THE IMPACT OF TWENTY-FIRST CENTURY CLIMATE CHANGE ON WILDLAND FIRE DANGER IN THE WESTERN UNITED STATES: AN APPLICATIONS PERSPECTIVE

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Abstract. High-temporal resolution meteorological output from the Parallel Climate Model (PCM) is used to assess changes in wildland fire danger across the western United States due to climatic changes projected in the 21st century. A business-as-usual scenario incorporating changing greenhouse gas and aerosol concentrations until the year 2089 is compared to a 1975–1996 base period. Changes in relative humidity, especially drying over much of the West, are projected to increase the number of days of high fire danger (based on the energy release component (ERC) index) at least through the year 2089 in comparison to the base period. The regions most affected are the northern Rockies, Great Basin and the Southwest – regions that have already experienced significant fire activity early this century. In these regions starting around the year 2070, when the model climate CO_2 has doubled from present-day, the increase in the number of days that ERC (fuel model G) exceeds a value of 60 is as much as two to three weeks. The Front Range of the Rockies and the High Plains regions do not show a similar change. For regions where change is predicted, new fire and fuels management strategies and policies may be needed to address added climatic risks while also accommodating complex and changing ecosystems subject to human stresses on the region. These results, and their potential impact on fire and land management policy development, demonstrate the value of climate models for important management applications, as encouraged under the Department of Energy Accelerated Climate Prediction Initiative (ACPI), under whose auspices this work was performed.

1. Introduction

Wildland fire statistics for the contiguous western United States show a strong positive trend in the annual number of fires starting in the 1950s that closely tracks the region-wide increase in area protected. Area protected refers to the total land area (in hectares) reported as under formal protection responsibility by wildland fire management agencies. In addition to federal and state lands, it includes private lands where federal and state agencies have assumed protection responsibility. Despite increases in area protected and in reported fires, average annual area burned reported for the Western U.S. decreased steadily up until the 1960s before increasing dramatically in the last three decades. The initial decrease can probably be attributed, at least in part, to increasingly effective fire suppression. Subsequent increases in reported average annual area burned probably reflect a combination

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of factors, including increased area protected, biomass accumulation due to fire suppression, and a greater tendency toward wet and dry extremes in the region that lead to more weather-driven fire events. While wildland fire suppression performs a valuable short-term function of protecting property and resources, it also has the effect of increasing fuel load due to the restriction of a natural process by which fuel is reduced or removed: wildfire. That is, fuels that do not burn remain on the landscape and will likely increase through additional vegetation growth stages if other reduction factors (e.g., disease, insects, prescribed fire, mechanical treatments) do not intervene. When fire finally does occur, the potential for the rapid growth of large, difficult-to-control wildfires is increased.

More efficient fire suppression in the first half of the 20th century may have helped to set the stage for resurgence of area burned in recent decades. However, this hypothesis is not uniformly applicable. Some studies suggest that the fuel-buildup concept has been inappropriately applied to closed-canopy ecosystems, particularly those of crown-fire regimes. Keeley and Fotheringham (2001) discuss this in relation to California shrublands, and Johnson et al. (2001) show that unnatural fuel buildup is also invalid for boreal and sub-alpine forests. This concept should also then apply to closed-canopy ecosystem forests in the U.S. Pacific Northwest (Agee, 1997) and the northern Rocky Mountains (Habeck, 1985). Large closed-canopy fires are weather-driven, and hence closely related to climate.

The widespread synchronous occurrence of very large, 'destructive' wildfires does not have to be an unnatural phenomenon. Large-scale climate patterns provide natural mechanisms that can synchronize fire occurrence over large regions. Swetnam and Betancourt (1998) note that: (1) the more synchronous the fires are across a region, the stronger the climate signal; and (2) climatic variability can amplify or mute anthropogenic effects. From a simplistic perspective, large anomalously wet areas promote more fuel loading, and large anomalously dry areas decrease fuel moisture and thus increase fire risk. Multi-wet years and multi-dry years will heighten the natural role of fire, whatever it is, during these regimes. The effect of anomalously wet years on fuel accumulation is relatively more important in dry, sparsely vegetated areas like the desert grass and shrub lands covering much of the Southwest (Kipfmueller and Swetnam, 2000). In forested areas where heavy fuels tend to accumulate over long periods, such as in the Northwest and at higher elevations around the West, anomalously dry conditions have a greater effect on fire danger (Agee, 1993; Swetnam and Betancourt, 1998; Donnegan et al., 2001). Karl et al. (1996) note a trend toward greater precipitation in much of the Southwest over the 20th century, which may have contributed to the increase in large fires in this region.

This becomes more complicated when Swetnam and Betancourt's (1998) second point is taken into account – the anthropogenic effects of land use practices, fire management strategies and climate change itself. To illustrate a simple example of the human role in the relations between climate and wildland fire, start with a healthy and stable forest ecosystem. Build a human community within this ecosystem, and then, while the residents are enjoying their communion with nature, suppose that an anomalous multi-year wet period (which increases the fuel loading) is followed by two years of drought. Without fuel treatment or fire prevention methods, fire managers responsible for community protection perceive a grave increase in fire risk. Perhaps the residents do not share this perspective. They are opposed to tree thinning and creation of defensible space for aesthetic reasons, and are opposed to prescribed fire for health reasons and fear of an escaped burn. Fire in the ecosystem now has two potential sources – lightning and humans. 'The extended urban and the resurgent wildland each persist ... both elements arcing fire across their shared landscape' (Pyne et al., 1996). And unbeknownst to both the fire managers and the residents, regional climate change is amplifying the problem because climatic extremes are becoming more extreme. Fire behavior becomes more erratic, with large flame lengths, torching, crowning, rapid runs and blowups due to extremely dry conditions. This is more than a musing example because it represents one of today's most pressing issues in land management.

In particular, year-to-year variability in annual area burned in the western U.S. has been dramatically higher over the last two decades than at any time during the last century for which there is historical data at hand. Since fire suppression managers must be prepared for the worst, rather than the average fire season, this has profound implications for the cost of wildfire management. Fire suppression costs closely track annual variations in area burned in large wildfires, so greater variability in wildfire seasons means fire suppression budget needs will also be highly variable from year to year. The greater preparedness required will also entail higher fixed costs for maintaining necessary equipment and skilled personnel. While greater variability in wildfire season severity and management resource needs poses a challenge to wildfire management, it also increases the value of climate information that enables forecasts of fire season severity or enhances efforts to manage risk factors such as fuels.

How, then, might twenty-first century climate and variability change the risks of wildland fire? Though natural variations will be an important part of future climate changes and variability, radiative forcings from increasing concentrations of atmospheric greenhouse gases and sulphate aerosols are expected to yield important human-induced changes. The Intergovernmental Panel on Climate Change (IPCC, 1995, 2001) has concluded that there is a strong likelihood of both global and regional climate change. The globally averaged surface temperature is projected to increase by 1.4 to 5.8 °C during the next 100 years, depending on the climate models and development scenarios used. Global average precipitation is expected to increase, as are changes in occurrences of extreme events, particularly those related to temperature and precipitation. These aspects of climate change, particularly in a regional context, will directly impact wildland fire.

Why assess future climate change and wildland fire? From a scientific perspective, it is important to understand the feedback processes between fire and climate/weather systems. For example, some of the more critical climate/weather influences on fire include atmospheric moisture, wind, drought, lightning and synoptic scale atmospheric-circulation patterns. Some of the critical fire influences on climate/weather include the numerous greenhouse gases and aerosols such as CO_2, CO, CH_4, H_2O, NO_x, NH_4, particulates (PM 2.5; PM 10), trace gases (including VOC) and trace hydrocarbons (e.g., Ryan, 2000) that are released to the atmosphere by fires. Likewise, there are climate/weather system interactions with the forest and grassland ecosystems, such as solar energy, temperature, atmospheric moisture, atmospheric chemistry and wind. Vegetation influences climate and weather via albedo, evapotranspiration, photosynthesis, respiration, methane production, convection, advection and desertification (e.g., Ryan, 2000). From a societal perspective, protection of life, property and resources are generally considered to be key aspects of wildland fire policy, but there are many other components in the human system of fire risk, such as perception, policy, hazard, education and economics. The economics of fire business is nontrivial. Issues include costs associated with protection, prevention, fuel treatments, insurance, recreation, timber, ranching and grazing, and biomass utilization. Virtually all fire agencies at least imply economic criteria as a basis of fire policy (Pyne et al., 1996). Though the numbers are difficult to ascertain, it is estimated that an average of two billion dollars are spent each year on activities related to wildfire suppression in the U.S. by federal, state and local agencies.

In this study, the United States Department of Agriculture (USDA) Forest Service National Fire Danger Rating System (NFDRS) is used with output from a general circulation model (GCM) to assess the impact of a business-as-usual climate scenario for the period 2010–2089 over the western U.S. We focus on the NFDRS Energy Release Component (ERC), which for fire managers is an indicator of both fire severity (the potential amount and extent of fire activity) and fire business (the decisions and economics of fire suppression and fuel treatments). Our primary focus is to examine decadal scale trends of ERC fire danger in the context of a historical base or 'observed' period (1975–1996). Thresholds of ERC are found by analyzing fire occurrence by size and expense, in addition to considering threshold values that might have applicability in fire management decisions. Daily ERC is computed from the GCM output and examined over 20-year periods through 2089 and related to the historical base period. GCM output is also compared to a set of observations to assess model confidence for the base period.

By focusing on fire danger, rather than hectares burned or numbers of fires, we reduce the complexity of the problem by removing numerous societal components of fire, land use and vegetation change. Thus, some assumptions are made in this analysis: (1) future changes in fire suppression strategy and other human activities, if any, will not impact fire danger (as long as there is vegetation to burn, then a potential for fire danger exists); (2) land use practices will continue in a manner familiar today (e.g., land use policy will not change either the perceived or actual risk of fire for communities and resources); and (3) though vegetation characteristics may change in response to climate, the fuel model is assumed to remain constant during the analysis period. This latter assumption is discussed further in the methods section. Section 2 provides a background discussion of previous GCM and fire studies to date; Section 3 discusses the GCM and fire danger models used in the study; Section 4 describes the ERC threshold analysis; Section 5 provides the overall results and discussion of the study; and finally, Section 6 summarizes the study conclusions.

2. Background

Studies using GCM outputs to examine the potential impact of climate change on wildland fire severity began appearing around 1990. Overpeck et al. (1990) discussed increased rates of forest disturbance (including forest fire) resulting from projected global warming, suggesting that the increase would be due largely to an increase in the frequency of ‘disturbance weather’ events such as drought, high winds, and natural ignition sources. A more specific approach to assessing seasonal fire severity rating and area burned was undertaken by Flannigan and Van Wagner (1990) for doubled CO_2 climate simulations. Using output from three GCMs, they showed a 46% increase in seasonal fire severity ratings for a set of Canadian weather stations with a corresponding similar increase in area burned. The authors suggested that this number might be within the range of natural variability. However, they also noted that if droughts became more common or relative humidities decreased, then this percentage could become much larger.

Torn and Fried (1992) examined the impacts of doubled CO_2 climate on area burned and the frequencies of escaped fires in northern California. Outputs from three GCMs were linked to the Changed Climate Fire Modeling System (CCFMS). This system is unique in that climate model output is tied directly to fire characteristics, such as rate of spread and burning indices, and human decisions in terms of dispatch rules and suppression tactics. The study found that the greatest impact of a doubled CO_2 climate would be increased area burned and frequency of escapes in grasslands as opposed to timber or heavy fuel areas.

Bergeron and Flannigan (1995) discussed the importance of regional climate variability on fire frequency. Using the Canadian fire weather index with inputs derived from GCM $1 \times CO_2$ and $2 \times CO_2$ scenarios, they showed decreased fire frequencies in a southern boreal forest of southeast Canada with doubled CO_2. Overcoming the predicted warming in this region due to doubled CO_2, increased precipitation and relative humidity, along with a reduced frequency of drought periods, caused the projected decreases.

Weber and Flannigan (1997) reviewed Canadian boreal forest ecosystem structure and function in a changing climate, with emphasis on impacts on fire regimes (i.e., fire intensity, frequency, seasonality, size, type (crown versus surface) and severity (depth of burn)). The importance of climate to fire regime is related to fire behavior, which is partly a function of fuel moisture, which in turn responds to atmospheric moisture (both precipitation and relative humidity), air temperature and wind speed. The direct effects of climate change on species distribution, migration, substitution and extinction must also not be forgotten. However, Weber and Flannigan suggested that climate-change impacts on fire might be more important than the direct impacts on species because fire can rapidly change a vegetation landscape that will fall more readily into a new equilibrium with climate.

Stocks et al. (1998) examined forest fire potential in Russian and Canadian boreal forests under warmer climate scenarios from four GCMs. Results from all four models suggested outcomes similar to those from a doubled CO_2 scenario – large increases in the areal extent of extreme fire danger in both countries. Here, fire danger is evaluated using GCM output to calculate the Canadian Fire Weather Index (FWI), which is then integrated from daily to monthly and seasonal values.

Flannigan et al. (2000) used two GCMs to assess climate change and forest fires over North America with emphasis on the U.S. The Canadian FWI was used to compute a seasonal severity rating (SSR) using the GCM output. The ratios of SSR for the year 2060 (approximately doubled CO_2 for both Canadian and Hadley GCMs) over the SSR for the 'present day' (1895–1994) was calculated and showed substantial regional variation over North America, but, in general increases of 10–50% over most of the U.S. The SSR increase implies increases in area burned and fire severity.

The length of the fire season in a changing climate is also subject to change. Wotton and Flannigan (1993) showed that doubling CO_2 in the forested parts of Canada could lengthen the fire season by 30 days on average, based on Canadian Forest Fire Danger Rating System criteria. This lengthening is primarily driven by the increased temperatures projected by the Canadian Climate Center GCM. Potentially drier fuels will result even if the precipitation patterns do not change significantly, however, less confidence was given to the model's projections of precipitation change. Nonetheless, a change in the fire season length has significant implications for fire management. Earlier start and later end dates implies a longer 'middle' to the season, requiring increased resource commitments and new treatment strategies.

Though little can be said about future trends in human caused fire starts, changes in the natural ignition source can be examined in GCM climate scenarios. Price and Rind (1994) used a GCM to examine global lightning distributions and frequencies in relation to a doubled CO_2 climate and a 2% decrease in the solar constant. The two scenarios yielded a 30% increase and 24% decrease, respectively, in global lightning activity with dependencies on season, location and time of day. Over much of the fire prone area in the U.S., lightning increases in the warming scenario by 25 to 50%. With fire-favorable fuel conditions, increased lightning would yield an increase in the frequency of natural fire occurrence. For a cooler climate, a corresponding decrease in lightning was projected, which would reduce the frequency of natural fire occurrence. These studies, along with the IPCC (1995, 2001) consensus of a warming climate during the 20th century, suggest that there will be regional changes in wildland fire activity in the 21st century.

Another important aspect of climate change information is its understanding in relation to ecosystem processes, since it is known that climate is one of several critical factors including soils, CO_2 and various disturbances (e.g., fire, insects) for vegetation composition, dynamics and structure. Fire is a primary disturbance, and an improved understanding of the links between broad-scale fire severity and climate change will increase the ability for prediction of potential changes in ecosystem structure, function and associated atmospheric feedbacks (McKenzie et al., 1996). Examples of feedback interactions between terrestrial vegetation and climate are discussed in Neilson and Drapek (1998) and Aber et al. (2001). Recent efforts to address ecosystem linkages utilizing Dynamic Global Vegetation Models (DGVM) include Woodward et al. (1995), Foley et al. (1996) and Neilson and Running (1996). Lenihan et al. (1998) and Thonicke et al. (2001) specifically address fire disturbance and fire severity in relation to global vegetation dynamics and climate.

3. Models

GCM output for this study was generated by the Department of Energy (DOE) supported Parallel Climate Model (PCM; Washington et al., 2000). A full description of this model and the PCM simulations can be found in Dai et al. (2004). Pierce et al. (2004) describe the PCM initialization procedure. Two PCM runs were utilized in this study. A historical run for the 1870–1998 period using historical radiative forcings by greenhouse gases and aerosols (Dai et al., 2001) provided the necessary model output to assess the 'present-day' fire danger. A business-as-usual (BAU) scenario for the period 2006–2099 as described by Dai et al. (2001) and similar to the IPCC scenario discussed in Leggett et al. (1992) was used to assess future climate and fire danger. The available grid size ($\sim$2.8° horizontal resolution) would be considered coarse for daily operational fire business, but we believe it to be sufficient for assessments of future climate and fire danger, both of which have a general tendency of larger scale spatial homogeneity. Undoubtedly, it would be of interest in a future study to perform similar analyses using regional models with finer horizontal resolutions or downscaling techniques to better account for topography in mountainous regions.

It would also be desirable to analyze more than one PCM future run or an ensemble group to increase confidence of the results. However, our requirement of 6-hourly output established computing storage constraints that limited the high-temporal resolution output to one run. Figure 2 in Stewart et al. (2004) strongly suggests that different PCM scenario runs show similar large-scale spatial structure for three different PCM future climate ensemble members. This increases the confidence in the fire danger results provided below, given that only one run was available for analysis.

U.S. fire danger analyses, assessments and operational activities are typically based on the National Fire Danger Rating System (NFDRS; Bradshaw et al., 1983). Numerous indices are generated from this system, including dead fuel moisture, live fuel moisture, ignition component, spread component, burning index, and the energy release component. NFDRS inputs include weather and fuel model, but there are also secondary inputs and many additional components within the system that are calculated based upon empirical studies of vegetation characteristics (e.g., fuel particle properties, fuel bed properties) and relationships between atmospheric variables and fuels (e.g., dead fuel moisture, live fuel moisture). Fire danger was chosen for this study because it is more closely related to climate factors over larger scales, than fire behavior that is more locally weather dependent.

Fire management personnel commonly use the energy release component (ERC) to assess current fire danger and develop management plans for both suppression and fire use. The calculated ERC is the available heat per unit area (kilojoules/m^2). Thus, the larger the ERC value, the 'hotter' and potentially more severe the fire; values typically range from 0 to 100, though they can be higher depending on weather extremes and fuel model. Values of ERC are heavily weighted on dead fuel moisture values, especially the moisture values of fuels with 100- and 1000-hour timelags. This timelag refers to the amount of time required for a wooden fuel stick of a particular size (7–15 cm for the 1000-hour) and initial moisture content to reach two-thirds equilibrium moisture content with an atmosphere of constant temperature and humidity. Dead fuels are exclusively controlled by environmental conditions (i.e., temperature, radiation, relative humidity and precipitation). The fuel moisture timelag implies that ERC is indicative of a climate index, such as the severity of a four to six month drought (Bradshaw et al., 1983). A description of the components and equations of NFDRS are given in Bradshaw et al. (1983) and Cohen and Deeming (1985).

Daily values of maximum and minimum relative humidity and temperature, zonal and meridional wind, and convective and large-scale precipitation at the surface were provided from the PCM historical and BAU runs. Primary operational weather inputs to ERC are daily maximum and minimum temperature and relative humidity; temperature and relative humidity at the local observation time of 1300, and precipitation amount and duration for the previous 24-hours from the observation time. The PCM model output was the proxy for operational weather inputs in the present analysis. Local 1300 time observations of temperature and relative humidity were derived as the average of the maximum and minimum values for each variable. Precipitation duration was estimated from daily convective and large-scale precipitation amounts. If the daily precipitation amount was convective, three hours of duration were assigned; if large-scale, a six-hour duration was assigned. These amounts are arbitrary, but were examined in an ERC sensitivity analysis. Precipitation duration and amount plays a minimal role in the ERC index, so duration time is an insignificant factor. Also, temperature plays a minimal role in the ERC value. Thus, of the primary inputs, relative humidity is the most important atmospheric factor for ERC, because dead fuel moistures are most sensitive to relative humidity, and these moistures are heavily weighted in the ERC calculation.

The fuel model used in NFDRS is also an important factor. There are 20 commonly used NFDRS fuel models (e.g., western grasses, sagebrush-grass, heavy slash). Each model has numerous parameters, including surface area-to-volume ratios, fuel loading, effective fuel bed depth, dead fuel moisture of extinction, and dead and live fuel heat of combustion. In this study, we used fuel model *G* with its associated fixed parameters. Fuel model *G* represents a dense conifer stand with understory and a heavy accumulation of litter and downed woody material (Deeming et al., 1977). As noted earlier, one of the assumptions in this study is that the vegetation type does not change substantially due to climate change during the twenty-first century, even though studies have suggested that change may occur (e.g., Bachelet et al., 2001). Our decision to maintain fuel model *G* throughout the twenty-first century reflects two considerations. First, even with climate change, fuel model *G* will likely be appropriate for those areas where it is currently used. In other words, the various fuel model parameters will still be representative of the area for sometime even with a changing climate. Second, fuel model *G* can be and is often used for regional fire management assessments even if other fuel models are applicable. This is primarily based on the fuel model parameters, which are in some sense considered generic for many applications, especially in the western U.S.

4. ERC Thresholds

The analysis focused on examining thresholds of ERC that have strategic importance to fire management and policy makers. To determine what these thresholds might be, we first examined suppression costs in the western U.S. Expensive fires do not have to be large, as cost is a function of protection priorities and available suppression resources. The ultimate cost of a fire is strictly a function of human response. For example, a large fire in the wilderness may be allowed to burn, thus accruing minimal suppression cost. On the other hand, a fire in a heavily populated intermix area may require extensive amounts of equipment and personnel, thus accruing costs of millions of dollars for a single event. Under these circumstances, the larger the fire, the more likely it will be expensive. In fact, the more expensive fires do tend to be the larger ones by USDA Forest Service standards ($\geq$ 40 hectares). Ninety percent of suppression costs are accounted for in the most expensive 20% of ranked large fires exceeding 40 hectares. Fires in this category have average suppression costs of more than $750,000 U.S. per fire.

Using USDA Forest Service 5100–29 fire reports, suppression costs were ranked for all western U.S. fires in the period 1980–2000. A subset of the original database was developed that included the date, location and size of each fire in which the suppression cost was $750,000 U.S. or larger. From a network of land management agency Remote Automatic Weather Stations (RAWS) across the U.S., the nearest representative station to each fire was determined, and ERC was calculated for the day of the fire start based on historical weather records from the Western Regional Climate Center's RAWS archive. If the nearest RAWS did not have complete data for the day of the fire start, then the next nearest RAWS was selected, and so on. If the final RAWS location exceeded 50 km, the fire was removed from the subset due to insufficient weather information. Though 50 km may seem a large distance for local weather influence, and indeed it can be, ERC tends to be broad in spatial scale. Therefore, distance is not believed to be a strong limiting factor in this particular analysis. The median distance of RAWS used in the analysis was 27 km. For the final analysis, 145 fires were identified that met the expense and fuel model *G* criteria discussed above. The bulk of these fires are in the northern Rockies and California. These are locations where, for fuel model *G*, suppression priorities have been costly during the past 20 years.

Of the 145 expensive fires, approximately 90% occurred with an ERC value of 50 or higher on the fire start day. Another group of 34 fires that occurred between 1980–2000 exceeding 400 hectares within 50 km radius of the same RAWS locations, but independent of the expensive fire dataset, was also examined in relation to ERC values. Though a small sample, 95% of these fires exceeded an ERC value of 60. Combining the two datasets yields occurrences of 97% for an ERC value ≥ 40, and 80% for an ERC value ≥ 60. Furthermore, 42 additional 'medium' sized fires in the 40–400 hectare range associated with the same RAWS locations yielded an ERC value exceeding 40 for all occurrences. Conversations with fire specialists independent of this study indicate that ERC values of 40 and 60 might be useful thresholds that can be related to management strategies and planning. Thus, two ERC thresholds seem appropriate for the climate change analysis: 40–59 and ≥ 60.

Finally, it is interesting to note that 3,683 fires of less than 40 hectares using the same RAWS locations had 80% of their associated ERC values exceeding 40. Thus, fire size is not uniquely determined by ERC. For example, there are various factors that could yield a reduced fire size given a large ERC value, such as low wind speeds during the early stages of the fire, causing slow rates of expansion, or aggressive initial attack on the fire with suppression resources that minimizes fire growth. This suggests a difficulty in correlating ERC to fire size, at least in any simple linear sense. Consequently, it will be difficult to correlate ERC directly with cost. Note that a fire danger index such as ERC is meant to represent an aspect of fire potential. As such, there can be many days with a high ERC value in which there is no fire occurrence, and therefore it is not surprising that simple linear correlations are difficult to obtain.

Despite this limitation, and although small fires can occur with virtually any value of ERC, the largest fires (≥ 400 hectares) tend to be associated with ERC values of 60 and higher, and large fires can be quite expensive. Since the largest fires tend to be associated with ERC values of 60 and higher, and given the current intermix era in fire suppression (Pyne et al., 1996), we will simplify and presume that high ERC days increase the risk of expensive fires. Thus, a greater frequency of days with ERC values greater than 60 are interpreted as a tendency toward larger overall suppression costs. Note that our definition of medium size (40–400 hectares) is actually considered to be large fires by Forest Service standards. Because there appears to be association between this fire size group and ERC values exceeding 40, ERC values from 40–59 were examined separately, and changes in the frequency of this range were presumed to reflect changes in the risk of medium sized fires.

5. Results

Realizing the important role that relative humidity plays in ERC, we first examined humidity in the historical climates (observed and PCM). The minimum (generally afternoon) humidity typically has the largest impact on daily fire behavior and fire danger. Figure 1 shows the PCM average annual number of days with a humidity minimum value of less than 30% during the base period 1976–95. Thirty percent (an arbitrary value) was chosen simply because lower humidity values are strongly associated with higher fire danger. As seen in the figure, there is a well-defined gradient in the number of days from 30 in the plains region to 180 in the desert Southwest. The 120-day contour runs from the Southwest, northward through the Great Basin and into Oregon.

A comparison of these PCM days to observed RAWS days for portions of the same base period is shown in Figure 2. An approximate 2.8° grid was developed from over 400 stations across the West to allow for a direct comparison with PCM. RAWS locations have varying lengths of record between approximately 1985 to present, and at least six years of data were required for inclusion in the analysis. The contours represent the PCM minus RAWS difference in the average annual number of days for the two climatologies, thus negative values indicate regions where PCM has fewer days with minimum relative humidity $\leq 30\%$ as compared to RAWS. There is a general tendency for PCM to underestimate the number of low humidity days from 60 to 100 over much of the West. However, from eastern Montana southward through New Mexico the differences are much higher (160 to 220 range). Some of these differences across the West might be attributed in part to a bias since most of the RAWS are observations from the latter half of the PCM base period (not the entire period), but the magnitudes suggest that the differences may be more PCM related than observation based. In fact, PCM temperatures tend to be lower than RAWS for the same period, something inherent within the model. These cooler temperatures will correspond to higher relative humidity values, and thus fewer days exceeding the designated minimum value. In other words, the PCM has a strong tendency to under-predict daily minimum relative humidity values. As

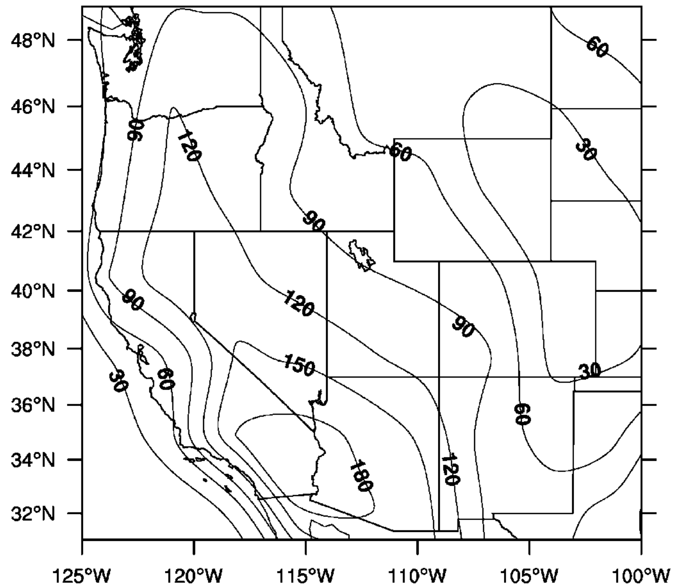

Figure 1. PCM mean annual number of days of minimum relative humidity ≤ 30% during the base period 1975–1996.

will be seen below, the implication of this is not necessarily negative, and may instead suggest that our final results are conservative.

Figures 3a-d show the difference between the average annual number of days with the minimum relative humidity having a value of 30% or less in a base period from 1976–95 and various BAU intervals of similar duration. The last period begins when CO_2 has been doubled in the model climate compared to the 'present day'. By 2010–2029 (Figure 3a), parts of the Southwest, interior Great Basin and northern Rockies are projected to experience 6 to 12 more 'dry' days compared to the base period. There is a slight decrease in the number of 'dry' days along the coast. By 2030–2049 (Figure 3b) there is a widespread decrease in the number of 'dry' days in comparison to the 2010–2029 period, but these counts still amount to about a one-week increase from the base period. However, over northwestern Texas, the number of 'dry' days increases by nearly three-weeks. During the 2050–2069 period (Figure 3c), the number of dry days increases by about 10 days over the northern Great Basin, but elsewhere changes are small or amount to reductions in the number of 'dry' days, e.g., over most of California and the Pacific Northwest. In the last period, 2070–2089 (Figure 3d), the largest increase in 'dry' days from the base period occurs over the Southwest and northwestern Texas, where nearly three additional 'dry' weeks are accumulated. This region of increased dryness extends northward over the Great Basin, but an approximate one-week decrease occurs over the Pacific Northwest and northern California. Some of these differences are likely associated with climate-change trends, and others probably are parts of naturally

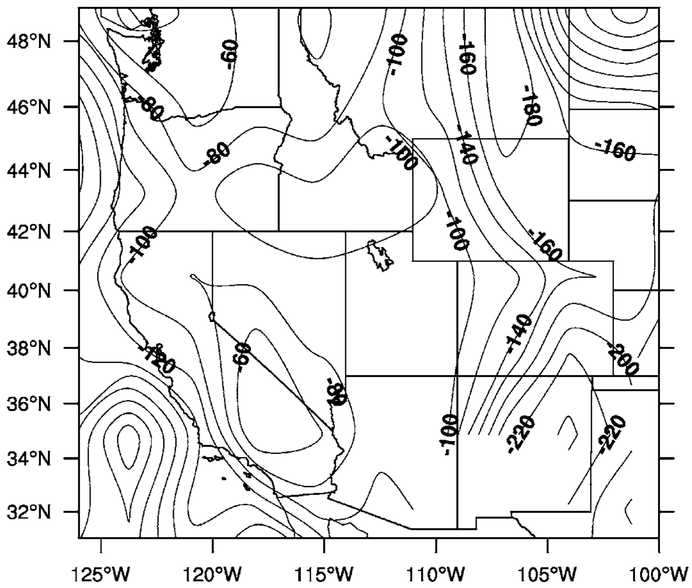

Figure 2. PCM minus RAWS mean annual number of days of minimum relative humidity ≤ 30% during the base period 1975–1996.

occurring interdecadal climate fluctuations (e.g., IPCC, 2001). However, by the 2070–89 period, the long-term trends are presumed to dominate, and differences shown in Figure 3d are believed to correspond to the direction and approximate magnitude of the 80-yr projected trend under BAU conditions.

These changes in minimum daily relative humidity will affect ERC, as will projected changes in maximum relative humidity, temperature and precipitation amount and duration, although minimum humidity is known to play a dominant role. Using the ERC thresholds described above, Figure 4 shows the average annual number of days with ERC values in the 40–59 range during 1976–1995 base period. Over most of the West during this period, this threshold occurred from one to two months on average. Figure 5a shows the pattern of changes in the number of days with ERC values in the 40–59 range during the 2010–2029 period compared to the base period. An increase of around one week occurs in Montana and central California. Otherwise, little change is noted elsewhere. In Figure 5b, comparing ERC in the 2030–2049 period to the base period, the number of days with ERC values between 40–59 increases in Montana to one to two weeks more than in the base period, and around one week in Washington, northern Idaho and southeast New Mexico. Elsewhere, little change occurs except for southern Idaho where a nearly one week decrease occurs. In Figure 5c the most notable increases in the number of days occurs in western Montana and Wyoming. The largest decrease in the number of days (approximately one week) occurs over the eastern Oregon and Washington border. During the 2070–2089 period with its doubled CO_2 climate

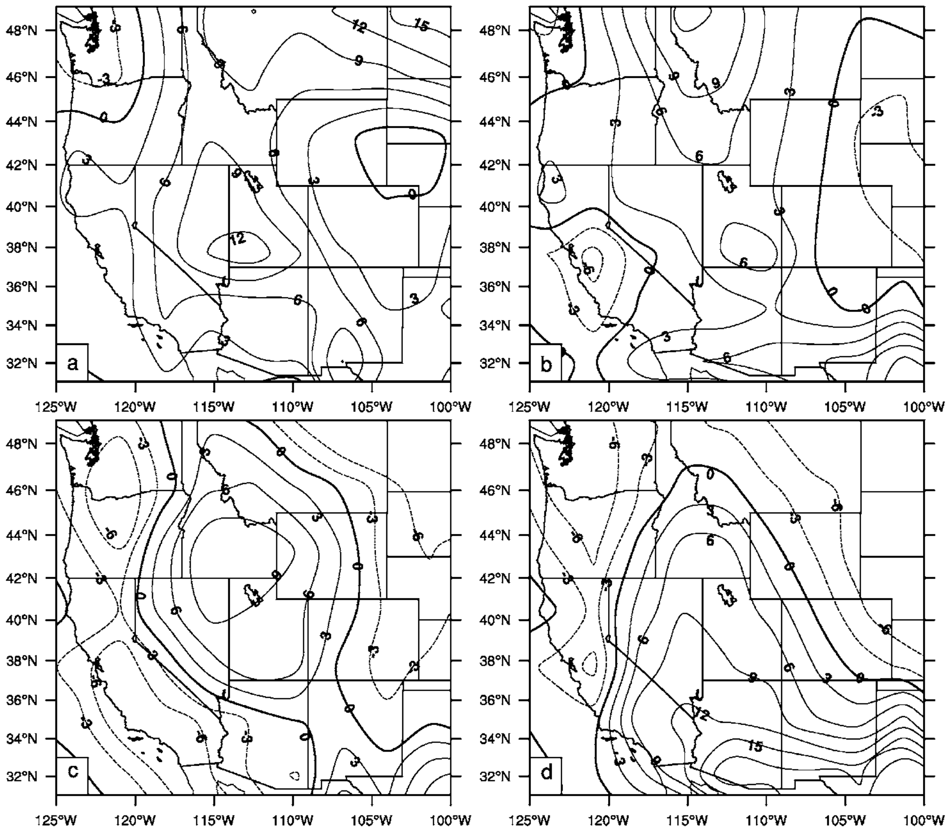

Figure 3. Difference in the mean annual number of days of minimum relative humidity ≤ 30% from the PCM BAU scenario and the base run period 1975–1996 for (a) 2010–2029, (b) 2030–2049, (c) 2050–2069, and (d) 2070–2089.

(Figure 5d), there is continued spatial variability in threshold occurrence. The most notable increases (1–2 weeks) occur in California, Arizona and New Mexico. There is nearly a one week decrease of occurrence in Idaho and eastern Oregon and Washington.

The ERC 60 and greater threshold represents the more extreme fire danger events, and for these, the climate-change signal appears much stronger. Figure 6 shows the average annual number of days of ERC 60 and greater during the 1976–1995 base period. Across most of the West, occurrence of this threshold is from one to three months, with the largest number of days in the desert southwest. Few days on average are noted in the Pacific Northwest, northern Rockies, and High Plains. Figure 7a shows the change in the number of days on which ERC was 60 or greater for the 2010–2029 period compared to the 1976–1995 base period. An increase of one to two weeks can be seen across most of the West. The primary exceptions are the Pacific Coast, Montana, Wyoming and Colorado. During the 2030–2049

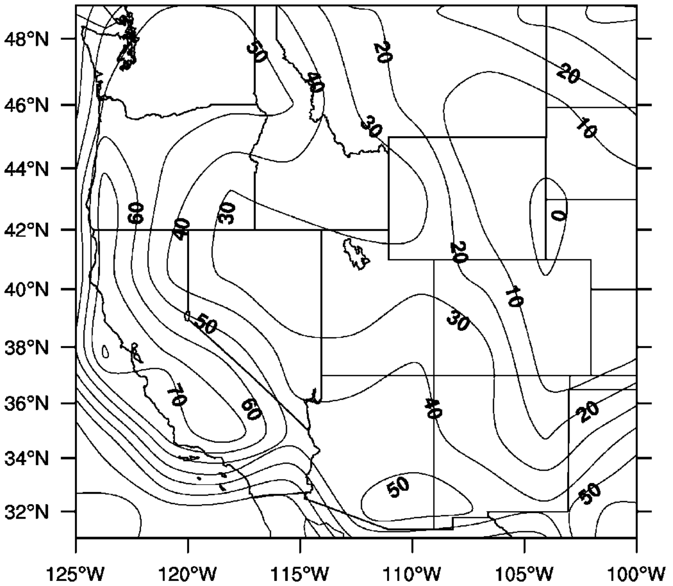

Figure 4. PCM mean annual number of days with ERC fuel model *G* threshold of 40–59 during 1975–1996.

period (Figure 7b) there is an increase over much of the West, though more on the order of a week or so, except over Idaho and eastern Oregon and Washington where an increase of nearly two weeks occurs. Figure 7c shows a generally similar pattern for the 2050–2069 period. Again the largest increases occur over Idaho and eastern Oregon and Washington. Figure 7d shows an especially strong pattern for the 2070–2089 period. An increase of nearly two weeks occurs over most of the West. For example, in southern Idaho the increase of average annual number of days is from 40 to 55, and in Arizona from 110 to 120 days. Notably, much of Montana, Wyoming and Colorado are projected to have little or no change.

An indication of the statistical strength of these changes can be assessed by a simple t-test of the annual standard deviations associated with the mean annual number of days of threshold occurrence for each of the four BAU periods shown in Figure 7. Figure 8 shows the t-test p-value for the periods (a) 2010–2029, (b) 2030–2049, (c) 2050–2069 and (d) 2070–2089, respectively. There are generally large areas of small p-values, and the smallest values tend to be associated with areas that have the largest increases in the number of threshold days. This lends some confidence that the results are due in part to climate change, and not just natural variability.

The substantial increase in number of days that the ERC thresholds in both Figures 5 and 7 can be primarily attributed to changes in relative humidity – probably a combination of both drier days and nights, but especially minimum humidity values. A general warming of the West under the BAU scenario (e.g., Dai et al.,

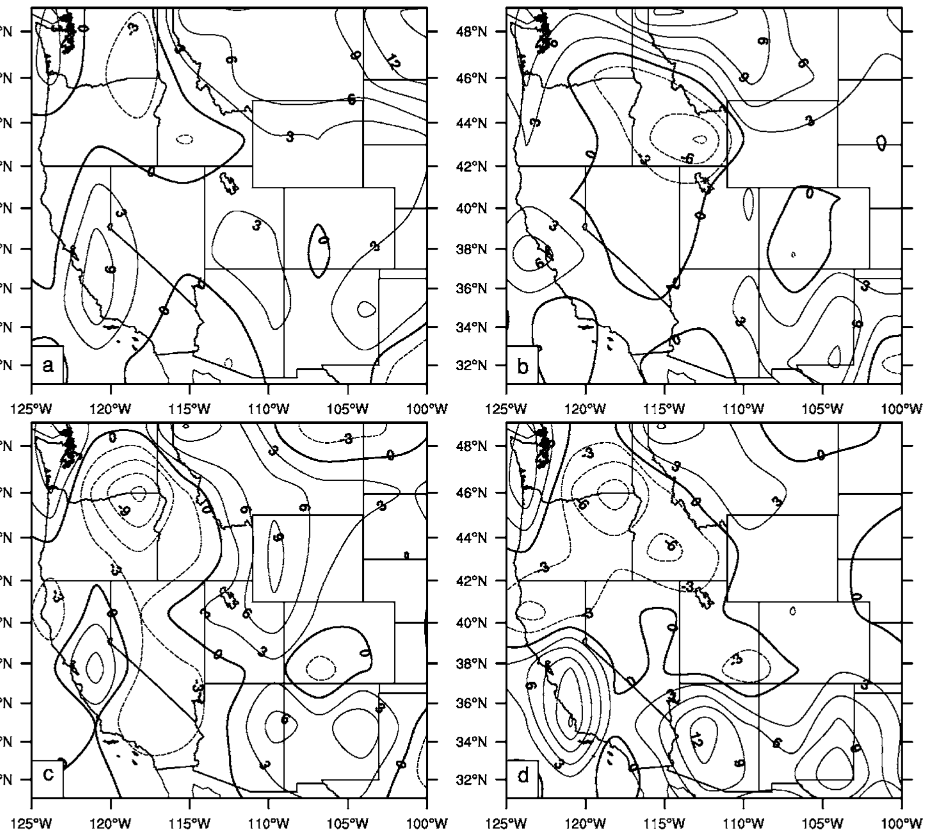

Figure 5. PCM BAU scenario and the base run period 1975–1996 difference in the mean annual number of days with ERC threshold of 40–59 for (a) 2010–2029, (b) 2030–2049, (c) 2050–2069, and (d) 2070–2089.

2001) has little projected effect on ERC (except through the relationship between temperature and relative humidity) because ERC is so much less sensitive to temperature than to humidity. The BAU projections also involve precipitation changes (e.g., Dai et al., 2001), but over the western U.S., the changes in numbers of days with precipitation are small and, as a consequence, have little impact on ERC. The strong spatial structure evident in the presented figures, especially Figure 7, can be directly attributed to the PCM output. A combination of the elements we focused on (temperature and relative humidity that tend to have large-scale homogenous structure in spatially coarse models on monthly and longer time scales), and precipitation duration that showed little change, likely contributed to the spatial structure results. Finer scale grids, such as from regional models, may well show more spatial variability.

An analysis of whether or not ERC thresholds were being exceeded earlier or later (than in the 'present day') indicated that the increases of threshold occurrence

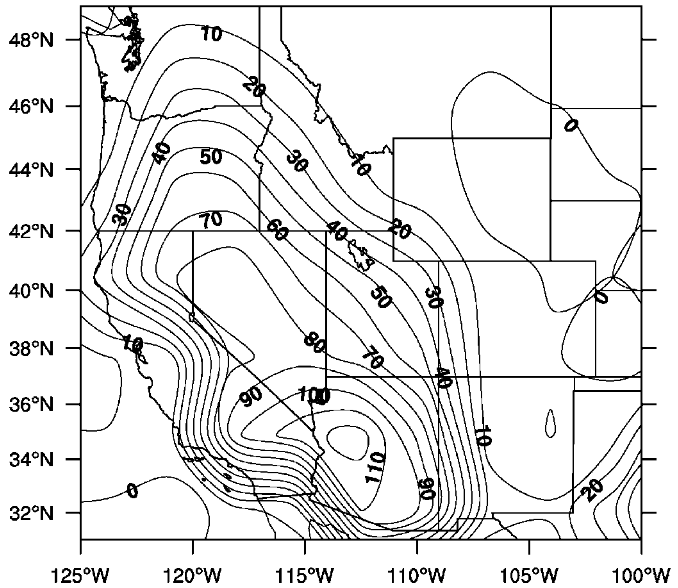

Figure 6. PCM mean annual number of days with ERC fuel model *G* threshold of ≥ 60 during 1975–1996.

seen in Figures 5 and 7 are the result of more occurrence days during the regular course of the season, rather than a change in season length. One possibility for this might be that PCM tends to overestimate relative humidity values as noted earlier. It would be of interest to examine the temporal aspects of ERC more fully in a future study.

In considering the projected changes, one could reasonably ask as to whether or not the PCM output was accurately reproducing ERC values for some historical period. Figure 9 shows contours of PCM computed ERC ≥ 60 days minus RAWS, similar to the humidity values derived in Figure 2. For several regions of the West – Arizona, California and the Pacific Northwest – the differences are small or nearly zero lending general confidence in the PCM output, at least for the base period. However, for portions of the Great Basin and Rockies, PCM underestimates high ERC values by as much as 40 days. New Mexico shows the largest differences (~ 60 days) coinciding with areas of large relative humidity differences shown in Figure 2. Since PCM underestimates both relative humidity for all of the West and ERC for much of the West, it could be suggested that the increased number of high ERC days in the projected climate scenario is also underestimated, and thus a conservative amount. The Colorado Rockies and the Front Range from Colorado up into Montana are distinct from the rest of the West in that they show no change in the large ERC threshold values (Figure 7). Whether this no-change area is realistic or results from humidity over-estimation is difficult to say. But there have been various GCM outputs that suggest this region could become wetter during

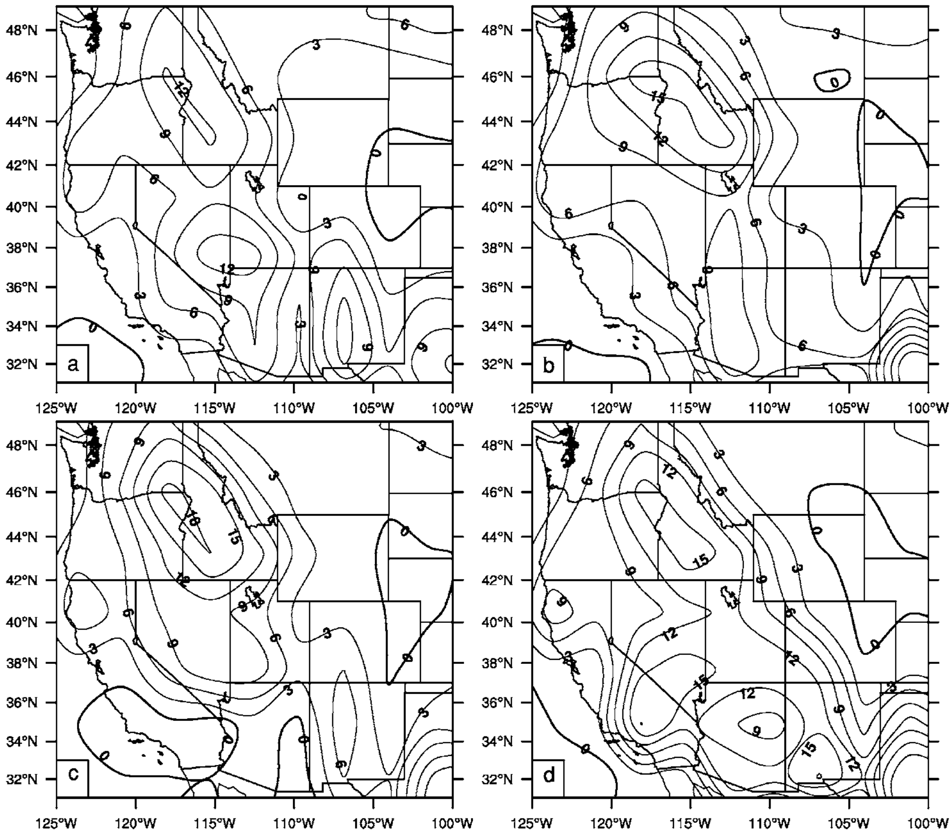

Figure 7. PCM BAU scenario and the base run period 1975–1996 difference in the mean annual number of days with ERC threshold of ≥ 60 for (a) 2010–2029, (b) 2030–2049, (c) 2050–2069, and (d) 2070–2089.

the twenty-first century (IPCC, 2001), which would then correspond to at most a minimal increase in the ERC thresholds and perhaps even a decrease or no change as shown.

6. Conclusions

The results of this study complement previous studies that assessed future wildland fire severity in the U.S. and North America based on projected climate change. Fire severity can be expected to increase given warmer and drier conditions, though this varies regionally given the projected climate. Our study adds to the previous work by utilizing a National Fire Danger Rating System index commonly used by fire management. This allows land management agencies to incorporate our results in their longer-term strategic planning and policy. Our methodology also allows us to

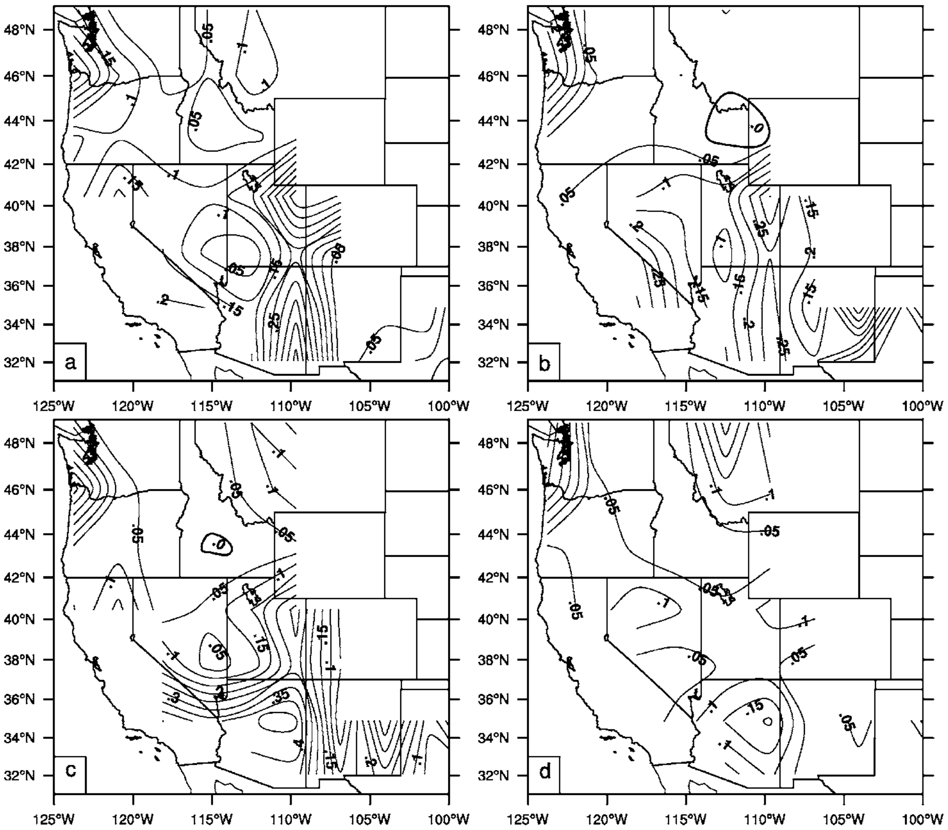

Figure 8. P-values based on t-test of standard deviations for the mean annual number of days of ERC ≥ 60 for (a) 2010–2029, (b) 2030–2049, (c) 2050–2069, and (d) 2070–2089.

speculate on economic factors related to fire suppression given fire danger change in a future climate scenario.

Based on the results found in this study, we conclude that:

1. High-temporal resolution PCM output can be used to compute value-added sector (e.g., wildland fire) specific products and applications. In this case, we have successfully produced and projected an index of fire danger (ERC) commonly used by fire management.
2. Bi-decadal patterns of relative humidity indicate general drying over the Great Basin and desert Southwest during the twenty-first century. The largest increases in the number of days with a minimum relative humidity of 30% or less occur in the Southwest during the latter part of the century by the time the climate model CO_2 concentrations have doubled.
3. PCM relative humidity is overestimated compared to RAWS observed values for a historical base period, but ERC thresholds are similar for several regions in the West for the same period, lending confidence in the future sce-

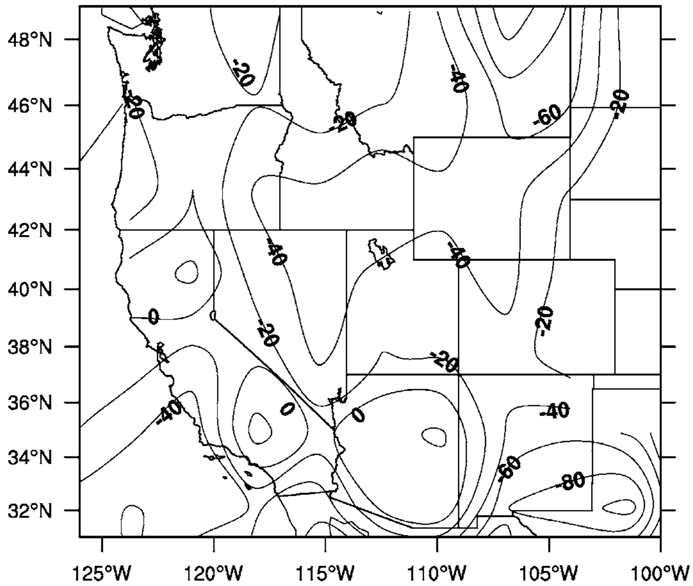

Figure 9. Mean annual number of days of ERC ≥ 60 for PCM minus RAWS during the base period 1975–1996.

nario results. Because PCM relative humidity values tend to be high, the ERC threshold results are likely conservative.

4. ERC index values of 40–59 and ≥ 60 were found to be readily derived thresholds based on analysis of large fire occurrence ($\geq$ 40 hectares). These thresholds may also have direct applicability to fire management decisions.
5. Regional changes in the occurrence of ERC indices in the range from 40–59 show bi-decadal and spatial variability. A nearly two week increase in threshold days occurs in the Southwest in the latter part of the century. A one week decrease in the number of threshold days occurs throughout the century in Idaho, and in eastern Oregon and Washington.
6. The ERC threshold index of 60 and greater, which corresponds to many of the largest and most expensive fires, shows substantial consistency throughout the twenty-first century. Nearly all of the western U.S. is projected to experience increases in the number of days that this large threshold value is exceeded by as much as two weeks depending on the region. The areas with the largest changes are the northern Rockies, Great Basin and the Southwest. These are regions that have already experienced substantial fire activity during the early part of the twenty-first century.
7. The Front Range and High Plains regions do not show substantial changes in ERC threshold occurrence during the century, but this index may not be well simulated by PCM for this region.

8. There is no one-to-one relationship between ERC and fire suppression costs. However, larger fires tend to be expensive, and more frequent occurrences of larger ERC values, in combination with intermixing of human with fire-vulnerable ecosystems, are expected to imply increased risks of more expensive fires.
9. Projected more frequent occurrences of larger ERC values suggests significant impacts on fire management in the future. New strategies and policy may need to be incorporated to address both suppression and fuel treatment needs in complex and changing ecosystems. The continued growth of the intermix and treatment debates (e.g., escaped burns, smoke and air quality issues) will exacerbate the problem.
10. This project successfully demonstrates the utilization of climate model output in addressing climate-driven impacts and the potential value of incorporating results into policy. Our results suggest that new fire management strategies and policies may be needed to address the added climatic risks.

Many ecosystems are fire-dependent (ecosystem dynamics that requires fire for the facilitation of successional pathways and biological diversity). Removing fire from a fire-dependent ecosystem and observing the result over time will likely lead to an undesirable outcome. Once source of evidence for this are the backyard experiments in fire removal now commonly in place – those areas referred to as the intermix or wildland/urban interface. Understanding how climate affects the fire regimes of ecosystems, and how ecosystems affect climate is the continuing challenge for inter-disciplinary climate and wildfire scientists. It is likely that climate change will amplify these effects as the ecosystems respond to change. How society will fully respond to and plan for these projected changes over time has yet to be seen. Policy makers face formidable challenges in ecosystem management and stewardship given socioeconomic desires and the physical outcomes from both climate change and human decisions.

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