the Texas plains, it is probable that both producing processes are operative.

Once an ice crystal growing in a dense supercooled cloud has become appreciably larger than a cloud droplet, its growth will be greatly accelerated by accretion of these droplets which will freeze on impact to form ice pellets of irregular shape (Mason, 1957). It appears that most rain of extra-tropical origin which falls from thick layered clouds is initiated almost entirely by the growth of ice crystals, which however, must aggregate to form snow flakes if they are to produce raindrops of the observed size.

There are, in general, three types of precipitation, all of which are characteristic to some extent of rainfall in the Texas High Plains. The first of these is the intermittent or continuous precipitation from a continuous cloud cover of the altostratus or nimbostratus type. This kind of precipitation is caused by the slow upglide of a large mass of air, due to convergence in the horizontal wind field. The second type is the showers or squalls of short duration that begin and end suddenly. This kind of precipitation, which originates from cumulonimbus clouds, is indicative of instability and is caused by the rapid rising of small bodies of air through the atmosphere (thermals). The third type is drizzle which falls from low stratus cloud layers. This kind of precipitation is indicative of stable air masses and is not connected with any appreciable vertical velocity. In fact, the small drops are able to fall out of the cloud because of the absence of an appreciable upward motion.

A. Texas Precipitation Seasons

In the study of possible methods of modifying Texas precipitation, it is important to recognize that the sequence of meteorological events leading to precipitation in one season of the year may not be the same as that producing precipitation in another season of the same year (Staley, 1959). Over most of Texas the heaviest rainfall occurs in the spring and fall as shown by the bar graphs in Figure 15. The graphs at Amarillo, Lubbock, and Midland are characteristic of the plains area. Note that a dominant portion of the annual precipitation falls in the seven month period from April thru October. Since this is the critical period as regards water supply, it will receive the major emphasis in this research.

The heavy rainfall in April and May is usually the result of convective activity set off by squall lines moving out ahead of frontal disturbances. It is doubtful that large-scale attempts at increasing this precipitation would be

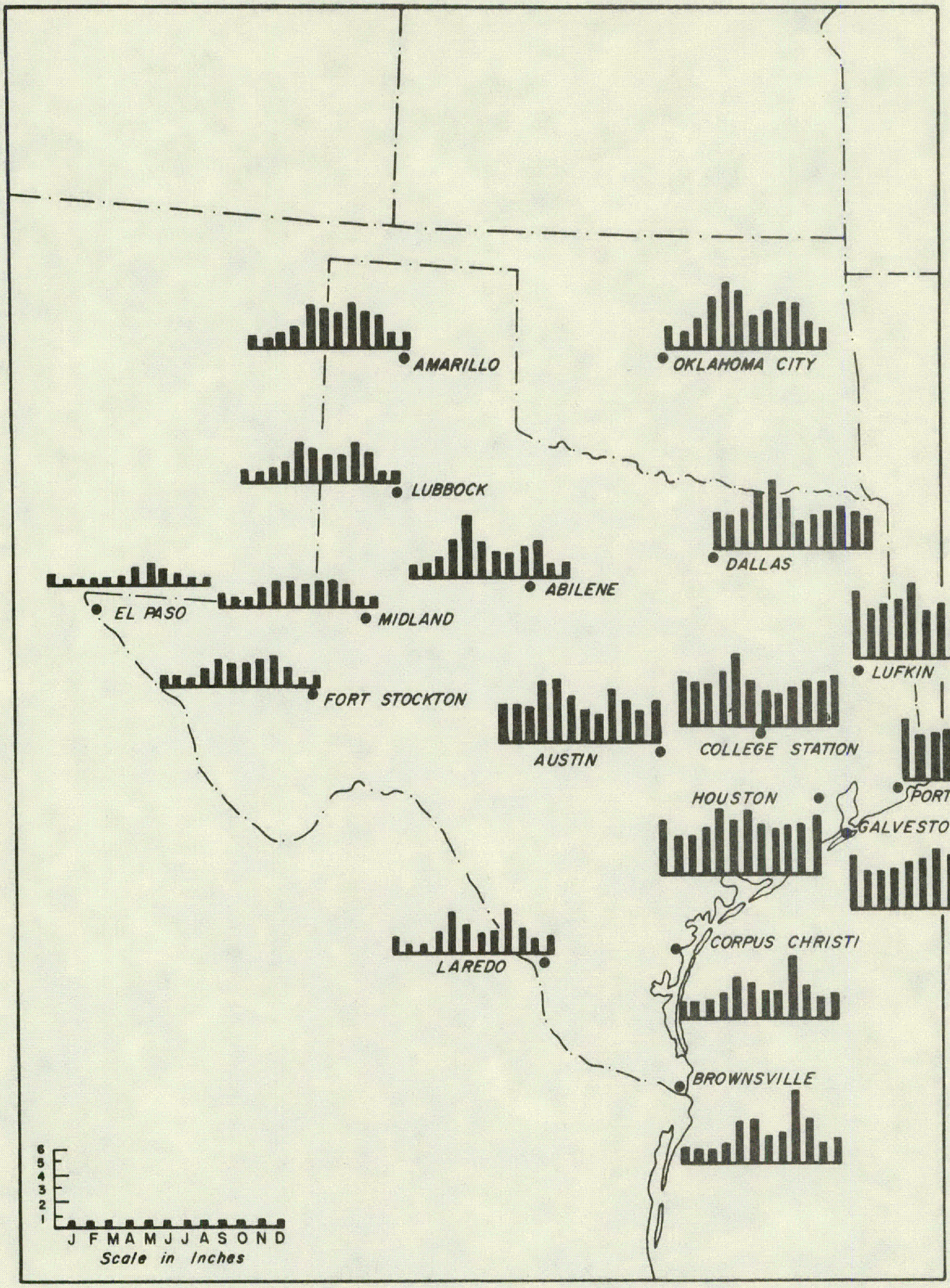


Fig. 15 Annual Precipitation Distributions for Texas Stations

Staley (1959)

effective, since once the necessary vertical motion is provided, the precipitation follows almost without exception. The highly localized nature of the precipitation is associated with the equally localized fields of vertical motion. The one hope which modification might hold is that these disturbances, often accompanied by hail and violent winds, could be made less violent by cloud seeding operations. Hail suppression experiments in the Soviet Union (Sokol, 1967) utilizing control areas and statistical analysis have suggested that seeding may reduce hail losses by as much as 90%.

Summer rainfall in the plains area is made up of scattered showery developments which depend mainly upon daytime heating, low-level moisture, and the absence of subsidence aloft. During much of the summer, the extension of the Atlantic anticyclone westward brings upper-level stability and inhibits vertical development in any but isolated cases. As will be discussed in the next section, general rainfall covering large areas and whose duration is greater than a few hours, is associated, even during the summer season, with frontal activity.

Heavy late summer and early autumn rainfall over most of Texas is mainly the result of tropical disturbances moving northward and westward from the Gulf of Mexico. In the plains area, frontal passages are becoming more frequent, and this, coupled with the Gulf moisture leads to an extension of the summer rainy season into the early fall. Late autumn and winter rains are usually the result of warm moist Gulf air overrunning continental polar air which is associated with a strong winter anticyclone.

The period from early November until mid-April is characteristically dry in the plains. Precipitation averages over a 50-year period (Portig, 1962) indicate that more than 80% of the annual rainfall occurs during the seven month period, April thru October. It is this rainy season which is of primary concern here.

Rainfall records at Amarillo are complete since 1892 while the period of record at Lubbock dates from 1911. These data are available in the climatic summaries of the United States published by the United States Department of Commerce Weather Bureau (1932, 1955, 1965). Frequency distributions of precipitation based on these periods of record are illustrated by percentage ogives in Figure 16 for Amarillo and Figure 17 for Lubbock. The ordinate in the

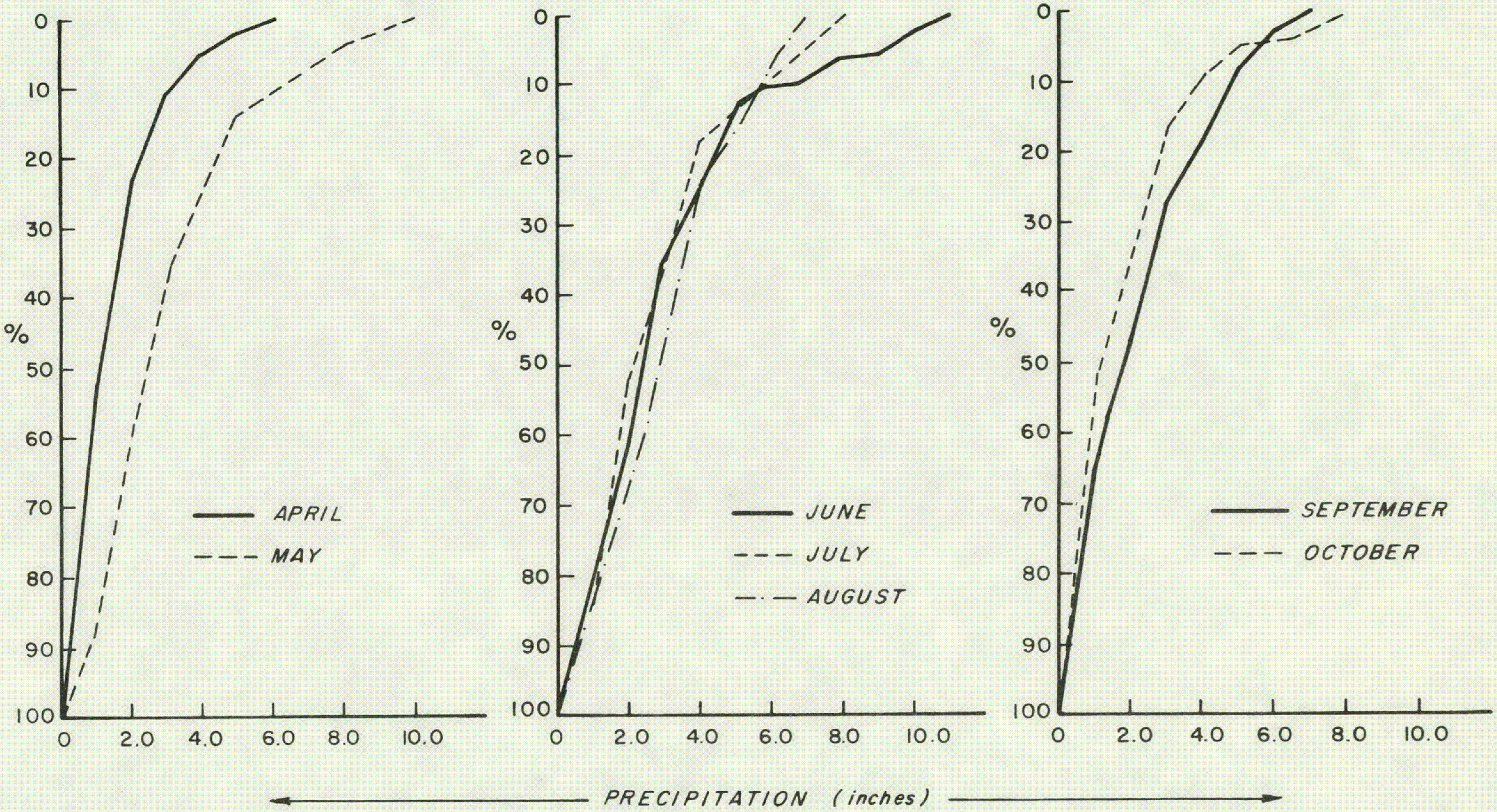


Fig. 16 Precipitation Frequency Ogives
Amarillo 1892-1968

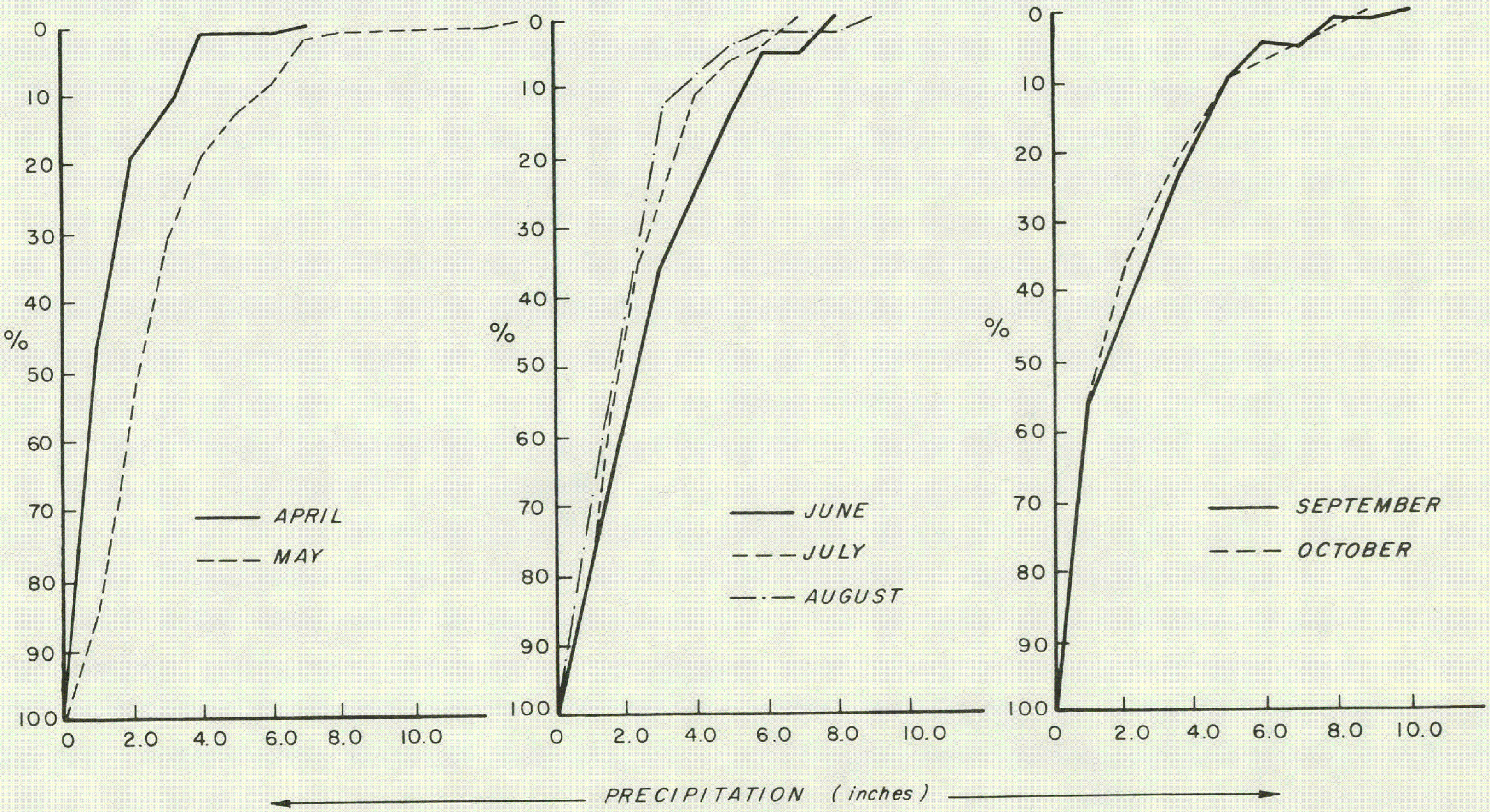


Fig. 17 Precipitation Frequency Ogives
Lubbock 1911-1968

diagrams is percentage cumulative frequency of occurrence while the abcissa is precipitation in inches. As an example in reading the curves, note that during April at Amarillo, precipitation amounts greater than one inch were observed 53% of the time. Thus, based on this data sample, there is a 53% chance that precipitation during April will be greater than one inch. For May, there is an 87% chance that the precipitation will be greater than one inch. These curves will be used in Section IV in comparing characteristically wet and dry months in the plains area.

B. Synoptic Events Related to Periods of Maximum Precipitation During the Rainy Season

Based on a network of 32 stations distributed throughout the study area, five years of precipitation data (1956-1960) were examined in order to select periods of maximum general precipitation. A list of stations used in the analysis is given in Appendix IV. The distribution of the stations is shown in Figure 19. The rain periods were selected solely on the basis of the amount and areal extent of precipitation. No synoptic features were considered in the selection process. Once the periods had been chosen, synoptic features characteristic of each case were noted and the results compiled so as to indicate the synoptic events most frequently associated with wide-spread rainfall in the Texas plains.

Results of the study showed that springtime precipitation is dominated by strong convective activity in association with fronts and squall lines. There were basically four synoptic patterns associated with precipitation during the spring season. The pattern responsible for the heaviest local rains involved a squall line moving ahead of a cold front which passed through the study area from the northwest. In situations of this type, strong convective showers were often associated with both the squall line and frontal passages. Large amounts of precipitation were deposited over a relatively short time period. These storms were more often than not accompanied by strong winds, hail, and occasionally, tornadoes. As was pointed out earlier it is doubtful that large scale attempts at increasing the precipitation would be effective, for once the situation has developed, precipitation falls almost without exception. In many instances, hail damage to crops offsets any benefit which might have been derived from the precipitation.

A more beneficial springtime rain situation as far as agriculture is concerned is offered by the second typical pattern, shown in Figure 18. In

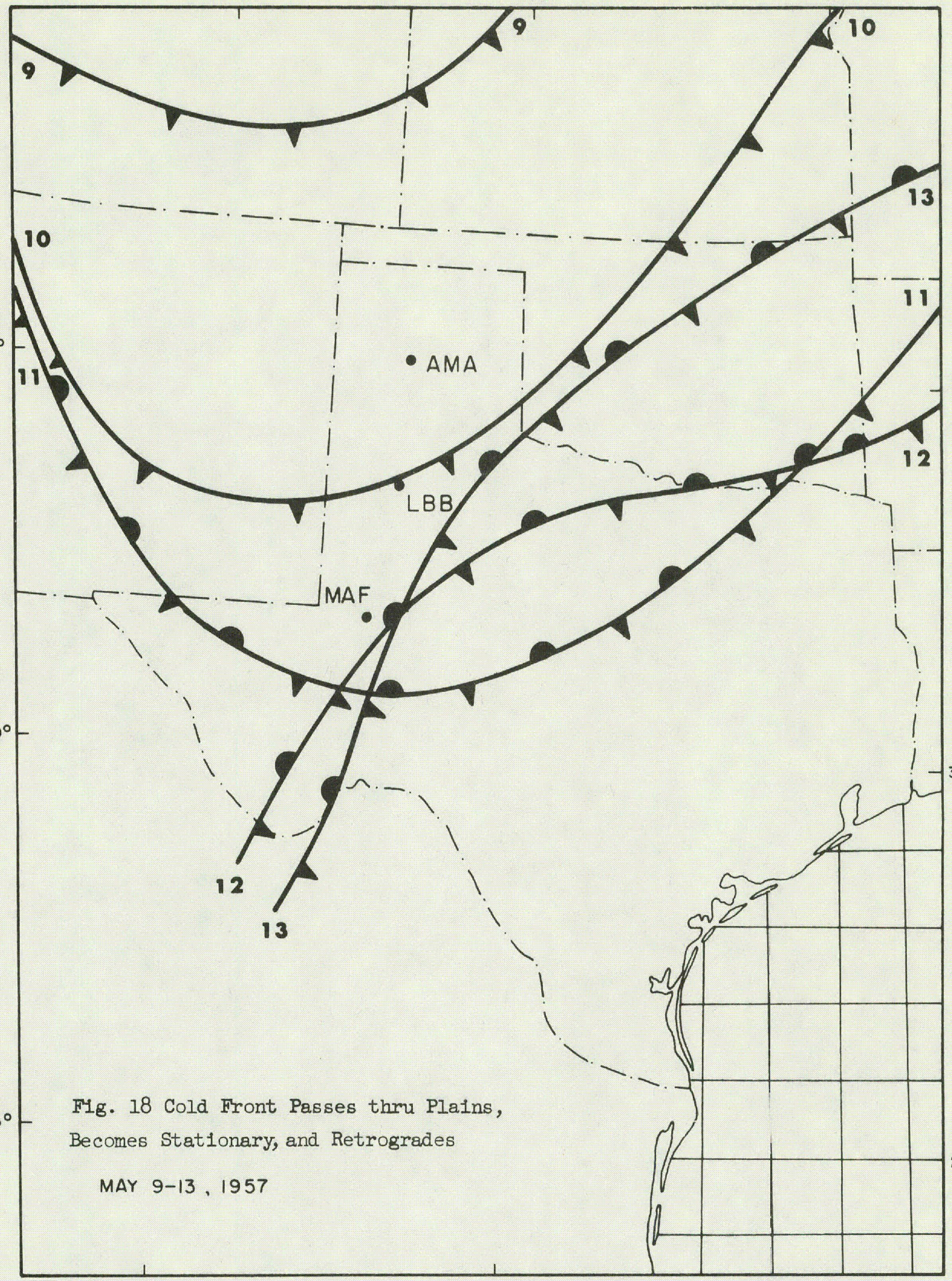


Fig. 18 Cold Front Passes thru Plains, Becomes Stationary, and Retrogrades

MAY 9-13, 1957

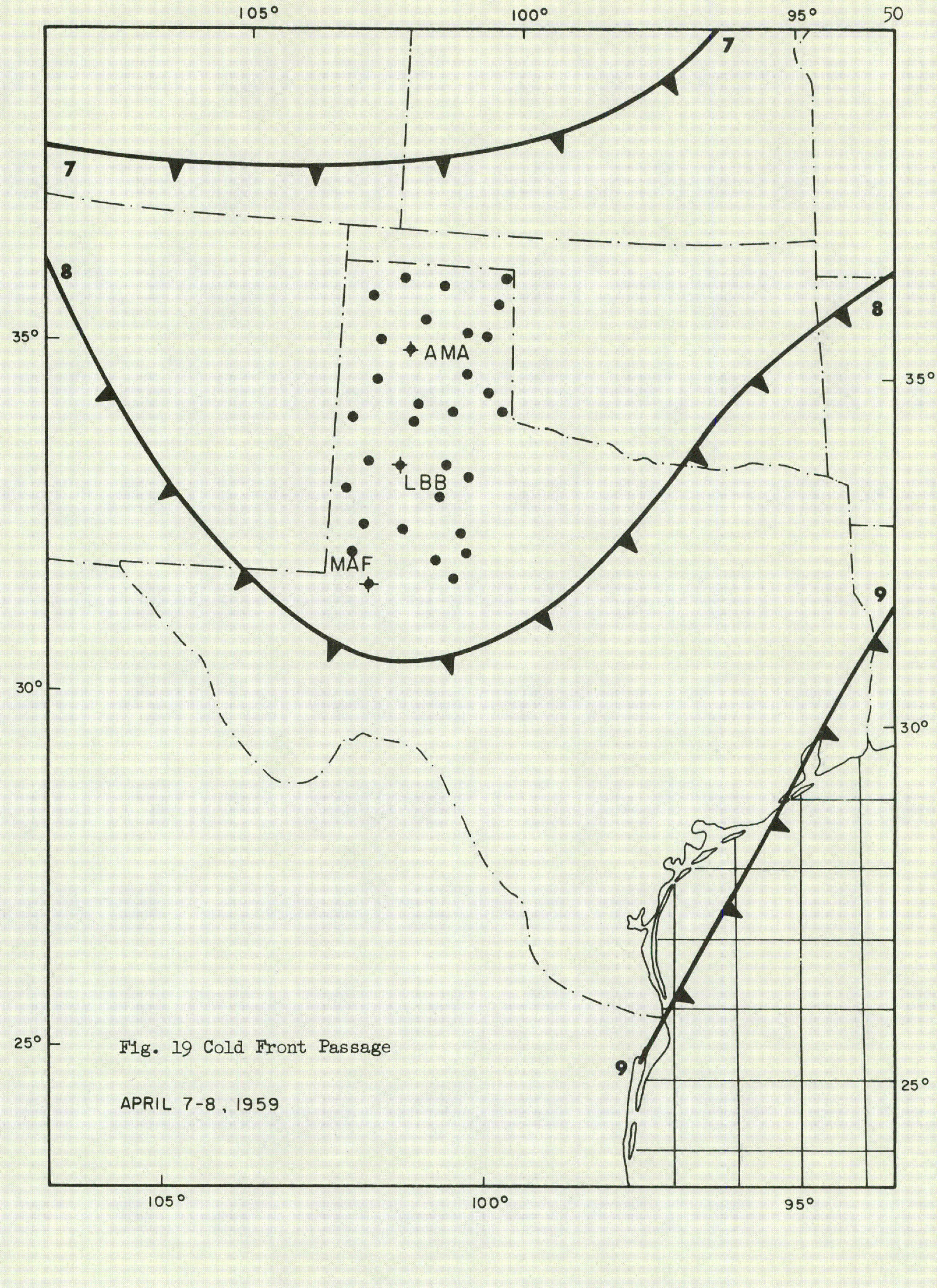


Fig. 19 Cold Front Passage

APRIL 7-8, 1959

this situation a cold front moves through the plains area and becomes stationary in north-central Texas. In many instances the front begins a retrograde movement, setting off warm-front type continuous precipitation over a wide area caused by warm, moist Gulf air overrunning a shallow layer of colder air at the ground. In situations of this type, light to moderate precipitation may fall intermittently for a period of five days or more. The slow, steady precipitation coupled with the lack of damaging wind and hail makes this a favorable pattern for agriculture.

The third pattern is a squall line passage not in association with a frontal system at the surface. This situation is usually connected with a closed low at upper levels to the west of the precipitation area. Cold impulses spawned by this system set off strong convection in the warm moist air mass at the surface. This, on some occasions, becomes a "metastable" situation characterized by a series of short waves setting off squall line activity at irregular intervals over a period of several days. The weather in this case may be quite severe, with strong winds, hail and occasional tornadoes.

The fourth pattern, illustrated in Figure 19, is a fast-moving cold front, more characteristic of winter, which affects the area for no more than a one day period as it moves rapidly southward. Precipitation is usually moderate during the passage of the front and gives way to clear skies shortly thereafter.

With the onset of summer, the Atlantic anticyclone extends westward, increasing upper level stability and, thus, inhibiting strong vertical development. This limits most precipitation to scattered showers which depend upon low level moisture and daytime heating. Showers in these instances may be extremely isolated, and, while they may be locally heavy in some areas, they rarely lead to large amounts of precipitation when averaged over the entire study area. In some cases, lessening of the upper-level stability coupled with strong surface heating and convergence can produce general shower activity over large areas. Even though these showers may be highly localized, their continuous development may lead to a significant deposit of precipitation.

It is more likely, however, that general rainfall patterns in summer are associated with frontal activity, and are relatively rare. A typical pattern is a cold front which passes through the plains area, decelerates, and becomes successively more diffuse as it moves southward, usually becoming stationary by the time it reaches the coast. Weather associated with the frontal passage is usually less severe than in the spring, but significant rainfall usually results. In some instances precipitation is prolonged when the front becomes stationary in central Texas and an overrunning pattern is established. A similar situation occurs when the front becomes stationary in the plains area and frontolysis subsequently takes place. Precipitation which occurs with this type of development is usually light to moderate and may last for a day or more. Heavier amounts of precipitation may occur with the passage of squall lines which form in association with some of the summer frontal activity. While these are usually not as severe as in the spring, they nevertheless may lead to heavy rain showers and occasional severe weather.

Frontal activity is again the prime cause of precipitation during the fall. This is especially true after mid-October when much of the rainfall is brought about by warm moist maritime tropical air from the Gulf overrunning continental polar air which has been swept southward. Occasionally, the cold air invades the region so repeatedly that there is little opportunity for return flow of Gulf moisture. These frontal systems are called dry northers. Early autumn rainfall, as was mentioned earlier, is due primarily to tropical disturbances moving northwestward from the Gulf of Mexico.

C. Clouds Characteristic of Rain Periods

An analysis of cloud types associated with periods of general precipitation in the Texas plains was carried out using the data described in the previous section. Cloud types were tabulated for each of the three seasons of interest to this investigation. The results are shown in Table 1. Entries in the table give the percentage of three-hourly observations which included reports of a particular cloud type.

Table 1. Clouds Characteristic of Rain Periods

Cloud Type	Spring	Summer	Fall
St	34%	23%	50%
Sc	15	13	14
Cu	26	24	7
Cb	15	24	5
As	5	3	3
Ac	19	33	9
Ci	26	38	8
Cs	4	5	1

No distinction was made in this analysis between precipitation regimes associated with different types of synoptic events. Also, it must be remembered that many of the clouds reported are in no way related to the occurrence of precipitation. For instance, stratus is the most abundant cloud type during rainy periods in the spring. This might lead one to conclude that most springtime precipitation is associated with stratus clouds. In Section II it was pointed out, however, that stratus is characteristic of early spring mornings at Amarillo and may have little or no relationship to precipitation except that it indicates the presence of low-level moisture.

As will be shown later in this section, most of the springtime precipitation is associated with cumulonimbus development. The figure of 15% in this case may be misleading for two reasons. In the first place, observations are made only at three hour intervals within the longer period characterized by general precipitation, and in order to be reported, a cloud must be present at the time of the observation. Secondly, cumulonimbus may be present in the area and not be reported if another type of cloud dominates the sky. An interesting feature which was noted in the spring is related to sky condition three hours prior to the formation of cumulonimbus clouds. There was definite evidence that cumulonimbus were more likely when cirrus clouds were present initially in conjunction with some form of cumulus. This became more evident in summer where, in 60% of the cases, cumulonimbus development was preceded by the combination of cumulus and cirrus clouds. This suggests that the cirrus clouds may be serving as a "seeder" in some way to enhance the development of cumulonimbus. The value of 60% is a conservative estimate, since, in some instances it is impossible to observe the presence of cirrus clouds. It would be helpful to check this result using hourly data which were not available to this investigation.

Note that during the fall rainy periods, stratus clouds were reported 50% of the time. This figure represents a combination of early morning stratus which may not reflect precipitation development, and stratus in association with cyclonic activity characteristic of this time of year. The small percentages for the other cloud types is no doubt affected by the observational difficulties associated with a stratus overcast.

It was decided that a more representative indicator of the relationship between cloud type and precipitation would be a rank-correlation analysis between these two variables. This type of analysis concerns items which are arranged in order of size or quantity although the exact size or quantity is not considered. In order to perform the analysis, data from each of the three stations were used to calculate mean monthly precipitation and mean monthly frequency of occurrence of the different cloud types. The months were then ranked according to the values of precipitation and cloud frequency. Consequently, each month is represented by numbers denoting its rank with respect to precipitation and its rank with respect to each of the eight most common cloud types. The month with the greatest mean monthly precipitation was ranked "1", the next highest was ranked "2" and so on until all of the months had been ranked. A similar procedure was applied to the cloud types. A correlation analysis was then made between the ranks in order to show which cloud types were most closely related to the occurrence of precipitation.

The rank correlation coefficient is given by

$$r = 1 - \frac{6 \sum (m - n)^2}{N (N^2 - 1)}$$

where m is the cloud frequency rank, n is the precipitation rank, and N is the number of pairs of observations considered in the analysis. The above equation is derived in Appendix III.

The correlations were performed according to seasons. The divisions were the classical ones of winter (Dec-Jan-Feb), spring (March-Apr-May), summer (June-July-Aug), and fall (Sept-Oct-Nov). Ten years of data were used for Amarillo and Lubbock while only eight years were available at Midland. Thus the rank correlation coefficients derived for Amarillo and Lubbock were based on 30 pairs while the results at Midland are based on only 24 pairs. Results of the investigation are shown in Table 2.

Two correlations were actually performed for each cloud type. Type 1 refers to the procedure, discussed above, of correlating precipitation with cloud frequency. Type 2 represents a correlation of precipitation with the reported amounts of the different cloud types. In most instances there is very little difference between the coefficients. Notable exceptions occur for summer cirrus and cumulus at Amarillo, and fall cumulonimbus at Midland. It is difficult to comment on the apparent discrepancy in the cirrus correlation at Amarillo because of the difficulties involved in observing cirrus, especially

Table 2. Rank Correlation Coefficients
of Precipitation and Cloud Frequency

Type	AMARILLO							
I	Winter		Spring		Summer		Fall	
(cloud frequency)	r	Type	r	Type	r	Type	r	Type
	0.54	St	0.74	St	0.56	Cb	0.70	St
	0.38	As	0.70	Cb	0.51	St	0.55	Cb
	0.17	Ac	0.47	Ac	0.31	Ci	0.50	Sc
	0.13	Sc	0.44	Cu	0.28	Sc	0.48	Ac
	0.02	Cs	0.32	Sc	0.06	As	0.42	Cu
	-0.28	Ci	0.11	Ci	-0.01	Ac	0.01	As
			0.09	As	-0.06	Cu	-0.06	Ci
			-0.19	Cs	-0.20	Cs	-0.23	Cs
II	0.53	As	0.73	Cb	0.65	Cb	0.70	St
(cloud amount)	0.46	St	0.68	St	0.42	St	0.62	Cb
	0.27	Ac	0.44	Cu	0.42	Sc	0.51	Sc
	0.10	Sc	0.29	Sc	0.27	Cu	0.42	Cu
	0.02	Cs	0.27	Ac	0.08	Ac	0.41	Ac
	-0.13	Ci	0.10	Ci	0.02	As	0.02	As
			0.07	As	-0.05	Ci	-0.02	Ci
			-0.23	Cs	-0.58	Cs	-0.26	Cs

Type	LUBBOCK							
I	Winter		Spring		Summer		Fall	
(cloud frequency)	r	Type	r	Type	r	Type	r	Type
	0.54	St	0.81	Cb	0.47	Sc	0.75	St
	0.28	Sc	0.68	Sc	0.36	St	0.59	Sc
	0.19	Ac	0.65	Cu	0.34	Cb	0.48	Cb
	0.04	Ci	0.58	St	0.11	As	0.36	Cu
	-0.14	As	0.10	Ci	-0.03	Ac	0.35	As
	-0.20	Cs	0.10	As	-0.04	Cs	0.15	Cs
			0.03	Ac	-0.15	Ci	-0.01	Ac
			-0.33	Cs	-0.24	Cu	-0.10	Ci

Table 2. Rank Correlation Coefficients

of Precipitation and Cloud Frequency

(Continued)

Type	LUBBOCK							
II	Winter		Spring		Summer		Fall	
(cloud amount)	r	Type	r	Type	r	Type	r	Type
	0.55	St	0.77	Cb	0.47	Cb	0.71	St
	0.27	Ac	0.66	Cu	0.46	St	0.53	Sc
	0.21	Sc	0.56	St	0.41	Sc	0.51	Cb
	0.11	Ci	0.53	Sc	0.18	Ac	0.42	As
	-0.11	As	0.15	Ci	0.09	As	0.41	Cu
	-0.16	Cs	0.06	As	-0.01	Cu	0.24	Cs
			-0.06	Ac	-0.01	Ci	0.19	Ac
			-0.40	Cs	-0.04	Cs	-0.05	Ci

Type	MIDLAND							
I	Winter		Spring		Summer		Fall	
(cloud frequency)	r	Type	r	Type	r	Type	r	Type
	0.62	Sc	0.90	Cb	0.51	Sc	0.53	Sc
	0.59	St	0.85	Cu	0.47	St	0.43	As
	0.07	Ac	0.33	Sc	0.41	Cb	0.42	St
	-0.02	As	0.30	St	0.40	As	0.42	Cb
	-0.02	Cs	0.17	Ci	0.25	Ci	0.31	Cu
	-0.31	Ci	-0.08	Ac	0.22	Cu	0.15	Ac
			-0.14	Cs	0.08	Ac	0.15	Cs
			-0.38	As	-0.01	Cs	-0.03	Ci
II	0.62	Sc	0.90	Cb	0.57	Sc	0.62	Cb
(cloud amount)	0.60	St	0.77	Cu	0.52	Cb	0.53	St
	0.18	As	0.34	Sc	0.46	St	0.51	Sc
	-0.02	Ac	0.26	St	0.40	Cu	0.35	As
	-0.14	Cs	0.20	Ac	0.27	As	0.33	Cu
	-0.17	Ci	-0.07	Ci	0.19	Ci	0.29	Ac
			-0.27	As	0.05	Ac	0.12	Ci
			-0.38	Cs	-0.01	Cs	0.05	Cs

the amount, in the presence of other clouds. Cumulus clouds are characteristic of summer at each of the stations and are not always indicative of precipitation. The significantly higher correlation coefficient at Amarillo in the case of the Type 2 correlation is probably related to the fact that higher amounts of cumulus indicate more substantial convective activity and a higher probability of the formation of cumulonimbus and precipitation. Note that the cumulus-precipitation correlation is higher in the case of Type 2 also at Midland. At Lubbock the coefficients are both negative and difficult to interpret. The higher correlation with cumulonimbus by the Type 2 process in the fall at Midland is probably indicative of the increase in precipitation probability with an increase in the amount of convective activity associated with larger amounts of cumulonimbus.

Winter precipitation at each station is associated with stratiform clouds which develop in conjunction with cyclonic activity characteristic of the season. The relatively high correlation with stratocumulus at Midland is indicative of greater vertical development in the winter clouds at this station. Note that the correlation with stratocumulus decreases in going north from Midland through Lubbock to Amarillo.

Spring and summer precipitation is most highly correlated with cumuliform clouds characteristic of convective activity. The relatively high coefficients in the case of stratus probably reflects both a correlation between precipitation and low-level moisture, and the association of stratus with frontal passages.

Fall precipitation is probably the most difficult tc define. Convective activity associated with low-level moisture and daytime heating continue during the early fall. This, coupled with convective showers set off by frontal activity, is responsible for the significant correlations with cumulus and cumulonimbus. The high correlation with stratus is once again due in part to nocturnal cooling in the presence of low-level moisture; however, stratiform clouds are also associated with weak frontal passages and with systems generated by tropical activity which generally lead to stable-type precipitation in the plains area.

The highest correlations were in the spring with cumulonimbus, while the lowest coefficients were derived for the winter season. The highest correlation during winter was with stratiform type clouds. The summer pattern is much the same as spring except that the coefficients are much lower due to the fact that summer air-mass convective showers are so widely scattered. The highest correlation during the fall is with stratiform clouds in conjunction with cyclonic activity. Cumulonimbus clouds are still prevalent, however, especially in the Midland area, where cumulonimbus had the highest coefficient in the fall.

D. Precipitable Water Vapor

It is obvious that precipitation must be a function of the amount of water contained in the atmosphere. One measure of atmospheric water content is "precipitable water". By definition, precipitable water vapor is the depth of water that would be accumulated on a flat, level surface of unit area if all of the water vapor in a column of the atmosphere were condensed and precipitated. Thus, the precipitable water vapor in a column of air may be expressed as the total mass, P_v , of water per unit area in the column. Thus,

$$P_v = \int_{z_1}^{z_2} \rho_v \, \delta z = - \int_{p_1}^{p_2} \frac{\rho_v}{g\rho} \, \delta p$$

where ρ is the density of the air, ρ_v the density of the water vapor, p is atmospheric pressure and g is the acceleration of gravity. Since specific humidity, q, is defined as the ratio of the density of water vapor to the density of moist air, the above relationship may be expressed as

$$P_v = - \frac{1}{g} \int_1^2 q \, \delta p \approx - \frac{1}{g} \int_1^2 m \, \delta p$$

where m is the mixing ratio, defined as the ratio of the density of water vapor to the density of dry air.

In practice, the formula used in calculating precipitable water from an actual atmospheric sounding is

$$P_{v_i} = \frac{\overline{q}_i \, \Delta p_i}{g}$$

where P_{v_i} is the precipitable water contained in a layer of atmosphere Δp_i pressure units thick. The total precipitable water is then the sum of the precipitable water contained in each layer, or

$$P_v = \sum_i P_{v_i}$$

Precipitable water is usually expressed as a length unit (cm) instead of a mass unit. This is permissible since in the cgs system the density of water is unity, making length and mass numerically equivalent in unit cross section.

In a recent report, Baker (1969) has made a statistical study of the depth of precipitable water for five stations in western Texas and eastern New Mexico. He found that a normal distribution adjusted for skewness and kurtosis may be used to describe adequately the frequency distribution of the observed depths of precipitable water grouped by pentads (5 day intervals). The data for February 29 were neglected so that the data for one year could be grouped into 73 pentads. Two of the stations used in the study, Amarillo and Big Spring are located in the area being investigated in the present research. The period on which the statistics were based at Amarillo was from July 1952 through May 1965 while at Big Spring the period of record was from July 1949 through May 1965.

The statistics derived by Baker have been used in the present investigation to construct percentage frequency ogives for precipitable water at Amarillo and Big Spring. For the purposes of this study, the data at Big Spring are considered to be applicable to Midland, since the stations are only 35 miles apart.

The frequency ogives for the seven months under investigation are shown in Figure 20 for Amarillo and Figure 21 for Big Spring. The curves indicate that at both stations, precipitable water increased from April to a maximum in July and August and then decreased during September and October. These curves will be used extensively in the next two sections as a standard to compare precipitable water amounts during characteristically wet and dry periods in the plains area.

In order to get some idea of the role played by precipitable water in affecting precipitation, it was decided to compare measured precipitable

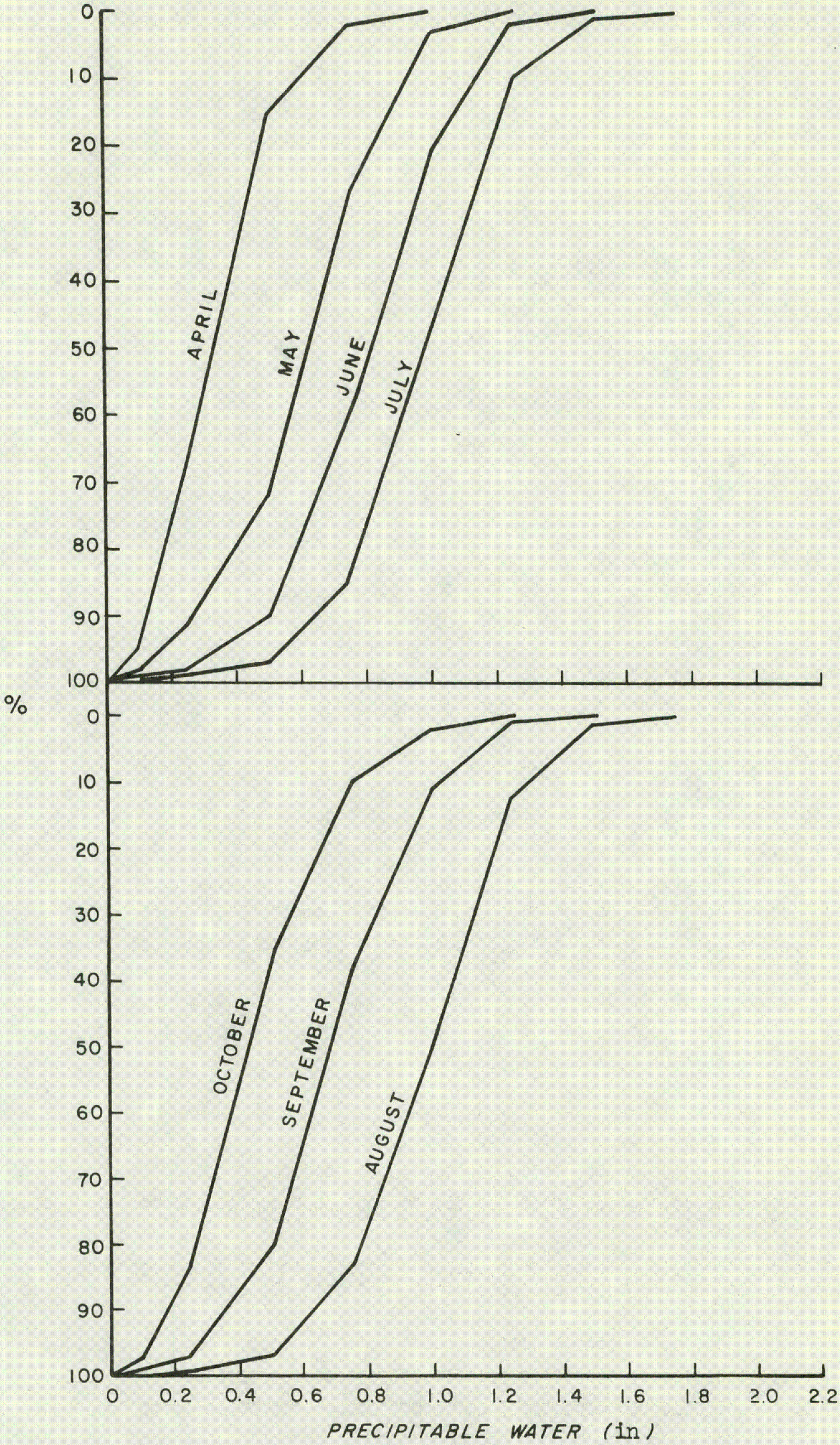


Fig. 20 Precipitable Water Percentage Ogives

Amarillo July 1952 - May 1965

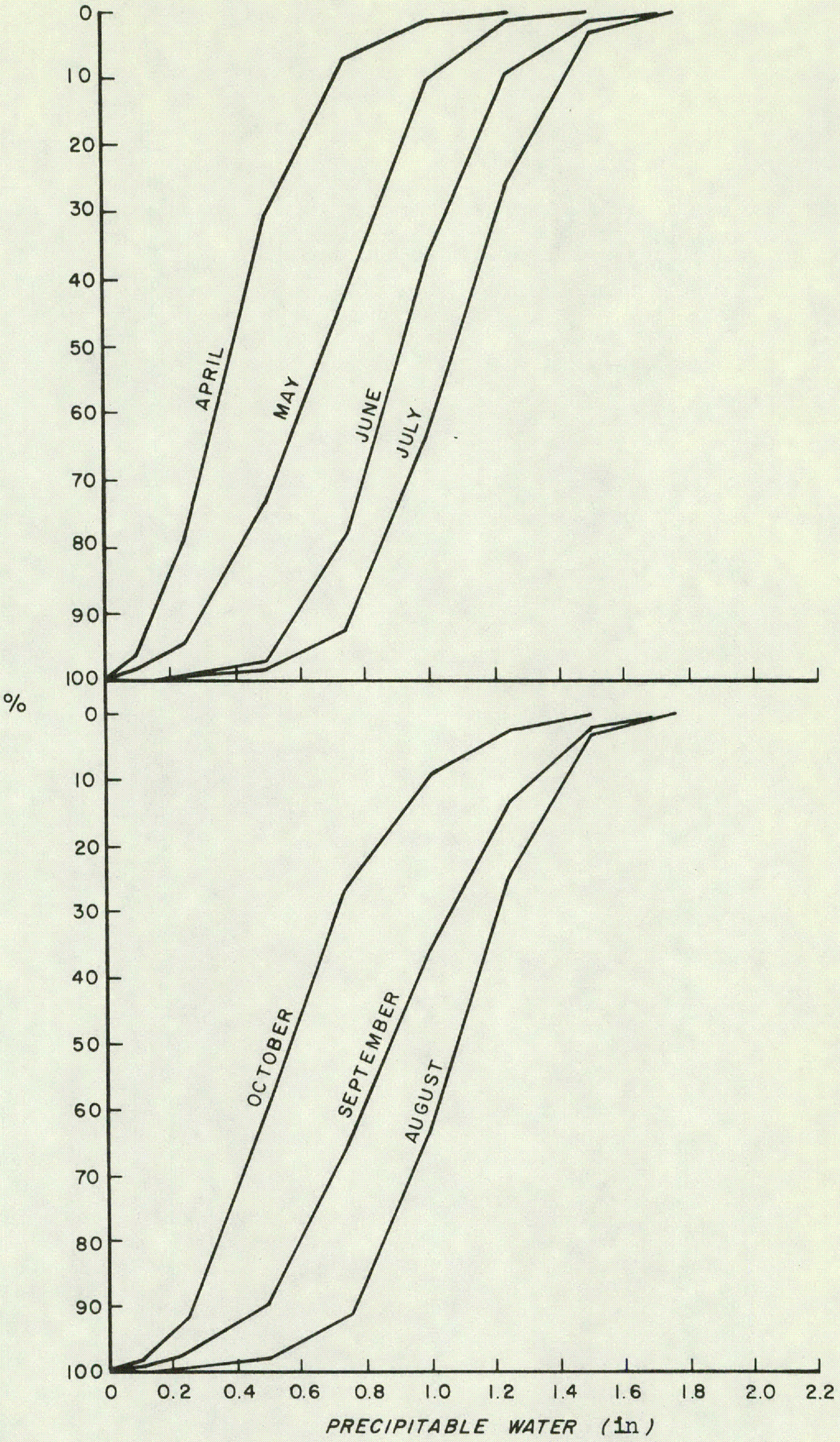


Fig. 21 Precipitable Water Percentage Ogives

Big Spring July 1949 - May 1965

water with the expected values derived from Baker's data for some of the major precipitation periods. The results of this study are shown in Tables 3, 4, and 5 for spring, fall, and summer, respectively. Reitan (1957) has shown that the summer rainfall in Arizona and the southwest is primarily determined by the moisture content of the air over the state. An inspection of the tables indicates that above-normal precipitable water is also characteristic of significant rainfall in the Texas plains. Column 8 in the tables gives the percentage of time that precipitable water would be expected to be greater than the observed value based on the distribution derived by Baker. On only 10% of the days was the value of precipitable water less than the median of the distribution. On the average, the probability of a day with greater precipitable water was 23% for spring and summer and 15% for the fall.

E. Atmospheric Stability

In dealing with atmospheric motions responsible for the production of clouds and precipitation, it is important to realize the role played by stability. Showalter (1953) has derived an extremely simple, thermodynamically sound and easily understood tool for making a very rapid check on convective instability.

The Showalter stability index is computed as follows: The 850 mb parcel is lifted dry adiabatically to saturation and then pseudo-adiabatically to 500 mb. The lifted 500 mb temperature is then subtracted algebraically from the observed 500 mb temperature. A negative number indicates instability (rising air warmer than its surroundings) and a positive number indicates stability in the atmospheric layer from 850 mb to 500 mb. Experience has indicated that any positive index of 3° or less is very likely to be associated with showers and quite likely to produce thunderstorms. Thunderstorms have increasing probability as the index falls from 1° to -2°. Negative values of -3° or greater may be indicative of severe thunderstorms.

Stability indices were computed for the selected rain periods discussed earlier and are given in column 9 of Tables 3, 4, and 5. Note that the values are lowest during summer and highest in the fall. Admittedly, the determination of the Showalter index in the colder months of the year is somewhat dubious, but it does serve to illustrate a comparison between wet and dry periods. Stability during dry periods will be discussed in Sections IV and V. Based on the criterion that any positive index of 3° or less is very likely to be associated

Table 3. Precipitable Water (cm) and Stability Index for Spring Precipitation Periods

AMARILLO								
Yr	Date	Sfc-850	850-700	700-500	500-400	Total	% above	Stability Index
57	Apr 26	0.215	0.606	0.427	0.048	1.30	25%	+7.4
	27	0.369	0.801	0.312	0.023	1.50	21	-1.1
	28	0.299	0.729	0.469	0.079	1.58	19	+5.8
	29	0.388	0.899	0.634	0.149	2.07	10	+3.7
	May 9	0.385	1.079	0.680	0.074	2.22	25	+3.8
	10	0.391	1.204	0.749	0.067	2.41	15	+6.0
	12	0.233	0.686	0.377	0.058	1.35	42	+8.0
	13	0.281	0.773	0.433	0.042	1.53	31	+2.5
	30	0.191	0.385	0.277	0.058	0.91	73	-0.4
	31	0.199	0.555	0.245	0.037	1.04	45	+1.3
58	May 12	0.358	0.884	0.593	0.094	1.93	17	-1.7
	13	0.464	1.131	0.595	0.082	2.27	7	-1.3
	14	0.507	0.924	0.332	0.036	1.80	22	+0.7
59	Apr 7	0.258	0.950	0.630	0.144	1.98	1	-2.3
	8	0.177	0.564	0.447	0.038	1.23	11	+2.2
60	May 30	0.479	1.193	0.816	0.143	2.63	7	+1.8
	31	0.453	1.019	0.678	0.115	2.26	24	+2.5
					Mean	1.77	23%	+2.3

Table 4. Precipitable Water (cm) and Stability Index for Fall Precipitation Periods

AMARILLO								
Yr	Date	Sfc-850	850-700	700-500	500-400	Total	% above	Stability Index
57	Oct 20	0.275	0.838	0.718	0.102	1.93	11%	+8.0
	21	0.287	0.807	0.566	0.037	1.70	19	+12.9
	22	0.388	0.990	0.459	0.045	1.88	12	+1.8
	23	0.223	0.563	0.353	0.029	1.17	42	+6.4
58	Sept 15	0.541	1.268	0.425	0.056	2.29	24	-0.9
	16	0.403	1.116	0.906	0.160	2.58	11	+4.8
59	Oct 30	0.223	0.823	0.780	0.145	1.97	1	+12.0
	31	0.282	0.952	0.664	0.037	1.94	1	+9.4

Table 4. Precipitable Water (cm) and Stability Index for Fall Precipitation Periods (Continued)

AMARILLO								
Yr	Date	SFc-850	850-700	700-500	500-400	Total	% above	Stability Index
60	Oct 15	0.317	0.889	0.467	0.030	1.70	23	+4.0
	16	0.333	0.892	0.561	0.030	1.82	19	+5.0
	17	0.382	1.119	0.884	0.158	2.54	1	+4.5
	18	0.352	0.961	0.514	0.040	1.87	12	+4.0
					Mean	1.95	15%	+6.0

Table 5. Precipitable Water (cm) and Stability Index for Summer Precipitation Periods

AMARILLO								
Yr	Date	Sfc-850	850-700	700-500	500-400	Total	% above	Stability Index
57	June 23	0.485	1.339	1.131	0.217	3.17	2%	+2.5
	24	0.486	1.147	0.691	0.043	2.37	35	+4.0
	Aug 14	0.490	1.253	0.983	0.182	2.91	32	+0.3
	15	0.520	1.254	0.947	0.124	2.84	36	+0.1
58	June 21	0.499	1.516	1.172	0.268	3.46	1	-2.0
	22	0.397	1.329	0.908	0.049	2.68	20	+4.0
	23	0.624	1.572	1.006	0.082	3.28	2	-2.2
	24	0.264	1.100	0.746	0.106	2.22	42	+0.7
	July 3	0.534	1.520	1.059	0.152	3.26	6	-0.1
	4	0.482	1.080	0.452	0.044	2.06	73	-2.0
	5	0.527	1.665	1.315	0.212	3.72	4	+0.8
	25	0.533	1.180	0.830	0.105	2.65	38	+2.0
	26	0.489	1.230	0.845	0.097	2.66	38	-1.0
	27	0.478	1.087	0.642	0.124	2.33	60	+1.9
	28	0.657	1.513	1.033	0.213	3.42	5	-2.3
59	June 22	0.537	1.421	1.006	0.233	3.20	2	-1.8
	23	0.592	1.609	1.225	0.295	3.72	< 1	-1.2
	July 14	0.533	1.395	1.188	0.260	3.38	6	0.0
	15	0.487	1.131	0.630	0.053	2.30	62	+2.6
	16	0.589	1.204	0.442	0.054	2.29	62	-0.9
	17	0.519	1.278	1.041	0.275	3.11	13	+1.2

Table 5. Precipitable Water (cm) and Stability Index
for Summer Precipitation Periods
(Continued)

AMARILLO								
Yr	Date	Sfc-850	850-700	700-500	500-400	Total	% above	Stability Index
60	July 4	0.514	1.313	0.919	0.214	2.96	20	-0.5
	5	0.588	1.510	1.183	0.277	3.56	7	+1.1
	6	0.601	1.458	1.052	0.213	3.32	13	+0.6
	7	0.634	1.555	1.262	0.309	3.76	3	+1.6
	8	0.636	1.521	1.071	0.201	3.43	10	+1.1
	9	0.601	1.426	0.896	0.193	3.12	18	+1.2
	Aug 9	0.597	1.390	1.023	0.266	3.28	9	-1.8
	10	0.574	1.431	1.163	0.201	3.36	8	+4.8
	11	0.531	1.213	0.686	0.045	2.48	54	+2.5
					Mean	3.01	23%	+0.6

with showers, precipitation could have been expected in 60% of the spring cases, 87% of the summer cases, and 17% of the fall cases. The mean stability indices were 2.3, 0.6, and 6.0 for spring, summer and fall respectively. It is interesting to compare these values to those computed by Semonin (1960) for average conditions over a 5-year period at Rantoul, Illinois. His calculations show a mean stability index for spring of 8.5, for summer of 4.0 and for fall of 8.0. While direct comparison is probably not advisable, it is apparent that the values for wet periods in the Texas plains are indicative of greater instability.

It should be noted that not all cases of convective instability will show a negative stability index, since the technique selects only the more pronounced cases of convective instability (Showalter, 1953). It is possible to have convective instability when the index is 6° if the air is quite dry at 500 mb. However, such cases might offer more resistance to convection than can be realized by the usual lifting mechanisms.

IV. A STUDY OF SOME CHARACTERISTICALLY WET AND DRY MONTHS IN THE TEXAS PLAINS

Thus far the investigation has been limited to a discussion of characteristic cloud types and amounts in the plains, their relation to some selected synoptic events producing precipitation, and computed values of precipitable water and stability during these periods.

It is the purpose of this section to compare some characteristically wet and dry months on the basis of clouds, precipitable water, water vapor flux, and synoptic situation, to obtain some idea of the role played by each in the production of precipitation.

A. Selection of Periods for Study

Maps of the total monthly precipitation over the plains area were constructed for each of the seven months considered in the investigation (April thru October) during the period from 1952 until 1960. Seventy stations were used in the analyses. On the basis of these 63 maps, months of maximum and minimum precipitation were selected for intensive study. The months selected are shown in Table 6.

As was shown in Figure 2, the period from 1952 until 1961 was composed of 5 years of below-normal precipitation and 5 years of above-normal precipitation so that the probability of finding a representative wet and dry month for each of the seven months studied was enhanced.

Table 6. Selected Wet and Dry Months in the Texas Plains

Month	Wet	Dry
April	1957	1956
May	1957	1953
June	1960	1953
July	1960	1957
August	1957	1956
September	1958	1956
October	1960	1952

In order to determine if the months selected were characteristically wet and dry with respect to the long-term mean monthly precipitation, comparison was made to the ogives in Figures 16 and 17. This comparison makes it possible to determine the percentage of time that the monthly precipitation during the period from 1892 until 1968 was greater (or less) than the month being considered at Amarillo. At Lubbock the long term mean is based on the period from 1911 until 1968. The results of this comparison are shown in Table 7, which also shows the mean monthly precipitation based on 30 years of data for 28 selected stations, and the total monthly precipitation for the wet and dry months based on these same 28 stations. Columns 4, 5, 7 and 8 are based on the longer periods of record at Amarillo and Lubbock.

Table 7. Precipitation During Wet and Dry Months

Month	Mean	Dry	% Above AMA	% Above LBB	Wet	% Above AMA	% Above LBB
April	1.57	0.28	90	86	3.43	8	7
May	3.32	1.09	86	82	5.39	13	11
June	2.60	0.66	89	83	4.39	20	20
July	2.48	1.23	78	68	6.65	7	2
August	2.15	0.91	83	72	2.01	67	44
September	2.04	0.13	96	96	2.63	34	36
October	2.05	0.00	100	100	5.35	5	9

As an example in interpreting the table, note that the total precipitation for the dry April (1956) was 0.28 inches while that for the wet April (1957) was 3.43 inches. This compares to a 30-year mean precipitation of 1.57 inches. Comparing these values with the ogives based on the total period of record it is shown that 90% of the months at Amarillo had greater amounts of precipitation than the dry month considered in this research. At Lubbock, 86% of the months were greater. As far as the wet month is concerned, only 8% of the Aprils at Amarillo and 7% of the Aprils at Lubbock had more precipitation than the wet month considered in this research.

In general, it can be seen that the months selected as being characteristic of wet and dry periods were truly representative. The only exception is the wet August. Note that 67% of the Augusts at Amarillo and 44% of Lubbock had a greater amount of precipitation than August 1957. This indicates that there were no Augusts during the period from 1952 until 1960 which had excessive precipitation compared to the long-term mean. Note that in the case of October 1952 there was no measurable precipitation during the month. This month is the driest month on record for the entire United States (Namias, 1960).

B. Clouds During Wet and Dry Months

Tables 8 and 9 are tabulations of cloud frequency and amount for wet and dry months at Amarillo and Lubbock respectively. With the exception of

Table 8. A Comparison of Cloudiness During Dry and Wet Months

AMARILLO

Date	Cloud Type	Frequency			Amount		
		Mean	Dry	Wet	Mean	Dry	Wet
April	St	22.7	6	71	154.0	41	540
Dry '56	Sc	30.2	16	32	190.2	100	189
Wet '57	Cu	26.5	27	29	54.6	35	83
	Cb	9.4	4	10	29.7	7	43
	As	7.5	9	16	42.3	55	73
	Ac	42.5	32	33	153.9	144	108
	Ci	75.0	83	62	277.9	259	248
	Cs	22.1	15	39	165.7	95	256
May	St	27.3	12	55	189.7	96	369
Dry '53	Sc	25.2	32	35	134.7	157	167
Wet '57	Cu	45.5	52	48	98.0	121	114
	Cb	29.0	13	22	97.7	29	77
	As	4.6	6	5	29.7	34	31
	Ac	59.0	42	67	191.3	124	226
	Ci	105.2	115	88	369.4	381	293
	Cs	16.9	38	14	121.6	282	91
June	St	10.7	6	17	61.1	30	101
Dry '53	Sc	16.4	15	17	81.9	44	75
Wet '60	Cu	54.6	47	36	107.6	98	97
	Cb	40.6	24	46	107.0	57	163
	As	4.0	1	7	27.5	10	53
	Ac	71.1	50	61	194.2	101	198
	Ci	103.5	77	117	305.4	247	325
	Cs	10.9	15	6	78.2	114	26

Table 8. A Comparison of Cloudiness During Dry and Wet Months

(Continued)

AMARILLO

Date	Cloud Type	Frequency Mean	Dry	Wet	Amount Mean	Dry	Wet
July	St	8.9	2	35	48.0	4	257
Dry '57 Wet '60	Sc	10.8	7	13	48.6	9	75
	Cu	66.0	76	55	148.3	172	149
	Cb	48.7	29	42	119.5	51	91
	As	3.2	0	2	19.1	0	8
	Ac	96.7	75	62	298.7	198	181
	Ci	131.4	142	126	355.7	335	330
	Cs	12.1	19	6	71.5	92	49
Aug	St	7.3	7	11	38.8	58	60
Dry '56 Wet '57	Sc	11.1	6	16	39.2	20	47
	Cu	66.0	63	65	136.6	119	172
	Cb	42.3	30	33	94.8	59	114
	As	2.5	2	4	19.4	4	21
	Ac	107.6	76	110	308.7	170	406
	Ci	117.3	142	123	299.0	424	250
	Cs	11.1	10	5	72.0	72	21
Sept	St	13.6	4	38	93.4	40	209
Dry '56 Wet '58	Sc	15.5	3	27	81.5	6	184
	Cu	33.3	18	41	57.6	12	142
	Cb	21.3	10	34	37.5	27	35
	As	3.0	1	5	22.1	7	41
	Ac	70.2	40	82	187.1	55	316
	Ci	65.6	59	83	149.7	156	192
	Cs	5.7	2	10	36.0	12	69

Table 8. A Comparison of Cloudiness During Dry and Wet Months

(Continued)

AMARILLO

Date	Cloud Type	Frequency Mean	Dry	Wet	Amount Mean	Dry	Wet
Oct	St	24.2	1	41	178.1	10	341
Dry '52 Wet '60	Sc	23.8	4	21	122.8	30	106
	Cu	13.1	4	14	21.3	1	17
	Cb	9.1	0	21	26.5	0	77
	As	5.2	4	0	39.0	38	0
	Ac	45.9	30	49	151.9	82	144
	Ci	68.7	58	60	173.1	96	117
	Cs	10.1	4	4	69.0	31	10

Table 9. A Comparison of Cloudiness During Dry and Wet Months

LUBBOCK

Date	Cloud Type	Frequency Mean	Frequency Dry	Frequency Wet	Amount Mean	Amount Dry	Amount Wet
April	St	13.4	2	43	101.1	20	349
Dry '56	Sc	31.4	26	53	204.3	195	325
Wet '57	Cu	19.9	21	16	46.3	34	78
	Cb	7.1	4	12	30.1	4	73
	As	3.3	3	6	22.8	28	46
	Ac	39.4	54	33	161.7	220	129
	Ci	63.0	55	73	244.2	151	321
	Cs	17.3	16	12	134.3	140	101
May	St	13.4	11	19	104.6	93	137
Dry '53	Sc	30.7	27	47	197.6	190	335
Wet '57	Cu	38.1	38	47	89.2	73	160
	Cb	26.3	10	26	106.6	51	129
	As	2.3	6	2	14.1	29	13
	Ac	49.6	21	44	178.6	83	183
	Ci	77.4	75	56	282.4	332	256
	Cs	12.9	21	5	93.6	169	38
June	St	7.2	0	2	44.1	0	16
Dry '53	Sc	21.1	9	15	110.8	35	60
Wet '60	Cu	46.8	32	36	94.8	68	62
	Cb	33.9	14	54	139.6	48	218
	As	2.2	3	1	13.5	24	6
	Ac	59.7	33	51	195.6	87	210
	Ci	71.9	60	76	213.8	177	255
	Cs	7.0	9	5	62.3	55	36

Table 9. A Comparison of Cloudiness During

Dry and Wet Months

(Continued)

LUBBOCK

Date	Cloud Type	Frequency			Amount		
		Mean	Dry	Wet	Mean	Dry	Wet
July	St	4.9	1	16	34.3	5	152
Dry '57 Wet '60	Sc	15.1	5	22	65.2	15	105
	Cu	63.8	61	32	109.4	128	65
	Cb	38.2	21	59	129.1	71	197
	As	3.9	0	0	30.6	0	0
	Ac	77.1	67	63	271.4	221	207
	Ci	85.1	128	69	269.1	483	175
	Cs	7.2	6	1	51.8	51	6
Aug	St	3.0	3	5	14.1	30	19
Dry '56 Wet '57	Sc	14.8	17	10	64.9	90	48
	Cu	55.5	38	50	112.7	69	107
	Cb	31.1	17	36	88.8	42	113
	As	1.6	0	1	11.5	0	7
	Ac	77.8	59	96	251.0	184	380
	Ci	87.6	95	85	259.3	316	297
	Cs	6.8	2	8	45.5	14	45
Sept	St	8.6	1	31	62.0	10	209
Dry '56 Wet '58	Sc	20.2	5	41	125.8	30	265
	Cu	27.4	13	51	68.0	20	213
	Cb	16.7	12	23	50.9	49	80
	As	1.2	0	2	9.3	0	11
	Ac	56.6	34	60	176.9	51	206
	Ci	41.3	54	68	121.4	133	182
	Cs	6.6	1	13	36.4	4	73

Table 9. A Comparison of Cloudiness During
Dry and Wet Months
(Continued)

LUBBOCK

Date	Cloud Type	Frequency			Amount		
		Mean	Dry	Wet	Mean	Dry	Wet
Oct	St	22.3	0	32	180.4	0	292
Dry '52 Wet '60	Sc	29.5	2	32	189.8	0	164
	Cu	11.1	0	14	23.4	0	23
	Cb	6.0	0	11	21.5	0	20
	As	2.5	0	1	17.5	0	0
	Ac	34.4	22	39	137.3	75	160
	Ci	45.5	33	34	130.7	80	112
	Cs	8.4	11	3	66.8	84	29

cirriform clouds, the data for cloud frequency are shown graphically in Figures 22a, 22b, and 22c. Cirrus clouds were omitted because of the observational difficulties which would tend to make these data non-representative.

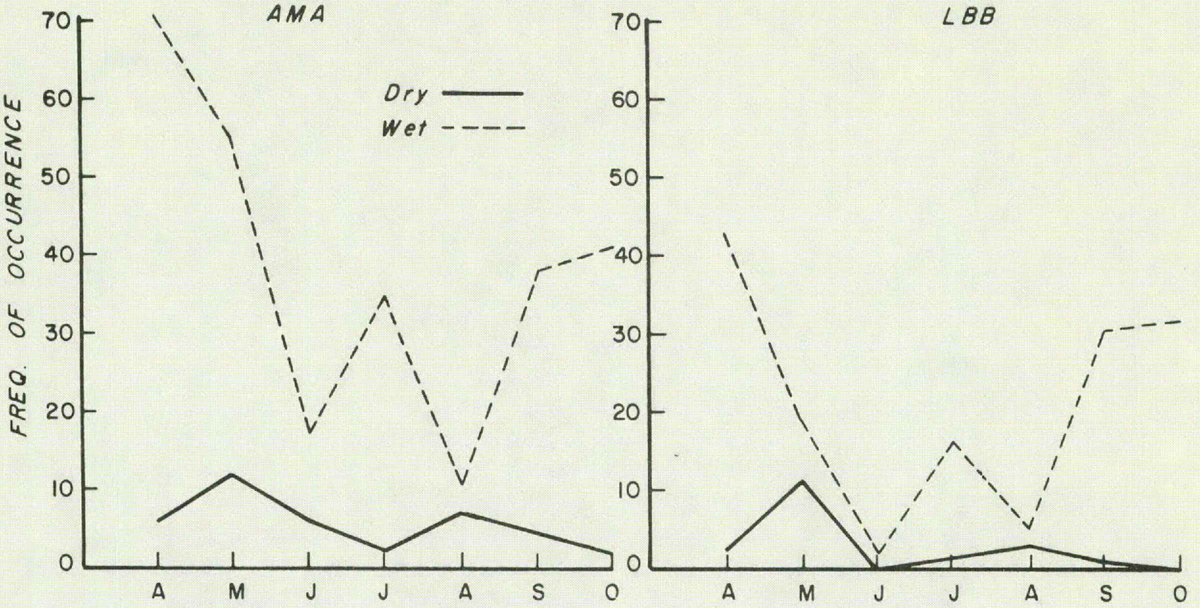
In each case, solid lines in the figures represent cloud frequency for the dry months and the dashed lines denote cloud frequency for the wet months. In the case of stratus, the frequency was higher for the wet month at both Amarillo and Lubbock. The large differences in the spring are accounted for in large part by early morning stratus indicative of low-level moisture during the wet months. This is true to a lesser extent of the other months also. Fall stratus occurs also in association with cyclonic activity. It is obvious that stratus is characteristic of the wet months and is practically nonexistent during dry months.

In the case of stratocumulus, there is a significant difference between wet and dry months in the spring and fall with low frequencies and smaller differences in the summer. The only case in which the dry month frequency was higher than the wet month frequency was in August at Lubbock. Recall that this month, August 1957, was really not characteristic of wet Augusts in the plains.

As expected, cumulonimbus development is considerably greater during the wet months. On only one occasion, August at Amarillo, could the difference be considered insignificant. Once again the exception occurs during August. Only 33% of the Augusts at Amarillo had less precipitation than August 1957.

It is interesting to note in Figure 22b that cumulus tends to have a higher summer frequency during the dry months, especially at Amarillo. Even during the spring there is very little difference between wet and dry months. This indicates that convective development was initiated during the dry months but, in most instances, was not strong enough to produce cumulonimbus clouds and subsequent precipitation. One might speculate at this point on the cloud modification possibilities offered by this situation, where cumulus clouds are plentiful but are not able by natural means to reach the precipitation stage. It is true that the natural precipitation efficiency (fraction of condensate that reaches the ground as precipitation) tends to be quite low for isolated cumulus clouds over flat terrain (Braham, 1952). This is due in part to the dry environment through which these clouds must penetrate. Entrainment of dry ambient air causes evaporation of the cloud droplets and consequently halts the growth of the cloud. It may be that these adverse environmental interactions

STRATUS



STRATO CUMULUS

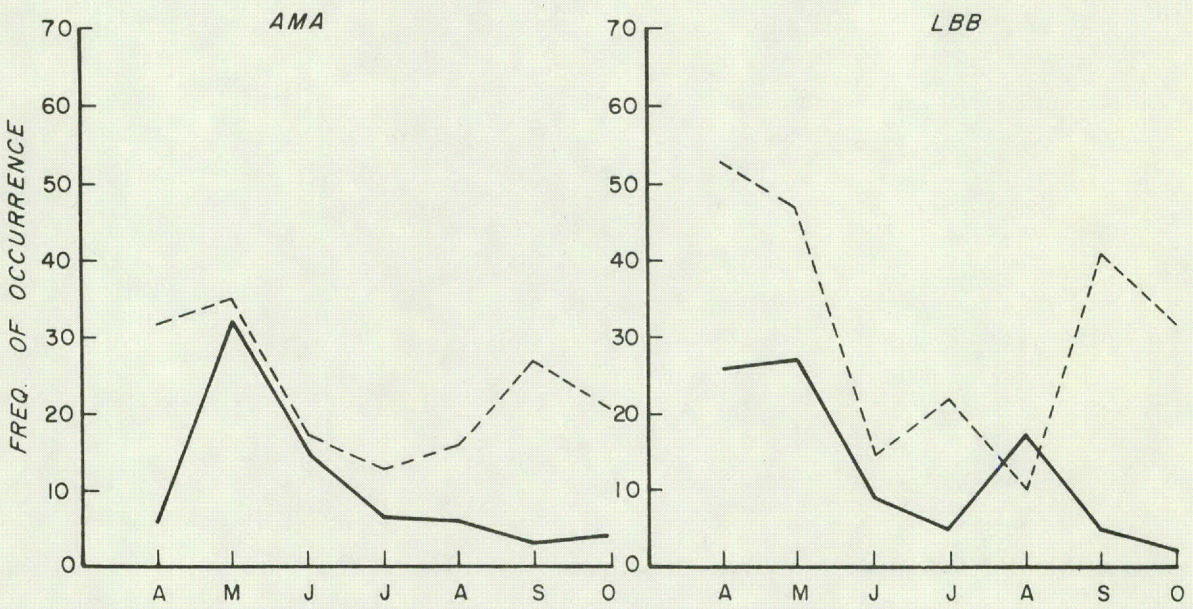


Fig. 22a Cloud Comparison for Wet and Dry Months
Amarillo and Lubbock

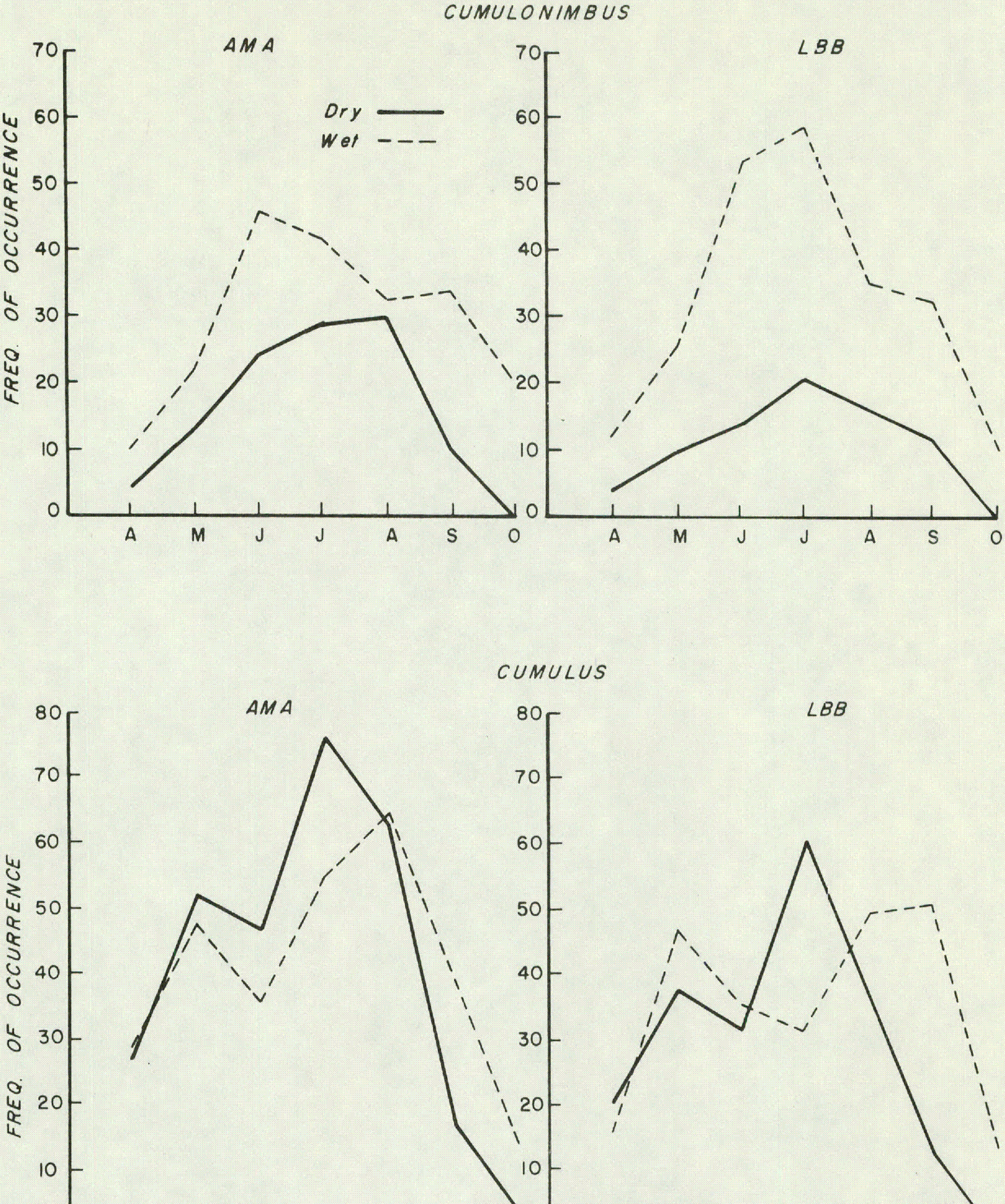
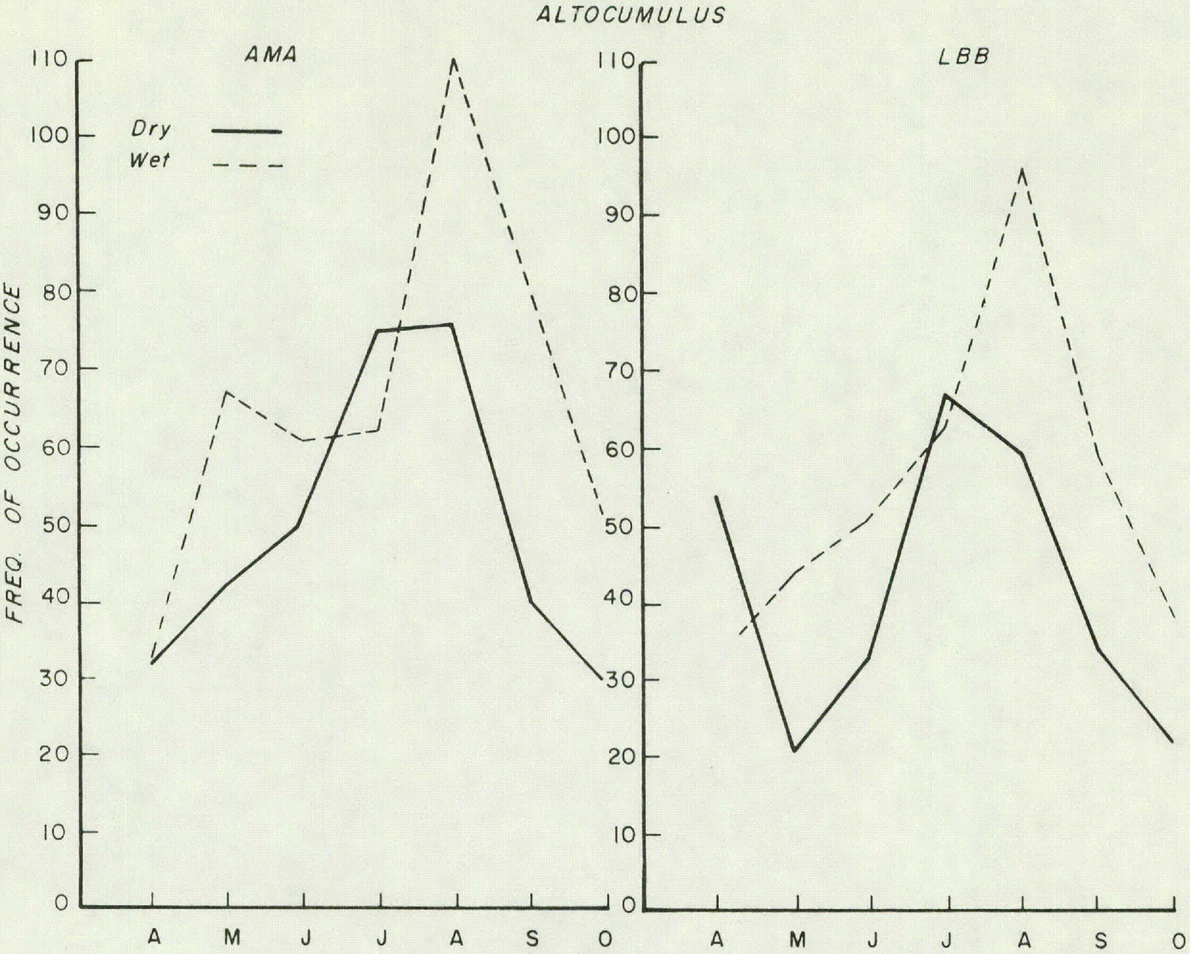
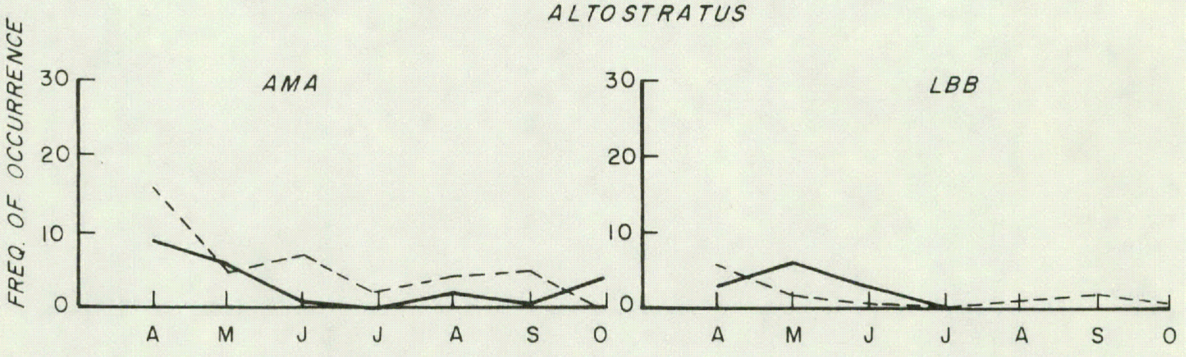


Fig. 22b Cloud Comparison for Wet and Dry Months
Amarillo and Lubbock



ALTOCUMULUS



ALTOSTRATUS

Fig. 22c Cloud Comparison for Wet and Dry Months
Amarillo and Lubbock

are sufficient to prevent artificial stimulation of precipitation. The fact is that we do not know enough about the microphysics and dynamics of this class of cloud to permit this type of judgment. According to the report of the Panel on Weather and Climate Modification to the National Academy of Sciences (1966), the sensible course of action is to carry out nucleation experiments at the same time that we seek to increase our basic knowledge about isolated cumulus clouds, watching carefully for clues as to vulnerable spots that may hold promise in achieving useful modification results.

Altocumulus frequency for the wet and dry months is shown in Figure 22c. Although this cloud type is not generally associated with significant amounts of precipitation, it is one of the two most abundant clouds occurring in the plains and is indicative of middle-level moisture. Note that, with three small exceptions, the frequency of occurrence for altocumulus is higher during the wet months. Curves for altostratus are also shown in Figure 22c, but the frequency in this case is so low that it is doubtful if any meaningful clues can be obtained. In most instances the frequency is higher for the wet months.

A study of the values for cloud amounts in Tables 8 and 9 leads to the same conclusions indicated by the cloud frequencies. As one would expect, fewer clouds are present during dry months. The one notable exception occurs again in the case of cumulus. Particularly during June and July, the amount of cumulus for the dry months appears to be equal to or slightly greater than that during the wet months. As was pointed out previously, this fact deserves more consideration as regards its implications relating to cloud modification efforts.

The only other cloud for which amounts are frequently higher during the dry months is cirrus. This is probably due to the fact that lower level clouds during wet months are able to obscure the cirrus clouds, thus they are not reported. Consequently, cirrus occurrence is probably underestimated, especially during wet months with considerable low and middle-level cloudiness.

C. Precipitable Water and Water Vapor Flux During Wet and Dry Months

Figure 23 shows a graphical comparison of precipitable water during wet and dry months for Midland. The computations were made according to the equation

$$P_v = \sum_i \frac{\overline{q}_i \, \Delta p_i}{g}$$

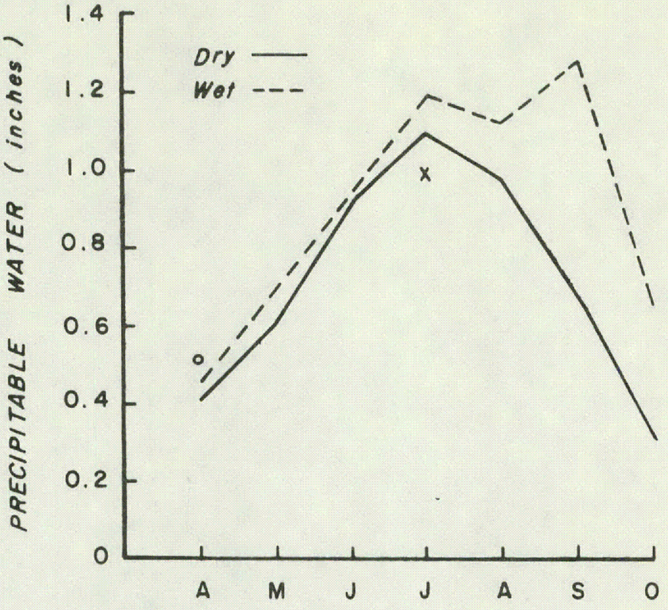


Fig. 23 Precpitable Water Comparison for Wet and Dry Months
Midland

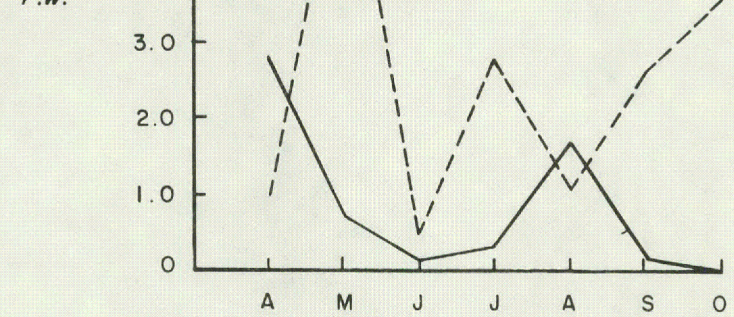


Fig. 24 Precipitation Index for Wet and Dry Months
Midland

Note that precipitable water for the wet months is equal to or slightly higher than the dry months for April thru July and significantly higher during August, September, and October. Values for Amarillo were plotted when available. For Amarillo, wet months are denoted by a small circle (o) and dry months by a cross mark (x). Table 10 is a summary of results for precipitable water. The table is complete for Midland and contains results for Amarillo when they were available. Columns 5 and 7 give the probability, based on the precipitable water vapor ogives in Figures 18 and 19, of an observation being greater than the value in columns 4 and 6 respectively. Considering the dry months, it is obvious that small departures of precipitable water from normal are characteristic of April thru July. In the case of August, September, and October, however, deficiencies in precipitable water are apparent. The wet months are generally characterized by precipitable water values above normal. The most pronounced departure occurred in the case of September, where precipitable water values for the wet month were well above normal.

In addition to precipitable water, one would like to have some cumulative measure of the effects of cyclonic or frontal activity and associated disturbances of temperature, moisture, and wind on precipitation. It was decided to define a "precipitation index", which is related to precipitation efficiency, in order to assess these effects. The precipitation index (PI) is defined as

$$\mathrm{PI} = \frac{\text{Mean monthly precipitation}}{\text{Mean monthly precipitable water}}$$

A comparison of the precipitation index for wet and dry months is shown in Figure 24. Higher values of the index are indicative of a higher level of atmospheric activity in triggering precipitation development. It is evident from the figure that dry months are characterized by lower values of the index during five of the seven months under consideration. The only exceptions are April and August where the indices are essentially the same for the two months within the accuracy of the computations.

Vertical distributions of precipitable water are shown for wet and dry months for Midland in Figure 25. It is obvious that the largest differences are accounted for by low-level moisture. Only in the case of the fall months, September and October, do there appear to be significant differences in precipitable water at upper levels. Note that June is the only month for which precipitable water during the dry month is greater than that for the wet month.

Table 10. Precipitable Water for Wet and Dry Months

Date		Condition	Mean Precip.	P.W. MAF	% above	P.W. AMA	% above
Apr	'56	Dry	0.28	0.41	48		
	'57	Wet	3.43	0.46	38	0.50	15
May	'53	Dry	1.09	0.61	59		
	'57	Wet	5.39	0.70	46	0.70	35
June	'53	Dry	0.66	0.91	52		
	'60	Wet	4.39	0.95	46	0.90	36
July	'57	Dry	1.23	1.09	48	0.99	47
	'60	Wet	6.65	1.19	32	1.09	34
Aug	'56	Dry	0.91	0.98	66		
	'57	Wet	2.01	1.12	44	1.13	32
Sept	'56	Dry	0.13	0.70	70		
	'58	Wet	2.63	1.28	12	0.99	11
Oct	'52	Dry	0.00	0.33	81		
	'60	Wet	5.35	0.65	40	0.53	32

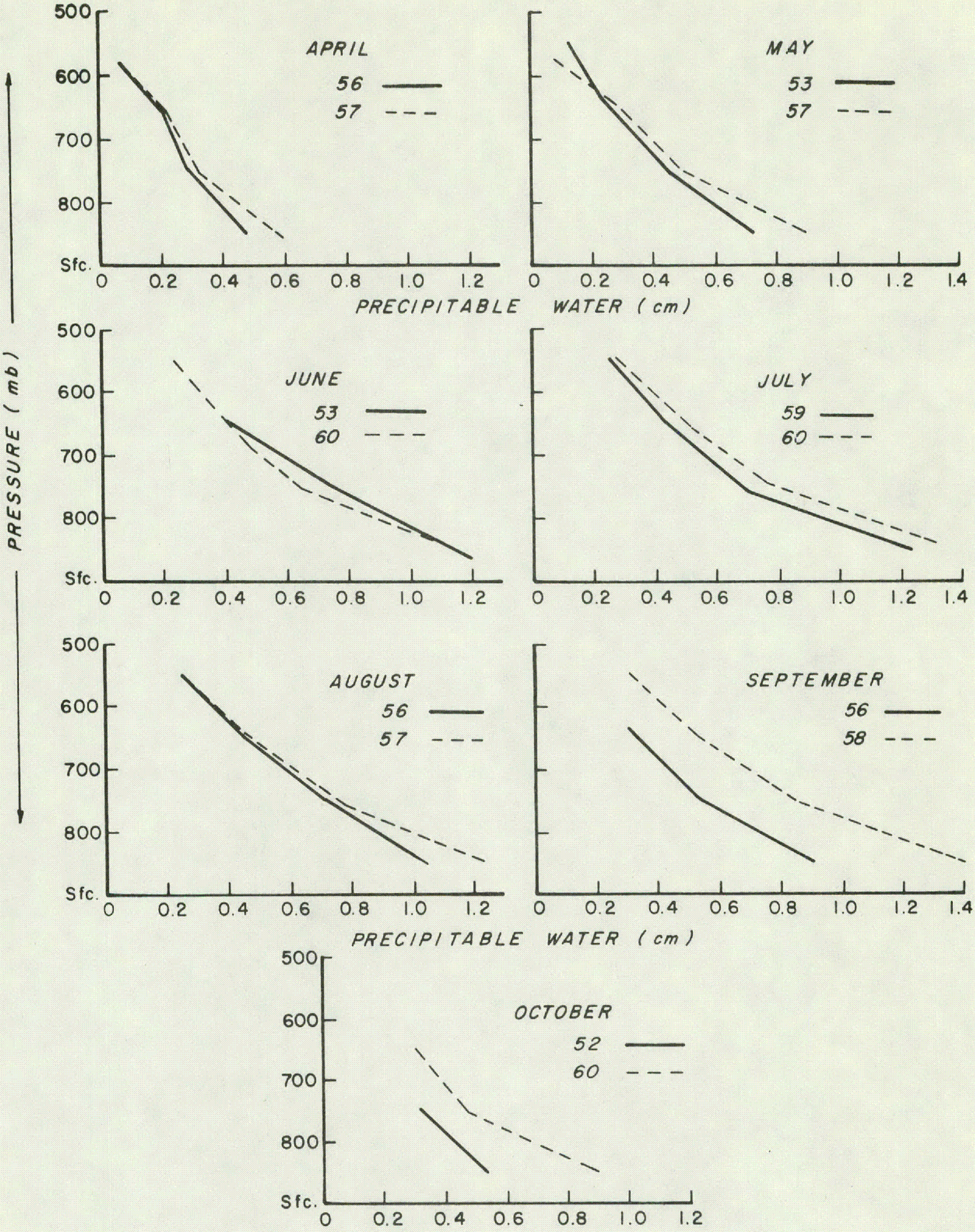


Fig. 25 Vertical Distribution of Precipitable Water for Wet and Dry Months Midland

An inspection of Figure 24, however, indicates that the precipitation index was quite high for the wet June which indicates that a high level of atmospheric activity was responsible for a greater precipitation efficiency during this month.

In general it is true that sufficient supplies of precipitable water in conjunction with some atmospheric disturbance to initiate vertical motion are necessary in order to realize significant amounts of precipitation. From the present study it appears that late summer and fall precipitation is more sensitive to changes in precipitable water. During the spring and early summer, only small differences in precipitable water for wet and dry months are noted, indicating that once the necessary vertical motion is provided, precipitation follows almost without exception.

To examine the importance of atmospheric motions in accounting for precipitation in the face of small variations in precipitable water, the transport of water vapor in the atmosphere was computed for wet and dry months. The amount of the transport is dependent upon the horizontal velocity of the water vapor. This advection of water vapor is given by

$$Q = \frac{1}{g} \int_{p_1}^{p_2} qv \, dp$$

where q is the specific humidity, v is the wind velocity and p is atmospheric pressure. Since velocity is a vector, we must specify a direction for each calculated value of the flux.

Precipitable water in a particular layer was previously expressed as

$$P_{v_i} = \frac{\overline{q}_i \, \Delta p_i}{g}$$

and the total precipitable water as

$$P_v = \sum_i P_{v_i}$$

Water-vapor flux in a particular layer can be expressed similarly as

$$Q_{v_i} = \frac{q_i V_i \Delta p_i}{g}$$

where the total flux is given by

$$Q_v = \sum_i Q_{v_i}$$

Flux is expressed in units of gm cm^{-1} sec^{-1}.

Figures 26 (a thru g) illustrate the flux of water vapor at Midland for each of the wet and dry months. The vertical scale on the diagrams is pressure. Fluxes in each layer are denoted by a magnitude given by the length of the arrow plotted in each layer, and a direction of flow, shown by the arrow. The scalar magnitude of the total flux is given at the bottom of each diagram.

Inspection of the diagrams leads one readily to the conclusion that the values of water vapor transport are greater during the wet months. During the wet April there is a slightly larger flux at all levels. The largest difference appears to be in the layer between 600 and 800 mb. The direction of transport is much the same at all levels for the dry and wet months.

The flux is greater at all levels in the case of the wet months during May also. In this case the most significant difference is in the layer between 800 and 900 mb. During the wet months the direction of the flow in this layer is from the south-southeast, which implies direct transport of Gulf moisture into the area. The direction in this same layer for the dry month is from the south-southwest. Note the considerable difference in total flux which is apparently accounted for primarily by this low-level transport.

In June, the major difference once again is in the layer between 800 and 900 mb. Since precipitable water values were much the same for the two June months, the implication is that higher wind speeds were prevalent in the lower levels during the wet month to effect the significant difference in flux. Note that there also was a small northerly transport at upper levels during the wet month, while during the dry month the upper levels are sufficiently dry to produce a negligible flux.

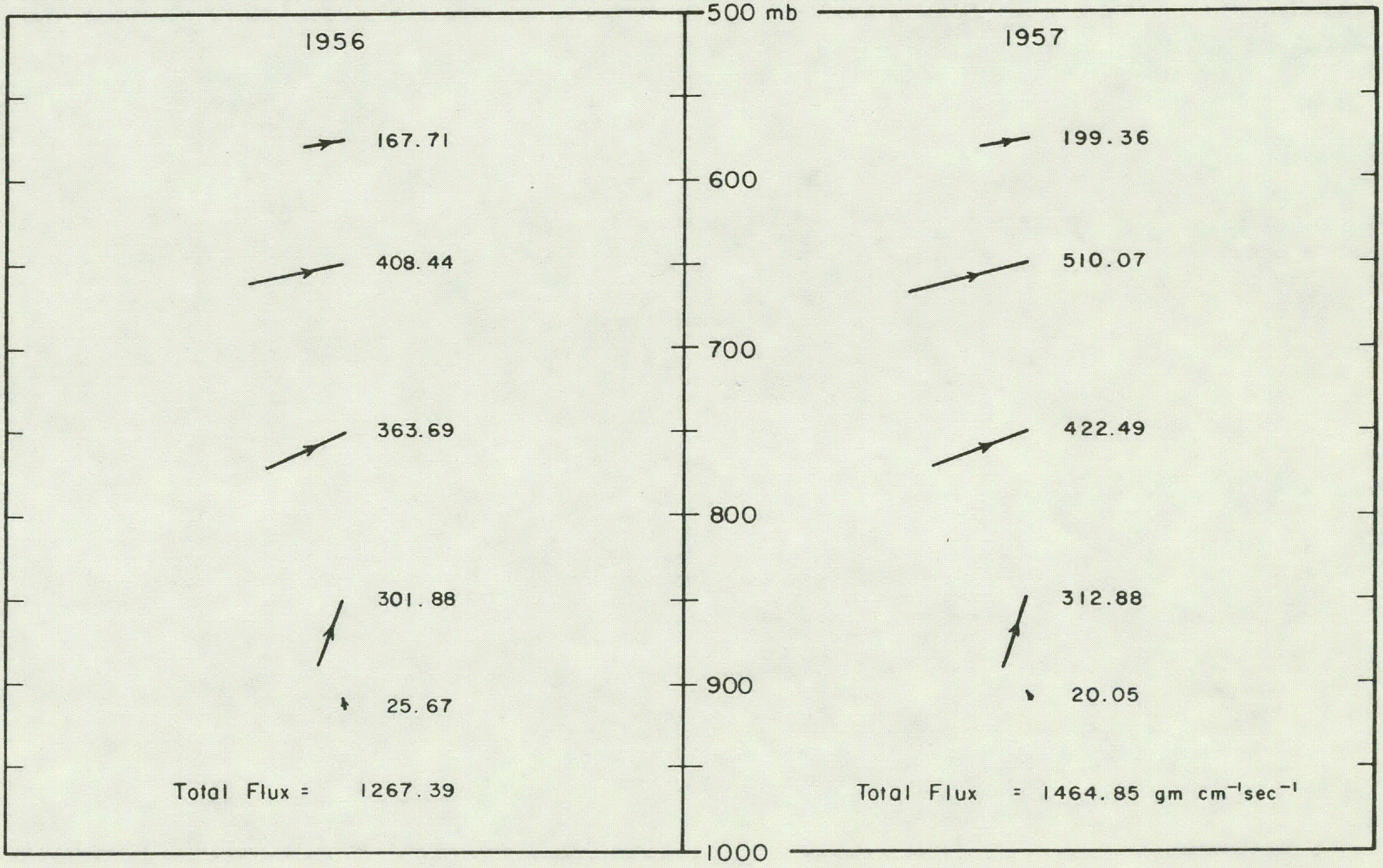


Fig. 26a Water Vapor Transport for Wet and Dry Months - April Midland

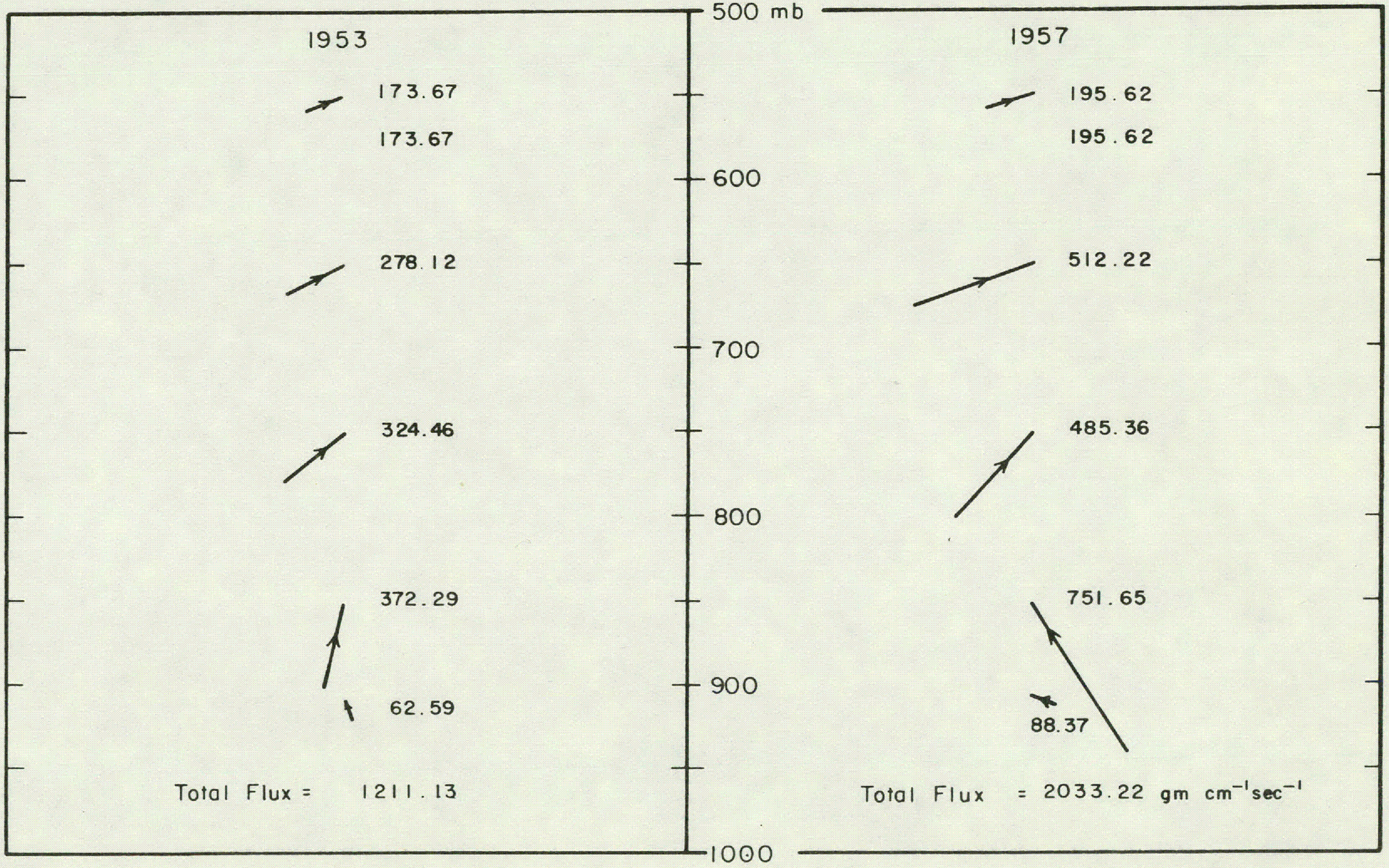


Fig. 26b Water Vapor Transport for Wet and Dry Months - May
Midland

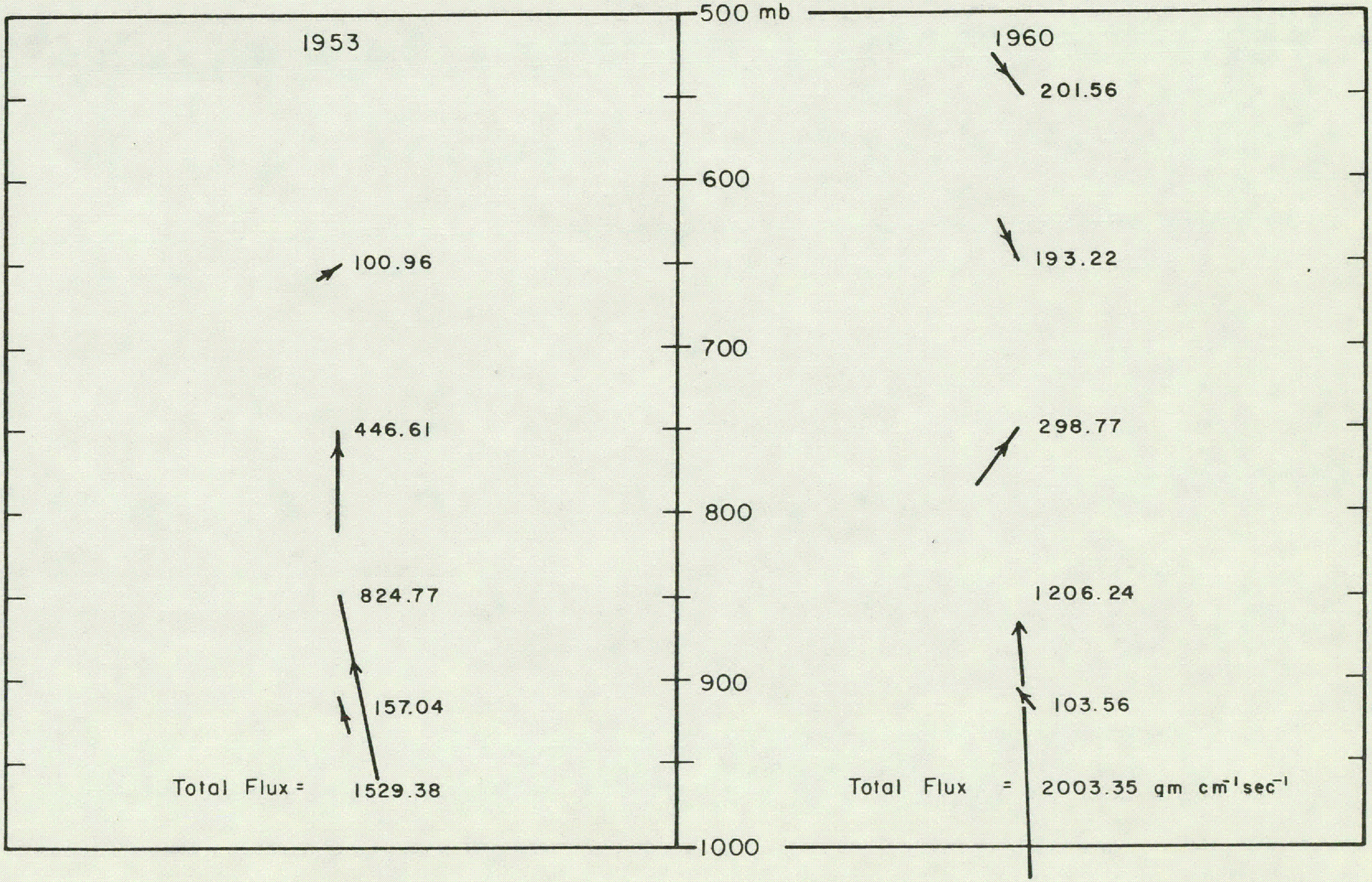


Fig. 26c Water Vapor Transport for Wet and Dry Months - June

Midland

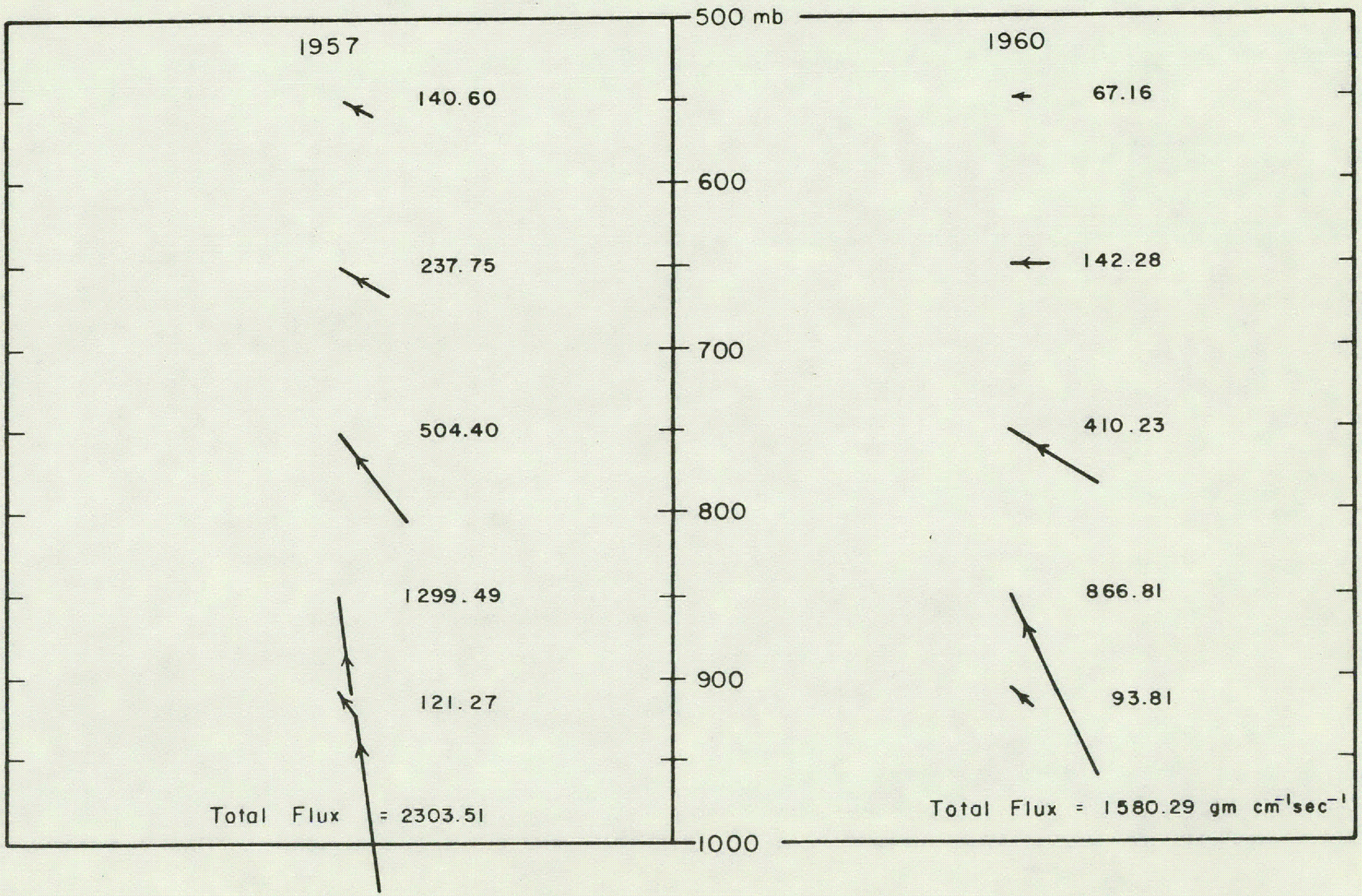


Fig. 26d Water Vapor Transport for Wet and Dry Months - July
Midland

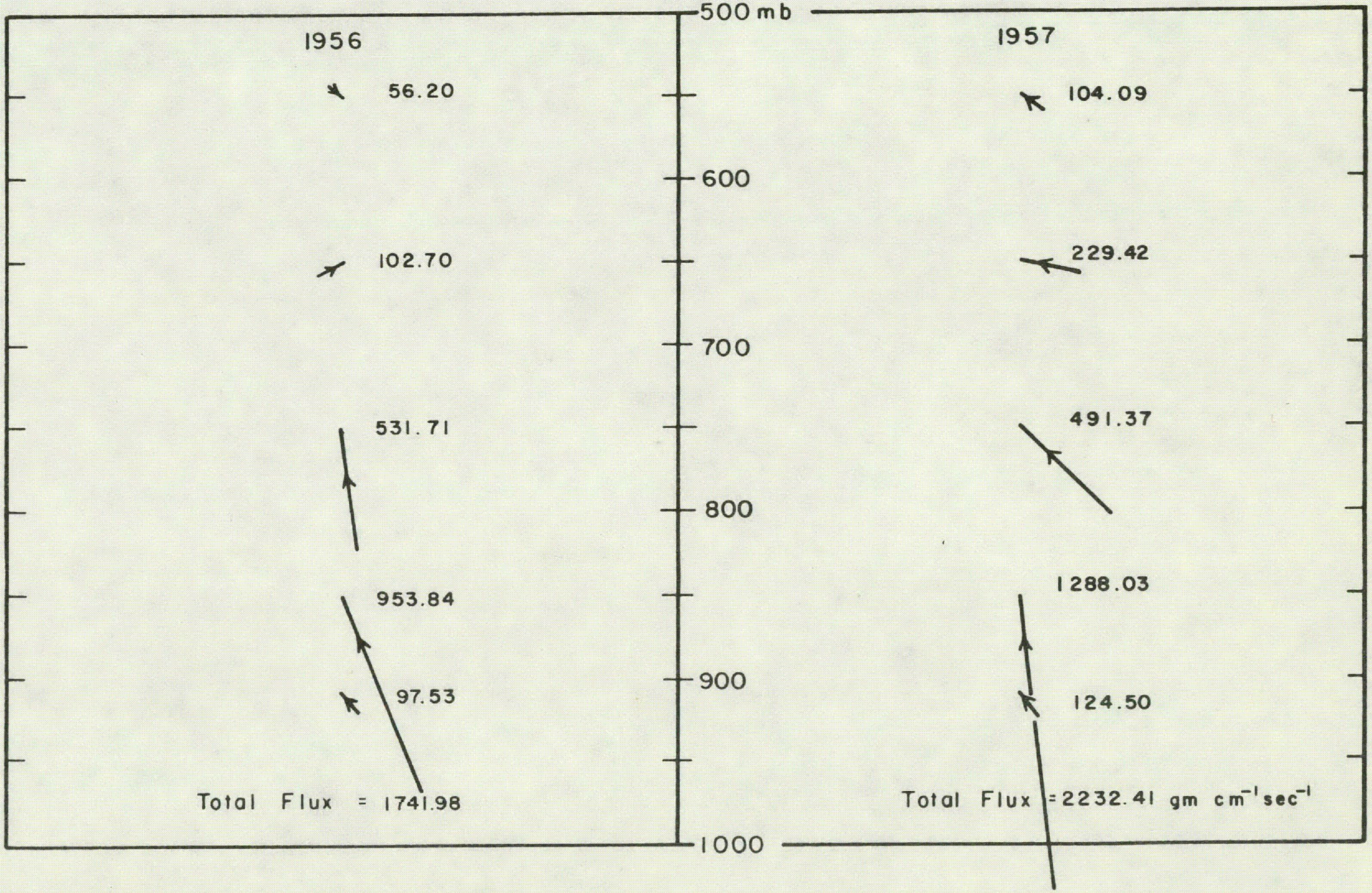


Fig. 26e Water Vapor Transport for Wet and Dry Months - August
Midland

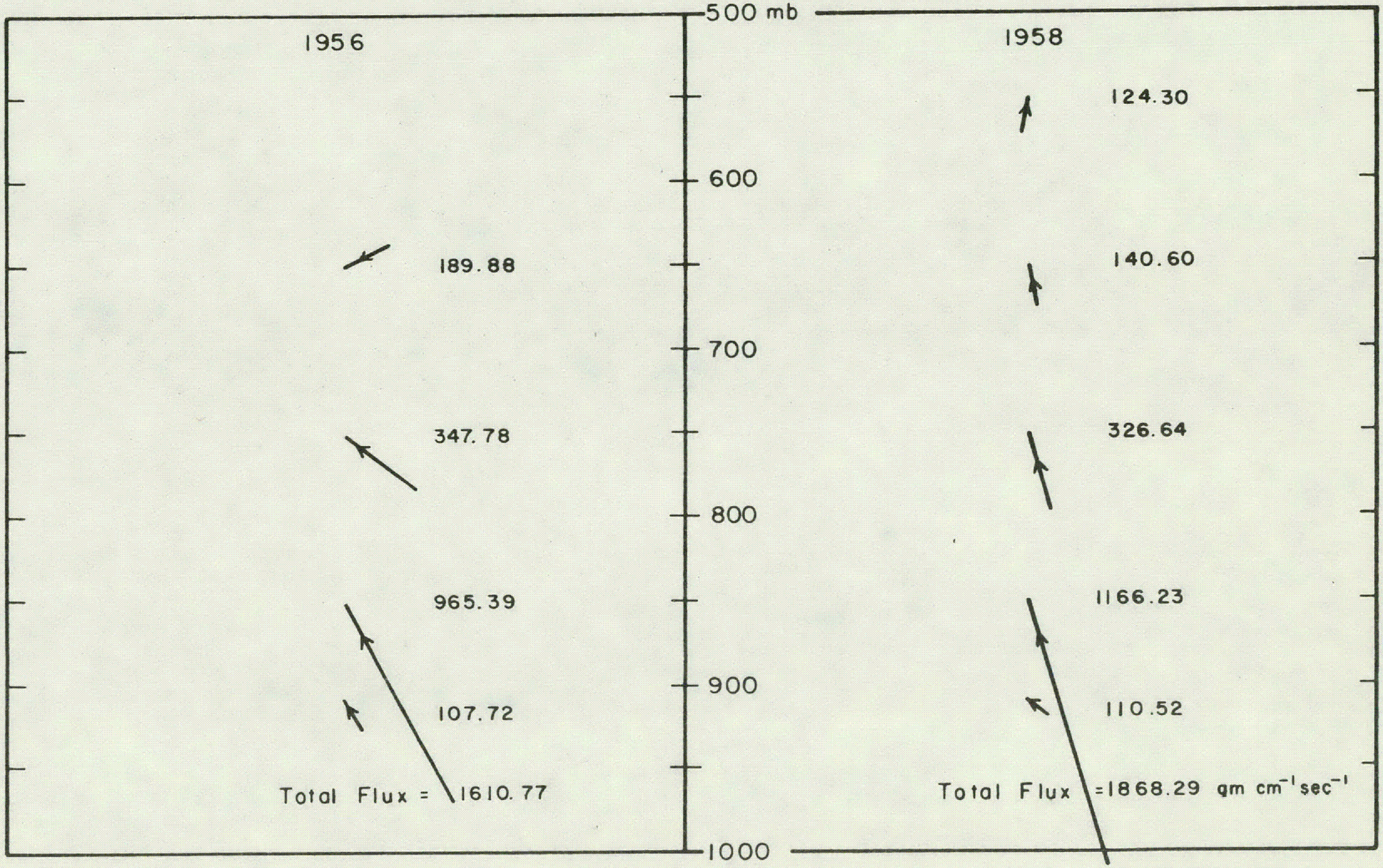


Fig. 26f Water Vapor Transport for Wet and Dry Months - September
Midland

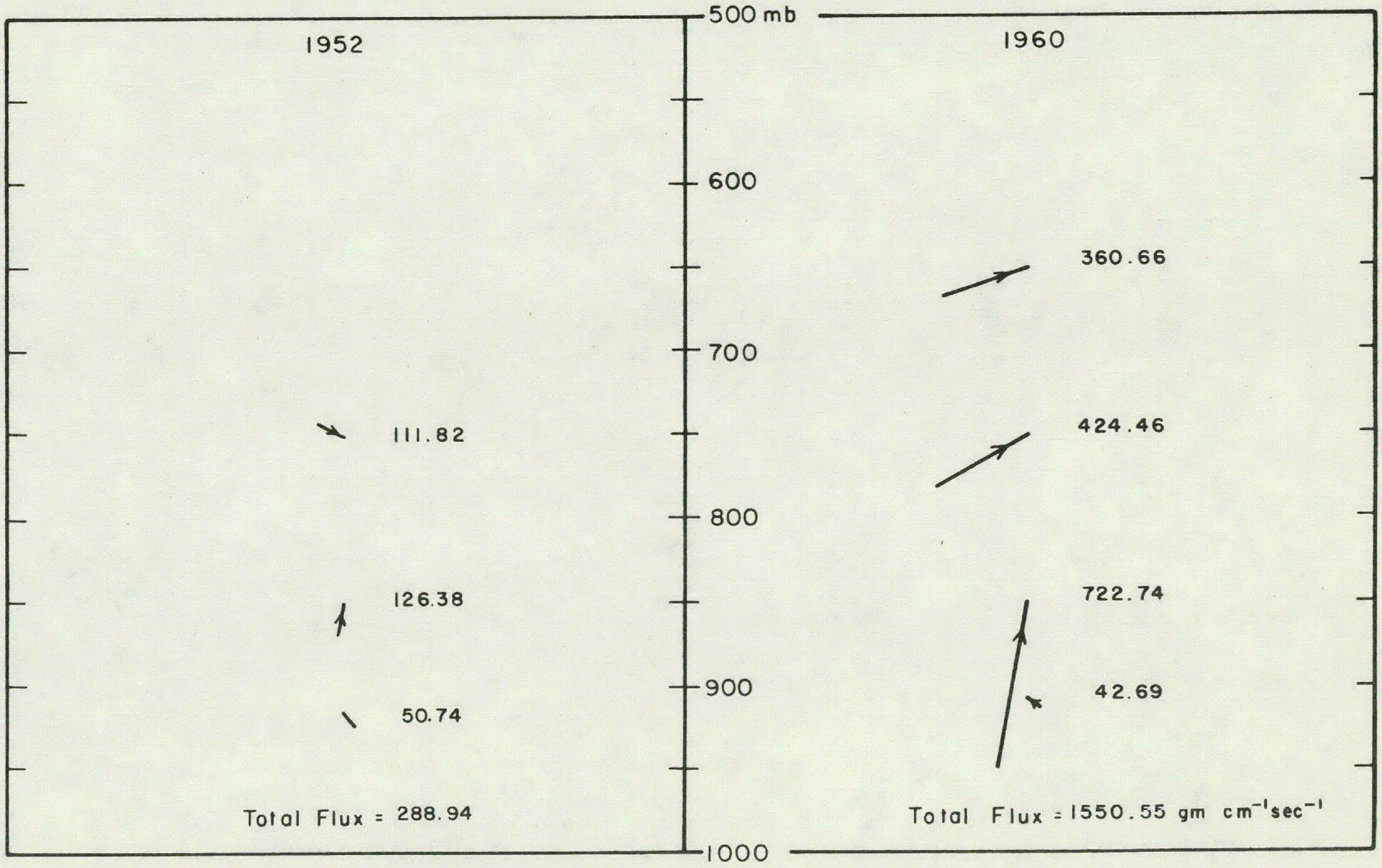


Fig. 26g Water Vapor Transport for Wet and Dry Months - October
Midland

July was unique in that a considerably greater flux of water vapor was noted during the dry month. It will be shown in the next section, however, that July 1957 was lacking in cyclonic activity so that even though large amounts of moisture were being transported across the area, there was no mechanism to initiate the production of precipitation.

A more typical pattern is exhibited in August, when once again there is a substantially larger transport in the 800-900 mb layer during the wet month. This same pattern is characteristic also of September.

It is evident from the October diagram that in 1952 there was an almost insignificant amount of water vapor transport across the plains area. The total flux during the wet month was more than five times greater than that of the dry month. Recall that October 1952 was the driest month on record in the United States.

D. Circulation Patterns Associated with Wet and Dry Months

Another factor which must be considered when discussing the dynamics of wet and dry periods is the associated atmospheric circulation patterns, and the storm tracks which result. It is these patterns which determine the flux of moisture into a particular area and also guide the storms which are largely responsible for developing the vertical motions which aid the precipitation process.

The wet and dry Aprils (1957 and 1956, respectively) were much the same in many respects. Mean temperatures were below normal during both months, although slightly more so in 1957. As was seen in previous sections, precipitable water and water vapor flux into the area were much the same, although in both instances the higher values occurred during the wet month. Precipitation during April 1956, however, was only about 25% of normal while that in 1957 was up to 300% of normal. Examination of the mean 850 mb and 700 mb charts for these months indicates that the reason for this difference in precipitation is probably two-fold. In the first place, storm centers during 1957 were steered further south in association with a 700 mb pressure trough through New Mexico and Arizona; whereas the mean 700 mb trough for April 1956 was over the California coast and the main storm track was north of the Texas plains. Storm tracks for both months are shown in Figure 27. Secondly, there was slightly greater moisture inflow into the plains area from the Gulf of Mexico during 1957 due to southeast winds

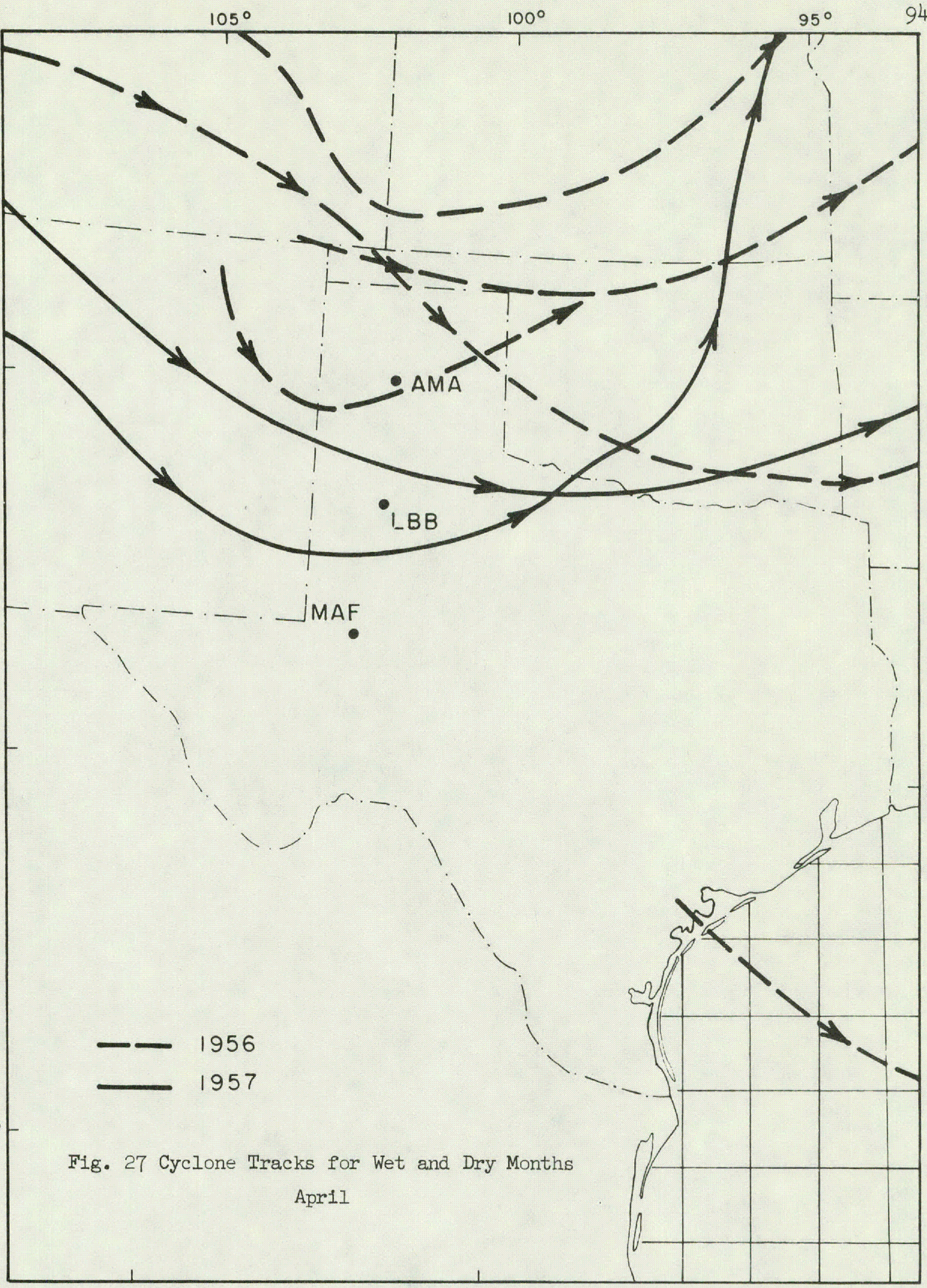


Fig. 27 Cyclone Tracks for Wet and Dry Months
April

at lower levels. Mean surface winds during 1956 were from the southwest.

The situation for May was a little different. In this case there was considerably more Gulf moisture transported into the plains area during 1957 in association with mean southeasterly winds in the lower levels. The low-level winds for May 1953 (dry) had more of a westerly component causing most of the moisture to affect only easterly portions of the state. An even more significant difference in this case, however, was the lack of cyclonic activity during May 1953. Note in Figure 28 that only one storm center passed through the plains area during May 1953, while in 1957, two storms passed through the area with two more in the near vicinity. This lack of storm activity would probably have limited precipitation to small amounts even if this moisture inflow had been much higher.

A somewhat different factor seemed to be responsible for the lack of precipitation during June 1953. In this case, the westward extension of the Atlantic anticyclone caused the area to be dominated by this feature of the circulation during the month. A high degree of stability and strong subsidence causing temperature to average 6 to 8 degrees above normal, retarded any vertical development which might have been initiated. During June 1960 the Atlantic anticyclone was much weaker and was centered far to the east of its 1953 position, allowing cyclonic activity to proceed in the production of above-normal amounts of precipitation.

A similar situation was responsible for the below-normal precipitation during July 1957. In this case, as was shown previously, the flux of moisture was greater over the plains area during the dry month of July 1957, but the high degree of stability in association with a mean high pressure area centered over northeast Texas and Oklahoma tended to prevent the development of precipitation. Another notable feature was the complete absence of cyclonic activity in the plains area during the month of July 1957. As a result of the high stability, temperatures during 1957 averaged 2 to 3 degrees above normal in association with relatively strong subsidence. In contrast, temperatures during July 1960 averaged 1 to 3 degrees below normal.

August was the month for which a representative wet period could not be found. Both August 1956 and August 1957 were relatively dry with respect to the normal August precipitation so that 1957 was termed wet only in comparison

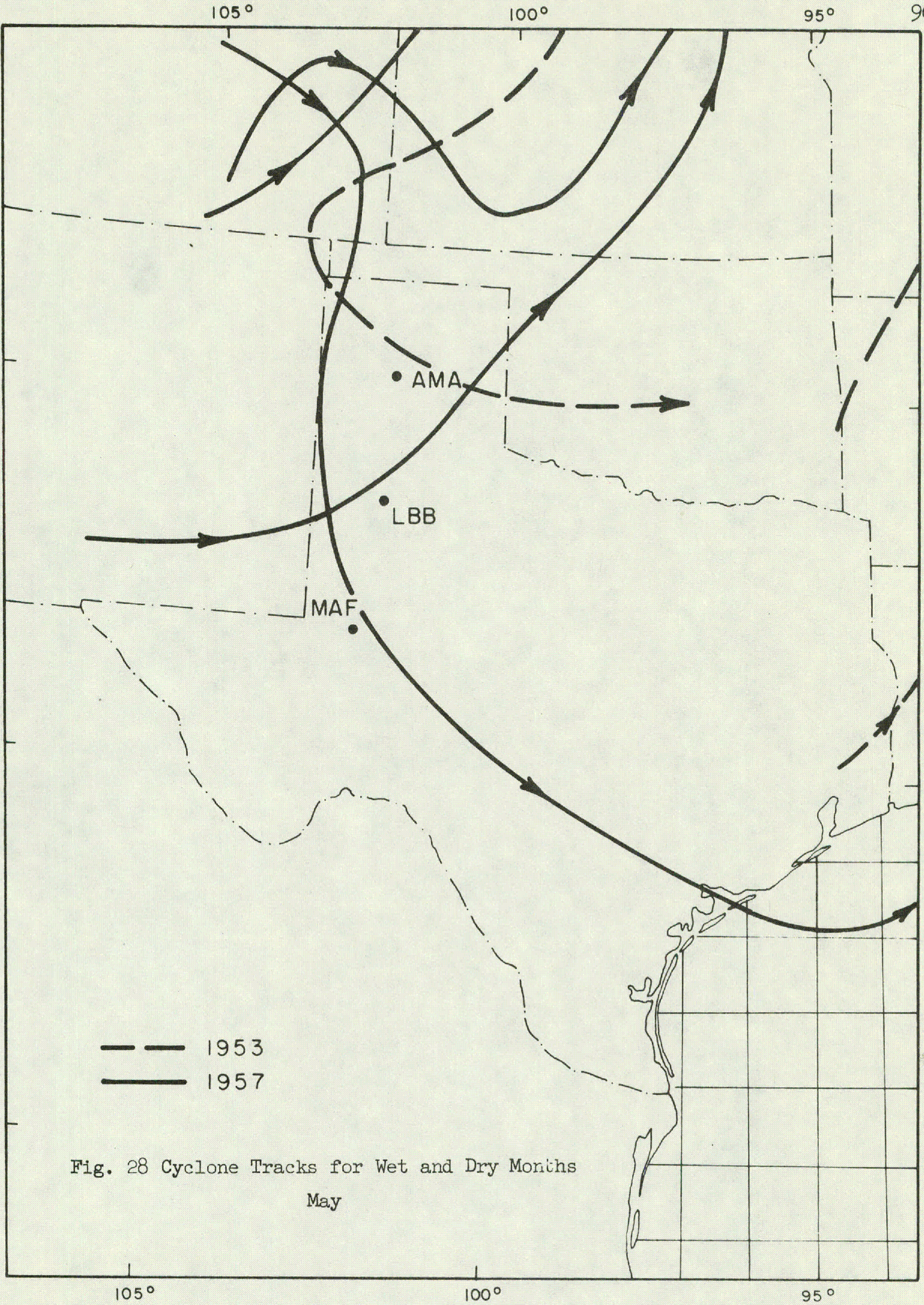


Fig. 28 Cyclone Tracks for Wet and Dry Months

May

to 1956. Fronts frequented the area on both occasions causing highly localized showers. Differences in the amount of precipitation can only be related to differences in atmospheric moisture. Note in Figure 21 that higher precipitable water values were associated with August 1957. Also the flux shown in Figure 26e was significantly greater in the case of the wetter month.

Both September 1956 and September 1958 were under the influence of the western portions of the Atlantic anticyclone. Temperatures in 1956 averaged 2 to 3 degrees above normal while those in 1958 were about 1 degree above normal. In 1958, however, orientation of the upper level contours was such that larger amounts of low-level moisture were able to penetrate into the plains area. Winds over Texas at 700 mb during 1956 were easterly while in 1958 they were from the south and south-southeast. A significant contribution to the September 1958 precipitation was brought about by the inland movement of Tropical Storm Ella.

In October 1952, the total precipitation which fell over the entire United States was the lowest of some 60 years of record. Namias (1960) has shown that the rainfall of October 1952 was only about one-fourth the amount normally received over the United States in October, the deficit amounting to about 3.3×10^{11} tons of water. As Namias points out, it is not surprising to see that this record dryness occurred at the time of the year when the westerlies and cyclone belts are characteristically far north and vertical stability is a maximum. The drought regime of this month is related to the macro-scale average monthly features shown in Figure 29 by the mean 700 mb contour pattern. This wave pattern has the same phase as the normal October pattern but its amplitude is much greater. The net effect of this amplification has been cited as threefold by Namias: (1) to deploy Canadian Polar air masses rapidly southeastward into the eastern United States, resulting in anomalous cold air in the east with the polar front frequently found off the eastern seaboard; (2) to effectively shut off most of the nation (except Florida) from access to moist air from the Gulf of Mexico (see Figure 26g); and, (3) to shunt cyclones away from borders of the United States. The last effect is illustrated with respect to the present study in Figure 30. Note that the only cyclone path in the vicinity for October 1952 terminates in the northeastern corner of Kansas. All of the other tracks are for October 1960 which was unusually wet in the plains area. In this case, low-level moisture was fed into the area, and coupled with cyclonic activity, produced about 250% of the normal precipitation for this month.

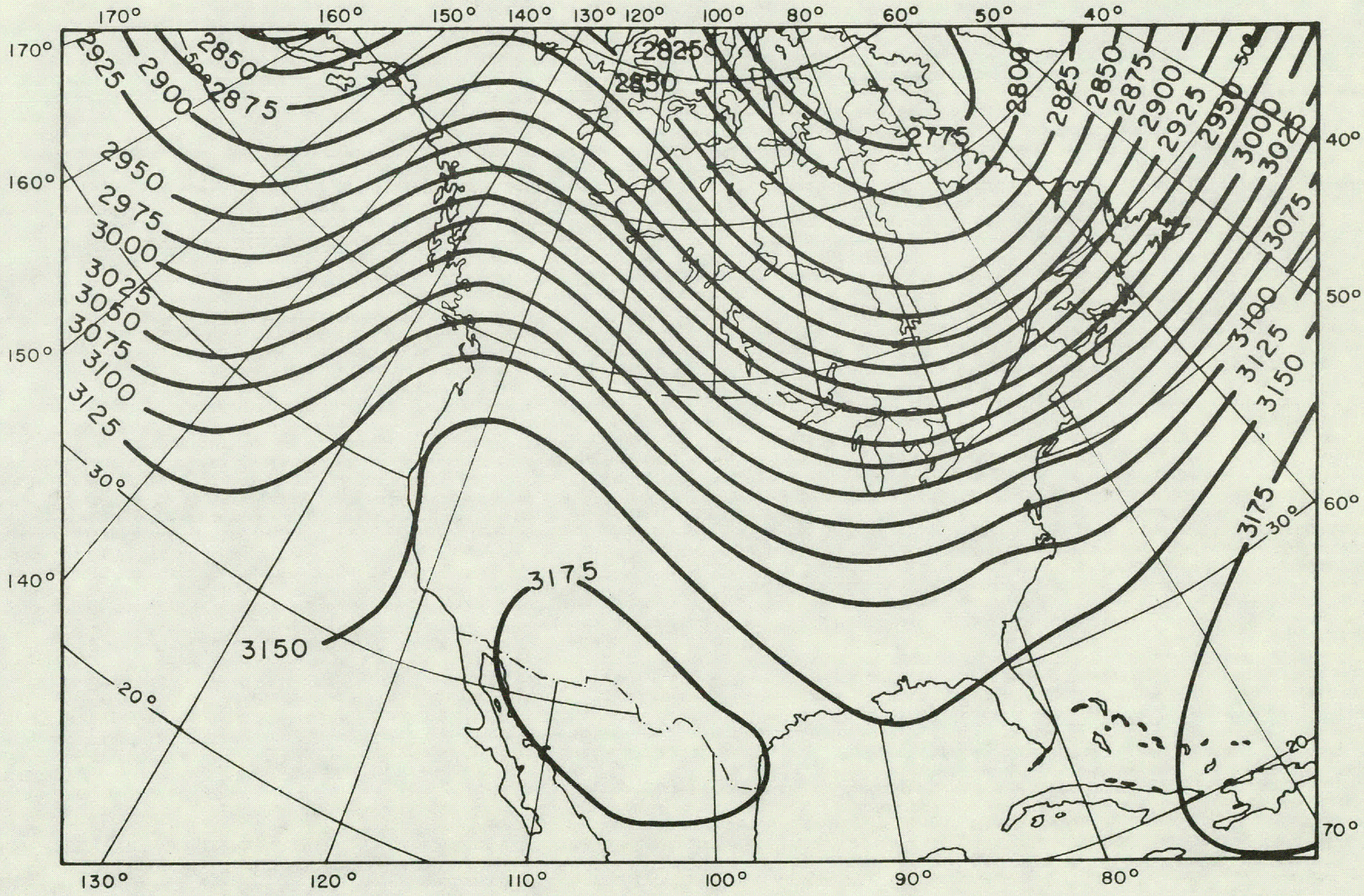


Fig. 29 700-mb Analysis - October 1952
Height is in Geopotential Meters

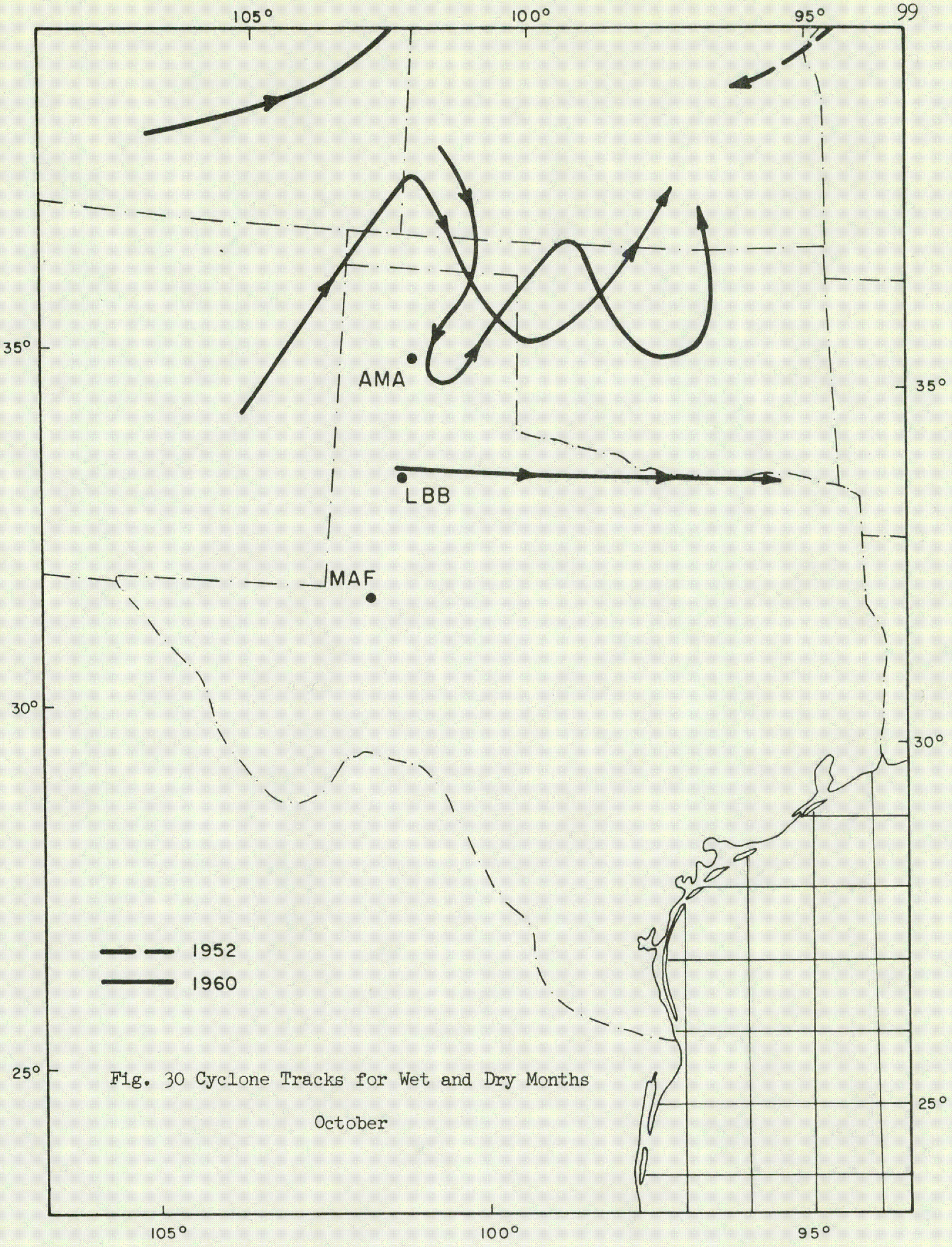


Fig. 30 Cyclone Tracks for Wet and Dry Months

October

V. DRY PERIODS IN THE TEXAS PLAINS

As was seen in the previous section, causes for long-term dry periods, on the order of a month, must be related to monthly mean values of precipitable water, water vapor flux, and to average circulation patterns over this time period. A dry month is dry by virtue of the fact that it is deficient in precipitation, not because precipitation is not observed.

In this section, dry periods of shorter duration are considered for which no measurable precipitation occurs. Precipitable water, stability, and low-level cloudiness are computed for these periods when artificial stimulation of precipitation would be most needed; that is when the natural precipitation process is either not functioning or is very inefficient.

The dry periods chosen for study in this investigation consist of at least five consecutive days in which no measurable precipitation occurred within a radius of 60 miles of each of two primary stations. So that cloud observations as well as computations of precipitable water and stability could be utilized, the two primary stations selected were Amarillo and Midland. The periods chosen and their durations are given in Table 11. The duration for these dry periods was about 6.2 days in the spring and fall and 7.7 days in summer. Individual stations experienced much longer dry periods, especially in the summer. It was felt, however, that point rainfall measurements might be misleading when compared to evaluations of precipitable water and stability.

A. Dry Period Cloudiness

Table 12 is a tabulation of clouds reported during the dry periods. It is obvious from a brief examination that low clouds are especially deficient. The mean cloud cover during spring, summer, and fall dry periods is 36%, 18% and 14% respectively. This compares to an expected mean cloud cover based on the cloud census in Section II (10 years at Amarillo and 8 years at Midland) of 41%, 35%, and 31% for spring, summer, and fall. The latter values represent averages of the mean cloud cover at Amarillo and Midland.

Table 13 gives the percentage of observations (3-hourly) which included particular cloud types. As a comparison, the expected percentage based on 10 years of data at Amarillo and 8 years of data at Midland is included along with the percentages for heavy precipitation periods taken from Table 1. As an example

Table 11. Dry Periods in the Texas Plains

	Date	Year	Duration (days)
I. Amarillo			
Spring	Apr 3 - 7	1958	5
	Apr 1 - 6	1959	6
	Apr 23 - 30	1959	8
	Apr 3 - 10	1960	8
	Apr 15 - 21	1960	7
Summer	July 3 - 18	1957	16
	Aug 28 - Sept 3	1958	7
	Aug 25 - 29	1959	5
	June 26 - 30	1960	5
Fall	Sept 15 - 19	1957	5
	Oct 1 - 5	1957	5
	Oct 27 - 31	1957	5
	Oct 3 - 10	1958	8
	Sept 10 - 15	1959	6
	Oct 16 - 26	1959	11
	Sept 1 - 6	1960	6
II. Midland			
Spring	Apr 7 - 11	1957	5
	Apr 2 - 6	1959	5
	Apr 22 - 26	1959	5
	Apr 15 - 19	1960	5
	May 2 - 9	1960	8
Summer	July 2 - 16	1957	15
	Aug 22 - 30	1957	9
	Aug 26 - Sept 3	1958	9
	June 14 - 18	1959	5
	Aug 1 - 6	1959	6
	Aug 10 - 14	1959	5
	June 17 - 21	1960	5
	Aug 2 - 6	1960	5
Fall	Sept 29 - Oct 4	1957	6
	Oct 7 - 11	1959	5
	Oct 22 - 27	1959	6

Table 12. Dry Period Cloud Types

Station	Date	St+sF	Sc	Cu+cF	Cb	As+Ns	Ac+Acc	Ci	Cs+Cc
AMA	Apr 3 - 7 '58	0	0	1	0	0	5	7	0
	Apr 1 - 6 '59	0	2	1	0	0	8	27	10
	Apr 23 - 30 '59	0	0	4	2	1	15	29	12
	Apr 3 - 10 '60	0	1	7	0	1	17	20	6
	Apr 15 - 21 '60	0	2	2	0	0	4	28	9
MAF	Apr 7 - 11 '57	0	0	4	0	0	12	21	3
	Apr 2 - 6 '59	0	0	0	0	0	11	28	5
	Apr 22 - 26 '59	0	1	1	0	1	15	30	1
	Apr 15 - 19 '60	1	0	2	0	0	5	12	5
	May 2 - 9 '60	3	2	12	2	0	12	19	0
AMA	July 3 - 18 '57	0	2	38	4	0	42	71	5
	Aug 28 - Sept 3 '58	0	0	7	7	0	17	29	6
	Aug 25 - 29 '59	0	1	13	2	0	17	15	3
	June 26 - 30 '60	2	2	1	2	0	1	13	0
MAF	July 2 - 16 '57	0	0	23	2	0	28	70	6
	Aug 22 - 30 '57	0	0	13	3	0	13	30	0
	Aug 26 - Sept 3 '58	0	2	9	5	0	23	36	1
	June 14 - 18 '59	0	0	9	2	0	8	24	0
	Aug 1 - 6 '59	0	1	14	4	0	0	18	0
	Aug 10 - 14 '59	0	1	16	0	0	4	10	0
	June 17 - 22 '60	0	0	2	6	0	15	29	2
	Aug 2 - 6 '60	0	0	15	4	0	7	20	0
AMA	Sept 15 - 19 '57	0	1	2	0	0	2	4	0
	Sept 29 - Oct 5 '57	0	0	2	1	0	13	8	10
	Oct 27 - 31 '57	1	0	3	0	0	12	21	5
	Oct 3 - 10 '58	0	0	2	2	0	15	13	2
	Sept 10 - 15 '59	0	1	0	0	0	2	18	0
	Oct 16 - 26 '59	1	1	0	0	0	10	16	0
	Sept 1 - 6 '60	0	1	13	0	0	7	1	0
MAF	Sept 29 - Oct 4 '57	0	0	1	0	0	4	14	3
	Oct 7 - 11 '59	2	3	2	0	0	2	11	0
	Oct 22 - 27 '59	0	0	0	0	0	6	10	0

Table 13. Cloud Percentages

Cloud		Spring (%)			Summer (%)			Fall (%)	
Type	Dry	Expected	Wet	Dry	Expected	Wet	Dry	Expected	Wet
St	0.8	10.0	34.0	0.3	4.0	23.0	0.8	8.0	50.0
Sc	1.8	11.0	15.0	1.1	5.0	13.0	1.3	8.0	14.0
Cu	6.8	15.0	26.0	20.4	25.0	24.0	4.8	10.0	7.0
Cb	0.8	8.0	15.0	5.2	18.0	24.0	0.6	6.0	5.0
As	0.6	2.0	5.0	0.0	1.0	3.0	0.0	2.0	3.0
Ac	21.0	21.0	19.0	22.3	37.0	33.0	14.0	24.0	9.0
Ci	44.6	37.0	26.0	46.5	47.0	38.0	22.3	28.0	8.0
Cs	10.3	8.0	4.0	2.9	5.0	5.0	3.8	3.0	1.0

in reading this table, stratus clouds during spring dry periods were reported in 0.8% of the observations. Based on long-term averages, they would be expected to be reported in 10% of the observations, while during rainy periods they were reported 34% of the time. Thus stratus clouds are highly correlated with springtime precipitation and have a frequency of occurrence far below normal during spring dry periods.

Reference to Table 2 indicates that the clouds most closely correlated with springtime precipitation are cumulonimbus, stratus, stratocumulus and cumulus. Note from Table 13 that spring dry periods are seriously deficient in each of these cloud types. Middle and high clouds appear in some instances to be more frequent during dry periods, but this is most likely due to the fact that they can only be observed in the absence of low-level cloudiness. For this reason only low-level clouds are important in this comparison.

Table 2 indicates that, during the summer season, the clouds most closely associated with precipitation are cumulonimbus, stratus, and stratocumulus. Once again, each of these cloud types exhibits lower-than-expected frequencies during dry periods, and higher-than-expected frequencies during wet periods. The same is true of fall, when the clouds correlated with precipitation are once again stratus, stratocumulus, and cumulonimbus and to a lesser extent, altostratus which includes nimbostratus. In each case, dry period frequencies are well below those expected on the basis of the cloud census. It should be noted that fall cumulonimbus during wet periods is slightly below the expected value also, which indicates that stratiform clouds are predominantly associated with precipitation during this season. It is possible that wet period cumulonimbus has been underestimated due to the abundance of low-level stratus.

In each of the seasons, it is apparent that low-level clouds are lacking during dry periods. Since cloud modification practices to initiate or increase precipitation are more readily performed on low clouds (Semonin, 1960), the data presented indicate that investigations on methods of initiating low clouds may be as important as the seeding of existing clouds.

B. Precipitable Water, Vapor Transport, and Stability During Dry Periods

Table 14 is a tabulation of precipitable water, water vapor flux and stability for the dry periods. Precipitable water is expressed in centimeters, flux in gm cm^{-1} sec^{-1} and stability index (Showalter, 1953) in degrees. Frequency ogives based on Baker's (1969) precipitable water distribution have been computed for each dry period. Probabilities that precipitable water would be higher during a particular period have been calculated using the ogives and are shown in the column adjacent to precipitable water. Note that on the average, during the spring dry periods, precipitable water values were slightly higher than normal. In the summer and fall, the mean precipitable water was slightly below normal. In only a few cases were there large deviations in precipitable water vapor. This is not to say, however, that small variations are not important. It appears in some cases that small deviations from normal may be significant in affecting the precipitation process.

An interesting comparison involves precipitable water during dry periods with values of this parameter for wet periods given in Tables 3, 4, and 5. This comparison is shown in Table 15. It is obvious that precipitable water is higher during the wet periods. It seems that large amounts of precipitation are associated with relatively high values of precipitable water, but that a serious lack of precipitable water is not a requirement for extended dry periods. This is especially true under conditions of high stability.

Also in Table 15 is a comparison of mean water vapor fluxes for wet and dry periods. The values in the table represent the magnitude of the flux; direction has not been considered. Note that for each of the three seasons, the flux during wet periods is significantly higher than that during dry periods. The mean seasonal fluxes were not available for comparison. Comparisons can be

Table 14. Precipitable Water, Flux, and Stability During Dry Periods

Date	Year	Station	P.W. (cm)	% above	Flux	S.I.
Apr 3 - 7	1958	AMA	0.60	63	882.21	9.8
Apr 1 - 6	1959	AMA	1.08	25	1174.00	7.7
Apr 23 - 30	1959	AMA	0.86	58	1227.20	7.1
Apr 3 - 10	1960	AMA	1.03	31	1075.78	6.5
Apr 15 - 21	1960	AMA	0.77	54	1248.61	9.1
Apr 7 - 11	1957	MAF	0.85	56	1091.38	11.0
Apr 2 - 6	1959	MAF	1.03	35	912.80	8.1
Apr 22 - 26	1959	MAF	1.18	44	1137.30	7.1
Apr 15 - 19	1960	MAF	1.24	44	1326.40	7.9
May 2 - 9	1960	MAF	1.32	52	1431.70	6.7
		Spring Mean:	1.00	46	1150.70	8.1
July 3 - 18	1957	AMA	2.21	67	1601.97	2.9
Aug 28 - Sept 3	1958	AMA	2.08	56	1689.91	3.4
Aug 25 - 29	1959	AMA	2.68	30	1990.29	1.0
June 26 - 30	1960	AMA	1.94	66	2043.90	2.0
July 2 - 16	1957	MAF	2.25	73	1713.93	2.0
Aug 22 - 30	1957	MAF	2.43	60	1793.23	1.5
Aug 26 - Sept 3	1958	MAF	2.24	69	1532.87	3.1
June 14 - 18	1959	MAF	2.31	48	1643.59	1.2
Aug 1 - 6	1959	MAF	2.80	52	1672.25	-0.4
Aug 10 - 14	1959	MAF	2.65	56	1811.65	1.3
June 17 - 21	1960	MAF	2.43	43	1815.43	-0.2
Aug 2 - 6	1960	MAF	2.79	45	2645.03	0.6
		Summer Mean:	2.40	55	1829.50	1.53

Table 14. Precipitable Water, Flux, and Stability
During Dry Periods
(Continued)

Date	Year	Station	P.W. (cm)	% above	Flux	S.I.
Sept 15 - 19	1957	**AMA**	1.56	64	1538.06	5.8
Oct 1 - 5	1957	**AMA**	1.28	48	1184.48	5.2
Oct 27 - 31	1957	**AMA**	0.90	60	939.82	11.7
Oct 3 - 10	1958	**AMA**	1.39	43	1070.10	6.0
Sept 10 - 15	1959	**AMA**	1.18	86	708.54	10.7
Oct 16 - 26	1959	**AMA**	1.10	49	1277.72	11.0
Sept 1 - 6	1960	**AMA**	2.43	27	1959.77	4.4
Sept 29 - Oct 4	1957	**MAF**	1.33	75	1045.86	8.2
Oct 7 - 11	1959	**MAF**	1.98	24	2056.93	4.4
Oct 22 - 27	1959	**MAF**	1.28	52	1133.13	11.8
		Fall Mean:	1.44	53	1291.44	7.9

made, however, with the fluxes calculated in Section IV for wet and dry months. These are given below:

	Dry	Wet
Spring (April, May)	1239.26	1749.03
Summer (June, July, Aug)	1858.29	1938.68
Fall (Sept, Oct)	949.85	1709.42

It seems apparent that periods of above-normal rainfall are associated with a greater flux of atmospheric water vapor. This is not to say, however, that large fluxes of water vapor, or indeed, high values of precipitable water, lead to precipitation. Another important factor which must be considered is stability.

Table 15. Precipitable Water and Stability
for Wet and Dry Periods

	P.W. (cm)		Stability (deg)		Flux (gm cm^{-1} sec^{-1})	
Season	Dry	Wet	Dry	Wet	Dry	Wet
Spring	1.00	1.77	8.1	2.3	1150.70	1617.20
Summer	2.40	3.01	1.5	0.6	1829.50	2403.03
Fall	1.44	1.95	7.9	6.0	1291.44	2407.78

Values of mean stability index for the dry periods are shown in Table 14 and comparisons with the wet periods are given in Table 15. In general, it appears that stable atmospheric conditions, which are unfavorable for the formation of precipitating clouds, are predominant during dry periods. Most exceptions to this rule occur in the summer, with a mean stability index for dry periods of 1.5. During this season, when temperatures are quite high, the effect of precipitable water is quite important. What is usually missing is a mechanism causing the initiation of precipitating clouds. Of course, it is quite likely that showers did occur in the area during some of the summer dry periods, but they were scattered such that they were not observed by the network of stations used in this investigation. It is apparent from a study of Table 14 that both available water and stability are important factors in the production of precipitation. During the spring and fall, stability appears to be the controlling factor. On several occasions during these two seasons relatively high values of precipitable water are present. Vertical development is retarded, however, by subsidence in association with a stable atmosphere. Values of the Showalter stability index are characteristically lower during the summer. Most of the summer dry periods occur in association with below-normal values of precipitable water.

It is interesting to note, however, that in a few of the summer dry periods, the ingredients for precipitation appeared to be present, but for some reason or another, precipitation was not realized. An example of this situation is the case of August 1-6, 1959 at Midland. The mean precipitable water in this case was very near normal and the Showalter stability index had a value of -0.4, which was the lowest mean index computed. This may serve to indicate that very slight deviations in the amount of precipitable water may be important to the formation of precipitation during the summer season as suggested previously.

Another example which is even more striking is the case of June 17-21, 1960 at Midland. In this case, the precipitable water was above normal for the season (the probability of higher precipitable water was 43%) and the computed stability index was -0.2, yet, no precipitation. The case of August 25-29 at Amarillo is another example of a period of high precipitable water content and relatively low stability index with no significant cloud development and precipitation.

Tables 16, 17 and 18 are two-dimensional frequency tabulations of stability index and precipitable water for the dry periods. Entries in the tables represent the number of days that precipitable water and stability were within certain joint limits. For example, during the fall dry periods there were 6 days when precipitable water was between 0.80 cm and 1.19 cm while the stability index was between 6.0° and 7.9°.

Occasions when the stability index and precipitable water seem to favor the production of precipitation are evident in the tables. During the fall there were four instances when the precipitable water was greater than 1.60 cm and the stability index was less than 1.9°. On two occasions the precipitable water greater than 2.0cm when the stability index was negative. During two of the spring dry periods the precipitable water was greater than 1.60 cm and the stability index was negative, while in the summer there were 10 occasions of negative stability

Table 16. Precipitable Water and Stability for Dry Periods

AMARILLO AND MIDLAND - Fall

P.W. Stab.	0.00 to 0.39	0.40 to 0.79	0.80 to 1.19	1.20 to 1.59	1.60 to 1.99	2.00 to 2.39	2.40 to 2.79
-1.9 - 0.0						1	1
0.0 - 1.9					1	1	
2.0 - 3.9					3	4	1
4.0 - 5.9			4	4	1	1	2
6.0 - 7.9		1	6	1	1		
8.0 - 9.9		1	4	4	1		
10.0 -11.9		1	3	4		1	
12.0 -13.9			5				
14.0 -15.9				1			
16.0 -17.9				1			
18.0 -19.9		1		2			
20.0 -21.9				1			

Table 17. Precipitable Water and Stability for Dry Periods

AMARILLO AND MIDLAND - Spring

P.W. Stab.	0.00 to 0.39	0.40 to 0.79	0.80 to 1.19	1.20 to 1.59	1.60 to 1.99	2.00 to 2.39	2.40 to 2.79
-1.9 - 0.0					2		
0.0 - 1.9				1	1		
2.0 - 3.9			1	3			
4.0 - 5.9		3	6	5	1		
6.0 - 7.9		4	4	3			
8.0 - 9.9		6	3	2			
10.0 -11.9		2	2	1			
> 12.0		8	2	1			

Table 18. Precipitable Water and Stability
for Dry Periods

AMARILLO AND MIDLAND - Summer

P.W. Stab.	0.80 to 1.19	1.20 to 1.59	1.60 to 1.99	2.00 to 2.39	2.40 to 2.79	2.80 to 3.19	3.20 to 3.59	3.60 to 3.99
-5.9 - (-4.0)								
-3.9 - (-2.0)						1	2	
-1.9 - 0.0				5	7	3	3	1
0.0 - 1.9		1	7	5	15	3	1	
2.0 - 3.9			5	6	5	1		
4.0 - 5.9		2	5	4	1			
6.0 - 7.9	1	1	2	2				
8.0 - 9.9		1						
10.0 -11.9		1						
12.0 - 13.3								

index associated with values of precipitable water greater than 2.80 cm. It is these periods which may hold the most promise for cloud modification efforts.

VI. SUMMARY AND CONCLUSIONS

This study has considered the relationship among cloudiness, precipitable water vapor, water vapor flux, stability, and precipitation in the Texas High Plains. It represents a different approach to learning more about some of those factors which exert control over the production and/or suppression of clouds and precipitation in the plains area.

The cloud census in Section II served two purposes: it presented the annual and diurnal variation of cloud types and amounts in the high plains, and, it served as a basis of comparison for the occurrence of clouds during wet and dry periods. Section III considered cloud occurrences during periods of above-normal precipitation in addition to a "rank correlation" study between cloud types and amounts and precipitation. Section IV was devoted to an investigation of characteristically wet and dry months. This section compared cloud occurrences, precipitable water vapor, water vapor flux, and storm activity during months with heavy and light precipitation. Investigations of dry periods of shorter duration were presented in Section V. The periods chosen for study consisted of at least five consecutive days in which no measurable precipitation occurred within a 60-mile radius of Amarillo or Midland. These two stations were chosen so that simultaneous values of cloud occurrences, precipitable water vapor, water vapor flux and stability index could be computed.

In summary, the following general statements can be made concerning the results of this research:

(1) the most common cloud types in the plains area are altocumulus and cirrus. Both of these have a maximum during the summer months but are prevalent throughout the year. Summer also owns the distinction of having the minimum number of both clear and overcast skies. This means that summer skies are usually populated by scattered clouds but overcasts are rare. Total cloud amount is a maximum during winter, decreasing to a sharp minimum in September. The fall season has the highest number of clear-sky observations.

(2) precipitation during the late fall and winter is associated with stratiform clouds which develop in conjunction with cyclonic activity. Spring and summer precipitation is most highly correlated with cumuliform clouds characteristic of convective activity. The

highest rank-correlation coefficients derived between clouds and precipitation were for cumulonimbus in the spring. The lowest coefficients were found in the winter.

(3) above-normal cloudiness is associated, as expected, with rainy periods in the plains. In practically all cases considered, fewer clouds were present during dry months. The one notable exception was summer cumulus which occurred with surprising regularity during both dry and wet periods. More intense convective development during wet periods led subsequently to the formation of cumulonimbus, which was definitely more prevalent during the wet periods.

(4) wet periods were generally characterized by above-normal values of precipitable water. During most dry periods, however, there were only small deviations from expected values (median of the distributions). This indicates that precipitable water is a fairly conservative quantity, especially during the summer and fall, in the Texas Plains. It appears that large amounts of precipitation are associated with relatively large amounts of precipitable water, but that a serious deficit in precipitable water vapor amounts was not a feature of extended dry periods.

(5) wet periods were further characterized by larger amounts of water-vapor transport, indicating a continuous supply of precipitable water to the area, and by unstable atmospheric conditions. Dry periods were generally associated with atmospheric stability, which is unfavorable for the formation of precipitating clouds. In most instances, extended dry periods were related to atmospheric circulation patterns which either served to cut off the supply of low-level moisture, produced subsidence and consequent stability, or both.

(6) items (3), (4), and (5) taken together permit the following generalization to be made: drought periods on the Texas High Plains may not be markedly deficient in water vapor, nor even clouds (in the summer season); the missing ingredients are atmospheric instability and associated circulation patterns. Drought on the Texas High Plains is therefore a relatively local

phenomenon under the control of atmospheric circulation on a large (possibly hemispheric) scale. Shorter-term dry periods may well be affected by migratory weather systems on a smaller (continental) scale.

It seems pertinent at this point to make some observations concerning the potential of cloud modification experiments in the high plains. Several instances were noted when the ingredients for precipitation appeared to be present, but precipitation was not observed to occur. It is occasions like these which hold the most promise in cloud modification studies. Summer cumulus was frequently observed during dry periods in summer. This indicates that convection was initiated but not strong enough, for one reason or another, to develop into precipitation-producing clouds. It is possible, but by no means certain, that these situations may lend themselves to successful seeding operations.

It is important that field research be initiated to evaluate the possibilities of artificially increasing rainfall in the Texas plains. It should be kept in mind, however, that there are good climatological reasons that the plains area is semi-arid. Primary among these is the "rain shadow" effect of the southern Rocky Mountains. Thus, attempts to modify clouds should be aimed at producing small increases during periods when the natural precipitation mechanism is not quite sufficient to produce measurable rainfall.

APPENDIX I

LOCAL CLIMATOLOGICAL DATA FOR AMARILLO, LUBBOCK AND MIDLAND

The descriptions which follow have been extracted from the Local Climatological Data Annual Summaries published by the Environmental Science Services Administration.

Amarillo, Texas The station is located 7 statute miles ENE of main post office in Amarillo on the northern high plains of Texas in the southwest-central part of the Texas Panhandle. The topography in vicinity of the station is rather flat and on the divide between the watersheds of the Canadian River and the Prairie Dog Town Fork of the Red River. There are numerous shallow lakes, often dry, over the area and the nearly treeless grasslands slope gradually downward to the east reaching a pronounced escarpment, the Caprock, about 60 miles east of Amarillo, dropping sharply from around 3,000 to near 2,000 feet m.s.l. The terrain gradually rises to the west and northwest to some 5,000 feet about 100 miles to the west where high tablelands and foothills of the Rocky Mountains commence. The Continental Divide in the Rockies is about 300 miles west of Amarillo. In the station vicinity there is upslope effect from north, east, and south, which helps produce fog and stratus particularly from late fall to early spring. Strong winds from southwest through north will occasionally result in blowing dust restricting visibility to less than 1 mile. To the east, south and west, most of the land is under cultivation, considerable of it irrigated, while to the northwest, north and northeast grazing land predominates. Soil of the area is chestnut loam interspersed with gray and red loams, all overlying a substratum of caliche.

Departures from normal precipitation are wide, with yearly totals ranging from 9.94 inches in 1956 to 39.75 inches in 1923. The area is occasionally subjected to prolonged droughts of several months duration, but as a rule the seasonal distribution is fairly uniform. Three-fourths of the total annual precipitation falls between April and September, occurring from thunderstorm activity. The average frequency of precipitation amounts include annually: 53 days with trace, 11 days .50 or more, 4 days 1.00 inch or more and 1 day 2.00 inches and over. An even snow cover is very unusual because of high winds. Snow is usually melted within a few days after it falls. Heavier snowfalls of 10 inches or more usually with near blizzard conditions have occurred

20 times in 72 years, usually over a 2-3-day period. The heaviest, 20.6 inches, occurred March 25-26, 1934, in 23 hours, much melting as it fell, the greatest depth on the ground reaching only 4.5 inches. The record greatest depth on ground was 16.5 inches February 26, 1903, when 17.5 inches fell in 49 hours. The most damaging blizzard occurred March 23-25, 1957, when 11.1 inches fell, reached a depth of 10 inches, and northerly winds averaged 40 m.p.h. with gusts over 50 m.p.h. for 24 hours producing severe drifting.

The Amarillo area is subject to rapid and large temperature changes, especially during the winter months, when cold fronts from the northern Rocky Mountain and Plains states sweep across the level plains at speeds up to 40 m.p.h. Temperature drops of from 40° to 60° within a 12-hour period are not uncommon in association with these fronts, and 40° drops have occurred within a few minutes. Normally, the coldest period occurs in mid-January, however, the record minimum temperature, -16°, occurred February 12, 1899. Long term records of 0°, or below, average less than 3 days per year. Normally, the warmest period occurs in July, but the record maximum temperature of 108° occurred June 24, 1953. Temperatures 100°, or higher, average 6 days per year, slightly more frequent in July than June or August. Usually there is low humidity and sufficient wind to prevent the high daytime temperatures from being particularly uncomfortable, and rapid cooling occurs at night..

Humidity averages rather low, frequently dropping below 20 percent and occasionally below 4 percent in the spring. Low humidity moderates the effect of high summer afternoon temperatures, and makes evaporative cooling systems very effective most of the time.

Severe local storms are infrequent, though a few thunderstorms, with damaging hail, lightning, and wind in a very localized area, occur most years, usually in spring and early summer. These storms are often accompanied by very heavy rain, which produces local flooding, particularly of roads and streets. Tornadoes are rare, one of record moving through the city of Amarillo late Sunday afternoon, May 15, 1949, causing 6 deaths and 87 injuries, with damage estimated at $4,800,000. In the county-wide area 10 tornadoes have been recorded in 70 years.

Lubbock, Texas Lubbock is located on the high, level surface of the South Plains Region of northwest Texas, at an elevation of 3,243 feet. The South Plains are part of the Llano Estacado which is isolated from the remainder of the High Plains by the Canadian River on the north and the Pecos River on the west and southwest. An erosional escarpment, the "Break of the Plains", often referred to as the Caprock, forms the eastern boundary.

The surface is featureless except for an erosional escarpment, small playas, small stream valleys, and low hummocks. The escarpment, from 50 to 250 feet high, results from headward erosion of streams to the east and southeast. Numerous shallow depressions of typically circular outline dot the area. During the rainy months, they form ponds and small lakes. A few small stream valleys, tributary to the Brazos River, constitute the only appreciable relief due to water erosion. There are few surface obstructions offered to horizontal winds, except southeast to east winds which are deflected upward by the erosional escarpment.

The climate of the area is semiarid, transitional between desert conditions on the west and humid climates to the east and southeast. The normal annual precipitation is 18.08 inches. Maximum precipitation usually occurs during May, June, and July when warm, moist tropical air is carried inland from the Gulf of Mexico. This airmass produces moderate to heavy afternoon and evening convective thunderstorms, sometimes with hail. Snow occasionally occurs during the winter months, but is generally light and remains on the ground only a short time. Precipitation in the area is characterized by its erratic nature, varying during the period of record from as much as 40.55 inches to only 8.73 inches annually, and from as much as 13.93 inches to none in 1 month.

The normal annual temperature is 59.7°. The warmest months are June, July, and August, with a normal daily maximum in July of 92°. The record maximum temperature of 107° occurred in June 1957 and July 1958.

The coldest months are December and January with a normal daily minimum temperature in January of 25.4° and a monthly mean of 39.2°. The record minimum temperature of -9° occurred in January 1947.

The heat of summer is moderated by low humidity and wind during the daytime. The high elevation and dry air allow rapid radiation after nightfall so most summer nights are cool, with a minimum in the sixties.

Midland, Texas Midland is located on the southern extension of the South Plains of Texas. The terrain is level with only slight occasional undulations. There is a marked downslope of about 900 feet per 100 miles to the east and southeast and upslope of about 600 feet per 100 miles to the north and west.

The climate of Midland is typical of a semiarid region. The vegetation of the area consists mostly of native grasses, and there are very few trees in the area, mostly mesquite.

Droughts occur with monotonous frequency. Several years which show an excess in precipitation might be misleading, since extremely heavy downpours would show as large accumulations but the runoff would be so great and rapid that little benefit would be derived from the rainfall.

Most of the annual precipitation in the Midland area comes as a result of very violent spring and early summer thunderstorms. These are usually accompanied by winds in excess of 40 m.p.h., excessive rainfall over limited areas, and sometimes hail. Due to the flat nature of the countryside, local flooding occurs, but this is of short duration. Tornadoes are occasionally sighted, mostly aloft, but the sparsity of population in the area, with most people concentrated in cities or towns, causes very infrequent damage or injury.

There is very little precipitation in the winter and infrequent snow. Fog and drizzle due to the upslope from the southeast occur frequently during night hours, but generally clear by noon.

During the late winter and early spring months, dust storms occur very frequently. The flat plains of the area with only grass as vegetation offer little resistance to the strong winds that occur. Dust in many of these storms remains suspended in the air for several days after the storm has passed. The sky is occasionally obscured by dust but in most storms visibilities range from 1 to 3 miles.

Daytime temperatures are quite hot in the summer, but there is a large diurnal range and most nights are comfortable. The normal daily maximums in the summer months range in the low to mid-nineties, while the normal minimums range in the upper sixties. In winter the temperature range is from the upper fifties to the low and middle thirties.

The temperature usually first drops below 32° in the fall about the middle of November and the last temperature below 32° in the spring comes early in April. However, below 32° temperatures have been recorded as early as October 31 and as late as April 20.

Winters are characterized by frequent cold periods followed by rapid warming. Springs have very violent thunderstorm activity, while summers are hot and dry, with numerous small convective showers. Extremely variable weather occurs during the fall. Frequent cold frontal passages are followed by chilly weather for 2 or 3 days, then rapid warming. Cloudiness is at a minimum.

The prevailing wind direction in this area is from the southeast. This, together with the upslope of the terrain from the same direction, causes frequent low cloudiness and drizzle during winter and spring months. Glaze occurs when the temperature is below freezing, but usually lasts for only a few hours. Maximum temperatures during the summer months frequently are from 2° to 6° cooler than those at places 100 miles southeast, due to the cooling effect of the upslope winds.

Very low humidities are conducive to personal comfort, because even though summer afternoon temperatures are frequently above 90°, the low humidity with resultant rapid evaporation, has a cooling effect.

APPENDIX II

DESCRIPTION OF CLOUD TYPES*

<u>Fog (F)</u> A suspension of very small water droplets in the air, generally reducing horizontal visibility at the earth's surface to less than 1 km (5/8 mile). When sufficiently illuminated, individual fog droplets are frequently visible to the naked eye; they are then often seen to be moving in a somewhat irregular manner. The air in fog usually feels raw, clammy, or wet. This hydrometer forms a whitish veil which covers the landscape; when mixed with dust or smoke, it may, however, take a faint coloration, often yellowish. In the latter case, it is generally more presistent than when it consists of water droplets only.

<u>Stratus (St)</u> Generally grey cloud layer with a fairly uniform base, which may give drizzle, ice prisms, or snow grains. When the sun is visible through the cloud, its outline is clearly discernible. Stratus does not produce halo phenomena except, possibly, at very low temperatures. Sometimes Stratus appears in the form of ragged patches called <u>fractostratus</u>.

<u>Stratocumulus (Sc)</u> Grey or whitish, or both grey and whitish, patch, sheet, or layer of cloud which almost always has dark parts, composed of tessellations, rounded masses, rolls, etc., which are non-fibrous (except for virga) and which may or may not be merged; most of the regularly arranged small elements have an apparent width of more than five degrees.

<u>Cumulus (Cu)</u> Detached clouds, generally dense with sharp outlines, developing vertically in the form of rising mounds, domes, or towers, of which the bulging upper part often resembles a cauliflower. The sunlit parts of these clouds are mostly brilliant white; their base is relatively dark and nearly horizontal. Sometimes cumulus is ragged. In this case it is called <u>fractocumulus</u>.

<u>Cumulonimbus (Cb)</u> Heavy and dense cloud, with a considerable vertical extent, in the form of a mountain or huge towers. At least part of its upper portion is usually smooth, or fibrous or striated, and nearly always flattened; this part often spreads out in the shape of an anvil or vast plume. Under the base of this cloud, which is often very dark, there are frequently low ragged clouds either merged with it or not, and precipitation sometimes in the form of virga. Often hanging protuberances like udders are seen on the under surface of

*These definitions have been taken from the International Cloud Atlas (1956) cumulonimbus clouds, in which case the name cumulonimbus mammatus applies.

Altostratus (As) Greyish or bluish cloud sheet or layer of straited, fibrous, or uniform appearance, totally or partly covering the sky, and having parts thin enough to reveal the sun at least vaguely, as through ground glass. Altostratus does not show halo phenomena.

Nimbostratus (Ns) Grey cloud layers, often dark, the appearance of which is rendered diffuse by more or less continously falling rain or snow, which in most cases reaches the ground. It is thick enough throughout to blot out the sun. Low, ragged clouds frequently occur below the layer, with which they may or may not merge.

Altocumulus (Ac) White or grey, or both white and grey, patch, sheet, or layer of cloud, generally with shading, composed of laminae, rounded masses, rolls, etc., which are sometimes partly fibrous or diffuse and which may or may not be merged; most of the regularly arranged small elements usually have an apparent width of between one and five degrees. Sometimes altocumulus clouds occur as altocumulus castellatus which presents, in at least some portion of its upper part, cumulus-like protuberances in the form of turrets which generally give the cloud a crenelated appearance. The turrets, some of which are taller than they are wide, are conneted by a common base and seem to be arranged in lines. The castellatus character is especially evident when the clouds are seen from the side.

Cirrus (Ci) Detached clouds in the form of white, delicate filaments or white or mostly white patches or narrow bands. These clouds have a fibrous (hair-like) appearance, or a silky sheen, or both.

Cirrostratus (Cs) Transparent, whitish cloud veil of fibrous or smooth appearance, totally or partly covering the sky, and generally producing halo phenomena.

Cirrocumulus (Cc) Thin, white patch, sheet or layer of cloud without shading, composed of very small elements in the form of grains, ripples, etc., merged or separate, and more or less regularly arranged; most of the elements have an apparent width of less than one degree.

APPENDIX III

DERIVATION OF FORMULA FOR RANK-CORRELATION COEFFICIENT

1. Standard definition of correlation coefficient is

$$r = \frac{\overline{mn} - \overline{m}\,\overline{n}}{\sigma_m \; \sigma_n} \qquad \text{(A)}$$

where m is the rank with respect to cloud frequency and n is the rank with respect to precipitation

2. Since $\overline{(m - n)^2} = \overline{m^2} - 2\,\overline{mn} + \overline{n^2}$

$$\text{then } mn = \frac{1}{2}\,\overline{m^2} + \frac{1}{2}\,\overline{n^2} - \frac{1}{2}\,\overline{(m - n)^2} \qquad \text{(B)}$$

Substituting (B) into (A) we get

$$r = \frac{\frac{1}{2}\,\overline{m^2} + \frac{1}{2}\,\overline{n^2} - \frac{1}{2}\,\overline{(m - n)^2} - \overline{m}\,\overline{n}}{\sqrt{\overline{m^2} - \overline{m}^2}\;\sqrt{\overline{n^2} - \overline{n}^2}} \qquad \text{(C)}$$

where $\sigma_m^{\,2} = \overline{m^2} - \overline{m}^2$ and $\sigma_n^{\,2} = \overline{n^2} - \overline{n}^2$

3. But $\overline{m} = \overline{n} = \dfrac{N + 1}{2}$ (D)

and $\overline{m^2} = \overline{n^2} = \dfrac{(N + 1)\,(2N + 1)}{6}$ (E)

where N is the number of precipitation-cloud frequency pairs in the ranked data.

4. Substitution of D and E into C yields

$$r = 1 - \frac{6\,\overline{(m - n)^2}}{N^2 - 1}$$

or

$$r = 1 - \frac{6 \sum (m - n)^2}{N\,(N^2 - 1)}$$

APPENDIX IV

STATIONS USED IN SECTION III B

Dalhart
Stratford
Spearman
Follett
Canadian
Borger
Pampa
Miami
Vega
Amarillo
Hereford
Clarendon
Memphis
Childress
Muleshoe
Tulia
Plainview
Silverton
Lubbock
Levelland
Crosbyton
Plains
Spur
Post
Seminole
Lamesa
Big Spring
Andrews
Snyder
Colorado City
Midland
Forsan

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