

CLIMATE VARIABILITY IN THE SHORTGRASS STEPPE¹

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Abstract.— Climatic variability at the Central Plains Experimental Range LTER in northeastern Colorado was evaluated from annual, decadal, and century perspectives. Spectral analysis separated climatic variation into 2-7 y and >10 y scales. The record is dominated by cold-wet and warm-dry years. El Niño years had on average higher annual precipitation than years with cold water anomalies in the equatorial Pacific. At the decadal level, variations in temperature and precipitation parallel those for the Central U.S. and broader regions. The temperature record has a significant 75-y trend of +2°C. Such variations in climate have impacts on the structure and function of the short-grass ecosystem.

Keywords: Colorado, Central Plains Experimental Range, Long-Term Ecological Research, scale, El Niño/Southern Oscillation, ecological response to climate variability, Vegetation Index.

INTRODUCTION

Ecosystems are responsive to climate variability at a range of temporal scales. Temperature, precipitation, and other climate variables (e.g., humidity, cloud cover) vary year-to-year and decade-to-decade in ways that are likely to influence ecosystem composition and function.

I present an analysis of variability in temperature and precipitation at a range of temporal scales (annual, decadal, century) for the shortgrass steppe region in the vicinity of the Central Plains Experimental Range (CPER) in northeastern Colorado. Questions I address are whether there are characteristic scales of variation in temperature and precipitation, whether these scales are the same for the two variables (e.g., are dry periods characteristically warm or cold?), and whether there are long-term trends in the record. These are important questions because they seek to characterize periodic and unidirectional changes in the external forcing on ecosystems. Such understanding provides a basis for the study of between-year and long-term changes in ecosystem dynamics.

In the context of interannual variability, I examine possible long-distance links (teleconnections) between the climate of the steppe region and a source of global climate variability, El Niño and the Southern Oscillation (ENSO). ENSO consists of quasi-periodic (generally 3-7 y) oscillations in ocean-climate dynamics of the tropical Pacific Basin (Philander and Rasmusson 1985). As part of these oscillations, El Niño is a strong warming of surface ocean waters in the central and eastern equatorial Pacific. ENSO teleconnections play a role in the climate dynamics of the extratropics (Yarnal 1985); impacts on ecological dynamics have been suggested for sites in the United States (e.g., Strub et al. 1985, Gosz 1988).

Finally, I discuss observational and modeling studies on the impacts of climate variability on the steppe ecosystem.

METHODS

Site Description

The CPER (40°49' N, 104°46' W, 1650 m above sea level) is operated by the USDA Agricultural Research Service (ARS) and is an NSF Long-Term Ecological Research (LTER) site. The vegetation at the CPER is shortgrass steppe dominated by perennial grasses *Bouteloua gracilis* and *Buchloe dactyloides*, with important succulent (*Opuntia polyacantha*) and subshrub components (Moir and Trlica 1976). Much of the surrounding region is grazed native grassland and cropland.

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The climate of the shortgrass steppe is characteristic of mid-latitude, continental semi-arid regions; it is classified as BSk (cold, steppe climate) in the Köppen-Geiger system (Müller 1982). The mean climate and water budget is described by Parton and Greenland (1987) based on the period 1951-1980. Monthly mean temperature peaks in July (21.6°C) and is lowest in January (-3.1°C). Mean annual precipitation is 309 mm, with maximum monthly precipitation usually occurring in May and June. Winter precipitation is associated with mid-latitude cyclonic storms and summer rainfall with cumulus convective storms that often initiate along the Rocky Mountain Front Range to the west and intensify as they progress eastward. Mean monthly precipitation does not exceed monthly actual evapotranspiration year-round (Parton and Greenland 1987).

Climate Data

The CPER

I used temperature and precipitation data from two climate stations on the CPER, one operated by ARS and the other by LTER. The ARS station is at an elevation of 1645 m above sea level (asl); the LTER station is at 1643 m asl. The stations are ~5 km apart. ARS data are for the period 1940-1973 (temperature data start in 1948, precipitation data are continuous from April 1947). LTER data used here are from July 1970 to May 1988. The records of these stations were concatenated, with the LTER data replacing ARS data in October 1970; this was considered appropriate because the stations are in close proximity and have strongly correlated traces for the period of overlap (monthly temperature $r^2=0.99$, monthly precipitation $r^2=0.74$; Parton and Greenland 1987). Monthly mean temperatures were calculated as an average of monthly mean minimum and maximum temperatures.

Grover

To analyze long-term behavior in regional climate, I used data from a National Weather Service cooperative station approximately 16 km west of Grover. This station, officially named Grover10W, has a 58-y record (1911-1969). It is roughly 25 km east-northeast from and 100 m asl below the LTER station. The station was moved several times during its history. For most of its operation (1929-1962), it was at 40°52'N, 104°25'W, and 1547 m asl. A significant move occurred in 1962 and is reflected in the temperature record (Fig. 1a).

Neither temperature nor precipitation monthly records for Grover are without gaps. To create a continuous record, gaps of usually one month (occasionally up to three months) were filled with corresponding long-term monthly means for 13 years in the temperature record and two years in the precipitation record. An advantage of this substitution is to retain years with nearly complete monthly data, although it reduces interannual variability and trends and blurs spectral signals.

Analysis

For analysis of interannual variability, blocking the data into 12-month periods is often arbitrary (e.g.,

calendar years). In this study, I used water year (October to following September) to associate fall and winter precipitation with the following growing season. Consequently, this annual period includes the approximate integrating period over which an important climate-ecosystem interaction, soil water recharge, operates. Water years are identified by the year the period ends: e.g., water year 1982 is October 1981-September 1982. Five-year running means of these data were constructed to investigate decadal and longer-term behavior.

Spectral analysis was used to identify characteristic scales of variation in the yearly data. This analysis characterizes periodic behavior in a time series and identifies frequencies at which there is high covariance between two time series (i.e., high coherence). This analysis was accomplished using time series analysis software (BMDP/P1T; Thrall and Engelman 1985). Statistical software (SPSS/PC+; SPSS and Norušis 1986) was used to test for linear trends in the data. The time series analyses were run on detrended data and used a wide band width. A wider band width strengthens the statistical stability of the analyses, although it reduces the spectral resolution.

Spatial Variability

Spatial variability may give rise to problems in interpreting these station data in a regional and ecological context. Point measurements of precipitation may not represent the 6280 ha CPER because winter-time winds redistribute snow across the landscape and summer convective precipitation events are often patchy in their occurrence. For example, growing season precipitation varied across the site by as much as 96 mm in 1988, an amount greater than the standard deviation of annual precipitation (Hazlett 1990). These effects can be ecologically important, influencing local soil water recharge (Burke et al. 1989) and contributing to spatial variability in biomass accumulation (Lauenroth and Milchunas, unpublished data) and community structure.

Southern Oscillation Index

To evaluate possible teleconnections with El Niño episodes and the Southern Oscillation (ENSO), I compared CPER data to a Southern Oscillation index (SST_{SO}) based on central and eastern equatorial Pacific sea surface temperature anomalies developed by Wright (1984). The sign of this index is opposite to that of SO indices based on sea level pressure: SST_{SO} is positive during El Niño episodes and negative during cold water ("anti-El Niño" or "La Niña") episodes. Wright's (1984) record for this index is for 1950-1983. Water year averages of SST_{SO} were included in correlation and spectral analyses.

RESULTS AND DISCUSSION

Water Year Time Series

Station Comparison

During the period of record overlap (1948-1969), there is a high correlation between CPER and Grover water year precipitation totals ($r=+0.67$, $p<0.001$;

Table 1, Fig. 1b). However, precipitation during the overlap period differs between the two sites ($p < 0.05$, t-test, Table 1). Greater precipitation at Grover likely reflects a regional gradient in precipitation (Cowie and McKee 1986): northeast of CPER, Grover is less in the rain shadow of the Front Range.

There is also a difference in temperature means between sites during the overlap period ($p < 0.01$, t-test; Table 1, Fig. 1a). This is primarily due to a divergence in temperature series after 1962 that reflects the change in Grover's location. For the period of overlap up to this station change, annual temperature means are not significantly different ($p > 0.5$, t-test) and are highly correlated ($r = +0.71$, $p < 0.005$; Table 1, Fig. 1a). The difference in temperature means calculated for each station's record ($\Delta T_{\text{CPER-GR}} = +0.5^\circ\text{C}$, Table 1) may be due to climatic trends and is discussed later.

Power Spectra

Both high and low frequency variability is evident in the temperature and precipitation time series (Fig. 1). The temperature power spectrum for Grover (Fig. 2a) shows peaks in variance for oscillations at periods around $2\frac{1}{2}$ -4 y and greater than ~ 20 y. The spectrum for precipitation (Fig. 2b) is broader with less well defined peaks at ~ 2 and $2\frac{1}{2}$ -5 y, as well as at > 10 y. This reveals a natural break in temporal dynamics between annual and decadal scales. Dye (1983) found comparable breaks in the precipitation spectra for stations throughout Colorado.

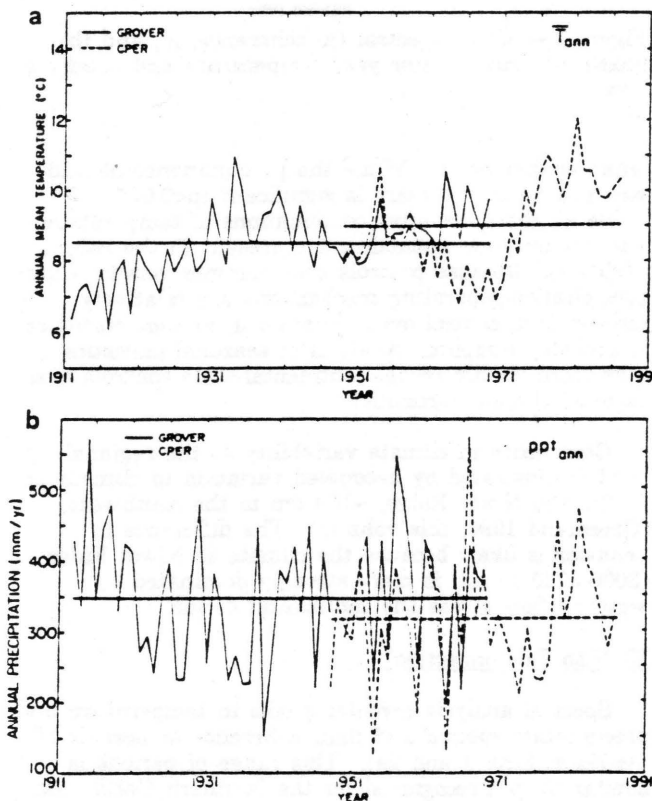


Figure 1.— (a) Water year mean temperature, $^\circ\text{C}$, and (b) precipitation, mm/yr, for CPER (---) and Grover10W (—). Horizontal lines are record means for each station.

Table 1.— Summary of CPER and Grover10W (GR) climate data for record and for period of overlap (1949-69 for T_{ann} , 1948-69 for ppt_{ann}). Numerical subscripts indicate other periods (e.g., 12-62 = 1912-62). Years are water years. Trends over station record (and also over 1912-62 for Grover) and corresponding significance levels (two-tailed t-test) are given. Station comparison over the full overlap period and over the overlap until 1962 are shown based on correlation analysis (r) and paired two-tailed t-test for difference of means (t). Level of significance for trends, r , and t are: * = $p < 0.05$ and ** = $p < 0.01$. T_{ann} = water year mean temperature ($^\circ\text{C}$); ppt_{ann} = water year precipitation (mm/y). Elevations (m asl) are approximate because of station location changes. sd = standard deviation. n/a = not applicable.

	CPER	GR	$\Delta(\text{CPER-GR})$	r	t
Elevation	1643	1547	+96		
<u>Record:</u>					
T_{ann}					
dates	1949-87	1912-69			
mean	9.0	8.5	+0.5		
sd	1.3	1.0	+0.3		
trend	+2.4**	+2.1**			
trend ₁₂₋₆₂	n/a	+1.7**			
ppt_{ann}					
dates	1948-87	1913-69			
mean	317	347	-30		
sd	88	95	-7		
trend	+52	-15			
trend ₁₃₋₆₂	n/a	+1			
<u>Overlap:</u>					
T_{ann}					
mean	8.2	9.0	-0.8	+0.14	3.2**
sd	0.9	0.7	+0.2		
mean ₄₉₋₆₂	8.6	8.6	0.0	+0.71**	0.5
ppt_{ann}					
mean	315	356	-41	+0.67**	2.4*
sd	102	93	+9		
mean ₄₉₋₆₂	300	373	-73	+0.77**	4.5**

Coherence (h^2) is analogous to the squared correlation between two variables within a given spectral band. A high coherence identifies a frequency at which variables strongly co-vary. There are peaks in the coherence between Grover temperature and precipitation series (Fig. 3a) in the short-period region ($2\frac{1}{2}$ -7 $\frac{1}{2}$ y, $h^2 > 0.3$) and in the long-period region (> 20 y, $h^2 > 0.4$). Analysis for CPER reveals a similar pattern with strong coherence at $3\text{-}3\frac{1}{2}$ y ($h^2 = 0.5$) and at 20 y ($h^2 = 0.4$). The phase of these spectral correlations (Fig. 3b) is such that temperature leads precipitation by $\sim \frac{1}{2}$ cycle across all frequencies; i.e., annual mean temperature and annual precipitation fluctuations are out of phase. Significance of the coherence and phase is discussed below in the context of annual and decadal variability.

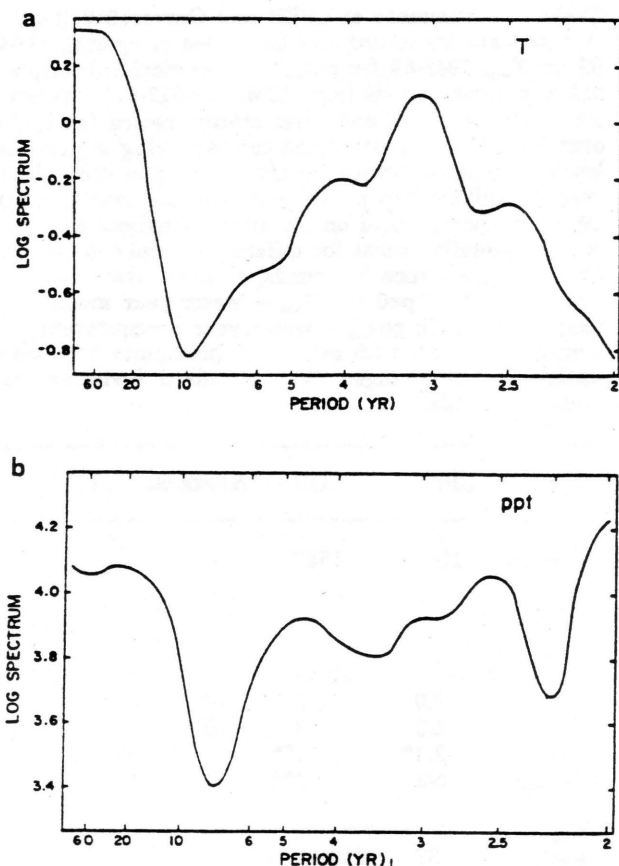


Figure 2.— Power spectra for Grover water year (a) temperature and (b) precipitation. Band width = 0.1167 yr^{-1} .

Interannual Variability

Comparison of temperature and precipitation time series (Figs. 1a and b) suggests that peaks in annual temperature often coincide with low precipitation years and vice versa (Table 2). Indeed, annual temperature and precipitation are negatively correlated ($r = -0.41$, $p < 0.02$). This is in accordance with the phase shift of $\frac{1}{2}$ cycle found in the coherence results (Fig. 3b). The alternation of warm dry years with cold wet years implies control by oscillations in position and intensity of the mid-latitude polar jet and subtropical high pressure centers: e.g., cold wet years occur when the jet is farther south than average, warm dry years

Table 2.— Contingency table of cold vs. warm and wet vs. dry years for Grover. Years are blocked based on water year mean temperature and precipitation greater vs. less than corresponding local (5-y running) mean to adjust for decadal trends. ($\chi^2 = 5.175$, $df = 1$, $p < 0.025$).

	$T < \bar{T}_{5y}$	$T > \bar{T}_{5y}$
$ppt < \bar{ppt}_{5y}$	11	17
$ppt > \bar{ppt}_{5y}$	17	8

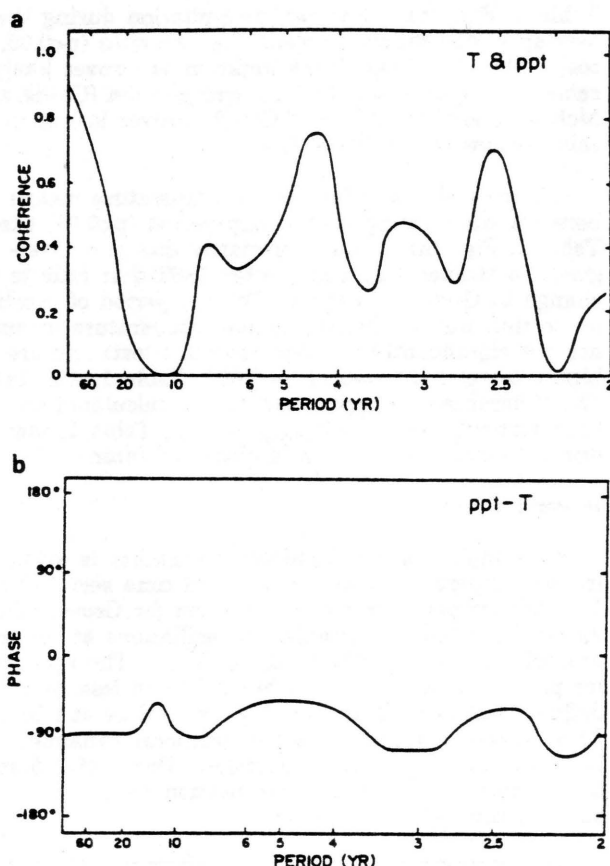


Figure 3.— Cross spectral (a) coherence, h^2 , and (b) phase for Grover water year temperature and precipitation.

when farther north. While the predominance of cold-wet and warm-dry years is significant ($p < 0.025$, Table 2), the alternative combinations of temperature and precipitation anomalies are present in the record (Table 2). Because controls over summer versus winter precipitation-generating mechanisms are relatively independent, control over variation in *annual* statistics is probably complex. Analysis of seasonal statistics may more readily reveal continental-scale controls over regional climate variability.

Complexity in climate variability at the regional level is illustrated by decoupled variation in climate at CPER and Niwot Ridge, $\sim 100 \text{ km}$ to the southwest (Greenland 1990, this volume). The difference in behavior is likely because the climate of Niwot Ridge (3000-3750 m asl) is more strongly dominated by westerly flow across the continental divide.

El Niño Teleconnection?

Spectral analysis revealed peaks in temperature and precipitation spectra and their coherence at periods of $2\frac{1}{4}$ - $7\frac{1}{2} \text{ y}$ (Figs. 1 and 2a). This range of periods is similar to that recognized for the Southern Oscillation (2-10 y, Rasmusson and Carpenter 1982) and so hints at a possible link to El Niño episodes.

There is a positive correlation between the annual Southern Oscillation SST Index (SST_{30}) and CPER

annual precipitation ($r=+0.30$, $p=0.11$), such that precipitation tends to be higher during El Niño years. There is no significant correlation with annual temperature. However, at periods of 3–4 y there is spectral coherence between SST_{30} and CPER temperature ($h^2=0.5$), as well as between SST_{30} and CPER precipitation ($h^2=0.3$). The ratio of annual precipitation during years with a strongly positive SST_{30} (El Niño years) to those with highly negative SST_{30} is 1.13 (Table 3), although only 5 of 9 El Niño years between 1951 and 1983 had greater than average precipitation. Sheaffer (personal communication) found that the corresponding El Niño to "anti-El Niño" ratio for summer precipitation in northeastern Colorado is on the order of 1.33. By comparison, the Sevilleta LTER region (central New Mexico) is more strongly influenced by tropical Pacific climate dynamics: the El Niño to "anti-El Niño" ratio is 1.59 for annual precipitation and 2.45 for winter-spring precipitation (Molles and Dahm, in Gosz 1988).

Observational and modeling studies of ENSO indicate that strongest teleconnections should be in winter, associated with the polar jet. For northern central North America inclusive of the shortgrass region, these teleconnections include increases in winter temperature and surface pressure (van Loon and Madden 1981, van Loon and Rogers 1981, Rasmusson and Wallace 1983). This is in accordance with greater annual temperatures observed at the CPER during El Niño years (Table 3). Increases in winter surface pressure suggest that El Niño years should have drier winters (Yarnal 1985). Sheaffer (personal communication) found this to be the case for NE Colorado: winter precipitation El Niño to "anti-El Niño" ratio is <0.75 . However, depressed winter precipitation has only a small impact on total annual precipitation during El Niño years since most precipitation at the CPER comes during summer.

Table 3.— Comparison of CPER water year mean temperature (T_{ann} , °C) and precipitation (ppt_{ann}, mm/y) for years with high vs. low eastern and central equatorial Pacific sea surface temperatures (SST). High SST years correspond to El Niño episodes and were selected as those years with annual SST_{30} exceeding the mean + $\frac{1}{2}$ its standard deviation (s.d.). SST_{30} falls below the mean – $\frac{1}{2}$ s.d. in low years and within the region prescribed by the mean $\pm \frac{1}{2}$ s.d. in 'Near Mean' years. Analysis is for water years 1951–1983. n = number of years. n/a = not applicable.

SST	ppt _{ann}	T _{ann}	n
High	343	9.3	9
Near Mean	313	8.7	14
Low	303	8.7	10
High:Low	1.13	n/a	
Δ (High-Low)	+40	+0.7	
Mean ₅₁₋₈₃	318	8.9	33

While a clear ENSO teleconnection is weak for the CPER, difficulty in finding such a signal in the climate of the steppe is expected. Four factors contribute to the problem. (1) Teleconnections are partly a function of mid-latitude circulation patterns prior to ENSO episodes (Yarnal 1985). Consequently, the character of extratropical teleconnections shifts over decades with shifts in hemispheric circulation (Carleton 1987, Sheaffer and Reiter 1985). (2) Southern Oscillation indices can fail to catch the timing or intensity of an ENSO episode because of variations in the location of equatorial SST and/or atmospheric anomalies (Yarnal 1985). This is because such indices are empirical and do not adequately reflect ocean-climate dynamics. (3) Large-scale studies show that ENSO-linked variation in climate for northern and central North America is less consistent in nature than for other parts of the continent (van Loon and Madden 1981, Blackmon et al. 1979). (4) ENSO teleconnections account for only a small portion of extratropical climate variability (Wallace and Blackmon 1983).

Decadal Variability and Long-Term Trends

Annual Temperature

A warming trend ($\Delta T=+3^\circ$) through the late 1930's and subsequent cooling trend until 1950 ($\Delta T=-1.5^\circ$) are observed in 5-y running means of the Grover data (Fig. 4a). A -3.5° warming in the 1970's is shown in the CPER data. These patterns agree with the general behavior of Northern Hemispheric temperatures reported by Hansen and Lebedeff (1987) and with that for eastern Colorado (Doesken et al. 1989) and the Midwest United States (Diaz and Karl 1988). The amplitude of the 1920's to 1950 oscillation in the Grover record is magnified from that for the Northern Hemisphere ($+0.4^\circ$ warming, -0.15° cooling) and the Midwest ($+1.5^\circ$, -1.0°), reflecting the steppe's continentality. While a regional trend in the 1950's and 1960's is not clear due to the Grover station location change in 1962 (Fig. 4a), the trend in CPER data clearly follows that for other stations in eastern Colorado (Doesken et al. 1989) and the central United States (Diaz and Karl 1988): a slight warming in the early 1950's followed by cooling into the late 1960's.

The long-term linear trend in the Grover temperature record (until the 1962 station move, 1912–1962 water years) is $+1.7^\circ\text{C}$; that for the 1949–1987 CPER record is $+2.4^\circ$ (Table 1). The accumulative 75-y trend is 2.1° , not adjusted for station differences. The slopes of the CPER and Grover trends are significantly different from zero ($p<0.01$, t-test), in spite of high year-to-year variability. This contrasts with Diaz and Karl's (1988) conclusion that there has been no century-scale change in temperatures across the United States. Doesken et al. (1989) showed that trends in mean annual temperature in eastern Colorado are dominated by increases in winter temperatures.

The result of a significant trend must be viewed cautiously before concluding that a regional change in climate has taken place. These results are only for two stations, each of which has a poor history with respect to location changes and data gaps. Other possible station changes such as in instruments, environs (e.g., buildings, vegetation), and time of day of

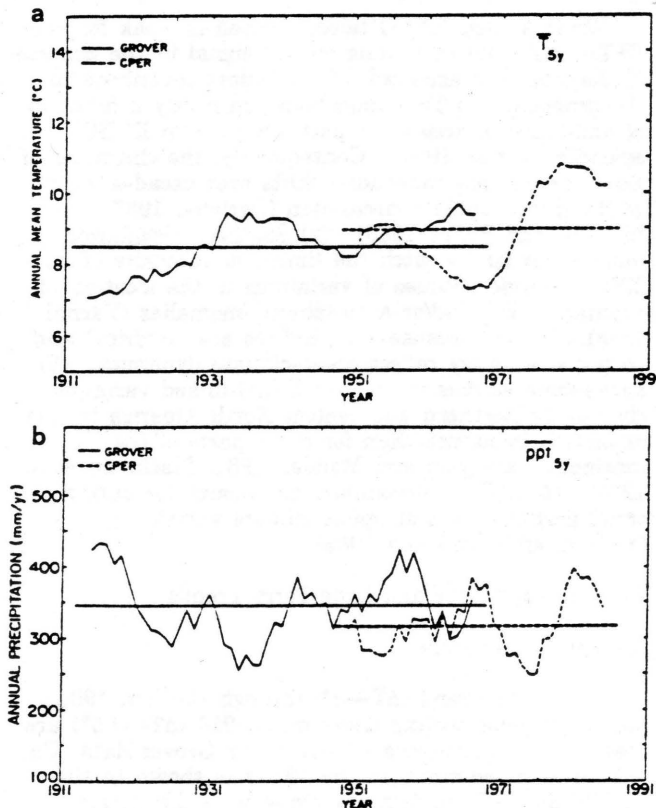


Figure 4.— As Figure 1, but for five-year running means.

observation could potentially play a role in changing station means.

Annual Precipitation

The five-year running means of annual precipitation show significant decadal variation (Fig. 4b), such as the 1930's drought. Again there is considerable disagreement between Grover and CPER during the period of overlap. However, the CPER record agrees with the independent analysis of United States precipitation by Bradley et al. (1987) and shows the wide-spread 1950's drought.

Linear trends in Grover and CPER precipitation series are not significant ($p > 0.25$, t -test; Table 1). This is in accordance with Bradley et al. (1987) who found no trend in annual precipitation for the United States since the 1850's.

Covariance

There is a general pattern of temperatures increasing from the 1910's until the mid-1930's, followed by a decrease into the late sixties and an increase since then (Fig. 4a). Superimposed on this apparent 50-y wave in temperature, recognized by Wigley and Raper (1987) for Northern Hemispheric temperatures, is a more rapid oscillation (15-20 y period) in precipitation (Fig. 4b). As a consequence, changes in the 5-y running means of temperature and precipitation follow the same pattern during some decades and opposite in

others. However, there is spectral coherence of temperature and precipitation at periods of 20 y or greater with a $\frac{1}{2}$ cycle phase shift ($h^2 > 0.4$, Fig. 3). This suggests that, as at the annual scale, multi-decadal variation in temperature and precipitation tends to be negatively correlated. This is supported by the pattern of droughts in the 1930's and 1950's being warmer than average and the wet 1910's and 1960's being colder.

Some of the observed decadal or longer-term changes may be linked to continental-scale shifts in circulation patterns that are in response to hemispheric or global changes in atmosphere-ocean climate dynamics (Balling and Lawson 1982, Sheaffer and Reiter 1985). Such shifts involve changes in the seasonal variation in intensity and position of the mid-latitude jet and the subtropical highs. Such changes significantly affect important abiotic controls over population, community, and ecosystem processes, such as the magnitude and timing of frosts and early growing season precipitation.

ECOLOGICAL SIGNIFICANCE

Identification of ecological responses to observed climatic variations is generally limited by a paucity of long-term biological data. However, some conclusions can be drawn based on available observations and modeling studies.

Interannual Variability

Net primary production of the shortgrass grasslands is strongly influenced by interannual fluctuations in precipitation (Lauenroth 1979). Lauenroth et al. (in preparation) compared field estimates of annual aboveground biomass production and annual precipitation at the CPER from 1941 to 1987. These data show that an extremely dry year reduces production for that and several years following. This suggests that dry episodes result in a reduction in the number of aboveground active meristems, constraining aboveground production in subsequent years, and cause belowground dieback, reducing the plants' ability to acquire water also in ensuing years (Webb et al. 1978).

Interannual variation in biomass development in the steppe is also influenced by the timing and amount of precipitation within the growing season. Seasonal dynamics of aboveground photosynthetically-active biomass can be inferred from satellite-based observations, such as the normalized-difference vegetation index (NDVI) (Goward et al. 1985, Justice et al. 1985). NDVI is derived from data from the Advanced Very High Resolution Radiometer (AVHRR) on NOAA series polar-orbiting satellites. Comparison of seasonal variation in NDVI and precipitation (Fig. 5) suggests that in 1983 and 1984 high March-May precipitation resulted in a strong June peak in green biomass. In contrast, in 1982, high mid- through late growing season precipitation corresponds to only a slight increase in late season biomass. These results suggest that early growing season precipitation is more crucial for the development of aboveground biomass than late season rainfall.

The frequency and timing of climatic events can also be critical for population and community level processes. For example, Lauenroth et al. (1987) showed that interannual variability in the occurrence of a combination of spring temperatures and precipitation events results in marked year-to-year variation in seedling establishment of blue grama (*Bouteloua gracilis*), with long-term consequences for community structure (Coffin and Lauenroth 1990).

These results demonstrate that to assess the impact of interannual climate variability on shortgrass ecosystems, between-year differences in climate need to be evaluated at seasonal and event levels as well as the annual level. While the resolution of an analysis must be tailored to response times of ecological processes of interest, the sensitivity of a particular process may not be limited to climate variability at a single scale because of interactions with biological processes operating at finer and coarser scales (Allen and Starr 1982, O'Neill et al. 1988). Such interactions generate time lags in the response of ecosystems to abiotic forcing.

Decadal and Long-Term Trends

Decadal and long-term climatic trends are expected to impact ecosystem dynamics through climatic controls

on rates of net primary production (NPP) and decomposition. Using a grassland ecosystem model (CENTURY, Parton et al. 1987), Kittel et al. (1990) tested the sensitivity of a Colorado shortgrass ecosystem to directional climatic change. In the model experiment, annual temperature was increased by 4.9°C (roughly twice the 1949-1987 trend observed at CPER) and annual precipitation increased by 46 mm, based on a CO₂-doubling climate change scenario (Hansen et al. 1984). After 50 years, simulated aboveground NPP increased by 40 percent. This response was driven by increased precipitation and increased availability of nitrogen that was released as soil organic matter decreased. The net loss of soil organic matter was due primarily to increased decomposition driven by the increase in temperature. These results illustrate the potential importance of climatic shifts to the shortgrass steppe and the role of system dynamics in determining the response to such change (Schimel et al. 1990).

Long-term climatic trends are also likely to influence grassland community structure by changing species establishment rates and shifting interspecific competitive interactions. Such structural changes would influence the impact of climate change on ecosystem processes.

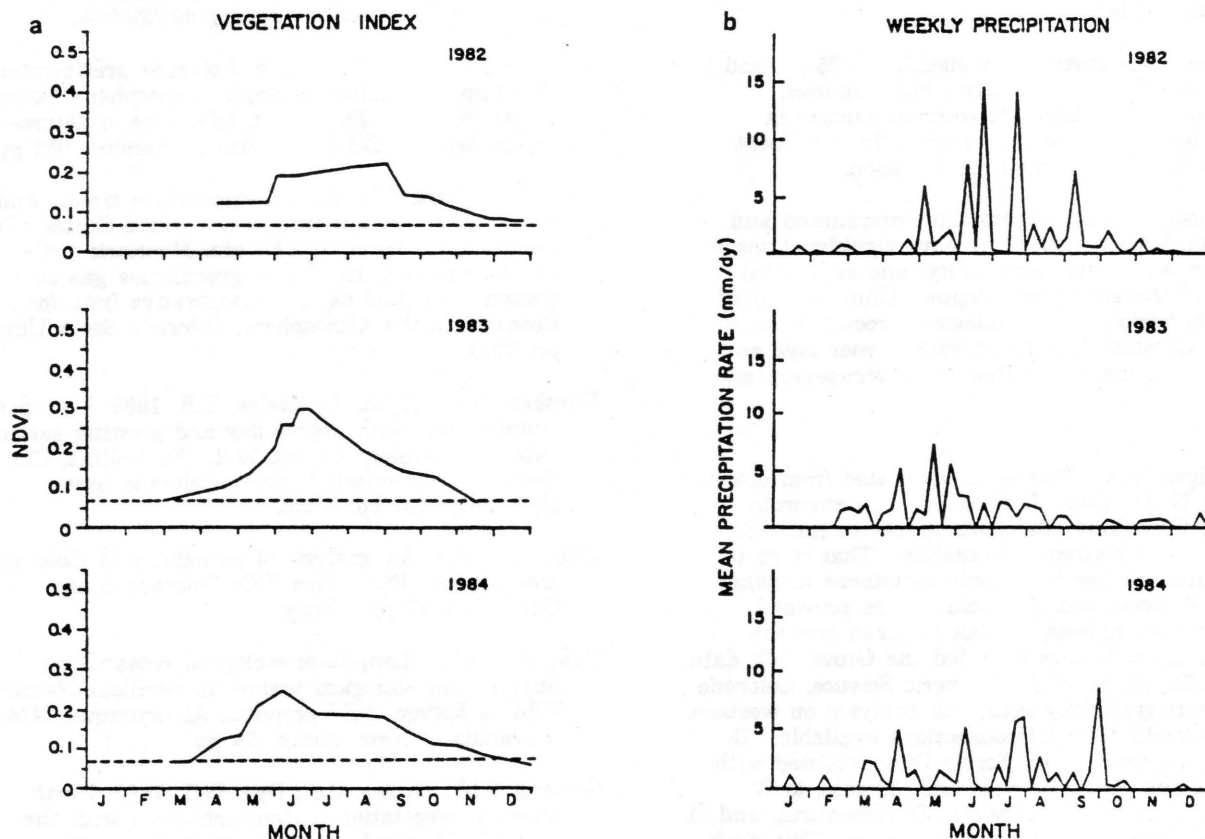


Figure 5.— (a) Envelope of weekly-composited normalized difference vegetation index, NDVI, for a 50x50 km region centered on the CPER in 1982, 1983, and 1984. (b) Weekly averages of CPER daily precipitation rate, mm/dy, for the same years. Dashed lines in (a) show a minimal threshold of 0.07 below which NDVI values are assumed to indicate no green biomass.

CONCLUSIONS

Climatic variability of the shortgrass steppe exhibits important characteristics that form a basis for evaluating its impacts on the grassland's ecological dynamics. These are:

(1) There is a natural break in the temporal dynamics of the steppe climate between annual and decadal+ scales. At both scales, variation in temperature and precipitation is generally $\frac{1}{2}$ cycle out of phase.

(2) At the annual scale, the phase relationship results in a predominance of cold-wet and warm-dry years, perhaps controlled by shifts in the position of the mid-latitude jet and subtropical highs.

(3) There is a positive correlation between annual precipitation and ENSO episodes. However, there are limits to the empirical detection of an ENSO signal because teleconnections are dynamic and may be inconsistent in this region.

(4) 20-50 y scale variations in the steppe temperatures match those in hemispheric and United States records and are of greater magnitude because of the region's continentality. There is shorter period variability in precipitation at the decadal scale, such that in some decades temperature and precipitation change in the same direction and in other decades in an opposite fashion.

(5) There is a statistically significant 75-y trend in temperature ($\sim +2^\circ\text{C}$), but known and unknown problems in station histories warrant caution in attaching importance to this trend. No significant trend was found for annual precipitation.

Ecological studies indicate that interannual and longer-term climate variability have significant consequences for ecosystem, community, and population dynamics in the shortgrass steppe. Climate-induced interannual variability in ecological processes can be complex, exhibiting significant year-to-year lags and sensitivity to climatic variation at within-season and event levels.

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