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North Pacific warming and intense northwestern U.S. wildfires

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[1] The tropical Pacific sea surface temperature (SST) anomalies such as La Nina have been an important predictor for wildfires in the southeastern and southwestern U.S. This study seeks seasonal predictors for wildfires in the northwestern U.S., a region with the most intense wildfires among various continental U.S. regions. Singular value decomposition and regression techniques are applied to summer wildfire and current and antecedent SST conditions during a period of 23 years. It is found that warming in the North Pacific is a major feature in the SST spatial pattern related to intense Northwest wildfires. The warming appeared in all the major wildfire events during the past two decades. The relation is statistically significant. The North Pacific SST, therefore, has potential to be a predictor for seasonal Northwest wildfires. **Citation:** Liu, Y. (2006), North Pacific warming and intense northwestern U.S. wildfires, *Geophys. Res. Lett.*, *33*, L21710, doi:10.1029/2006GL027442.

1. Introduction

[2] Wildfire is one of the major natural disasters in the U.S. that threaten human life and property. Millions of acres of forest and other ecosystems are burned annually. In 2000, for example, there were more than 100 thousand wildfires that consumed 8.4 million acres. Nearly 30 thousand people were involved in wildland firefighting efforts, costing the federal agency fire suppression about $1.4 billion (National Interagency Fire Center, Wildland fire statistics, 2002, available at http://www.nifc.gov/stats/index.html). Wildfires also have environmental consequences through affecting atmospheric carbon concentration, air quality, and regional climate [*Riebau and Fox*, 2001; *Page et al.*, 2002; *Liu*, 2005].

[3] Seasonal predictions of fire risks provide invaluable aid to fire and land managers in planning fire suppression and other fire-related activities [*Brown et al.*, 2002; *Westerling et al.*, 2002; *Roads et al.*, 2005]. Wildfires in the Southeast and Southwest are found to be more active during La Nina events [*Simard et al.*, 1985; *Swetnam and Betancourt*, 1990; *Brenner*, 1991], which can affect the North America atmospheric processes through teleconnections [*Ropelewski and Halpert*, 1986; *Harrison and Larkin*, 1998]. This relation has been used for seasonal prediction of wildfires in these regions [e.g., *O'Brien et al.*, 2002]. However, prediction of seasonal wildfires in the Northwest, which are the most frequent and intense among various continental U.S. regions, remains a big challenge. Unlike the Southeast and Southwest where wildfires occur mostly in the spring, those in the Northwest occur mostly in the summer (June-August), when La Nina and other tropical Pacific SST anomalies have the least effects on the North America atmospheric processes [*Barnett*, 1981; *Morehouse*, 2000]. There has been little previous work of this sort focusing on this region and the only work [*Simard et al.*, 1985] found no statistically significant relationships between the tropical Pacific SST and wildfires in this region.

[4] It was found in the 1990s that SST anomalies in the North Pacific can impact climate in the mid-latitude U.S. regions [*Wallace et al.*, 1992; *Ting and Wang*, 1997; *Lau et al.*, 2004]. Great Plains summer precipitation, for example, was found to be significantly correlated with the North Pacific SST [*Ting and Wang*, 1997]. Inspired by this finding, this study turns to attention from the tropical to North Pacific SST for a possible predictor for the Northwest wildfires. Current and antecedent SST conditions of fire seasons are important for understanding spatial SST patterns corresponding to intense fire activity and for developing predictive relationships. Both are examined in this study.

2. Data and Methods

[5] A historic fire dataset [*Bureau of Land Management*, 2003] was used in this study. This dataset has individual fires over the lands owned by five U.S. federal agencies (Bureau of Land Management, Bureau of Indian Affairs, Fish and Wildlife Service, National Park Service, and USDA Forest Service). It covers a period from the early 1900s to 2002, with the most complete data from 1980. The parameters include burn area, number, location, type, and cause. This data has been used to understand fire-weather relationships [*Westerling et al.*, 2003] and fire emissions [*Liu*, 2004]. Note that the data do not include fires on state and private lands, which contribute to a substantial portion of the acres burned in the Southeast.

[6] The global 2-degree extended reconstructed SST data over 140°E–90°W, 20°S–60°N during 1980–2002 [*Smith and Reynolds*, 2003] were used. Seasonal series was constructed using monthly values. State averages of precipitation and temperature obtained from the Climate Data Center of the U.S. National Oceanic and Atmospheric Administration were used for analysis of weather anomalies.

[7] Singular value decomposition (SVD) [*Bretherton et al.*, 1992] was used to identify spatial patterns of Pacific SST anomalies connected to U.S. wildfires. SVD is similar to the empirical orthogonal function (EOF), a popular principle component analysis technique, in the regard that both realize the separation of a field in space-time domain into spatial patterns (principal components) and temporal series (expansion coefficients). But unlike EOF that is applied to a single field, SVD is applied to two fields with the resulting spatial patterns of the two closely related to

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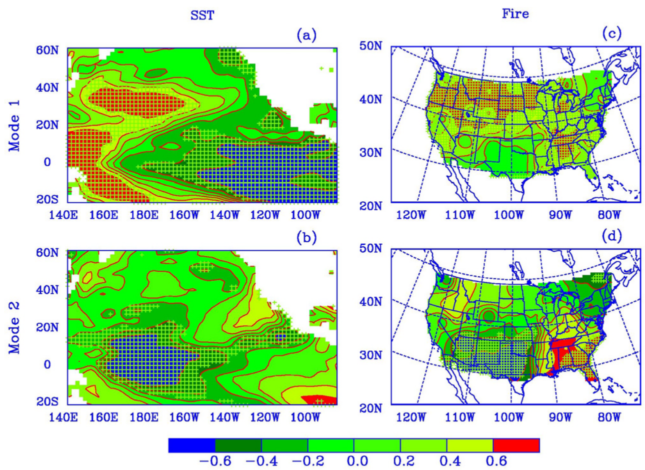

Figure 1. Spatial patterns (principal components) of the leading SVD modes: (a and b) SST patterns of the 1st and 2nd modes and (c and d) corresponding fire patterns. The values, weighted by the singular values, represent correlation coefficients between an original field and the SVD temporal series (expansion coefficients) of the other field. The values in the dotted areas reach the 5% Monte Carlo statistical significance level.

each other. SVD has been applied to studies on the relations between SST and North America meteorological fields [*Wallace et al.*, 1992; *Ting and Wang*, 1997; *Wang and Ting*, 2000].

3. Results

3.1. SST and Wildfire Coupled Patterns

[8] Figure 1 shows spatial patterns of the first two leading SVD modes. The two modes contribute substantially to the relationships between SST and fire, as indicated by the large values of the squared covariance fraction (SCF) of 67.1 and 19.4%, respectively (a measure of the relative importance of SVD mode in the relationship between the two fields), the normalized root-mean-squared covariance fraction (NCF) of 22.0 and 11.8% (a measure of the corresponding absolute importance), and the correlation coefficients of 68.5 and 66.5% between the SVD expansion coefficient series (Table 1).

[9] The 1st mode contributes to about 25 and 38% of total SST and fire variances, respectively. The SST pattern (Figure 1a) is characterized by positive values (warming) in the central North Pacific and the western tropical Pacific, and negative ones (cooling) in the eastern tropical Pacific. The corresponding wildfire pattern (Figure 1c) is characterized by positive values (intense fires) in the Northwest, Midwest and South, and negative values (weak fires) in the Southwest, South, and Northeast. This result suggests that warming in the North Pacific and cooling in the eastern tropical Pacific are closely related to intense Northwest wildfires.

[10] The central and western tropical Pacific SST, on the other hand, is important to wildfires in the southern U.S. regions, as indicated by the 2nd mode, which contributes to about 14 and 21% of total SST and fire variances, respectively. The SST pattern is characterized by negative values in the Pacific region (Figure 1b), and the wildfire pattern is characterized by negative values in the Southwest and South, and positive ones in the Southeast (Figure 1d).

[11] The Monte Carlo method was used to test significance levels of the correlation coefficients shown in Figure 1. This method is a type of resampling process used to produce a probability estimate. The original data samples consist of 23 years of independent units. The order of the data was randomly rearranged multiple times (it was 19 times for this study), in principle, destroying the correlation of SST and fire and thus providing a statistical distribution of uncorrelated data for null hypothesis testing. The test steps can be found in, for example, *Wu et al.* [2006]. The test results indicate that the North Pacific warming and the tropical Pacific cooling, and the corresponding intense fire anomalies in the Northwest reach the 5% Monte Carlo significance level.

[12] The coupled SST spatial pattern of warming in the North Pacific and cooling in the tropical Pacific is actually seen in a couple of seasons before summer, as indicated by the correlation between the summer fire temporal series of the 1st SVD mode and winter and spring SST fields (Figure 2). Correlation coefficients of 0.6 or higher (warming) appear in the North Pacific for both seasons. Meanwhile, coefficients of –0.4 or below appear in the central and eastern tropical Pacific for the spring. This SST

Table 1. Statistics of the Two SVD Leading Modes of Summer SST and Summer U.S. Fires[a]

Mode	SCF, %	NCF	r, %	σ_{SST}, %	σ_{fire}, %
1	67.1	0.220	68.5	24.8	37.9
2	19.4	0.118	66.5	13.9	20.9

[a]*SCF*, *NCF*, *r,* and σ, represent squared covariance function, normalized root-mean-squared covariance fraction, correlation coefficient of SVD expansion coefficient series, and variance ratio (SVD expansion coefficient series to original data series), respectively.

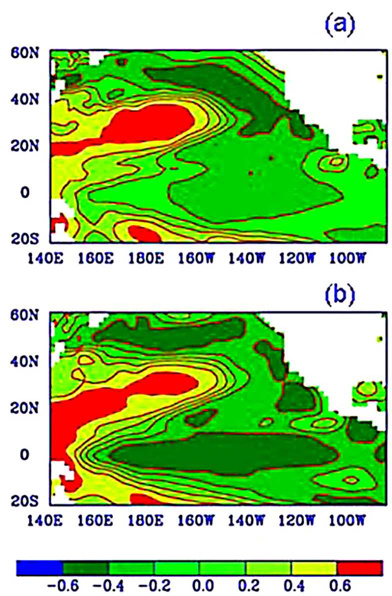

Figure 2. Correlation coefficients between summer wildfire temporal series of the 1st SVD mode and (a) winter and (b) spring SST fields. The critical correlation coefficient at the 5% significance level is 0.4.

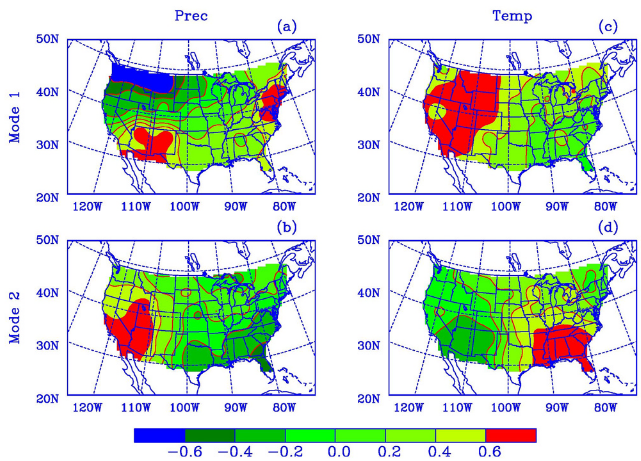

Figure 3. Correlation coefficients of precipitation with SST temporal series of (a) 1st and (b) 2nd SVD modes. Positive (negative) values indicate wet (dry) weather. (c and d) Same as Figures 3a and 3b except for temperature. Positive (negative) values indicate hot (cool) weather. The critical correlation coefficient (absolute value) at the 5% significant level is 0.4.

similarity between adjacent seasons, reflecting the persistence property of seasonal SST variability [*Namias and Born*, 1970; *Deser et al.*, 2002], suggests a close relation between North Pacific SST of an earlier season and subsequent summer Northwest wildfires. This relation is essential for the SST anomalies to be a predictor for the wildfires.

[13] Observational and modeling studies on ocean-atmosphere interaction have indicated the substantial effects of the North Pacific SST on the seasonal North America atmospheric circulation and weather [*Wallace et al.*, 1990; *Ting and Wang*, 1997; *Lau et al.*, 2004; *Wu et al.*, 2005]. Warming in the North Pacific would lead to a tendency in the development of an anti-cyclonic atmospheric circulation system, a poleward shift of the subtropical jet and storm tracks over the eastern North Pacific and western North America, and reduction in moisture transport from the ocean. As a result, hot and dry weather is likely to develop in these regions.

[14] Figure 3 shows the continental U.S. spatial patterns of weather anomalies corresponding to the SST variability, as measured by correlation coefficients of precipitation and temperature with SST temporal series of the leading SVD modes. In the anomalies related to the 1st SVD mode, temperature is increased in the western U.S. regions. Meanwhile, precipitation decreases in the Northwest, but increases in the Southwest. The hot and dry weather in the Northwest is a most conducive atmospheric condition for intense wildfires [*Liu*, 2004]. Therefore, wildfires intensify in the region. The atmospheric anomalies related to the 2nd SVD mode are characterized by drying and warming (wetting and cooling) in the Southeast (Southwest). Wildfires are intense (weak) accordingly.

3.2. Individual Fire Events

[15] The summer SST patterns for the six years when Northwest summer fires were the most intense during 1980–2002 were examined to understand the relative importance of the North Pacific warming and the tropical Pacific cooling. (The summer fires in the continental U.S. were also the most intense in the six seasons). In three years (1988, 1999, and 2000), strong cooling (SST anomalies of −0.6°C or below) occurred in the central and eastern tropical Pacific (Figures 4a–4c), a phenomenon typically seen during a La Nina event. A typical example of the cool SST and intense fire relation was the 1988 catastrophic Yellowstone National Park wildfires [*Romme and Despain*, 1989], which were preceded by a strong La Nina event [*Trenberth et al.*, 1988]. In 1994 and 1996 (Figures 4d–4e), however, strong cooling occurred only in limited areas of the eastern tropical Pacific (east of 110°W), and SST anomalies were either slightly negative or positive in the rest of the tropical Pacific. In 2002 (Figure 4f), SST anomalies in the tropical Pacific were even mostly positive.

[16] Strong warming (SST anomalies of 0.6°C or above), on the other hand, occurred approximately between 20–40°N and 150°E–150°W in each of the six years, though the location and extent varied from one year to another (in 1996, a cool area penetrated into the warming region). The consistency suggests that the warming is more important than the cooling to the intense wildfires.

3.3. Statistical Significance

[17] To evaluate the statistical significance of the SST anomalies as a potential predictor, correlation coefficients between the spring SST and summer wildfires were calculated. SST grid values were averaged over 25–35°N, 160°E–160°W in the North Pacific. Wildfires were aver-

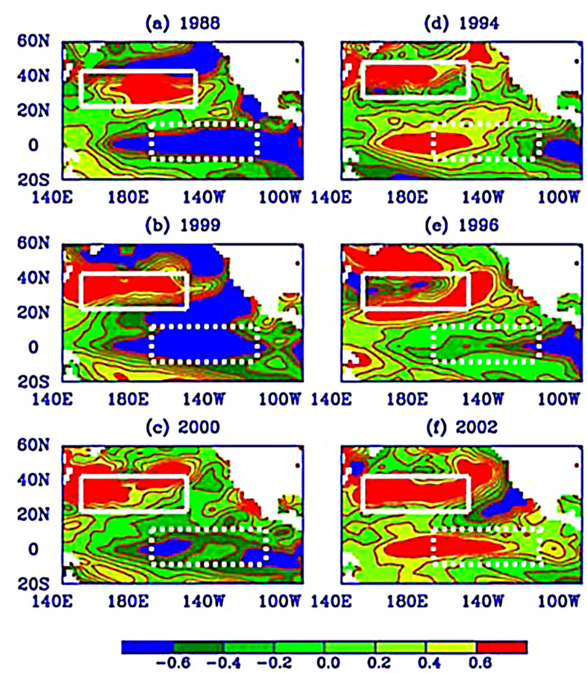

Figure 4. Summer SST anomalies (°C) during six intense wildfire seasons, expressed as departure from the average over 1980–2002. The seasons are divided into two groups: (a–c) with La Nina-like SST anomalies and (d–f) without La Nina-like SST anomalies. The boxes indicate the target North and tropical pacific regions, respectively.

aged over each of the 10 U.S. Forest Service (FS) regions, that is, North (N), Rocky Mountain (RM), Inter-Mountain (IM), Pacific North (PN), Pacific South (PS), Southwest (SW), South (S), Southeast (SE), North Central (NC), and Northeast (NE) (Note that this is a previous classification. SE is merged into S in the current classification). N, RM, IM, and PN are regarded as parts of the Northwest. For comparison, the coefficients with spring SST averaged over 5°S–5°N, 150°W–90°W (the NINO3 region) in the tropical Pacific were also calculated.

[18] The coefficients with the North Pacific SST (Figure 5a) are positive for all the FS regions except NC. In contrast, those with the tropical Pacific SST (Figure 5b) are negative in all the FS regions except S. Another difference is that the coefficients with the North Pacific SST reach 5% significance level in all the four Northwest regions except PN, but those with the tropical Pacific SST reach the significance level only in IM. This provides additional evidence that the warming in the North Pacific is more important than the cooling in the tropical Pacific in terms of their relation to the Northwest wildfires.

[19] A wildfire can be caused by either natural or non-natural reasons or combined. In the dataset used for this study, natural causes account for about 66% of all fires in occurrence number and about 78% in burned area in summer (Table 2). The ratios are much higher than the corresponding annual of 47 and 69%. Atmospheric parameters (lightning, wind, and drought, etc.) can contribute to a wildfire, regardless of cause, by increasing ignition chances and providing favorable circumstances for fire spread. Considering that all the parameters are affected by SST, wildfires of both natural and non-natural causes have been used in the above analysis. A separate correlation calculation using the wildfires with natural cause only is basically the same: the correlation coefficients between the spring North Pacific SST and summer Northwest wildfire reach 5% significance level in N, RM, and IM (Figure 5a); those between the spring tropical Pacific SST and summer Northwest wildfire is the largest in IM, though it no longer reaches the significant level (Figure 5b).

Table 2. Ratio of Naturally Caused Fires to All Fires in the Contiguous U.S.

	Winter	Spring	Summer	Fall	Annual
Number, %	0.98	13.02	65.94	31.60	46.57
Area, %	0.5	19.80	78.2	29.37	68.59

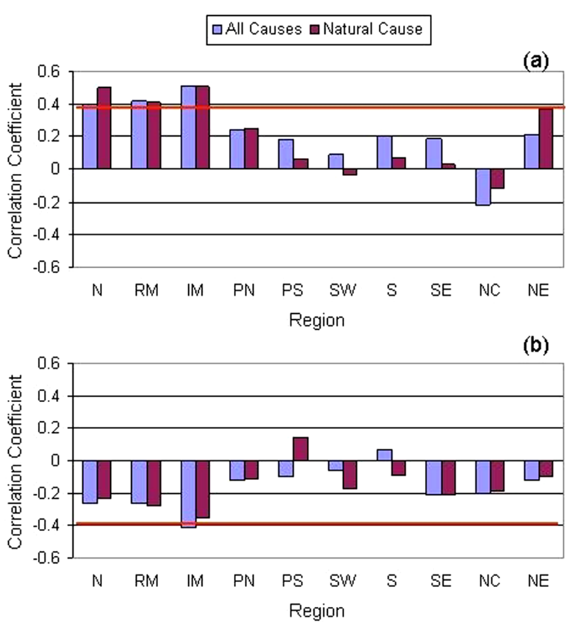

Figure 5. Correlation coefficients between spring SST and summer wildfires. (a) North Pacific SST and (b) tropical Pacific SST. Blue and brown bars for each USDA Forest Service region (see the text for full region name) represent fires of all causes and natural cause only, respectively. The critical correlation coefficient (absolute value) at the 5% significant level is 0.4.

[20] It has been concluded that intense wildfires in the Northwest are closely related to warming in the North Pacific. This result is expected to have some important implications for seasonal fire predictions. Statistical prediction techniques of spring wildfires in the Southeast and Southwest have been developed using the tropical Pacific SST as a predictor [*O'Brien et al.*, 2002]. Potential exists to develop similar techniques for prediction of summer wildfires in the Northwest using the North Pacific SST as a predictor. In addition, dynamical models have been developed recently for seasonal wildfire predictions with some skills over many western U.S. locations [*Roads et al.*, 2005]. The skill for Northwest wildfires could be improved through better understanding and representing the North Pacific SST variability and its tele-connections with the North America atmospheric processes.

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