CLIMATE CHANGE IN YELLOWSTONE NATIONAL PARK: IS THE DROUGHT-RELATED RISK OF WILDFIRES INCREASING?

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Abstract. The increased frequency of wildfires in the United States has become a common prediction associated with the build-up of greenhouse gases. In this investigation, variations in annual wildfire data in Yellowstone National Park are compared to variations in historical climate conditions for the area. Univariate and multivariate analytical techniques reveal that (a) summer temperatures in the Park are increasing, (b) January–June precipitation levels are decreasing, and (c) variations in burn area within the Park are significantly related to the observed variations in climate. Outputs from four different general circulation model simulations for $2 \times CO_2$ are included in the analyses; model predictions for increasing aridity in the Yellowstone Park area are generally in agreement with observed trends in the historical climate records.

1. Introduction

The 'Popular Vision' (Michaels, 1990) of the greenhouse effect incorporates a number of ecological catastrophes including, among others, a substantial rise in global temperature, melting of ice caps, a rise in sea level, increased frequency of drought, and a magnification in severe storm activity. In addition, literally hundreds of magazine and newspaper articles along with at least a dozen television documentaries and feature stories, have suggested that the greenhouse effect will increase the frequency of wildfires in the western United States. The outbreak of wildfires in this region during the summer of 1988, and in particular, the large fires in Yellowstone National Park in that same summer, occurred during a time when the greenhouse effect was literally front page news. The image of wildfires in the western United States, for any number of reasons, has become an integral part of the 'Popular Vision' of the greenhouse world.

While many of the greenhouse predictions have been debated widely in the climatological literature, little empirical research has been conducted on the relation between historical climate change and wildfire activity. Because of the uncertainties in the climate-wildfire linkage (Christensen *et al.*, 1989; Romme and Despain, 1989a, 1989b; Swetnam and Betancourt, 1990) and the uncertainties of climate model outputs at sub-continental scales (Dickinson, 1989), climatologists and ecologists tend to present predictions of increased wildfire activity cautiously

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in the scientific literature (e.g., Overpeck *et al.*, 1990; Schneider, 1990; Romme and Turner, 1991). Recognizing the need for more research in this area, the purpose of this paper is to (a) determine the relation between Yellowstone Park wildfires and local climate variations during the period of historical records, (b) examine trends in fire-related climate variables, and (c) compare observed trends in fire-related climate variables in the Yellowstone area to the predictions made by a number of climate models for the 2 × CO_2 condition.

2. Data

Three data bases for this study include (a) historical records of burn area in Yellowstone National Park, (b) climate records for the area, and (c) model predictions for the climatic changes in the Yellowstone Park area associated with a doubling of CO_2. Specifically, these data bases include:

(a) Burn area data were collected by the U.S. National Park Service at Yellowstone National Park and were compiled by Taylor (1969, 1974) for the period from Park establishment in 1872 to 1970. In the first few decades of Park history, Taylor (1969) found a number of years in which no specific references to fires were made (e.g., 1872–1878), which suggests that no large fires occurred in these years. Prior to 1930 most burns were located and recorded, but areas were not always accurately measured. Yellowstone National Park Research Office biologist Don Despain enhanced the quality of the data for this period by estimating burn areas in the recorded locations from even-age forest stands visible on air photos. Data for 1930–1970 are complete and are published in Taylor (1974), and data for 1971–1990 are from unpublished USNPS-Yellowstone files. In recognition of uncertainties in the earliest burn area data, the period of record used in this study is restricted to 1895–1990 (Table I).

Burn areas were influenced during part of the study period by fire suppression efforts. The effectiveness of fire fighting before the use of aircraft (i.e., prior to the mid-1940s) was probably minimal (Romme and Despain, 1989c). From 1972–1988, a natural fire policy was in effect; only those fires which were human-caused or which directly threatened developed areas were fought. The natural fire policy was abandoned on 21 July 1988, but the large number of fire starts occurring later that summer were fought with little resulting reduction of the 1988 burn area, which totalled nearly 400,000 ha (Schullery, 1989). Thus, fire suppression most likely reduced burn areas and partly obscured climate-fire relations in some years during the period of about 1945 to 1971 (Romme and Despain, 1989c) and in 1989. It is unlikely that climate-fire relations were completely masked by suppression efforts, because as shown by the example of 1988, even modern fire-fighting technology cannot effectively control fires in Yellowstone during climatic conditions highly conducive to burning.

Forest successional stage also partly determines the flammability of Yellowstone lodgepole-dominated forests. Fire regimes in these forests are characterized by

TABLE I: Burn area (hectares) in Yellowstone National Park*

1895	0	1920	0	1945	0	1970	0
1896	0	1921	32	1946	339	1971	27
1897	0	1922	40	1947	1	1972	0
1898	0	1923	0	1948	34	1973	0
1899	0	1924	1186	1949	1209	1974	336
1900	729	1925	0	1950	0	1975	0
1901	520	1926	0	1951	0	1976	627
1902	0	1927	0	1952	27	1977	4
1903	0	1928	0	1953	713	1978	2
1904	259	1929	162	1954	20	**1979**	**4260**
1905	0	1930	41	1955	12	1980	2
1906	0	**1931**	**8245**	1956	79	**1981**	**8342**
1907	0	1932	830	1957	10	1982	0
1908	0	1933	912	1958	30	1983	0
1909	0	1934	219	1959	7	1984	0
1910	**8957**	1935	130	1960	275	1985	13
1911	0	1936	9	1961	265	1986	0
1912	0	1937	1	1962	1	1987	393
1913	0	1938	0	1963	13	**1988**	**395570**
1914	729	1939	748	1964	6	1989	4
1915	0	**1940**	**8345**	1965	20	1990	100
1916	129	1941	0	1966	119		
1917	0	1942	440	1967	1		
1918	0	1943	221	1968	1		
1919	**2834**	1944	26	1969	2		

* Boldface type denotes years with large fires (>2500 ha) defined for the purposes of discriminant analysis.

stand-replacing fires which occur at relatively long intervals of 150 to 300 years or more, and flammability tends to increase as stands approach maturity over these intervals. The last series of extensive fires (comparable in scale to the 1988 burns) apparently occurred in the early to mid-1700s (Romme, 1982; Barrett and Arno, 1990). Thus, the area of mature forest may have increased over the study period, resulting in an increasing probability of large fires. However, many stands would have reached a mature and flammable state by the beginning of the study period, and the burn area data (Table I) do not show a simple increasing trend over the study period.

(b) Divisional mean monthly temperature and total monthly precipitation data are used to represent climatic conditions over the period 1895–1989. Virtually all of Yellowstone National Park is contained within the Yellowstone Drainage and Snake Drainage climate divisions of Wyoming. These climate divisions are dominated by harsh, mid-latitude, high elevation conditions with short cool summers and long, cold winters; precipitation occurs in all seasons although winter and spring produce highest precipitation totals (Dirks and Martner, 1982; Despain, 1987).

Because most fires of significant areal extent in the region occur between the months of July and September (Overpeck *et al.*, 1990), the divisional climate data were seasonalized into a concurrent fire season and a seasonal antecedent period. It is noteworthy that during the time when the natural fire policy was in effect (1972–1988), no significant fire (>0.1 ha) occurred prior to July 1, and no fires started later than September 25. Accordingly, the seasonal antecedent period extends from January–June, while the concurrent summertime fire season extends from July–September. The seasonalized climate data were then averaged for the two divisions; the climate data matrix extends from 1895–1989 and contains four variables including antecedent temperature and precipitation and summertime temperature and precipitation.

While one may have chosen various drought indices to relate climate to fire activity, temperature and precipitation are used in the analyses so that direct comparisons can be made between the historical analysis and the 2 × CO_2 predictions of various general circulation models. The multivariate scheme used in this study also allows temperature and precipitation to be weighted according to their importance to wildfire activity; drought indices use weightings for temperature and precipitation that may not be appropriate for the linkage to fires in the Park. And although wind speeds during the fire season can contribute significantly to the growth and maintenance of the wildfires (Schullery, 1989), no long-term comparable wind data exist for the study area.

(c) Predicted temperature and precipitation changes in the Yellowstone National Park area for 2 × CO_2 equilibrium climate are readily available from the Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), United Kingdom Meteorological Office (UKMO), and Oregon State University (OSU) climate models. Key references for the models used in this study include Hansen *et al.* (1983), Schlesinger and Jiang (1988), Wetherald and Manabe (1988), Manabe and Wetherald (1987), Schlesinger and Mitchell (1987), Mitchell (1988), and Mitchell *et al.* (1990). The predicted changes in mean monthly temperature are available on a monthly basis while the predicted changes in total monthly precipitation are available for three-month time spans. The simulation temperature outputs were seasonalized for comparisons with the selected January–June and July–September time periods. The three-month precipitation outputs forced an offset of one month yielding an antecedent season of December–May and a concurrent fire season of June–August. Given the relative stability of the models on a month-to-month basis, this one-month offset is not likely to have a substantial influence on the resultant comparisons. Ultimately, the model results were averaged to determine the mean expected change in temperature and precipitation for 2 × CO_2 (Table II).

3. Methods and Results

We used several univariate and multivariate statistical techniques to analyze the wildfire-climate relation in the Yellowstone Park area. We established the linear

TABLE II: Predicted climate changes in Yellowstone National Park for doubling of CO_2*

Season	Variable	UKMO	OSU	GFDL	GISS	Mean
Jan.–June	Temp. (°C)	+6.3	+2.5	+4.2	+4.9	+4.5
July–Sept.	Temp. (°C)	+6.6	+2.7	+5.6	+4.3	+4.8
Dec.–May	Precip. (%)	+27	+15	+17	+20	+20
June–Aug.	Precip. (%)	+24	+5	−15	+10	+6

* See text for description of models and their outputs.

time trend in each of the four climate variables using simple regression analysis with the year of record representing the independent variable. The statistical significance of the results was assessed by determining whether or not the slope, with its associated standard error, was different from zero (throughout the study, statistical significance is determined for the 0.99 level of confidence). Results from the regression analyses indicated a significant increase in the summer temperatures of 0.87 °C over the 95 years of record, and a significant decrease in seasonal antecedent precipitation of over 61 mm. The antecedent temperatures and the summer precipitation both increased, but not at a rate that was statistically significant (see Tables III and IV).

The climate data were orthogonally transformed using principal components analysis with a varimax rotation. We used the principal components analysis to reduce the original matrix of four columns (one for each variable) and 95 rows (one for each year) to a new matrix of 95 rows, but with fewer summary variables that capture much of the variance in the original matrix. For each computed component, we generated loadings that show the correlation between each of the original variables and the component. When the loadings are squared and summed, an eigenvalue is determined; when this eigenvalue is divided by the number of variables (four in this case), the portion of variance in the original matrix explained by the component is determined. The technique produces as many components as there are original variables, and the components combine to account for all of the variance in the original matrix. The component scores are standardized (mean = 0, standard deviation = 1) over the 95 cases, the components are orthogonal to one another (they are perfectly uncorrelated), and hopefully, a small number of these components will capture most of the variance in the original matrix.

When the principal components technique was applied to the matrix of temperature and precipitation variables, the first two components explained 67.1% of the variance in the original matrix. The loadings (Table III) show the first component has a large, positive loading on summer temperature and a large, negative loading on summer precipitation; the first component is related to summer drought. The second component has a large, positive loading on the antecedent temperature and a large, negative loading on antecedent precipitation; therefore, the second component is interpreted as an antecedent drought factor.

TABLE III: Descriptive statistics and principal component loadings for the Yellowstone National Park temperature and precipitation data

Climate variable	Mean	Standard deviation	Component loadings	
			Comp. # 1	Comp. # 2
Antec. temp. (°C)	−0.4	1.0	−0.10	0.81
Antec. precip. (mm)	269	50	−0.23	−0.74
Summer temp. (°C)	12.9	0.8	0.76	0.31
Summer precip. (mm)	103	36	−0.85	0.13

TABLE IV: Selected statistics for the Yellowstone National Park climate/wildfire relation

Variable	*r* (burn)	*r* (time)	ΔX (95 years)	ΔX ($2 \times CO_2$)
Antec. temp.	0.19	0.20	0.72	+4.46
Antec. precip.	−0.33	−0.35	−61.02	+53.54
Summer temp.	0.36	0.31	0.87	+4.80
Summer precip.	−0.54	0.08	9.73	+6.19
Component # 1	0.55	0.10	0.36	+2.96
Component # 2	0.24	0.38	1.32	+2.22
Discriminant score	−0.56	−0.34	−1.22	−3.88

Note: *r* (burn) is the Spearman rank-order correlation coefficient with the burn data (Table I); *r* (time) is the correlation coefficient with the year of record: ΔX (95 years) is the observed linear change over the 95-year study period; and ΔX ($2 \times CO_2$) is the predicted change given a doubling of CO_2.

A plot of the component # 1 scores (Figure 1) and results presented in Table IV indicate that the summer drought is increasing, but not at a significant rate. The component scores for the antecedent drought variable, however, reveal a statistically significant linear increase associated with both the decreasing precipitation levels and the increasing temperatures (Figure 2, Table IV). These analyses suggest that, for whatever reason, the antecedent-season climate conditions of the past century have become increasingly more arid in the area of Yellowstone National Park.

Due to the lack of normality in the burn-area data (the few large values highly skew the distribution), Spearman rank-order correlation coefficients were calculated between the fire data and each of the original four climate variables and the two principal components. Statistically significant results show burn area to be positively related to summer temperature and component # 1 (the summer drought factor) and negatively related to antecedent and summer precipitation. When squared and summed, the Spearman rank-order correlation coefficients associated with the two orthogonal components suggest that over 36% of the variance in the burn data can be explained by the climate variables selected in this study. The squared Spearman rank-order correlation coefficients show that most of this 36% explained variance is accounted for by component # 1; the summer conditions are

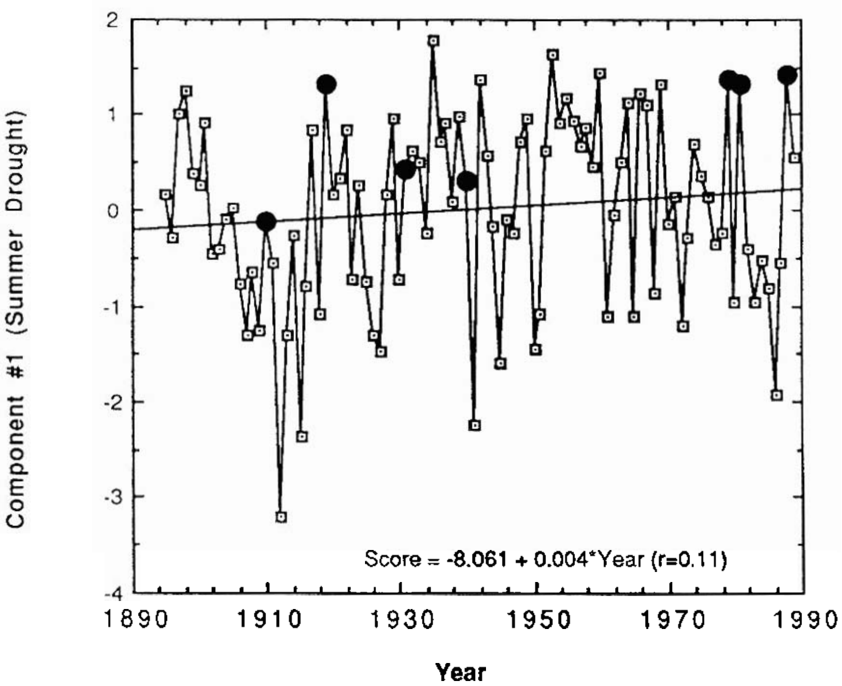

Fig. 1. Plot of the time series of component # 1 (summer drought) scores from 1895–1989. The closed circles represent years with large fires as defined in Table I.

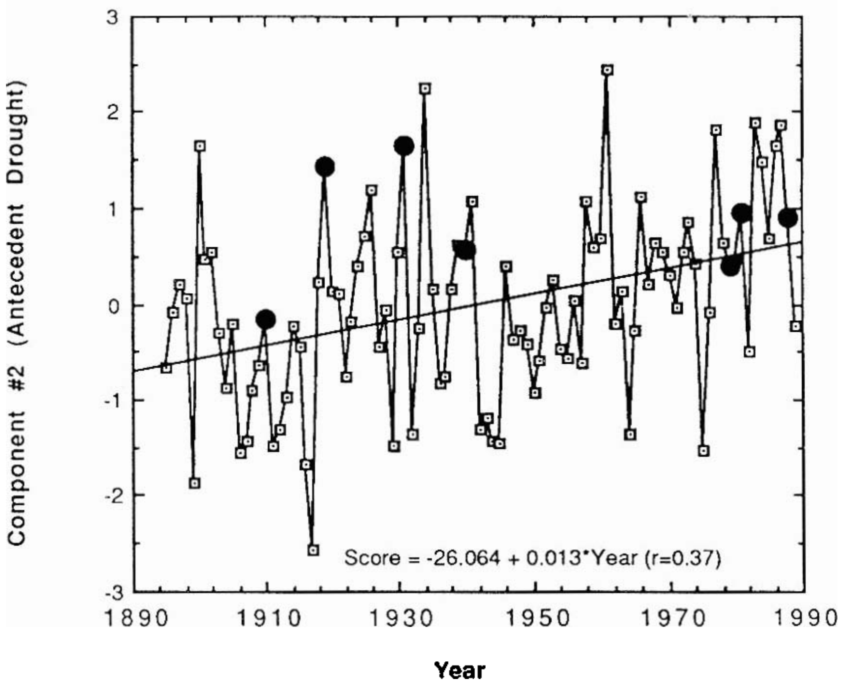

Fig. 2. Plot of the time series of component # 2 (antecedent drought) scores from 1895–1989. The closed circles represent years with large fires as defined in Table I.

obviously much more important than the antecedent season conditions in determining the fire potential.

Climatic conditions which are not well represented by temperature and precipitation may account for some of the unexplained variance. For example, although we were unable to include wind in this analysis, wind speed undoubtedly has major effects on fire behavior as well as drought severity. In addition, local and/or short-term anomalous conditions (e.g., severe local drought) may be poorly expressed in the time- and space-averaged monthly divisional data. Non-climatic influences on the burn area record, such as fire suppression and forest succession effects, probably complicate the climate-fire relations even further.

We next conducted discriminant analysis as an additional test of the relation between seasonal climate and wildfire activity in Yellowstone National Park. The burn data were sub-divided into two groups – one that contained the seven years with large fires (these seven years contribute over 97% of all burn area recorded over the study period) and a second that contained the remaining years with smaller fires, or no fires at all (Table I). Using only the two components, F_1 and F_2, as discriminating variables, we determined the discriminant function to be $d = -0.77F_1 - 0.73F_2$; a time series of discriminant scores, d, was generated from this relation (Figure 3). When the discriminant score is <-0.58, the discriminant model classifies the year in the group of years with large fires; discriminant scores >-0.58 are classified in the group of small fires. Six of the seven large-fire years were correctly reclassified using the discriminant model, and 67 of the 88 years with no or

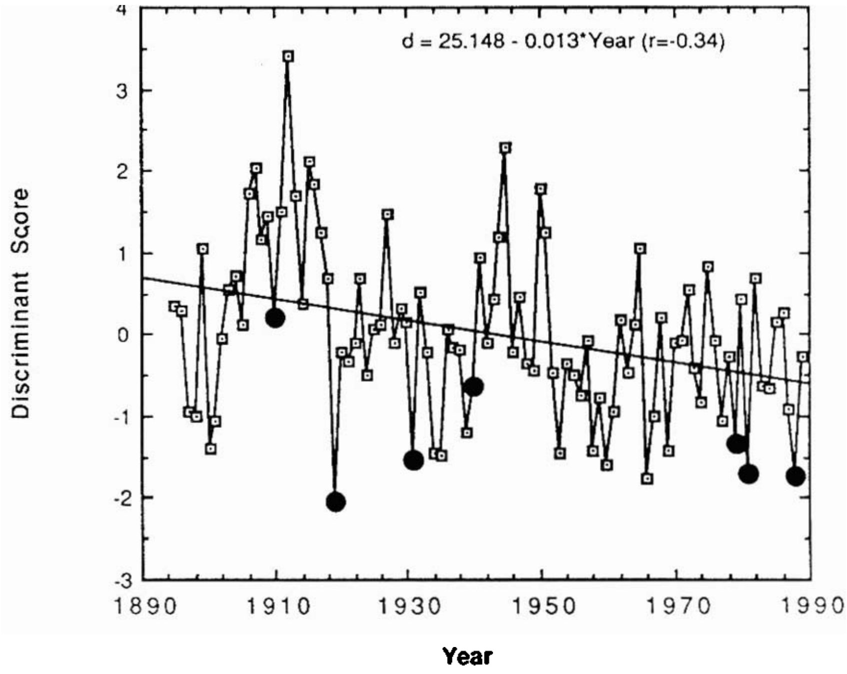

Fig. 3. Plot of discriminant scores over the 1895–1989 time period. The closed circles indicate years with large fires as defined in Table I.

small fires were correctly reclassified. The discriminant model correctly reclassified a total of 76.8% of all cases.

A Spearman rank-order correlation coefficient between the burn area and the discriminant scores equals −0.56, and is larger than any other correlation coefficient with the fire data. A plot of the discriminant scores (Figure 3) reveals a significant linear decrease over the 1895–1989 time period; this decrease suggests a trend toward conditions more conducive to wildfires over the 95-year study period.

Finally, we determined the component scores based on the mean model predictions for Yellowstone Park for a doubling of CO_2. Using the mean temperature and precipitation $2 \times CO_2$ predictions from the various models (Table II), we generated component scores from the original principal components analysis. The score for the first component (summer drought) for the $2 \times CO_2$ predictions is 2.96 while the score for the second component (antecedent drought) is 2.22. Therefore, the predicted discriminant score for the $2 \times CO_2$ condition is −3.87; this discriminant score is lower than any score recorded over the past century (Figure 3). Given that the discriminant scores have shown a linear decrease of 1.22 over the study period, the estimate of a 3.87 decrease with a doubling of CO_2 may be an overestimation, but nonetheless, reasonable.

4. Concluding Remarks

The results of this research show climate changes in the Yellowstone National Park area including (a) increasing temperatures in the fire season, (b) decreasing precipitation in the antecedent season, and (c) a trend to drought conditions in the antecedent season. Variations in burn-area data in the Park are statistically significantly linked to antecedent and summer season precipitation, summer temperature, and a component summarizing variations in summer drought conditions. Overall, there has been a significant trend over the century leading to a set of climatic conditions that favor the outbreak of wildfires.

However, the climatic trend in Yellowstone Park may or may not be considered a greenhouse signal. The numerical climate models generally predict increased aridity for the region (e.g., Rind *et al.*, 1989, 1990; Overpeck *et al.*, 1990; Mitchell *et al.*, 1990), and the trends in the historical data presented in this study are both consistent with expectations given the model predictions and consistent with climate trends found in other forested areas (e.g., Schindler *et al.*, 1990). Because the numerical climate models predict more rainfall in the area, the prediction of increased aridity comes largely from increased evapotranspiration associated with substantial predicted increases in local temperatures. The observed increasing aridity in Yellowstone Park appears to be related to the increase in temperature (generally consistent with the models), and a decrease in precipitation in the antecedent season (inconsistent with the models).

Nonetheless, the climate change towards increasing aridity, and therefore, a climate-induced increase in the fire hazard, is a very real feature in the historical records for the Yellowstone Park area. And while wildfire hazard in the Park is only partially related to climate (Arno, 1980; Lewin, 1988; Romme and Despain, 1989a, 1989b; Christensen *et al.*, 1989), the trend of the past century is significant and should be carefully monitored in the immediate future.

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