Regional relationships between climate and wildfire-burned area in the Interior West, USA

Brandon M. Collins, Philip N. Omi, and Phillip L. Chapman

Abstract: Recent studies have linked the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) with drought occurrence in the interior United States. This study evaluates the influence of AMO and PDO phases on interannual relationships between climate and wildfire-burned area during the 20th century. Palmer's Drought Severity Index (PDSI) is strongly related to burned area at both regional and subregional scales. In the southern Interior West, PDSI is most strongly related to yearly burned area during warm-phase AMO, while for the same period no significant relationships exist between PDSI and burned area in the central Interior West. During cool-phase PDO, interannual climate has little influence on burned area in either the northern or the central Interior West. The opposite is true for the southern Interior West and the eastern slope of the Colorado Rockies using the Southern Oscillation Index and PDSI, respectively. The western slope of the Colorado Rockies is the only climate division or region in which burned area is not related to preceding PDSI. During warm-phase PDO, current PDSI explains 67% of the interannual variance in burned area on the western slope. These regional and temporal differences are most likely governed by variations in fuel dynamics associated with dominant regional and subregional vegetation types.

Résumé : Des études récentes ont établi un lien entre l'oscillation multi-décennale de l'Atlantique (OMA), l'oscillation décennale du Pacifique (ODP) et les périodes de sécheresse dans les régions intérieures aux États-Unis. Cette étude évalue l'influence des phases de l'OMA et de l'ODP sur les relations entre le climat et les superficies brûlées annuellement pendant le 20e siècle. L'indice de sévérité de sécheresse de Palmer (ISSP) est étroitement relié aux superficies brûlées tant à l'échelle régionale que sub-régionale. Dans le sud de la région intérieure ouest, l'ISSP est le plus étroitement relié aux superficies brûlées durant la phase chaude de l'OMA alors qu'il n'y a pas de relation significative entre l'ISSP et les superficies brûlées dans le centre de la région intérieure ouest durant la même période. Pendant la phase froide de l'ODP, le climat a peu d'influence sur les superficies brûlées annuellement tant dans le nord que dans le centre de la région intérieure ouest. Le contraire est vrai pour le sud de la région intérieure ouest et le versant est des Rocheuses au Colorado en utilisant respectivement l'indice d'oscillation méridionale (IOM) et l'ISSP. Le versant ouest des Rocheuses au Colorado est la seule région climatique où les superficies brûlées ne sont pas reliées à l'ISSP antérieur. Durant la phase chaude de l'ODP, l'ISSP explique 67 % de la variation dans les superficies brûlées d'une année à l'autre sur le versant ouest. Ces différences régionales et temporelles sont fort probablement déterminées par les variations dans la dynamique des combustibles associés aux types de végétation qui dominent à l'échelle régionale et sub-régionale.

[Traduit par la Rédaction]

Introduction

Interannual fluctuations in the timing, severity, and extent of wildfires are strongly linked with climate. By altering moisture availability, climate directly influences how readily fuel (live and dead vegetation) burns. During drought conditions fuel moisture is low, consequently less heat is required to begin combustion (Rothermel 1972). As a result, widespread fire often coincides with drought (Renkin and Despain 1992). Climate can also indirectly influence the amount of fuel that can burn. Wetter conditions can increase the moisture available for plant growth, which ultimately increases fuel loads. Several tree-ring-based studies of multicentury fire patterns have shown that an antecedent increase in moisture, followed by drought, leads to extensive synchrony in fires (Swetnam and Betancourt 1998; Brown and Shepperd 2001; Stephens and Collins 2004). The effect of this wet–dry sequence is a net increase in fuel readily available for burning.

The connection between moisture availability and fire varies across vegetation types, depending on the fuel dynamics. In areas where fine fuels (grasses, forbs, light shrubs, etc.) are prevalent, fuel accumulation is responsive to antecedent climatic conditions (1–2 years previously). Thus, years with

Received 25 April 2005. Accepted 2 November 2005 Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 21 March 2005.

B.M. Collins[1,2] and P.N. Omi. Department of Forest, Rangeland, and Watershed Stewardship, 120 Forestry, Colorado State University, Fort Collins, CO 80523-1472, USA.
P.L. Chapman. Department of Statistics, 200 Statistics, Colorado State University, Fort Collins, CO 80523-1877, USA.

[1]Corresponding author (e-mail: bcollins@nature.berkeley.edu).
[2]Present address: Department of Environmental Science, Policy, and Management, 137 Mulford Hall, University of California, Berkeley, CA 94720-3114, USA.

 doi:10.1139/X05-264

Fig. 1. Climate regions for the Interior West and climate divisions for Colorado. Interior West climate regions are based on air-mass boundaries identified by Mitchell (1976). Colorado is not included in any of the Interior West climate regions. Colorado climate divisions are based on divisional climate data from the National Climatic Data Center, and represent major watershed boundaries in Colorado.

widespread fire tend to correspond to previously wet conditions in grassland-dominated areas, such as the Great Basin, and in the open pine forests that dominate much of the southwestern USA (Westerling et al. 2003). The importance of antecedent moisture declines in the closed-canopy mixed–conifer forests of the northern and to a lesser extent the central Interior West (Veblen et al. 2000; Sherriff et al. 2001; Littell 2002). In these areas, extensive fire is limited more by drought than by fine-fuel accumulation (Schoennagel et al. 2004).

In addition to linking fire directly with moisture availability, several studies have shown that synoptic-scale climatic processes relate to increased fire activity. In the southern and to a lesser extent the central Interior West, the El Niño – Southern Oscillation (ENSO) has been shown to relate to both yearly burned area and historically reconstructed fire events (Swetnam and Betancourt 1990; Swetnam and Betancourt 1998; Veblen et al. 2000). Additionally, recent work has shown that the Pacific Decadal Oscillation (PDO) can enhance the connection between widespread fire and ENSO in these regions (Westerling and Swetnam 2003). Both ENSO and PDO influence moisture availability by altering precipitation and temperature patterns throughout the Interior West (Cayan 1996; Mantua et al. 1997; Dettinger et al. 1998; McCabe and Dettinger 1999). Thus, the connection between these processes and fire is driven by fluctuations in moisture availability, which ultimately affect fuel moisture and fuel quantity.

Both ENSO and PDO cycle between warm (positive) and cool (negative) phases caused by episodic fluctuations in Pacific Ocean sea-surface temperatures (SSTs). In the Interior West the climatic effects of these warm and cool phases are reversed between the southern and northern regions. During warm-phase ENSO, or El Niño conditions, and warm-phase PDO, the southern Interior West experiences substantially wetter and slightly cooler winters, while in the northern Interior West, winters tend to be warmer and drier than usual (Cayan 1996; Western Regional Climate Center 1998). The effects of cool-phase ENSO, or La Niña conditions, and cool-phase PDO are opposite to those associated with the warm phases. The strength of ENSO-related climatic effects can depend on the PDO phase, which shifts at 20- to 30-year intervals (Brown and Comrie 2004). As a result, the effects of ENSO and PDO vary at annual to decadal time scales, but in general the effect of ENSO on climate is more consistent in the southern Interior West, while the effect of PDO is more consistent in the northern Interior West (Mantua et al. 1997).

The Atlantic Multidecadal Oscillation (AMO) is yet another influence on moisture availability that could be used to further elucidate our understanding of climate–fire relationships. Like ENSO and PDO, AMO alternates between warm and cool phases (based on SST anomalies in the North Atlantic Ocean) that differentially affect precipitation patterns. During warm-phase AMO much of the Interior West is drier, mainly because of below-average summer precipitation (Enfield et al. 2001). This warm-phase AMO may also create a synergistic effect when it co-occurs with cool-phase PDO, resulting in extensive long-term drought (Gray et al.

(–1 and –2 years) seasonal climate indices.

Cool-phase AMO (1965–1994)				Warm-phase PDO (1926–46, 1977–98)				Cool-phase PDO (1947–1976)			
–2	–1	0	R^2	–2	–1	0	R^2	–2	–1	0	R^2
		– –	0.44		++	– –	0.42 (0.46)				ns
			OLS		0.34		AR1				OLS
	++		0.35 (0.59)		++	(–)	0.35 (0.71)		(+)		0.10
	0.67		AR1		0.71		AR1				OLS
	++		0.33	(+)	++	–	0.38 (0.73)		+	– –	0.47
			OLS		0.79		AR1				OLS
			ns				ns				N.S.
			OLS				OLS				OLS
– –			0.27 (0.56)	–		–	0.16 (0.64)				ns
	0.58		AR1		0.67		AR1				OLS
– –	–		0.32 (0.45)	– –			0.21 (0.66)		(–)	++	0.35
	0.43		AR1		0.68		AR1				OLS
(+)			0.19		(–)		0.08				ns
			OLS				OLS				OLS
		++	0.22				ns				ns
			OLS	0.70	0.74		AR2				OLS
			ns			(–)	0.23				ns
			OLS						0.67		AR1

and winter (December, January, February) averages for both the Southern Oscillation Index (SOI) and the Pacific Decadal Oscillation (PDO) index. Positive for $p < 0.01$. Autocorrelation estimates for significant lag parameters are reported below directional relationship indicators, along with the final model type significant ($p < 0.05$). R^2 values reported are just regression-model R^2 values, with the total model R^2 value in parentheses. Total R^2 and regression R^2 values

values were as low as –4.6. The PDO and AMO indices are based on SSTs in the North Pacific Ocean and North Atlantic Ocean, respectively. However, they differ in that the PDO index is constructed from the leading principal component of monthly SST (Mantua et al. 1997), while the AMO index is the 10-year running mean of SST anomalies (Enfield et al. 2001). Monthly values of the PDO and AMO indices typically range from –3 to 3 and from –0.5 to 0.5, respectively. For both indices, positive values correspond to warm phases of oscillation, while negative values correspond to cool phases. PDSI is constructed using monthly precipitation and temperature and is a measure of moisture status over prolonged periods. PDSI accounts for precipitation, evapotranspiration, and soil moisture conditions (Palmer 1965; Rollins et al. 2002). PDSI values usually range from –6 to 6, with positive values corresponding to wetter conditions and negative values to drought conditions. For Interior West climate regions, we averaged annual statewide PDSI values for each state included in the climate region to obtain one PDSI time series for each region. For the Colorado climate divisions we used PDSI time series specific to each climate division. We obtained both statewide and divisional PDSI time series from the National Oceanic Atmospheric Administration (NOAA 2003*a*).

We used 3-month averages for the winter season (December, January, February) as yearly SOI (NOAA 2003*b*), PDO index (obtained from Mantua 2003), and AMO index (obtained from NOAA 2005) values. Relationships between climate and burned area were generally strongest with winter averages, relative to annual or summer averages, for all three indices. In addition, winter averages may be preferred over summer averages for forecasting fire-season potential. For PDSI, however, climate – burned area relationships were strongest with the averages for the summer season (June, July, August). Summer-season averages may be more optimal for studying fire–climate relationships because the summer PDSI captures the moisture availability prevailing during the Western fire season (Baisan and Swetnam 1990). We therefore only report results using summer PDSI, despite the loss in forecasting potential.

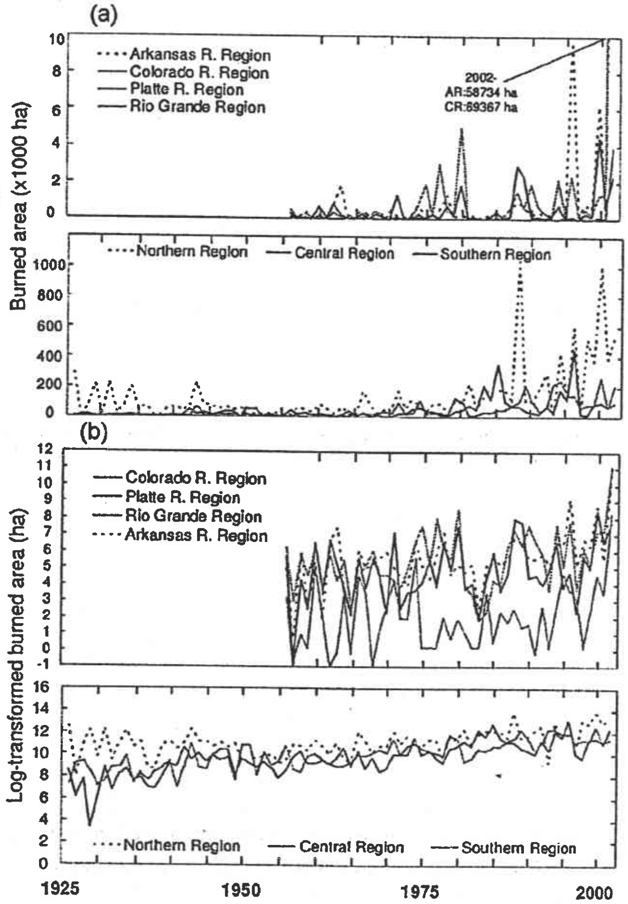
Statistical analyses

We analyzed relationships between yearly burned area and the different climate indices with lagged regression, using an autoregressive error model. The mathematical expression for this model is

$$[1] \qquad Y = \alpha + \beta_0 x_0 + \beta_{-1} x_{-1} + \beta_{-2} x_{-2} + \epsilon_t - \Phi_1 v_{t-1} - \Phi_2 v_{t-2}$$

where Y is the response in burned area, α is the intercept, x_0, x_{-1}, and x_{-2}, are contemporaneous and lagged (1 year and 2 year) values for a given climate index, ϵ_t is a normal random variable mean 0 and variance σ^2, and v_{t-1} and v_{t-2} are the autoregressive error terms. Balzter et al. (2005) found that a linear combination of climate indices adequately modeled burned area in central Siberia. Furthermore, results from regression models are simple to interpret and easily conveyed.

Fig. 2. (*a*) Yearly burned areas for Colorado climate divisions (above) and Interior West climate regions (below). (*b*) As above, but for log-transformed yearly burned areas.



Analysis was run using the Autoreg Procedure from the SAS® computer software package (SAS Institute Inc. 2003). This procedure adjusts for serial autocorrelation in the burned-area time-series data to account for lack of independence of the regression error terms. The error terms were assumed to have an autoregressive structure with up to two terms (Brockwell and Davis 2002). The outputs from the analysis provide slope estimates and p values for the main effects of the current and lagged indices on the regression of yearly burned area. Positive or negative relationships between yearly burned area and the contemporaneous values of the climate indices, along with values for each of the 2 years prior to all years in the burned-area time series, were determined using the slope estimates. Each slope is the estimated change in log burned area for a unit change in one lagged year of a particular index, holding the other lagged years for that index in the model constant. We used a backward selection, starting with lag –2 years, to eliminate lagged climate indices with $p > 0.10$. We chose to include lagged climate indices up to 2 years previously because incorporating lagged indices preceding 2 years previously may be outside the scope of current fire-management planning. Once a lagged index parameter was identified ($p = 0.10$), all parameters having shorter lags (–1 year, 0 years) were retained in the model. This is based on a hierarchical modeling procedure that was also used in eliminating autoregressive coefficients from the model (Brockwell and Davis 2002). The importance of individual lagged climate index parameters was judged by the p values associated with each parameter. The strength of the regression model for each region and climate-index combination was determined from the total proportion of the variance explained (R^2).

We performed this lagged regression analysis for five separate time periods to examine potential temporal variability in climate – burned area relationships associated with multidecadal PDO and AMO phase shifts. The complete burned-area time series (1926–2002) was separated into warm-phase AMO (1930–1964) and cool-phase AMO (1964–1994), as well as warm-phase PDO (1926–1946, 1977–1998) and cool-phase PDO (1947–1976) (Mantua 2000; Enfield et al. 2001). Because the burned-area time series available for the Colorado climate divisions was shorter, we only examined three different time periods: complete times series (1956–2002), warm-phase PDO (1977–1998), and cool-phase PDO (1956–1976).

Results

Interior West climate regions

Relationships between yearly burned area and summer PDSI are stronger than those with winter SOI, PDO index, and AMO index (AMO-index results are not reported because they lack significant relationships) (Table 2). Burned area for all three regions shows significantly positive relationships with preceding (–1 year lag) PDSI followed by significantly negative relationships with current (0 year lag) PDSI. With the exception of the central region, this pattern is consistent during both warm-phase AMO and warm-phase PDO. The strength of the relationships varies among the time periods we analyzed. The strongest PDSI – burned area connection for the southern Interior West is during warm-phase AMO, while for the northern and central regions it is cool-phase AMO and warm-phase PDO (Table 2). Additionally, cool-phase AMO is the only time period we analyzed in which current PDSI is not significantly related to burned area in the southern region. During cool-phase PDO, burned area in the central region shows a much weaker association with PDSI, while no significant relationship exists between PDSI and burned area for the northern region (Table 2).

During warm-phase AMO, both contemporaneous (positively associated) and antecedent (negatively associated) SOI are significantly related to burned area in the southern Interior West, while a weaker relationship exists with only antecedent (negatively associated) SOI during cool-phase AMO (Table 2). The same contrast is even more evident in the different PDO phases. During cool-phase PDO, antecedent and current SOI are significantly related to burned area, thus explaining a higher proportion of variance ($R^2 = 0.35$), while during warm-phase PDO, only antecedent SOI is significantly related to burned area, with a much lower associated variance explained ($R^2 = 0.21$). Burned area in the central region shows a significantly negative association with antecedent and current SOI. As with the southern region, neither the signal of antecedent and current SOI nor the strength of the

Table 3. Relationships between log-transformed annual burned area in Colorado climate divisions and contemporaneous (0) as well as lagged (–1 and –2 years) seasonal climate indices.

	Complete series (1956–2002)				Warm-phase PDO (1977–98)				Cool-phase PDO (1956–1976)			
Index and region	–2	–1	0	R^2	–2	–1	0	R^2	–2	–1	0	R^2
PDSI (June, July, Aug.)												
Arkansas R.		++	– –	0.44 (0.49)		(+)		0.18		++	– –	0.54
	0.31			AR2				OLS				OLS
Colorado R.			– –	0.46 (0.54)			– –	0.67				ns
	0.31			AR2				OLS				OLS
Platte R.		++	– –	0.31		+	–	0.26			(–)	0.18
				OLS				OLS				OLS
Rio Grande		++	–	0.21				ns		++	(– –)	0.45 (0.49)
				OLS				OLS	–0.61			AR2
SOI (Dec., Jan., Feb.)												
Arkansas R.				ns				ns				
				OLS				OLS				OLS
Colorado R.		(+)		0.09				ns				ns
				OLS				OLS				OLS
Platte R.	(–)		(+)	0.25 (0.29)				ns				ns
	0.34			AR2				OLS				OLS
Rio Grande				ns				ns			–	
				OLS				OLS				OLS
PDO (Dec., Jan., Feb.)												
Arkansas R.				ns				ns				ns
				OLS				OLS				OLS
Colorado R.				ns			(–)	0.14				ns
	0.35			AR2				OLS				OLS
Platte R.			++	0.15				ns		(+)	++	0.56 (0.60)
				OLS				OLS		–0.54		AR1
Rio Grande				ns				ns				ns
				OLS				OLS				OLS
AMO (Dec., Jan., Feb.)												
Arkansas R.	(–)		++	0.30 (0.37)	(–)		+	0.34		(–)	(+)	0.18
	0.31			AR2				OLS				OLS
Colorado R.			+	0.09 (0.25)				ns				ns
	0.39			AR2				OLS				OLS
Platte R.				ns	(–)			0.18				ns
				OLS				OLS				OLS
Rio Grande			+	0.09				ns		–		0.30 (0.36)
				OLS				OLS	–0.45			AR2

Note: The results are from an autoregressive error model using summer (June, July, August) averages for the Palmer Drought Severity Index (PDSI) and winter (December, January, February) averages for the Southern Oscillation Index (SOI), the Pacific Decadal Oscillation (PDO) index, and the Atlantic Multidecadal Oscillation (AMO) index. The direction and significance of relationships and R^2 values, as well as autocorrelation estimates and final model selection, are as described in Table 2.

relationships is consistent across the time periods we analyzed. The strongest connection between SOI and burned area exists during cool-phase AMO for the central region (Table 2).

Burned area in the northern region appears to be weakly related to PDO index. Positive relationships exist between burned area and antecedent (–2 year lag) PDO index for the complete time series, as well as during cool-phase AMO (Table 2). A stronger positive relationship between contemporaneous PDO index and burned area in the central region exists during cool-phase AMO. As with weak or non-existent relationships of PDSI and SOI with burned area in the northern and central regions during cool-phase PDO, no PDO index signal is evident during cool-phase PDO for any region (Table 2).

Colorado climate regions

Summer PDSI shows a strong negative relationship with current burned area for all Colorado climate divisions (Table 3). In addition, prior (–1 year lag) PDSI is positively related to burned area for all divisions except CR. These patterns are evident in the complete time series, as well as during cool-phase PDO. During warm-phase PDO, PDSI – burned area relationships were weaker or non-existent, with the exception of a strong negative relationship with current PDSI for CR (Table 3).

Relationships between winter SOI, PDO index, and AMO index are generally weaker and less consistent between climate divisions (Table 3). Current SOI and PDO index are both positively related to burned area in PL. This PDO index – burned area relationship is exceptionally strong during cool-phase PDO ($R^2 = 0.56$). Burned area in AR, CR, and RG shows a significantly positive association with current AMO index, which is evident for AR in all time periods analyzed and only evident for CR and RG when the complete time series is used (Table 3).

Discussion

Moisture availability clearly plays an important role in determining yearly wildfire extent. Positive associations between preceding PDSI and burned area suggest that short-term fuel accumulation is critical in leading to an increase in wildfire extent throughout the Interior West. This signal is evident in all three Interior West regions and is fairly consistent among the different time periods we analyzed. However, temporal variation in the strength of the PDSI signal indicates that AMO and PDO phases affect moisture availability – burned area relationships differentially across the Interior West.

The lack of significant contemporaneous PDSI and SOI signals during cool-phase AMO, along with the fact that PDSI – burned area relationships are weakest for this time period, suggests that climate is somewhat decoupled from burned area in the southern Interior West during cool-phase AMO. This may be due to an overall increase in live- and dead-fuel moisture caused by the extended period of increased summer, or monsoonal, precipitation associated with cool-phase AMO (Enfield et al. 2001). This is in contrast to the longer term drought conditions associated with warm-phase AMO, which would have an overall drying effect on fuels, especially coarser fuels (Renkin and Despain 1992; Haywood et al. 2004). The combination of decreased moisture content in coarser fuels and increased fine-fuel continuity resulting from enhanced fine-fuel production during an anomalously wet year (positive prior PDSI) may explain the strong link between climate and extensive fire during warm-phase AMO.

Stronger relationships of PDSI and SOI with burned area during cool-phase AMO in the central Interior West suggest that the prolonged period of increased summer precipitation intensifies the connection between climate and burned area. This opposite effect of AMO, in addition to the lack of a contemporaneous PDSI signal in all time periods, suggests that climatic influences on fuel dynamics in the central Interior West differ from those in the southern Interior West (Swetnam and Betancourt 1990). These differences are most likely explained by the greater proportion of "lighter" fuel (shrubs and grasses) in the central Interior West (Knapp 1995; Westerling et al. 2003). Consistent with the results from this study, both Knapp (1995) and Westerling et al. (2003) found that extensive burned area in the central Interior West was related to antecedent moisture availability, not current moisture availability. The authors of both studies explained that since this area experiences substantial moisture deficit in most years, it is the production of fine fuels (particularly annual grasses) associated with increased antecedent moisture conditions, rather than current drought, that leads to more widespread fire. Fine-fuel productivity can be further augmented by the long-term increase in summer moisture availability during cool-phase AMO, which would extend the growing season for grasses and some shrubs (Ehleringer et al. 1991; Knapp 1995; Dodd et al. 1998; Skinner et al. 2002). The combined effect of increased antecedent moisture availability at interannual time scales and increased moisture availability at interdecadal time scales drives fuel accumulation, which leads to stronger connections between climate and burned area in the central Interior West.

Knapp (1995) hypothesized that this relationship with antecedent moisture and not contemporaneous moisture may be due in part to the abundance of cheatgrass (*Bromus tectorum*) in the central Interior West (Humphrey and Schupp 2001). Since cheatgrass is an annual grass, it can take advantage of the increased moisture by producing more seed for future generations. Establishment of these future generations adds to the fuel load, creating a potential for an increase in area burned following a year of increased moisture availability (Knapp 1995). Addressing this hypothesis will most likely require finer spatial resolution than that of this study to separate out burned area of the forests from that of the lower elevation zones where cheatgrass is abundant.

The differential effect of PDO phases on the strength of PDSI – burned area relationships in the northern Interior West is much more pronounced than that of AMO phases. The lack of a significant PDSI signal during cool-phase PDO compared with the strong relationship with prior and current PDSI during warm-phase PDO suggests that the wintertime signature of PDO has a strong effect on climate–fire relationships (Cayan 1996). The fact that a similar pattern exists with PDO index – burned area relationships during cool- versus warm-phase PDO further supports this hypothesis. The extended period of generally cooler and wetter winters during cool-phase PDO may effectively reduce fuel flammability by increasing the moisture content in all fuel size classes, resulting in a weaker link between climate and burned area. The opposite is true during the drier and warmer winters associated with warm-phase PDO, resulting from the same effect on fuels described previously for warm-phase AMO in the southern Interior West. Apparently, the more summertime signature of AMO phases does not affect the strength of climate – burned area relationships as much as the wintertime signature of PDO (Cayan 1996; Enfield et al. 2001).

The phases of PDO also affect the signal and strength of SOI – burned area relationships in the southern Interior West. The strong positive relationship between contemporaneous SOI and burned area during cool-phase PDO is in contrast to the weaker but significantly negative lagged relationship with SOI during warm-phase PDO (Table 2). This essentially means that prior El Niño events tend to relate to more extensive fire during the wetter phase of PDO (warm phase in the southern Interior West), while current La Niña conditions lead to more extensive fire during the drier cool-phase PDO. One explanation for the differential effect of El

Niño and La Niña on burned area during warm- versus cool-phase PDO lies in the fact that ENSO may force PDO fluctuations (Newman et al. 2003). In other words, the phases of PDO may just be long-term expressions of ENSO, which would explain why the effect of El Niño (La Niña) events in the southern Interior West would be accentuated during warm (cool)-phase PDO (Brown and Comrie 2004). Thus, fuel accumulation associated with El Niño conditions may be intensified during warm-phase PDO, while the drying effect on fuels associated with La Niña conditions would be intensified during cool-phase PDO. As a result, burned area responds to opposite SOI signals in warm- versus cool-phase PDO.

The effect of PDO phases on climate – burned area relationships is noticeable at the subregional scale as well. During cool-phase PDO, the climate divisions on the eastern slope of the Colorado Rockies (AR and RG) show a strong wet to dry reversal in the PDSI signal that is much weaker or non-existent during warm-phase PDO. This reversal in moisture availability is evidence that fuel accumulation is important in leading to extensive fire, as described previously. However, the lack of strong relationships with prior or current PDSI during warm-phase PDO suggests that neither fuel accumulation nor drought leads to widespread fire during this time period. This is difficult to interpret given the uncertainty associated with the effect of PDO phases on climate in eastern Colorado.

On the western slope of the Colorado Rockies (CR) only current PDSI is related to burned area, a relationship that is exceptionally strong during warm-phase PDO. In addition, relationships between burned area and SOI, PDO index, and AMO index are much stronger during cool-phase PDO for RG, PL, and RG, respectively. These differences suggest that burned area in CR responds quite distinctly to fluctuations in both interannual moisture availability and interdecadal shifts in PDO. Because of the generally higher elevation, the CR drainage comprises more subalpine forest types that support fire regimes different from those found on the eastern slope (Veblen et al. 2000; Donnegan et al. 2001; Sherriff et al. 2001; Schoennagel et al. 2004). As a result, the climatic conditions leading to more widespread fire differ between the eastern and western slopes of the Colorado Rockies. The lack of an antecedent PDSI signal indicates that fuel is abundant enough to carry fire in most years, but is not readily combustible because of its high moisture content (Sherriff et al. 2001; Schoennagel et al. 2004). Intensive short-term drought can dry fuels to the point that they become readily combustible. This relationship is accentuated during warm-phase PDO, which in the CR drainage is associated with generally wetter conditions (Hidalgo and Dracup 2003). Apparently, interannual drought during a decadally wet period is strongly tied to extensive burned area in western Colorado.

We recognize that spatial synchrony of climate signals potentially diminishes at the subregional scale of this analysis (Swetnam and Betancourt 1990). This most likely explains the weaker and less consistent connections between burned area and SOI, PDO index, and AMO index. However, the agreement in PDSI – burned area relationships suggests a high degree of spatial synchrony across the three eastern climate divisions with respect to antecedent moisture, as well as throughout Colorado with respect to contemporaneous drought. Although we anecdotally contribute east–west slope differences in climatic signals to elevational and vegetative disparities, we feel that there is a legitimate contrast in climate–wildfire relationships for the Colorado Rockies, which may exist in other parts of the Rocky Mountains also. This could be particularly true in extensively mountainous areas where a "rain shadow" effect exists. Climate–fire relationships for the eastern slope of the Rocky Mountains in Montana, and to some extent Wyoming, could be very different from those for the Idaho Rockies. Because burned area over all of Idaho, Montana, and Wyoming is aggregated, the ability to detect this potential east–west slope difference is lost. Perhaps future research at a finer spatial scale could incorporate a more comprehensive analysis of this hypothesis that includes examining vegetation effects or other local effects (management practices, ignition sources) on climate–fire relationships. This type of analysis is beyond the scope of this study.

Conclusion

Variations in climate forced by multidecadal oscillations in the Pacific and Atlantic oceans correspond to distinct shifts in the influence of climate on wildfire extent during the 20th century. By testing relationships between regionally aggregated burned area and multiple climate indices we have identified how interdecadal climatic fluctuations affect interannual climate – burned area relationships, and to what extent these relationships vary throughout the Interior West. The strongest relationships between climate and burned area at both the regional and subregional scale exist using PDSI. Warm-phase AMO in the southern Interior West and both cool-phase AMO and warm-phase PDO in the northern and central Interior West correspond to periods in which moisture availability is strongly tied to burned area. During cool-phase PDO, climate has little influence on burned area in both the northern and central Interior West. However, in the southern Interior West, ENSO is strongly related to burned area during cool-phase PDO. In addition, during cool-phase PDO, PDSI is strongly associated with burned area on the eastern slope of the Colorado Rockies. The western slope of the Colorado Rockies is the only climate division or region in which burned area is not related to prior PDSI. During warm-phase PDO, current PDSI explains 67% of the variance in interannual burned area on the western slope. These regional and temporal differences in climate – burned area relationships are most likely governed by variations in the fuel dynamics associated with dominant regional and subregional vegetation types. The different fuel dynamics in each vegetation type most likely correspond to different fire regimes (Schoennagel et al. 2004).

Recognizing the regional and temporal variation in the relative influence of climate on fire extent is critical in being able to anticipate interannual wildfire activity. This is especially true given our increasing ability to predict climatic anomalies, such as drought and more extreme fluctuations in ENSO (Clarke and Van Gorder 2001; Panu and Sharma 2002). Managers could use the climatic signals identified in this study to forecast wildfire extent for current fire seasons based on both the short-term (interannual) and long-term (interdecadal) climate experienced in a given region. Preplanning management decisions regarding optimal staffing levels and equipment deployment, as well as decisions on implementing fuel-reduction activities (wildland fire use, prescribed fire, or mechanical treatments) should incorporate climatically based fire-season forecasts. The findings from the subregional analysis emphasize a potential for masking finer scale variations in climate – burned area relationships when conducting regional analyses. As a result, managers must take local factors into account when integrating regional climate – burned area relationships in local fire-management planning.

Acknowledgements

We sincerely thank Bill Romme and Peter Brown for their help in developing ideas and making comments throughout this research project. We also thank Esther Schnur for helping compile the data used in this project. Comments by three anonymous reviewers, as well as Scott Stephens, strengthened this paper immensely. This research was funded by the Southern Forest Experiment Station and the Joint Fire Science Program by way of a Graduate Research Assistantship at Colorado State University.

References

Baisan, C.H., and Swetnam, T.W. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, U.S.A. Can. J. For. Res. **20**: 1559–1569.

Balzter, H., Gerard, F.F., George, C.T., Rowland, C.S., Jupp, T.E., McCallum, I., Shvidenko, A., Nilsson, S., Sukhinin, A., Onuchin, A., and Schmullius, C. 2005. Impact of the Arctic Oscillation pattern on interannual forest fire variability in Central Siberia. Geophys. Res. Lett. **32**. L14709, doi:10.1029/2005GL022526..

Box, G.E.P., and Jenkins, G.M. 1976. Time series analysis: forecasting and control. Holden-Day, San Francisco, Calif.

Brockwell, P.J., and Davis, R.A. 2002. Introduction to time series and forecasting. 2nd ed. Springer-Verlag, New York.

Brown, D.P., and Comrie, A.C. 2004. A winter precipitation 'dipole' in the western United States associated with multidecadal ENSO variability. Geophys. Res. Lett. **31**. L09203, doi:10.1029/2003GL018726.

Brown, P.M., and Shepperd, W.D. 2001. Fire history and fire climatology along a 5 degree gradient in latitude in Colorado and Wyoming, USA. Palaeobotanist, **50**: 133–140.

Cayan, D.R. 1996. Interannual climate variability and snowpack in the western United States. J. Clim. **9**: 928–948.

Clarke, A.J., and Van Gorder, S. 2001. ENSO prediction using an ENSO trigger and a proxy for western equatorial Pacific warm pool movement. Geophys. Res. Lett. **28**: 579–582.

Dettinger, M.D., Cayan, D.R., Diaz, H.F., and Meko, D.M. 1998. North-south precipitation patterns in western North America on interannual-to-decadal timescales. J. Clim. **11**: 3095–3111.

Dodd, M.B., Lauenroth, W.K., and Welker, J.M. 1998. Differential water resource use by herbaceous and woody plant life-forms in a shortgrass steppe community. Oecologia, **117**: 504–512.

Doesken, N.J. 2002. Climate of Colorado [online]. Colorado Climate Center, Colorado State University, Fort Collins, Colo. Available from http://climate.atmos.colostate.edu/climateofcolorado.shtml [updated May 2003; cited January 2003].

Donnegan, J.A., Veblen, T.T., and Sibold, J.S. 2001. Climatic and human influences on fire history in Pike National Forest, central Colorado. Can. J. For. Res. **31**: 1526–1539.

Ehleringer, J.R., Phillips, S.L., Schuster, W.S.F., and Sandquist, D.R. 1991. Differential utilization of summer rains by desert plants. Oecologia, **88**: 430–434.

Enfield, D.B., Mestas-Nuñez, A.M., and Trimble, P.J. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. Geophys. Res. Lett. **28**: 2077–2080.

Gray, S.T., Betancourt, J.L., Fastie, C.L., and Jackson, S.T. 2003. Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains. Geophys. Res. Lett. **30**. No. 6, 1316, doi:10.1029/2002GL016154.

Haywood, J.D., Stagg, R.H., and Tiarks, A.E. 2004. Relationship between Palmer's Drought Severity Index and the Moisture Index of Woody Debris in the Southern Coastal Plain. USDA For. Serv. Gen. Tech. Rep. SRS-071. pp. 39–43.

Hidalgo, H.G., and Dracup, J.A. 2003. ENSO and PDO effects on hydroclimatic variations of the Upper Colorado River basin. J. Hydrometeorol. **4**: 5–23.

Humphrey, L.D., and Schupp, E.W. 2001. Seed banks of *Bromus tectorum* dominated communities in the Great Basin. West. N. Am. Nat. **61**: 85–92.

Knapp, P.A. 1995. Intermountain West lightning-caused fires — climatic predictors of area burned. J. Range Manage. **48**: 85–91.

Littell, J.S. 2002. Determinants of fire regime variability in lower elevation forests of the northern greater Yellowstone ecosystem. M.Sc. Thesis, Montana State University, Bozeman, Mont.

Mantua, N.J. 2000. How does the Pacific Decadal Oscillation impact our climate? Clim. Rep. **1**: 1–4.

Mantua, N.J. 2003. PDO Index [online]. Department of Atmospheric Sciences, University of Washington, Seattle, Wash. Available from http://jisao.washington.edu/pdo/PDO.latest [updated Febuary 2004; cited May 2003].

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Am. Meteorol. Soc. **78**: 1069–1079.

McCabe, G.J., and Dettinger, M.D. 1999. Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States. Int. J. Climatol. **19**: 1399–1410.

McCabe, G.J., Palecki, M.A., and Betancourt, J.L. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. Proc. Natl. Acad. Sci. USA, **101**: 4136–4141.

McKee, T.B., Doesken, N.J., and Kleist, J. 2000. A history of drought in Colorado: lessons learned and what lies ahead. Water in the Balance, Colorado Water Resources Research Institute, Fort Collins, Colo. Vol. 9. pp. 1–20.

Mitchell, V.L. 1976. Regionalization of climate in the western United States. J. Appl. Meteorol. **15**: 920–927.

Mock, C.J. 1996. Climatic controls and spatial variations of precipitation in the western United States. J. Clim. **9**: 1111–1125.

Newman, M., Compo, G.P., and Alexander, M.A. 2003. ENSO-forced variability of the Pacific decadal oscillation. J. Clim. **16**: 3853–3857.

NOAA. 2003*a*. Palmer Drought Severity Index [online]. National Oceanic Atmospheric Administration, US Department of Commerce, Washington, D.C. Available from ftp.ncdc.noaa.gov/pub/data/cirs [updated May 2003; cited May 2003].

NOAA. 2003*b*. Southern Oscillation Index (difference in standardized sea level pressure between Tahiti and Darwin, Austra-

lia) [online]. National Oceanic Atmospheric Administration, Climate Prediction Center, US Department of Commerce, Washington, D.C. Available from http://www.cpc.ncep.noaa.gov/data/indices/index.html [updated February 2004; cited April 2003].
NOAA. 2005. Atlantic Multidecadal Oscillation Index (unsmoothed, long version) [online]. National Oceanic Atmospheric Administration, Climate Diagnostic Center, US Department of Commerce, Washington, D.C. Available from http://www.cdc.noaa.gov/ClimateIndices/ [updated February 2005; cited February 2005].
Palmer, W.C. 1965. Meteorological drought. Weather Bureau Research Pap. 45, US Department of Commerce, Washington, D.C.
Panu, U.S., and Sharma, T.C. 2002. Challenges in drought research: some perspectives and future directions. Hydrol. Sci. J. **47**: S19–S30.
Renkin, R.A., and Despain, D.G. 1992. Fuel moisture, forest type, and lightning-caused fire in Yellowstone National Park. Can. J. For. Res. **22**: 37–45.
Rollins, M.G., Morgan, P., and Swetnam, T. 2002. Landscape-scale controls over 20th century fire occurrence in two large Rocky Mountain (USA) wilderness areas. Landsc. Ecol. **17**: 539–557.
Ropelewski, C.F., and Jones, P.D. 1987. An extension of the Tahiti–Darwin Southern Oscillation Index. Mon. Weather Rev. **115**: 2161–2165.
Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. US For. Serv. Res. Pap. INT-115.
SAS Institute Inc. 2003. The SAS system for Windows: statistical software package. Version 8.02 [computer program]. SAS Institute Inc., Cary, N.C.
Schoennagel, T., Veblen, T.T., and Romme, W.H. 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. Bioscience, **54**: 661–676.
Sherriff, R.L., Veblen, T.T., and Sibold, J.S. 2001. Fire history in high elevation subalpine forests in the Colorado Front Range. Ecoscience, **8**: 369–380.
Skinner, R.H., Hanson, J.D., Hutchinson, G.L., and Shuman, G.E. 2002. Response of C-3 and C-4 grasses to supplemental summer precipitation. J. Range Manage. **55**: 517–522.
Stephens, S.L. 2005. Forest fire causes and extent on United States Forest Service lands. Int. J. Wildland Fire, **14**: 213–222.
Stephens, S.L., and Collins, B.M. 2004. Fire regimes of mixed conifer forests in the north-central Sierra Nevada at multiple spatial scales. Northwest Sci. **78**: 12–23.
Swetnam, T.W., and Betancourt, J.L. 1990. Fire – Southern Oscillation relations in the southwestern United States. Science (Washington, D.C.), **249**: 1017–1020.
Swetnam, T.W., and Betancourt, J.L. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. J. Clim. **11**: 3128–3147.
US Department of Agriculture. 1987. National Forest fire reports (1956–1986). US Department of Agriculture Forest Service, Washington, D.C.
US Department of Agriculture. 1998. Wildfire statistics (1926 to 1997). US Department of Agriculture Forest Service, Division of Cooperative Forest Fire Control, Washington, D.C.
Veblen, T.T., Kitzberger, T., and Donnegan, J. 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. Ecol. Appl. **10**: 1178–1195.
Westerling, A.L., and Swetnam, T.W. 2003. Interannual to decadal drought and wildfire in the western United States. Eos, **84**: 545–560.
Westerling. A.L., Gershunov, A., Brown, T.J., Cayan, D.R., and Dettinger, M.D. 2003. Climate and wildfire in the western United States. Bull. Am. Meteorol. Soc. **84**: 595–604.
Western Regional Climate Center. 1998. El Niño, La Niña, and the western U.S., Alaska and Hawaii [online]. Western Regional Climate Center, Desert Research Institute. Available from www.wrcc.dri.edu/enso/ensofaq.html [updated June 1998; cited February 2004].

Canadian Journal of Forest Research

Table of Contents

Volume 36, Number 3, March 2006, Including papers from The North American Long-Term Soil Productivity Study
ISSN 1208-6037
