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The Fire-Climate Connection

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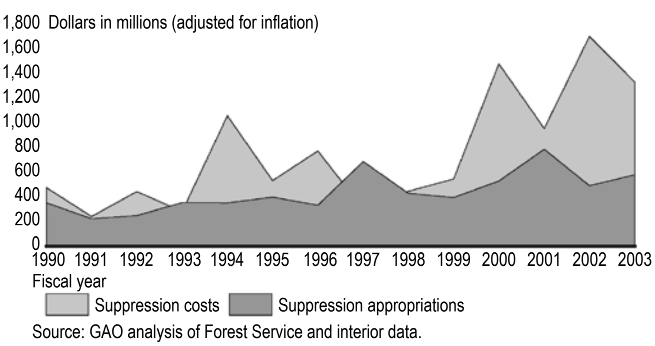
The Fire-Climate Connection

JFSP-funded research is exploring and quantifying relationships among the large-scale drivers of climate and the occurrence and extent of wildfire in the various regions of the western United States.

In recent decades, large fires in the West have become more frequent, more widespread, and potentially more deadly. In 2003, a particularly severe fire season, wildfires burned about 4 million acres, destroyed 5,000 structures, and took the lives of 30 firefighters.

In addition, dealing with wildfires is becoming more and more expensive. The 2003 fire season racked up more than $1 billion in suppression costs. The bill for suppressing wildfires on public lands has exceeded the amount appropriated almost every year since 1990, according to the General Accounting Office.



Wildfire suppression costs have exceeded appropriations almost every year since 1990. (Reprinted from GAO-04-612.)

Wildfire has always been a periodic visitor to western forests, part of the cycle of natural dynamics that make these forests what they are. Until recently, the standard explanation for increased wildfires in recent decades has been an unnatural buildup of fuel stemming from a century of fire suppression. Ecologists now say the story is far more complicated than that—that climate, in fact, can have a stronger fingerprint in many areas.

A complex of stressors

Climate is, of course, the most important natural shaper of forest ecosystems. It affects the location and composition of forests and the frequency and extent of periodic fire. Climate, interacting with the ecosystem to produce wildfire regimes, is largely responsible for the considerable differences in the forest types that exist across the West at various latitudes and elevations. Factors such as precipitation, temperature, and topography (which, over the long haul, is also driven by climate) combine to influence the vegetation that can grow in a given place, as well as the timing, severity, and extent of burns. These in turn influence the type of forest that gets established. Forests thus owe their distinctive identities to historical patterns of climate and recurring fire.

Pre-twentieth-century fire was highly variable across different landscapes. Large, stand-replacing fires were typical of forests in cool, wet climates, such as coastal Douglas-fir and interior, high-elevation lodgepole pine and Engelmann spruce. In contrast, lower-lying forests in warmer, drier climates tended to experience less intense fires more often, about every 5 to 20 years. Such fires in the ponderosa pine forests of the high desert of the southwestern United States or the mixed conifer forests of the Sierra Nevada, for instance, would kill many young trees and most shrubs, but would spare the older, fire-resistant trees and renew a grassy or herbaceous understory.

Recent decades have brought a shift to more-severe fires in some locations, disrupting historical patterns and putting unaccustomed stress on forest ecosystems, especially those adapted to low-level periodic fire. The fires' effects are often exacerbated by drought and insect attack, both of which are expected to increase with rising temperatures. These assaults add up to a complex of stressors that can alter the composition and structure of forest ecosystems.

Quick turnaround

The rise of global temperatures that began in the past century was a rapid reversal of a much longer cooling trend. The effects of warming are not smooth or steady, but discontinuous in space and time. In general, the places and times that were coolest to start with have warmed the most: nighttime low temperatures, winter temperatures, and temperatures at high latitudes and high altitudes. Not only rising mean temperatures are of concern, however, but also an increase in the variability of the climate that might lead to more extreme weather events.

Fire scientists and land managers are particularly worried about the confluence of warming temperatures, high fuel loads, and impending drought in particular areas. "Many of us who work in climate and ecology think we're facing another megadrought, a natural trigger to stand-replacing fires—but this time with unnaturally large fuel loads in some forests poised for severe burns," says Tom Swetnam, a forest ecologist and fire scientist who directs the Laboratory of Tree-Ring Research at the University of Arizona. Some scientists predict that the area burned in wildfires will double or even triple over the next 50 years. At risk are human communities, soil productivity, forest biodiversity, drinking water sources, and habitat for sensitive species.

In extreme cases, a one-two punch of high-severity fires and a warming climate could alter environmental conditions so much that native seedlings would have a hard time getting established after a stand-replacing fire. As far as can be determined from ancient records, past climate changes, although slower than this one, have produced large ecological reorganizations along with dramatic changes in fire regimes. "Systems can change quickly when ecological thresholds are exceeded," says Don McKenzie, research ecologist with the Fire and Environmental Research Applications (FERA) team of the USDA Forest Service Pacific Northwest (PNW) Research Station. "Unfortunately, we don't always know what those thresholds are until we see them appear in specific ecosystems, usually in unique ways."

What is more, scientists worry that increasing fires will erode the capacity of forests to absorb carbon from the atmosphere. Currently, forests in the western United States are net carbon sinks, soaking up 20 to 40 percent of all carbon sequestered in the country. That means they help soften the greenhouse effect by taking up carbon emitted into the atmosphere from natural and human sources. If current wildfire trends continue, however, the forested landscape may become a source of carbon rather than a sink.

Urgent questions

Recent research by climatologists, biologists, geographers, and fire ecologists has revealed that fires in western forests are more strongly linked to climate than was previously thought. But the specific linkages are as yet poorly understood. More practically, from a land-management perspective, it is not easy to sort through the scientific findings and pick out the most useful ones for planning and on-the-ground management.

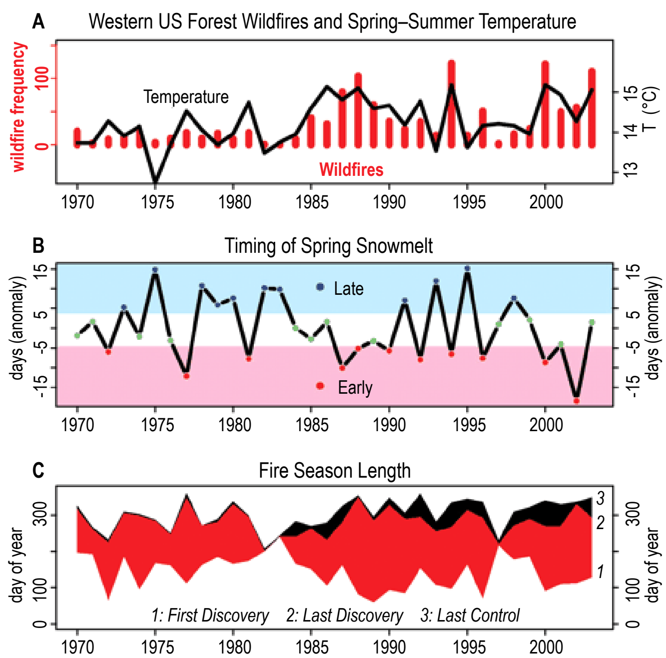
The questions have become urgent with successive record-setting fire seasons in 2005 and 2006. A key study published in *Science* in August of 2006 used real-time

Calculating Carbon

Carbon dioxide is a natural product of the combustion of living or once-living material. A wildfire throws enormous quantities of carbon dioxide into the air. Estimating exactly how much is a complicated business, because forests vary widely in the amount of biomass—living or once-living matter—they contain. Carbon moves constantly between its solid and gaseous states. Trees take in carbon during the summer growing season and release it during winter dormancy. (In mild-winter areas, some trees and other vegetation photosynthesize and fix carbon all year long.)

The amount of carbon dioxide released in a wildfire depends on the total biomass of the forest burned and how thoroughly it is burned. Biomass in a temperate coniferous forest may measure 1,000 kg to the hectare, according to John Christie, a chemist at LaTrobe University in Victoria, Australia. Carbon dioxide contains about 27 percent carbon. Therefore, if a fire were to consume the total biomass of such a forest, each burned hectare would theoretically release 27 percent of its biomass, or 270 kg, as carbon into the atmosphere.

In reality, no wildfire is so efficient, says Christie, so such estimates need to be moderated considerably. In addition, biomass contains other elements that are emitted as gas and particulate matter. Nevertheless, more and bigger wildfires threaten to turn forests into an increasing source of atmospheric carbon dioxide, a major contributor to global warming.



(A) The red bars indicate annual frequency of large (>400 ha) wildfires in western U.S. forests; the black line indicates mean March through August temperature. (B) The black line traces the timing of streamflow in snowmelt-dominated streams from 1970. (C) Length of the annual fire season from 1970, shown as the length of time between the first and last large-fire ignition and last large-fire control. (From Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313 (5789): 940–943, 18 August 2006; Reprinted with permission from AAAS.)

climate records to make a strong link between rising temperatures and increasing wildfire in the northern Rocky Mountains. The researchers, led by A.L. (Tony) Westerling of the University of California at Merced, found that warming temperatures and earlier springs are triggering increased wildfire activity in forests in the northern Rockies.

In the face of these trends, what's a manager to do? How does climate affect fire conditions on the land? And how will a changing climate alter those patterns? Scientists supported by the Joint Fire Science Program (JFSP) and others are striving to discover and quantify the cascade of dynamics between large-scale movements of ocean and atmosphere and the specific weather conditions that influence when and where a wildfire will occur. They are also working on turning fire-climate research into practical tools for managers—developing reliable support for decisions on how to make landscapes more resilient to fire and how to allocate fire suppression and fuel-treatment dollars where they will do the most good.

Weather

Does climate affect wildfire? It is well known that fire risk is tied to weather, and weather conditions are a key influence on whether wildfire will occur and how far it will spread.

Specifically—and forest managers know this well from experience—drought is the key factor in how many fires will be ignited that year and how much land they will burn. Summer drought is particularly important in the dry West; in the eastern United States winter and spring precipitation is very important. "We all know we get fires when it's hot and dry," says Carl Skinner, geographer and science team leader at the Forest Service Pacific Southwest Research Station in Redding, California. "We're trying to understand what sets us up for these hot, dry periods."

Drought affects soil moisture, which affects dryness of fuels, which affects both the likelihood they will ignite and the size of the area the fires will burn. Drought is intimately bound up with fire's other main factor, temperature. Warmer air leads to more evaporation of water from the surface. If soil is completely dry, evaporation decreases and its cooling effects are diminished, so that surface temperatures rise even further—a positive feedback that increases drought's severity.

Temperature also affects the timing of seasonal events: for example, spring snowmelt in the Rocky Mountains. Timing of snowmelt has a big influence on how dry the summer will be and how much moisture will be in the soil, and hence how severe the fire season will be.

At the other end of the scale from the local weather effects are the large-scale physical processes making them happen. "The Earth's climate is a system of interactions between the Sun's energy and the Earth's atmosphere, oceans, and biosphere," according to Tony Westerling, lead author of the study linking increased wildfire with earlier springs in the Rockies. "Weather is the observed

Springtime in the Rockies

A key piece of research on the fire-climate connection strongly suggests that a changing climate is driving the increase in frequency and extent of wildfires in the northern Rockies. The paper, by A.L. Westerling, H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam, was published in August 2006 in *Science*. It draws on a large set of weather measurements to show that higher temperatures are causing spring to come earlier in the northern Rockies, leading to drought and increased fire later in the summer.

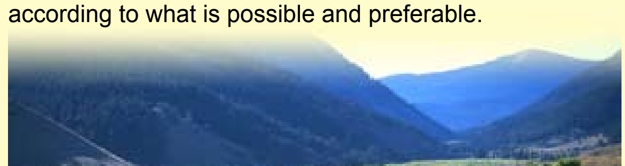
The researchers examined a comprehensive timeline of 1,166 large wildfires that occurred in the West since 1970 and compared it with rainfall records in seven different forested areas. Over that 35-year period, they found that spring and summer temperatures were on the rise, snowpacks were melting earlier, and the summer dry season was becoming longer and hotter. The length of the fire season (the period when large wildfires are actually burning) has increased by 78 days—more than a month on average at both ends of the summer. Four times as many wildfires have occurred since 1987 as during the previous 17 years, and six times as much acreage has burned.

The researchers attribute the increase to rising spring and summer temperatures, an earlier snowmelt, and a consequently longer dry period in the summer and fall. Early-snowmelt years had five times as many fires as late-snowmelt years.

Effects varied by region and forest type. The greatest increase in frequency of wildfire was in mid- to high-elevation spruce-fir and lodgepole pine forests in the northern Rockies. These are forests where fire is an infrequent visitor, and so suppression efforts have had little effect on natural patterns. Forests in the Southwest, which have a more extensive history of fire suppression, showed almost as great an increase in large fires, but the increase seems less strongly related to earlier snowmelt.

If climate change rather than fuel buildup is the main driver of forest fires in these areas, say Westerling and his coauthors, then year-by-year restoration and fuel treatments alone—the cornerstone of current federal wildfire policy—will not be very effective in reducing the area burned.

However, in many situations, fuel treatments have been shown to reduce the severity of fires when they do strike. Long-term management plans will need to anticipate what a changing climate will do to a given forest or region and prescribe fuel treatments and restoration measures according to what is possible and preferable.



precipitation, temperature, wind, etc., that result from those interactions."

To put it in a nutshell, there would seem to be no question that climate influences wildfires. But how much of an influence is it? And at what scales is that influence strongest?

Some studies indicate that factors not directly linked to climate—such as local topography, or a human flicking a cigarette out a car window—may be more important at smaller scales. For example, in one JFSP-funded study, Don McKenzie and colleagues with the FERA team in Seattle analyzed historical wildfires in eastern Washington State. They looked for links among the fires' spatial and temporal patterns of spread, the topography of the land burned, and climatic variation. At medium to large scales, drought—a function of climate—was the governing factor in both occurrence and rate of spread of wildfires. However, at smaller scales, within a 20-hectare watershed for example, local topography was the biggest factor in the variability of fire regimes.

Similarly, Carl Skinner and colleagues Valerie Trouet, Alan Taylor, and Andrew Carleton found that humans may be more important than climatic patterns in ignitions of forest fires next to busy highways.

Current research seeks to pin down the finer points of this spatial and temporal variability. What are the mechanisms by which climate works its will? How are its impacts distributed through space and time? Can these impacts be predicted? These are some of the questions at the scientific heart of the matter.

Climate

The climate of western North America is strongly affected by patterns of circulation of warmer and cooler water in the eastern Pacific Ocean. The ocean's restless movements produce evaporation patterns that drive shifting configurations of warm and cool air in the atmosphere above, resulting in high-pressure ridges and low-pressure troughs. Somewhat like the hills on land, these airy structures route the atmospheric currents in certain pathways as they move to equalize the pressure differential.

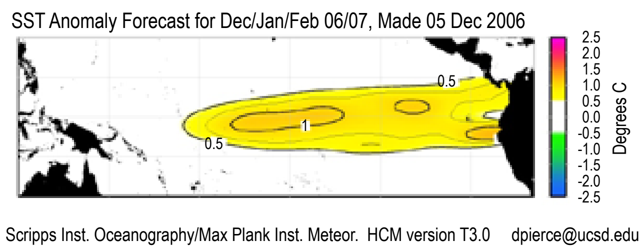
The patterns of these pathways govern the occurrence and location of storms over the continent. The storms, in turn, determine precipitation—where, when, and how much rain or snow falls. These patterns also influence the timing and location of thunderstorms that may or may not carry precipitation, but which are accompanied by lightning that can ignite wildfires.

These ocean cycles, scientists have discovered, are not random but roughly cyclical. Two interrelated cycles of conditions in the Pacific Ocean have a lot to do with recurring multi-year patterns of cool and wet or hot and dry weather in the western and southern United States. These oscillations are known as the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). ENSO describes a 3- to 7-year cycle of wind and wave conditions of the Pacific Ocean around the Equator. Its two extremes are called El Niño and La Niña.

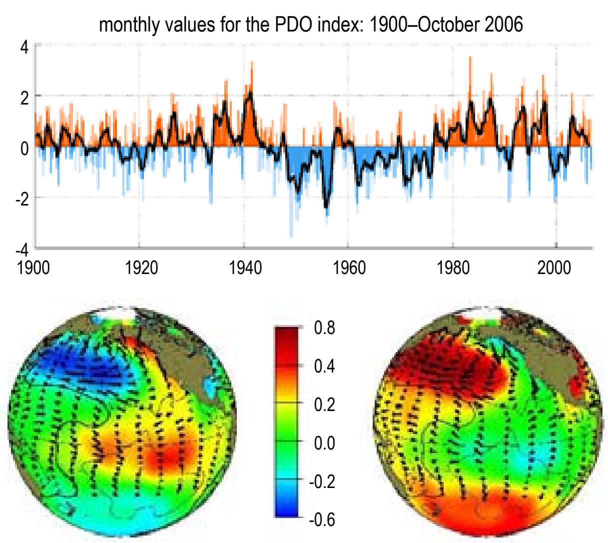
El Niño years bring unusually warm, wet conditions to the southwestern United States and across the South to Florida, and unusually cold, dry conditions to the Northwest. La Niña flops those effects, providing the rainy Pacific Coast with more rain and withholding it from the dry Southwest.

The Pacific Decadal Oscillation describes a pattern with a period of 20 to 30 years. Warm springs and dry summers in the Pacific Northwest have been linked to positive phases of the Pacific Decadal Oscillation.

A third cycle, the Atlantic Multi-decadal Oscillation (AMO), has a period of between 20 and 40 years. This cycle affects air temperature and rainfall over much of North America and Europe.



El Nino is a pattern of fluctuating sea surface temperature (SST) anomalies in the Pacific Ocean. An anomaly in the range of 1.5 to 3.5 degrees C is considered characteristic of an El Nino; the warmer and more widespread the water, the stronger the El Nino. (Reprinted with permission from David Pierce, Scripps Institution of Oceanography.)



The Pacific Decadal Oscillation (PDO), like El Nino-Southern Oscillation (ENSO), is a pattern of variability of ocean temperatures, although with a period of 20 to 30 years. The most marked climatic effects of PDO occur in the north Pacific and western North America. Two full PDO cycles have been mapped in the past century; cooler conditions prevailed from 1890–1924 and again from 1946–1976, while warmer regimes prevailed from 1925–1946 and again from 1977 to the mid-1990s at least. (Reprinted with permission from Nate Mantua, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle.)

How Do Oceanic and Atmospheric Cycles Affect Climate?

Seattle's legendary raininess and Arizona's legendary dryness both owe their existence to the eternal swirling of warm and cool waters in the Pacific Ocean.

El Niño is the warm-water phase of a 3- to 7-year cycle of wind and wave conditions of the eastern Pacific Ocean around the Equator.

In average years, strong east-to-west trade winds continuously push water away from the South American shore and pile it up in the western part of the Pacific. About every 3 to 7 years these winds weaken. Less water gets shoved westward, so the water in the eastern Pacific stays warmer. Eventually a pool of relatively warm water (about 30°C) develops off the west coast of South and Central America. The water in the western Pacific is cooler, about 22°C.

The evaporation of water from this warm pool releases great amounts of heat and moisture into the upper atmosphere, enough to affect the path of the jet streams that control the weather over the continents. In addition, the warmer the water gets, the weaker the winds become, resulting in a positive feedback that causes the water to get still warmer.

The warm pool also generates a westward surface current of very long, very shallow waves. Over the course of several months, these waves hit the shores of southeast Asia and head back east again, readjusting the ocean temperature along the way so that there is less difference between east and west. According to some scientists, this returning wave is what breaks the feedback loop. Others believe the causes are more random. In any event, El Niño gradually vanishes and is eventually replaced by its opposite pole, La Niña.

The 20- to 30-year Pacific Decadal Oscillation is a cycling of warmer and cooler sea-surface temperatures and surface heights in a huge horseshoe of ocean sweeping around the Pacific Rim. The phase of the current cycle is characterized by warmer temperatures and higher sea surfaces inside the horseshoe's curve and cooler temperatures in the wedge-shaped patch of equatorial waters between its legs. At the opposite phase of the cycle, the warm and cool regions are reversed; the horseshoe cools off and the wedge warms up.

Each of these two oscillations produces its own effects on weather patterns over western and southern North America. When their phases coincide in particular ways, these effects may be either magnified or minimized. Climatologists speculate that the cool-horseshoe-warm-wedge phase of the PDO is associated with El Niño events, and the opposite phase with La Niña events. The PDO was in the cool-horseshoe phase between 1976 and 1999, a period dominated by El Niño events. The cycle now appears to be shifting to the warm-horseshoe phase, which will likely bring warmer-than-usual winters and increased drought to the southwestern United States.

The recently discovered Atlantic Multi-decadal Oscillation (AMO) is a 20- to 40-year cycling of sea-surface temperature in the north Atlantic. The temperature difference is small, about 1 degree Fahrenheit, but the area is large—the whole sweep of ocean between the equator and Greenland. The AMO affects air temperature and rainfall over much of the Northern Hemisphere, especially North America and Europe. It is associated with frequency of severe droughts and Atlantic hurricanes. It may have been partly responsible for the Dust Bowl drought of the 1930s and for a less-severe dry spell in the 1950s.

The AMO has been in a warm phase since the mid-1990s, which may account partly for the severity of recent hurricane seasons. Because its effects are large-scale and long-lasting, the AMO may either mask or exaggerate the global-warming signal.

The research

The fire-climate connection is a story both ancient and modern, told in tree rings, historical snowpack, large-scale ocean and atmospheric dynamics, and contemporary weather records. Climatologists and fire ecologists have been probing this connection from their separate spheres for many years. Recently, they have begun a cross-disciplinary effort to uncover the story.

Their tools include extensive records of past and present conditions, indices (mathematical descriptions) of climatic and fire-related processes constructed from these records, and statistical models and computer models that use these data to describe present and future vegetation conditions, and hence future fire risks under a variety of climate scenarios. "Fire climatology is coming of age," says Tom Swetnam. "More people are paying attention to it, and there are more opportunities to use the new knowledge in climatology and apply it to fire science."

"Fire climatology is coming of age. More people are paying attention to it, and there are more opportunities to use the new knowledge… and apply it to fire science."

The story, like all stories, begins with the past—in this case, a rich storehouse of climate-related records. Besides extensive documentation of historical wildfires—ignition date, extent, severity, longevity, and other important information—scientists can obtain decades-long records of temperature, precipitation, streamflow, snowpack, first and last frost dates, and related data from many places.

Other records from farther back in time include growth rings and fire scars from old trees, logs, and stumps, and also

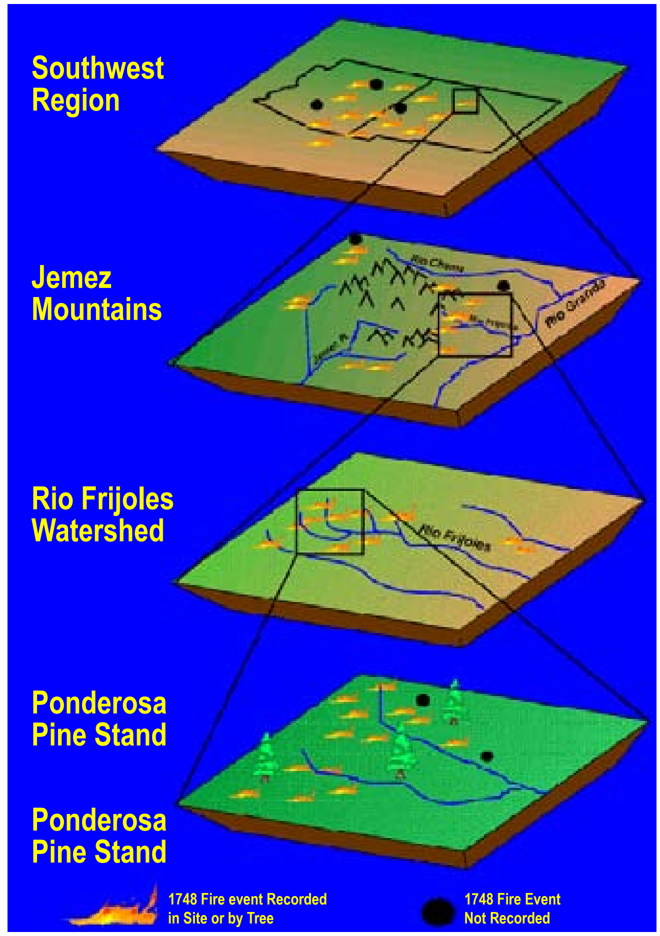
Researcher Charles Lafon of Texas A&M University sampling a fire-scarred Table Mountain pine snag from the George Washington National Forest of Virginia. (Reprinted with permission from Henri D. Grissino-Mayer.)

the accretions of coral reefs, which can provide information from a few centuries to several thousand years in the past. For even older information, scientists can examine packrat middens, samples from ancient lakebeds, and ice cores from glaciers. These records offer glimpses of climate and landscape conditions as far back in time as 40,000 years or more.

These ancient records vary in their spatial and temporal resolution, but they complement one another, enabling researchers to piece together a picture of the Earth's climate cycles through geologic time. Pollen and charcoal layers from 8,000-year-old lake sediments reveal much about the vegetation community and fire history of that place and time. The composition of gases in 14,000-year-old glacial ice points to the composition of gases in the atmosphere then, and that in turn tells scientists much about what the climate was like when that ice layer became entombed.

Tom Swetnam has just completed a study comparing the timing of prehistoric wildfires to the configuration of ocean oscillations that would have been occurring when the fires burned. He and four colleagues analyzed 33,795 fire-scar dates at 238 sites in the western United States, the largest paleo-fire record yet assembled. They then reconstructed the overlapping cycles of ENSO, PDO, and AMO and compared them with the fire-scar data. They found strong ties between certain phases of these ocean cycles and rashes of synchronous wildfires within a subregion or across a whole region.

In a similar study, Don McKenzie of FERA and colleagues used fire-scar data dating from as far back as the year 1257, along with tree-ring chronologies, to reconstruct regional climatic trends. Their analysis also showed a link between drought years and widespread fires. "Whether you look at charcoal records going back thousands of years, fire-scar records from the last 500 years, or the detailed 20th

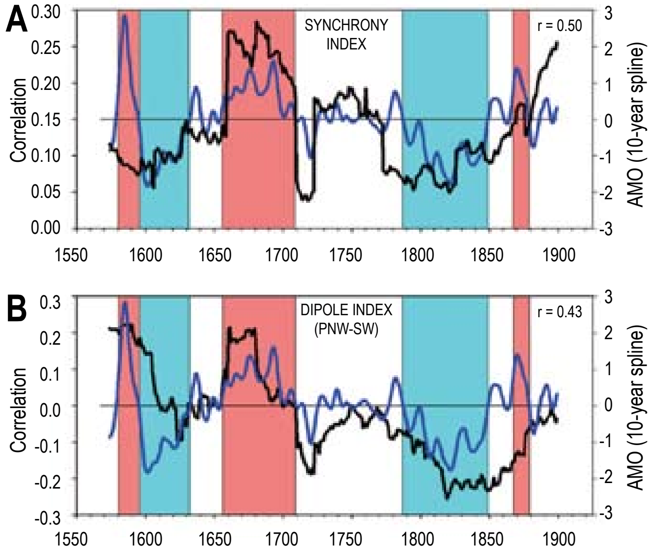


This cross-scale comparison shows the evidence at varying scales of the largest regional fire in the Southwest during the past 400 years, which occurred in 1748. The synchrony of the 1748 fire year among fire-scarred trees at the smallest spatial scale (a forest stand) is shown in the bottom panel. Patterns of synchrony, which are a measure of the relative extent of fire (area burned), are then illustrated at higher levels of aggregation (larger scales, coarser grain size) up through the watershed, mountain range, and finally the region (uppermost panel). (Reprinted with permission from Tom Swetnam.)

century fire record," McKenzie says, "the climate drivers of fire appear to be the same." A sampling of other recent work follows:

- In a JFSP-supported study, Penelope Morgan of the University of Idaho and colleagues from the Forest Service looked at historical fires within diverse vegetation types in Idaho and Montana, including Yellowstone National Park. They compared data from these fires with climate data and found that the worst years for fire were those in which warm springs were followed by dry summers during a positive (warm) phase of the PDO.

- In another JFSP-funded study, Steve Hostetler of the U.S. Geological Survey and colleagues from the University of Oregon and the Forest Service found a clear link between ignitions and extent of fires in eight



Fire synchrony reconstructed from tree rings (black line) and reconstructed Atlantic Multi-decadal Oscillation (blue line). Light-blue and light-red shaded areas indicate periods of high and low AMO, respectively. This graph shows the strong role of AMO in determining patterns of drought across the western U.S. Fire was strongly synchronous across western North America during 1650–1749 and 1850–1924 and weakly synchronous during 1550–1649 and 1750–1849. The highest degree of fire synchrony occurred between 1660 and 1710, coinciding with the longest and warmest phase of the AMO during the past five centuries. (Reprinted from p. 546 of Kitzberger, Brown, Heyerdahl, Swetnam, and Veblen: Contingent Pacific-Atlantic Ocean influence on multicentury wildfire synchrony over western North America. Proceedings of the National Academy of Sciences doi:10.1073/pnas.0606078104, published online Dec. 29, 2006.)

Western regions over the past 21 years and a particular set of wildfire-linked climatic variables, derived from both model simulations and observed conditions, that occurred in each area in the previous year. They used their findings to develop a manager's atlas of climatic controls of wildfire, broken down into the eight regions.

- In the JFSP-supported study mentioned previously, Don McKenzie, Amy Hessl of West Virginia University, David Peterson with the Forest Service's FERA team, and colleagues found a quasi-periodic tie between ENSO and PDO and fire occurrence in eastern Washington between 1650 and 1900, but also found that, on the watershed scale, fuel influences fire more than climate does.

- Looking at prehistoric climate data reconstructed from fire scars in Jeffrey pine growth rings near Lake Tahoe and the northern Sierra Nevada, A.H. Taylor of Penn State and R.M. Beaty of the Australian research institute CSIRO found that years with widespread fires were preceded by wet conditions 3 years before the fire, and were also associated with a change of PDO phase from warm (positive) to cold (negative).

- Investigating the relationship between fires of the Pacific coast and atmospheric circulation patterns, Valerie Trouet of Penn State and colleagues found that large fire years were characterized by, among other things, an intensified high-pressure ridge over the western continent, which is typical of a positive phase of the PDO. They suggest that atmospheric circulation patterns may be a reliable index of the likely severity of the upcoming fire season.

- Paul Duffy of the University of Alaska-Fairbanks and colleagues looked at relationships between ocean-atmosphere patterns and fires in boreal Alaska forests over the past 53 years. They found strong links between PDO values in January and February and precipitation in May and June. They also found strong links between January–February values from another index, describing atmospheric patterns over the eastern Pacific,

Chris Baison and Tom Swetman

Fire-scarred cross-section of ponderosa pine from Bandelier National Monument. Fire dates on the cross-section illustrate that wildfire was once frequent on the landscape at Bandelier. Repeated surface fires cause a sequence of overlapping wounds. The heat-killed wood tissues extend into the annual rings, which can be dated to the calendar year. (Reprinted with permission from Tom Swetnam.)

© Henri D. Grissino-Mayer, University of Tennessee

This image shows a well-formed "catface" (fire-scarred basal wound) on a living ponderosa pine (*Pinus ponderosa*) tree on Mesita Blanca in el Malpais National Monument in New Mexico. (Reprinted with permission from H.D. Grissino-Mayer, University of Tennessee, *http://web.utk.edu/~grissino/gallery.htm*.)

and precipitation from March through August. Their work suggests that PDO and other such indices can be used to predict the number of hectares likely to burn in an upcoming fire season.

In the course of this work, researchers are refining the indices they've developed to quantify the dynamic patterns of weather and climate. An index is essentially a distillation of past measurements into a mathematical description of a process, such as a cycle of ocean currents or air circulation. Indices are used as yardsticks to evaluate present or hypothetical future conditions.

PDO and ENSO are key indices of ocean and atmospheric patterns. The mathematics of these indices reflects the temporal movements of these cycles through their phases—their progress through time from one extreme to the other. The indices are also spatially explicit—that is, they are maps showing where the movements are occurring in the ocean or the atmosphere.

T.S. Rupp

The Long Creek fire of 2002, near Ruby, Alaska. Fire is the dominant landscape-scale disturbance mechanism in Interior Alaska. (Reprinted with permission from T. Scott Rupp.)

Other indices have been developed to describe dynamics on land. For example, the Palmer Drought Severity Index, incorporating current and past measures of soil moisture, is used along with current and predicted weather conditions to evaluate the likelihood of large or dangerous fires.

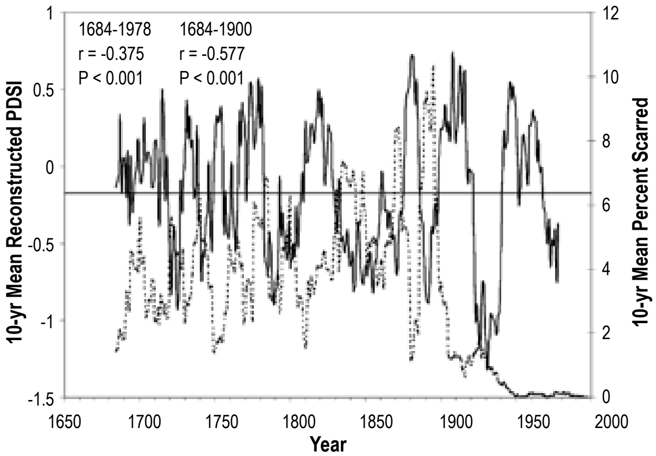
The Haines Index, taken from measurements of atmospheric stability and moisture conditions, helps in evaluating how conducive the atmosphere is to spread of fire in the absence of wind. Another common index, the Energy Release Component Index, describes moisture in woody material, which governs how fast the wood ignites and burns.

Of course, the more accurately a process can be described mathematically, the more reliable an index it produces. Scientists are continually refining their climate and fire indices by incorporating new data gained in the course of their work. For instance, they may test an index of ocean conditions against today's conditions in a particular area, and then use that index to work backward to reconstruct conditions of the past. Data gained from that reconstruction are then used to help better understand the potential variation in the index.

These indices are crucial components of the statistical models scientists use to identify connections between climate and wildfire. They are also an important source of data for computer models used to project future vegetation conditions, and hence the likelihood of increased fire under a variety of climate scenarios.

The uncertain future

Don McKenzie of FERA and his colleagues have used statistical models and 20th century fire records to project that, over the next century, fire will probably burn twice or three times as much land in the West as it does today. "Of



Ten-year average of Palmer Drought Severity Index (PDSI) reconstructed from tree rings (1684–1978) (solid line) and ten-year average of percentage of trees scarred over time (dotted line). PDSI is used to evaluate the likelihood that weather conditions in a given area are conducive to wildfire. This timeline shows that, up until the introduction of widespread wildfire suppression early in the 20th century, years with low fire occurrence happened during moist, cool periods, and major fires tended to follow abrupt changes in PDSI from positive to negative. (Reprinted with permission from David Peterson.)

course it's logical that a warmer climate will cause more fire," McKenzie says, "but now we can quantify the increase based on known relationships between fire and climate in the past."

The year 2002 brought the warmest summer on record in many places. The ocean patterns point to an impending La Niña cycle coupled with a warming Atlantic. That configuration is associated with drought across the northern United States. By itself, this drying trend is within the range of natural climate variability and may have little to do with global climate change. But it will likely be exacerbated by the long, hot summers brought about by the buildup of greenhouse gases in the atmosphere.

Most modeling studies suggest that warming temperatures will bring more precipitation overall. However, the distribution of moisture is likely to be highly uneven, with some areas receiving more rainfall and others—notably the already-dry Southwest—experiencing increased drought.

Computer modeling by Forest Service bioclimatologist Ron Neilson at the PNW Research Station suggests that continued warming and increasing wildfires may cause whole ecosystems to shift. Neilson and his team have recently developed a dynamic vegetation model that simulates not only the degree but the trajectory of vegetation change under a variety of climate-change scenarios.

Simulations by Neilson's new model suggest that, in general, climate warming will lead to denser vegetation and higher fuel loads. The frequency, intensity, and amount of biomass consumed is projected to increase in the West under virtually all the model's scenarios. In dry ecosystems, this increased biomass "is much like pouring fuel on a fire," Neilson says.

The new model projects that some drier regions will get wetter, causing woodlands to expand, and creating more biomass and hence bigger fuel loads. In other areas, drought stress will cause plants to die back and become flammable. In either case, the ensuing proliferation of wildfires could wipe some coniferous forests off the landscape in those areas and replace them with savannas, woodlands, and grasslands.

Other modeling by Neilson's team suggests that, with warming temperatures:

- The area of mixed conifer and hardwood forests in the Northeast could decrease significantly as the range of that forest type shifts north into Canada.
- Certain southwestern desert species could migrate north as far as eastern Washington.
- Widespread drought could increase wildfire in the Great Lakes, the Southeast, and the Northwest.

Studies of the effects of the ENSO cycle on western forests reveal that ENSO's influence ranges along a wide northwest-to-southeast band, with the more pronounced effects toward the ends. A common analogy scientists offer is a child's teeter-totter—the El Niño phase makes conditions cooler and drier in the Pacific Northwest, and warmer and wetter in the Southwest and South.

Some scientists have speculated that this teeter-totter effect drives a cyclical fire pattern in the Southwest. During a wet El Niño year, a southwestern forest can grow a lot of fuel. Then when the phase shifts, the fuel produced in the wet years dries out, potentially producing higher fuel loads and more extensive burns. If global warming makes the extremes of the ENSO cycle more extreme—which some scientists think will happen—it may produce a cyclical pattern of fires in the Southwest as the wet years produce more fuel to burn in the dry years.

Wade Wahrenbrock

Canopy fire explodes in a stand of dead spruce in Alaska. (Reprinted from *Fire Management Today*, Volume 66, No. 4.)

Michael Flannigan of the Canadian Forest Service and Susan Conard and Douglas McRae of the USDA Forest Service are studying the effects of climate change on fire in boreal forests. At a recent fire-ecology conference, Flannigan presented a wrap-up of modeling studies that point strongly to increases in the frequency and severity of wildfires in the far north, linked to rising temperatures, drier fuels, and more thunderstorms. Flannigan and colleagues estimate that the area burned in Canada will increase by 74 to 118 percent by the end of the century. Fire regimes will respond rapidly and strongly to warming temperatures, they say, and the rate of these changes may not be linear. "We may reach a tipping point," says Flannigan, "where dramatic and unexpected changes in the circumboreal fire regime may be the result of climate warming."

Help for land managers

Scientists and land managers have been working for some years now on seasonal forecasting of temperature, drought, and wildfire activity. Better understanding of the links between fire and climate will help with short-range forecasting of fire seasons by incorporating normal climatic variability. Even a few weeks' heads-up on a dangerously hot, dry fire season will give managers a brief planning window. It will also help policymakers plan for climate change over the long term.

"If we understand water relations at broad scales, we have a handle on the mechanisms governing flammability of forest fuels."

Early knowledge would aid decisions about where to allocate scarce fire protection and suppression dollars and how to prioritize fuel-management projects. For example, research on the ocean-climate connection promises to help managers anticipate the likely precipitation patterns in a given area a season or so out.

Scientists are also exploring and refining the strong link between fire and water—specifically, fuel moisture and spring snowmelt—using a new generation of models that simulate the hydrology of a forested area. "If we understand water relations at broad scales," says Dave Peterson, research biologist with FERA, "we have a handle on the mechanisms governing flammability of forest fuels."

Because the northern Rockies show a more dramatic increase in wildfires than any other area in the West, a predictive tool would be highly useful there. In a 2005 report to the Forest Service's Rocky Mountain Research Station, Tony Westerling describes a method that makes it possible to forecast by April 1 whether the forthcoming fire season will be more intense than average. The method combines the Palmer Drought Severity Index (PDSI) with the spatial distribution of sea-surface temperatures in the northern Pacific Ocean and historical average temperatures from March to August for the area in question.

Even a short-term forecast cannot be very precise. Fire seasons are highly variable year to year, and much of that variability comes from factors other than temperature or precipitation. But, Westerling says, it may be possible to anticipate whether the forthcoming season will be a really bad one.

Long-term planning for climate change requires a different view from short-term seasonal forecasting—certainly a longer view, but also a coherent view about how climate change is affecting the climatic processes that govern wildfires. "Climate variability and climate change are two different things," says Westerling. "Distinguishing between them is important in the sense that they call for different prescriptions. Climate variability is something we can address only with management and adaptation, while climate change can also be addressed with mitigation and prevention."

A clearer picture

Climate is an important influence on wildfire, albeit one of a complex tangle of factors. Work by Westerling, Swetnam, Skinner, Peterson, McKenzie, Neilson, Flannigan, Taylor, and others is providing a clearer picture of what role climate plays, where its effects are most felt, and how warming temperatures may be altering those effects. Their research is helping to clarify the kinds of events that can be forecast with the most confidence. It may be a long time before managers can predict the fine details of the forthcoming fire season, but it may soon be possible to anticipate the big ones and take precautions.

The research continues to refine which climate phenomena drive which fire factors at what scales and in what regions. Managers of a forest in a given region can learn which indices, or combinations thereof, best describe the pattern of fire that occurs in their region. "No one index will work everywhere," says Carl Skinner. "They need to be regionally based, depending on what influences the storm tracks and moisture patterns where you are." Steve Hostetler's fire atlas, for one example, gives monthly fire and climate data for the years 1980–2000 in eight western regions, ranking each year into a high, normal, or low fire year. The atlas codifies and graphically displays the historical data of most interest to managers in one accessible place.

Over longer time scales, the research also reveals more details about the effects of large-scale patterns like El Nino-Southern Oscillation or the Pacific Decadal Oscillation. Being able to accurately map ocean dynamics through time helps to clarify the background variability against which to gauge a climate-change signal. In addition, understanding these cycles better can help public land management agencies (and private landowners, for that matter) incorporate climate variability, whether or not it is linked to global warming, into long-term planning.

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