Climate of the Central Colorado Plateau, Utah and Arizona: Characterization and Recent Trends

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Abstract. The climate of the central portion of the Colorado Plateau is characterized using data from 27 climate stations. Mean annual temperature ranges from 16.9 °C at Lee's Ferry (978 m) to 4.4 °C at Bryce Canyon National Park (2412 m). Precipitation varies from 138-405 millimeters, and is weakly bimodal, with a strong late summer-early fall peak and a weaker late winter-early spring peak. Annual Thornthwaite potential evapotranspiration rates vary from 993 to 474 mm, and at all stations, rates exceed annual precipitation. Temperature, precipitation and evapotranspiration are all strongly controlled by elevation. Latitude and longitude have some additional effects on some variables. A strong southeast to northwest decline in temperature occurs across the study region. An analysis of trends among nine stations with good records reveals that annual minimum temperatures have increased significantly in most areas since the 1960's. Those stations that fail to show this trend do show significant increases in winter minimum temperatures. Maximum temperatures have not responded in the same manner, and some high elevation stations document declines in maximum temperatures. Longer-term records at Escalante and Lee's Ferry confirm the warming trend back to 1925 and 1944, respectively. Precipitation amounts have changed relatively little, although there is a weak trend towards increasing winter season precipitation. There is no evidence in the data for a strengthening of the summer monsoon, which is a prediction of some global warming models. Potential impacts of global warming scenarios and changes in extent and timing of precipitation on the vegetation and rare species of the Colorado Plateau are discussed.

Key words: central Colorado Plateau, climate, global warming, potential evapotranspiration, temperature, precipitation.

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INTRODUCTION

The Colorado Plateau consists of a series of plateaus formed from sedimentary rocks, with scattered laccolithic ranges such as the Henry Mountains, San Francisco Peaks, and Navajo Mountain. Elevation of the Plateau averages between 1500-1800 m, with several mountains exceeding 3300 m. The Colorado River has cut through the Plateau from northeast to southwest, and has carved a series of deep canyons ranging from 1400 m on the east edge in Colorado to 370 m on the west edge along the Grand Wash Cliffs in Arizona. Relatively little is known about the climate of the Plateau, particularly in the central region where population is sparse.

The central portion of the Colorado Plateau (Fig. 1) includes some of the lowest elevations on the Plateau. Along the Colorado River elevations range from 1219 m at Moab to 978 m at Lee's Ferry, a drop of only 241 m in 450 km. Along the river corridor, extensive mesas range in elevation from 1400-1800 m. The high Wastach and Kaibab Plateaus to the north, west and southwest produce an extensive rain shadow effect on this portion of the Plateau. Average annual rainfall throughout much of the region is < 200 mm, and to the north and east of the Henry Mountains, in the San Rafael and Green River deserts, is < 150 mm.

In this study, the climate of the central Colorado Plateau is characterized, using temperature, precipitation, and potential evapotranspiration, and their relationships with elevation. Because of the interest and speculation regarding the possible effects of global warming in the region, trends in temperature and precipitation are examined in detail for selected stations. The main objectives of this study are to (1) characterize the climate of the central Colorado Plateau, (2) provide regression equations for relationships between climate variables and elevation, and (3) document recent trends in climate.

BACKGROUND AND SETTING

The climate of the study area can be classified as temperate-arid (Walter 1985), with hot summers, extensive periods of frost in the winter, and low and variable precipitation. The average freeze-free season varies from > 200 days along the Colorado River to < 20 at the summit of the highest mountains (Ashcroft et al. 1992). Most of the study area experiences 120 or more frost-free days a year. During winter, the polar jet stream lies to the north of the study area, preventing most winter storms from reaching the Colorado Plateau (Mitchell 1976, Petersen 1994). Occasionally, the winter high-pressure ridge over the western U.S. moves westward into the Pacific Ocean. This allows the development of a low-pressure trough between the Sierra-Cascade Mountains and Rocky Mountains, bringing winter storms into the region. As the region warms in the spring, the polar jet stream moves northward, replaced by high pressure. When this high pressure begins to move north in late June or July, warm, wet air from the Gulf of Mexico moves northwest into the region, bringing the late summer monsoons. The average position of the northern edge of these monsoons bisects the Colorado Plateau from northeast to southwest (Petersen 1994; Fig. 1). This position varies from year to year, producing highlyvariable summer and early fall precipitation in the study area. In some years, late summer tropical hurricanes off Baja, California bring extensive rain into the region from the southwest up the Colorado River Valley (Petersen 1994).

The study area comprises roughly the west-central portion of the Plateau, ranging from 36-38° latitude and 110-112° longitude (Fig. 1). The study area lies along the eastern edge of the Wastach Plateau, and is bounded on the north by the Book Cliffs, the east by the high plateaus of Canyonlands and the La Sal Mountains, the southeast by the Abajo and Chuska Mountains, and the south by the high rim of Black Mesa. Southeastern Utah, including towns like Moab, Monticello, and Blanding, are not included because preliminary inspection of climate data revealed a significant increase in summer moisture in that area; this may be an orographic effect produced by the high mountain masses of the La Sal, Abajo, and southern Rocky Mountains, or a closer proximity to the Gulf of Mexico.

The vegetation of the study area consists primarily of a variety of arid and semiarid plant communities. Extensive areas below ca. 1500 m are dominated by either *Coleogyne ramosissima* (blackbrush) shrubland on shallow soils, or mosaics of shrubland and grassland types in sandy soils. Clay barrens are common and generally vegetated by ephemeral annual forbs or dwarf shrubland that is dominated by species of *Atriplex*. Above ca. 1500 m, extensive areas are dominated by stands of *Pinus edulis* (two-needled pinyon) and *Juniperus osteosperma* (Utah juniper). *Pinus ponderosa* (Ponderosa pine) woodlands occur at elevations above 2300 m on the higher mountains. Above ca. 2700 m, a mixed conifer forest can be found, dominated by *Pseudotsuga menziesii* (douglas fir), *Abies concolor* (white fir), and *Populus tremuloides* (aspen). Patches of *Abies bifolia* (Rocky Mountain subalpine fir) -- *Picea engelmannii* (Engelmann spruce) forest, subalpine meadows, and alpine tundra occur on the summits of the highest mountains above ca. 3000 m (Spence et al. 1995).

METHODS

The data set consists of monthly, yearly, and total record means for minimum, maximum, and annual temperature (T), and precipitation (PCP). Climate stations and basic data are listed in Table 1, along with information on duration of record and elevation. Figure 1 shows the area under consideration and the station locations. In all, 27 stations with records of 10 years or greater were utilized. Data were taken from the World Wide Web site maintained by the Desert Research Institute at the University of Nevada, Reno (www.wrcc.dri.edu/summary). Data was first inspected for gaps in records. If a particular monthly value was missing, the missing value was estimated as the mean monthly value of the previous year and following year. Data were then converted to metric values. Seasons were used for certain comparisons. Seasons are defined as follows: winter (December-February), spring (March-May), summer (June-August), and fall (September-November). Growing season (April-September) and winter season (October-March) were also compared. Latitude and longitude for each station were recorded, and two vectors were calculated using the pythagorean theorem, one from the southeast to northwest (135° to 315°), the

Table 1. Climate data for selected stations on the central Colorado Plateau. PCP=precipitation, Tann=annual mean temperature, and POTE=Thornthwaite potential evapotranspiration. The recording period and duration in years for each station is also listed.

Station	Elevation[1]	PCP[2]	Tann[3]	POTE[2]	Record	Yrs
(1) Page	1372	164	14.5	853	1959-1998	39
(2) Lee's Ferry	978	153	16.9	993	1916-1998	82
(3) Wahweap	1136	158	15.7	911	1967-1998	31
(4) Big Water	1250	171	14.7	859	1963-1998	35
(5) Escalante	1773	278	9.4	622	1901-1998	97
(6) Bullfrog	1165	152	15.2	899	1967-1998	31
(7) Hite	1058	144	16.2	941	1949-1962	13
(8) Hite Marina	137	136	16.0	942	1968-1978	10
(9) Hite Ranger Station	1220	214	15.5	919	1978-1998	20
(10) Hans Flat	2012	248	10.6	667	1981-1998	17
(11) Mexican Hat	1265	159	13.6	810	1948-1998	50
(12) Natural Bridges NM	1982	320	10.3	652	1965-1998	33
(13) Hanksville	1313	138	11.8	745	1948-1998	50
(14) Boulder	2034	272	9.3	614	1954-1998	44
(15) Sandy Ranch	1615	193	10.1	660	1963-1988	25
(16) Bryce Canyon Airport	2312	307	4.4	474	1948-1983	35
(17) Bryce Canyon NP	2412	405	5.1	484	1959-1998	39
(18) Henrieville	1832	264	9.2	605	1963-1979	16
(19) Monu. Valley Mission	1616	188	13.4	783	1961-1989	18
(20) Betatakin	2222	310	9.9	628	1948-1998	50
(21) Navajo Mountain	1835	233	9.8	635	1956-1975	19
(22) Capitol Reef NP	1679	193	12.1	731	1967-1998	31
(23) Fruita	1677	174	11.7	711	1948-1967	19
(24) CANY-Needles	1536	214	11.8	727	1965-1998	33
(25) CANY-Neck	1808	231	11.4	713	1965-1998	33
(26) Kayenta	1735	195	11.5	698	1915-1978	63
(27) Green River	1241	159	11.4	773	1893-1998	105

[1] Elevation in meters
[2] Precipitation and POTE in millimeters
[3] Temperature in °C

second from southwest to northeast (225° to 45°). The position of each station was determined along these two vectors, which roughly correspond to Gulf of California and Gulf of Mexico air masses and storm tracks. After the effects of elevation were removed, a series of regressions were run among latitude, longitude, two vectors 45° off the vertical-horizontal coordinates, and climate variable residuals.

Potential evapotranspiration (POTE) rates were calculated for each station. POTE determines the potential annual loss of water for a region from evaporation and plant transpiration. Thornthwaite's POTE was used because it is widely applied in North America, and its weaknesses and strengths are well known. The principal

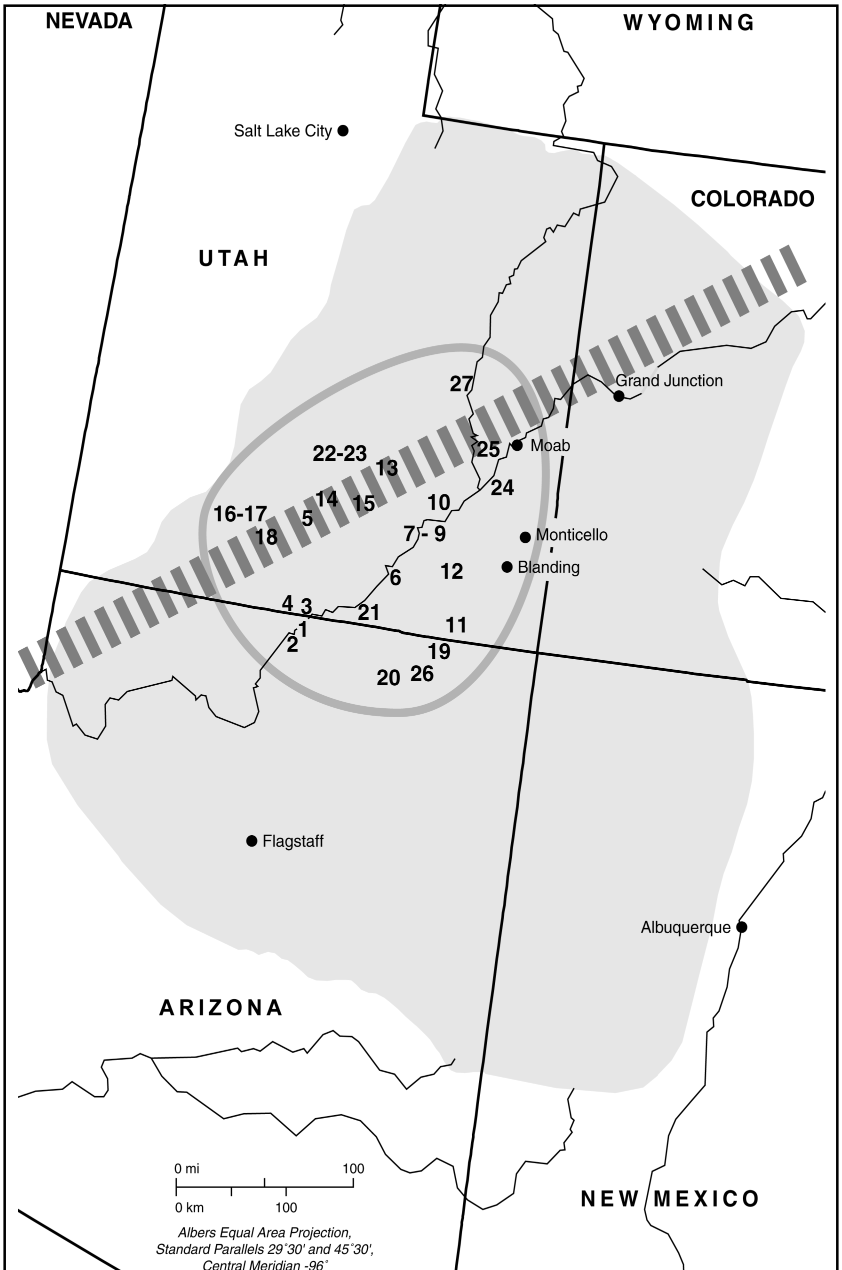

Figure 1. The Colorado Plateau, outlined in gray. Climate stations within the study area, encompassed in dark grey circle, are numbered (see Table 1). The heavy, dashed line represents the approximate boundary of regional air masses and the average northern limit of the summer monsoon season in the region (from Mitchell 1976, Petersen 1994).

weakness is that it tends to underestimate values in extremely arid regions. Thornthwaite's POTE (e) is calculated as:

$$e = 1.8(10t/I)a \qquad (1)$$

where: a = a constant,
t = monthly mean temperature in °C, and
I = annual temperature index obtained by summing the monthly values.

An assumption was made that climate variable means and variances were stationary throughout the duration of each station's record. This may not be the case, particularly for stations with long term records (e.g., Escalante, 98 years). Generally, this is a reasonable assumption (Rowlands 1993), particularly given the relatively short period of time under consideration (e.g., 30-50 years).

For analysis of trends in climate variables, a subset of nine of the 27 stations were selected. These were selected because of relatively complete records back to 1966, and because they represent an elevational gradient. This elevational gradient ranges from 978 m at Lee's Ferry to 2412 m at Bryce Canyon National Park. These nine stations were analyzed in relation to three T and three PCP variables. Trends were examined for the period 1966-1998 (33 years) using linear regression. For those stations with longer records, a second set of analyses was completed for the duration of each record.

RESULTS

Characterization

Summary climate data can be found in Table 1. Mean annual temperature (T) varies from a high of 16.9° C at Lee's Ferry to 4.4° C at Bryce Canyon Airport. Precipitation (PCP) is generally low at most stations, ranging from 136 mm at the Hite Marina to 405 mm at Bryce Canyon National Park. Because of the generally low PCP and hot summers, POTE rates are relatively high, ranging from 993 mm at Lee's Ferry to 474 mm at Bryce Canyon Airport. POTE exceeds PCP for all stations. Even at the highest elevations around Bryce Canyon National Park (2300-2400 m), POTE exceeds PCP, on average, seven months of the year. For all stations, however, winter season (December-February) PCP exceeds POTE.

There is strong seasonal control for all T and PCP variables. A breakdown of PCP by season shows that, for most stations, it peaks in fall (September-November). For all stations, 30% of summed yearly PCP occurs in fall, followed by 27% in summer. Winter and spring are somewhat lower, with 22% and 21%, respectively. A weakly bimodal pattern occurs for most stations, with a late summer-early fall peak, and a second smaller peak in late winter. The driest months of the year tend to be May and June, and the wettest months July and August. At intervals of every two-three years, September and October tend to have the heaviest PCP.

Climate diagrams for three stations, Page (1372 m), Escalante (1773 m), and Bryce Canyon National Park (2412 m) are depicted in Figure 2.

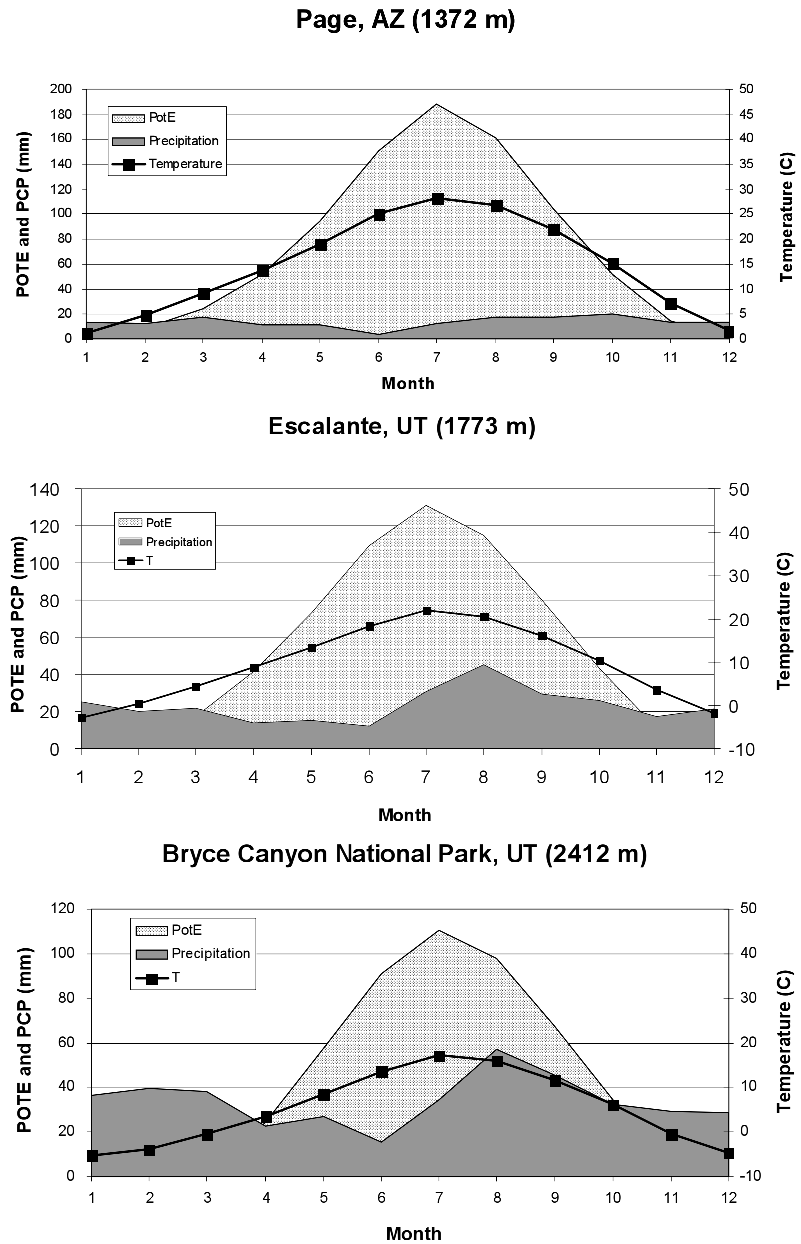

Figure 2. Simplified climate diagrams plotting mean monthly temperature (°C), mean precipitation (mm), and potential evapotranspiration rates for three climate stations on the central Colorado Plateau. The year starts in January (month 1) and goes to December (month 12). **a**. Page, Arizona (1372 m); **b**. Escalante, Utah (1773 m); **c**. Bryce Canyon National Park, Utah (2412 m).

Elevational Relationships

All climate variables are strongly controlled by elevation. The regression equations for PCP, annual T, and POTE are:

$$\text{Precipitation (mm)} = 0.1498 * \text{elevation in meters} - 25.7 \ (r^2=0.802) \quad (2)$$
$$\text{Annual T } (^\circ C) = -0.007 * \text{elevation in meters} + 23.168 \ (r^2=0.817) \quad (3)$$
$$\text{POTE (mm)} = -0.3148 * \text{elevation in meters} + 1244.5 \ (r^2=0.847) \quad (4)$$

Figure 3 shows the relationship among elevation, PCP, and POTE. As elevation increases, PCP increases and POTE decreases in a linear manner. The point at which the two lines intersect is known as the arid-humid boundary, where the PCP/POTE ratio is one. On the central Colorado Plateau, this boundary, based on where the two lines intersect in Figure 3, is estimated to lie at ca. 2730 m.

The relationship among annual maximum and minimum T, and elevation is similar, with T decreasing as elevation increases. All three curves are essentially identical, with the same slopes. The regression equations for maximum and minimum annual T are:

$$\text{Maximum annual T } (^\circ C) = -0.007 * \text{elevation in meters} + 30.817 \ (r^2=0.935) \quad (5)$$
$$\text{Minimum annual T } (^\circ C) = -0.007 * \text{elevation in meters} + 15.577 \ (r^2=0.596) \quad (6)$$

The relationship between annual minimum T and elevation is much weaker than that for annual and maximum T. This may result from influences by local topographic factors, such as depressions or valleys, that can cause winter temperature inversions. The adiabatic lapse rate, using mean annual T, is -0.70° C for each 100-meter increase in elevation.

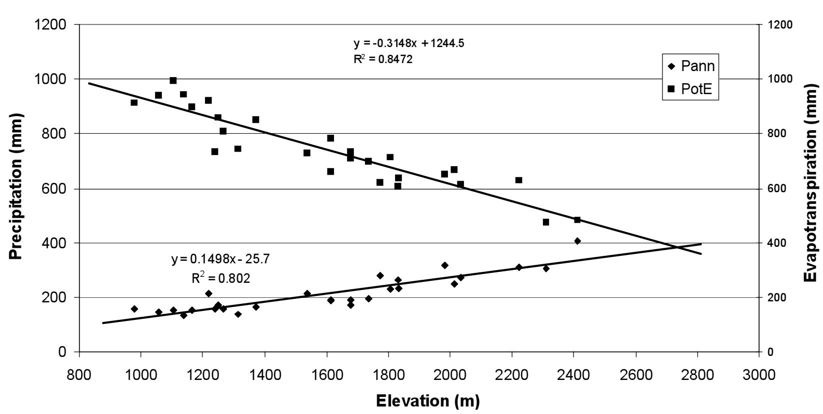

Figure 3. The relationship among precipitation (PCP), potential evapotranspiration (POTE), and elevation on the central Colorado Plateau. The regression curves, regression equations, and variance are noted for the two curves.

Summer PCP increases more rapidly with elevation than winter PCP, although the differences are rather slight (winter PCP regression slope = 0.038, summer PCP slope = 0.047). PCP increases at almost the same rate for both growing (April-September) and winter (October-March) seasons (growing season regression slope = 0.076, winter season slope = 0.074).

Geographic Relationships

Regression analysis indicates that elevation shows the strongest relationship with climate variables (Table 2). Regressing the residuals against latitude shows a trend of increasing winter PCP at higher latitudes, as one would expect. Winter PCP declines along a southwest to northeast vector in the study area. Growing season PCP shows a weak relationship with longitude, decreasing from east to west. Spring PCP exhibits a weak southeast to northwest increase.

All three T residuals show some relationships with geographic position, including both latitude and the SE to NW vector (Table 2). Both annual and maximum T

Table 2. Summary of linear regressions of climate residuals after the effects of elevation are removed against latitude, longitude, and two 45° vectors, a southeast to northwest vector, and a southwest to northeast vector. The arrows indicate the direction of the trends. As the vector value increases northward (↑) the value of the climate residual either increases (↑) or decreases (↓) in value. The results of the regression are also displayed (ns=not significant, *P*>0.15).

	Latitude	Longitude	SE→NW	SW→NE
Precipitation				
Annual	ns	ns	ns	ns
Growing Season	ns	p=0.154	ns	ns
Vector/PCP		↑/↓		
Winter Season	ns	ns	ns	ns
Winter	P=0.025	ns	ns	p=0.038
Vector/PCP	↑/↑			↑/↓
Spring	ns	ns	p=0.102	ns
Vector/PCP			↑/↑	
Summer	ns	ns	ns	ns
Fall	ns	ns	ns	ns
Temperature				
Annual	p=0.034	ns	p=0.029	ns
Vector/T	↑/↓		↑/↓	
Maximum	p=0.001	ns	p=0.020	ns
Vector/T	↑/↓		↑/↓	
Minimum	ns	ns	p=0.070	ns
Vector/T			↑/↓	
POTE	p=0.022	ns	ns	ns
Vector/POTE	↑/↓			

decline as latitude increases, as expected, but minimum T does not change along this gradient. All three T variables exhibit significant declines along the SE to NW vector.

Climate Trends

Regression analysis reveals numerous significant trends in T variables for most stations (Table 3). With few exceptions, T has increased over the last 33 years. Many of these increases are statistically significant. For minimum T, all stations show either an increase, or no trend. For those stations showing this trend, the change in minimum T varies from approximately 0.5 to 1.9^{o} C, depending on the station. Minimum T at Wahweap, on Lake Powell, has not changed in the last 33 years. However, January mean minimum T at Wahweap has shown strong increases ($p=0.020$). The largest increases in minimum T since 1966 have been at Page, the CANY-Needles, and Escalante. The smallest changes have been at Lee's Ferry, Wahweap, and Bryce Canyon National Park. Although there is only a weak, nonsignificant trend towards increasing minimum T since 1966 at Lee's Ferry, a significant increase has occurred ($p=0.050$) since 1944 (there are numerous gaps prior to this year). Only the two highest elevation stations, Bryce Canyon National Park and Betatakin, show weak increases or no trends in minimum T. Annual mean T parallels minimum T, with trends in the same direction. However, maximum T has decreased at two high-elevation stations since 1966, Natural Bridges National Monument and Bryce Canyon National Park. At the same time, however, maximum T has increased at Betatakin. Overall, maximum T shows fewer definite trends compared with annual and minimum T.

PCP trends are more variable in the study area (Table 4). There is a weak trend towards increasing PCP among the nine stations. Five stations show increases in annual PCP, while the other four show no trend. Most of the increases in PCP are in the winter months rather than the summer months; few are significant.

Table 3. Mean temperature trends in the last 33 years (since 1966) at selected climate stations on the central Colorado Plateau. Trends ($p\leq0.25$) are indicated as either increasing (↑) or decreasing (↓) using regression. Significance of each regression is shown (ns=not significant, $p>0.25$, no trend (→)).

	Annual Mean		Annual Maximum		Annual Minimum	
Station	Trend	Significance	Trend	Significance	Trend	Significance
Lees Ferry	↑	p=0.226	↑	p=0.174	↑	p=0.256
Wahweap	→	ns	↑	p=0.156	→	ns
Mexican Hat	↑	p=0.017	↑	p=0.070	↑	p=0.033
Page	↑	p<0.001	↑	p=0.140	↑	p<0.001
Needles	↑	p=0.016	→	ns	↑	p=0.008
Escalante	↑	p=0.001	↑	p=0.054	↑	p<0.001
Natural Bridges	→	ns	↓	p<0.001	↑	p=0.002
Betatakin	↑	p=0.089	↑	p=0.008	→	ns
Bryce Canyon	→	ns	↓	p=0.043	↑	p=0.118

Table 4. Mean precipitation trends in the last 33 years (since 1966) at selected climate stations on the central Colorado Plateau. Trends ($p \leq 0.25$) are indicated as either increasing (↑) or decreasing (↓) using regression. Significance of each regression is shown (ns=not significant, $p>0.25$, no trend (→)).

	Annual		Winter Season		Growing Season	
Station	Trend	Significance	Trend	Significance	Trend	Significance
Lees Ferry	↑	p=0.124	↑	p=0.198	→	ns
Wahweap	↑	p=0.111	↑	p=0.124	→	ns
Mexican Hat	→	ns	→	ns	→	ns
Page	↑	p=0.165	→	ns	↑	p=0.028
Needles	→	ns	→	ns	→	ns
Escalante	→	ns	→	ns	→	ns
Natural Bridges	→	ns	→	ns	→	ns
Betatakin	↑	p=0.105	↑	p=0.174	→	ns
Bryce Canyon	↑	p=0.028	↑	p=0.071	→	ns

Four stations have longer records that are fairly complete: Lee's Ferry, Escalante, Mexican Hat, and Betatakin. Table 5 displays the results of linear regression of climate variables over time for these four stations. For Lee's Ferry, the long-term record reveals a highly-significant increase in minimum T since 1944, but no changes in annual or maximum T. The trend towards increasing winter season PCP, since 1966, becomes significant when extended back to 1944 (Fig. 4). For Mexican Hat,

Table 5. Mean temperature and precipitation trends for four stations with long-term records on the central Colorado Plateau. Trends ($P \leq 0.25$) are indicated as either increasing (↑) or decreasing (↓) using regression. Significance of each regression is shown (ns=not significant, $P>0.25$, no trend (→)).

	TEMPERATURE					
	Annual Mean		Annual Maximum		Annual Minimum	
Station	Trend	Significance	Trend	Significance	Trend	Significance
Lees Ferry[1]	→	ns	→	ns	↑	*P*=0.054
Mexican Hat[2]	↓	*P*=0.142	↓	*P*=0.055	→	ns
Escalante[3]	↑	*P*<0.0001	↑	*P*<0.0001	↑	*P*<0.0001
Betatakin[4]	→	ns	↑	*P*=0.174	↓	*P*=0.099
	PRECIPITATION					
	Annual		Growing Season		Winter Season	
Station	Trend	Significance	Trend	Significance	Trend	Significance
Lees Ferry[1]	→	ns	→	ns	↑	*P*=0.072
Mexican Hat[2]	↑	*P*=0.061	→	ns	↑	*P*=0.038
Escalante[3]	↓	*P*=0.009	↓	*P*=0.005	→	ns
Betatakin[4]	↑	*P*=0.065	→	ns	↑	*P*=0.079

[1] Years 1944-1998; [2] Years 1949-1998; [3] Years 1925-1998; [4] Years 1951-1998

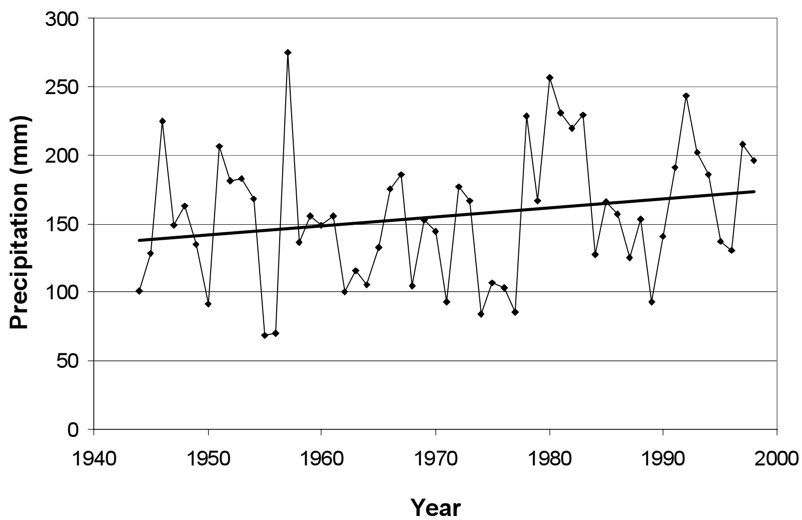

Figure 4. Mean annual precipitation in millimeters for Lee's Ferry, Arizona, between 1944-1998. The linear regression curve is also displayed (slope=0.65).

extending the record back to 1951 reveals a slight cooling trend overall and significant increases in winter PCP. The longest record, Escalante, reveals a highly-significant increase in all T variables since 1925 (Fig. 5), while at the same time PCP has decreased significantly during the growing season (April-September). Finally, T at Betatakin shows an unusual trend of decreasing minimum T and slightly increasing maximum T. Winter season PCP has increased significantly since 1951.

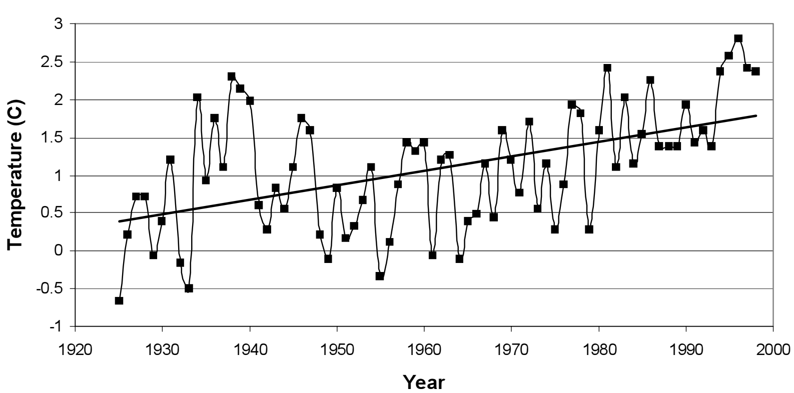

Figure 5. Mean annual minimum temperature in °C for Escalante, Utah, between 1925-1998. The linear regression curve is also displayed (slope=0.02).

Changes in both T and PCP will affect POTE rates. Combining the general trend towards increasing temperature, with no or minor increases in PCP, POTE rates will increase in the study area. Figure 6 plots current POTE rate curves against elevation for the 27 stations, and future conditions based on a 3° C increase in annual T with no changes in PCP. The regression curves show that POTE + 3° C does not increase uniformly across the elevational gradient. The slope of the regression line steepens as T increases. POTE increases as much as 15% at some stations under the warming scenario; for example, POTE at Lee's Ferry increases from 993 mm to 1136 mm. By comparison, the current POTE rate at Tucson in the Sonoran Desert is 1100 mm.

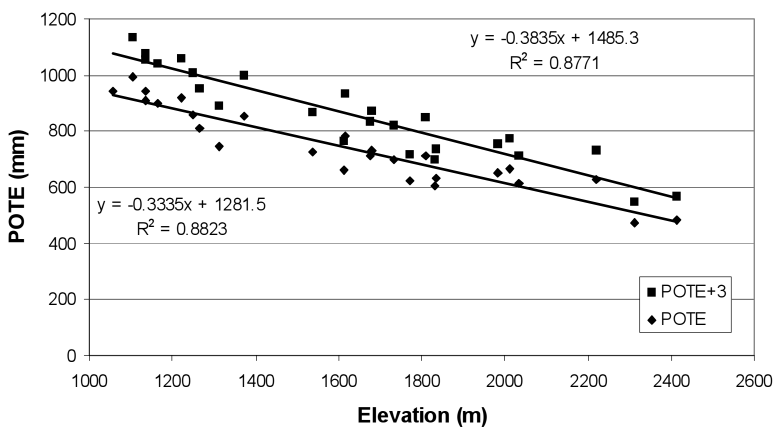

Figure 6. The relationship between current evapotranspiration rates (POTE) in millimeters and potential POTE rates with a 3° C increase in mean annual temperature is plotted against elevation for the central Colorado Plateau. The regression curves and equations for the two relationships are also displayed.

DISCUSSION AND CONCLUSIONS

Climate

This study has presented an analysis of the climate of the central Colorado Plateau, and has examined recent trends in precipitation and temperature for selected climate stations. The study area comprises a relatively uniform climate region based on an analysis of geographic variables. Other than expected relationships between temperature and latitude, there are few changes in climate across the study area. The principal exception to this is a significant southeast to northwest decline in temperature. This may reflect the change across the boundary of the two air masses that separate the southern and eastern portions of the Colorado Plateau from the northern and western portions (Mitchell 1976). This boundary is much broader than implied by Figure 1, as its position shifts along this vector from year to year.

Figures 4 and 5 illustrate, at single stations, the extremely high year to year variability in temperature and precipitation for all stations in the region. The Lee's Ferry precipitation record reveals a cycle of high precipitation episodes followed by low periods at ca. 10-year intervals since 1944. This pattern is similar at other stations, with changes between high and low precipitation at cycles of ca. every 8-12 years. The pattern for temperature is somewhat more variable, but again, a strong cyclic pattern can be discerned with climate records that have been analyzed in detail. This variability is typical of arid climates throughout the world (Evenari et al. 1985). Coefficients of variation are high for most stations, ranging from 20-50% for climate variables.

Two principal global circulation models are the Goddard Institute for Space Science (GISS) and the Geophysical Fluid Dynamics Laboratory (GFDL). With a predicted doubling in CO_2 content, the GISS model predicts a 4.7° C increase and an 8% precipitation increase in the western U.S. (Hansen et al. 1988). For the GFDL model, the comparable predictions are 4.2° C and 30% increase (Manabe and Wetherald 1987). Both are in agreement that much of the precipitation increase is likely to result from a strengthening of the summer monsoon rather than increases in winter precipitation. More recently, two other models, the Hadley Centre and the Canadian Climate Centre models, have been analyzed with respect to the western U.S. (NAST 2000). The Canadian model predicts larger increases in temperature (4.5-6.0° C), while the Hadley model is similar to the GFDL and GISS models. Both models also predict increases in precipitation of 25-50%, but differ from the GISS and GFDL models in that the increases are predicted to be in winter precipitation rather than summer precipitation.

The climate data suggest two principal trends in the last 30-40 years in the study area: (1) significantly increasing minimum temperatures, and (2) slight increases in winter precipitation. The first trend is consistent with all GCM models, while the second is consistent with predictions of the Hadley and Canadian models, but not with predictions of the GISS and GFDL models. For the central Colorado Plateau, there is no evidence for a strengthening of the summer monsoon since 1966. Escalante, at the northwestern edge of the study area, has experienced a significant decline in summer precipitation (Table 3). Mexican Hat, at the southeastern edge of the study area, where the effects of a strengthened monsoon should become apparent first in the region, has had no significant changes in summer precipitation since 1951 (Table 3).

These trends may reflect one of two possible climate scenarios: global warming or short-term (decadal) climatic oscillations and variability. During the last 100 years, there have been several episodes of warming and cooling. For example, the 1930's and 1940's were relatively warm in the study area, and were followed by relatively cool conditions in the 1960's and 1970's. Hence, the high temperatures recorded in the last 20 years may be part of this cyclic phenomenon. At present, the regional and global climate data are inadequate to clearly differentiate these two possibilities, at least at the regional level. Assuming that the trends presented in this study continue, and are early signs of global warming, a variety of hypotheses can be presented on the potential responses of vegetation as well as individual species.

Potential Effects on the Vegetation of the Colorado Plateau

One effect of increasing temperatures, with little or no increase in precipitation, is increased evapotranspiration rates over time. Although the effects of this are probably not discernable at present, due to the high variability in climate, this trend could have consequences in both the short- and long-term future of the Colorado Plateau vegetation. Recent studies in the shortgrass steppe of the Great Plains have shown that increases in minimum temperatures can be linked with changes in abundance and productivity of herbaceous species. Alward et al. (1999) showed that the dominant native warm-season C_4 grass, blue grama (*Bouteloua gracilis*), may have declined as a result of warming. Consequences of increased minimum temperatures include earlier spring growth of cool season C_3 species, including exotics, that can then deplete soil moisture prior to the green-up or germination of warm season species like blue grama. Competition for available nutrients may also change with increased growth of cool season species. Given the current trend of increasing winter precipitation discernable on the central Colorado Plateau, the most likely short-term effect on arid vegetation would be increases in cool-season herbaceous and woody species, and declines in warm season species, most of which are grasses. Long-term predictions for all models are that grasslands and woodlands on the Colorado Plateau will increase, while arid scrub vegetation will decrease substantially.

Effects in higher elevation, semi-arid and humid vegetation are less well understood. Increased evapotranspiration stress during the summer may cause declines in growth and recruitment at the lower limits of pinyon-juniper woodlands. Warmer temperatures, without an increase in the summer monsoonal precipitation, could reduce growth rates and seedling recruitment, and increase mortality in Ponderosa pine, a species that is closely tied to warm season precipitation. Over the long term, an increase in annual temperature of 3° C, without significant increases in precipitation, will raise the arid-humid boundary by approximately 90 m, from 2730 m to 2820 m (estimate based on intersection of POTE and precipitation lines for a 3° C increase scenario, not illustrated). This could significantly reduce the extent of high elevation coniferous forests, subalpine meadows, and alpine tundra, on the Colorado Plateau. However, this scenario seems unlikely based on the predictions of increased precipitation found in all models.

A combination of increases in temperature and precipitation is likely to have complex effects on the vegetation of the Colorado Plateau. Long-term shifts in vegetation boundaries and changes in temperature and precipitation may have significant impacts on populations of relict plant species and the many rare and often edaphically-restricted plant species that are characteristic of the Colorado Plateau (Spence 1995, TNC 1993). Also, the GCMs predict increased variability in precipitation, with dry and wet years alternating. This could change fire regimes, as fuel loads would build up during wet phases. If a drought period subsequently followed, there would be an increased chance of potentially destructive stand-replacing fires in the forest, woodland and grassland communities of the Colorado Plateau.

Although all the GCM models discussed predict increases in precipitation in the western U.S., the differences between them are relatively large. The consequences of an 8% increase in precipitation, compared with a 50% increase, are likely to be very different for arid and semi-arid vegetation in the region. Also important is the timing of these increases, because many dominant plant species on the Colorado Plateau, and elsewhere in the Southwest, differentially utilize warm-season and cool-season moisture (Ehleringer et al. 1991, Comstock and Ehleringer 1992). Although it will be some time before we better understand the potential changes in timing and extent of precipitation in the region brought about by global warming, enough climate data are currently available to model these potential future climates, based on global warming and different scenarios of precipitation changes.

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