

CHAPTER 6

CLIMATE AND FOREST WILDFIRE IN THE WESTERN UNITED STATES

Anthony Westerling

1. INTRODUCTION

Forest and wildfire managers in the western U.S. are very familiar with weather information and forecasts provided by various public and private sources. Even very sophisticated users of these products, however, may be less familiar with climate information and forecasts and their applications. Partly this is because the scientific community has made rapid progress in climate, and particularly climate forecasting, as a field of applied study in recent decades. Integrating these new research findings into management systems is a difficult and time-consuming process. Sophisticated users of weather information may also be less comfortable using climate information because, conceptually, the two are so different: weather is something we all experience every day, while climate is an abstraction.

As an abstraction, however, climate provides powerful tools for understanding recent developments in forest wildfire in the western U.S. Climate and wildfire research, and the practical experience of many forest managers, show that summer drought is a very important driver of interannual variability in forest wildfire (Balling et al. 1992, Swetnam and Betancourt 1998, Kipfmüller and Swetnam 2000, Veblen et al. 2000, Donnegan et al. 2001, Heyerdahl, Brubaker and Agee 2002, Westerling et al. 2003b). In turn, the duration and severity of summer drought in western forests is highly sensitive to variability in spring and summer temperature at higher latitudes and elevations and its effect on snow (Westerling et al. 2006). Trends in temperature and the timing of the spring snowmelt explain much of the dramatic increase in large forest wildfire frequency in the West in recent decades (Westerling et al. 2006), and these trends in wildfire are probably driving most of a similar increase in fire suppression costs.

Recent research has demonstrated the feasibility of producing seasonal forecasts of temperature, drought, and wildfire activity in the western U.S. (Alfaro et al. 2005a, Alfaro et al. 2005b, Westerling et al. 2002, Westerling et al. 2003a). Based on surveys of fire managers in California and the Southwest (conducted by Corringham, Westerling and Morehouse, manuscript in preparation), these forecasts may be useful for planning wildfire suppression budgets, allocating resources within the annual cycle of fire seasons in different parts of the U.S.,

and prioritizing fuels management projects. Obstacles remain however, from mismatches between the timing of decision-making and the time horizon of skillful forecasts, to institutional constraints on managers' ability to use climate information and forecasts for wildfire and fuels management.

This chapter has three goals. First, to define what climate, as opposed to weather, is, and to explain what this implies for climate versus weather forecasts. Second, to describe the scientific community's current understanding of the relationships between climate variability and forest wildfire in the western United States. And finally, to demonstrate a forecast application that exploits these relationships, and their potential applications to the business of forest wildfire management.

2. CLIMATE VERSUS WEATHER

The best way to think about climate and weather is that climate is a process, and weather is an outcome of that process. That is, the Earth's climate is a system of interactions between the Sun's energy and the Earth's oceans, atmosphere and biosphere. Weather is the observed precipitation, temperature, wind, etc., that result from those interactions. Understanding the difference between climate and weather is important because it gives us insight into the limitations of what a description of climate (i.e., a *climatology*) or a climate forecast can provide for fire and forest management applications.

A climatology is often expressed as a statistical description of the average or *normal* outcomes (weather) of the climate system, such as the average rainfall or temperature to be expected in a given place and time of year, and the typical variability that has been observed around that average. This is different from a description of all the possible outcomes. We might have an idea about the range of possible outcomes based on a physical model or inferences drawn from observations, but a typical climatology is a statistical description of past weather observations available for a particular region. An example is the empirical history of standardized August temperature anomalies (i.e., deviations from the mean for that month) for 110 western U.S. climate divisions collected from 1895 to 2004 (Figure 6.1, vertical grey bars) (Karl and Knight 1985, NCDC 1994). These temperature anomalies are normally distributed, such that the observed probability of any given mean August temperature can be approximated by a smooth curve calculated from the mean and variance of the historical temperature anomalies (the black line in Figure 6.1).

In conceptual terms, a climate forecast is a forecast of what kind of climate process will be operating at some point in the future, and a weather forecast is a forecast of what outcomes should be expected from the climate processes operating at some point in the future. In practical terms, the greatest distinctions between weather and climate forecasts are their lead times, duration and their degree of uncertainty. A weather forecast makes a prediction about rainfall, precipitation, wind, etc., over relatively short time horizons: the next hour, day, or

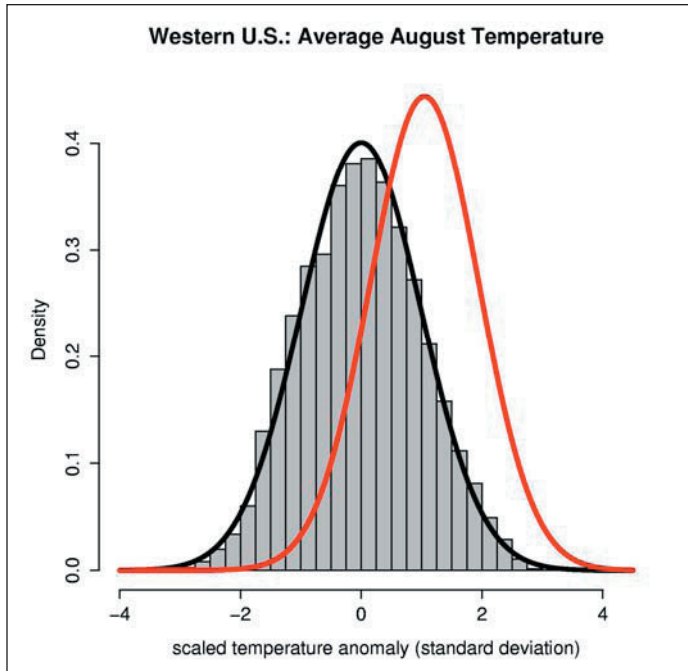


Figure 6.1. Scaled western U.S. August temperature anomalies (i.e., deviations from the mean for that month) for 110 climate divisions from 1895-2004 are used to calculate an empirical probability density (vertical grey bars) that is closely approximated by a normal distribution with mean = 0 and variance = 1 (black line). The subset of August mean monthly temperatures following a July with mean temperature > 2 standard deviations above the mean for all July's is also normally distributed, with mean = 1 and variance = 0.8 (red line). The red line represents a forecast for August temperature conditional on observed July temperature being > 2 standard deviations above the July mean.

week. A climate forecast makes a prediction about these parameters over longer time horizons: over the next month, over a season starting a year from now, etc. Because a weather forecast deals with the near future, the range of likely outcomes for a weather forecast is narrower than for a climate forecast. This is because the conditions immediately preceding tomorrow's forecast (that is, today's observations) are well known, while the conditions immediately preceding next month's or next season's forecast are not yet observed. Since the climate is such a complex system, the longer the time between observations and prediction, the harder it is to confidently predict what will happen at any point in time. As a result, a weather forecast might specify the chance of rain tomorrow afternoon, while a climate forecast would more likely specify the chance that the cumulative total rainfall

over the next month or season will be above or below normal.

A climate forecast usually provides a description of expected outcomes conditional on observations in the recent past. As an extreme case, a climatology can be thought of as a forecast of the future climate system based on all available past observations. Such a forecast might change gradually from year to year, as additional observations are incorporated into parameters like the mean and variance that describe some aspect of the climate system.

A more useful forecast would be one that uses past associations between observations and subsequent outcomes. For example, scientists have observed that after an El Niño develops—signified by warmer than average sea surface temperatures in the eastern equatorial Pacific—above average rainfall and temperatures have often subsequently been experienced in the U.S. Southwest (Dettinger et al. 1998, Gershunov et al. 1999). A climate forecast might describe the likelihood of these outcomes conditional on an El Niño signal having been observed (or not) in the Pacific. Going back to the western U.S. August temperature example (Figure 6.1), a climate forecast might take advantage of persistence in temperature trends; warmer than average Julys tend to be followed by warmer than average Augusts. Looking at August temperature anomalies following very warm July temperatures (when the July temperatures were more than 2 standard deviations above the mean, i.e., in the top 2.3% of observed July monthly mean temperatures), mean August temperatures are warmer than average (1 standard deviation above the mean, i.e., in the top 15.9% of observed August monthly mean temperatures). The temperature forecast for August, conditional on the temperatures observed in July, can be represented by a curve that uses the mean and variance of the subset of August temperature anomalies that followed a very warm July to calculate the conditional probability of experiencing any given August temperature (Figure 6.1, grey line).

In terms of practical applications for fire management, weather forecasts are appropriate for supporting operational decisions during a fire season, since they deal directly with variables of interest to fire managers with short time horizons suitable to managing a fire. Climate forecasts are more appropriate for activities that precede a fire season or take place over a longer period, like budgeting and pre-positioning resources for fire suppression, undertaking pre-suppression activities to reduce the risk of wildfire ignition and spread, and prioritizing resources for fuels management projects.

3. CLIMATE AND FOREST WILDFIRE

3.1 Moisture, fuel availability, and fuel flammability

Climate affects wildfire risks primarily through its effects on moisture availability. Wet conditions during the growing season promote fuel—especially fine fuel—production via the growth of vegetation, while dry conditions during and prior to the fire season increase the flammability of the live and dead vegeta-

tion that fuels wildfires (see, for example, Swetnam and Betancourt 1990, 1998; Veblen et al. 1999, 2000; Donnegan 2001, Westerling et al. 2003b). Moisture availability is a function of both cumulative precipitation and temperature. Warmer temperatures can reduce moisture availability via an increased potential for evapo-transpiration¹, a reduced snowpack, and an earlier snowmelt. In much of the West, three quarters or more of annual water year (ie, October to September) precipitation occurs by the end of May (Westerling et al. 2003a). Snowpack at higher elevations is an important means of making part of winter precipitation available as runoff in late spring and early summer, and a reduced snowpack and earlier snowmelt consequently lead to a longer, drier summer fire season in many mountain forests (Westerling 2006).

For wildfire risks in most western forests, interannual variability in precipitation and temperature appear to have a greater effect on forest wildfire via their short-term effects on fuel flammability, as opposed to their longer-term affects on fuel production. By way of illustration, we show average Palmer Drought Severity Index (PDSI, see NCDC 1994) values for the month of ignition and also for the March prior to the growing season one year earlier for 1166 large forest wildfires on USDA Forest Service (USFS) and USDI National Park Service (NPS) lands in the western United States, by elevation (Figure 6.2). PDSI is a meteorological drought index that uses precipitation and temperature anoma-

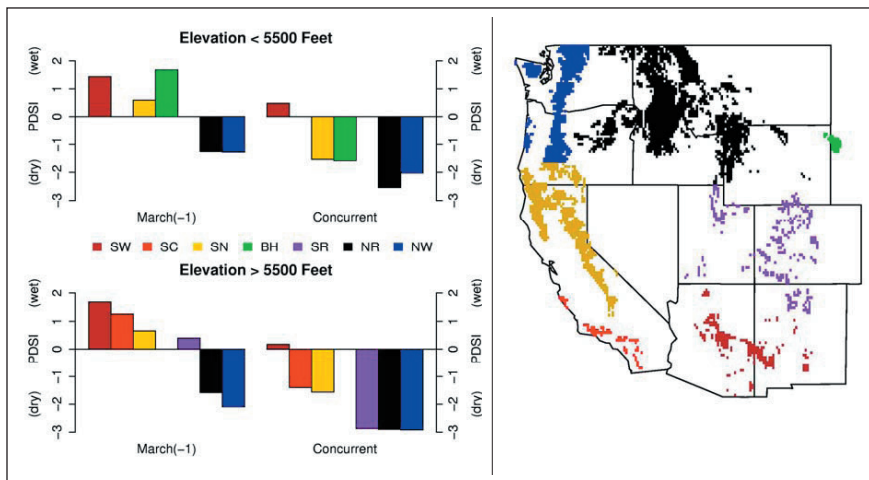


Figure 6.2. (left) Average Palmer Drought Severity Index values for the month a large forest wildfire started, and for the March a year or more before, by elevation for seven forest regions (regions shown at right). Regions are roughly ordered by mean latitude from south to north. BH had too few fires above 5500 feet, and SR too few below 5500 feet, to calculate representative mean PDSI values.

¹ I.e., evaporation from soils and surface water, and from vegetation.

lies to estimate the duration and severity of long-term drought (Alley 1984 and 1985). Positive values of the index represent wet conditions, and negative values represent dry conditions. We use it here as an indicator of the moisture available for the growth and wetting of fuels.

This analysis included all fires over 1000 acres that have burned since 1970 in land management units that have been reporting consistently since 1970 for the two agencies, and account for the majority of large forest wildfires west of 101°W Longitude in the contiguous U.S. (see Westerling et al. 2006 (online supplement) for a detailed description of this data set). The fires have been aggregated into seven regions: mountain ranges of Arizona and New Mexico excluding the Southern Rockies (SW), the mountains of coastal southern and central California (SC), the Sierra Nevada and southern Cascades and Coast Ranges (SN), the Black Hills of South Dakota and Wyoming (BH), the Central and Southern Rockies between 35.3 and 42° N (SR), the Northern and Central Rockies between 42 and 49° N Latitude (NR), and the Cascades and Coast Ranges above 43.1° N (NW) (see Figure 6.2).

For all but SW, conditions were drier than average when large forest wildfires burned, with the magnitude of the drought increasing roughly with latitude and elevation (Figure 6.2). In the SW, the frequency of large wildfires peaks in June, ignited by monsoonal lightning strikes before the monsoon rains wet the fuels (Swetnam and Betancourt 1998). Since the lightning ignitions are associated with subsequent precipitation, it is possible that the monthly drought index may tend to appear to be somewhat wetter than conditions were at the time of ignition.

In the two northernmost regions—NR and NW—conditions also tended to be drier than normal in the preceding year: extended drought increased the risk of large forest wildfires in these wetter northern forests. In SW, SC, SN and SR, the preceding year is wetter than average. For fires above 5500 feet in elevation, the importance of surplus moisture in the preceding year was greatest for the southernmost regions. Swetnam and Betancourt (1998) found that moisture availability in antecedent growing seasons was important for fire risks in open pine forests in the SW where fine fuels play an important role in providing a continuous fuel cover for spreading wildfires, but not in mixed conifer forests. Looking at the western U.S. more broadly, the moisture necessary to support denser forest cover tends to increase with latitude and elevation. Consequently, the shift in Figure 6.2 from wet to dry growing season conditions a year before a large fire as one moves from the forests of the SW to those of the NW is broadly consistent with a decreasing importance of fine fuel availability—and an increasing importance of fuel flammability—as limiting factors for wildfire as moisture availability increases on average.

3.2 Forest Wildfire and the Timing of Spring

There has been a dramatic increase in the incidence of large forest wildfire in the western U.S. since the early 1980s, with the number of fires increasing over

500 percent and area burned increasing nearly 760 percent (Figure 6.3, Table 6.1). While the incidence of large forest wildfires has increased everywhere in the West, the change in the Northern Rockies has been extraordinary: an 1100 percent increase in large fires, and a 3500 percent increase in area burned (Table 6.1). As a result, the NR accounts for a rising share of western forest wildfires—from under 28 percent before 1985 to over 55 percent subsequently—as well as a rise from 14 percent to 61 percent of area burned in western forests (Figure 6.3, Table 6.1). With the NR accounting for 60 percent of the increase in western wildfires and 67 percent of the increase in area burned, understanding the factors behind the increase in NR forest wildfire activity is key to understanding the recent trends and interannual variability in western forest wildfire.

Westerling et al. (2006) note that the NR has a large forested area between about 5500 and 8500 feet in elevation where the length of the average season completely free of snow cover is relatively short (two to three months) and highly sensitive to variability in regional temperature, increasing roughly 30% in the earliest third of snowmelt years over the season length in the latest third of snowmelt years. They observed that in years with an early spring snowmelt, spring and early summer temperatures were higher than average, winter precipitation was below average, the dry soil moistures typical of summer in the region came sooner and were more intense, and vegetation was drier.

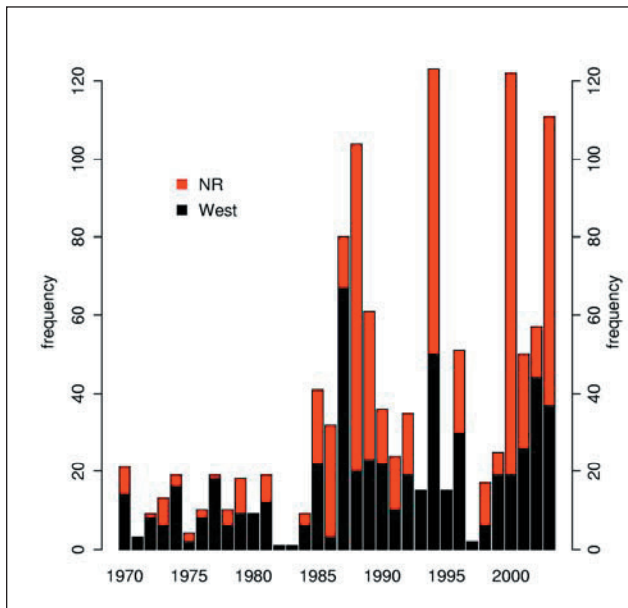


Figure 6.3. Annual number of forest fires greater than 1000 acres (total column height). Red shaded area indicates the annual number of large fires in the Northern Rockies.

Table 6.1. Change in Large Fire Frequency and Area Burned, 1970–1984 versus 1985–2003.

	Change in Frequency	1970–1984 share of total	1985–2003 share of total	Change in Area Burned	1970–1984 share of total	1985–2003 share of total
NW	256% 1.84 (0.08)	10%	6%	558% 1.83 (0.08)	8%	6%
NR	1100% 3.64 (0.00)	28%	55%	3523% 2.43 (0.03)	14%	61%
BH	250% 1.76 (0.09)	4%	2%	42% 0.12 (0.90)	9%	2%
SN	343% 2.52 (0.02)	24%	18%	671% 2.24 (0.04)	22%	19%
SR	104% 1.30 (0.21)	12%	5%	464% 1.18 (0.25)	7%	5%
SC*	71% 0.65 (0.52)	4%	1%	-74% -1.23 (0.24)	27%	1%
SW	354% 3.52 (0.00)	16%	12%	371% 2.70 (0.01)	11%	6%
WEST	507% 4.68 (0.00)	100%	100%	759% 3.22 (0.00)	100%	100%

The statistics here are for only those wildfires greater than 1000 acres that burned primarily in forests, of which there were only 19 in SC since 1970. SC has experienced a number of large wildfires that ignited and primarily burned in chaparral, but spread to and burned substantial forested area, such as the Cedar fire in October 2003, that are not included here and might significantly affect the results for SC.

The consequences of an early spring for the NR fire season are profound. Comparing fire seasons for the earliest versus the latest third of years by snowmelt date, the length of the NR wildfire season (defined here as the time between the first report of a large fire ignition and last report of a large fire controlled) was 45 days (71%) longer for the earliest third than for the latest third. Sixty-six percent of large fires in NR occur in early snowmelt years, while only nine percent occur in late snowmelt years. Large NR wildfires in early snowmelt years, on average, burn 25 days (124%) longer than in late snowmelt years.

As a consequence, both the incidence of large fires and the costs of suppressing them in the NR are highly sensitive to spring and summer temperatures (Figures 6.4A and B). Both large fire frequency and suppression expenditure appear to increase with spring and summer average temperature in a highly non-linear fashion. Suppression expenditure in particular appears to undergo a shift near 15°C. Temperatures taken separately above and below that threshold are not

significantly correlated with expenditures, but the mean and variance of expenditures increase dramatically above it.

4. SEASONAL FORECASTS FOR WILDFIRE IN THE NORTHERN ROCKIES

Given that the Northern Rockies has played such a dominant role in wildfire in western forests in recent decades, it makes a good candidate for an example forecast. Given its sensitivity to temperature, the key to forecasting wildfire activity in the Northern Rockies is whether spring and summer temperature can be forecast with any skill in the western U.S. Alfaro et al. (2005, 2006) report significant skill forecasting maximum summer temperature on time horizons of a month to a season in advance. Westerling (2005) has applied the same methodology to forecast average March through August temperature as of April 1 for use in wildfire forecasting applications.

North Pacific sea surface temperatures (SSTs) and PDSI for western U.S. climate divisions, both observed in March, are used to forecast average spring and summer temperatures by climate division using Canonical Correlation Analysis (CCA, see Barnett and Priesendorfer 1987, Westerling et al. 2002, Alfaro et al. 2005 for a detailed description of the forecast methodology). The CCA methodology matches spatial patterns in North Pacific SST anomalies and spatial patterns in western U.S. PDSI observed in March to spatial patterns in March – August average temperatures for western U.S. Climate Divisions (Figure 6.5). SSTs are useful here because the oceans store heat, and the pattern of surface temperature anomalies in the oceans influences subsequent weather patterns, providing some predictive skill on seasonal time scales. The El Niño/La Niña cycle is an example of a well-known index describing patterns in the spatial distribution of SST anomalies in the Pacific that is associated with variability in climate in the western U.S. PDSI, as a proxy for soil moisture, is useful as a predictor because “particularly for non-arid inland areas, a wet soil tends to depress the concurrent and subsequent monthly mean temperature, while a drier-than-normal soil is favorable for higher-than-expected monthly means...” (Durre et al. 2000).

A cross-validated regression model using forecast temperature and observed PDSI as predictors (Figure 6.6) explains 47% of the variability in the log-transformed NR fiscal-year area burned from 1977-2003 (adjusted R^2 of 0.47), and 42% of the variability in NR log-transformed fiscal-year suppression costs (adjusted R^2 of 0.42).² Cross-validation in this case means that the coefficients

² The model specification is $\ln(Y) = T \times \text{PDSI} + \epsilon$, where $\ln(Y)$ is the natural logarithm of either fiscal-year area burned or fiscal year suppression costs for fires on Forest Service lands in the NR, T is the regional temperature forecast, PDSI is the local climate division PDSI value for March, and ϵ are the errors. Fiscal year area burned data were provided by Krista Gebbert, USDA Forest Service Rocky Mountain Research Station.

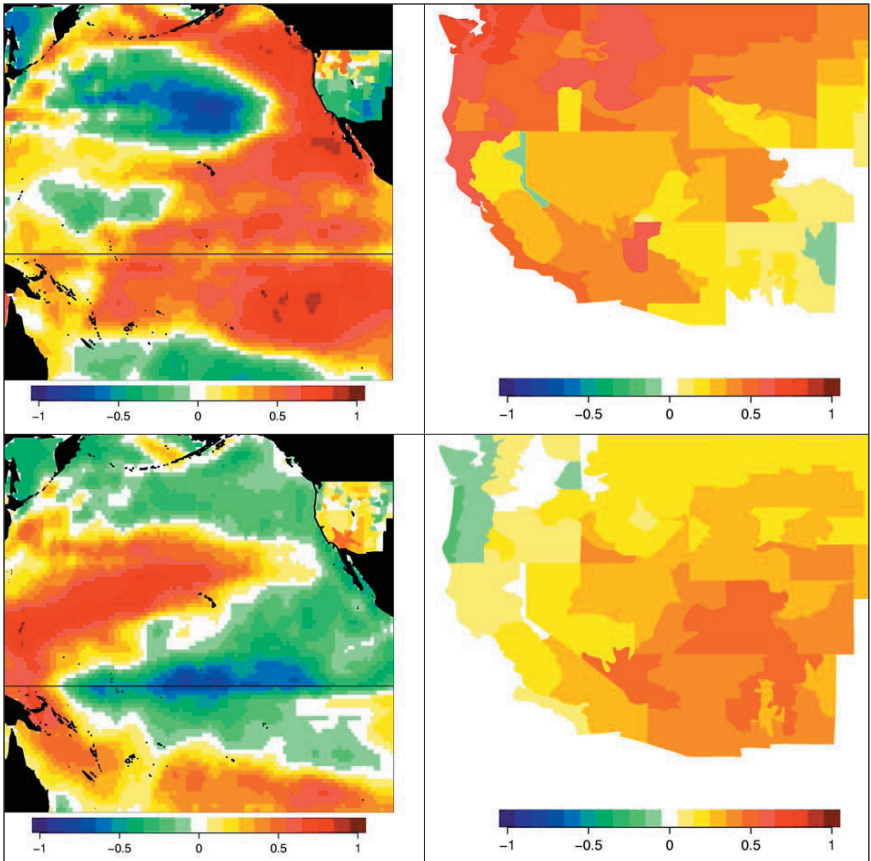


Figure 6.5. Spatial patterns in March Pacific sea surface temperatures and drought (PDSI) associated with spatial patterns in spring and summer (March to August) average temperature. Upper left: correlations between the 1st Canonical Correlation predictor and both gridded Pacific SSTs and negative climate division PDSI. Negative PDSI is used so that a positive correlation with PDSI indicates a positive correlation with dry conditions, and a positive correlation with SSTs indicates a correlation with warm anomalies in the Pacific. Upper right: correlations with the 1st Canonical Correlation predictor and MAMJJA average temperature by climate division. Lower left and lower right: as above, for 2nd Canonical Correlation predictor. A linear combination of these two patterns allows us to predict average temperature.

for both the temperature forecast model and the log-area burned forecast model were recalculated for each year, while withholding information about the year being retrospectively forecast when calculating the model coefficients used to make that year's forecast. Consequently, the results appear less skillful than they

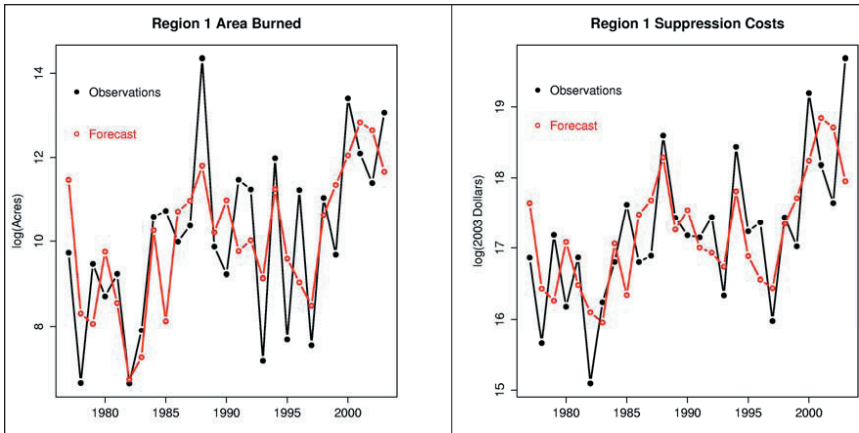


Figure 6.6. (Left) Region 1 log area burned forecast and (Right) Region 1 log suppression expenditures forecast models. The forecasts are leave-one-out cross-validated regressions on cross-validated CCA MAMJJA Temperature forecasts and the interaction between the March Palmer Drought Severity Index and the MAMJJA Temperature forecast.

would for the same model without cross-validation, but they are a better indication of the true forecast skill³ to be expected on average.

While a cross-validated R^2 of 0.47 or 0.42 is actually considered to be quite good for a seasonal forecast, it is important to keep in mind the limitations of models like this. The quantities being forecast—area burned or suppression costs—are highly variable from year to year, are not conveniently normally distributed like the temperature anomalies in Figure 6.1, and much of that variability is driven by factors other than seasonal temperature and precipitation. The log-transformation used in modeling area or cost (as in Figure 6.6) tends to obscure the very large absolute forecasting errors observed in high-temperature (and therefore high-fire-risk) years (Figure 6.7). For example, for the nine years with the highest temperatures (one third of the sample), the absolute level of the forecast errors averaged about \$70 million (adjusting for inflation to 2003 constant dollars), or about 75% of the actual expenditures for each year.

While there is a high level of uncertainty associated with these forecasts using PDSI and Pacific SSTs, they are very good at telling us whether we are about to experience one of the infrequent but very active fire seasons that account for the majority of suppression costs (Figure 6.7). In most years there are relatively few large fires and suppression costs are low, while a handful of extreme years

³ “Forecast skill” refers to the accuracy with which the forecast anticipates reality.

There are many ways to assess this accuracy, including measures such as correlation, percentage of variance explained, and probability of surprise. These three particular measures are reported for the example forecast model presented here.

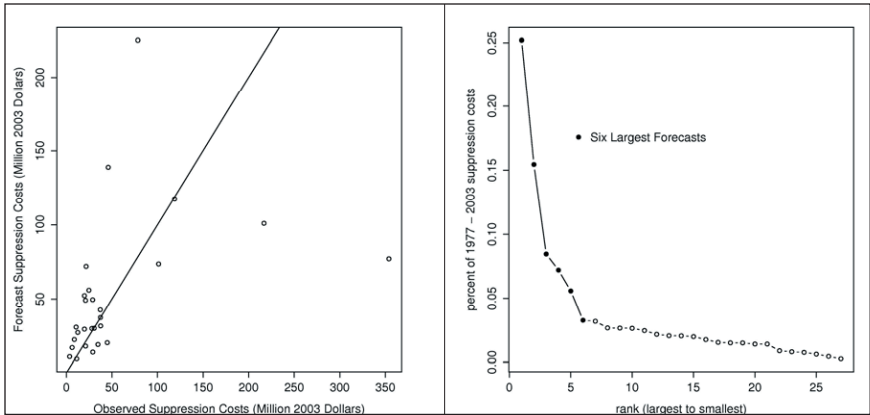


Figure 6.7. (Left) Northern Rockies observed versus forecast suppression cost 1977–2003. Diagonal line is the 45° line where observations would equal forecast values. Forecast model distinguishes between high and low suppression cost years. (Right) Ranked fiscal-year observed suppression costs for USDA Forest Service in the Northern Rockies (Region 1) as percent of total for 1977–2003. The six largest suppression cost years account for 65% of 1977–2003 USFS suppression expenditures in Region 1, and are also the six years with the largest forecast suppression costs.

accounts for the majority of the impacts from wildfire. In NR, the five largest years (all greater than \$65 million) account for 62% of the Forest Service’s suppression expenditures there since 1977 (and 83% of total area burned there since 1977). Cross-validated retrospective forecasts correctly estimated that 21 of the 27 years in the sample would cost below \$65 million (Table 6.2). Of the six remaining years—all forecast to be above \$65 million—five were observed above \$65 million. The sixth was still among the years with the six largest observed suppression costs.

Drought indices and North Pacific sea surface temperatures observed in March are sufficient to make a skillful categorical forecast that can distinguish between “mild” and “extreme” fire years in the Northern Rockies. In terms of the climate

Table 6.2. Northern Rockies Contingency Table: Observations versus Forecasts of Extreme Fire Years’ Suppression Costs

Observed	Forecast	
	< \$65 Million	> \$65 Million
< \$65 Million	21	1
> \$65 Million	0	5

forecast framework introduced in the first section, this is equivalent to forecasting a season in advance which of two probability distributions for wildfire will be pertinent. While we do not have enough realizations (years) to describe these probability distributions empirically (as in e.g. Figure 6.1), it may be possible to parameterize them sufficiently to describe shifts in the probability of extremes (see Holmes et al., this volume).

Forecasts of area burned or suppression costs made on April 1 come at least three months prior to the NR fire season, which is usually concentrated in July and August. While the Forest Service's fiscal year begins in October, an April forecast is still potentially useful for reallocating suppression resources across regions within the over-all allocation for suppression. In addition, with advance notice of a potentially active fire season, the agency may re-allocate funds from other activities to suppression. Forecasts at this lead-time may also be used to support seasonal hiring decisions, and decisions regarding the use of prescribed fire to meet vegetation management objectives.

5. CONCLUSION

While concerned with many of the same variables—such as precipitation and temperature—climate forecasts are different from weather forecasts. Climate forecasts are made at much longer lead times than weather forecasts (months to seasons rather than days to weeks in advance), but they are not simply long-lead weather forecasts. Climate forecasts are less precise than weather forecasts: they describe changes in underlying processes that are often expressed in terms of changes in average or cumulative conditions over longer time frames than a weather forecast.

Forest wildfire in the western U.S. is strongly influenced by spring and summer temperatures and by cumulative precipitation. The effect of temperature on wildfire risks is related to the timing of spring, and increases with latitude and elevation. The greatest effects of higher temperatures on forest wildfire in recent decades have been seen in the Northern Rockies, and a handful of fire seasons account for the majority of large forest wildfires and of total suppression expenditures in that location. A seasonal climate forecast for spring and summer temperatures would thus be of value in anticipating the severity and expense of the forest wildfire season in much of the western U.S., and would be of particular value in the Northern Rockies.

In an example application of a climate forecast for the Northern Rockies, seasonal temperature forecasts using Pacific sea surface temperatures and proxies for soil moisture (PDSI) allow managers to anticipate extreme fire seasons in the Northern Rockies with a high degree of reliability. As is often the case with climate forecasts however, forecasts for the Northern Rockies do not provide a large degree of precision: while they can indicate whether a mild or active wildfire season is likely, they cannot provide a precise estimate of the level of area burned or suppression expenditures given a mild or extreme forecast.

6. REFERENCES

- Alfaro, A., A. Gershunov, D. Cayan, A. Steinemann, D. Pierce and T. Barnett, 2004: A Method for Prediction of California Summer Air Surface Temperature. *EOS*, 85(51), 553, 557-558.
- Alfaro, A., A. Gershunov and D. Cayan, 2006: Prediction of summer maximum and minimum temperature over the central and western United States: The role of soil moisture and sea surface temperature. *J. Climate*, in press.
- Alley W. M. 1984: The Palmer Drought Severity Index: limitations and assumptions. *Journal of Climate and Applied Meteorology*, 23, 1100-1109.
- Alley W. M. 1985: The Palmer Drought Severity Index as a Measure of Hydrologic Drought. *Water Resources Bulletin*, 21, 105-114.
- Balling R. C., G. A. Meyer and S. G. Wells 1992: Relation of Surface Climate and Burned Area in Yellowstone National Park. *Agricultural and Forest Meteorology*, 60, 285-293.
- Barnett T. P., R. Preisendorfer 1987: Origins and levels of monthly and seasonal forecast skill for the United States surface air temperatures determined by canonical correlation analysis, *Monthly Weather Review*, 115, 1825-1850.
- Durre, I., J. Wallace and D. Lettenmaier, 2000: Dependence of extreme daily maximum temperatures on antecedent soil moisture in the contiguous United States during summer. *J. Climate*. 13, 2641-2651.
- Dettinger, M. D., D. R. Cayan, H. F. Diaz, and D. M. Meko, 1998: North-south precipitation patterns in western North America on interannual-to-decadal time scales. *J. Clim.*, 11, 3095.
- Donnegan J. A., T. T. Veblen, S. S. Sibold, 2001: Climatic and human influences on fire history in Pike National Forest, central Colorado. *Canadian Journal of Forest Research*, 31, 1527-1539.
- Gershunov, A., T.P. Barnett and D.R. Cayan, 1999: North Pacific interdecadal oscillation seen as factor in ENSO-related North American climate anomalies. *EOS*, 80 (3), 1, 25-30.
- Heyerdahl, E.K, L.B. Brubaker, and J.K. Agee. 2001. Factors controlling spatial variation in historical fire regimes: A multiscale example from the interior West, USA. *Ecology* 82(3): 660-678.
- Karl T. R., R. W. Knight 1985: 'Atlas of Monthly Palmer Hydrological Drought Indices (1931-1983) for the Contiguous United States.' Historical Climatology Series 3-7, National Climatic Data Center, Asheville, NC.
- Kipfmueller K. F., T. W. Swetnam 2000: Fire-Climate Interactions in the Selway-Bitterroot Wilderness Area. USDA Forest Service Proceedings RMRS-P-15-vol-5.
- NCDC, 1994, Time Bias Corrected Divisional Temperature-Precipitation-Drought Index. Documentation for dataset TD-9640. Available from DBMB, NCDC, NOAA, Federal Building, 37 Battery Park Ave. Asheville, NC 28801-2733. 12pp
- Swetnam TW, J. L. Betancourt, 1990: Fire-Southern Oscillation Relations in the Southwestern United States. *Science*, 249, 1017-1020.

- Swetnam T. W., J. L. Betancourt, 1998: Mesoscale Disturbance and Ecological Response to Decadal Climatic Variability in the American Southwest. *Journal of Climate*, 11, 3128-3147.
- Veblen T. T., T. Kitzberger, J. Donnegan, 2000: Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. *Ecological Applications*, 10, 1178-1195.
- Veblen TT, Kitzberger T, Villalba R, Donnegan J (1999) Fire history in northern Patagonia: the roles of humans and climatic variation. *Ecological Monographs*, 69, 47-67.
- Westerling, A.L., A. Gershunov, D.R. Cayan and T.P. Barnett, 2002: "Long Lead Statistical Forecasts of Western U.S. Wildfire Area Burned," *International Journal of Wildland Fire*, 11(3,4) 257-266.
- Westerling, A.L., A. Gershunov and D.R. Cayan, 2003a: "Statistical Forecasts of the 2003 Western Wildfire Season Using Canonical Correlation Analysis," *Experimental Long-Lead Forecast Bulletin*, 12(1,2).
- Westerling, A.L., T.J. Brown, A. Gershunov, D.R. Cayan and M.D. Dettinger, 2003b: "Climate and Wildfire in the Western United States," *Bulletin of the American Meteorological Society*, 84(5) 595-604.
- Westerling, A.L., H.G. Hidalgo, D.R. Cayan, T.W. Swetnam 2006: "Warming and Earlier Spring Increases Western U.S. Forest Wildfire Activity" *Science*, 313: 940-943. online supplement: <http://www.sciencemag.org/cgi/content/full/sci;1128834/DC1>