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GRASSLAND CLIMATOLOGY OF THE PAWNEE GRASSLAND

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ABSTRACT

This report is presented in two parts: first, an analysis of historical data provides a climatological summary principally concerning precipitation and temperature of the Pawnee Grassland; and second, an analysis of historical data describes the solar radiation distributions in time and space over the North American grassland region.

Part I

A study of the climate of the Pawnee National Grassland, of northeastern Colorado is presented. The analysis concentrated on temperature and precipitation using historical data available from climatological weather stations. Spatial and yearly precipitation variability within the Pawnee Grassland is examined. A storm analysis is described in which summer storms producing more than one inch of rainfall are shown to be an important factor in the yearly precipitation variability. An extreme value analysis was performed on storm precipitation. A two-state, first-order Markov chain was used to calculate precipitation probabilities.

The temperature analysis is based upon maximum and minimum daily temperatures. Results include seasonal temperature variation, diurnal temperature variation, extreme value temperature analysis, length of growing season, and monthly range of temperature. Probabilities are calculated with a three-state first-order Markov chain so that sequences of temperature may be generated.

Through correlation studies, yearly variations in precipitation, wind, and temperature are shown to be related.

Part II

The spatial and temporal changes in incoming solar radiation are summarized for fourteen stations over the west-central United States. The area encompassed is within 97° to 118° west longitude and 33° to 49° north latitude. The period of study covers twenty years, 1950 through 1969. Deviations from long-term station monthly means are used as a basis for this analysis in order to minimize interstation calibration problems. The average monthly deviations of the area are accumulated for annual totals. The results of the analysis show that there is a trend in the average annual radiation received over the area amounting to a 725 langley decrease per year (0.5% decrease per year). The magnitude of this trend is stronger in the southern latitudes of the study area and is most pronounced in the summer months. Variations superimposed upon the trend are investigated and shown to be correlated with the relative annual average cloudiness. The effects of volcanism and extraterrestrial forces, e.g., solar cycle variations, are discussed.

PART I: SUMMARY OF THE CLIMATOLOGICAL STUDY

PAWNEE NATIONAL GRASSLAND

INTRODUCTION

The Great Plains, bisecting the North American continent, is a vast region whose vegetation is dominated by the grasses. The existence of a tremendous expanse of grass is a fairly rare phenomenon on the Earth. Vegetation in any particular area, barring man's influence, is basically a result of the soils and the climate. This study of a Great Plains grassland climate, therefore, has been an analysis of one of the major causes of the existence of the North American grassland.

This project is part of the International Biological Program (IBP), which is conducting an intensive ecological study of the Pawnee National Grassland as representative of a grassland biome. The Pawnee Grassland, located in northeastern Colorado, was chosen largely because it has remained relatively free from man's influence for thirty years. Our study used data from climatological weather stations to determine some of the present characteristics and principal features of the climate of the area. As part of a large research effort, the study was undertaken with an eye toward utilization of the results by other workers in the program.

The relative lack of population and industry is one reason why little work has been done on a climatology of short grass prairie regions. Rosenberg(1963, 1965) presented a comprehensive climatic atlas of central Nebraska, but this is considered a midgrass region.

Several climatological summaries of Colorado have been published (Trimble 1908, 1918; Berry 1959). These reports give a brief summary of the high plains climate. In general, it is uniform from place to place with low relative humidity, abundant sunshine, light rainfall, moderate to high wind movement, and a large daily range of temperature. Crow (1957) published an excellent paper on the effect of Colorado's climate on her economy.

Probably the most thorough analysis on the climate of the plains was done by Borchert (1950). His work covered the entire North American grassland. His findings indicate a homogeneity to the climate of the entire area. He showed that precipitation gradually increases from the western edge of the grassland to the Mississippi River, but the climate is similar, i.e., relatively wet, hot summers and dry, cool winters. According to Borchert, major droughts have a tendency to occur simultaneously over the entire grassland.

Although this is a study of only a small section of the grassland, Borchert's findings suggest that the results should be generally applicable over most of the North American prairie. The research concentrated on temperature and precipitation analysis since these parameters are the only data with long-term records in the area.

DATA SOURCES AND QUALITY

Climatology is a synthesis of past weather over a region and is only as good as the available data. The climatologist is limited by the number of weather stations, types of data recorded, and the length of each climatological record. Tables 1 and 2 give the history of the precipitation and temperature records from stations used in this study. Their locations are illustrated in Fig. 1.

A large amount of the data came from United States Weather Bureau cooperative observer stations. These data are published monthly in the Climatological Summary, and are also available from the National Weather Records Center in Asheville, North Carolina. The data from

Table 1. Location and history of precipitation stations used in study.

Station	Record Type	Record Length (years)	Dates of Records	Latitude (N)	Longitude (W)	Elevation (ft)
Akron	Monthly	30	3/1/30-2/28/35, 3/1/37-2/28/62	40° 10'	103° 09'	4538
Briggsdale	Yearly	15	1/51-12/65	40° 39'	104° 20'	4855
Cheyenne	Monthly	30	1/38-12/67	41° 19'	104° 49'	6126
CPER	Daily	24	3/1/40-2/28/41, 3/1/44-2/28/67 except 11/44 12/44,1/47, 2/47,3/47	40° 51'	104° 43'	5394
Estes Park	Monthly	30	1/37-12/66	40° 23'	105° 31'	7525
Fort Collins	Daily	30	3/1/31-2/28/61	40° 35'	105° 05'	5004
Fort Lupton	Monthly	30	1/31-12/60	40° 06'	104° 49'	4888
Greeley	Monthly	30	1/37-12/66	40° 25'	104° 41'	4648
Grover	Daily	30	3/1/37-2/28/67	40° 51'	104° 24'	5090
Kauffman	Daily	30	3/1/37-2/28/67	40° 50'	102° 56'	5250
Julesburg	Daily	30	3/1/31-2/28/47 3/1/49-2/28/62	41° 00'	102° 51'	3469
New Raymer	Yearly	17	1/51-12/67	40° 36'	103° 50'	4783
Nunn	Yearly	15	1/51-12/52, 1/54-12/67	40° 42'	104° 47'	5185
Pine Bluffs	Monthly	30	1/38-12/67	41° 11'	104° 04'	5047

Table 2. Location and history of temperature stations used in study.

Station	Record Type	Record Length (years)	Dates of Records	Latitude (N)	Longitude (W)	Elevation (ft)
Akron	Daily Max. & Min.	30	3/1/30-2/28/35, 3/1/37-2/28/62	40° 10'	103° 09'	4538
CPER	Daily Max. & Min.	20	3/1/48-2/28/62	40° 51'	104° 43'	5394
Fort Collins	Daily Max. & Min.	30	3/1/31-2/28/61	40° 35'	105° 05'	5004
Grover	Daily Max. & Min.	20	3/1/47-2/28/60, 3/1/61-2/28/68	40° 51'	104° 24'	5090
Kauffman	Daily Max. & Min.	20	3/1/46-2/28/64, 3/1/66-2/28/68	40° 50'	102° 56'	5250
Julesburg	Daily Max. & Min.	30	3/1/31-2/28/47, 3/1/49-2/28/62	41° 00'	102° 51'	3469

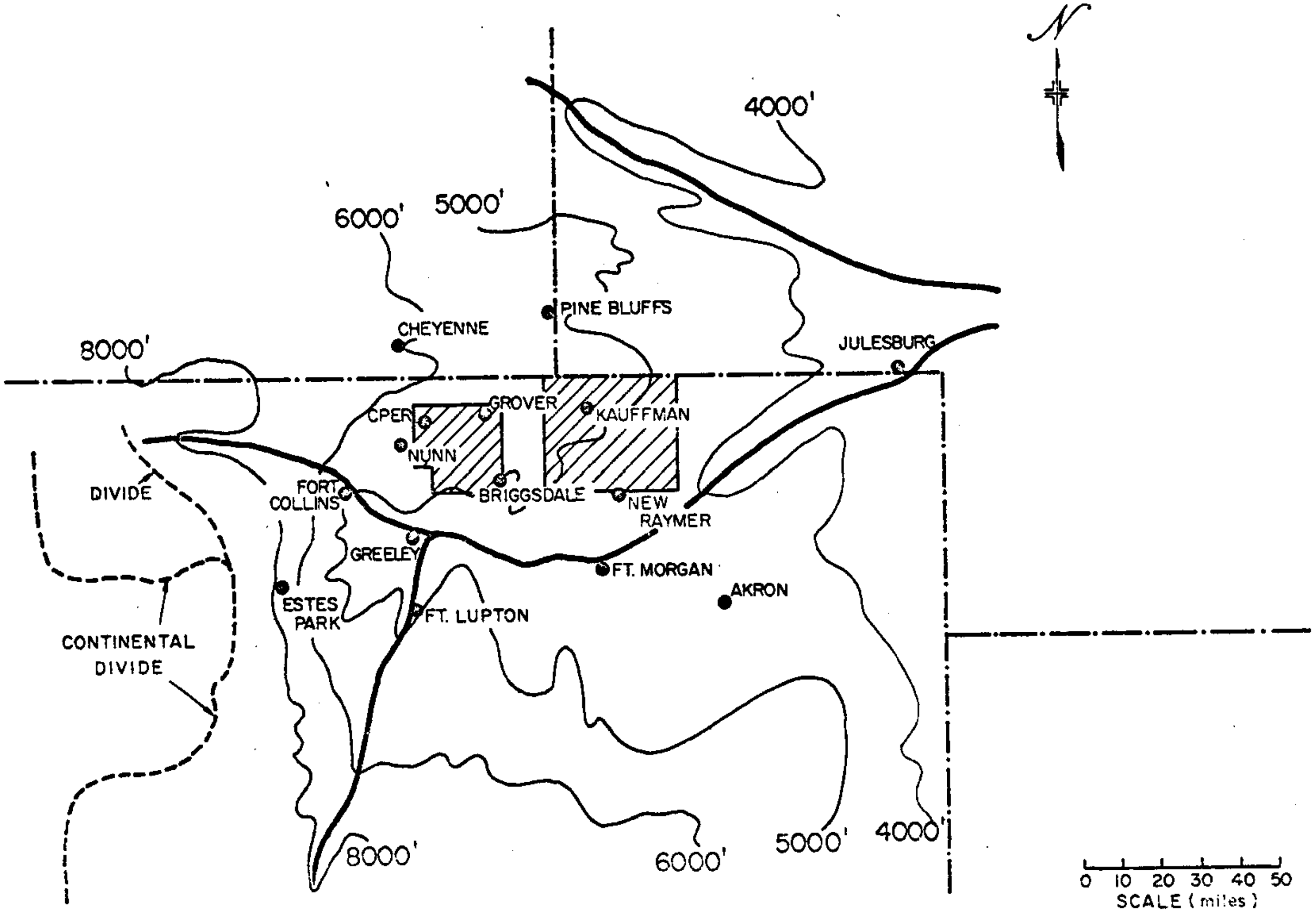


Fig. 1. Location of climatological stations used in this study. Cross-hatched areas indicate Pawnee National Grassland.

the Central Plains Experimental Range Station (CPER) were made available through the courtesy of the Agricultural Research Service, United States Department of Agriculture. Temperature and precipitation records from Fort Collins, Akron, and Julesburg were obtained on magnetic tape from the climatic library for the Colorado State University Agricultural Engineering Project 207, W-48.

Since the entire region is sparsely populated, there is a relative shortage of climatic data. Only three stations: CPER, Grover, and Kauffman, are located in or near the Pawnee National Grassland with daily weather records beginning thirty years ago. Much of the analysis of this climatology is centered on these three stations, which will be referred to as the grassland network. All stations listed in Tables 1 or 2 are occasionally combined into a synoptic scale network covering northeastern Colorado for the analysis of gross climatic features.

One of the major problems is the limited quantity of data. Three parameters generally available are daily precipitaion, daily maximum temperature, and daily minimum temperature. A short wind record is also available at CPER, but no other meteorological data exists for the area. A rather short record length exists for the stations in the area. As implied in Table 1, no station immediately adjacent to or located within the Pawnee Grassland was in operation before the late 1930's. The drought of the early 30's and the resulting dust conditions drove many farmers from eastern Colorado and made it apparent that a more intensive climatological network was necessary. Precipitation records span a maximum of 30 years, while temperature records span 20 years. It is unfortunate that only short records are available.

However, we have found through variance tests (Marlatt and Riehl 1963, Marlatt 1969) that, with the existing record, the average annual precipitation at each of the grassland stations is within 7% of the true long-term mean. The short length of the data also precludes any direct analysis of climatic change.

The quality of the records is more difficult to determine than the quantity. The precipitation data is generally quite complete. However, such data is systematically biased on the low side due to wind effects on the collection of precipitation particles (Weiss and Wilson 1958). This bias is also a function of precipitation type, being extreme for windblown snowfall. One may partially correct for this deficiency by shielding the gauge. The data from the grasslands, however, are from unshielded gauges so we must be aware of possible systematic errors, particularly during the winter.

Another possible bias in the precipitation data comes when an attempt is made to estimate areal precipitation from a gauge network. Studies of this problem have shown that on the average, as one increases the density of stations, the areal precipitation increases (LaRue and Younkin 1963, U.S. Weather Bureau 1947). One would intuitively anticipate such a result since a sparse network would at times completely miss even large thunderstorms. For the Pawnee Grassland, each gauge of approximately 50 sq inches is assumed to sample 500 sq miles (2×10^{12} sq inches). Thus, the errors due to both instrument deficiencies and sampling deficiencies act, over a long record, to bias the data toward the low side.

In the daily temperature records of the grassland network, there were some instances occurring in which the maximum and minimum temperatures for several days were missing. If only one day's record was missing, a value was inserted by averaging the temperature on the day preceding and the day following the record gap. On a longer set of missing temperatures, the gap was filled by averaging the temperatures at the other two grassland stations. However, two of these stations had several months of temperature data missing. Rather than attempt to interpolate these missing data, we substituted a previous year with good data. Thus, the 20 year temperature record for Grover is from 1947-1959 and from 1961-1967.

The biggest problem with respect to data quality is the CPER temperature record, which has been taken from a Bourdon Tube thermograph. As Landsberg (1968) points out a thermograph is subject to several possible mechanical errors. These errors do not affect the maximum-minimum thermometer combinations used at the other grassland stations. In addition, the CPER thermograph has now been in continuous service for 22 years and most probably has not been adjusted or calibrated during that time. It can thus be expected that the temperature record is somewhat less reliable at CPER than at the other two grassland network stations.

Comparison of the CPER temperature record with the other two grassland stations (Grover and Kauffman) revealed that the temperature at CPER was distinctly lower during some periods. To analyze the maximum temperature record at CPER, we calculated the difference between the combined, average monthly maximum temperature at Grover and Kauffman and the average monthly maximum temperature at CPER for each month of the 20 year record. The difference was then plotted as a time series for each month of the year. The same procedure was used to analyze the minimum temperature. The graphs showed that the temperature difference was small (less than 3°F) and oscillated around zero until about 1960. Since then, the CPER temperature record has been relatively lower than the records at the other stations.

To test the hypothesis that the CPER temperature record was lower only over the last few years, we calculated a mean maximum temperature for the period June to September over the first five and the last five years of the CPER record. This was also done for the averaged Grover-Kauffman record. We found no significant difference between the mean maximum temperatures at CPER as compared to Grover-Kauffman during the first five years, but over the last five years the CPER maximum temperature record was significantly lower than the Grover-Kauffman record at the 95% confidence level. A similar result arises from the analysis of the minimum temperature records for the period November to February. The other sections of the record did not show such behavior, because the largest errors in the CPER record were found at the extremes, i.e., the maximum temperatures in the summer and the minimum temperatures in the winter.

From this analysis we concluded that a correction should be applied to the following temperature data at CPER: (i) maximum temperature from June to September since 1960, (ii) maximum temperature from April to October since 1962, (iii) maximum temperature from April to November since 1964, (iv) minimum temperature from November to February since 1962, (v) minimum temperature from November to April since 1963, and (vi) minimum temperature from October to April since 1964.

The exact form of the correction was determined by calibration of the CPER thermograph. We calibrated it in a controlled temperature chamber against a reference thermometer and found that the instrument did indeed read low at most temperatures. The largest error, 6%, was produced at low temperatures. A correction equation was developed by applying a least squares fit to the calibration data, and was used on the data during the periods listed above. The correction equation was:

$$T_{corr} = 1.022T - 0.0007149(T^2) = 4.770$$

where T_{corr} = corrected temperature in degrees Fahrenheit

where T = thermograph temperatures in degrees Fahrenheit

Admittedly, this is not an ideal situation, but the shortage of stations has prompted us to correct and use this data. Furthermore, the site of much of the intensive analysis connected with the IBP project is located very near the CPER station. Any need for temperature data by other investigators will therefore probably require the use of the CPER record. For this climatology, averaging over the grassland network should largely dampen out the remaining errors.

The instruments collecting the data used in this climatology are located 6 ft above the ground in conventional Weather Bureau instrument shelters. However, it is the temperature within three inches of the ground that has the greatest effect on the low-growing vegetation of the region. Marlatt (1965) showed that nighttime surface temperatures on the Pawnee Grassland generally fall within 5°F of air temperatures measured at shelter height. He reported that daytime differences, however, are often as large as 25° to 30°F. Marlatt also found horizontal temperature gradients as high as 13°F per inch around clumps of buffalo grass. One must consequently be very cautious when applying the air temperature analysis presented in this paper to any ecological study near the ground.

Recognizing the possibility of minor errors and data limitations, we nevertheless assume the data available are reasonably representative of the region and proceed to summarize the climate of the grasslands.

GENERAL FEATURES OF THE TOPOGRAPHY AND CLIMATE

The terrain of the Pawnee National Grassland is flat to gently rolling with a few buttes projecting above the general topography. Elevations range from 4,500 ft to 5,500 ft, the result of a gentle slope from southeast to northwest.

The Pawnee Grassland is almost exclusively an original catchment basin. The vast majority of water available in the area comes directly from precipitation. No streams originating in the Rocky Mountains flow through the grasslands. Indeed, the streams and lakes of the area are ephemeral in nature, existing only during the wettest part of the year. Runoff is negligible from late summer to early spring because of low precipitation. Winter storage in the form of a snowpack is also nil, largely because high insolation, moderate to high wind movement, and relatively warm days combine to sublimate most of the snow from winter storms back into the atmosphere. Rasmussen (1968) discussed sublimation of the winter snowpack at the lower elevations of the upper Colorado River basin and demonstrated that the lower elevations provided little of the runoff from the total basin. The low elevation of the upper Colorado River basin is similar in many meteorological respects to the Pawnee Grassland region. Thus, the precipitation during the growing season is of prime importance to the grassland ecosystem.

Eastern Colorado, which includes the grasslands, has a semiarid continental climate with an average of less than 15 inches of precipitation annually. Using traditional nomenclature, it would be classified as having a cool steppe climate (Haurwitz and Austin 1944).

Probably the greatest influence on the climate is the Rocky Mountains, a very large north-south mountain range whose eastern extremity is located 30 miles west of the Pawnee Grassland. This mountain range, oriented perpendicular to the prevailing wind flow, causes orographic precipitation on the western slope leaving only relatively dry air flowing down its eastern slope and over the grasslands. This forces the principal moisture source to become the Gulf of Mexico, which is located 1,000 miles to the southeast. The supply of moisture therefore becomes intermittent since eastern Colorado is located in the belt of prevailing westerlies of the atmosphere.

The mean wind flow during the year has a profound effect on the seasonal precipitation. Borchert (1950) showed that the mean atmospheric flow in the winter above the frictionally disturbed layer near the earth's surface is composed of fairly strong westerlies (Fig. 2). Consequently, the air has little water vapor available in the winter for precipitation. Furthermore, a long-wave ridge dominates the upper flow over the western United States, displacing the average storm track north of Colorado (Williams 1968). With few storms crossing the region and little water vapor available, low winter precipitation results. This precipitation consists of light snowfalls over large areas and is caused principally by large-scale cyclones.

There is a large number of sunny, dry days during the winter. Moist tropical air masses are effectively kept from the region by

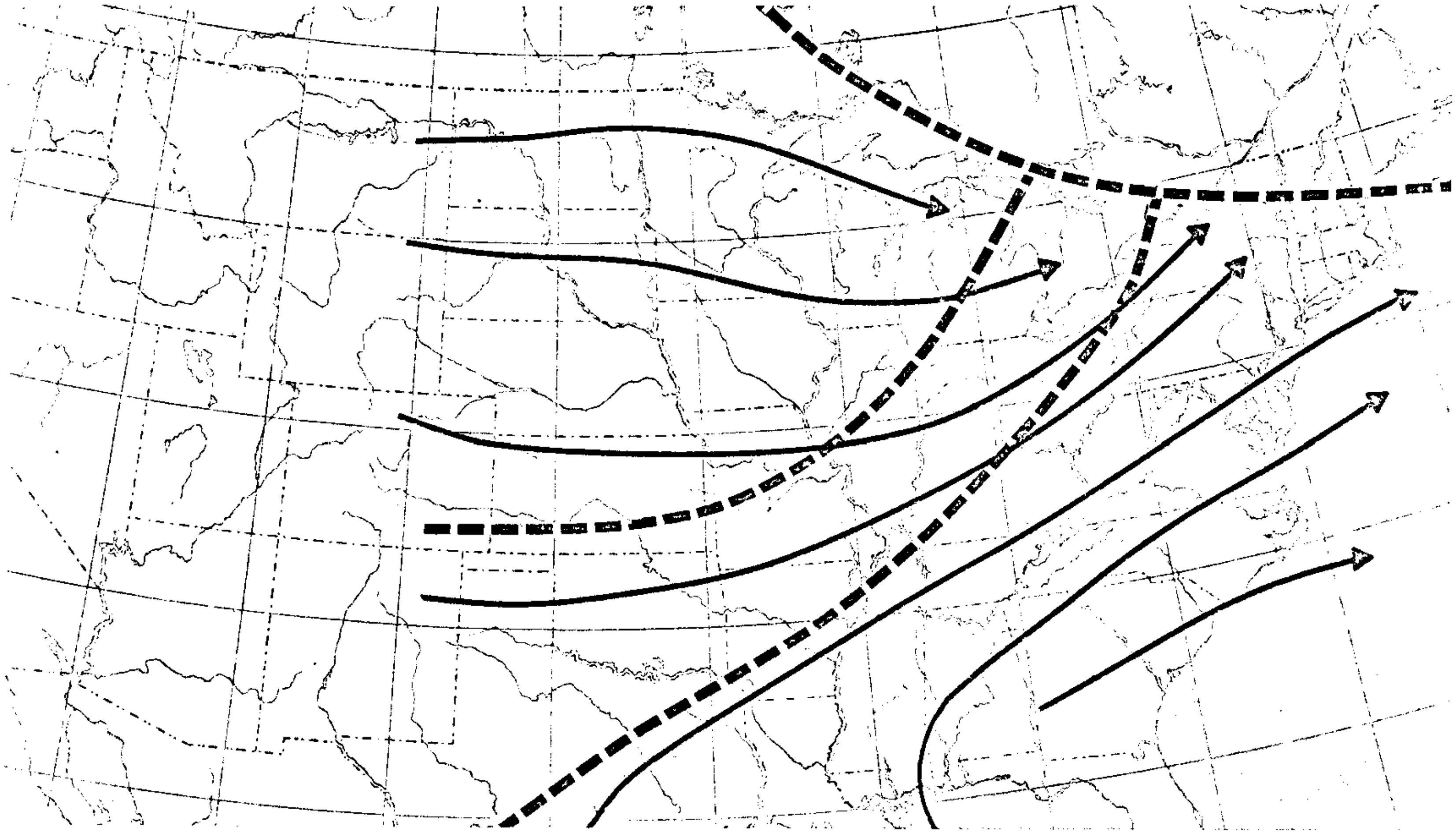


Fig. 2. Streamlines taken from Borchert (1950) of prevailing winds during January above the frictionally disturbed air layer. Dashed lines indicate most frequent storm tracks.

the mean westerlies. Therefore, the dominant air mass is continentally polar which is characteristically dry and cold. At this latitude, however, relatively strong insolation quickly modifies the air mass to allow the days to be warm. Large and relatively fast changes in temperature take place as cold fronts, cold polar outbreaks, or chinook winds occur.

The precipitation in the summer is much higher than in the winter. A strong semipermanent high pressure system that is established over the Atlantic Ocean during the summer provides, at times, a southerly wind flow which brings moisture-laden winds up from the Gulf of Mexico. Fig. 3, taken from Borchert (1950), illustrates this mean wind flow. A combination of traveling weather disturbances, moist Gulf air, and solar heating can produce the intense convective thunderstorms characteristic of the summer rainfall. Thunderstorm activity over the Pawnee Grassland is also aided by the proximity of the Rocky Mountains. Development of thunderstorms takes place first over the mountains as a result of intense solar heating and orographically-induced vertical air motion. These thunderstorms generally come off the mountains late in the morning and pass over the Pawnee Grassland in the afternoon. According to Dirks (1969), the time of maximum thunderstorm occurrence is later for stations further from the mountains. This last statement is valid as far out as eastern Kansas, which has its largest number of thunderstorms around midnight. On days when meteorological conditions favor development these thunderstorms will build to a height of more than 50,000 ft over the Pawnee National Grassland.

One consequence of the relatively high land elevations and dry surface air is that thunderstorm development, and the resultant

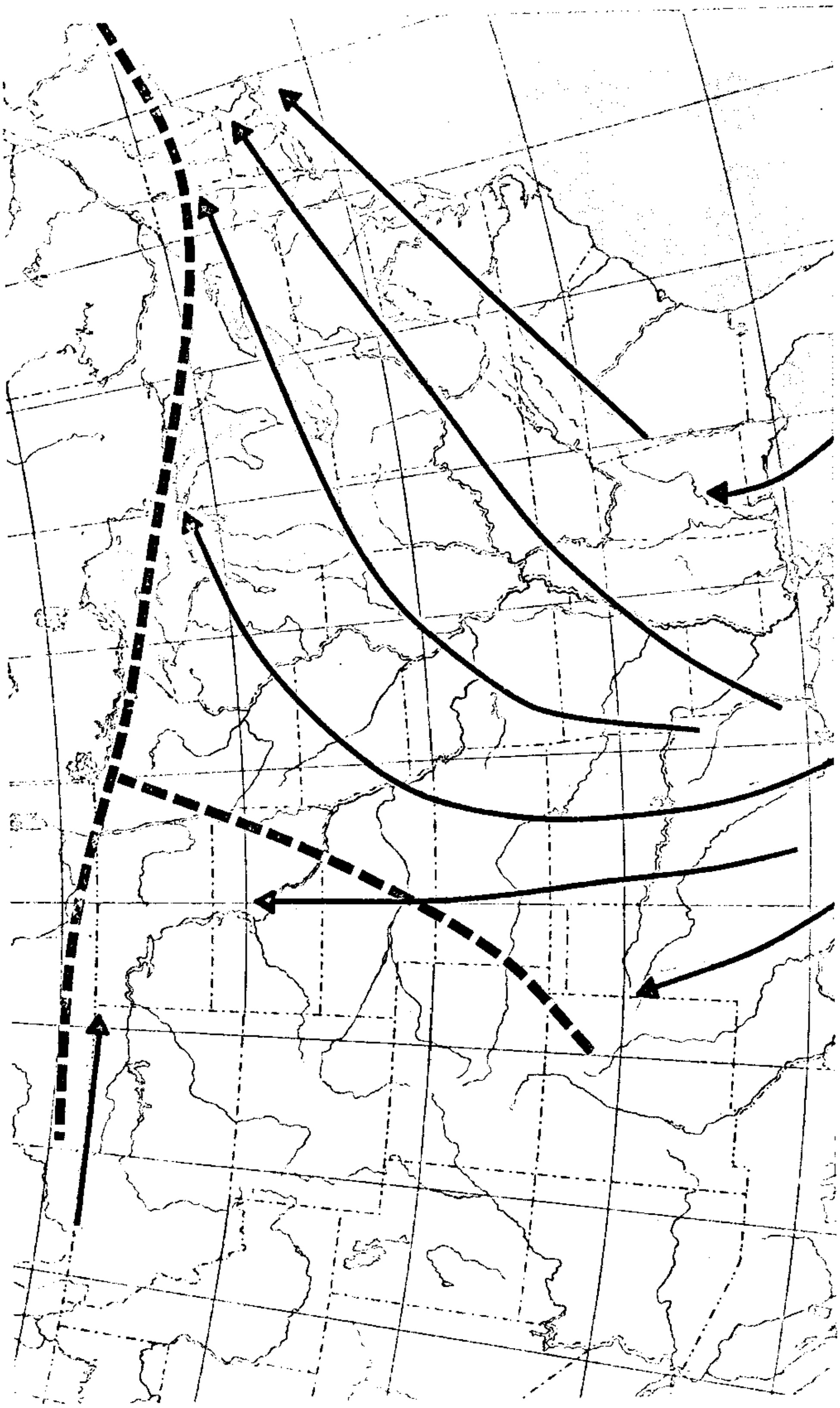


Fig. 3. Streamlines taken from Borchert (1950) of prevailing winds during July above the frictionally disturbed air layer. Dashed lines indicate most frequent storm tracks.

precipitation, occurs somewhat differently than in areas near sea level. The average height of the base of summer clouds over the grasslands is on the order of 12,000 ft above mean sea level (Renne 1969), as contrasted with 6,000 ft over the Atlantic Coastal region and 2,000 ft over the sea. According to Renne, cloud base over the high plains can vary from 4,000 ft to more than 11,000 ft above the land surface. With such high cloud bases it is fairly common for intense thunderstorms to produce only small amounts of precipitation with most of the water being evaporated in the dry layer below cloud base. Two other consequences result from summer thunderstorm activity: the precipitation tends to be spotty and irregular, and there is a relatively high incidence of hailstorms.

Synonymous with a continental climate is a large annual temperature range. For the Pawnee Grassland it is 44°. In contrast, San Francisco, which is located at about the same latitude, has a maritime climate with an annual temperature range of approximately 12°.

PRECIPITATION ANALYSIS

Precipitation is perhaps the single most important climatic element to the grassland ecosystem. Although precipitation is relatively low in the Pawnee Grassland, a large proportion of it comes during the growing season when it can be most efficiently utilized. One of the principal characteristics of precipitation is its inherent variability. Therefore, a large part of this analysis will be concerned with studying this variability, both in space and time.

It is generally acknowledged that as the annual average precipitation gets lower, the precipitation becomes more variable from year to year.

A look at Nunn, the station with the lowest annual average precipitation, shows a tremendous variability. In less than 20 years the precipitation varied between 3.04 and 16.35 inches, an increase of 540% from the driest to the wettest year. All stations in the grassland network received at least two and one half times more precipitation in the wettest year than in their driest year. Generally, a wet year at one station would be considered wet at all stations. However, all stations did not record their highest precipitation on the same year or their lowest precipitation on the same year.

An example of extreme spatial variation, which is much more pronounced during the summer months, occurred on July 16, 1953. Grover, the centrally located station, recorded 2.25 inches of rain; CPER, 20 miles to the west, received 0.03 inches of rain; and Kauffman, 25 miles to the east, recorded no rain. In the summer there were very few days in which the entire grassland network recorded at least one-fourth inch of rain. These discontinuous precipitation events are rather difficult to analyze individually. However, over 30 years these irregularities appear to be removed by averaging, leaving smooth means of yearly and seasonal precipitation over the entire region as shown in Table 3. This data was combined and used in making the isohyetal map of annual precipitation (Fig. 4).

For this study summer was defined as April through September, and winter was defined as October through March. The first characteristic shown is the overwhelming amount of the annual precipitation that falls during the summer. Averaged over the Pawnee Grassland, 80% of the mean annual precipitation falls from April to September. In addition, the three wettest months, May, June, and July, produce 50% of the annual

Table 3. Annual and seasonal precipitation.

Station	Annual (inches)	Summer (inches)	Winter (inches)
Akron	16.76	13.06	3.68
Briggsdale	11.90	-	-
Cheyenne	14.87	10.93	3.93
CPER	11.78	10.07	2.15
Estes Park	15.96	11.33	4.63
Fort Collins	14.15	10.36	3.79
Fort Lupton	12.62	9.30	3.32
Greeley	11.71	8.69	3.02
Grover	13.23	10.52	2.71
Kauffman	13.90	11.34	2.56
Julesburg	16.31	12.86	3.45
New Raymer	13.42	-	-
Nunn	10.55	-	-
Grassland Network	13.12	10.64	2.48

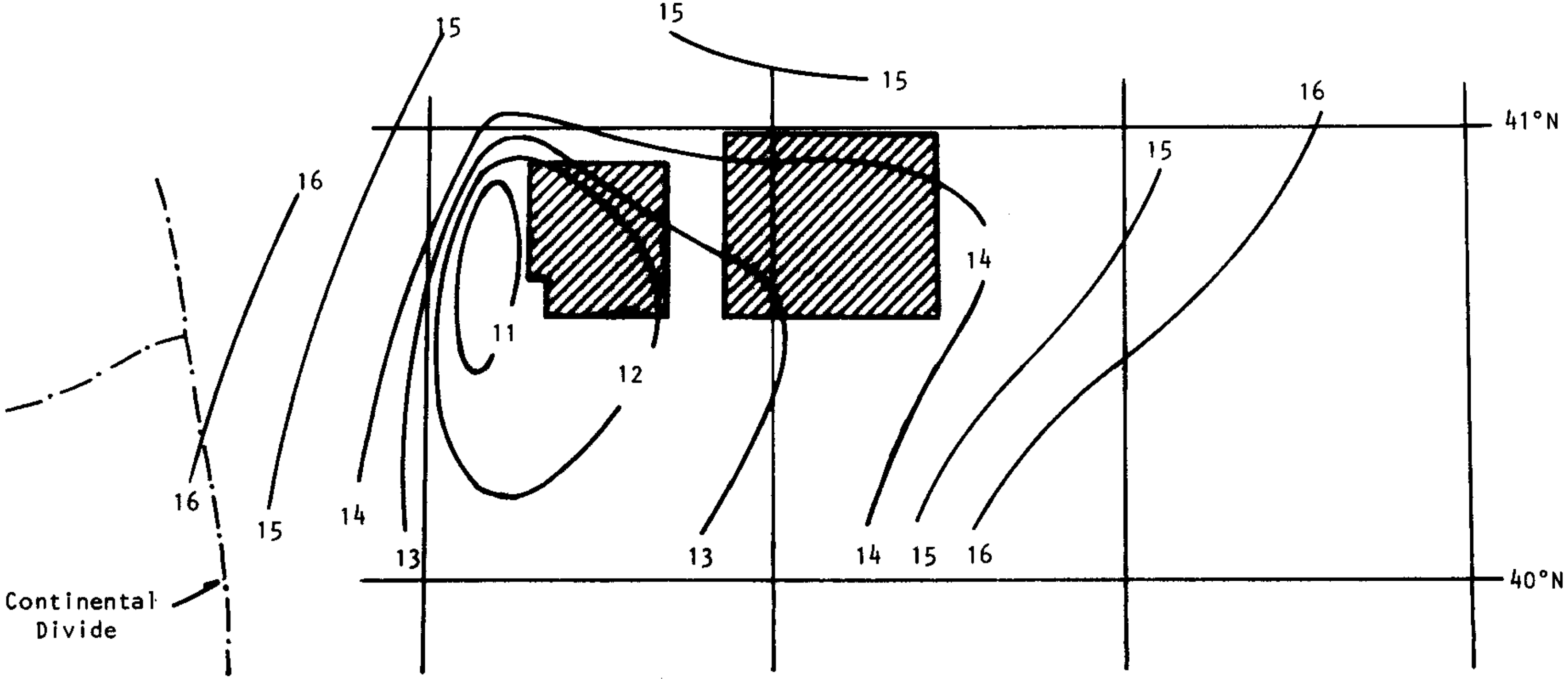


Fig. 4. Isohyetal map of average annual precipitation of northeastern Colorado. Cross-hatched areas indicate the Pawnee National Grassland.

total. The dryness of the winter is emphasized by the fact that the average total precipitation for November, December, January, and February accounts for only 8% of the annual precipitation. Fig. 5 presents the mean monthly precipitation. This precipitation pattern is almost identical for all of northeastern Colorado, including Julesburg on the eastern Colorado border and Fort Collins at the base of the foothills.

It is immediately evident from Fig. 5 that there is a large relative variability in the monthly precipitation regime. One measurement of this is the coefficient of variation:

$$C = \frac{S}{Y}$$

where S = monthly standard deviation

Y = mean monthly precipitation

This value is usually expressed as a percentage. For the grasslands the lowest value for C, 42%, comes in May. The highest value for C, 100%, occurs in January. The greatest relative variance, therefore, occurs in the months with the lowest precipitation and vice versa.

This analysis suggests that, although the winter has a very large year-to-year variation, the difference between a "wet" or "dry" year lies in the amount of rainfall that comes in the summer.

Spatial Variation

Fig. 4 illustrates the spatial variation in precipitation. The minimum annual precipitation for northeastern Colorado appears to occur somewhere on the western edge of the Pawnee Grassland, near Nunn. This is about 25 miles from the foothills. Unfortunately, Nunn has one of the shortest records in the study and uses a tipping-bucket rain gauge.

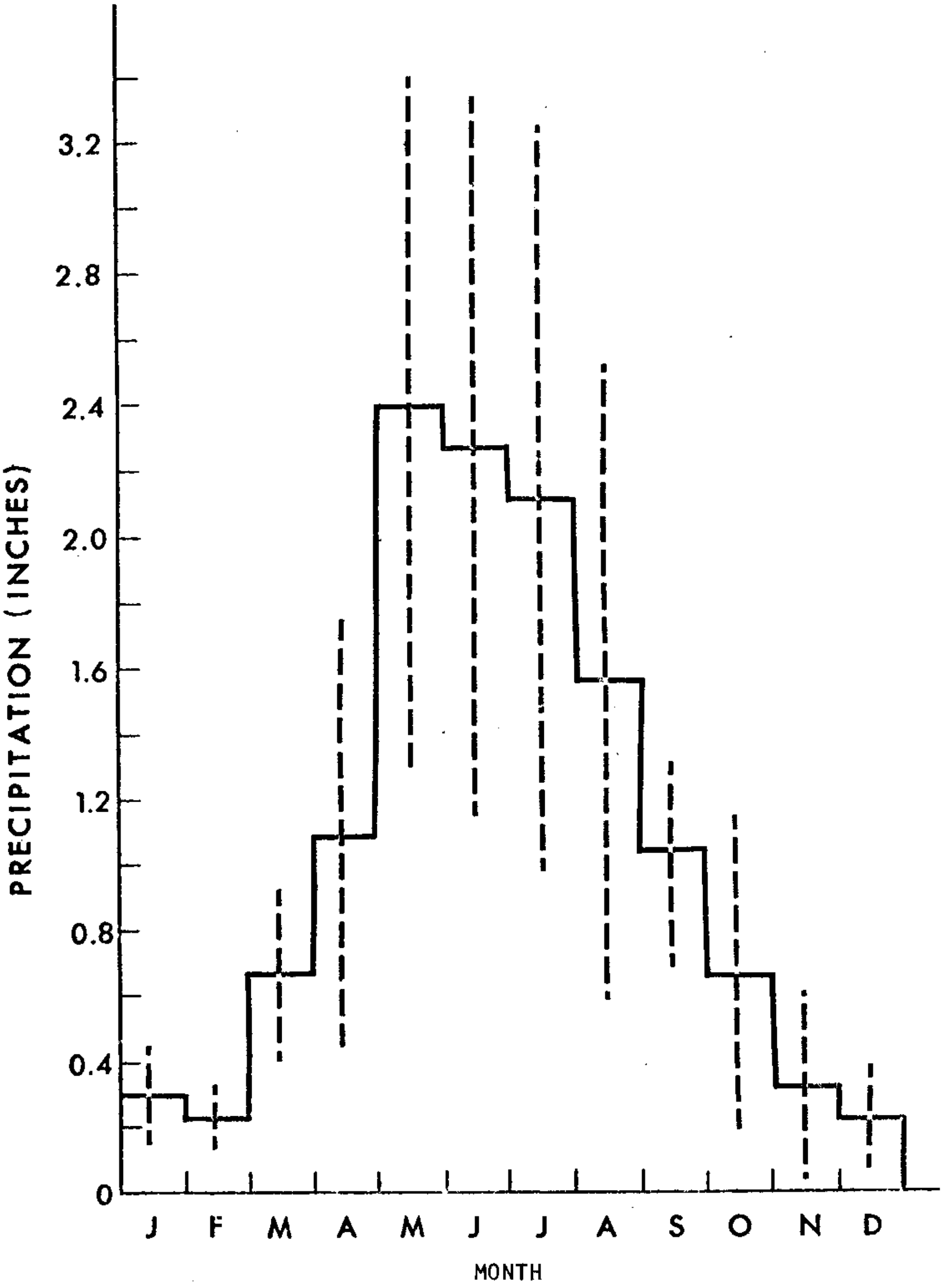


Fig. 5. Average monthly precipitation for grassland network (solid line). Dashed lines denote ± 1 standard deviation around average monthly values.

Landsberg (1968) points out that this type of rain gauge is not very accurate, especially in heavy rains. There may be some doubt, therefore, as to the exact magnitude of Nunn's precipitation. Our analysis is in general agreement with isohyetal maps of Colorado compiled by the U.S. Weather Bureau (1960). The Weather Bureau's location of the minimum precipitation area 25 miles east of Nunn was based on fewer stations and a shorter record.

In a previous report (Bertolin and Rasmussen 1969) no latitudinal variation of precipitation was shown over the Pawnee National Grassland. The report also demonstrated a marked longitudinal precipitation variation within the Pawnee Grassland. An annual precipitation increase of 20% occurs over 45 miles of relatively uniform terrain with a surface elevation change of only 300 ft. There is also an increase in precipitation from the western edge of the Pawnee Grassland westward to the foothills of the Rocky Mountains. The result is an example of the classical rainshadow effect that occurs on the lee side of any mountain range. The average annual precipitation decreases from the continental divide to a minimum near Nunn and then increases eastward to the Mississippi River and beyond. We will now investigate the rainshadow in more detail.

If precipitation is only a function of elevation, it might be expected that CPER and Nunn would have the highest rather than the lowest precipitation in the area. In order to find other factors that are controlling the precipitation, three stations will be compared: Fort Collins near the foothills; CPER in the maximum rainshadow belt; and Kauffman in the eastern part of the Pawnee Grassland. The year will be broken into four quarters for analysis, the most important being late winter (February-April) and early summer (May-July).

The heaviest snowfalls occur in Fort Collins when an easterly wind allows the orographic effect caused by the foothills to enhance precipitation. The topographic gradient is highest right at the foothills. This orographic effect diminishes as one goes eastward toward the grasslands. Heavy wet snowfalls are thus higher in the foothills area than on the plains. Since two-thirds of the 2.4 inch average annual precipitation increase from CPER to Fort Collins comes in late winter, the orographic effect on snowfall must therefore be chiefly responsible for higher precipitation at Fort Collins.

Of the 2.2 inch average annual increase in precipitation from CPER to Kauffman, 1.4 inches comes in early summer. Since the dominant rainfall-producing mechanism during early summer is the cumulus cloud system, one may assume that the additional precipitation is caused by greater convective activity in the atmosphere over Kauffman. Dirks (1969) showed that the only meteorological factors present during development of mesoscale convective systems were a certain amount of convective instability and a tongue of warm moist air at low levels. The source of this warm, moist air is the Gulf of Mexico, but eastern Colorado lies far enough northwest of the Gulf that the supply is not dependable. Thus, thunderstorm activity is also irregular. Quite often summer surface weather maps show a "dew-point front" located in eastern Colorado. The warm, moist air conducive to thunderstorm development is present east of the front, but west of the front the air is too dry to support thunderstorm activity. The increase in rainfall from CPER to Kauffman is then most likely a result of sufficient moisture being present more often over Kauffman, the easternmost station.

Direct evidence of the higher frequency of convective storms in eastern Colorado comes from radar data on thunderstorms (Schleusener and Henderson 1962; Schleusener, Henderson, and Hodges 1963). We constructed two squares that were 35 miles on a side and centered one on the western Pawnee Grassland and one on the eastern Pawnee Grassland. By counting the number of thunderstorms passing through or originating in each of the squares, we obtained a measure of the convective activity in that square. Table 4 shows that the easternmost square had 45 more thunderstorms in three years. This is an increase of 42% in the number of thunderstorms, more than enough to account for the precipitation increase across the grasslands.

In summary, greater convective activity, as shown by higher thunderstorm frequency, is responsible for a large proportion of the increase in precipitation from CPER to Kauffman. The decrease in precipitation from Fort Collins to CPER is due to the lessening of the orographic upslope effect, which is especially important during the winter. These two local phenomena, superimposed on the large-scale influence of the Rocky Mountains on the general circulation, cause the sharp rainshadow found in the Pawnee Grassland.

Storm Analysis

Precipitation events often last more than one day so that analysis of daily precipitation data arbitrarily breaks up continuous events. Analysis of periods such as weeks or months is unsatisfactory because it tends to gloss over the significant events. We wish to perform a "natural period" analysis such that the individual period of precipitation is dealt with, whatever its length. The following analysis describes

Table 4. Number of thunderstorms passing through or originating in a 35-mile square centered on the Pawnee National Grassland from 1961-1963.

	Square Centered on Western Pawnee Grassland	Square Centered on Eastern Pawnee Grassland
Number of Thunderstorms	107	152

an attempt to perform this work for the grassland network. In some cases, particularly during the summer, the precipitation occurs in a very short period. For this investigation, such shower precipitation is included as a daily value since no finer resolution is available due to the sampling procedure.

This study used the storm definition given by Marlatt and Riehl (1963). They defined a storm as any number of consecutive days producing at least 0.10 2.5 mm inch of rain, with each day having a minimum of 0.06 1.5 mm inch. Thus, any total precipitation less than 0.10 inch is not sufficient to be considered a storm. Furthermore, a series of days with heavy rain separated by one day with 0.05 inch or less will be considered as two separate synoptic events, and the result noted as two storms.

The storm analysis consisted of dividing the storm precipitation into five classes: .10 to .25 inch, .26 to .50 inch, .51 to .75 inch, .76 to 1.00 inch, and greater than 1.00 inch. It was found that storms greater than 1.50 inch occurred too seldom to warrant further investigation. For most of the analysis we used thresholds based on the storm categories listed above. Thus, storms were studied that produced greater than 1.00 inch of precipitation, greater than 0.75 inch, greater than 0.50 inch, etc.

We ran a multiple stepwise linear regression analysis using the precipitation from each storm threshold, the two seasonal precipitations, and the total yearly precipitation for each station in the Pawnee Grassland. Table 5 presents the average correlations of the three grassland stations. Table 6 gives the variance, or the square of the linear correlation, which is the amount of year-to-year variability explained by the correlations shown in Table 5. Therefore, 11% of the

Table 5. Linear correlation results of precipitation regression analysis.

	Precipitation									
	Summer Season					Winter Season				
	>1.0 inch	>.75 inch	>.50 inch	>.25 inch	>.10 inch	>1.0 inch	>.75 inch	>.50 inch	>.25 inch	>.10 inch
Seasonal	.86	.92	.95	.99	.99	.40	.57	.73	.86	.92
Yearly	.80	.86	.88	.93	.94	.18	.28	.14	.33	.31

Yearly Precipitation: Summer = .94, Winter = .32

Table 6. Variances derived from precipitation regression analysis.

	Precipitation									
	Summer Season					Winter Season				
	>1.0 inch	>.75 inch	>.50 inch	>.25 inch	>.10 inch	>1.0 inch	>.75 inch	>.50 inch	>.25 inch	>.10 inch
Seasonal	.74	.84	.90	.97	.99	.16	.33	.53	.73	.86
Yearly	.64	.75	.77	.87	.89	.03	.08	.02	.11	.10

Yearly Precipitation: Summer .89, Winter = .11

yearly precipitation variability is explained by the winter precipitation, and 89% of the yearly variability is explained by the summer precipitation. Winter precipitation from storms greater than .50 inch have virtually no effect on the yearly precipitation variability. In contrast, summer rainfall coming only from storms greater than one inch accounts for 74% of the summer precipitation variability and 64% of the annual precipitation variability. At the same time, only 33% of the average annual precipitation is derived from summer storms larger than one inch. Thus, the total winter precipitation has little effect on the yearly precipitation, while there is a strong effect from large summer storms.

In view of the relative storm frequency over the grasslands, as shown in Table 7, these results are reasonable. An average of slightly less than three major storms occurs during the summer, each producing more than one inch of rain and lasting two and one-half days. In the winter there is only one major storm of that magnitude every five years, which lasts about two days. A surprising development is that a "major" storm lasts longer in the summer than the winter, while summer rainfall generally comes in short bursts from thunderstorms. In the summer our definition of a storm in many cases must be incorporating two or more distinct thundershowers occurring on consecutive days. However, our definition of a storm should still be valid, since consecutive daily thundershowers are generally caused by a persistent synoptic condition.

Large storms are very important to the water budget of the Pawnee National Grassland because three or four major storms can contribute 40-50% of the entire yearly precipitation. Those years receiving a high number of large storms are the wet years. The two driest years on the record were years in which some stations reported no major storms.

Table 7. Frequency of storms over the Pawnee National Grassland.

	No. Storms/Season >1 inch	Average Length of Storms/Season >1 inch	Total No. Storms/Season	Average Length of Storms/Season
Summer	2.7	2.5 days	19.0	1.4
Winter	0.20	1.9 days	6.6	1.2

There is another reason for putting one's emphasis on large rainfalls. Several authors, including Crow (1957), have mentioned that light rain showers are very inefficient in delivering water to the hydrological system. A very high percentage of the precipitation is immediately returned to the atmosphere via evaporation and is therefore not available for surface runoff or ground water recharge.

Markov Chain Analysis

Synthesizing daily probabilities of wet or dry days is a useful consequence of a daily precipitation analysis. The results would be helpful in discerning precipitation trends during the year, and could be used in generating sequences of wet and dry periods for a grassland ecosystem model. Besson (1924) showed that sequences of rainy days occurred with improbable frequency based on daily probabilities equal to the ratio of the number of rainy days to the total length of record. He therefore concluded that past weather has an influence on present weather and that initial precipitation probabilities did not adequately reflect the true state of the weather.

During the last 10 years increased interest has developed in techniques to determine a more accurate method of calculating probabilities. Several authors (e.g., Gabriel and Neumann 1962, Feyerherm and Bark 1967) have had considerable success in using Markov models to calculate probabilities of rainfall. A Markov chain takes into account the influences of past weather on today's weather. A first-order chain includes yesterday's weather in determining the precipitation probability for today; a second-order chain includes the past two day's weather in determining the probability for today, and so forth.

Table 8. Probabilities of occurrence of a dry day for Pawnee Grassland.

Period Begins	Wet ≥ 0.01 inch			Wet ≥ 0.05 inch			Wet ≥ 0.10 inch		
	Dry	Dry/Dry	Dry/Wet	Dry	Dry/Dry	Dry/Wet	Dry	Dry/Dry	Dry/Wet
Mar. 01	85	88	75	88	89	81	92	92	86
Mar. 08	89	91	75	90	92	78	93	94	76
Mar. 15	89	89	81	90	90	82	93	93	93
Mar. 22	86	89	68	89	90	71	91	92	68
Mar. 29	88	91	71	90	92	63	93	94	64
Apr. 05	81	83	71	83	85	79	87	87	85
Apr. 12	86	89	65	88	90	69	91	92	78
Apr. 19	87	90	69	89	91	72	92	93	76
Apr. 26	80	84	64	83	85	75	87	88	83
May 03	82	87	56	85	89	63	88	90	73
May 10	75	80	58	78	83	61	82	86	64
May 17	69	77	53	72	78	58	78	80	70
May 24	70	75	58	73	76	65	78	79	74
May 31	71	75	63	74	77	64	79	81	72

Table 8. (Continued).

Period Begins	Wet ≥ 0.01 inch			Wet ≥ 0.05 inch			Wet ≥ 0.10 inch		
	Dry	Dry/Dry	Dry/Wet	Dry	Dry/Dry	Dry/Wet	Dry	Dry/Dry	Dry/Wet
June 07	75	81	59	78	83	61	81	85	68
June 14	75	78	66	77	79	68	81	82	72
June 21	82	86	67	84	87	66	87	90	70
June 28	80	83	66	82	85	67	85	87	72
July 05	80	83	69	84	86	71	86	87	78
July 12	76	79	69	80	82	73	84	85	80
July 19	78	81	67	80	83	66	83	85	73
July 26	77	78	73	80	82	77	84	85	83
Aug. 02	79	81	67	82	83	74	84	85	80
Aug. 09	85	86	80	88	88	87	92	92	92
Aug. 16	81	83	70	83	84	77	87	88	78
Aug. 23	81	84	65	84	86	70	86	88	71
Aug. 30	86	89	66	89	91	72	91	93	74
Sept.06	87	90	66	90	92	71	93	94	73
Sept.13	89	92	67	91	92	74	92	94	76
Sept.20	83	86	67	86	88	67	87	89	70
Sept.27	91	93	66	92	94	65	93	95	71

Table 8. (Continued).

Period Begins	Wet $\geq$ 0.01 inch			Wet $\geq$ 0.05 inch			Wet $\geq$ 0.10 inch		
	Dry	Dry/Dry	Dry/Wet	Dry	Dry/Dry	Dry/Wet	Dry	Dry/Dry	Dry/Wet
Oct. 04	94	95	89	95	96	96	97	97	96
Oct. 11	91	92	83	92	93	85	94	94	84
Oct. 18	90	91	81	91	92	84	93	93	86
Oct. 25	93	94	76	94	95	75	95	96	79
Nov. 01	91	92	88	93	93	91	95	96	91
Nov. 08	93	94	86	95	95	88	96	97	92
Nov. 15	90	90	92	92	92	98	94	94	99+
Nov. 22	96	96	97	97	97	97	98	98	99+
Nov. 29	96	96	90	97	97	94	98	98	83
Dec. 06	91	92	88	94	94	92	95	96	92
Dec. 13	96	97	88	98	98	87	98	98	89
Dec. 20	93	94	84	95	95	88	96	97	84
Dec. 27	95	95	95	96	96	94	97	98	97

Table 8. (Continued).

Period Begins	Wet ≥ 0.01 inch			Wet ≥ 0.05 inch			Wet ≥ 0.10 inch		
	Dry	Dry/Dry	Dry/Wet	Dry	Dry/Dry	Dry/Wet	Dry	Dry/Dry	Dry/Wet
Jan. 03	93	94	69	93	95	72	96	97	86
Jan. 10	93	94	87	95	96	93	98	98	92
Jan. 17	93	93	93	96	96	99+	98	98	99+
Jan. 24	88	89	78	90	91	81	94	94	93
Jan. 31	95	95	84	97	97	97	99	99	99+
Feb. 07	92	94	75	94	95	76	97	97	88
Feb. 14	91	93	78	93	94	79	96	97	69
Feb. 21	93	93	85	94	95	87	97	97	89

Recently it has been shown (Lowry and Guthrie 1968, Heermann 1965) that a first-order Markov chain is sufficiently accurate for determining precipitation or no precipitation probabilities in most areas. If a first-order chain is used, one then has a set of conditional probabilities:

i. The probability that today will be dry given yesterday dry,

ii. The probability that today will be dry given yesterday wet,

iii. The probability that today will be wet given yesterday dry, and

iv. The probability that today will be wet given yesterday wet.

Note that the probability of a wet day is $P_{wet} = 1 - P_{dry}$; therefore *iii* is simply 1.00 - *i*, and *iv* is simply 1.00 - *ii*.

The most common method used in a Markov chain precipitation analysis is to treat precipitation as a two-state process, i.e., it is either wet or dry. By following this assumption, we ran into the problem of defining a wet day. Since different thresholds of a wet day may be required depending upon the use of the results, precipitation probabilities are provided for three thresholds: 0.01 inch, 0.05 inch, and 0.10 inch.

The computer program for the calculation of probabilities using the Markov chain model was supplied by Heermann. The results for the grassland network are shown in Table 8. Three columns are provided for each threshold precipitation in the table. The first column is strictly an initial probability of a dry day calculated by dividing the number of dry days on that date by the total record length. The second column gives the probability that today will be dry given yesterday dry, and the third column gives the probability that today will be dry given yesterday wet. Using standard probability notation, P(wet/dry) is the probability that today will be wet given yesterday dry.

It should be noted that the daily probabilities are given on a weekly basis. No significant daily variation was found within weekly periods, so daily probabilities are presented for each week of the year. Some of the fluctuation visible in Table 8 from week to week is random variation due to the short record length. In virtually all cases, the probability of a day being dry increases if yesterday was dry and decreases if yesterday was wet. Thus, the results obtained by the Markov chain analysis are intuitively correct.

It is possible to generate probabilities for a sequence of wet and dry days of any length using these results. For instance, a sequence of four days consisting of dry, dry, wet, dry days would be calculated as follows:

$$P_{\text{sequence}} = P(D) \cdot P(D/D) \cdot P(W/D) \cdot P(D/W)$$

where the daily probabilities come from Table 8.

The probability of rain is highest in week 12. Since this study uses the climatological year, week 1 starts on March 1st and week 12 is the third week in May. Furthermore, it can be seen that the probability of precipitation increases sharply from the middle of April to late May and then gradually diminishes over the next five months. By the middle of October the probability of precipitation is very low and remains roughly constant through February. It is worthwhile to note that under the most favorable conditions, i.e., a preceding wet day in late May, the probability of rain is still just under 50%.

Extreme Precipitation Amounts

Extreme value statistics are used extensively in hydrology for forecasting maximum floods and rainfall intensities expected in 100 or

1000 year periods. We applied the extreme value techniques to determine the maximum amount of rainfall that could be expected from a single storm over the Pawnee Grassland in 100 years. Each of the three stations in the grassland network was treated separately, but one average for the grasslands will be reported since the results were very close.

The technique used was described by Landsberg (1952) and Chow (1951). The equation used in the calculation is:

$$X = \overline{X} + KS_x$$

Where X = extreme storm expected in 100 years

$\overline{X}$ = mean of the extreme yearly storms observed to present

S_x = standard deviation of the extreme yearly storms observed to present

K = frequency factor

Values for K were obtained from tables provided by Landsberg (1952).

The results show that the maximum storm in 100 years should be 4.7 inches. In thirty years of record the largest storm was 4.2 inches. There have been only two storms at each of the three stations that have produced three or more inches of rain. The inherent randomness of these very large rainstorms of more than three inches is evident, since these six storms occurred in five different years.

The Skewed Precipitation Distribution

We have mentioned spatial variation and the monthly variation of precipitation, but the marked day-to-day variation should also be noted. It is quite possible to have one or two days during the summer in which one and one-half inches or more of rain is recorded, followed and preceded by days of zero rainfall. Averaged over the grassland network, only 17% of the days with precipitation produce 75% of the annual total. Since measurable precipitation is recorded on an average of 52 days per year, 75% of the mean annual precipitation comes on only 19 days of the year. Most of the precipitation therefore comes in about 5% of the year, a result that complements the high correlation found between summer storms greater than one inch and the annual precipitation.

TEMPERATURE AND WIND ANALYSIS

Temperature is a more homogeneous climatic parameter than precipitation. Given the relatively uniform terrain and the lack of strong localized climatic effects, spatial variation of temperature throughout the region should be quite low. Table 2 presents data on the stations used for temperature analysis.

Fig. 6 presents the average monthly maximum and minimum temperature for the grasslands. Standard deviations for both temperatures are given in Fig. 7. The standard deviation shows that there is less variation in the minimum than in the maximum temperature and that the temperature in the summer is more stable than in the winter. Largest fluctuations, therefore, occur in the maximum temperature during the winter. From Fig. 7 it can be expected that the maximum temperature will be within 14° of the mean only two-thirds of the time during mid-winter.

The passage of frontal systems explains most of this temperature variability, especially in the winter. Normally radiational effects are important during winter in the dry clear air. The days are relatively warm with highs reaching into the 60's; the nights are

/27

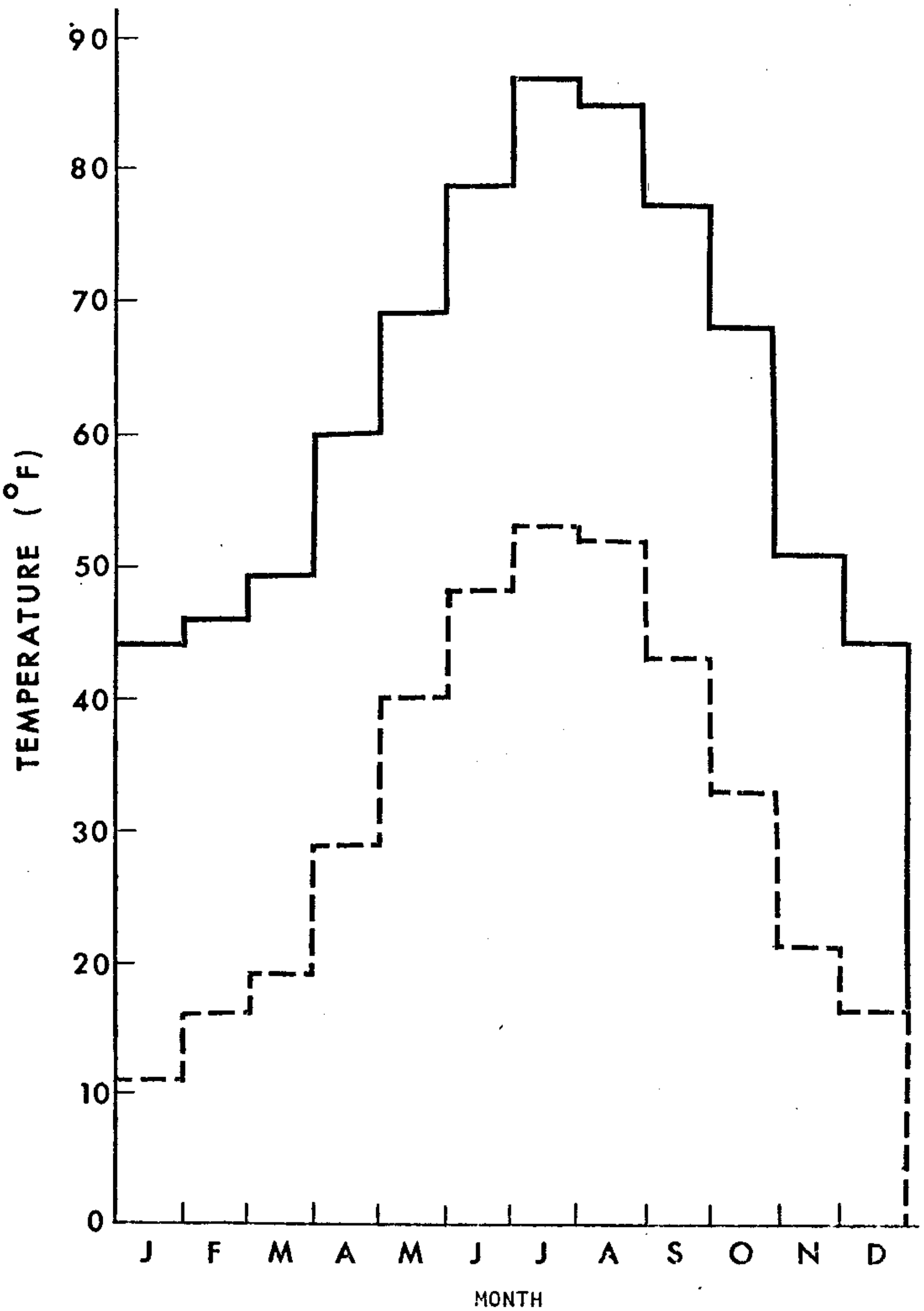


Fig. 6. Average monthly maximum and minimum temperature for the grassland network. Dashed line indicates minimum temperature.

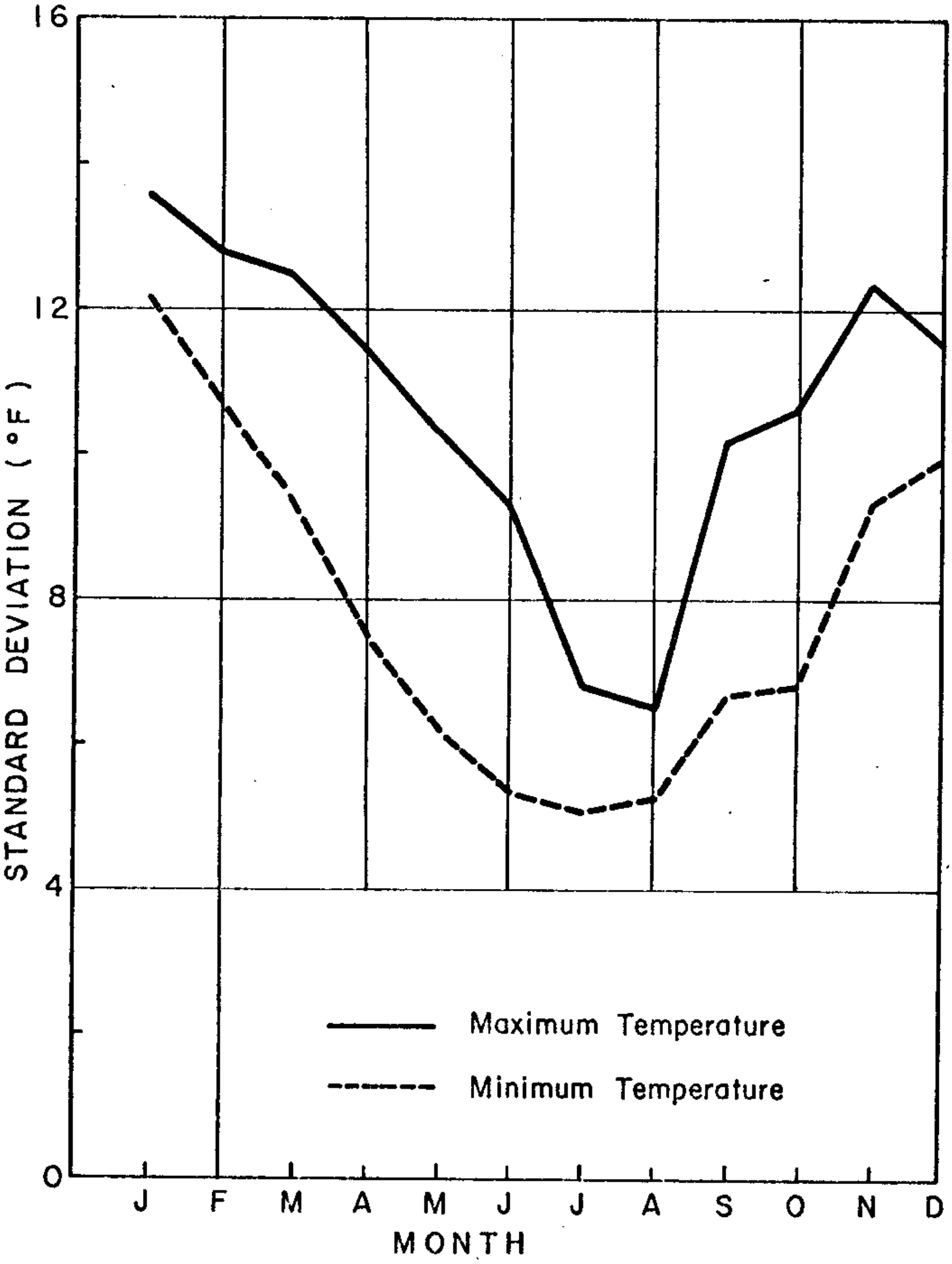


Fig. 7. Standard deviation of maximum and minimum temperatures for grassland network.

cold caused by large radiational losses from the earth. If a cold front passes through, however, the maximum temperature can easily be depressed 30 or 40 degrees.

What might be termed as an opposite effect to a cold front also occurs here. Chinooks can develop in the lee of the Rocky Mountains and in the valleys of the Alps (Riehl 1956) and are most pronounced in the winter. A chinook wind is composed of warm, very dry downslope flow and is usually quite strong. Within an hour of the start of the chinook surface temperature rises of 30 or 40 degrees are not uncommon. A chinook wind occasionally causes the maximum temperature of the day to occur at midnight.

The extent of a chinook varies considerably. Under extreme conditions they can be felt 150 miles from the foothills, but they can also be a very localized phenomenon. Visher (1954) shows the effect of chinooks in eastern Colorado by a northward bulge during the winter of the weekly mean isotherms. During the study of chinooks, the value of the continuous thermograph record at CPER partially compensated for the problems caused by the inaccuracy of the record. From this data we were able to establish that chinooks do occur relatively frequently at CPER, 30 miles from the foothills.

An extremely strong chinook that struck along much of the Colorado foothills was studied by Lovill (1969). The effect of the chinook lasted 18 hours near the foothills at Boulder, Colorado. The thermograph at CPER registered a 15° temperature rise starting at 9 PM on the same day and lasting for 6 hours. Immediately thereafter, a cold front came through; within 6 hours the temperature at CPER had fallen 44°.

Using the available thermograph records, chinooks at CPER could only be identified at night since diurnal heating masks their effect during the day. Furthermore, wind speed, which exhibits a definite increase during a chinook, is only recorded at CPER as a daily average, thereby making it unsuitable for this study. The effects at CPER varied from a 7° rise in 3 hours to a 23° rise in less than 1 hour. From the data at hand we estimate that approximately 20 chinooks of various intensities can be expected during the winter evenings on the western section of the Pawnee Grassland.

Spatial Variation

Despite the expected uniformity of temperature over the region, we examined evidence of spatial variation carefully. It was found that the error of the instruments was larger than the possible variation across the Pawnee Grassland. When the synoptic scale network is used, we find that the mean maximum temperature increases in the summer from the foothills to the Eastern Colorado border, but that the minimum temperature in the winter is constant.

This increase in mean maximum temperature in summer is due, at least in part, to the lower land elevation near the Eastern Colorado border. Assuming the typical dry atmosphere of the summer, the change in elevation alone would account for approximately 6° increase in temperature. As noted in Table 1, all stations in the Pawnee Grassland are at about the same altitude, therefore there are no elevation effects on the temperature among the grassland stations.

Markov Chain Analysis

In contrast to the Markov chain analysis of precipitation, little work has been done in this area with regard to temperature. Heermann (1967) studied the possibilities of using a Markov chain to calculate temperature probabilities. In his analysis a cold day was characterized when the minimum temperature went below a 0°, 20°, or 32° threshold; a hot day was characterized when the maximum temperature exceeded thresholds of 80° and 90°. Heermann found that a Markov chain of greater than first-order was required to determine daily probabilities of surpassing these thresholds.

Further investigation revealed that a first-order Markov chain would adequately describe the persistence of temperature if the concept of a normal temperature was employed. The normal temperature was defined as a smoothed daily maximum value; a cold temperature was then any temperature more than 3°, 6°, or 9° below this. In each case, Heermann showed from Chi-square statistics that the persistence of cold days was adequately described by a first-order Markov chain.

From this work it has been a logical step to develop a three-state Markov chain comprising warm, normal, and cold temperature sectors. A band of 6° on either side of a smoothed maximum or minimum temperature denotes a normal temperature; above this band are warm temperatures; below it are cold temperatures. This band width was chosen as representing one standard deviation of the maximum temperature during the summer; empirically it has given good results. It would be a simple matter, however, to change the width of the band. Given yesterday's temperature, we thus have three possibilities for today's temperature: it can stay in the same temperature sector or make a transition to either of the other two temperature sectors. The definition of a "normal" temperature presented a problem. Since each temperature record is only 20 years, the mean maximum or minimum temperature shows a great deal of day-to-day fluctuation. It was felt that this fluctuation was of a random nature, and therefore a smoothed "normal" curve was obtained using a Fourier filter technique.

The probabilities were then calculated by the same method used in the Markov chain precipitation analysis. The three-state, first-order Markov chain yielded nine transition probabilities plus the initial probabilities.

P(N): Initial probability of temperature being within normal band.
P(W): Initial probability of temperature being warm.
P(C): Initial probability of temperature being cold.
P(N/N): Transition probability of today being normal given yesterday normal.
P(W/N): Transition probability of today being warm given yesterday normal.
P(C/N): Transition probability of today being cold given yesterday normal.
P(W/W): Transition probability of today being warm given yesterday warm.
P(N/W): Transition probability of today being normal given yesterday warm.
P(C/W): Transition probability of today being cold given yesterday warm.
P(C/C): Transition probability of today being cold given yesterday cold.
P(N/C): Transition probability of today being normal given yesterday cold.
P(W/C): Transition probability of today being warm given yesterday cold.

The "initial" probabilities, P(N), P(W), and P(C), are calculated without using the Markov chain. They are simply a reflection of how many times the past temperature was in the normal, warm, and cold bands on each day. Given that yesterday was in one temperature range, there are only three possibilities for today's temperature. Thus, P(W/N) + P(C/N) + P(N/N) must equal 1.0. This holds true for the results, except that rounding produces errors of 0.01 or 0.02.

These daily probabilities were averaged by weeks for the individual grassland network stations, similar to the precipitation analysis. It was felt that this step was justified, since the relatively short record length produced very large and insignificant scattering of the daily temperature probabilities.

Since the daily smoothed temperature varied a maximum of 3° within a week, perhaps one normal temperature per week would be sufficiently accurate for the calculations, and less cumbersome to use. Daily temperature probabilities were therefore calculated using the smoothed temperature at the midpoint of each week. These values were then averaged to give weekly probabilities. There was no significant difference in the weekly probabilities calculated using daily or weekly normal temperatures, so the latter were used in this study.

Comparison between the weekly temperature probabilities at the three grassland stations showed, as expected, that the results were very similar. Therefore, the results at the three stations were combined by linear averaging to give temperature probabilities over the entire Pawnee National Grassland.

Even after combining weekly average probabilities over the three stations, there still remained a large amount of apparently random variation.

Most of this scatter would undoubtedly be removed if the record length were 100 years rather than 20 years. In an attempt to smooth the results satisfactorily without losing trends, the weekly probabilities were combined into four week averages. It was found that four week intervals could be used without destroying the important long-term trends. What remains, then, are daily transition probabilities for warm, normal, and cold maximum and minimum temperatures over four week intervals for the Pawnee National Grassland. Tables 9 and 10 present the results.

The tables reveal that the minimum temperature has a higher probability of being in the normal band than the maximum temperature. This was substantiated earlier in the discussion of standard deviations of the temperature record. Furthermore, both the standard deviation and the Markov chain results agree in showing more stability in the summer temperatures than in the winter temperatures.

The following statements concerning both the maximum and the minimum temperature probabilities can be made from Tables 9 and 10:

i. Normal temperatures are very likely to occur in summer.

ii. It is twice as likely in the winter as in the summer for a cold or warm temperature to persist.

iii. Interdiurnal temperature changes from below normal to above normal or vice versa are very unlikely.

In summary, these results show that normal temperatures (within 6° of the smoothed average temperature) tend to prevail over the summer, but are less common in the winter. Cold or warm temperatures are very likely to return to normal in the summer. In the winter, however, it is quite probable that once a cold or warm spell sets up it will persist.

This last point can be verified from a study of synoptic weather maps. A cold polar outbreak in winter with general high pressure and

Table 9. Probabilities of maximum temperature for Pawnee Grassland (notation explained in text).

Period Begins	PN	PW	PC	PN/N	PC/N	PW/N	PN/W	PC/W	PW/W	PN/C	PC/C	PW/C
Mar. 01	.36	.34	.31	.44	.24	.32	.26	.09	.65	.34	.60	.05
Mar. 29	.38	.34	.29	.46	.21	.32	.33	.09	.60	.32	.58	.08
Apr. 26	.41	.32	.28	.48	.26	.27	.27	.06	.66	.42	.54	.05
May 24	.49	.28	.24	.60	.19	.20	.35	.04	.62	.41	.57	.02
June 21	.59	.24	.17	.72	.10	.18	.42	.03	.55	.46	.53	.00
July 19	.67	.16	.14	.74	.12	.13	.49	.04	.48	.62	.36	.01
Aug. 16	.56	.24	.20	.68	.15	.16	.35	.03	.60	.46	.52	.02
Sept.13	.42	.33	.24	.54	.20	.25	.33	.04	.62	.35	.60	.05
Oct. 11	.42	.32	.27	.46	.26	.28	.35	.08	.56	.38	.53	.08
Nov. 08	.37	.36	.27	.42	.23	.35	.36	.06	.56	.28	.63	.09
Dec. 06	.39	.30	.30	.47	.26	.25	.32	.07	.60	.32	.59	.09
Jan. 03	.36	.31	.31	.44	.26	.30	.32	.06	.62	.32	.62	.06
Jan. 31	.36	.34	.30	.47	.25	.28	.29	.06	.64	.32	.60	.08

Table 10. Probabilities of minimum temperature for Pawnee Grassland (notation explained in text).

Period Begins	PN	PW	PC	PN/N	PC/N	PW/N	PN/W	PC/W	PW/W	PN/C	PC/C	PW/C
Mar. 01	.52	.24	.25	.61	.18	.21	.44	.04	.52	.41	.55	.05
Mar. 29	.58	.22	.20	.62	.18	.20	.54	.03	.44	.52	.41	.07
Apr. 26	.67	.16	.17	.73	.12	.15	.53	.03	.44	.54	.43	.03
May 24	.77	.12	.12	.83	.07	.10	.51	.03	.45	.57	.41	.02
June 21	.79	.12	.10	.82	.08	.10	.52	.03	.45	.69	.29	.02
July 19	.79	.12	.09	.82	.08	.10	.66	.01	.33	.70	.29	.01
Aug. 16	.71	.15	.14	.76	.10	.14	.63	.03	.34	.58	.43	.02
Sept.13	.64	.18	.18	.69	.16	.16	.58	.02	.39	.56	.41	.03
Oct. 11	.62	.19	.19	.68	.15	.16	.58	.05	.36	.48	.46	.06
Nov. 08	.55	.24	.21	.63	.17	.20	.50	.05	.45	.37	.56	.06
Dec. 06	.48	.27	.25	.59	.20	.21	.42	.04	.54	.35	.57	.09
Jan. 03	.39	.32	.29	.51	.21	.27	.33	.05	.62	.28	.67	.06
Jan. 31	.44	.31	.25	.55	.20	.26	.36	.04	.61	.35	.60	.05

low temperatures over Colorado has a tendency to persist for several days. In contrast, the development of a high pressure ridge over the United States in the winter will force the storm track far to the north of Colorado. This ridge will cause clear and quite warm days to prevail until the ridge breaks down. The mean of these two conditions gives the "average" winter temperature, an excellent example of a misleading statistic. In the summer neither cold continental air outbreaks nor high pressure ridges are as intense or persistent, as the Markov chain results show.

These results can also be used to calculate the probability of any combination of normal, warm, or cold days desired. The calculations are similar to the example given in the Markov chain precipitation analysis, so they will not be repeated here.

Diurnal Variation

In the analysis of temperature data one immediately notes that the diurnal variation of temperature is relatively large for the grassland data. Fig. 8 illustrates the monthly average and maximum diurnal variations for the grasslands. There is little seasonal change in either case. The largest diurnal variation appears to come in late summer, but the increase from the rest of the year may or may not be significant.

Two other points are significant, however. Each station has experienced at least one day when the maximum diurnal variation was at least 60°. Furthermore, the average diurnal variation at Kauffman was consistently higher, averaging 2° more than the other stations. Since Kauffman is located in a broad shallow valley, it is probable that cold air drainage causes this larger diurnal variation.

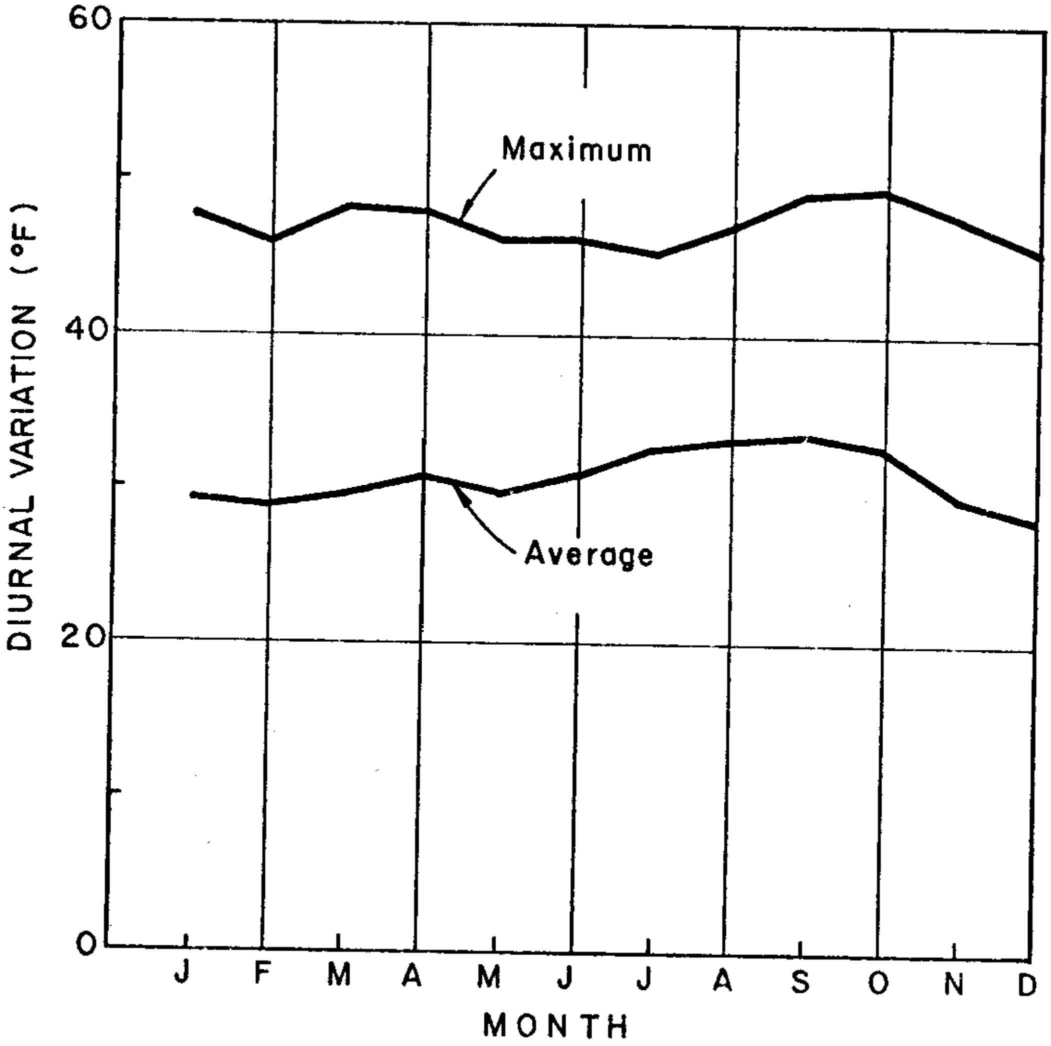


Fig. 8. Monthly maximum and average diurnal variation of the grassland network.

Extreme Temperature Values

The technique for obtaining extreme precipitation amounts was also used to calculate the extreme maximum and minimum temperatures expected on the Pawnee Grassland in 100 years. The coldest and warmest temperature recorded during each year over the 20 year record was used as the extreme values observed to the present. Each grassland station was treated separately, and then the results were combined by averaging. The possible extreme temperatures thus calculated are 110° and -38°. The values are reasonable, since the present observed extremes are 105° and -29°.

The record minimum temperature occurred simultaneously at the three grassland stations. The same is true for the record maximum temperature. This is in marked contrast to the extreme precipitation events occurring at the three stations, as mentioned earlier in the precipitation section.

Growing Season

A factor of importance to the ecology of the Pawnee Grassland is the growing season, or frost-free period. This has been calculated for 32°, 28°, and 24° thresholds, and is shown in Table 11. The data are for the grassland network and are shown as probabilities, i.e., the 10% probability means that 10% of the growing seasons were at least that long. The 50% probability figure is the median value; half the growing seasons were longer and half were shorter. Again, there was no significant variation among the grassland stations.

The median value, 128 days, is considerably shorter than the mean value of North America at 40° latitude. Other stations at the

Table 11. Probability of frost-free period being at least stated length for Pawnee Grassland.

Probability	32°F	28°F	24°F
10%	149 days	168 days	187 days
25%	139 days	156 days	183 days
50%	128 days	148 days	168 days
75%	116 days	134 days	156 days
90%	111 days	131 days	141 days

same latitude but further east on the Great Plains have a growing season of about 180 days (Environmental Science Service Administration 1966). A 30% shorter growing season on the Pawnee Grassland is mainly the result of an elevation difference of 4500 ft.

Other Climatic Parameters

For nine years the daily wind velocity has been recorded at CPER and should be representative of the region. Table 12 presents monthly and yearly wind averages.

Only five days per year have an average wind speed greater than 10 miles per hour. However, this is a misleading statistic since this is an average over 24 hours. Certainly the average wind speed exceeds 10 mph during the daylight hours on many days, but low wind movement at night disguises this fact in the data.

INTERRELATIONS BETWEEN PARAMETERS

Early in this study it was noted that there appeared to be more than a casual relationship between wind, temperature, and precipitation. We found that dry years commonly had above normal temperatures. Furthermore, examination of the wind record at CPER indicated that dry years also tended to have high winds. Other investigators have also noted this correlation (Rose 1936, Borchert 1950).

These three factors are not causes, but rather symptoms of general trends in the atmosphere. As noted in the introductory section, northeastern Colorado has a fairly strong westerly circulation in the winter but weak westerlies in the summer. In years of low precipitation the westerly circulation is much stronger than normal in the summer,

Table 12. Monthly and yearly wind averages for CPER (mph).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Average Wind Speed	6.83	7.34	7.70	8.29	7.21	5.96	5.10	5.17	5.55	5.84	5.87	6.20	6.40

approaching a winter circulation pattern (Borchert 1950). Thus, dry years have the moist air from the Gulf replaced by dry continental air during the summer. In addition, the storm track is shifted to the north as a result of the strong westerlies.

This strong westerly pattern would be expected to produce higher than normal surface winds and at the same time give abnormally low precipitation. Higher than normal temperatures would result from the greater amount of insolation available.

These concepts were tested with the data in the Pawnee Grassland. Unfortunately, the wind record limited the study to nine years, from 1959 to 1967. However, this included 1964 which was one of the driest years on record. Table 13 presents the results of a correlation analysis of these parameters.

The high negative correlation between rainfall and average summer wind velocity fits the theory well. It is significant that a much lower correlation between yearly precipitation and average yearly wind velocity exists, since it is the summer circulation and not the yearly circulation that determines a wet or dry year. A negative correlation was also found between average maximum temperature and summer rainfall, but the relationship is not as strong. A noteworthy point is the very low correlation between minimum temperature averages and precipitation.

We can infer from these results that dry years could be harmful to the biome in more than one aspect. Not only will a dry year have low precipitation, but it will be accompanied by higher than average temperatures, wind movement, and therefore higher evapotranspiration. The net effect is that the need for water is highest during the years when it is least available.

Table 13. Correlations between climatic parameters, 1959-1967.

	Average Wind	Average Maximum Temperature	Average Minimum Temperature
	Summer		
Summer Precipitation	-0.77	-0.53	+0.14
	Yearly		
Annual Precipitation	-0.43	-0.53	-0.22

SUMMARY AND CONCLUSION

It has been shown that the Pawnee National Grassland has a semiarid steppe climate and receives most of its rain in late spring and summer. Winters are dry and generally have relatively mild temperatures. In contrast with temperature, precipitation is a highly variable parameter. Particularly during the summer, precipitation becomes almost random in nature varying tremendously from day to day, from station to station, and from year to year.

No spatial variation with respect to temperature was found, but there was a marked precipitation increase from west to east. The maximum "rainshadow" of the Rocky Mountains between 40° 30' and 41° N latitude lies on the western edge of the Pawnee Grasslands.

An analysis of storms over the region showed that the year-to-year variability of precipitation could be explained chiefly by the few large summer storms that occur each year. The difference between a wet year and a dry year was determined by the number of large convective storms that occurred. The total precipitation coming in the six months defined as summer correlated very highly with the annual total, while the opposite was true for the winter precipitation.

Probability tables of both precipitation and temperature were developed using a Markov chain analysis. The results were useful in studying the climate and can be used to generate sequences of weather.

Significant inverse correlations were found between average summer maximum temperatures and rainfall and between average summer wind speed and rainfall. The latter was especially high. It follows, then, that the climate is not a series of discrete parameters, but the result of interactions between forces which affect all aspects of the climate.

It should be remembered that the climate varies a great deal within 6 ft of the ground. One cannot directly apply this climatology, which utilized data taken 6 ft above the ground, to the climate at the surface. Temperature extremes, for instance, are more pronounced close to the ground. Only at night do the temperatures at six ft and at the surface approach each other. Thus, ecological investigators should be aware that the plants on the Pawnee National Grassland thrive in a climate somewhat different than, but of course closely related to, the climate presented here.

Recommendations

A further study of the Markov chain temperature chain analysis is in order. More rigid statistical proof of the validity of the Markov chain for determining temperature probabilities, too involved to be included here, should be attempted.

A study of the synoptic climatology of the Pawnee Grassland using data from standard Weather Bureau maps would be helpful. Average synoptic conditions encountered during normal and drought periods would be interesting to compare.

An effort should be made to increase both the density and quality of the climatological stations. While in general the data is good, we have seen temperature shelters within 20 ft of incinerators, precipitation gauges close to buildings, and tipping-bucket rain gauges inoperative for several weeks at stations not used in this study. Short-term collection of other meteorological data is being undertaken in connection with the IBP project, but long-term records of parameters other than temperature and precipitation would be desirable. Parameters directly related to biome processes should be emphasized in future data collection programs.

Lastly, it would be interesting to reevaluate the climate of this area after 100 years of data have been collected to verify the results and investigate any climatological trends.

PART II: A SUMMARY OF SOLAR RADIATION DATA, WEST CENTRAL UNITED STATES

BACKGROUND

Recent attempts to model the grassland ecosystem rely on a suitable description of the driving forces (e.g., Van Dyne 1969). Fig. 9 illustrates a nine compartment multi-trophic level model that has solar energy, temperature and precipitation as the driving forces. The purpose of this paper is to report on research designed to understand the climatology of solar radiation reaching the earth's surface over the North American grassland region (Fig. 10). This climatology is to be used as one input into a grassland ecosystem model.

Our summary is based on up to 20 years of monthly solar radiation data (published monthly in the *Climatological Data, National Summary*) taken by the observing network of the National Weather Service (NOAA) at 14 stations over the west-central United States (Fig. 11).

ANALYSIS

The solar radiation is derived from pyranometers, instruments that historically have been difficult to calibrate. In order to minimize the inter-station calibration problems, the analysis was based upon that study of deviations from long-term monthly average values at each station. The analysis procedure follows:

Let R_{ijk} denote the monthly total solar radiation received at the earth's surface at each station where the subscripts:

i denotes the station $i \leq 14$

j denotes the month

k denotes the year

i. Determine the long-term monthly average for each station

$$\bar{R}_{ij} = \frac{1}{n} \sum_{k=1}^{n} R_{ijk} \qquad n \leq 20$$

COMPARTMENT MODEL

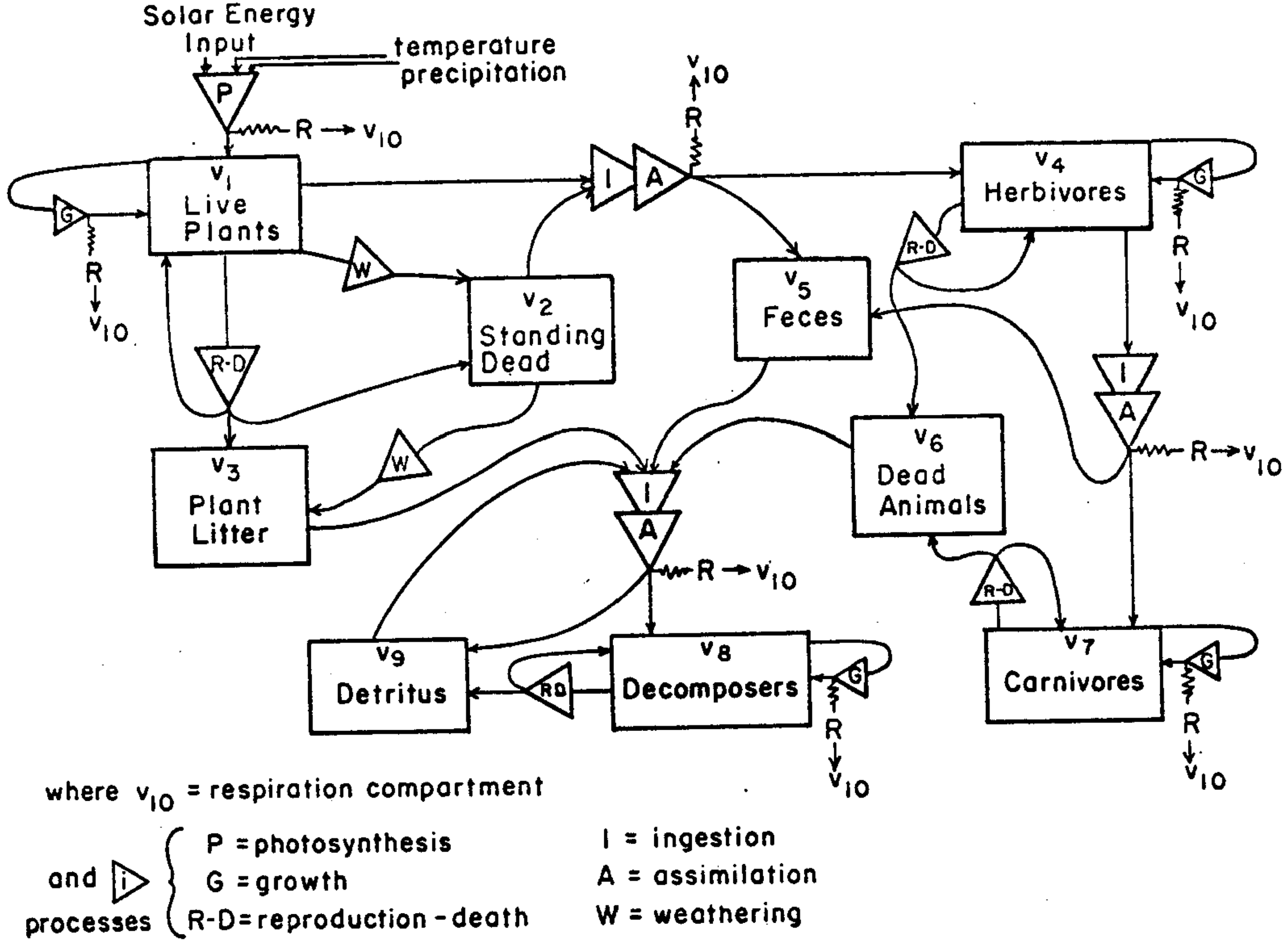


Fig. 9. A model diagram for a nine-compartment multiptrophic level grassland ecosystem. Energy flow is shown by arrows, and compartments, in squares, are connected through processes, triangles. At many steps there is a respiratory energy loss, R, to the environment, ν_{10} (Van Dyne 1969).

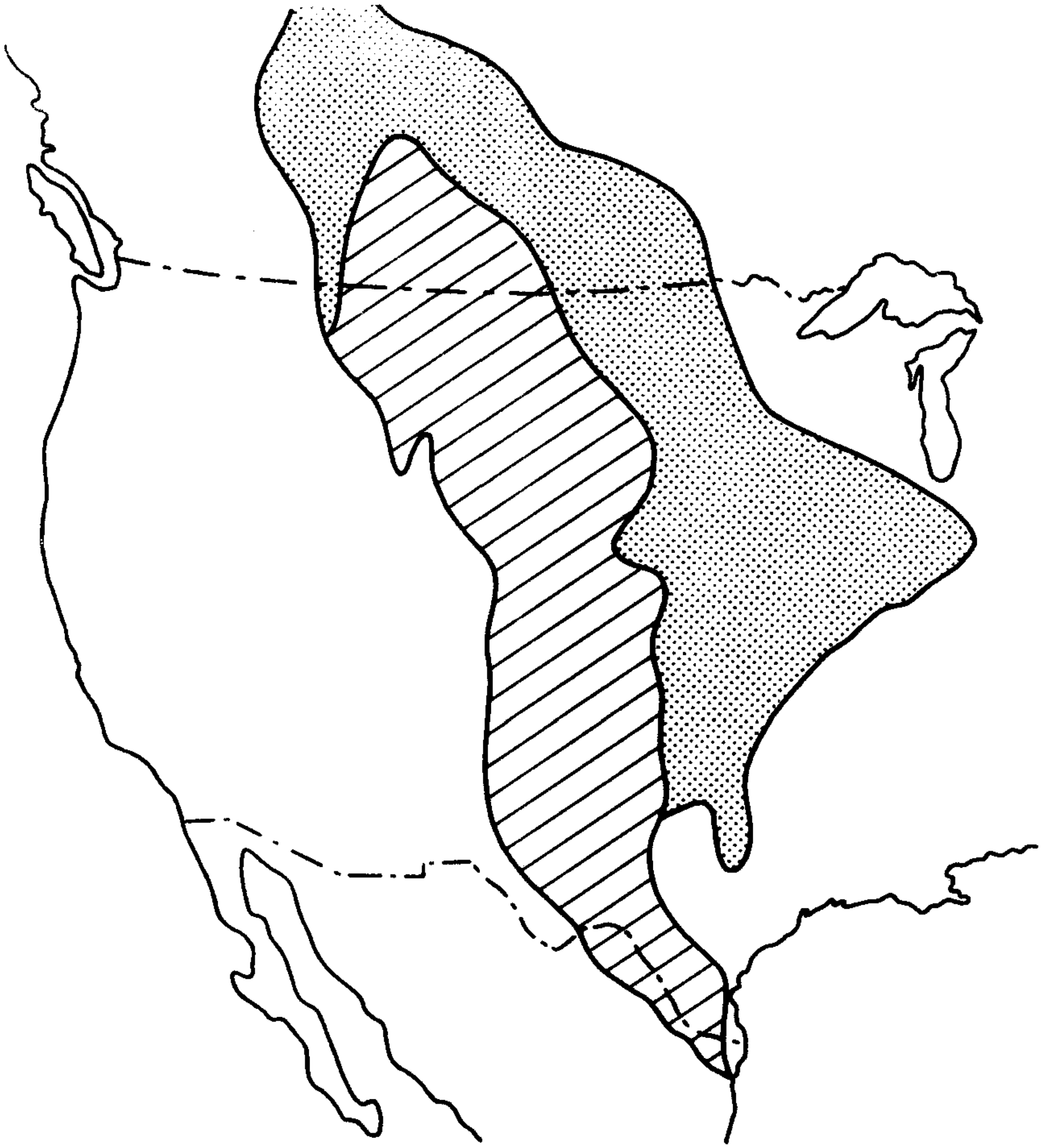
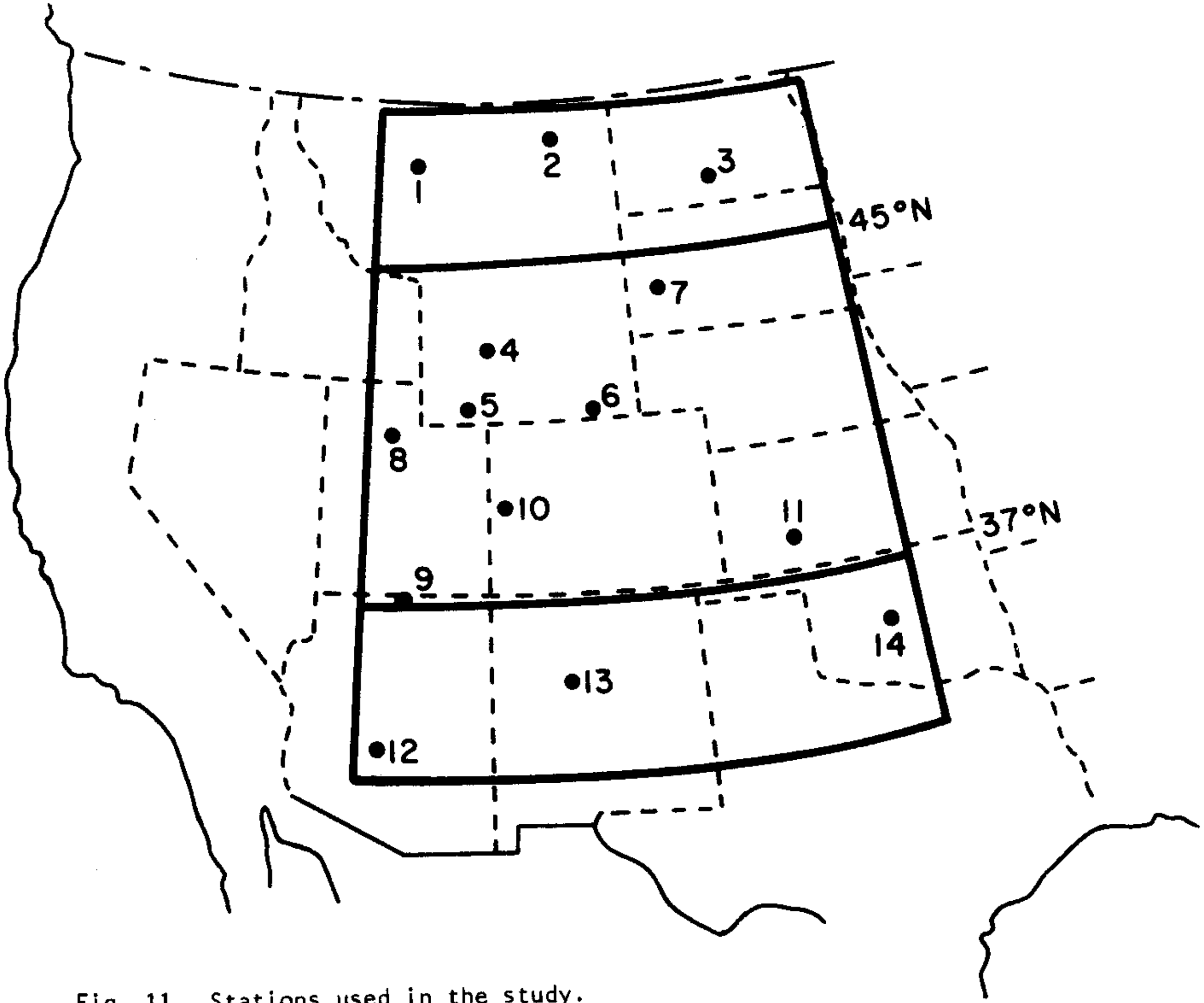


Fig. 10. North American grasslands (Borchert 1950) include shortgrass (hatched area) and mixed grass and tallgrass (shaded area).



1. Great Falls
2. Glasgow
3. Bismark
4. Lander
5. Flaming Gorge
6. Laramie
7. Rapid City
8. Salt Lake City
9. Page
10. Grand Junction
11. Dodge City
12. Phoenix
13. Albuquerque
14. Oklahoma City

Fig. 11. Stations used in the study.

Where the monthly deviations are

$$R'_{ijk} = R_{ijk} - \overline{R}_{ij}$$

ii. Area average the deviations

$$\tilde{R}'_{jk} = \frac{1}{m} \sum_{i=1}^{m} R'_{ijk} \qquad m \leq 14$$

iii. Determine the annual summation of the area averaged monthly deviations

$$\hat{\tilde{R}}'_{k} = \sum_{j=1}^{12} \hat{\tilde{R}}'_{jk}$$

iv. Study and try to physically explain the characteristics of the time series

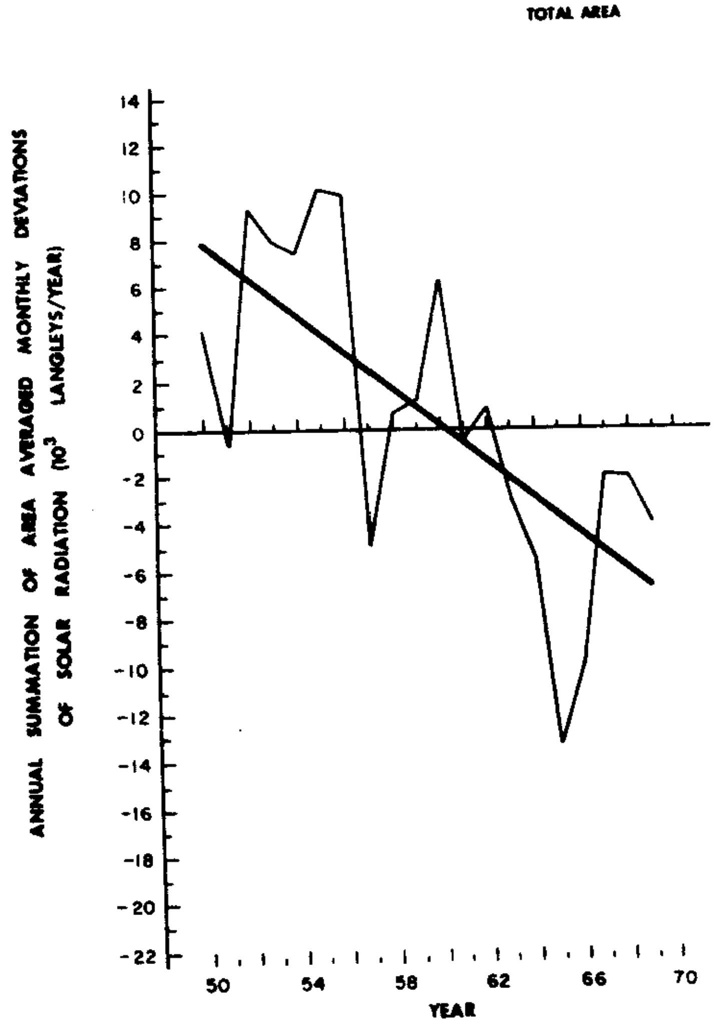
$$\hat{\tilde{R}}'_{k}$$

In addition, the above analysis procedures were followed for the three northernmost stations and for the three southernmost stations separately in order to define the spatial variability over the grassland network.

RESULTS

Fig. 12 shows the time series $\hat{\tilde{R}}'_{k}$. The trend line is the simple linear regression line fitted to the data. The trend over the 20 year sample goes from +8000 to 6500 langleys per year, a range of 14,500 langleys over the 20 year period. The average total annual radiation over the area is 15.33×10^4 langleys per year. The trend then amounts to a 10% change in annual radiation received over the 20 year period.

Cause of this systematic trend during recent years has been hypothesized as increasing atmospheric turbidity (Budyko 1968, National Center for Atmospheric Research 1970, among others). The



TOTAL AREA

Fig. 12. Time series and trend of $\hat{\tilde{R}}'_k$, 1950-1960. All stations.

magnitude of the trend reported here is generally stronger than other researchers have found. The systematic degradation of the instruments is a possible source of error and must be evaluated prior to drawing firm conclusions with regard to this trend.

Fig. 13 shows the parallel analysis done for the three northern stations and the three southern stations respectively. There is definite spatial variation of trend showing a much amplified trend over the lower latitude belt.

Upon removing the trend in Fig. 12, we obtain the time series shown in Fig. 14 (solid curve). These variations in solar radiation appear to have a quasi-periodic nature with an amplitude similar to the 20 year trend. Variations of this magnitude and frequency are most likely related to relative cloudiness from year to year. To test this hypothesis, the percent of possible sunshine records were summarized for 10 stations located within our solar radiation network. Annual deviations from the 20 year average annual value were determined and the percent possible sunshine deviation converted to radiation values assuming that the annual sunshine deviations would be realized as solar radiation deviations with the same ratio as the average annual solar radiation over the average annual percent of possible sunshine. This deviation in solar radiation is plotted as the time series with the dashed line in Fig. 14. Exceedingly good agreement is obtained over the first 13 years of record; the curves diverge over the last seven years of record. Considering the crude method of estimating cloudiness, this analysis looks promising. Our current research involves explaining the inconsistency between the two curves of Fig. 14 over the last seven sample years. Following this, links with atmospheric

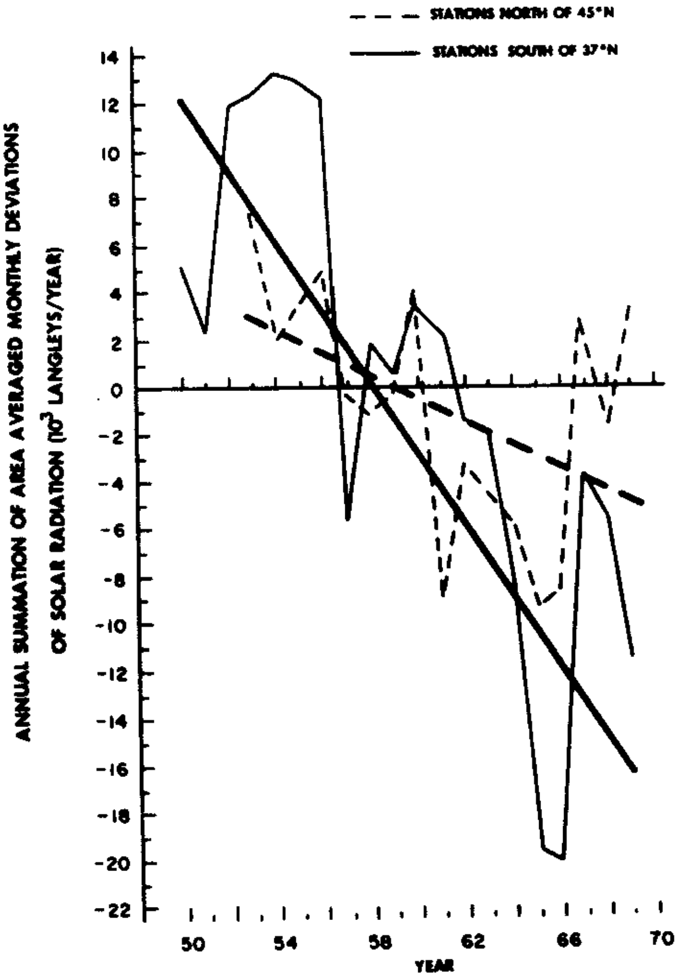


Fig. 13. Time series of $\hat{\tilde{R}}'_k$ over northern and southern latitude belts (see Fig. 3.)

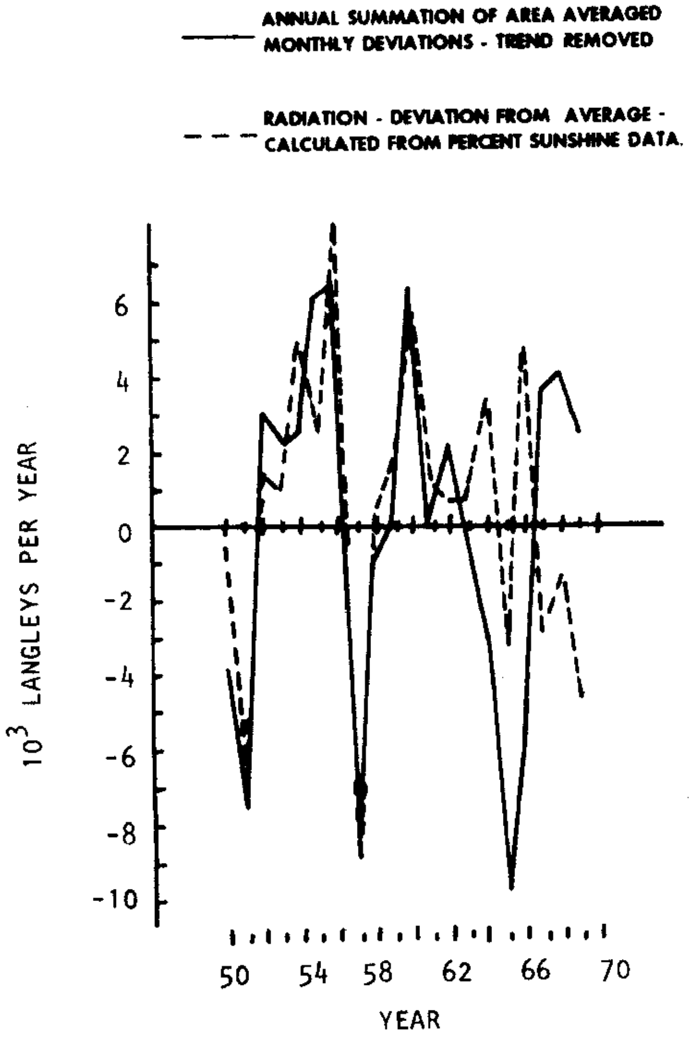


Fig. 14. $\hat{\tilde{R}}'_k$, solid line, $\tilde{R}'_k$, trend removed. Dashed line radiation variation inferred from percent possible sunshine data.

circulation changes will be studied in order to understand the cloudiness-solar radiation variability.

Recently Kondratyev and Nikolsky (1970) reported variations in the intensity of the solar radiation received at the extremity of the earth's atmosphere. These variations were measured using balloon borne observation platforms. Kondratyev and Nikolsky provide a relationship between the Zurich sunspot number and the intensity of the solar radiation received at the extremity of the earth's atmosphere. The annual average sunspot number as tabulated in the *Journal of Geophysical Research* (1950 through 1969) was converted to the solar output following Kondratyev's curve. This data then was normalized so that for each year the fractional deviation from average was obtained. The net change in the solar radiation received at the ground each year due to solar activity then was determined by multiplying the average annual radiation received by this fractional deviation. The results are shown as the dashed curve in Fig. 15. The parallelism between curves is good, except for early in the period when, of course, the trend line and therefore the deviations are less certain.

The interactions suggested in Fig. 14 and 15 provide a possible linkage between the solar radiation input and resulting short-term climate variations amplified through changing circulation patterns and changes forced by the solar radiation perturbations. Lamb (1970) describes a similar interplay of radiation, circulation, and precipitation parameters related to climatic change of Europe, Asia, and Africa.

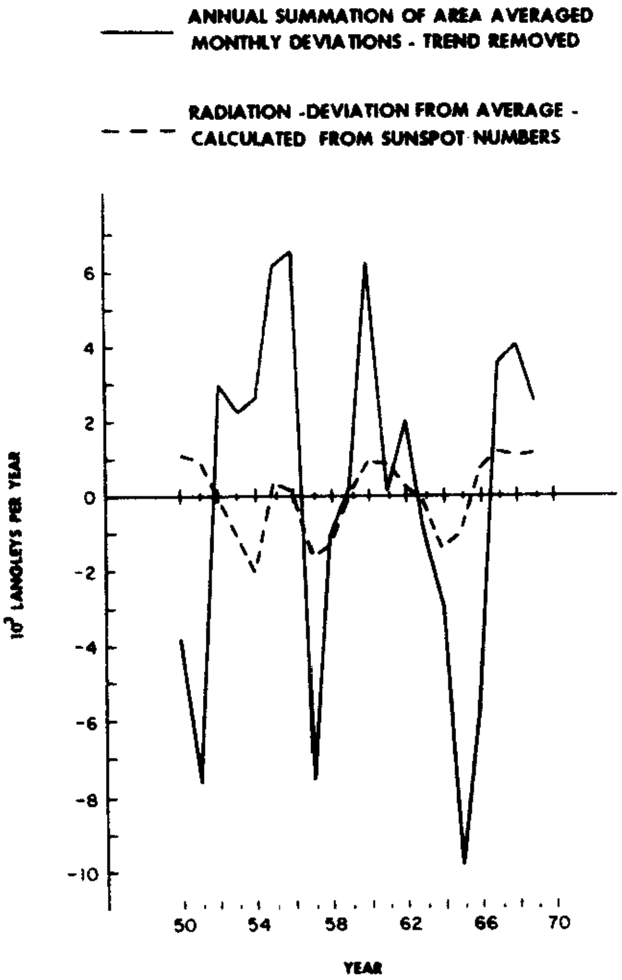


Fig. 15. Solid line $\hat{\tilde{R}}'_k$, trend removed. Dashed line radiation variation inferred from sunspot variation following Kondratyev and Nikolsky (1970).

CONCLUSIONS

Twenty years (1950-1969) of monthly solar radiation data over the west-central United States have been summarized and show a trend in annual radiation received amounting to a change of 10% over the 20 year period. Superimposed upon this trend are variations in solar energy received that have periods from five to eight years and appear to be related to relative cloudiness variations, perhaps a reflection of quasi-periodic atmospheric circulation changes. An interesting correlation between the Kondratyev-Nikolsky sunspot measurements and the observed solar radiation is found.

These variations in solar radiations will be used in the construction of the grasslands ecosystem model. The variations could be important in determining the current and future ecological patterns over this great expanse of the North American continent.

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APPENDIX I

HISTORICAL MAXIMUM AND MINIMUM DAILY TEMPERATURE READINGS FROM STATIONS CPER, KAUFFMAN, AND GROVER

Temperature data from stations CPER, Kauffman, and Grover are stored as Grassland Biome Data Set A2U70BB. Data are stored as card images, four cards per month, in the following format:

Columns	Contents
1- 8	Station Identification (A8)
9	Maximum/Minimum Code 1 = Minimum Temperatures 2 = Maximum Temperatures
10-11	Year
12-13	Month
14	Card Number This Month, and Temperature Type 1 = First Maximum or Minimum Card 2 = Second Maximum or Minimum Card
15-62	Temperature Readings (16I3)

APPENDIX II

HISTORICAL DAILY PRECIPITATION READINGS FROM STATIONS CPER, KAUFFMAN, AND GROVER

Historical daily precipitation readings from stations CPER, Kauffman, and Grover are stored as Grassland Biome Data Set A2U70CB. Data are stored as card images, 3 cards per month, in the following format:

Columns	Contents
1- 9	Station Identification (A9)
10-11	Year
12-13	Month
14-15	Day of First Precipitation Value on this Card (1, 13, or 25)
16-51	Precipitation Values (12F3.2)