Atmospheric variability contributes to increasing wildfire weather but not as much as global warming

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Devastating wildfires have occurred around the world in recent years. While fire has always been part of the landscape, the trend toward increasingly widespread and severe wildfires is a key sentinel of the rapidly intensifying risks caused by global warming and climate change. Using atmospheric observations and climate model simulations, Zhuang et al. (1) quantify the relative contributions of natural climate variability and anthropogenic climate forcing to the increasing area burned in the western United States. They find that atmospheric variability can explain at most approximately one-third of the historical trend in atmospheric aridity that is conducive to wildfire. By contrast, global warming has contributed at least two-thirds of the rising trend in atmospheric aridity.

Understanding the causes of increasing wildfire risk is a critical scientific and societal challenge. First and foremost, the rapidly increasing size and intensity of wildfires is having severe impacts. In California, the eight largest wildfires in recorded history have occurred in the past 5 y, and 9 of the 17 largest have occurred in the past 2 y (including the two largest and six of the top seven). Recent fires have had widespread impacts on people and ecosystems. Just in California alone these impacts include dozens of lives lost and tens of thousands of homes destroyed, leading to extended displacement of individuals, families, and communities. In addition, the massive plumes of smoke that have blanketed much of the western United States have impacted millions of people and have accounted for up to half of fine particulate matter pollution in some areas of the region (2). Recent fires have also exceeded the intensity to which fire-adapted vegetation is accustomed, posing risks to ecosystems and individual species such as California's giant sequoias (e.g., ref. 3).

While California's fires have received much public attention, similar challenges are playing out throughout the western United States and in other areas of the world (as demonstrated, for example, by Australia's massive 2020 wildfire season). The urgency and complexity of wildfire risks—including the roles of ecosystem processes, vegetation management, ignition, land use, and disaster preparation and response—make them a critical test case for disentangling the impacts of climate change from other factors that affect the exposure and vulnerability of people and ecosystems. Lessons learned from wildfire studies should therefore be particularly relevant for understanding and responding to other climate risks.

Much effort has already been devoted to the question of how global warming is influencing wildfire. For example, the potential effects of warming on snowmelt, streamflow, and fuel aridity have been identified for many years (e.g., ref. 4). In the western United States, area burned has increased substantially (5–7), including estimates as high as a 10-fold increase in forested area burned over the past four decades (8). Analyses isolating the influence of fuel aridity on area burned suggest that historical warming has accounted for approximately half of the cumulative forested area burned over that time (5, 6). Further, high-severity fires have also been increasing (9), as have the frequency of the most extreme wildfire weather days [both in areas of the western United States (5, 10) and in a variety of ecosystems around the world (11)].

This robust body of research clearly identifies the effects of rising temperature on "fuel aridity"—or the dryness of the vegetation—as the primary pathway by which global warming has been influencing wildfire risk. The effects of climate on fuel aridity are challenging to quantify exactly, but the role of climate can be well-summarized at interannual scales by considering the vapor pressure deficit, or VPD. VPD is a measure of how far the atmospheric vapor pressure is below that of saturated conditions at the

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Author contributions: N.S.D., A.G.K., and C.B.F. analyzed data and wrote the paper.

The authors declare no competing interest.

See companion article, "Quantifying contributions of natural variability and anthropogenic forcings on increased fire weather risk over the western United States," 10.1073/pnas.2111875118.

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Published November 10, 2021.

same temperature. It is a key determinant of the rate at which wildfire fuels dry out, and thus of their overall aridity and flammability (cf. ref. 12). Across multiple timescales, VPD affects both the moisture levels of dead fuels (which fluctuate with the surrounding meteorological conditions) and the water balance—and thus moisture levels—of live vegetation fuels [including the likelihood that they turn to dead fuels (13)]. As a result, VPD has frequently been found to covary strongly with burned area in the western United States (e.g., refs. (5 and 14), as verified by Zhuang et al. (1).

VPD depends on atmospheric humidity but has an even greater dependence on temperature, because of temperature's considerable effect on saturated vapor pressure. As a result, rising temperatures have caused significant historical VPD trends. There has been substantial analysis of these long-term trends in VPD driving vegetation fuel aridity (e.g., ref. 5). What has been less clear—and much more difficult to robustly quantify—is the role that natural variability in the larger-scale atmospheric circulation (as opposed to anthropogenic warming alone) plays in shaping those long-term VPD trends.

To quantify these factors, Zhuang et al.'s (1) analysis centers on a related goal: to predict what the daily VPD would be based only on the atmospheric weather patterns that shape conditions at the surface, with the residual being attributed to anthropogenic warming. To do so, Zhuang et al. use an "ensemble constructed flow analog" approach. This is one of many clustering approaches that can be used to study the relationship between patterns in the atmosphere and surface climate variables (e.g., refs. 15–18). Zhuang et al. use their "ensemble constructed flow analog" approach to predict daily VPD based on the spatial pattern of atmospheric pressure. (Their framework assumes these pressure patterns to be entirely the result of atmospheric variability, although they acknowledge that this is a conservative assumption.) They then use the difference between the predicted and actual VPD to calculate the fraction not explained by the patterns of atmospheric pressure. These residuals can be used to quantify the contribution of anthropogenic warming to the VPD that occurred on a particular day and can also be aggregated to calculate the contribution of anthropogenic warming to the long-term VPD trend.

Using this approach, the atmospheric pressure patterns account for 32% of the observed trend in warm-season VPD over the western United States over the past four decades. This indicates that anthropogenic warming accounts for approximately two-thirds of the historical trend.

To test the influence of uncertainties in this analysis (including ways in which anthropogenic forcing can modulate the atmospheric pressure patterns), Zhuang et al. (1) apply the same approach to a large suite of climate model simulations run with and without human forcings (19). Using this model-based

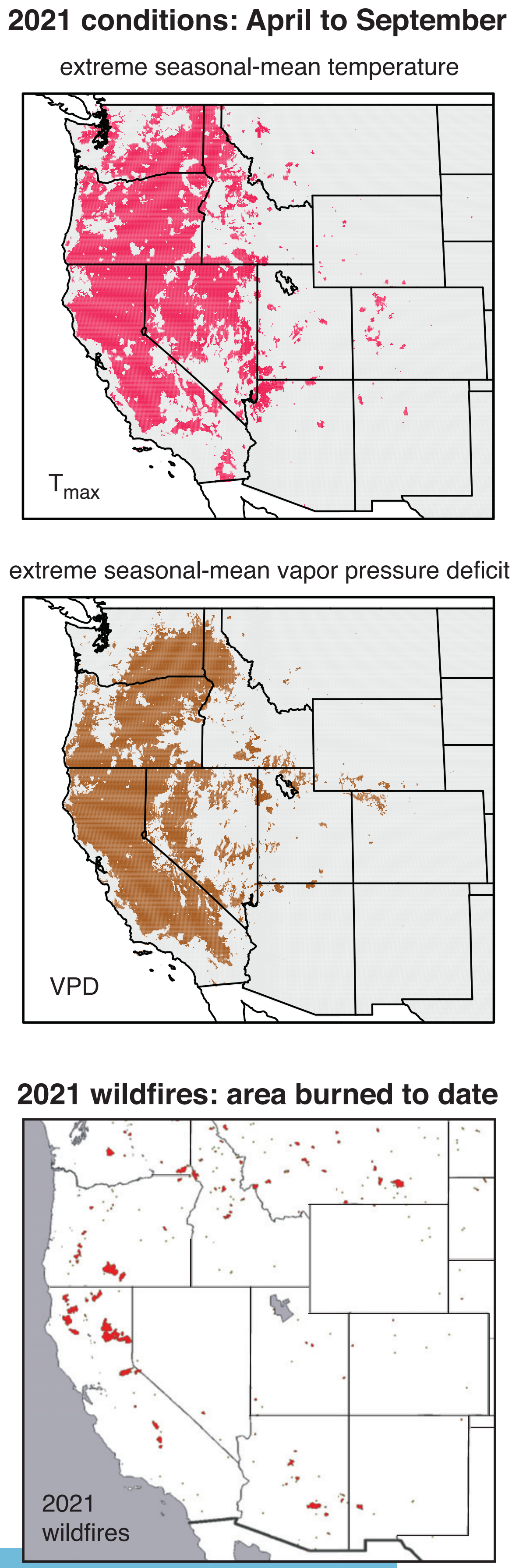

Fig. 1. **Continuing vulnerability to wildfire risk in the western United States in 2021. (*Top*) Areas of the western United States for which the mean daily maximum temperature from 1 April 2021 through 30 September 2021 was the "record highest" (since 1979, according to UC Merced's Climate Toolbox: https://climatetoolbox.org/tool/Climate-Mapper). (*Middle*) As in *Top* but for VPD. (*Bottom*) The 2021 wildfire perimeters to date (1 January 1 to 8 October, according to the National Interagency Fire Center: https://data-nifc.opendata.arcgis.com/datasets/nifc::wfigs-current-wildland-fire-perimeters/about).**

analysis, they conclude that the contribution of anthropogenic warming could be even stronger, accounting for almost 90% of the historical VPD trend. Zhuang et al. attribute this difference between the observations- and model-based results to the strong imprint of natural variability on the single historical realization of the climate system that is recorded in the observations, compared with the substantially reduced variability that results from averaging many climate model realizations together to uncover the mean response to anthropogenic forcing.

Zhuang et al. (1) also analyze the conditions during the Creek and August Complex fires in 2020, the largest single- and multiple-start fires in California's history. Critically, the VPD anomalies at the start of those two fires were the most extreme ever, in terms of what would have been predicted from their respective atmospheric pressure patterns. Zhuang et al.'s analysis suggests that anthropogenic warming contributed between one-third and one-half of the unprecedented atmospheric aridity associated with those two record-setting wildfires.

Zhuang et al.'s (1) analysis adds insight to our understanding of the role of global warming in amplifying wildfire risks. On top of the substantial evidence that global warming has been increasing wildfire risk through the effect of rising temperature on atmospheric and vegetation aridity, we now have rigorous quantification of the contribution of atmospheric variability to the observed trends in atmospheric aridity. This leads to a much-improved understanding of the contribution of historical anthropogenic warming to the climatic conditions associated with individual extreme wildfires, as well as a framework that is readily generalizable to other regions. This capacity is relevant not only for understanding the impacts of global warming on wildfire, but also more generally for calculating the contribution of global warming to the costs of individual extreme events (e.g., ref. 20).

The recent surge in wildfire activity in the western United States and the region's continuing vulnerability (Fig. 1) are a result of several factors, including climate, past land management, installed infrastructure, and current land use. Moderating wildfire risk is a key priority for the region's future. Understanding the roles of anthropogenic warming and atmospheric processes is a key element in the risk reduction discussion.

1 Y. Zhuang, R. Fu, B. D. Santer, R. E. Dickinson, A. Hall, Quantifying contributions of natural variability and anthropogenic forcings on increased fire weather risk over the western United States. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2111875118 (2021).
2 M. Burke *et al.*, The changing risk and burden of wildfire in the United States. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2011048118 (2021).
3 A. P. Hill, C. B. Field, N. S. Diffenbaugh, Even fire-adapted giant sequoias can't withstand California's megafires. *The Hill* (2021). https://thehill.com/opinion/energy-environment/574763-even-fire-adapted-giant-sequoias-cant-withstand-californias. Accessed 11 October 2021.
4 A. L. Westerling, H. G. Hidalgo, D. R. Cayan, T. W. Swetnam, Warming and earlier spring increase western U.S. forest wildfire activity. *Science* **313**, 940–943 (2006).
5 J. T. Abatzoglou, A. P. Williams, Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 11770–11775 (2016).
6 P. Gonzalez *et al.*, 2018. "Southwest" in *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, D. R. Reidmiller et al., Eds. (US Global Change Research Program, Washington, DC), pp. 1101–1184.
7 A. P. Williams *et al.*, Observed impacts of anthropogenic climate change on wildfire in California. *Earths Futur.* **7**, 892–910 (2019).
8 P. B. Duffy *et al.*, Strengthened scientific support for the Endangerment Finding for atmospheric greenhouse gases. *Science* **363**, eaat5982 (2019).
9 S. A. Parks, J. T. Abatzoglou, Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985 to 2017. *Geophys. Res. Lett.* **47**, e2020GL089858 (2020).
10 M. Goss *et al.*, Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environ. Res. Lett.* **15**, 94016 (2020).
11 J. T. Abatzoglou, A. P. Williams, R. Barbero, Global emergence of anthropogenic climate change in fire weather indices. *Geophys. Res. Lett.* **46**, 326–336 (2019).
12 B. E. Potter, Atmospheric interactions with wildland fire behaviour–I. Basic surface interactions, vertical profiles and synoptic structures. *Int. J. Wildland Fire* **21**, 779–801 (2012).
13 R. H. Nolan *et al.*, Linking forest flammability and plant vulnerability to drought. *Forests* **11**, 779 (2020).
14 A. P. Williams *et al.*, Correlations between components of the water balance and burned area reveal new insights for predicting forest fire area in the southwest United States. *Int. J. Wildland Fire* **24**, 14–26 (2014).
15 P. Yiou, R. Vautard, P. Naveau, C. Cassou, Inconsistency between atmospheric dynamics and temperatures during the exceptional 2006/2007 fall/winter and recent warming in Europe. *Geophys. Res. Lett.* **34**, L21808 (2007).
16 A. Jézéquel, P. Yiou, S. Radanovics, Role of circulation in European heatwaves using flow analogues. *Clim. Dyn.* **50**, 1145–1159 (2018).
17 J. Cattiaux *et al.*, Winter 2010 in Europe: A cold extreme in a warming climate. *Geophys. Res. Lett.* **37**, L20704 (2010).
18 F. V. Davenport, N. S. Diffenbaugh, Using machine learning to analyze physical causes of climate change: A case study of U.S. Midwest extreme precipitation. *Geophys. Res. Lett.* **48**, e2021GL093787 (2021)
19 V. Eyring *et al.*, Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958 (2016).
20 N. S. Diffenbaugh, F. V. Davenport, M. Burke, Historical warming has increased U.S. crop insurance losses. *Environ. Res. Lett.* **16**, 84025 (2021).