Earth's Future

COMMENTARY

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A Warming Climate Adds Complexity to Post-Fire Hydrologic Hazard Planning

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Key Points:

- Climate change will likely increase the frequency of damaging post-wildfire flash floods and debris flows
- Decision-makers are in need of resources to support planning for the changing characteristics of these hazards
- While Kean & Staley, 2021, https://doi.org/10.1029/2020ef001735 is a step forward, precipitation scaling factors, reanalyses, and additional monitoring efforts are needed

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Abstract Climate change will likely increase the frequency of damaging post-wildfire floods and debris flows, amplifying the threat to life, property, and infrastructure situated in susceptible areas. Decision-makers are in need of resources to support planning for the changing characteristics of these hazards. A novel framework for evaluating post-fire debris flow recurrence intervals (Kean & Staley, 2021, https://doi.org/10.1029/2020ef001735) supports this need and allows for the integration of emerging information. While this is a valuable step forward, simulations of past and future climate at relevant spatial and temporal scales as well as additional monitoring efforts are needed to effectively address post-fire hydrologic hazards in a warming climate.

1. A Need for Post-Fire Debris Flow Hazard Information

Wildfire removes vegetation and weakens root strength, making burned areas more susceptible to erosion. Wildfire can also alter the physical and chemical characteristics of soil, creating a hydrophobic layer which increases runoff and may lead to damaging floods and debris flows in steep terrain. For example, following the 2017 Thomas Fire in Southern California, the devastating 9 January 2018 debris flows in the community of Montecito resulted in 23 deaths and nearly $1B in damages (Lancaster et al., 2021). In a meeting following the event, a Santa Barbara County resource manager made a plea to researchers: "I need to know how frequently I can expect post-fire debris flows of this magnitude in this area." Managers in other susceptible areas have expressed similar concerns for events in their area of responsibility.

Impactful post-fire debris flows are not new to southern California, though the penultimate fatality event occurred in 2003 when 16 people died in debris flows emanating from the Old/Grand Prix burn areas in the San Bernardino Mountains (Oakley et al., 2017). The Montecito event renewed focus on post-fire debris-flow preparedness, with understanding the recurrence intervals of these events in the current and future climate as key concerns in planning efforts.

Southern California's well-documented history of impactful post-fire debris flows compared to other susceptible regions makes it an excellent "laboratory" for research and development of decision support tools. Kean and Staley (2021) utilize Southern California's data to provide the first known framework to estimate recurrence intervals for minor and major post-fire debris flows in the region. This tool allows for evaluation of recurrence intervals in both a stationary and warming climate. Emerging research from disciplines relevant to post-fire hazards (e.g., soil, wildfire, and climate science) can be readily integrated into this framework. While regionally focused, this tool is applicable to other locations susceptible to post-wildfire debris flows provided the requisite data on rainfall triggering thresholds, burn severity, and wildfire recurrence can be collected.

2. Debris Flow Recurrence Interval as a Pre-Fire Decision Support Tool

The time between wildfire and precipitation events is decidedly brief in California, such that pre-fire planning presents significant advantages. For example, the 2018 Montecito debris flow occurred before the Thomas Fire was 100% contained (Lancaster et al., 2021). Observations over the past 60 years demonstrate a delayed onset of the rainy season in California (Lukovic et al., 2021). This allows dry conditions to extend into the autumn/winter offshore wind season (Abatzoglou et al., 2021; Swain, 2021), amplifying wildfire risk (Goss et al., 2020). Climate model projections suggest further "sharpening" of the precipitation

Figure 1. Emily Fudge, a member of a USFS Burned Area Emergency Response team, evaluates the 2020 Apple Fire burn area in Riverside County, CA, for post-fire hydrologic hazards. With already brief and potentially shortening time periods to conduct such evaluations, there is value in tools that enable assessment of hazardous areas before wildfire occurs. Photo: Yonni Schwartz, USFS.

season (Swain et al., 2018), exacerbating the potential for increased wildfire activity and shortening the timespan between major wildfires and the onset of precipitation. This situation is not unique to California; in the western US, summer and fall convective precipitation often occurs within the wildfire season, leaving little time for post-fire preparations. For example, the 2017 Pinal Fire in Arizona experienced its first debris flows on June 16 (Raymond et al., 2020), only a few days after containment was achieved (Globe-Miami Times, 2017). Arizona's 2004 Willow fire was contained on July 17 and experienced damaging debris flows on July 23 (Pearthree & Youberg, 2004), among many others. The lead time for accurate forecasts of short-duration, high intensity rainfall events associated with post-fire debris flow initiation is also brief. The potential for such events can be recognized a few days in advance, but estimates of timing, location, intensity may not come into clear view until hours before the event (e.g., Cannon et al., 2020).

Given these circumstances, pre-fire efforts to mitigate post-fire hydrologic hazards may be more successful and feasible than rapid post-fire response (Figure 1). The tool presented in Kean and Staley (2021) supports pre-fire planning decisions such as where to target mitigation efforts, informing building codes and landscape practices, where to focus education of residents, or in developing targeted evacuation plans. This information can be incorporated into state, county, or local entity Hazard Mitigation Plans, which may already highlight post-wildfire debris flows as a hazard (e.g., Ventura, 2015). Additionally, Kean and Staley's (2021) decision support tool utilizes resources and frameworks managers are familiar with, such as the NOAA Atlas 14 (Bonnin et al., 2006) and models for quantifying earthquake hazards. This can increase decision-maker confidence in the use of this tool in the context of climate change (e.g., Ball et al., 2019).

3. Precipitation Intensification in a Warming Climate

NOAA Atlas 14 is commonly used to determine the recurrence interval of rainfall events that trigger post-wildfire debris flows in the areas of the US where it is available (e.g., Cannon et al., 2008; Oakley et al., 2018; Staley et al., 2020). However, one major limitation of using Atlas 14 for planning purposes is that it assumes a stationary climate-and it is clear that extreme precipitation events have already increased in response to climate change across continental North America (Kirchmeier-Young & Zhang, 2020). For resilient and sustainable resource management, it is critical that decision-makers utilize tools and information that account for the hydrologic changes anticipated in a warming climate (Milly et al., 2008).

To assess the impacts of climate change on post-wildfire debris-flow frequency and magnitude, Kean and Staley (2021) apply the Clausius-Clapeyron (C-C) relation, which states that the amount of water vapor at saturation increases at a rate of 7%/°C. The authors use the first-order assumption, following from C-C, that rainfall intensifies at the same rate of water vapor in the atmosphere (Trenberth et al., 2003). The C-C relation is applied as a scaling factor to NOAA Atlas 14 precipitation frequency estimates. This is a reasonable estimate for a first approach, though a review of research from various locations has demonstrated that sub-daily rainfall (such as the sub-hourly durations relevant to post-fire debris-flow hazards) may intensify at a rate greater than the C-C relation suggests (Fowler et al., 2021). This is due to factors such as changes in cloud processes and characteristics, storm structure (areal extent, duration, and movement), among others. Additionally, planetary-scale circulation changes in a warming climate may affect the frequency, duration, spatial extent of precipitation-producing weather systems, increasing or decreasing the frequency of extreme hourly to sub-hourly events depending on season and location (Fowler et al., 2021). Nearly all of the sub-daily precipitation intensification literature reviewed by Fowler et al. (2021) focuses on warm season rainfall events in deep convective environments. Most US West Coast post-wildfire debris flows occur in the cool season in association with mid-latitude frontal systems and feature comparatively shallow convection (e.g., Oakley et al., 2017, 2018). Thus, it is challenging to extrapolate existing research on precipitation intensification to this region.

New research addressing sub-daily precipitation intensification in California's cool season has mixed results with respect to super-CC scaling. A pseudo-global warming simulation over the continental US found an average scaling rate of 6.7%/°C for hourly extremes in the winter season, approximating the C-C relation (Prien et al., 2017; see visualization of this output for Southern California in Figure 2). In contrast, a selection of strong atmospheric river events in downscaled global climate model simulations in California's Sierra Nevada and found scaling ~6–16% greater than expected from the CC relation (Huang et al., 2020). Though post-wildfire debris flows in California often occur in association with atmospheric rivers (Oakley et al., 2017), it is important to consider storms featuring mesoscale characteristics that drive these and other geohazards (e.g., Collins et al., 2020) such as narrow cold frontal rainbands or convection within cutoff low-pressure systems that may or may not be associated with ARs (Cannon et al., 2020; Oakley et al., 2017, 2018). Future research must address scaling factors associated with these and other relevant atmospheric processes as well as changes in the atmospheric processes themselves due to warming. It is likely that scaling factors will vary across storm characteristics, precipitation duration, season, location, or event magnitude (e.g., Zhang et al., 2017; Swain et al., 2020) and there may be several appropriate "storm" scaling factors. Thus, converging on a single "climate" scaling factor (i.e., a single multiplier that can be applied to a duration in NOAA Atlas 14) may be challenging. If a single scaling factor is not appropriate, an ensemble approach encompassing a range of potential scaling factors may be useful to assess a range of potential changes in debris-flow recurrence intervals.

4. Model Output at Relevant Spatial and Temporal Scales is Needed

Earth system models are an essential tool for both understanding changes in atmospheric processes driving precipitation intensification and determining scaling factors. Currently, the spatial and/or temporal scales of model products are too coarse for effective application to the post-fire debris-flow problem, where the 15-min precipitation duration is most critical (e.g., Kean et al., 2011) and information is needed at the "small catchment" scale (~a few km^2). All known downscaled climate projections or pseudo-global warming simulations available to the research community offer hourly outputs as their finest timescale for precipitation. Some examples of other limitations of these hourly products that include California are that they are too coarse (e.g., NA-CORDEX simulations at 25 km; (Mearns et al., 2017)), don't represent large-scale circulation changes and cover a short period (Prein et al., 2017), or are focused on a narrow subset of events (Huang et al., 2020).

Cost and availability of computing resources and storage have been limitations to higher resolution products (e.g., Zhang et al., 2017), as well as the issue that utilizing higher spatial resolution does not always provide more useful information (e.g., Prein et al., 2015; Jewworek et al., 2019). Lack of communication of data needs between the geomorphology and atmospheric modeling communities may also have hindered development of useful products, though several are now emerging. The National Centers for Atmospheric

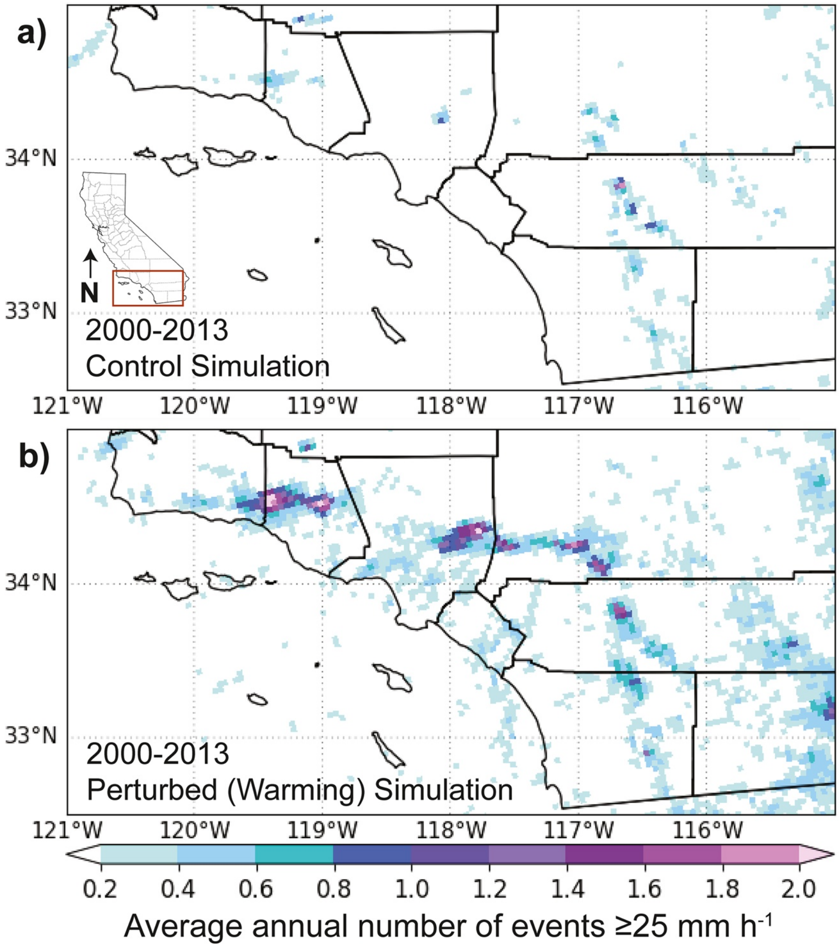

Figure 2. The average annual number of hourly precipitation events exceeding 25 mm h^{-1} in Southern California for (a) a control simulation and (b) a pseudo-global warming simulation representing late-century warming, both at 4 km and for the period of October 2000 through March 2003. This simulation output was sourced from and is described in Prein et al., (2017). Note that large-scale circulation changes anticipated in a future climate are not accounted for in this type of experiment. In the "perturbed" simulation, the average annual number of >25 mm h^{-1} events increases more than twofold in the region's high terrain. The 25 mm h^{-1} threshold was selected for examination as representative of the peak rainfall intensity of 24 mm h^{-1} for 15 min used as a "design storm" in USGS post-fire hazard assessments (USGS, 2021). While these quantities are not equal, in the absence of a 15-min product, it provides insight to how the frequency of rainfall intensities capable of triggering post-wildfire debris flows might change in a warming climate. Gridded datasets such as this, especially at sub-hourly resolutions for historic and future periods offer benefits for the study of geohazards.

Research (NCAR) is developing the "CONUS 404," a 40-year reanalysis at 4 km, with a 15-min precipitation product, for the continental US (NCAR, 2021). Such products help overcome issues such as lack of observed data and/or lack of rainfall recurrence interval products. Forthcoming climate projection products, such as NCAR's "CONUS 2," a 20-year 4 km climate simulation offering precipitation at 1h and 5-min timescales (NCAR, 2021) support the development of appropriate scaling factors as well as understanding changes in atmospheric processes driving rainfall intensification. Additionally, high-resolution reanalysis and projection products can provide inputs to hydrologic and debris-flow models to assess the changing characteristics of post-fire hazards under different weather and climate conditions.

Despite spatial and temporal resolution increases in climate models, internal variability (variability resulting from the inherently chaotic nature of the atmosphere) limits the application of model output to planning for future post-fire hydrologic hazards (Deser, 2020). Internal variability can create uncertainties in precipitation projections (e.g., Huang et al., 2020; Payne et al., 2020) which are most pronounced in mid-latitude regions in the cool season (Deser, 2020). The use of large ensemble simulations may help to define or constrain a range of potential precipitation outcomes, or to highlight particular sources of uncertainty for atmospheric processes of interest (Mankin et al., 2020). However, due to computational limitations, there is a balancing act among model resolution, number of ensemble members, simulation length, and other factors.

5. Monitoring is Key for Expansion of Decision Support Tools to Other Regions

Field monitoring programs produce data necessary for constraining rainfall intensity-duration thresholds and calibrating models for post-wildfire debris flows, thus supporting both immediate post-fire hazard monitoring as well as contributing to long-term planning and improved understanding of hazards in an area. Observations from one well-documented region (e.g., Southern California) cannot necessarily be extrapolated to another due to unique weather, climate, ecology and geology. As calibrated debris-flow models and thresholds are the basis of the decision support tool presented in Kean and Staley (2021) for Southern California, similar information is necessary to apply this tool in other debris flow-susceptible regions. It is critical to capture the timing of post-fire debris-flow initiation and associated rainfall intensities. Monitoring sites to capture this information may vary in their complexity, though at the most basic level include paired observations of rainfall intensity and flow response (occurrence or lack of a debris-flow response). More complex monitoring sites may include tipping bucket precipitation gauges and laser stage gauges to capture this information (e.g., Kean et al., 2011), while low-cost monitoring can be conducted utilizing rain gauges paired with pressure transducers and/or cameras and post-event site evaluations (e.g., Kean et al., 2012; McGuire & Youberg, 2020). Preparing a post-fire monitoring strategy before a fire occurs may help managers stay within budget, minimize challenges in rapid deployment, and get the most benefit out of monitoring efforts.

Rain gauges used in monitoring efforts have the limitation of only providing information at a point, while weather radar offers spatially explicit information. A challenge is that post-fire debris flows occur in complex terrain where, in the US, operational NEXRAD weather radars may have poor coverage. Supplemental weather radar observations provide critical information on rainfall rates supporting both "nowcasting" during intense rainfall events and determining rainfall intensity and duration over areas not well-represented by gauges. Radar observations may take the form of a strategically placed network of high-resolution radars (e.g., Cifelli et al., 2018). Another approach is using mobile radars temporarily deployed to locations of concern (e.g., Jorgensen et al., 2011). These mobile radars provide high spatial and temporal resolution (as high as 60 m and 2 min) within a radius of up to 40 km (Cifelli et al., 2018) and can be used to collect detailed information on intensity and spatial variability of precipitation across a burn area. However, radar must be used with caution for this application as there are challenges and limitations in converting radar observations to rainfall intensity, especially for the US West Coast (e.g., Jorgensen et al., 2011).

Observations can be costly, though some expense can be mitigated by leveraging existing networks. For example, California has invested in a diverse sensor network that can be utilized for observing, understanding and forecasting extreme weather events (Hatchett et al., 2020). New observations to expand debris-flow monitoring in California can leverage infrastructure from this existing network. For other regions seeking to develop monitoring networks, lessons learned from established observational networks can inform a streamlined and cost-effective network development.

6. Conclusion

A post-fire debris flow of similar magnitude to Montecito will likely occur again. Historically, post-fire debris-flow preparedness has been reactive and following wildfire, though recent conversations suggest a move toward pre-fire preparedness (e.g., Tillery & Haas, 2016; Staley et al., 2018), paving the way for the application of new decision support tools (e.g., Kean & Staley, 2021). Addressing post-fire debris-flow hazards is a complex, multi-disciplinary problem; only the management, atmospheric science, and observational components were touched upon herein. Advances in soil and wildfire science, ecology, social science, are also critical in understanding and mitigating current and future impacts of these hazards. Kean and Staley (2021) brings these pieces together in a framework that can be modified and refined as new research findings emerge and serves as a mechanism for planning for climate change and post-wildfire debris-flow impacts. This tool and subsequent development of inputs to the tool and expansion to other regions contributes to resilience and preparedness of communities and reduction in loss of life and property.

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