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Fire-climate interactions in forests of the American Pacific coast

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[1] We investigate relationships between climate and wildfire activity between 1929 and 2004 in Pacific coast forests of the United States. Self-Organizing Mapping (SOM) of annual area burned in National Forests (NF) in California, Oregon, and Washington identifies three contiguous NF groups and a fourth group of NF traversed by major highways. Large fire years in all groups are dry compared to small fire years. A sub-hemispheric circulation pattern of a strong trough over the North Pacific and a ridge over the West Coast is characteristic of large fire years in all groups. This pattern resembles the Pacific North American (PNA) teleconnection and positive phase of the Pacific Decadal Oscillation (PDO). A reverse PNA and negative PDO phase characterizes small fire years. Despite the effect of fire suppression management between 1929 and 2004, forest area burned is linked to climatic variations related to large-scale atmospheric circulation patterns. **Citation:** Trouet, V., A. H. Taylor, A. M. Carleton, and C. N. Skinner (2006), Fire-climate interactions in forests of the American Pacific coast, *Geophys. Res. Lett.*, *33*, L18704, doi:10.1029/2006GL027502.

1. Introduction

[2] Fire is a key process influencing the structure, composition, and development of forests in western North America [*Agee*, 1993]. Widespread suppression of fire in the most fire prone forests in the western United States in the 20th century has increased the risk of severe fire because of unusually large accumulations of forest fuel [*Allen et al.*, 2002]. Reducing fire risk and associated losses of life, property, and forest is a central goal of forest management in this region. Understanding the factors that contribute to wildfire activity is therefore essential to the development and effective implementation of forest management.

[3] Climatic variation (inter-annual and inter-decadal) has been linked to forest fire activity in the pre-fire suppression period by tree-ring studies. Widespread burning occurs when dry years enhance fuel flammability; the preceding wet years often promote burning in dry years by increasing fuel production [*Swetnam and Betancourt*, 1990; *Heyerdahl et al.*, 2002; *Taylor and Beaty*, 2005]. Recent work has linked local and regional variations in fire activity to variations in hemispheric and even global-scale atmospheric circulation patterns such as El Niño Southern Oscillation (ENSO) [*Swetnam and Betancourt*, 1990], and the PDO [*Hessl et al.*, 2004]. Modes of circulation associated with the ENSO and the extra-tropical PDO are even thought to contribute to spatial variation in wildfire activity in western North America during the fire suppression period [*Hess et al.*, 2001; *Westerling and Swetnam*, 2003; *Gedalof et al.*, 2005; *Duffy et al.*, 2005].

[4] This study identifies the relationships between climate and area burned in NF in the Pacific coast states during the period 1929–2004. We use SOM to identify groups of NF with similar temporal patterns of area burned and use a composite analysis to compare fire-climate interactions among NF groups. Climatic measures include indices of soil moisture, modes of atmospheric circulation associated with ENSO and PDO, and geopotential height. Climatic data are composited for the ten years with the most and least area burned to identify climate-area burned relationships. Identifying these relationships provides a foundation for the use of hemispheric-scale atmospheric circulation patterns to predict upcoming fire season severity.

2. Materials and Methods

2.1. Fire Data

[5] Fire activity in NF of the Pacific coast states is represented by data on annual area burned in 37 NF in Washington, Oregon, and California for 1929–2004. The data were compiled from USDA Forest Service Annual Fire Reports. Recording of smaller-sized fires is suspected to have been limited in earlier years, causing temporal variability in the quality of the data set. This temporal variability, however, is unlikely to have affected fire-climate interactions, since inter-annual patterns of area burned are driven largely by large fire events [*Keeley*, 2004]. Although we limit our fire-climate analysis to area burned in NF, the results should be applicable to other forested lands in the Pacific coast states. A linear regression ($r^2 = 0.87$) for California (1908–2002) of annual area burned in NF, and in all (i.e., state, private, federal) lands (data derived from the Fire and Resource Assessment Program (FRAP) data set from the California Department of Forestry) indicates that inter-annual variation in area burned in NF is a strong indicator of inter-annual variation in burned area at the state level. We converted area burned to z-scores for the fire-climate analysis to standardize for different sized NF.

2.2. Climate Data

[6] The influence of moisture conditions on area burned was identified using Palmer Drought Severity Index (PDSI) [*Palmer*, 1965], an index of soil moisture that integrates immediate (i.e., same month) and lagged (previous months') precipitation and temperature into a single value. PDSI is a common moisture index used in fire-climate studies [*Swetnam and Betancourt*, 1990; *Westerling and Swetnam*,

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2003]. PDSI time series (1929–2004) were derived for the 26 climate divisions [*Karl and Knight*, 1985] comprising the study area. PDSI time series for annual (September to August), fall (September to November (SON)), winter (December to February (DJF)), spring (March to May (MAM)), and summer (June to August (JJA)) periods were calculated and used in the analysis. The spatial and temporal variability in PDSI-values [*Guttman et al.*, 1992] was minimized by calculating z-scores.

[7] The influence of teleconnections on fire extent was identified using time series (1929–2004) of the winter (DJF) Southern Oscillation Index (SOI) data [*Ropelewski and Jones*, 1987] and the annual PDO index (PDOI) data [*Mantua et al.*, 1997]. The associations of hemispheric circulation with variation in area burned were determined using a synoptic atmospheric data set (2.5° gridded measurements) of lower- to mid-tropospheric (700 hPa) geopotential height. These Reanalysis data (available at http://www.cdc.noaa.gov) [*Kalnay et al.*, 1996] cover the period 1948 to 2004, during which two PDO phases occurred: a negative phase from 1948–1977 and a positive phase from 1977–2004. We derived seasonal (as above) anomalies of geopotential height (i.e., departure from the 1948–2004 base period) for each year of the analysis.

2.3. National Forest Groups

[8] Groups of NF with similar temporal patterns of area burned were identified with a SOM using the annual area burned in each of the 37 NF. SOM is a non-linear, iterative, artificial neural network, statistical clustering technique [*Kohonen*, 1989] that permits identification of groups with control over the number of output groups. The number of groups is arbitrarily chosen, allowing scaling with respect to subsequent analyses. There is always a trade-off in identifying the number of groups using SOM. If the number of groups is small, the within-group variance increases and the groups become more generalized [*Crane and Hewitson*, 2003]. Conversely, if the number of groups is too large, unique conditions within a group are over-emphasized, preventing generalization. We chose to group the NF area burned data into 8 groups, which is expected to emphasize large-scale synchroneity among wildfires related to climate, rather than local patterns that reflect landscape structure or forest management [*Agee*, 1993]. The latter influences include fuel types and loads, topography, and logging. The ability to capture non-linear relationships among environmental variables makes SOM particularly suited to examining the influence of climate on wildfire activity [*Crane and Hewitson*, 2003].

2.4. Fire-Climate Analysis

[9] To permit a direct comparison of PDSI and fire extent, PDSI time series from climatic divisions overlapping the four NF groups identified by the SOM were averaged, yielding moisture conditions for each NF group. Sets of extreme fire years (i.e., 10 years with most and 10 years with least extensive area burned) were identified in each NF group, and composite PDSI z-scores, SOI, PDOI, and geopotential height were calculated for each set of fire years. The significance level of differences in composite climatic conditions between the types of extreme fire years in each NF group was identified using a Student's t-test.

3. Results and Discussion

3.1. National Forest Fire Groups

[10] The eight-group SOM (Figure 1) yielded four large groups of NF and four small groups consisting of one or two NF. Reducing the number of groups for SOM did not alter this overall structure: members of large groups were recombined and the small groups remained separated (not shown). The temporal variation of fire extent in the NF in the small groups is distinct from the other NF. Given our focus on large-scale fire-climate interactions, we restrict our analysis to the four large groups of NF. The SOM method organizes groups by similarity. Consequently, the temporal pattern of area burned in group 8 is quite different from those in group 1 and group 3, which are more similar.

[11] Three of the four NF groups are spatially coherent: group 1 includes mainly Washington and northern Oregon; group 3 mainly northern California and the southern Coast ranges; and group 8 mainly southern Oregon. Members of group 6 occur in each state and include NF in southern California, the Sierra Nevada, central Oregon, and Washington. Region 6 forests are bisected by busy highways in locations with relatively high populations and dry summers. The large fires in this group are generally human caused, whereas in groups 3 and 8 large fires are generally lightning caused [*McKelvey and Busse*, 1996]. SOM is sensitive to outliers (extremely large fire years), which may explain why the Sequoia NF in southern California is in the same group as the NF in southwestern Oregon (group 8). All of these forests (group 8) experienced very large fires in 2002. A sensitivity analysis of the SOM, excluding the largest fire year for each NF, yielded some difference in membership to the four largest NF groups (overall 61% of the NF remained in the same group). The spatial coherence and distribution of groups, however, were comparable, although areas covered by individual groups increased or decreased according to changing group memberships. Because of the importance of extreme fire years with respect to fire management, we decided to base the SOM on the entire data set.

[12] The areas of western Washington, southwestern Oregon and northern California are each primarily represented by a single NF group: they receive much more precipitation than drier climate regions to the south or in eastern Oregon [*Thompson et al.*, 1999]. With fuel generally abundant, large fire years are more synchronized by very dry years than those in dry climates, where fuels are more limited but dry enough to burn in most years [*Swetnam and Betancourt*, 1990].

3.2. Influence of Moisture and Teleconnections on Fire

[13] Mean summer PDSI was lower (drier) in large than small fire years in each NF group (Table 1). This was also true for the winter and spring preceding the summer fire season, and for annual PDSI. The difference in summer PDSI between large and small fire years was strongest for NF group 1 (Washington and northern Oregon) and weakest in NF group 3 (northern California), where dry summer conditions prevail most years. Differences in PDSI between large and small fire years for the

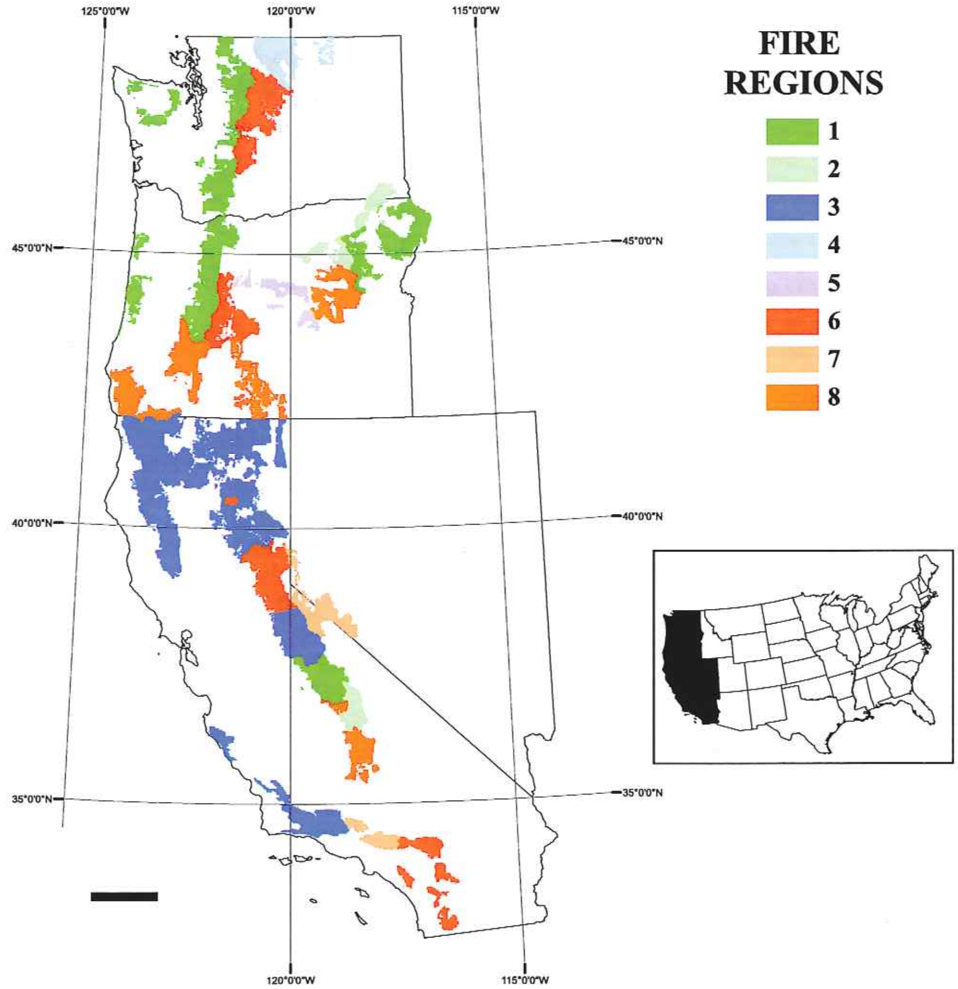

Figure 1. Distribution of SOM NF groups of California, Oregon, and Washington.

winter and spring preceding the summer fire season were smallest in NF group 1.

[14] There were no differences in annual PDSI between large and small fire years for years preceding the fire year, or for SOI or PDOI in any of the NF groups (results not shown).

3.3. Fire and Atmospheric Circulation

[15] Sub-hemispheric circulation patterns in years with high and low annual area burned were consistent across all NF groups. Accordingly, we present only the analysis for NF group 3 for the ten largest and smallest fire years. In years with large fires, there were positive anomalies of geopotential height over the eastern North Pacific (Figure 2a). This high-pressure ridge weakens zonal westerly flow, blocks moist marine air from the eastern Pacific, and reduces winter precipitation on the Pacific coast [*Dettinger et al.*, 1998]. In the winter and spring preceding large fire years, the ridge pattern over the Pacific coast is characteristically associated with a deepened Aleutian Low, which may also be displaced westward. Thus, years with large fires occurred after a multi-season period of atmospheric conditions that reduced precipitation. The distinct trough and ridge pattern over the North Pacific and North America in large fire years resembles the positive PNA teleconnection pattern [*Wallace and Gutzler*, 1981], and is also associated with large fire years in the Pacific Northwest

Table 1. Mean Seasonal (SON, DJF, MAM and JJA) and Annual Z-Scores of PDSI Values for Large and Small Fire Years in Four NF Groups in California, Oregon, and Washington as Determined by the SOM Regionalization Method

	SON	DJF	MAM	JJA	Annual
			Region 1		
Large	−0.02	−0.18	−0.17	−0.89[a]	−0.44[b]
Small	0.19	0.25	0.25	0.66[a]	0.41[b]
			Region 3		
Large	0.25	−0.71[a]	−0.53[b]	−0.54[a]	−0.5[a]
Small	0.32	0.91[a]	0.74[b]	0.78[a]	0.89[a]
			Region 6		
Large	−0.44	−0.59[b]	−0.66[a]	−0.81[a]	−0.28[a]
Small	0.4	0.3[b]	0.61[a]	0.79[a]	0.34[a]
			Region 8		
Large	−0.59	−0.64	−0.96[a]	−0.87[a]	−0.97[a]
Small	0.19	0.46	0.53[a]	0.71[a]	0.55[a]

[a]Significance levels of the student's t-test comparing the difference between the means in large and small fire years in each group are indicated thus $P < 0.01$.

[b]Significance levels of the student's t-test comparing the difference between the means in large and small fire years in each group are indicated thus $P < 0.05$.

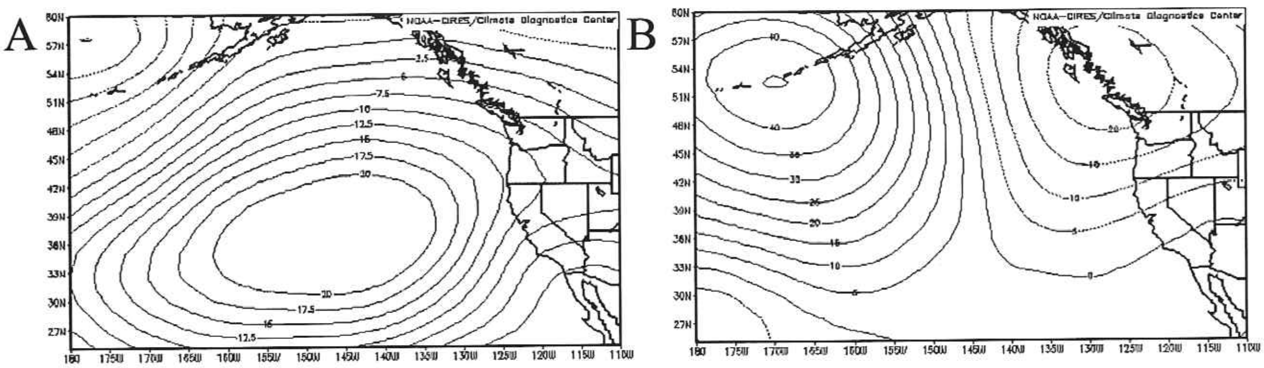

Figure 2. Winter (DJF) 700 hPa geopotential height anomalies for (a) large and (b) small fire years in NF group 1 (Washington and northern Oregon). Positive anomalies are indicated by full lines, negative anomalies by dashed lines. The circulation features were broadly similar for large and small fire years in the other NF groups.

(PNW) [*Gedalof et al.*, 2005] and western Canada [*Skinner et al.*, 1999; *Duffy et al.*, 2005].

[16] In small fire years the sub-hemispheric circulation pattern was opposite that of large fire years, and resembled the reverse PNA mode for western North America (Figure 2b). The Aleutian Low was weaker (i.e., positive height anomalies), and negative geopotential height anomalies over the West Coast enhanced convergence and uplift of marine air, resulting in above-normal precipitation in western North America. The pattern of a weakened Aleutian Low resembles a cool or negative PDO phase (1948–1977), where high SSTs in the central North Pacific accompany a stronger-than-normal jet stream and low geopotential heights, to produce wet conditions on the Pacific coast. During a positive or warm PDO phase (1978–2005) conditions essentially are reversed (Figure 2a).

[17] In the PNW, large fire years during the pre-and post-fire suppression period are associated with positive PDO phase conditions [*Hessl et al.*, 2004; *Gedalof et al.*, 2005]. Our analysis suggests that the influence of the PDO on fire extent covers the entire Pacific coast, including California. The synchroneity of the fire-climate interaction of California with the PNW, however, may not be stable over time. The PDO teleconnection pattern exhibits a dipole between the northwestern and southwestern United States, with the pivot point in California, shifting south or north on decadal time-scales [*Dettinger et al.*, 1998; *Westerling and Swetnam*, 2003]. For NF in California, the shifts may associate fire-climate interactions with the PNW in some decades and the Southwest in others [*Westerling and Swetnam*, 2003], altering the interaction of fire with PDO. In the northern Sierra Nevada, California, fire extent prior to Euro-American settlement was unrelated to PDO or PDSI conditions in some decades and associated with a negative PDO and PDSI in others [*Taylor and Beaty*, 2005]. Although an interdecadal association between fire extent and PDO phase was found for the contemporary period in this study, variations in the geographic position of the PDO dipole may cause shifts in this spatial association over longer time periods, particularly for NF groups 3 and 6.

4. Conclusion

[18] A non-linear regionalization technique (SOM) was applied to time series data of fire extent for National Forests in California, Oregon and Washington to identify spatial associations between fire and climate along the Pacific coast since 1930. Spatial coherence of the NF groups indicates that SOM is an appropriate regionalization technique for landscape-scale analyses. In each of the four NF groups, large fire years were associated with low moisture conditions compared to small fire years. Dry conditions during the fire season had the strongest effect on fire extent, but dry antecedent conditions in winter and spring were also important. The scale of these fire-climate interactions is strongly regional.

[19] There was a common sub-hemispheric circulation pattern associated with fire extent in the study period for all NF groups. Large fire years were characterized by an intensified high-pressure ridge over western North America that promotes surface drying, and a deepened Aleutian Low; both features are typical of a positive PDO phase and a positive PNA pattern. The opposite patterns characterize small fire years, indicating a more-or-less linear interaction between sub-hemispheric circulation and fire extent for the study period, at least in extreme years.

[20] Despite the influence of human-induced climate change [*Gillet et al.*, 2004], fire suppression, and other forest management activities on Pacific coast forest fire regimes during the 20th century [*Agee*, 1993; *Skinner and Chang*, 1996; *Kasischke and Turetsky*, 2006], fire extent is still linked to inter-annual climate variations. Climate variability influences wildfire activity on a regional scale and, inter-seasonally, may permit reliable fire predictions on this scale. On synoptic scales, fire extent along the Pacific coast of the United States is associated with sub-hemispheric teleconnection patterns, especially the PDO. Inclusion of the inter-decadal climatic regulation of fire extent into forest management plans could increase the effectiveness of fire management organizations in responding to heightened fire risk in forests in the Pacific coast states.

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