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**Key Points:**
- Anthropogenic climate change has already increased the likelihood of autumn wind-driven extreme fire weather conditions in the western US
- Increased autumn fuel aridity and warmer temperatures during dry wind events increased the likelihood of extreme fire weather in 2017 and 2018 indices by 40%
- Present-day anthropogenic climate change has slightly decreased the prevalence of strong offshore downslope winds

**Supporting Information:**
Supporting Information may be found in the online version of this article.

**Correspondence to:**
L. R. Hawkins,
Linnia.Hawkins@oregonstate.edu

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# Anthropogenic Influence on Recent Severe Autumn Fire Weather in the West Coast of the United States

**Linnia R. Hawkins[1], John T. Abatzoglou[2], Sihan Li[3,4], and David E. Rupp[5]**

[1]Forest Ecosystems & Society, Oregon State University, Corvallis, OR, USA, [2]Management of Complex Systems, University of California, Merced, CA, USA, [3]Environmental Change Institute, School of Geography and the Environment, University of Oxford, Oxford, UK, [4]Oxford e-Research Centre, University of Oxford, Oxford, UK, [5]Oregon Climate Change Research Institute, College of Earth, Ocean, and Atmospheric Science, Oregon State University, Corvallis, OR, USA

**Abstract** Extreme wind-driven autumn wildfires are hazardous to life and property, due to their rapid rate of spread. Recent catastrophic autumn wildfires in the western United States co-occurred with record- or near-record autumn fire weather indices that are a byproduct of extreme fuel dryness and strong offshore dry winds. Here, we use a formal, probabilistic, extreme event attribution analysis to investigate the anthropogenic influence on extreme autumn fire weather in 2017 and 2018. We show that while present-day anthropogenic climate change has slightly decreased the prevalence of strong offshore downslope winds, it has increased the likelihood of extreme fire weather indices by 40% in areas where recent autumn wind-driven fires have occurred in northern California and Oregon. The increase was primarily through increased autumn fuel aridity and warmer temperatures during dry wind events. These findings illustrate that anthropogenic climate change is exacerbating autumn fire weather extremes that contribute to high-impact catastrophic fires in populated regions of the western US.

**Plain Language Summary** Over the last several years, California and western Oregon have seen their largest and most destructive wildfires on record. The rapid and extensive growth of many of these fires that invaded populated areas was driven by strong, dry, offshore, downslope autumn winds over fuels that had become exceedingly dry over the summer and remained dry into autumn. We used simulations of both the modern-era climate and a climate that could have been, absent human influence, to investigate the effect of anthropogenic climate change on the likelihood of extreme fire weather conditions (warm, very dry, and very windy) that were present during recent catastrophic wildfires. Despite a small decrease in the frequency of strong offshore winds, anthropogenic climate change has already increased the likelihood of extreme autumn fire weather across most of the west coast of the US through higher temperature and drier fuels, heightening the risk to life and property.

## 1. Introduction

Widespread increases in the burned area over the past half-century are evident across the western United States (US) despite decreases in the number of ignitions (Bowman et al., 2020; Keeley & Syphard, 2019). Several factors are suspected to have contributed to long-term increases in fire activity including the legacy of aggressive and successful fire suppression that has increased aboveground biomass (Rogers et al., 2020), increased human settlement in fire prone lands (Syphard et al., 2007), and climate change that increases fuel dryness and extends the fire season length (e.g., Abatzoglou & Williams, 2016). Extreme wildfires often occur during fire weather extremes (Stavros et al., 2014). This is particularly true in autumn in California and the Pacific Northwest US as a byproduct of chronically dry fuels prior to the onset of the rain season, which creates a flammable landscape, and strong offshore, downslope winds that drive rapid rates of fire spread (Nauslar et al., 2018; Williams et al., 2019). For example, the 2020 Labor Day fires in western Oregon spread rapidly under conditions of near record downslope winds and near record-breaking fire weather (Abatzoglou, Rupp, et al., 2021).

Studies have documented increases in autumn fire weather indices and the number of high fire danger days over the past four decades in California (e.g., Goss et al., 2020; Khorshidi et al., 2020). While such changes are consistent with anthropogenic climate change (ACC), statistically rare wind-driven fire weather extremes that have been linked with recent catastrophic fires present a potentially more tenuous link to human-caused climate change given they are a function of both thermodynamic and dynamic elements (National Academy of Sciences, 2016).

Whereas the thermodynamics effects of ACC through fuel drying and increased vapor pressure deficit are more straightforward, the dynamic effects of ACC associated with winds are less clear (Williams et al., 2019). For example, studies on projected changes in offshore Santa Ana winds of southwestern California provide contradictory results (Hughes et al., 2011; Jin et al., 2015; Miller & Schlegel, 2006; Yue et al., 2014), though recent studies indicate projected attenuation of Santa Ana winds in autumn (Guzman-Morales & Gershunov, 2019; Wang et al., 2020). However, the existing literature does not address the influence of ACC on autumn offshore winds elsewhere in California and western Oregon, nor the relative contribution of ACC via thermodynamic and dynamic effects on rare wind-driven fire weather extremes that may occur once every couple of decades.

The science of extreme event attribution has experienced major advances over the last decade and helps provide context for characterizing climate and weather extremes (Bellprat et al., 2019; National Academy of Science, 2016; Uhe et al., 2021). It has, however, been used sparingly for wildfire although some studies exist for individual fire seasons (Kirchmeier-Young et al., 2019; van Oldenborgh et al., 2021) and individual fire events (Tan et al., 2018). While attribution of wildfire is confounded by multiple complementary factors associated with human influence, isolating the influence of ACC in top-down atmospheric factors that enable and drive extreme fires addresses a key aspect of fire risk. Here, we use this attribution framework to determine if, and by how much, ACC has altered the probability of the rare extreme wind-driven fire weather conditions during autumn, similar to conditions observed during several recent high-impact fires in California and Oregon. We specifically focus on offshore wind-driven autumn fire weather conditions from southwestern California to western Washington as such fires can comprise a majority of burned area in a given year (Kolden & Abatzoglou, 2018), are often co-located with human settlement (Jin et al., 2015), and have been associated with secondary impacts such as downstream air quality and de-energization of the electrical grid (Aguilera et al., 2021; Abatzoglou et al., 2020).

Here we examine how ACC altered the likelihood of extreme autumn fire weather experienced across the western US using large ensembles of regional climate model simulations. We further decompose the influence of ACC on the likelihood of the individual components contributing to fire weather indices. Additionally, we examine the role of offshore wind events and the influence of ACC on the frequency of such events.

## 2. Methods

### 2.1. Wind Driven Fires

We examine representative regions in the western US where recent large fires have occurred and were driven by strong offshore winds such as Santa Ana and Diablo winds of California (Jin et al., 2015; Keeley & Syphard, 2019; Kolden & Abatzoglou, 2018; Mass & Ovens, 2019) and East winds of western Oregon (Abatzoglou, Rupp, et al., 2021). Within these regions, we focus on several recent large catastrophic offshore wind-driven autumn wildfires with widespread impacts on communities including the Wine Country Fires in October 2017, the Camp fire in November 2018, and North Complex Glass fires in September 2020 (all in Northern California), the Woolsey fire in November 2018 in Southern California, and the Lionshead fire in September 2020 in western Oregon. These fires provide archetypes of extreme offshore wind-driven autumn fires and guide an objective set of criteria for attribution analyses. To characterize the meteorological conditions associated with each fire relative to a long-term record (1979–2020), a suite of fire weather metrics were calculated using daily meteorological data from gridMET (Abatzoglou, 2013) at the centroid of each fire (Figure 1).

### 2.2. Climate Simulations

Climate simulations were generated through the volunteer computing platform Weather@home (Guilliod et al., 2017; Mote et al., 2016). Our configuration of Weather@home nests the Hadley Centre Regional Climate Model (HadRM3P) at 0.22° × 0.22° horizontal resolution in the Hadley Centre Atmospheric Model (HadAM3P) with updated global and regional model parameters (Hawkins et al., 2019; Li et al., 2019).

We used two large initial condition ensembles of simulations. The first represents modern-era climate conditions (actualClim) that use observed concentrations of greenhouse gases, aerosols, and observed sea surface temperatures (SSTs; Donlon et al. [2012]) for September 2016 through December 2018. The second ensemble represents the climate that would have been without human influence (naturalClim) over the same time period using pre-industrial concentrations of greenhouse gases and aerosols and observed SST's with the anthropogenic

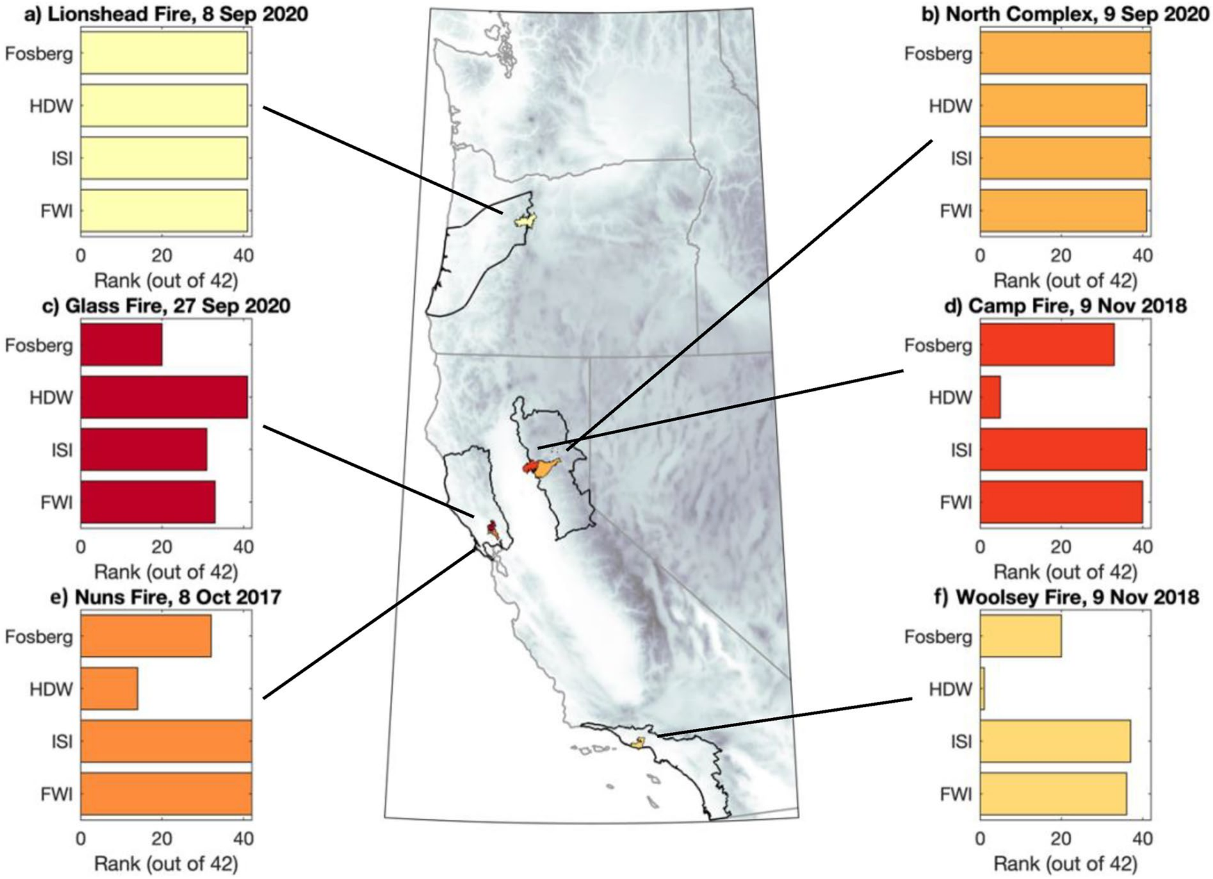


**Figure 1.** Recent significant offshore wind-driven wildfires in the western US. Inset map shows fire perimeters with gray illustrating elevation and black polygons showing the corresponding Predictive Service Areas. Ranked fire weather variables for each fire event are shown for the higher value on either the discovery date or day after, for the Fosberg Fire Weather Index (Fosberg), the Hot-Dry-Windy Index, the Initial Spread Index, and the Fire Weather Index. Variables are ranked from smallest to largest relative to local September-November maximum daily values during 1979–2020.

signal removed (Schaller et al., 2014; Uhe et al., 2016). Each large ensemble consists of 1000 simulations from September 2016 through December 2018, generated by perturbing the initial potential temperature field of each ensemble member. We excluded the first year as an additional model spin-up and use 2,000 realizations of autumn weather (September through November (SON), 2017 and 2018) for analysis. Model outputs consisted of daily (precipitation) or instantaneous values (near-surface wind speed (WS), temperature (TA), relative humidity (RH)) at 21Z (1300 LST) corresponding to the approximate times used in the daily fire danger rating systems. Similar, smaller ensembles (402 actualClim and 1,008 naturalClim realizations) were generated with additional diagnostics to examine the prevalence of offshore downslope winds using 21Z wind velocity, temperature, geopotential height at various pressure levels. See Section S1 for additional detail.

### 2.3. Fire Weather Indices

We calculated three fire weather indices influenced by wind speed and associated with difficulty in fire containment and potential rates of spread given the nature of these wind-driven fires: (a) the fire weather index (FWI) from the Canadian Forest Fire Danger Rating system (Van Wagner, 1987), (b) the Hot-Dry-Windy (HDW) index (Srock et al., 2018), and (c) the Fosberg fire weather index (FFWI; Fosberg [1978]). Notably, FFWI and HDW do not consider fuel moisture or antecedent conditions. Furthermore, we considered two subcomponents of the FWI as diagnostics: the initial spread index (ISI) and the build-up index (BUI). The ISI weakly considers antecedent information through fine fuel moisture content and is strongly influenced by wind speed while the BUI is a measure of the longer-term antecedent build-up of fuel drying that does account for the combined influence of temperature, humidity, and precipitation but excludes the influence of wind speed. Finally, we included vapor pressure deficit (VPD) given that it has been shown to be the leading control of fire activity in California (Chen et al., 2021) and observed increases in VPD during autumn have increased the number of high fire potential days in California (Williams et al., 2019). We consider this suite of fire weather metrics given their different formulations, sensitivities to meteorological inputs, and the role of antecedent conditions in the resultant metric.

### 2.4. Attribution

We estimated the change in the likelihood of extreme fire weather metrics attributable to ACC by comparing the frequency of occurrence of extremes between the actualClim and naturalClim ensembles. We specifically examined all extreme fire weather metrics and associated meteorological variables (temperature, relative humidity, windspeed, and VPD) corresponding to the day of the maximum FWI ($FWI_{max}$) in SON of each simulation year. This harmonization allows us to focus on the most extreme autumn fire weather conditions each year as defined by the widely used FWI, rather than disparate days from different metrics which impedes inter-metric comparisons. We note that our general attribution conclusions were held when examining each metric independently by its maximum value each autumn.

Extreme fire weather conditions were defined as the gridcell 95th percentile of autumn maximum daily FWI in the naturalClim ensemble, that is, 1-in-20 years autumn event under pre-industrial climate conditions. This threshold was based on the magnitude of fire weather extremes coincident with the recent representative fires (see Section 3.1 below). Similarly, we defined gridcell extremes in other fire weather indices or meteorological variables using the same protocol. We defined the risk ratio as in the $P_{actual}/P_{natural}$ where $P_{actual}$ and $P_{natural}$ are the probabilities of the extreme event occurring in the actualClim ensemble and the naturalClim ensemble respectively . A risk ratio of two means that the 1-in-20 years event is two times as likely to occur in the actualClim ensemble than in the naturalClim ensemble. We estimated confidence intervals for the risk ratio by bootstrap using $n = 10{,}000$ iterations and sampling ensemble members with replacement. Changes were considered statistically significantly where the 95% confidence interval excluded one. For regional analyses, we calculated the risk ratio for each grid cell then averaged over the four Predictive Service Area (PSA) boundaries—a management unit used by the US fire agencies—covering regions with recent large wind-driven fires (Figure 1).

### 2.5. Winds

We explicitly examined anthropogenic-forced changes in offshore downslope winds to accompany the fire weather analyses. Due to increased complexity relative to the fire weather index analysis, we limited the spatial extent to regions with well-known offshore downslope winds focusing on East winds along the Oregon Cascades, Diablo winds along the Sierras of Northern California, and Santa Ana winds in the Transverse Range of southern California.

We adapted the method of Abatzoglou, Hatchett, et al. (2021) to identify conditions suitable for offshore, downslope winds based on the cross-barrier 700-hPa horizontal wind speed $u \geq 13$ m s$^{-1}$ and the 700-hPa vertical wind speed $\omega \geq 0.6$ Pa s$^{-1}$. We added the criterion that near-surface relative humidity $\leq$30% (e.g., Edinger, 1964; Smith et al., 2018) to constrain wind events to those that yield elevated fire weather potential (for more detail, see Section S2 in Supporting Information S1). We found that HadRM3p showed credible winds and downslope wind climatologies to those seen with ECMWF ReAnalysis 5 (ERA5; Hersbach et al. [2020]) including extremes similar to those present in recent major wildfires (see Section S2–S3; Figures S1–S6 in Supporting Information S1). We calculated the change in SON frequency of offshore, downslope wind conditions between the naturalClim and actualClim ensembles for each region and investigated if an ACC signal could be detected on near-surface meteorological variables (VPD, RH, and WS), conditional on the presence of these conditions. Note that unlike our fire weather index analysis focused on very-rare extremes, the analyses of winds considered all offshore downslope winds that met the above criteria, rather than 1-in-20 years events.

## 3. Results

### 3.1. Extreme Fire Weather

Each of the six representative downslope wind-driven autumn fires occurred during fire weather extremes (Figure 1). All fire events had at least one fire weather index that ranked in the 95th percentile for autumn maximum

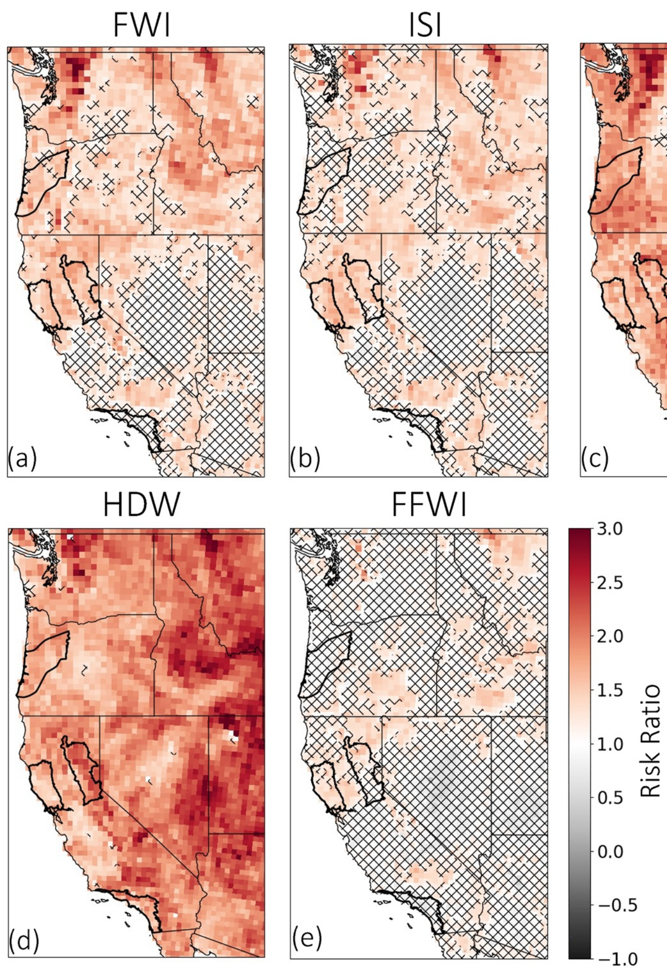


**Figure 2.** Simulated risk ratio of extreme autumn fire weather metrics in modern-era simulations relative to preindustrial simulations. Hatching represents regions where changes were not statistically significant (i.e., the bootstrapped 95% confidence intervals do not exclude one). Predictive service area regions are outlined in black.

daily values between 1979 and 2020 (40th out of 42 years), including several that coincided with the most extreme autumn fire weather metrics on record.

We found that ACC increased the frequency of autumn fire weather extremes across portions of the western US (Figure 2) relative to pre-industrial levels (Figure S7 in Supporting Information S1). Extreme $FWI_{max}$ were, on average, 40% more likely due to ACC across the western US (the regional mean of the grid cell risk ratios was 1.40) with significant increases detected across 65% of the domain including along the west coast of Washington, Oregon, and northern California, although notably not in southern coastal California (Table S1 in Supporting Information S1). On days where the $FWI_{max}$ was above the 95th percentile, the regional average temperature was 1.15°C warmer in the actualClim ensemble than in the naturalClim ensemble (Table S2 in Supporting Information S1). Similarly, the relative humidity was 0.1% higher, the VPD was 1.52 hPa higher, and the wind speed was 0.17 m/s lower in the actualClim ensemble, averaged over the domain.

Large increases in the frequency of extreme BUI and HDW were detected across the region (Figures 2c and 2d), whereas changes in the FFWI index were not significant (Figure 2e). Differences in the response of ACC across fire weather metrics are posited to be a consequence of the sensitivity of each metric to simulated changes in climate. For example, the HDW index is highly sensitive to VPD, which has increased in SON across the western US (Ficklin & Novick, 2017), and increased significantly on extreme $FWI_{max}$ days in actualClim simulations (Table S1; Figure S8 in Supporting Information S1). Similarly, increased temperature coincident with $FWI_{max}$ days in the actualClim simulations facilitates an increase in fire weather indices absent changes in wind speed

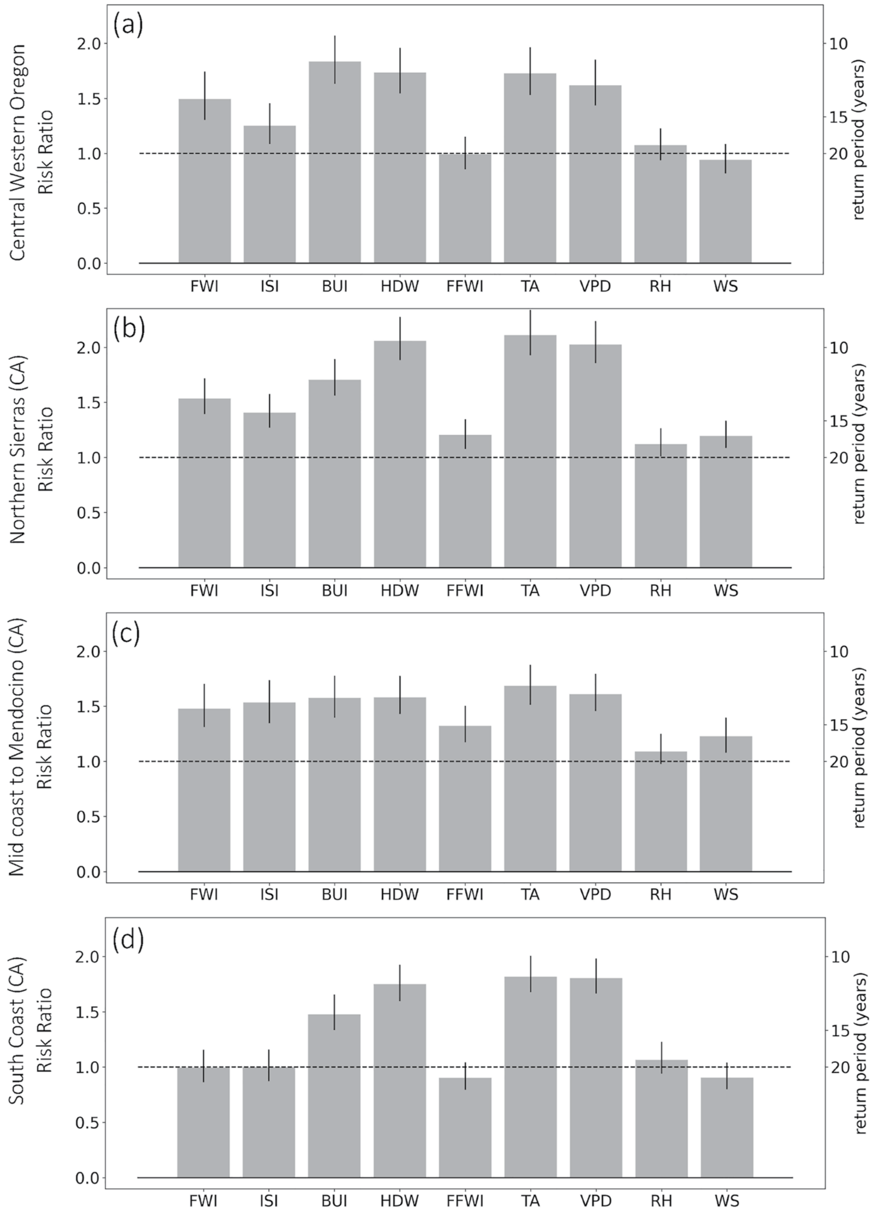


**Figure 3.** Risk ratio of maximum autumn fire weather metrics above the naturalClim 95th percentile (1-in-20 years return interval) in modern-era climate simulations relative to preindustrial simulations for the Central Western Oregon (a), North Sierras (b), Mid Coast to Mendocino (c), and South Coast (d) predictive service area regions (depicted in Figure 1) with bootstrapped 95% confidence intervals. Right hand axes show the return period (years) in the actualClim ensemble corresponding to the naturalClim 1-in-20 years event. Horizontal dashed line represents no change in probability.

itself. By contrast, the FFWI is most sensitive to wind speed and relative humidity, and only weakly sensitive to temperature. No significant decreases in any of the fire weather indices were detected within the domain.

The risk ratio of extreme fire weather varied among the four PSA regions (Figure 3). In the Central Western Oregon region, ACC increased the probability of extreme $FWI_{max}$ by 49% (risk ratio of 1.49). This increase was most strongly linked to increases in fuel dryness which manifest through the BUI, with smaller contributions from ISI. On days when $FWI_{max}$ occurs, the risk ratio of temperature and VPD were 1.72 and 1.61, respectively. The increase in VPD influenced the probability of extreme HDW, which increased by 73% despite a slight decrease in the likelihood of extreme wind speed.

In PSA regions in northern California, all fire weather metrics (excluding relative humidity) showed significant increases in the likelihood of extremes. In the northern Sierra region, the risk ratio of the HDW index was 2.06. This indicates that ACC has made extreme autumn HDW conditions twice as likely, that is, ACC has made a 1-in-20 years HDW event a 1-in-10 years event. The increase in likelihood is primarily driven by an increase in aridity rather than a change in wind speed.

Along the southern California coast, we did not detect a significant increase in the frequency of FWI, ISI, or FFWI. This is primarily due to the slight decline in extreme wind speed during extreme fire weather days in this region. The South Coast PSA region did show an increase in aridity with risk ratios for extreme temperature and VPD of 1.82 and 1.80, respectively. The increase in aridity lead to detectable increases in the probability of extreme BUI and HDW which had risk ratios of 1.48 and 1.75, respectively. Notably, the influence of BUI on FWI extremes in southern California was negligible given the region's exceptionally long dry season and formulation of the index which make changes in FWI extremes more sensitive to changes in ISI when the BUI is high.

### 3.2. Offshore Winds Analysis

Offshore, downslope wind frequency decreased from the naturalClim to the actualClim scenario in all regions (Figure 4b; Table S3 in Supporting Information S1), though the only statistically robust decrease was seen in Santa Ana wind frequency (region CAd). These results suggest that ACC may already be reducing Santa Ana frequency, consistent with projected changes under global warming through the 21st century (Guzman-Morales & Gershunov, 2019; Wang et al., 2020). Similarly, extreme offshore downslope wind frequency decreased in all regions (Table S3 in Supporting Information S1). The consistency in the sign of the changes across all regions also suggests that an anthropogenically forced decrease in the prevalence of such offshore downslope winds is a general consequence of ACC across western US mountain ranges and not limited to Santa Ana winds of southern California.

When offshore, downslope conditions did occur, VPD was 5%–9% higher in the actualClim scenario across the six regions (Figure 4c), driven primarily by a 0.8–1.4°C warming (Table S4 in Supporting Information S1). Non-significant decreases in relative humidity were found in all regions (Figure 4c). Similarly, during extreme offshore downslope wind conditions temperatures were 0.7–2.4°C warmer in the actualClim scenario (Table S5 in Supporting Information S1). Finally, we found no regionally consistent nor statistically significant changes in near-surface wind speed accompanying downslope wind days (Figure 4c).

## 4. Discussion and Conclusions

Our regional modeling experiment demonstrates that human-caused climate change has already substantially increased the likelihood of extreme fire weather metrics that have been linked with recent catastrophic wind-driven autumn fires from California to Oregon. Across several regions that have experienced high-impact autumn wind-driven fires, we estimate that anthropogenic climate change increased the likelihood of fire weather extremes viewed through metrics like FWI and HDW by at least 50% (Figure 3). Likewise, while the direction of trends in fire weather indices concurs with previous studies (e.g., Goss et al., 2020; McEvoy et al., 2020), our findings are unique given that we isolate the anthropogenic influences for extreme fire weather conditions across a host of fire weather indices. By contrast, decreased frequency in autumn dry, offshore, downslope fire-spreading winds appears to be an emergent anthropogenic signal along the western US from southern California to northwest Oregon, expanding on the findings of Guzman-Morales and Gershunov (2019) for southern California. The increased likelihood of autumn fire weather extremes with anthropogenic climate change appears to be primarily driven by thermodynamic responses that facilitate increased fuel aridity and increased VPD and temperature during fire weather extremes.

Studies have shown potential links between interannual-to-multidecadal climate variability and the frequency of offshore winds in southern California (e.g., Rolinski et al., 2019). However, the specific influence of longer-lived climate modes on recent autumn wind-driven fire extremes examined herein remains unclear. While our ensembles of simulations were limited to pooling SST conditions in 2017 and 2018, we found statistically similar risk ratios when investigating 2017 and 2018 separately (Table S6 in Supporting Information S1). This suggests that the anthropogenic signal was a robust driver across the years. Although beyond the scope of this study, how the

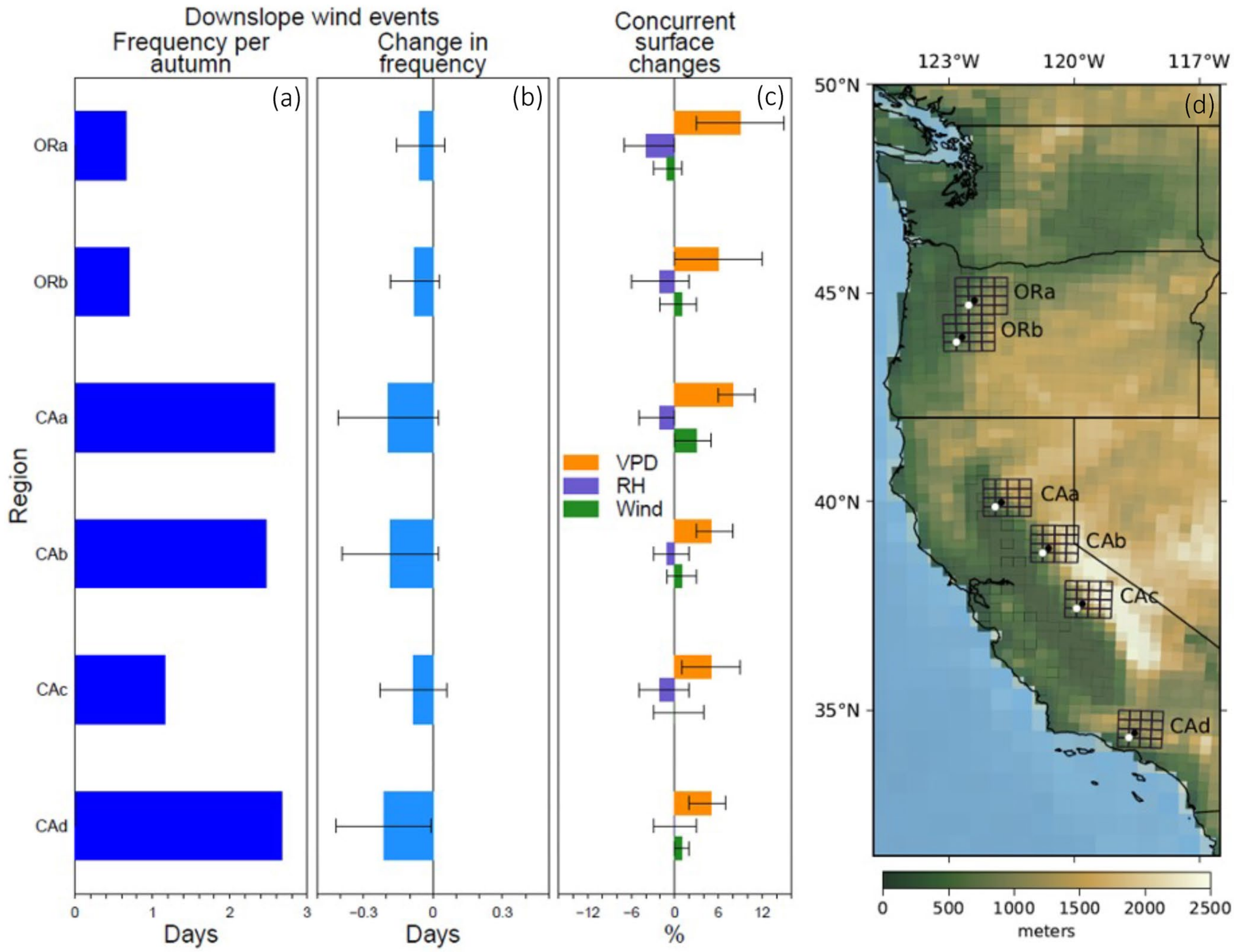


**Figure 4.** Anthropogenic influence on characteristics of autumn (September through November) downslope wind events at 21Z by region. (a) Simulated ensemble mean frequency of downslope wind events under modern era forcing (circa 2018); (b) change in frequency of events from preindustrial to modern era forcing; (c) relative change from preindustrial to modern era forcing in 2-m vapor pressure deficit (VPD), 2-m relative humidity (RH), and 10-m wind speed (Wind) during downslope wind events; (d) surface elevation map of the west coast US showing the regions analyzed. The highlighted 4 × 4 grids show the cells used to identify cross-barrier and downward winds at 700 hPa. The black and white circles mark the locations where 10-m winds (black) and 2-m VPD and RH (white) were extracted.

interannual-to-multidecadal climate variability regulates the response of extreme wind-driven autumn wildfire weather to ACC merits further research.

Attribution science has rarely been applied to wildfire events given the complex interactions among ignitions, land management, and weather conditions. While we stop short of attributing fire behavior characteristics (e.g., fire spread rate, totally burned area) to anthropogenic climate change, the distillation of changing likelihoods of extreme fire weather aid in overall risk modeling efforts. We note that our findings are specific to the geography, season, and wind-driven fire archetype, and cannot be compared directly to the attribution of extreme summer fire seasons in previous studies (Kirchmeier-Young et al., 2019; Lewis et al., 2020). Observed and projected delayed onset of autumn precipitation in California hasten the potential for compound fuel aridity-offshore wind extremes that yield fire weather extremes (Luković et al., 2021; Swain et al., 2018; Swain, 2021). We examined the anthropogenic influence on the timing and magnitude of autumn rains but results were inconclusive, compelling further investigation into the interactions between thermodynamic and dynamic drivers of anthropogenic-driven changes in fire weather conditions.

This study demonstrates that anthropogenic climate change has already increased the likelihood of autumn wind-driven extreme fire weather conditions in the western US. In concert with non-climatic factors such as biomass accumulation and encroachment of settlement in fire-prone lands, this has increased overall fire risk motivating the adoption of fire-adaptation systems that may ameliorate fire potential and are ecologically appropriate for the landscape (e.g., Kolden & Henson, 2019; Moritz et al., 2014). Finally, the approaches used here can guide near-term fire risk assessments toward directing appropriate adaptation efforts, and better elucidate how different fire typologies are directly influenced by anthropogenic climate change.

## Data Availability Statement

Postprocessed model simulations and code used in this study are achieved at:https://doi.org/10.5281/zenodo.5600650. Publicly available datasets used in this study were acquired from the following repositories: ERA5: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview; gridMET: http://thredds.northwestknowledge.net:8080/thredds/reacch_climate_MET_catalog.html.

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