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Effects of climate change on snowpack and fire potential in the western USA

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Abstract We evaluate the implications of ten twenty-first century climate scenarios for snow, soil moisture, and fuel moisture across the conterminous western USA using the Variable Infiltration Capacity (VIC) hydrology model. A decline in mountain snowpack, an advance in the timing of spring melt, and a reduction in snow season are projected for five mountain ranges in the region. For the southernmost range (the White Mountains), spring snow at most elevations will disappear by the end of the twenty-first century. We investigate soil and fuel moisture changes for the five mountain ranges and for six lowland regions. The accelerated depletion of mountain snowpack due to warming leads to reduced summer soil moisture across mountain environments. Similarly, warmer and drier summers lead to decreases of up to 25% in dead fuel moisture across all mountain ranges. Collective declines in spring mountain snowpack, summer soil moisture, and fuel moisture across western mountain ranges will increase fire potential in flammability-limited forested systems where fuels are not limiting. Projected changes in fire potential in predominately fuel-limited systems at lower elevations are more uncertain given the confounding signals between projected changes in soil moisture and fuel moisture.

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1 Introduction

In the western US, snow is the primary source of water storage (Cayan 1996). Most of the annual precipitation occurs during the cool season and is returned to the atmosphere in the spring and early summer through evapotranspiration, except at the highest elevations and northern coastal areas, where it is predominantly released as runoff and streamflow (Barnett et al. 2005). This annual cycle makes the region particularly vulnerable to changes in climate, which alter the timing and duration of the snow season, and subsequent water availability throughout the dry summer months. Widespread declines in April 1 snow water equivalent (SWE) have been seen at snow course sites across mountains of the western USA over the past 50 years (e.g., Mote 2006; Hamlet et al. 2005). Declines in snowpack were more pronounced in temperate ranges than the colder, interior ranges, suggesting that the loss in spring snowpack was a result of warming temperatures (Mote et al. 2005). Spring runoff in snowmelt-dominated rivers in the western USA has shifted earlier by 1 to 3 weeks over the past 50 years, which has been attributed to warming temperatures (Stewart et al. 2005) and to decreased mountain precipitation (Kormos et al. 2016).

Projected changes in climate unanimously show continued and accelerated increases in temperature across the western USA through the twenty-first century (Sillmann et al. 2013). Regional changes in precipitation, by contrast, are more uncertain and differ substantially (even by sign) among global climate models (Kharin et al. 2013). Luce et al. (2013) suggested that declines in streamflow in the northwestern USA since 1950 could be attributed to declines in orographic precipitation associated with a reduction in the strength of lower-tropospheric winter westerlies. Lute et al. (2015) found that annual snowfall water equivalent was projected to decline across the western USA by the mid-twenty-first century and that low-snowfall years would become more frequent.

Stewart et al. (2004) among others (e.g., Wood et al. 2004; Lundquist and Flint 2006) have projected that spring runoff timing could shift earlier by more than a month by the end of the twenty-first century, which has strong implications for summer soil moisture. Soil moisture integrates non-linear impacts of temperature, precipitation, vapor pressure deficit, and wind into the moisture content of vegetation and thus may be a proxy for vegetation and duff dryness, making it an important indicator of ecosystem function (e.g., Littell et al. 2008) and of fire potential in flammability-limited forested regimes. Higuera et al. (2015) showed that summer soil moisture explained over 60% of interannual variability in area burned across the Northern Rocky Mountains. Fluctuations in winter snowpack can have a strong impact on the occurrence of large fires (Westerling et al. 2006) in the western USA, as spring snowpack influences soil moisture in the subsequent summer. Similarly, fuel moisture is an important proxy for potential ignition and fire spread and strongly correlates with the amount of area burned (Flannigan et al. 2005; Abatzoglou and Kolden 2013).

The frequency of large fires and area burned in wildland fires over the western USA have increased markedly over the past several decades (Westerling et al. 2006; Dennison et al. 2014; Littell et al. 2009. These trends are projected to continue, with widespread increases in large fire frequency (Westerling et al. 2011a; Stavros et al. 2014) and area burned (Westerling et al. 2011b; Littell et al. 2010; Turner et al. 2016). Although projected changes in wildfire activity across the western USA have been estimated using contemporary climate-fire relationships, it is likely that contemporary climate-fire relationships may be non-stationary under a changing climate (McKenzie and Littell 2016). Past studies (e.g., Littell et al. 2009; Littell and Gwozdz 2011; Abatzoglou and Kolden 2013) have defined two general climate-fire regimes that are applicable to the western USA. Wildfires in primarily lower-elevation rangelands are associated with years of higher fuel abundance that result from increased moisture availability, while wildfires in primarily higher-elevation forested areas are associated with moisture deficits that result in increased fuel aridity (Abatzoglou and Kolden 2013). A long history of fire suppression across parts of the western USA complicates these climate-fire relationships. Despite historical differences in fire suppression and different climate-fire relationships, prior studies have not distinguished between projected changes in fire potential between upland and lowland areas over a domain as large as the western USA.

In this study, our objective is to understand how future changes in climate will affect snowpack, soil moisture, and fuel moisture in upland and lowland regions of the western USA. We focus on the links between hydrologic changes in snowpack and soil moisture, associated both with changing snow processes in the uplands and precipitation changes in the lowlands, and changes in fuel moisture. We also evaluate their combined implications for summer aridity and fire potential. Using an ensemble of ten GCMs allows us to evaluate a broader range of possible outcomes and highlight where projections are consistent (or not) among models. Our intention is not to model changes in fire activity (e.g., burned area, fire frequency), but rather to examine projected changes in fuel aridity metrics that are proximate drivers of interannual variability in fire activity across parts of the region (e.g., Higuera et al. 2015). By the term fire potential, we mean the potential for fire to occur. The vulnerability components of fire risk are beyond the scope of our study.

2 Approach

2.1 Domain

Our domain consists of five mountain regions and six lowland regions in the western USA. The mountain ranges include the Sierra Nevada mountains, Cascades, Northern and Southern Rockies, and White Mountains (Fig. 1). The lowland regions consist of the Great Basin, Coastal North, Coastal South, Northwest Interior, Missouri, and Lower Colorado (Fig. 1). The Missouri, Lower Colorado, and Great Basin regions are defined by USGS Hydrologic Unit Code (HUC) 02 boundaries (Watershed Boundary Dataset for HUC-02s 2015). For Missouri HUC-02, only the area west of 103° is included. The mountain regions were defined as

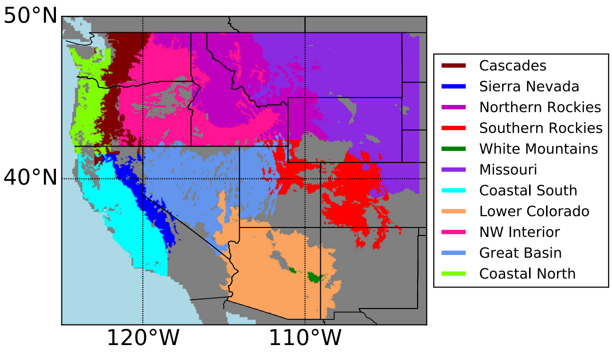


Fig. 1 Map of mountain ranges and lowlands in the western United States included in this study

consisting of the 1/16° latitude-longitude grid cells for which the historical (1970–1999) model-simulated mean April 1 SWE exceeded 10 mm.

2.2 Climate forcing datasets and downscaling

We used meteorological inputs from Livneh et al. (2013) for historical Variable Infiltration Capacity (VIC) model simulations, which we compared to SNOTEL observations (Online Resource 1) and which were also used to define the April 1 SWE threshold for mountain ranges. Our comparison to SNOTEL observations served as a validation for modeled SWE (see Online Resource 1 and Supplementary Materials). Hydrologic simulations were driven by precipitation, maximum and minimum temperature, and wind speed outputs downscaled using the Multivariate Adaptive Constructive Analogues (MACA) statistical downscaling approach (Abatzoglou and Brown 2012). Meteorological inputs used as the training dataset for the MACA downscaling were taken from Livneh et al. (2013) from 1950 to 2011. We used ten GCMs (Online Resource 2), selected from the Coupled Model Intercomparison Project 5 (CMIP5) archive (Taylor et al. 2011) based on their ability to simulate the historical climate in the western USA (Rupp et al. 2013). For each GCM, we used downscaled climate taken from the control forcing (1960–2005) and future forcing (2006–2099) experiments, with the latter including both Representative Concentration Pathways (RCPs) 4.5 and 8.5.

Since Livneh et al. (2013) used a standard lapse rate of −6.5 °C/km over the western USA, this may have introduced biases into our meteorological forcings, particularly over topographically complex regions that have heterogeneous lapse rates, such as on the windward side of the Cascades (Minder et al. 2010), which can significantly impact hydrologic modeling (Mizukami et al. 2013). Behnke et al. (2016) showed, however, that Livneh et al. (2013) is one of the better-performing gridded climate datasets over the contiguous USA (CONUS), despite the lapse rate assumption. While the choice of downscaling approach adds an additional layer of uncertainty (Gutmann et al. 2014), Mizukami et al. (2016) found that the choice of downscaling method resulted in less variability than the choice of hydrologic model. Thus, we expect that the inter-model variation between GCMs in our study is much larger than the spread that would have resulted from using multiple downscaling methods. However, dynamical downscaling methods, in contrast to the statistical downscaling that was used in this study, might have yielded different results.

2.3 Hydrological modeling

The VIC model (Liang et al. 1994) Version 4.1.2.l was run in energy balance mode at a 1/16° spatial resolution and a 3-hour time step over the western USA. Model spin-up was accomplished by running the model with gridded historical inputs from Livneh et al. (2013) for 1950–1959 for all simulations for the control period and with 1995–2005 downscaled output from each GCM (and each scenario) for the future runs. Hydrological fluxes and states were then archived at a daily time step. VIC model parameters were taken from Livneh et al. (2013) and were calibrated to observed and/or naturalized flows in Livneh et al. (2013) for multiple large river basins across the western USA. The VIC model output, as well as the MACA-downscaled GCMs, is archived at the University of Idaho Applied Climate Science Lab at http://climate.nkn.uidaho.edu/IntegratedScenarios/ (Northwest Knowledge Network) and is publicly available.

2.4 Fuel moisture modeling

The US National Fire Danger Rating system (NFDRS) estimates dead fuel moisture (DFM) for different sized fuel classes (Cohen and Deeming 1985). We computed 100 and 1000-hour DFM using regression equations for equilibrium moisture content (EMC) developed by Simard (1968) and used by the NFDRS (Cohen and Deeming 1985; see Supplemental Materials). The 100 and 1000-h DFM correspond to the timescale of exponential decay of DFM with respect to the EMC, with 1000-h fuel representative of larger-diameter fuels that respond more slowly to fluctuations in EMC than 100-h fuels.

2.5 Analysis periods

We partitioned the control and future simulations into four 30-year periods: historical (1970–1999), 2020s (2010–2039), 2050s (2040–2069), and 2080s (2070–2099). We used these periods throughout our study to evaluate projected hydrologic changes during the twenty-first century. We also examined transient changes during the twenty-first century. Climate change results were calculated by comparing future GCM simulations with the control simulation from the same GCM.

3 Results

3.1 Temperature and precipitation projections

Average winter (November–March) temperature increases in all mountain ranges throughout the twenty-first century (Online Resource 3). Warming rates are generally larger over continental areas than maritime areas. For RCP 8.5, temperature increases exceed +4 °C by the 2080s and exceed +5 °C in the Northern and Southern Rockies. The Southern Cascades exhibit the least warming of the five mountain ranges, but still experience an increase of nearly +4 °C in the 2080s.

For most of the mountain ranges and lowland regions, the ensemble mean total winter precipitation increases up to 30% by the 2080s, with the exception of the White Mountains in Arizona and the Lower Colorado, which are projected to experience reductions in winter precipitation in the ensemble mean (Online Resource 4). The southern part of the Lower Colorado basin, in particular, shows a reduction greater than 30% by the 2080s in RCP 8.5. There are large differences between the 2020s, 2050s, and 2080s for RCPs 4.5 and 8.5, with increases becoming larger in the Missouri basin, the southern part of the Northwest Interior and the northern part of the Great Basin. Spring (March–May) ensemble mean precipitation shows a similar pattern in the Northwest Interior and the Missouri basin but shows decreases in the Great Basin.

3.2 Projected changes in snowpack

Shifts in precipitation and temperature impact snowpack across the domain. Figure 2 shows the ensemble mean of simulated SWE aggregated by mountain range as well as the full range and the interquartile range of aggregate SWE predicted by the ensemble of GCMs. Although the magnitude of the decline differs among models, decreasing trends

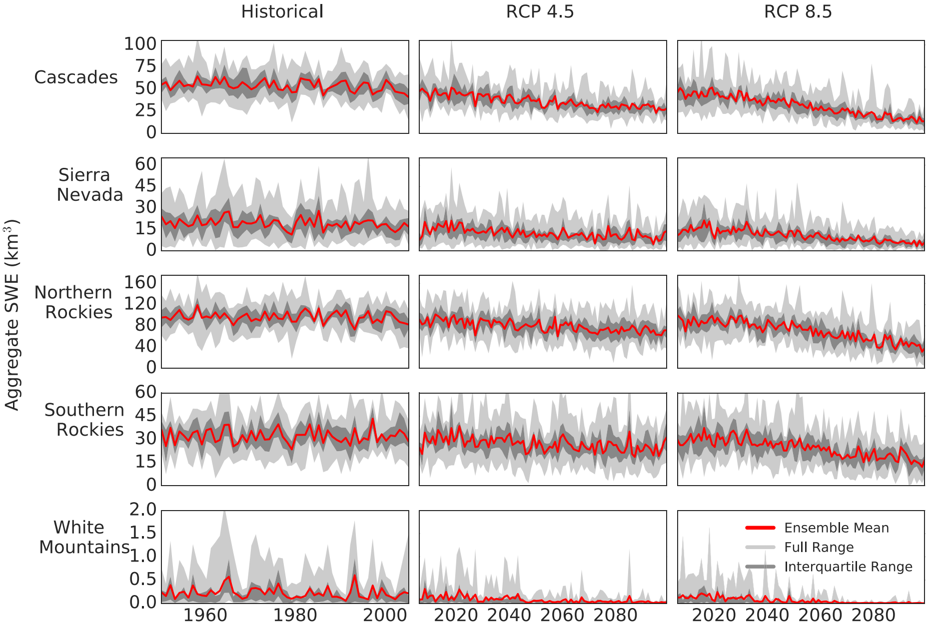
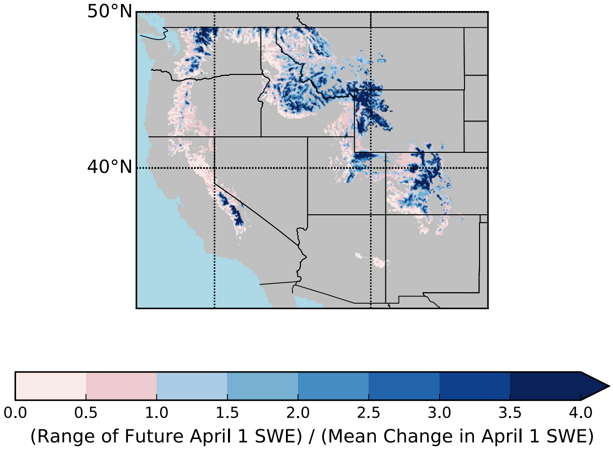


Fig. 2 Simulated April 1 SWE aggregated by volume over each mountain range for the five mountain regions. *Light gray* shows the full range projected by the GCMs, *dark gray* shows the interquartile range, and *red* shows the ensemble mean of the GCMs

are robust across all future simulations for mean April 1 SWE storage (in km^3) between the historical and future periods (Online Resource 6). The greatest relative decline in SWE is projected in the White Mountains, which by the end of the twenty-first century are projected to be nearly free of snow (95% reduction, ensemble mean) or entirely snow-free (maximum projected changes). Although the Northern Rockies also show a large decrease for RCP 8.5, it is substantially smaller in relative terms (48%) than for the Cascades, Sierra Nevada, and White Mountains, which have average projected losses of 65, 65, and 95%, respectively (Online Resource 6). Much of the differential effects of climate change on SWE can be explained in terms of elevation and thus temperature (see Online Resources 8 and 9).

Even though increases in temperature lead to a lower fraction of precipitation falling as snow and earlier melt, the spread in projected changes in precipitation contributes to uncertainty about the magnitude of spring snowpack change in some areas of the western USA. Figure 3 compares the spread in April 1 SWE projections (from all ten GCMs) for RCP 8.5 for the 2050s with the mean change in April 1 SWE (across all ten models) between the future and historic period (1970–1999). A higher value indicates that the range of SWE projections is larger than the mean projected change in SWE. For example, a value of 4 indicates that the range of SWE projections is 4 times greater than the mean projected change in SWE. High ratios occur in parts of the Cascades, Sierras, and much of the Northern and Southern Rockies, while low ratios occur in mid to lower-elevation areas. Luce (2016) used the same metric based on snow simulations at selected SNOTEL sites and found similar results for locations in the Northern and Southern Rockies.

Fig. 3 Uncertainty in projected losses of SWE (absolute value of the difference between maximum and minimum April 1 SWE projected by the GCMs for RCP 8.5 2040–2069 divided by the mean projected change). *Red areas* indicate that the mean projected change is greater than the spread between GCMs. *Blue areas* indicate that the spread is larger than the mean projected change



3.3 Projected changes in soil moisture

Figure 4 shows the ensemble mean total column soil moisture storage for summer (June–August) for the historical period as well as projected changes for the 2050s for RCP 8.5. For each grid cell, the minimum annual average summer soil moisture from the control simulation has been subtracted from each year in the historical and future time periods. For most upland regions, large decreases in summer soil moisture result from earlier snowmelt, reducing soil moisture recharge that historically occurs during late spring and early summer snowmelt. The largest decreases occur in the Sierra Nevada and Southern Cascades, as well as parts of the Northern and Southern Rockies. Absolute declines in soil moisture in these mountain systems are accentuated because they historically have higher summer soil moisture. By contrast, changes in soil moisture for lowland regions are smaller in magnitude and feature differing signals. The largest decrease occurs in the Coastal North, with smaller decreases in the Coastal South and parts of the Lower Colorado and Missouri basins. Soil moisture storage is projected to increase in the Northwest Interior, Great Basin, and the southern part of the Lower Colorado. However, individual GCMs show varied projections for the lowland regions (Online Resource 10). The spread between GCMs for soil moisture in the lowlands is due to the dependence of summer soil moisture on winter, spring, and summer precipitation (Online Resources 4 and 5).

3.4 Projected changes in fuel moisture

Figure 5 shows historical and projected changes in 100-h DFM averaged over June–September, which encompasses much of the primary fire season for the western USA. Historical DFM values are substantially lower at low-elevation sites relative to the uplands as higher elevation areas typically receive more precipitation and have lower temperature and vapor pressure deficits. In the mountain ranges, nearly all areas experience decreases in DFM, from a relatively minor decrease in the 2020s to a much larger relative decrease (greater than 25%) by the 2080s. This pattern is particularly strong in the Cascades and Northern Rockies, areas that were also projected to experience

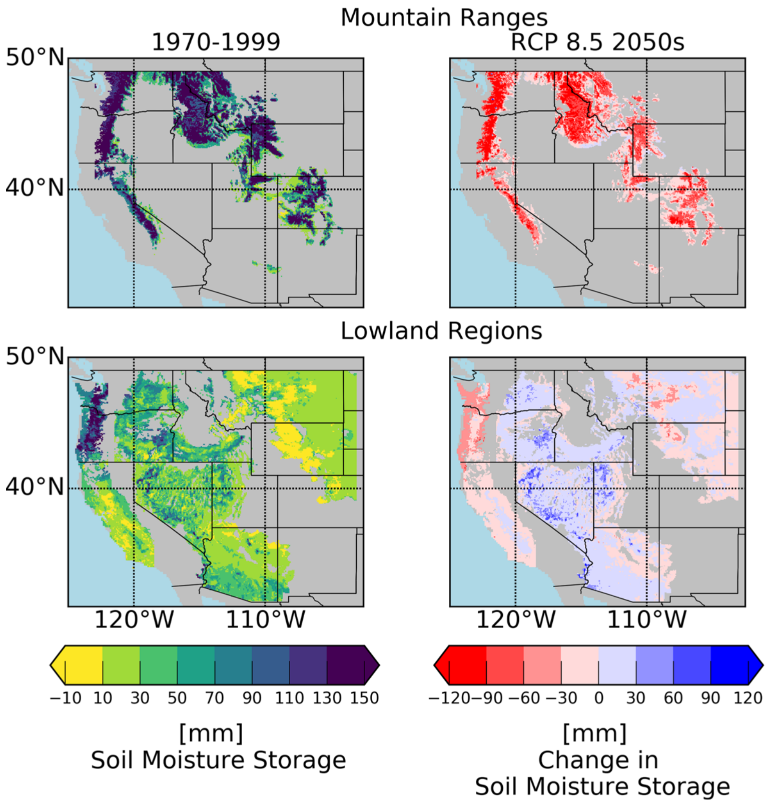


Fig. 4 Ensemble-mean simulated summer (JJA) soil moisture in storage for control simulations (*left column*) and change in storage between RCP 8.5 2040–2069 and the control period (*right column*) for the mountain ranges and lowland regions. The minimum summer soil moisture from the control period has been subtracted from each grid cell for control and future periods

increased aridity during the fire season based on decreasing summer soil moisture. DFM projections for the lowlands are more varied. Most of the lower elevations are projected to see declines in DFM, although at substantially smaller magnitudes than for neighboring higher elevation regions. Portions of the Lower Colorado show increases in DFM by the 2080s, presumably due to increases in summer precipitation in downscaled climate projections. The increasing and decreasing signals observed for 100-h DFM are largely the same for 1000-h DFM (Online Resource 11), with larger decreases in 100-h DFM in the Northwest Interior and Missouri regions.

Projected changes in DFM are not robust across GCMs in all areas. Online Resource 12 shows the number of models with positive changes minus the number of models with negative changes in 100-h DFM for RCP 8.5 in the 2080s. A negative number indicates that a majority of models shows a decrease in DFM, while a positive number indicates an increase in DFM. There is less agreement among models in the Sierra Nevada and Coastal South, as well as the Southern Cascades and the Southern Rockies, with little to no agreement in the southern part of the Coastal South and the Lower Colorado. Results for 1000-h DFM are similar, except with greater agreement for the Great Basin and Lower Colorado regions (Online Resource 13).

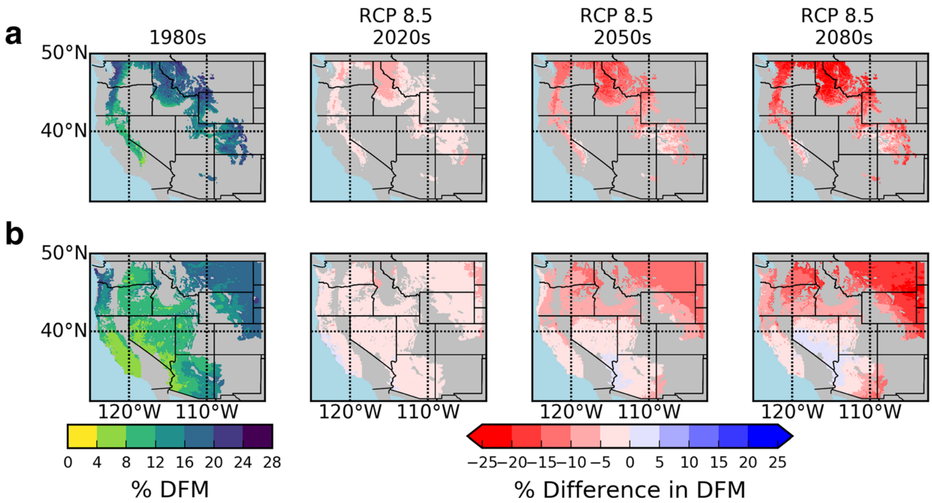


Fig. 5 Ensemble-mean summer (JJAS) 100-h dead fuel moisture (DFM) shown over **a** the five mountain ranges and **b** the six lowland regions, for the control period (1970–1999) and RCP 8.5 2010–2039, 2040–2069, and 2070–2099. For the control period, % DFM is shown, and for future periods, the % difference in DFM. DFM was calculated using the NFDRS algorithm for fuel moisture

4 Discussion

Our projected snowpack changes are generally consistent with previous studies that have examined changing snowpack in the western USA (e.g., Maurer 2007). Our results show relatively large declines in snowpack in all mountain ranges for all future scenarios and GCMs (Online Resource 7). Spring snowpack in mountains near the Pacific Coast is extremely sensitive to warming temperatures, while snowpack in more continental mountain ranges (Northern and Southern Rockies) is more sensitive to changes in precipitation (Online Resource 9), a result that is consistent with Adam et al. (2009) and other recent studies (e.g., Scalzitti et al. 2016; Luce et al. 2014). This sensitivity to warming temperatures explains the strong decline in snowpack in the Cascades and Sierra Nevada that is robust to potential increases in precipitation. The Cascades are projected to lose up to 81% of April 1 SWE storage, or up to 47.3 km^3 of total SWE by the 2080s. The Sierra Nevada are projected to lose up to 76% of SWE storage, or up to 13.4 km^3 of total SWE.

These declines translate into dramatic losses of a key source of water storage for the surrounding regions, many of which primarily rely on snowmelt for water supply. For example, the San Joaquin Basin in California has over 80 dams, with a total storage capacity of about 9.5 km^3 (7.7 million acre-feet) on the San Joaquin, Merced, Tuolumne, and Stanislaus rivers (California Environmental Protection Agency 2011). The maximum projected loss of SWE storage in the Sierra Nevada exceeds the San Joaquin Basin total storage capacity by 40%. Even the average projected loss of SWE storage in the Sierra Nevada for RCP 8.5 in the 2080s (11.3 km^3) exceeds the San Joaquin total storage capacity.

Future projected declines in April 1 SWE translate to declining summer soil moisture for all mountain ranges. Low summer soil moisture, in turn, is closely linked to fire potential and burned area in forested systems like the Northern Rockies (e.g., Higuera et al. 2015). Thus, projected declines of summer soil moisture in the mountain ranges lead to increased drought and are likely to increase the potential for wildfire in systems where large fires have historically coincided with such conditions (e.g., Westerling et al. 2003), but significant uncertainty remains with regard to projected changes in snowpack, soil moisture, and fire potential. Our findings are mostly consistent with previous studies that have identified the Sierra Nevada, Cascades, and Northern Rockies as the most at-risk areas in the western USA for increasing fire activity in a changing climate (Westerling et al. 2011a, b; Barbero et al. 2015; Littell et al. 2010; McKenzie and Littell 2016), with the exception of fire potential projections in the Yellowstone region in Westerling et al. (2011b), which our results contradict.

Summer soil moisture at lower elevations shows a mixed response to climate change. The Northwest Interior, Lower Colorado, and Great Basin are projected to experience increased summer soil moisture, while modest decreases are projected for the Missouri and Coastal North regions. The Coastal South region lacks a strong signal. Summer soil moisture increases in these basins are due to increased spring precipitation (Online Resource 5), which supersedes the effects of warming temperatures (Online Resource 3). There is much larger uncertainty in precipitation than temperature projections (Kharin et al. 2013); hence, the lack of robust agreement for areas where spring snowpack does not strongly influence summer soil moisture. The weaker drought-fire relationships, particularly for rangeland-dominated regimes, and lack of robust changes in soil moisture are less informative for projecting future fire potential in the lowland regions.

Similar differences are apparent in DFM changes between mountains and lowland regions. Decreases in 100-h DFM across mountain ranges, in concert with declines in soil moisture, suggest the potential for increased fire activity. Decreases in DFM in the lowland regions may enhance fire potential in flammability-limited fire regimes, but may not substantially alter fire potential in arid systems. Moreover, the models show a lack of agreement in changes in DFM in areas where the projected change in summer soil moisture lacks a distinct signal, such as in the Coastal South region (Online Resource 10). The confounding signals of increased summer soil moisture and decreased DFM in regions such as the Northwest Interior may have interesting impacts on fire regimes that warrant additional analysis, but are beyond the scope of this study.

5 Conclusions

Projected effects of climate change across the western USA contrast strongly for mountains and lowlands. The water balance of the mountainous portions of the domain is strongly linked to snow accumulation and ablation, which is strongly temperature-sensitive but varies across the domain. Changes in April 1 SWE in the higher-elevation areas of the Northern and Southern Rockies, North Cascades, and Southern Sierra are more uncertain due to larger spread in precipitation projections, whereas in other parts of the mountainous west, temperature projections dominate. Warming temperatures will result in declining snow water storage, and consequently, moisture inputs to the soil column will increase in winter and decrease in spring and summer. The result will be substantial reductions in summer soil moisture storage and increases in water deficit. We project large decreases in DFM in mountain ranges, which would increase fire potential.

The main conclusions of our work are as follows:

- In the five mountain regions, we project large declines in spring snowpack and summer soil moisture, primarily due to warming temperatures. This will result in April 1 SWE losses by the 2080s of up to 81% for the Cascades and 76% for the Sierra Nevada mountains.

- Ensemble mean summer soil moisture is projected to decrease in the mountain ranges and to increase in lowland regions. In the lowland regions, trends are not robust across GCMs due to differences in precipitation projections.
- Dead fuel moisture content (as represented by 100-h and 1000-h DFM) is projected to decrease in the mountain ranges and mostly increase in the lowland regions (for the ensemble mean). Lowland increases are of much smaller magnitude than the mountain decreases. Changes in fuel moisture content, however, are not robust across the western USA.
- Overall, we conclude that the mountain ranges are on average likely to experience higher fire potential under future climate projections. Other parts of our domain may also experience increased potential, but there is greater uncertainty in the lowland regions, where there is less agreement between GCMs, as well as in the Sierra Nevada, where there is disagreement between soil moisture and fuel moisture projections.

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References

Abatzoglou JT, Brown TJ (2012) A comparison of statistical downscaling methods suited for wildfire applications. Intl J Clim 32:772–780. doi:10.1002/joc.2312

Abatzoglou JT, Kolden CA (2013) Relationships between climate and macroscale area burned in the Western United States. Intl J Wildland Fire 22(7):1003–1020. doi:10.1071/WF13019

Adam JC, Hamlet AF, Lettenmaier DP (2009) Implications of global climate change for snowmelt hydrology in the twenty-first century. Hydrol Process 23:962–972. doi:10.1002/hyp.7201

Barbero R, Abatzoglou JT, Larkin NK, Kolden CA, Stocks B (2015) Climate change presents increased potential for very large fires in the Contiguous United States. Intl J Wildland Fire. doi:10.1071/WF15083

Barnett TP, Adam JC, Lettenmaier DP (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438:303–309. doi:10.1038/nature04141

Behnke R, Vavrus S, Allstadt A, Albright T, Thogmartin WE, Radeloff VC (2016) Evaluation of downscaled, gridded climate data for the conterminous United States. Ecol Appl 26(5):1338–1351. doi:10.1002/15-1061

California Environmental Protection Agency, State Water Resources Control Board (2011) Lower San Joaquin River Committee Administrative Materials. Available at: http://www.waterboards.ca.gov/centralvalley/water_issues/salinity/lower_sanjoaquin_river_committee/administrative_materials/2011apr28/2011apr28_mtg_ag_item4_rsrc_dev.pdf

Cayan DR (1996) Interannual climate variability and snowpack in the Western United States. J Clim 9:928–948. doi:10.1175/1520-0442(1996)009<0928:ICVASI>2.0.CO;2

Cohen JD, Deeming DE (1985) The National Fire Danger Rating System: basic equations. USDA and Forest Service, Pacific Southwest Forest and Range Experiment Station. Gen Tech Rep PSW-82.

Dennison PE, Brewer SC, Arnold JD, Moritz MA (2014) Large wildfire trends in the Western United States, 1984–2011. Geophys Res Lett 41:2928–2933. doi:10.1002/2014GL059576

Flannigan MD, Logan KA, Amiro BD, Skinner WR, Stocks BJ (2005) Future area burned in Canada. Clim Chang 72:1–16. doi:10.1007/s10584-005-5935-y

Gutmann E, Pruitt T, Clark MP, Brekke L, Arnold JR, Raff DA, Rasmussen RM (2014) An intercomparison of statistical downscaling methods used for water resource assessments in the United States. Water Resour Res 50:7167–7186. doi:10.1002/2014WR015559

Hamlet AF, Mote PW, Clark MP, Lettenmaier DP (2005) Effects of temperature and precipitation variability on snowpack trends in the Western United States. J Clim 18:4545–4561. doi:10.1175/JCLI3538.1

Higuera PE, Abatzoglou JT, Littell JS, Morgan P (2015) The changing strength and nature of fire-climate relationships in the Northern Rocky mountains, U.S.A., 1902–2008. PLoS One 10(6):e0127563. doi:10.1371/journal.pone.0127563

Kharin VV, Zwiers FW, Zhang X, Wehner M (2013) Changes in temperature and precipitation extremes in the CMIP5 ensemble. Clim Chang 119(2):345–357. doi:10.1007/s10584-013-0705-8

Kormos PR, Luce CH, Wenger SJ, Berghuijs WR (2016) Trends and sensitivities of low streamflow extremes to discharge timing and magnitude in Pacific Northwest mountain streams. Water Resour. Res 52. doi: 10.1002/2015WR018125

Liang X, Lettenmaier DP, Wood EF, Burges SJ (1994) A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J Geophys Res 99:14415–14428. doi:10.1029/94JD00483

Littell JS, Gwozdz R (2011) Climatic water balance and regional fire years in the Pacific Northwest, USA: linking regional climate and fire at landscape scales. Ecol Stud 213:117–139. doi:10.1029/94JD00483

Littell JS, McKenzie D, Peterson DL, Westerling AL (2009) Climate and wildfire area burned in Western U.S. ecoprovinces, 1916–2003. Ecol Appl 19(4):1003–1021. doi:10.1890/07-1183.1

Littell JS, Oneil EE, McKenzie D, Hicke JA, Lutz JA, Norheim RA, Elsner MM (2010) Forest ecosystems, disturbance, and climatic change in Washington State, USA. Clim Chang 102:129–158. doi:10.1007/s10584-010-9858-x

Littell JS, Peterson DL, Tjoelker M (2008) Douglas-fir growth in mountain ecosystems: water limits tree growth from stand to region. Ecological Monographs 78(3):349–368. doi:10.1890/07-0712.1

Livneh B, Rosenberg EA, Lin C, Nijssen B, Mishra V, Andreadis KM, Maurer EP, Lettenmaier DP (2013) A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: update and extensions. J Clim 26:9384–9392. doi:10.1175/JCLI-D-12-00508.1

Luce CH (2016) Effects of climate change on snowpack, glaciers, and water resources in the Northern Rockies Region. In: Halofsky JE, Peterson DL, Dante-Wood SK, Hoang L, Ho JJ, Joyce LA (eds) Climate change vulnerability and adaptation in the Northern Rocky Mountains, Gen. Tech. Rep. RMRS-GTR-xxx. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins

Luce CH, Abatzoglou JT, Holden ZA (2013) The missing mountain water: slower westerlies decrease orographic enhancement in the Pacific Northwest USA. Science 342(6164):1360–1364. doi:10.1126/science.1242335

Luce CH, Lopez-Burgos V, Holden Z (2014) Sensitivity of snowpack storage to precipitation and temperature using spatial and temporal analog models. Water Resour Res 50:9447–9462. doi:10.1002/2013WR014844

Lundquist JD, Flint AL (2006) Onset of snowmelt and streamflow in 2004 in the Western United States: how shading May affect spring streamflow timing in a warmer world. J Hydrometeorol 7:1199–1217. doi:10.1175/JHM539.1

Lute AC, Abatzoglou JT, Hegewisch KC (2015) Projected changes in snowfall extremes and interannual variability of snowfall in the Western United States. Water Resour Res 51:960–972. doi:10.1002/2014WR016267

Maurer EP (2007) Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios. Clim Chang 82:309–325. doi:10.1007/s10584-006-9180-9

McKenzie D, Littell JS (2016) Climate change and the eco-hydrology of fire: will area burned increase in a warming Western US? Ecol Appl. doi:10.1002/eap.1420

Minder JR, Mote PW, Lundquist JD (2010) Surface temperature lapse rates over complex terrain: lessons from the Cascade Mountains. J Geophys Res 115, D14122. doi:10.1029/2009JD012493

Mizukami N, Clark MP, Slater AG, Brekke LD, Elsner MM, Arnold JR, Gangopadhyay S (2013) Hydrologic implications of different large-scale meteorological model forcing datasets in mountainous regions. J Hydrometeorol 15:474–488. doi:10.1175/JHM-D-13-036.1

Mizukami N, Clark MP, Gutmann ED, Mendoza PA, Newman AJ, Nijssen B, Livneh B, Hay LE, Arnold JR, Brekke LD (2016) Implications of the methodological choices for hydrologic portrayals of climate change over the contiguous United States: statistically downscaled forcing data and hydrologic models. J of Hydromet 17(1):73–98. doi:10.1175/JHM-D-14-0187.1

Mote PW (2006) Climate-driven variability and trends in mountain snowpack in western North America. J Clim 19:6209–6220. doi:10.1175/JCLI3971.1

Mote PW, Hamlet AF, Clark MP, Lettenmaier DP (2005) Declining mountain snowpack in western North America. Bull Am Meteorol Soc 86(1):39–49. doi:10.1175/BAMS-86-1-39

Northwest Knowledge Network (NKN) University of Idaho applied climate science lab, http://climate.northwestknowledge.net/

Rupp DE, Abatzoglou JT, Hegewisch KC, Mote PW (2013) Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. J Geophys Res Atmos 118:10884–10906. doi:10.1002/jgrd.50843

Scalzitti J, Strong C, Kochanski A (2016) Climate change impact on the roles of temperature and precipitation in Western U.S. snowpack variability. Geophys Res Lett 43. doi: 10.1002/2016GL068798

Sillmann J, Kharin VV, Zwiers FW, Zhang X, Bronaugh D (2013) Climate Extremes indices in the CMIP5 multimodel ensemble: part 2. Future climate projections. J Geophys Res Atmos 118:2473–2493. doi:10.1002/jgrd.50188

Simard A (1968) The moisture content of forest fuels—a review of the basic concepts. Technical report. USDA, Forest Service, Ottawa

Stavros EN, Abatzoglou JT, McKenzie D, Larkin NK (2014) Regional projections of the likelihood of very large wildland fires under a changing climate in the contiguous Western United States. Clim Chang 126(3–4): 455–468. doi:10.1007/S10584-014-1229-6

Stewart IT, Cayan DR, Dettinger MD (2004) Changes in snowmelt runoff timing in western North America under a "business as usual" climate change scenario. Clim Chang 62:217–232. doi:10.1023/B:CLIM.0000013702.22656.e8

Stewart IT, Cayan DR, Dettinger MD (2005) Changes toward earlier streamflow timing across western North America. J Clim 18:1136–1155. doi:10.1175/JCLI3321.1

Taylor KE, Stouffer RJ, Meehl GA (2011) An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93. doi:10.1175/bams-d-11-00094.1

Turner DP, Conklin DR, Vache KB, Schwartz C, Nolin AW, Chang H, Watson E, Bolte JP (2016) Assessing mechanisms of climate change impact on the upland forest water balance of the Willamette River Basin. Or Ecohydrol. doi:10.1002/eco.1776

Watershed Boundary Dataset. Coordinated effort between the United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS), the United States Geological Survey (USGS) and the Environmental Protection Agency (EPA). Watershed Boundary Dataset for HUC-02s: Great Basin, Missouri, Lower Colorado. Available URL: http://datagateway.nrcs.usda.gov. Accessed 15/07/2015

Westerling ALR (2016) Increasing Western US forest wildfire activity: sensitivity to changes in the timing of spring. Philos Trans R Soc B 371:20150178. doi:10.1098/rstb.2015.0178

Westerling AL, Gershunov A, Cayan DR, Dettinger MD (2003) Climate and wildfire in the Western United States. BAMS 84:595–604. doi:10.1175/BAMS-84-5-595

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase Western U.S. forest wildfire activity. Science 313:940. doi:10.1126/science.1128834

Westerling AL, Bryant BP, Preisler HK, Holmes TP, Hidalgo HG, Das T, Shrestha SR (2011a) Climate change and growth scenarios for California wildfire. Clim Chang 109:445–463. doi:10.1007/s10584-011-0329-9

Westerling AL, Turner MG, Smithwick EAH, Romme WH, Ryan MG (2011b) Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. PNAS 108(32):13165–13170. doi:10.1073/pnas.1110199108

Wood AW, Leung LR, Sridhar V, Lettenmaier DP (2004) Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Clim Chang 62:189–216. doi:10.1023/B:CLIM.0000013685.99609.9e