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Widespread Wildfires Over the Western United States in 2020 Linked to Emissions Reductions During COVID-19

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Key Points:

- The impacts of COVID-19 emissions reductions on weather conditions for wildfire over the western United States in 2020 were investigated
- The COVID-19 emissions reductions increased surface air temperature and decreased precipitation and relative humidity
- Reductions in aerosols explain one-third of the observed wildfire risk increase, whereas greenhouse gas decrease counteracts this influence

Supporting Information:

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

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Abstract

Widespread wildfires struck the western United States in 2020, damaging properties and threating human lives. Meanwhile, the COVID-19 pandemic spread across the globe, which disrupted human activities. Here, we investigate the effects of the emissions reductions during the pandemic on fire weather in 2020 over the western United States by using an earth system model together with observations. We show that reductions in aerosols dominate the increases in wildfire risks, whereas greenhouse gas decrease counteracts this influence. The aerosol emissions reductions increased surface air temperature and decreased precipitation and relative humidity due to a weakened moisture transport, which explains one-third of the observed increase in wildfire risks during August–November over the western United States in 2020. This study suggests that COVID-19-related emissions reductions have an unexpected influence on wildfires, highlighting a different but important role of human activities in affecting wildfire risks.

Plain Language Summary

Widespread wildfires struck the western United States in 2020 and caused devastating damage on the environment and society. Due to the COVID-19 pandemic, human activities were restricted and resulted in reductions in anthropogenic emissions. Based on climate model and observational data, our results show that the COVID-19 emissions reductions in particular matter increased surface air temperature and decreased precipitation and relative humidity, which explains one-third of the observed increase in the risk of wildfires over the western United States in 2020.

1. Introduction

Wildfires in the United States set a new record in 2020 according to the National Interagency Fire Center (NIFC, 2020), with the total area of land burned more than 10.2 million acres, exceeding the 10-year average for 2010–2019 by 51%. Wildfires destroyed several towns in California and Washington (Burke et al., 2021), damaging properties and threatening human lives. The air pollution from fire burning can be elevated and transported over long distances and therefore has a far-reaching impact on air quality and human health (Li et al., 2021). As a response to global climate change, wildfire activities have increased in the western United States in recent decades (Goss et al., 2020; Westerling et al., 2006; Williams et al., 2019).

In the same year, the outbreak of coronavirus disease 2019 (COVID-19) has caused an unprecedented public health crisis and a major damage to the global economic system (Lu et al., 2020). Faced with the rapid growth of cases and deaths, countries all over the world have taken protective measures to slow down the spread of infection (Tian et al., 2020). With the declaration of national emergency in the United States on March 13, 2020, states across the country imposed immediate lockdown, resulting in restricted activities for millions of people. These restrictions are believed to have substantially reduced anthropogenic emissions of air pollutants and greenhouse gases (GHGs). With the combined government policy and activity data, Le Quéré et al. (2020) estimated that carbon dioxide (CO_2) emissions in the United States decreased by 207 (112–314) Mt over January–April in 2020 relative to the same period of 2019. From March to April, anthropogenic nitrogen oxides emissions in major United States cities were estimated to have decreased by 10%–40% (Goldberg et al., 2020; Keller et al., 2021; Xiang et al., 2020).

Aerosols can influence atmospheric radiation balance and climate through direct and indirect radiative effects. They change surface and atmospheric temperature directly through scattering and absorbing solar radiation (Yu et al., 2022). By serving as cloud condensation nuclei or ice nuclei, aerosols can interact with clouds and alter precipitation efficiency (Haywood & Boucher, 2000; Rosenfeld et al., 2008). Many studies have reported that variations in aerosol emissions could have an impact on regional climate. Based on an aerosol-climate model focusing on Europe, Sillmann et al. (2013) found that the reduction of aerosol emissions in the future may greatly strengthen the warming effect and increase the risk of extreme temperature and precipitation. Yang et al. (2020, 2022) showed that aerosols reductions related to COVID-19 lockdown warmed the surface air by 0.05–0.15 K in eastern China and intensified the regional summer rainfall as well. Rosenfeld (2000) concluded that urban and industrial air pollution substantially suppress precipitation in Australia by analyzing satellite data.

Widespread increases in wildfire activity in recent decades have been found to be closely related to the increased fire weather risk caused by changes in human-driven GHGs and aerosol emissions (Touma et al., 2021). Based on climate model projections, Abatzoglou and Williams (2016) found that anthropogenic climate change contributed to about 55% of the observed increase in fuel dryness from 1979 to 2015 in the western United States forests. In western Canada, the risk of extreme fire weather attributable to anthropogenic forcing increased six-fold from 2011 to 2020, greatly extending the fire season (Kirchmeier-Young et al., 2017). Combining analysis of the Fire Weather Index and large ensembles of climate models, van Oldenborgh et al. (2021) found that fire risk driven by anthropogenic forcing increased by more than 30% during the 2019/2020 fire season in Australian compared to 1900, resulting in dozens of deaths and more than 2,000 houses destroyed (Phillips & Nogrady, 2020).

In view of the influence of anthropogenic emissions variations on fire weather, we explore the potential impacts of the emissions reductions of aerosols and GHGs due to the COVID-19 on the extreme wildfire in the western United States in 2020. By using observational data and model simulations, we investigate the emission reduction-induced variations in temperature, humidity, precipitation, and fire risks during 2020 wildfire period (August–November) in the western United States. The results of this study are expected to provide useful information for further understanding the role of anthropogenic forcing in wildfire risk and planning climate change mitigation.

2. Methods

2.1. Model Description and Experimental Design

In order to explore the climate impact of abrupt emissions reductions, model simulations were conducted using the fully coupled Community Earth System Model (CESM, version 1.2.2, Hurrell et al., 2013), as part of the Covid multi-Earth system model intercomparison project (CovidMIP, Jones et al., 2021). In this study, the model is used to simulate the major aerosols, including sulfate, black carbon (BC), primary organic matter, and secondary organic aerosol with a four-mode modal aerosol module (MAM4, Liu et al., 2016) in its atmospheric component, Community Atmosphere Model version 5 (CAM5). Aerosols are mixed internally within a same mode and externally among the different modes. CESM simulations were conducted with 30 vertical layers at a horizontal resolution of 2.5° longitude by 1.9° latitude. On top of the default CAM5 physics, several additional features are included in the model version used in this study to improve the performance in aerosols wet scavenging and convective transport (Wang et al., 2013).

During the outbreak of COVID-19, emissions were significantly reduced from industry, transportation, and other activities in the United States. The emissions of aerosols and precursors (sulfur dioxide, SO_2, and volatile organic compounds in this study) in 2020 are adopted from Forster et al. (2020). In the western United States, where wildfires often occur, the anthropogenic emissions of SO_2, BC, and organic carbon were reduced by 6%–18%, 9%–18%, and 3%–12%, respectively, in 2020 (Figure S1 in Supporting Information S1). As provided by the CovidMIP input data, the annual average global GHGs concentrations of nitrous oxide (N_2O), CO_2, and methane (CH_4) decreased from 331.95 ppb, 412.46 ppm, and 1901.9 ppb to 331.93 ppb, 412.06 ppm, and 1900.2 ppb, respectively, related to COVID-19.

Emissions of aerosols and precursor gases and GHGs concentrations used in the baseline simulations are obtained from the CMIP6 (the Coupled Model Intercomparison Project Phase 6) SSP (Shared Socioeconomic Pathways) 2–4.5 emission scenario (experiment Baseline), which represents the medium part of the range of plausible future forcing pathways. Two sets of sensitivity experiments (Covid_All/Covid_Aero) were conducted to explore the impact of emissions changes caused by COVID-19. The Covid_Aero experiment is designed to reflect the impact of COVID-19-induced aerosol changes with reductions in aerosol emissions alone. The Covid_All experiment includes the reductions in both GHGs concentrations and emissions of aerosols and aerosol precursors. All sensitivity simulations are branched from Baseline experiment on January 1, 2020, with the reductions in emissions/concentrations imposed. For each of the experiments (Baseline, Covid_All, and Covid_Aero), 10 ensemble members are performed with a small initial perturbation to atmospheric temperature. The detailed protocol and simulations can be found in Jones et al. (2021) and Yang et al. (2022).

2.2. Wildfire Weather Indices

In this study, four wildfire weather indices are selected as indicators of fuel aridity, which have established an interannual link with burned area in the forest system: (a) reference potential evapotranspiration (ET_o), (b) climatic water deficit (CWD), (c) vapor pressure deficit (VPD), and (d) McArthur forest fire danger index (FFDI).

ET_o and CWD are important water balance metrics that have been shown to relate well to fire severity (Kane et al., 2015; Littell et al., 2010). We calculate the ET_o (mm/month) using the solar radiation (R_s) based method, which has been simplified by Irmak et al. (2003) based on the FAO56-PM method. It requires solar radiation (R_s) and average temperature (T_{mean}) as input parameters to estimate ET_o. CWD (mm/month) is calculated by the difference between ET_o and precipitation. ET_o is given by:

$$\mathrm{ET_o} = -0.611 + 0.149 R_s + 0.079 T_{\mathrm{mean}} \tag{1}$$

where R_s is downward solar radiation at the surface.

VPD is an index to illustrate the difference between moisture in the air and potential water holding capacity, which is used to measure the impact of temperature and moisture on vegetation water loss (Marlon et al., 2012; Seager et al., 2015). As an indicator of short-term dryness, it becomes increasingly popular in wildfire risk assessment. VPD (Pa) is given by the following expression:

$$\mathrm{VPD} = \frac{(100 - \mathrm{RH})}{100} \times \mathrm{SVP} \tag{2}$$

$$\mathrm{SVP} = 610.7 \times 10^{7.5T/(237.3+T)} \tag{3}$$

where T is the surface air temperature, RH (%) is relative humidity, and SVP (Pa) is saturation vapor pressure.

FFDI (unitless) characterizes the likelihood of fire occurrence, speed of spread, intensity, and difficulty of extinguishing (Noble et al., 1980; Sharples et al., 2009). It is calculated based on T, RH, wind speed (U), and drought factor (DF). DF is a function of time since the last rain, the amount of rain, and soil dryness. It was designed to estimate the fuel available for combustion. Similar to previous studies (e.g., Sharples et al., 2009), we set DF as 10 in this study. FFDI is defined as:

$$\mathrm{FFDI} = 2\exp(-0.45 + 0.987 \ln \mathrm{DF} + 0.0338T - 0.0345\mathrm{RH} + 0.0234U) \tag{4}$$

3. Results

3.1. Wildfire Weather Changes Due To COVID-19 Emissions Reductions

The decreasing aerosol load in the emission reduction simulations results in a lower aerosol optical depth (AOD) in the western United States (Figure S2 in Supporting Information S1). The total AOD in the visible band over the southwestern United States (US) decreased by more than 10% in the Covid_Aero simulation. The AOD decrease caused by the reduction of aerosols and GHGs is not as large as that caused by the reduction in aerosols alone, mainly due to the difference in their impact on the relative humidity.

The radiative effects of aerosols that heat or cool the air can alter atmospheric circulations. The reduction in aerosols during the COVID-19 caused anomalous cooling of the atmosphere over 35°–45°N in the western United States (Figure S3 in Supporting Information S1), which is due to the reduction of solar-absorbing BC aerosols verified by another simulation with BC emission reduction alone (Figure S3c in Supporting Information S1), considering that the climate in higher latitudes is very sensitive to BC perturbation (Yang et al., 2019), while the BC influence is weaker at low altitudes south of 40°N. Compared with the Baseline experiment, the simulated atmospheric heating rate had a decrease of −0.15 K/day in the aerosol emission reductions experiment. It produced an anomalous subsidence in the western United States. The subsidence is stronger in the Covid_All

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experiment than Covid_Aero and the heating rate is as high as −0.25 K/day, which is mainly due to the enhanced cooling effect related to the reduction in GHGs concentration. The anomalous atmospheric cooling due to the combined effect of reducing GHGs and aerosols is farther north than reducing aerosols alone likely because GHGs concentrations were uniformly reduced but reductions in aerosol emissions have spatial heterogeneity and is also related to the feedbacks of circulation and cloud changes. The stronger cooling anomaly in the lower atmosphere in Covid_All is because GHGs mainly absorb longwave radiation from the surface, while BC aerosol absorbs solar radiation having strong impacts on heating rate at high altitudes in Covid_Aero.

The anomalous subsidence can lead to positive anomalies of sea level pressure (SLP), which then affect atmospheric dynamical processes, cloud formation, and lifetime (Koch & Del Genio, 2010; Koren et al., 2004). Figure 1a shows the observed 850 hPa winds and the SLP anomalies in 2020 wildfire period relative to the climatological mean of previous 41 years (1979–2019) from ERA5 reanalysis. Observed anomalous positive SLP off the northwestern the United States induced anomalous northerly winds and weakened the transport of moist air toward the western United States. The changes in SLP with and without emission reductions in model experiments show the similar intensity and position of the circulation anomalies in the observations during 2020 wildfire period relative to the climatology (Figures 1b and 1c), suggesting that the observed anomalies in SLP can by potentially attributed to emission reductions related to COVID-19. This anomalous atmospheric circulation transports less moisture from adjacent oceans to the western United States that further reduces precipitation and clouds.

Under the control of high SLP, the reduction of moisture suppressed the formation of low-level clouds in the western United States. The simulated low-level cloud amount decreased by about 3% in the high-pressure controlled area in the western United States (Figure S4 in Supporting Information S1). In the two emission reduction scenarios, the spatial variations of low-level cloud amount are consistent with the location of SLP anomalies.

Although the global temperature response to COVID-19-induced emission reductions is shown to be small (Jones et al., 2021), the regional response could be significant (Yang et al., 2020, 2022). Observed temperature in the 2020 wildfire period (August–November) experienced remarkable increases compared to the previous 41 years, with the largest increase over 3.0 K in the southwestern US (Figure 2a). Primarily due to the decreases in aerosols, more solar radiation could reach the surface, which heated the surface air and increased the surface air temperature. In addition, the decrease in low-level cloud amount also contributed to the increase in surface air temperature. Both Covid_All and Covid_Aero experiments show the similar spatial distribution of the surface air temperature increases in the southwestern US (Figures 2b and 2c), which can explain 10% (±6%) and 12% (±6%), respectively, of the observed temperature increase for the same period. The increases in surface air temperature in Covid_All are similar to Covid_Aero, both having a maximum warming over 0.4 K relative to Baseline. The anomalous northerly wind brought cold air from high latitudes, which explains the decreased temperature in central United States in model simulations.

Meteorological drought measured by precipitation and RH anomalies can increase the chances of wildfires. Relative to the climatological mean over 1979–2019, both the precipitation and RH in the wildfire period of 2020 are significantly reduced in the southwestern US (Figure 2), with the maximum decreases larger than 1.2 mm/day and 15%, respectively. Due to the less moisture transport, the simulated precipitation and RH also decreased significantly in the southwestern US due to the combined effect of reductions in both GHGs and aerosols (Covid_All) and reductions in aerosols alone (Covid_Aero), especially in areas with severe wildfires, such as California, Arizona, and Oregon, contributing to 27% (±11%) and 49% (±15%) of the decreases in the observed precipitation and 16% (±6%) and 29% (±12%) of the decreases in the observed RH, respectively, in the southwestern US. These indicate that reductions in aerosols could be the crucial factor causing the fire weather in 2020. In Covid_All experiment, the decreases in precipitation, RH, and clouds are caused by the decrease in moisture transport from the Pacific Ocean concentrated in 40°–45°N, while in Covid_Aero experiment, the decreases in precipitation, RH, and clouds over 35°−40°N are due to less transport from Gulf of California and Gulf of Mexico, which are the main moisture sources in the southwestern US (Jana et al., 2018).

3.2. Increased Wildfire Risk Associated With Emissions Reductions

Fuel aridity is important for assessing wildfire risk. In recent decades, fuel aridity has become the main driver of the interannual changes in wildfire areas in the western United States (Abatzoglou & Kolden, 2013; Williams & Abatzoglou, 2016). The human-induced climate change is an important reason for the growth of wildfire risk

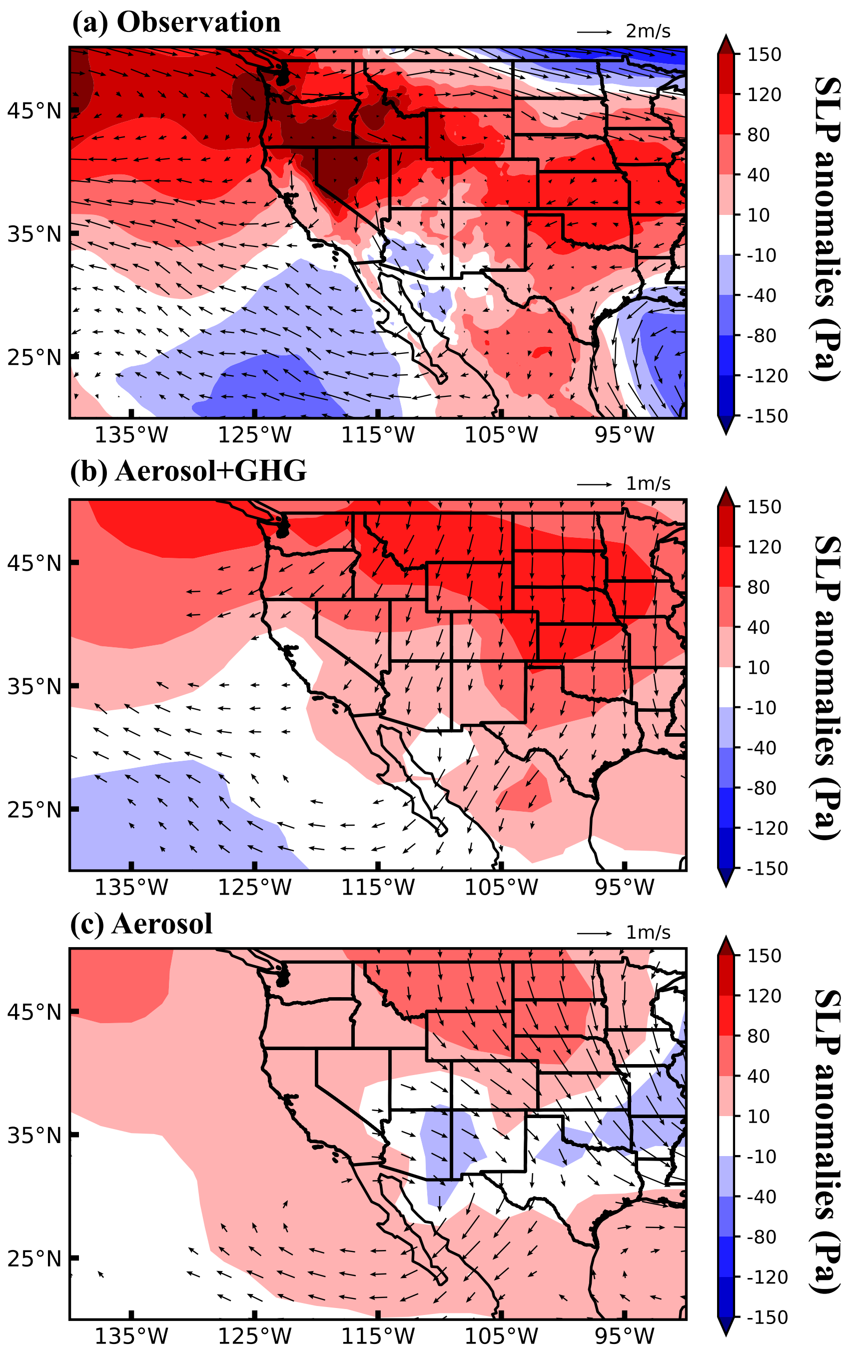

Figure 1. (a) Observed anomalies of August–November mean sea level pressure (SLP) (Pa, shaded) and 850 hPa winds (m s^{-1}, vector) in 2020, relative to the historical average over 1979–2019. The meteorological fields from 1979 to 2020 are obtained from ERA5 reanalysis data. (b) and (c) are same as (a) but for the simulated SLP and circulation changes in Covid_All and Covid_Aero, respectively, compared to Baseline. Only circulation changes that are statistically significant at the 90% confidence level are shown in (b) and (c).

(Abatzoglou & Williams, 2016). Four wildfire risk metrics are calculated based on the ERA5 reanalysis data and climate modeling outputs from CESM (Figure 3). In general, the spatial distribution of the changes in the wildfire risk indicators in the western United States due to emission reductions during the COVID-19 are similar to that between 2020 and the previous 41 years based on observational data.

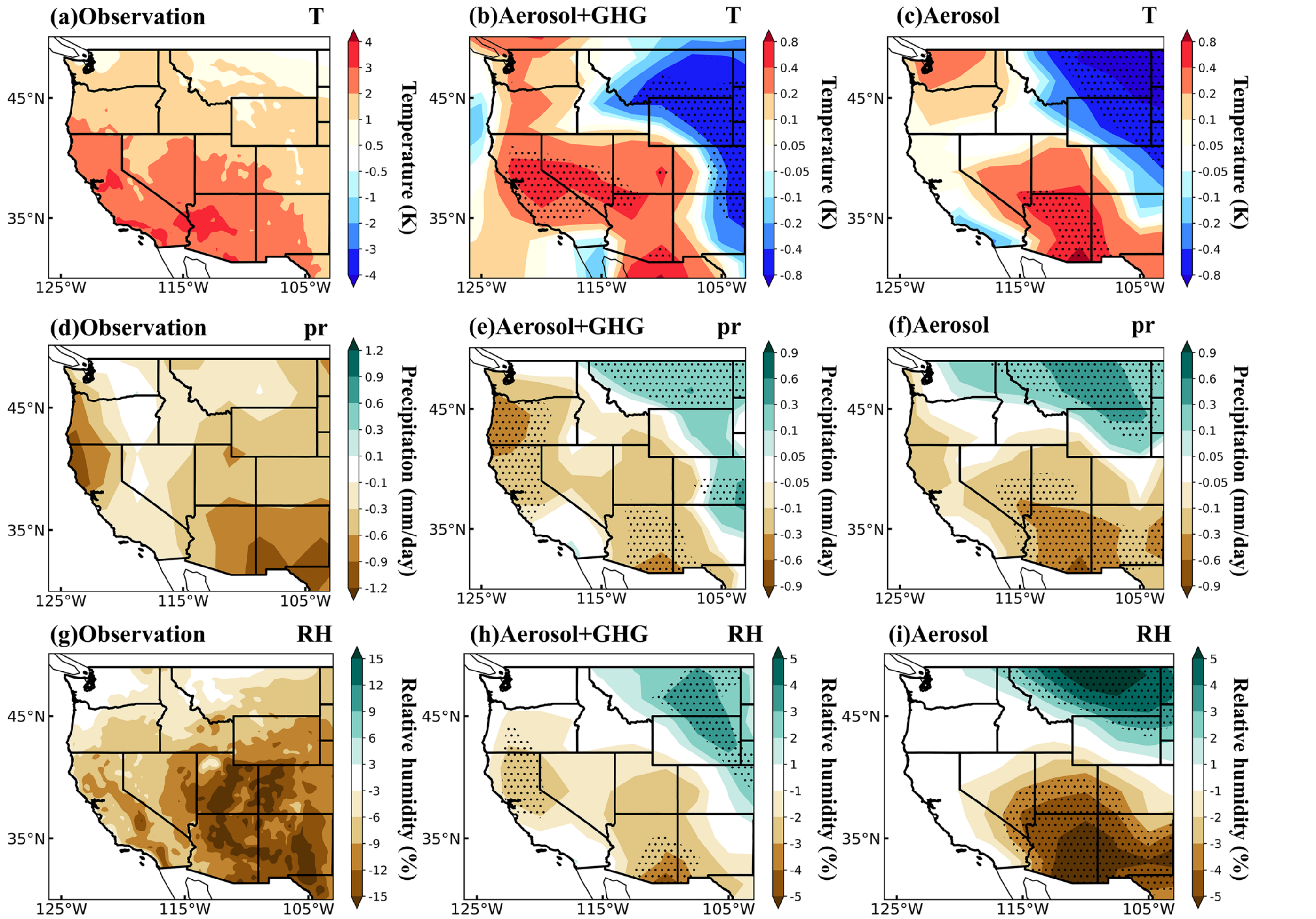

Figure 2. Spatial distribution of changes in August–November mean (a, b, c) surface air temperature (*T*, K), (d, e, f) precipitation rate (pr, mm day^{-1}), and (g, h, i) relative humidity (RH, %) in 2020 over the western United States for observation (left), Covid_All (mid), and Covid_Aero (right), compared to the Baseline simulation. The observed surface air temperature and relative humidity changes in 2020 relative to the historical period of 1979–2019 are obtained from ERA5 reanalysis data. The observed precipitation rate changes in 2020 relative to the historical period of 1979–2019 are obtained from the Global Precipitation Climatology Project (GPCP). The stippled areas indicate statistically significant differences at the 90% confidence level based on a two-tailed Student's *t* test.

Based on the definition, ET_o is mainly determined by temperature changes. Compared with 1979–2019, the temperature rise in 2020 led to an increase in ET_0 by about 3–12 mm/month in major forest areas in the southwestern US. The changes in ET_0 induced by emission reductions during COVID-19 are in the range of 1.5–3.5 mm/month, explaining 29% (±11%) and 49% (±17%) (Figure 4) of the observed ET_0 increase in the southwestern US (32–42°N, 106–120°W), respectively, due to the combined effect of reductions in GHGs and aerosols (Covid_All) and reductions in aerosols alone (Covid_Aero).

Meanwhile, CWD is calculated as the difference between precipitation and ET_0. The more its value decreases, the higher the risk of wildfire is. It can be seen from the observation that the average CWD during the wildfire period in 2020 was reduced by 6–36 mm/month relative to 1979–2019, reflecting an increased risk of wildfires in the western United States. Reductions in anthropogenic emissions of aerosols and GHGs increased temperature and decreased precipitation, accounting for 28% (±11%) (Covid_All) and 49% (±17%) (Covid_Aero) of the observed increase in wildfire risk characterized by CWD in the southwestern US.

For VPD driven by both temperature and RH, it increased in the southwestern US in 2020, with the magnitude larger than 6 hPa. The simulated impact from emission reductions only accounted for 8% (±2%) (Covid_All) and 12% (±6%) (Covid_Aero) of the observed increase in this metric.

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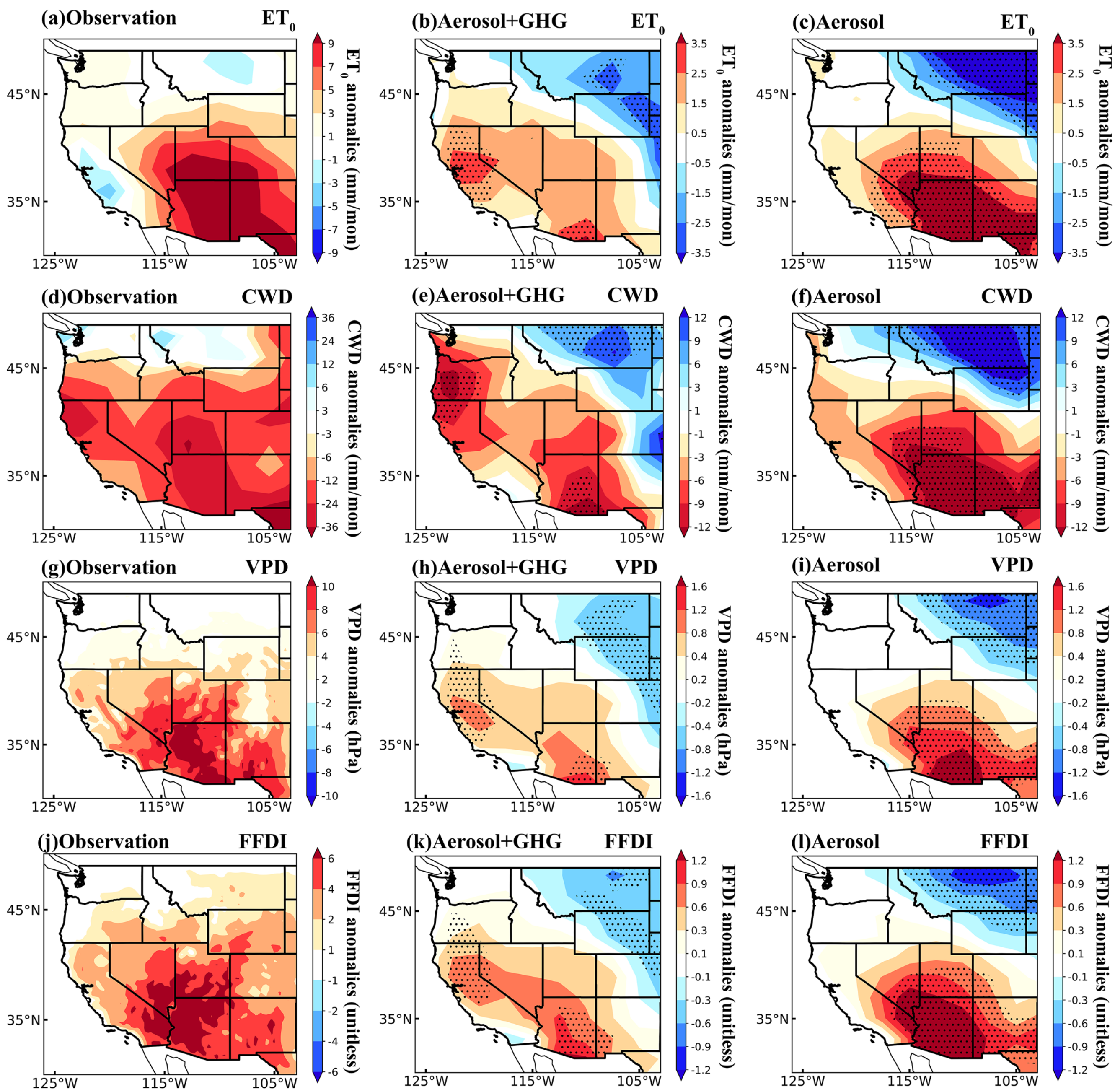

Figure 3. Observed anomalies of August–November mean (a) evapotranspiration (ET$_o$), (d) climatic water deficit (CWD), (g) vapor pressure deficit (VPD), and (j) McArthur forest fire danger index (FFDI) in 2020 over the western United States with respect to the historical period of 1979–2019 from ERA5 reanalysis data. The corresponding changes in (b, c) ET$_0$, (e, f) CWD, (h, i) VPD, and (k, l) FFDI simulated in Covid_All (middle) and Covid_Aero (right) compared to Baseline. The stippled areas in simulations indicate statistically significant differences at the 90% confidence level based on a two-tailed Student's *t* test.

FFDI is a function of temperature, RH, and wind speed. As expected, high temperature, low RH, and weak winds can increase the risk of forest wildfires. FFDI increased by 2–6 over the southwestern US in 2020 relative to 1979–2019 mean. The COVID-related emission reductions account for 11% (±4%) (Covid_All) and 19% (±10%) (Covid_Aero) of the observed increases in this fire risk indicator.

The higher proportions of the observed changes in wildfire indices attributed to COVID-19-related emissions reductions in aerosols alone than the combined effects of emissions reductions in aerosols and GHGs suggest that reductions in aerosols dominate the increases in 2020 wildfire risks in the southwestern US, whereas GHG decrease counteracts this influence.

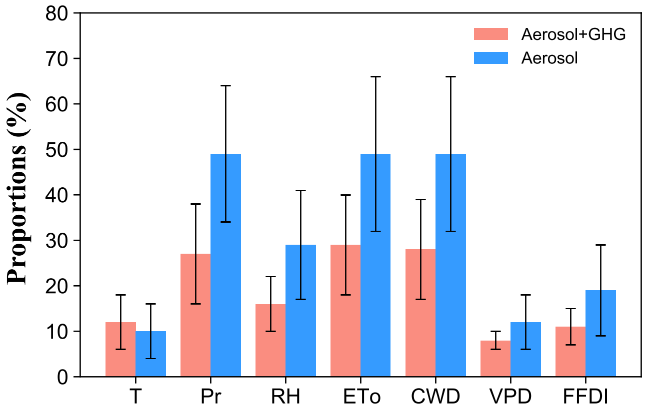

Figure 4. Proportions of the observed changes in wildfire weather and indices in the southwestern US (32–42°N, 106–120°W) attributable to COVID-19-related emissions reductions in aerosols and greenhouse gases (GHGs) from Covid_All (pink) and in aerosols alone from Covid_Aero (blue) relative to Baseline. Error bar represents the standard deviation of 10 ensemble members.

4. Discussions and Conclusions

The western United States experienced widespread wildfires in 2020, resulting in a large number of economic losses and casualties. Based on observational data and model simulations, we investigated the impacts of COVID-19 related anthropogenic emissions reductions on favorable fire weather for wildfire occurrences over the western United States during wildfire period in 2020. We found that reductions in aerosols dominated the enhanced wildfires in the southwestern US during the COVID-19, explaining 34% (median of the four fire indicators ranging over 12%–49%) of the observed increase in wildfire risks characterized by different indices during wildfire period in 2020, while the combined effect of emissions reductions in GHGs and aerosols attributes to 20% (8%–29%) related to dampening effect from reductions in GHGs.

This study highlights the response of wildfire weather to reductions in anthropogenic emissions. In a continuous period, the reduction of aerosols, precursor gases, and GHGs caused anomalous subsidence and positive anomalies of SLP. The anomalous atmospheric circulation induced by emissions reductions is in agreement with the observation, which weakens the transport of moist air from adjacent oceans to the western United States and subsequently reduced precipitation and clouds. As expected, emission reduction experiments found a robust significant response with an increase of fuel aridity in the western United States during the wildfire period, which is more conducive to the occurrence of wildfires. Studies showed that warm season from May to September is the main fire season in the western United States (Abatzoglou & Williams, 2016; Zhuang et al., 2021), especially July–September when fire risk is the highest and many extreme fires in 2020 occurred. We also found that COVID-19-related aerosol emissions reductions can explain 10%–33% of the observed increase in the risk of wildfires in the southwestern US during July–September in 2020 (Figure S5 in Supporting Information S1).

This study examines the responses of wildfire risks to COVID-related emissions reductions mainly based on simulations using the CESM model. We note that due to the complexity of different models in aerosol physical and chemical processes and climatic impacts, the responses related to emissions reductions need further investigation with more climate models in future studies. The simulated climatology and anomaly of wildfire weather could be different from those in the real world, which can also lead to the bias of the results. Note that we also tested the climate responses to the anthropogenic emissions reductions during the COVID-19 using the Energy Exascale Earth System Model (E3SM) and also found an anomalous surface warming over the western United States (not shown). The aerosol loading in the western United States is not only affected by the local emissions, but also by the aerosol transport from remote sources including East Asia. Using an explicit aerosol source tagging technique implemented in CESM, we found that emissions from East Asia contributed to 26% of sulfate burden and 15% of BC burden over the southwestern US during 2005–2014 (Yang et al., 2018). Therefore, remote emission reductions may also have an impact on the wildfire weather conditions over the western United States by atmospheric teleconnections, which warrants future studies.

Previous studies have pointed out the potential contribution of climate change to the increasing fire risks over the western United States (e.g., Zou et al., 2021). From the perspective of the COVID-19-induced emissions reductions, this study shows that the sudden and rapid emission reduction will have a certain impact on the increase of wildfire risk, although the emissions reductions caused by the pandemic vary according to national policies and stages in the future restrictions. It provided an opportunity to explore the response of weather and climate to short-term emission changes and its impact on extreme events such as wildfires and flooding.

Data Availability Statement

The daily precipitation data covering 1979–2020 are publicly available from the Global Precipitation Climatology Project (GPCP, https://www.ncei.noaa.gov/data/global-precipitation-climatology-project-gpcp-monthly/access/, last accessed: 27 April 2022). The anomalies of meteorological fields from 1979 to 2020 can be obtained from ERA5 reanalysis data (https://doi.org/10.24381/cds.f17050d7, last accessed: 27 April 2022). The modeling results are available at https://doi.org/10.5281/zenodo.6482166 (last accessed: 27 April 2022).

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