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Integration of meteorology and geomorphology for enhanced understanding of post-fire debris-flow hazards

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Abstract. Through precipitation, the fields of meteorology and geomorphology are fundamentally linked, thus interdisciplinary efforts are needed to advance understanding and warning of rainfall-driven geohazards. With a focus on recent efforts specific to post-fire debris flows in California, our presentation provides an overview of the benefits and challenges of working in an interdisciplinary team of meteorologists and geomorphologists, as well as results of a recent project demonstrating advancement through the integration of these fields. In this project, we combine high-resolution ensemble precipitation forecasts with post-fire debris-flow models to explore the feasibility and potential value of providing probabilistic post-fire debris-flow hazard information over a burn scar. In sharing these examples, we emphasize the multi-benefit nature of these efforts, and encourage future interdisciplinary efforts that improve warning and mitigation of rainfall-driven geohazards.

1 Introduction

California experiences frequent, damaging post-wildfire debris flows [1-2]. Post-wildfire debris flows are initiated by runoff during short-duration, high-intensity rainfall, with rainfall over a 15-minute duration being a good predictor [3-4]. Historically, post-fire debris-flow research broadly describes meteorological conditions triggering debris flows as “convective storms” or “frontal storms” [1]. However, from a meteorological perspective, there are a range of atmospheric conditions within these broad categories that affect the intensity, duration, and spatial extent of precipitation over a burn scar, which influences geomorphic response. These atmospheric processes relevant to debris-flow hazards generally operate on a spatial scale of ~2-200 km, and a temporal scale of <24h [5], referred to as the “mesoscale”. This is in contrast to the larger “synoptic scale”, featuring cyclones and atmospheric rivers, and smaller microscale processes, though interactions across scales can influence weather outcomes.

Understanding the mesoscale characteristics of storms that produce post-fire debris flows is critical to interpreting past events and being able to skillfully predict outcomes in future events, including the provision of early warning to communities at-risk. In a paper describing priority research needs on post-fire runoff, Moody et al. [6] state that, “collaboration between post-wildfire researchers and mesoscale meteorologists will be needed to advance the measurement, understanding and prediction of temporal and spatial variations in rainfall over burn areas.” Herein, we share recent interdisciplinary California-focused work among meteorologists and geomorphologists (encompassing geologists, hydrologists, civil engineers, and other non-meteorologists working on the post-fire debris-flow topic) to advance understanding and early warning of post-fire debris flows. We note the benefits of such collaborations, challenges and suggestions to overcome them, as well as present the results of recent interdisciplinary research that combines mesoscale atmospheric modeling with post-fire debris-flow likelihood, volume, and inundation modeling to provide probabilistic hazard information as an example of advancements through interdisciplinary work.

2 Interdisciplinary efforts between meteorologists and geomorphologists

There are numerous ways geomorphologists and meteorologists can work collaboratively to improve understanding of post-fire hydrologic hazards. One such approach is using post-fire debris-flow observations such as event timing, magnitude, observed rainfall, and examining the atmospheric conditions associated with the triggering rainfall. This can help contextualize the storm characteristics as a rare or common event, giving insight beyond the rainfall annual recurrence interval.

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As a recent example, Figure 1 shows radar reflectivity associated with a post-fire debris flow on the Bond Fire in southern California. This is a feature known as a "narrow cold frontal rainband" (or NCFR), a narrow band of high-intensity rainfall along a storm's cold front. Such features are relatively common in this area; southern California experiences approximately three such events per year [7].

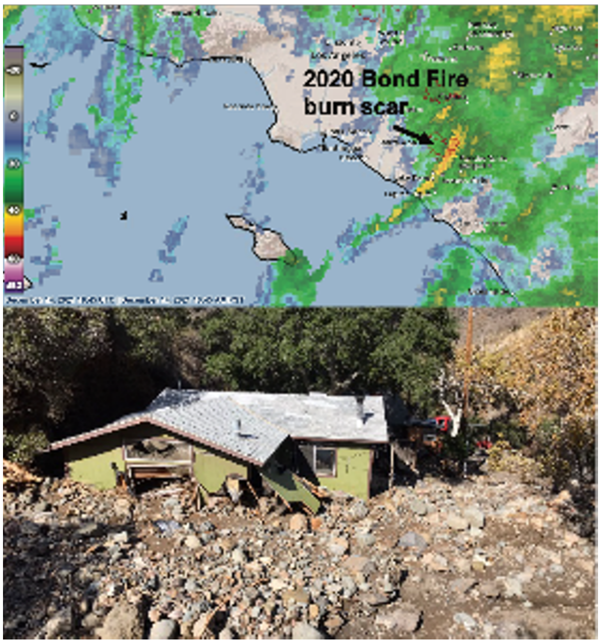

Fig. 1. Radar reflectivity on 14 December 2021 at 18:45 UTC showing a narrow cold frontal rainband impacting the 2020 Bond Fire burn scar, outlined in red (top); image from California-Nevada River Forecast Center. A home destroyed in the debris flow associated with this rainfall event (bottom); image from California Geological Survey.

Conducting such analyses over numerous events and locations reveals regional patterns of atmospheric features and conditions associated with debris-flow events [2], as well as an understanding of the types of atmospheric events that are most likely to pose the greatest potential for impactful events. In the US, the National Weather Service is the entity responsible for issuing watches and warnings for post-fire debris flows to the public. Having information on atmospheric conditions associated with past impactful debris flows contributes to forecaster situational awareness and confidence in issuance of watches and warnings.

Working collaboratively allows for novel use of atmospheric datasets or methods that may not have been previously known to the geomorphology community. This may include rain gauge data, gridded precipitation estimates, forecast tools or resources, and other weather information. These interdisciplinary interactions also lead to the exploration of science questions and situational awareness needs, facilitating the development of new precipitation or weather products that support post-fire debris-flow research. Historically, tools needed to evaluate the precipitation characteristics of past debris-flow events (e.g., gridded quantitative precipitation estimates) and future potential for debris-flow hazards (climate model projections) have only been available at spatial and temporal scales too coarse for effective use. While this is due in part to the computational resources required to produce high-resolution information, it has also been due to a lack of demand for high-resolution products. A strong relationship between the two disciplines provides a pathway for requests to reach weather and climate modelers, and in turn provides justification for these modelers to develop high-resolution products. With recent efforts to communicate these needs, more high-resolution products are emerging [8].

Though there are numerous benefits, conducting interdisciplinary work is not without challenges. Members of an interdisciplinary science team likely use different terminology, norms, research methods, and may have different goals. Tasks likely require interdependence across researchers from different disciplines, which can at times make it challenging to plan a workflow [9], thus progress may not be as linear as when working in a single discipline. From the authors' experience, developing a new interdisciplinary collaboration requires patience, a willingness to ask questions about the field that is not your own, and to listen and learn. There can be presumptions researchers have about their knowledge of the other field that create a barrier for communication of scientific information. A first step towards success is to find research team members who have openness to interdisciplinary work [9]; not all researchers are well-suited to these collaborations. Some scientists lack interest outside their field or do not give sufficient consideration the nuances that are important to other fields (e.g., meteorologists may have limited interest in the range of post-fire hydrologic responses). Overcoming these challenges may require persistence to find the right teammates as well as time to build trust and understanding among the interdisciplinary team members.

3 Interdisciplinary collaboration example: Forcing debris-flow models with ensemble precipitation forecasts

The National Weather Service is moving towards probabilistic hazard information and impact-based decision support [10]. Thus, there is a need to develop methods to integrate atmospheric models and debris flow models in a way that they can be used operationally and provide probabilistic and impact-based information on post-fire debris-flow hazards.

To address this need, we experiment with using probabilistic precipitation forecast information as an input to debris-flow hazard models. We utilize a 100-member ensemble forecast from a numerical weather model at 1-km horizontal resolution with a 24-hour lead time for two storm events featuring narrow cold frontal rainbands. We focus on the Thomas Fire burn area in southern California, as major debris flows initiating from within the burn scar on 9 January 2018 resulted in 23 deaths and nearly $1 billion in damages [11-12]. Both storms selected for the forecast simulation, 9 January 2018 and 2 February 2019, resulted in impacts on the Thomas Fire burn scar. Though we ran the forecast retrospectively, the inputs selected to initiate the forecast model run retain the uncertainty of the forecast as if it were run 24 hours prior to the event.

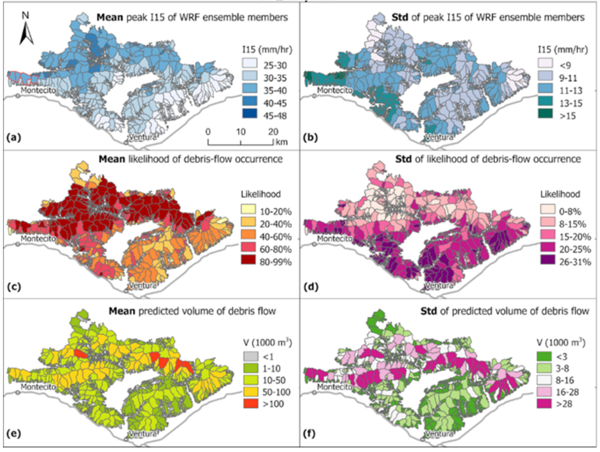

Fig. 2. Likelihood and volume analysis for the Thomas Fire burn area for the 9 January 2018 storm event. Left panels show the Weather Research and Forecasting model (WRF) rainfall forecast ensemble mean and right panels show the standard deviation for each watershed for peak I_{15} rainfall (a,b); probability of debris-flow occurrence (c,d); debris-flow volume estimate (e,f). Watersheds outlined in red in (a) experienced notable impacts. Figure developed by Tao Liu.

The storm maximum 15-minute intensity was calculated for each of the 100 forecast ensemble members for each storm and used as an input to models that predict post-fire debris-flow likelihood [4] and volume [13] at the watershed scale. From there, we can calculate statistics for debris-flow likelihood and volume such as the ensemble mean and standard deviation (Fig. 2) or number of ensemble members with likelihood or volume over a specified threshold. Lastly, we used the outputs of the likelihood and volume models as inputs into a debris-flow inundation model [14] to generate maps of debris-flow inundation extent. Propagating data from the precipitation forecast ensemble into the inundation model, which requires debris-flow volume (a function of I_{15}) as an input, provides information on the potential range of area inundated with the incoming storm (Fig. 3), as well as the ability to calculate likelihood of inundation for a location in a forecast storm.

Probabilistic hazard information such as that presented in this experiment quantifies uncertainty in both the precipitation forecast and potential debris-flow response, providing enhanced information over a deterministic (singular) precipitation forecast or application of a uniform rainfall intensity over a burn area. This approach supports decision-makers in identifying areas most likely to have impactful debris flows and provides them a sense of the potential range of outcomes associated with the incoming storm, which can help determine how to manage storm response resources. This is especially valuable given the growing size and frequency of wildfires in California.

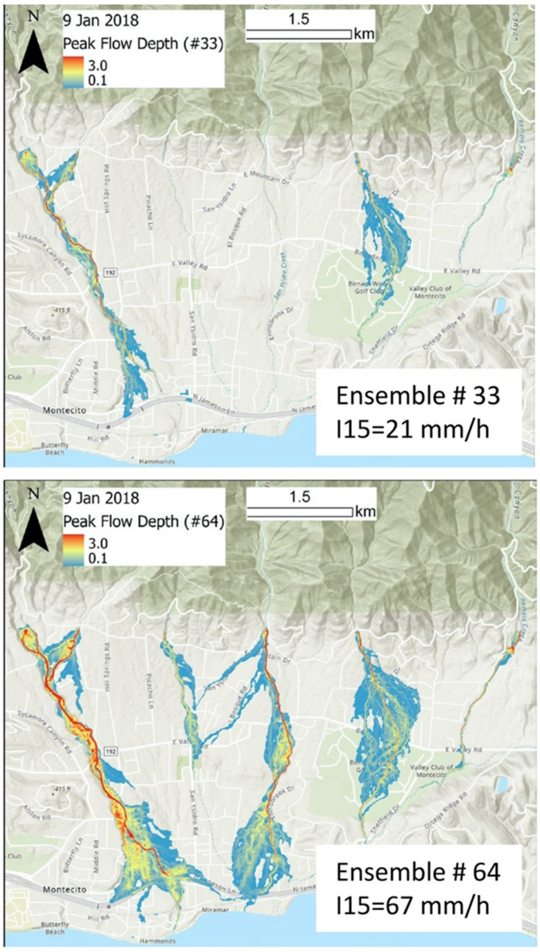

Fig. 3. Example of inundation outcomes for several watersheds within the Thomas Fire burn area using precipitation input from two forecast ensemble members with different maximum 15-minute rainfall intensities (I_{15}) for the 9 January 2018 storm that impacted the area. Use of the ensemble allows for display of a range of possible outcomes.

4 Final Remarks

This work provides a proof-of-concept for probabilistic debris-flow hazard information based off of ensemble precipitation forecasts, though there are several limitations to consider in moving this experiment towards operations. Running large ensemble weather forecasts at high resolution is very computationally expensive. Additional research needs to be done to optimize the model setup such that it provides sufficient uncertainty quantification while running fast enough to be used operationally. Mesoscale models can represent features producing short-duration, high-intensity rainfall, but can struggle with exact location, timing, and intensity of these features out past a few hours of forecast lead time. The use of an ensemble helps overcome this issue. Debris-flow likelihood, volume, and inundation models are subject to large uncertainty and may not perform well outside of locations for which there has been sufficient data collected to calibrate them.

Additionally, this work demonstrates progress towards the development of an operational tool that provides probabilistic hazard information for post-fire debris flows. Such advancement will be a major step forward in situational awareness and warning of these hazards. These advances would not be possible without close collaboration between the geomorphology and meteorology communities. While we focus on post-fire debris flows here, interdisciplinary collaborations in these two fields have also led to improved understanding of other rainfall-driven geohazards, such as shallow landslides [15]. These collaborations are beneficial, if not necessary, to advance early warning systems and improve tools that support risk management. We encourage geomorphology and meteorology colleagues to seek out collaborations to facilitate progress in both fields that supports improved warning and mitigation of rainfall-driven geohazards.

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