Damages Associated with Excessive Rainfall Outlooks (ERO) and Missed Flash Floods

MEIRAH WILLIAMSON,[a,b] KEVIN ASH,[a] MICHAEL J. ERICKSON,[c,d] AND ESTHER MULLENS[a]

[a] *Department of Geography, University of Florida, Gainesville, Florida*
[b] *Illinois State Water Survey, University of Illinois Urbana–Champaign, Champaign, Illinois*
[c] *Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, Colorado*
[d] *NOAA/NWS/NCEP/Weather Prediction Center, College Park, Maryland*

(Manuscript received 18 April 2022, in final form 7 March 2023, accepted 8 March 2023)

ABSTRACT: Flash flooding is the most damaging and deadly type of flooding event in the continental United States (CONUS), and one of the deadliest hazards worldwide. The Weather Prediction Center's (WPC) Excessive Rainfall Outlook (ERO) is used to highlight regions at risk of receiving excessive rainfall that can lead to flash flooding. While EROs have been validated by the WPC across several metrics, an analysis of flash floods that were not forecast by EROs, which we define as missed flash floods, has not been performed, nor have damages associated with missed flash floods been examined. Using EROs, flash flood data from the Unified Flooding Verification System (UFVS), and flash flood damage data from the National Centers for Environmental Information (NCEI) Storm Events Database, this research investigates the characteristics of missed flash floods. We find that missed damages occur most frequently in summer and least frequently in winter, but that only 9.2% of flash flood damages and 23.2% of damaging events are missed by the ERO. Missed damaging flash flood events occur frequently in the U.S. Southwest. In this region, missed damages and missed events are primarily attributed to the North American monsoon (NAM). We also investigate forecast flash floods by ERO risk category. High risks incur the most damages despite having the fewest number of damaging events, indicating that the ERO is able to distinguish higher-impact events. The ERO predicts damaging flash floods well, although the Southwest and urban areas broadly could be investigated further to ensure that the potential of damaging flash floods are accurately forecast.

KEYWORDS: Forecasting; Flood events; Societal impacts

1. Introduction

Floods are among the most damaging and deadly weather-related hazards worldwide. In the United States, flash floods account for up to 90% of total flooding fatalities and are concentrated in regions with one or more of the following: steep topography, densely populated urban areas, and high precipitation totals and rates (Zevin 1994). Densely populated areas at highest risk include the northeast Interstate-95 corridor, the Ohio River Valley, and Flash Flood Alley, which contains the populous cities of San Antonio, Dallas, and Austin, Texas (Ashley and Ashley 2008; Saharia et al. 2017a). In the western United States, damaging and fatal flash floods occur in areas near mountain ranges with steep topography such as the Rocky Mountains, the Cascades, and mountain ranges across California. Overall, nearly 60% of flash flooding fatalities occur in urban or suburban areas (Ashley and Ashley 2008) and occur most frequently most during the warm season across the continental United States (CONUS) (Špitalar et al. 2014; Saharia et al. 2017b; Ahmadalipour and Moradkhani 2019).

Similarly, flood damages to property and infrastructure have spatial and seasonal patterns. The Ohio, Missouri, and upper Mississippi basins frequently exceed $8 million in flood damages per year, as do parts of the mid-Atlantic region (Downton et al. 2005). Missouri, California, and Texas frequently exceed $100 million in flooding damages (Downton et al. 2005). States with small populations in the Rocky Mountains and West rarely incur flood damages of more than $2 million per year (Downton et al. 2005). However, flood damage analysis usually focuses on all types of floods, making it difficult to infer the damages from flash flooding alone. Across CONUS, flash flood damages have increased significantly between 1996 and 2017 (Ahmadalipour and Moradkhani 2019), linked in part to an increase in the frequency of intense precipitation.

Given their pronounced societal and economic impacts, flash floods remain a priority in weather forecasting. Accurate short- and medium-term forecasts of flash flood potential are critical for the mitigation of impacts associated with flash flooding through societal preparation, planning, and response. Accurate extreme precipitation forecasts are critical to this process (Fritsch and Carbone 2004; Erickson et al. 2021). However, forecasting extreme precipitation events through quantitative precipitation forecasts (QPF) from dynamical models remains one of the biggest challenges in operational meteorology (Fritsch and Carbone 2004; Sisson and Gyakum 2004; Sukovich et al. 2014; Sharma et al. 2017). Although models are improving, small errors in QPF lessen the accuracy of flash flood forecasts (Sharma et al. 2017). Flash flood forecasts tend to be least accurate during warm seasons, when convection is the most frequently occurring storm mode causing extreme precipitation. In contrast, forecasts are most accurate during cool seasons, when synoptic systems are the dominant cause of extreme precipitation (Fritsch and Carbone 2004; Sisson and Gyakum 2004; Sukovich et al. 2014; Sharma et al. 2017; Erickson et al. 2019).

Corresponding author: Meirah Williamson, meirahw@illinois.edu

DOI: 10.1175/WAF-D-22-0035.1

This research is focused on a CONUS-scale spatial evaluation of the Excessive Rainfall Outlook (ERO) product developed by the Weather Prediction Center (WPC). The ERO is an impact-based forecast product used by the National Weather Service (NWS) since 1978 to highlight regions at risk of flash flooding due to excessive rainfall (Cooley 1978). The ERO is defined as the probability of rainfall exceeding flash flood guidance (FFG) within 40 km of a point, and it contains four risk categories based on flash flood probability thresholds (section 2a). Although the ERO is primarily based on QPF, forecasters consider antecedent environmental and meteorological conditions such as land use, topography, slope, basin size, urbanization, soil moisture, and streamflow, among others (Barthold et al. 2015; WPC 2020). WPC forecasters also draw on their expertise to identify weather patterns associated with extreme precipitation and use a variety of models to examine the meteorological and hydrologic factors that produce flash flooding.

Corresponding to its continued refinement as an operational product, the ERO has been evaluated in terms of its forecast skill to capture the probabilities and spatial areas of greatest risk. For example, Erickson et al. (2021) found the ERO to be well-calibrated to the average expected probability across risk categories. In addition to examining the seasonality and meteorological causes of ERO risk categories, ERO risk categories have been evaluated in an impacts context, based on their total damages over a specified temporal period. Carbin and Lamers (2019) found that High Risk issuances are rare (4% of days) but account for nearly 90% of flood related damages and over 40% of flood related fatalities. These studies illustrate the accuracy and skill associated with flash flood forecasting, but there remain additional aspects of the EROs that have been less studied, which this paper addresses.

We examine a few specific questions using geospatial analysis and an impacts perspective. First, to what extent do damaging flash flood events occur outside of *any* ERO risk level at a 1-day lead time (which we define as "missed events"), and in what seasons and regions is this most prevalent? Second, what are the typical estimated damages and meteorological causes of missed events? Finally, is there any spatial consistency in areas that experience higher or lower damages per event over CONUS, or by risk category? This final question builds upon Carbin and Lamers (2019) to examine the spatial distribution of damages by risk categories outside of High Risk, which have not yet been enumerated. Improving our geospatial understanding of where flash floods occur, where they cause damage, and whether there are regions that are particularly susceptible can help improve flash flood forecasting to advance our understanding of impacts, and for protection of life and property (Chen et al. 2016; Terti et al. 2017; Ahmadalipour and Moradkhani 2019).

2. Data and methods

a. Data

1) EROs and the UFVS

The ERO is a dynamic forecast product and is regularly updated based on new numerical weather prediction guidance and evolving environmental conditions. The ERO is issued for Day 1 (valid from the current day to 1200 UTC the next day), Day 2 (valid from 1200 UTC the next day to 1200 UTC two days into the future), and Day 3 (valid from 1200 UTC two days to 1200 UTC three days into the future). Day 4 and Day 5 EROs are issued experimentally as of February 2022. Each day the forecast is modified at specific update times, although the ERO issued for Day 1 can have unscheduled issuances in special circumstances. The ERO contains four risk categories, each of which correspond to a probability threshold for excessive rainfall exceeding FFG: Marginal Risk indicates a 5%–10% chance of rainfall exceeding FFG within 40 km of a point, Slight Risk a 10%–20% chance, Moderate Risk a 20%–50% chance, and High Risk a greater than 50% chance. Areas that are not issued an ERO have less than a 5% chance of rainfall exceeding FFG within 40 km of a point. Effective February 2022, the risk categories were adjusted so that Marginal Risk indicates at least a 5% chance of rainfall exceeding FFG within 40 km of a point, Slight Risk at least a 15% chance, Moderate Risk at least a 40% chance, and High Risk at least a 70% chance. An overview of FFG and how it is calculated by River Forecast Centers (RFC) is provided in the appendix.

The ERO has been continuously evolving since its inception in 1978 and the ERO with four risk categories (Marginal, Slight, Moderate, and High) has only existed since August 2016 (WPC 2016). To keep the ERO risk categories consistent, our research uses four years of data spanning 1 September 2016–31 August 2020. Although Day 1 EROs are also issued at 0100 and 1500 UTC, we use only the Day 1 EROs issued at 0900 UTC (which span 24 h; 0100 and 1500 UTC span 11 and 20 h, respectively) to examine events at a short lead time, but still prior to event onset. This initial Day 1 forecast is also used by local weather forecast offices (WFO) as part of their decision-making process when issuing flash flood warnings (D. Berc 2021, personal communication; L. Hopper 2021, personal communication). This timeframe and the time at which the Day 1 EROs are issued (0900 UTC is the early morning hours in the United States) is critical in staging and preparation for adverse conditions by local emergency managers.

The WPC has compared the ERO to the Unified Flooding Verification System (UFVS), which is a suite of four flash flooding proxies and observations including Local Storm Reports (LSRs) of flash floods, U.S. Geological Survey (USGS) river gauge observations, Stage IV analysis exceeding FFG, and Stage IV analysis exceeding 5-yr Average Recurrence Interval (Erickson et al. 2021). Because no single dataset can capture all flash floods, the UFVS is designed to capture most flash flood events (Herman and Schumacher 2018; Erickson et al. 2019, 2021). Flash flood proxies and observations within the UFVS have a radius of influence (ROI) of 40 km applied around each instance, which is consistent with the WPC's definition of the ERO (Erickson and Nelson 2018). Day 1 EROs and the UFVS were obtained from the WPC (https://ftp.wpc.ncep.noaa.gov/ERO_verif/day1/).

2) NCEI storm events database

The National Centers for Environmental Information (NCEI) Storm Events Database contains records of significant weather phenomena that result in death, injuries, and property and crop damage. The Storm Events Database is the most comprehensive database for damages from severe weather events in the United States, particularly for flood events. The U.S. Army Corps of Engineers requires monetary damage estimates for flood reports, which provides confidence that damaging flash flood events are well-reported (NWS 2021).

Because the Storm Events Database separates flash flood and flood events—the distinction is determined by the Storm Events Database preparer—only damages from flash floods are included in this analysis (NWS 2021). Broadly, flash floods are defined as a rapid flow of water into a dry area or a rapid water level rise in a stream beginning within minutes or hours of the causative event, such as moderate to heavy precipitation. Other guidelines within the NWS's Storm Data Preparation manual help the Storm Events Database preparer determine if a flood event is a flash flood (e.g., a person or vehicle being swept away by flowing water or a state road closed by high water are flash flood indicators) (NWS 2021). Estimates for the time at which flash floods begin and end are also made by the preparer, which allowed us to convert local times to UTC to match flash floods to Day 1 EROs. The Storm Events Database separates severe weather occurrences by episode ID and event ID. Episode IDs group flash floods caused by the same meteorological event, while event IDs describe the specific flash flood event and its impacts. For this research, we use event IDs to represent flash flood events because a single episode ID can span multiple counties and thus may only be partially well-forecast by the ERO. Overall, we identified 3483 damaging flash flood events between 1 September 2016 and 31 August 2020.

b. *Methods*

1) MISSED FLASH FLOODS

Missed flash floods are defined as flash floods that fall outside of the ERO. The regionality of missed flash floods and their associated damages are determined by comparing EROs, flash flood observations and proxies from the UFVS, and flash flood property damage data from the Storm Events Database. To determine the spatial distribution of missed flash floods, we used grid based EROs and flash flood observations and proxies from the UFVS. EROs and flash floods from each day were compared to determine where flash floods fell outside of an ERO. An example of the daily verification process is shown in Fig. 1 using a Day 1 ERO from 1200 UTC 15 August to 1200 UTC 16 August 2018. Figure 1a shows a Day 1 ERO overlayed with flash floods. Figure 1b shows flash floods that were not captured by the ERO. If a UFVS grid point did not overlap an ERO grid point, it was considered to be outside the ERO and thus an area where a flash flood was missed. Missed flash floods were aggregated seasonally [i.e., March–April–May (MAM), June–July–August (JJA), September–October–November (SON), December–January–February (DJF)].

2) DAMAGES

A county was considered to have incurred damages from a flash flood outside of an ERO if at least one grid point from a missed flash flood intersected the county. Figure 1b shows

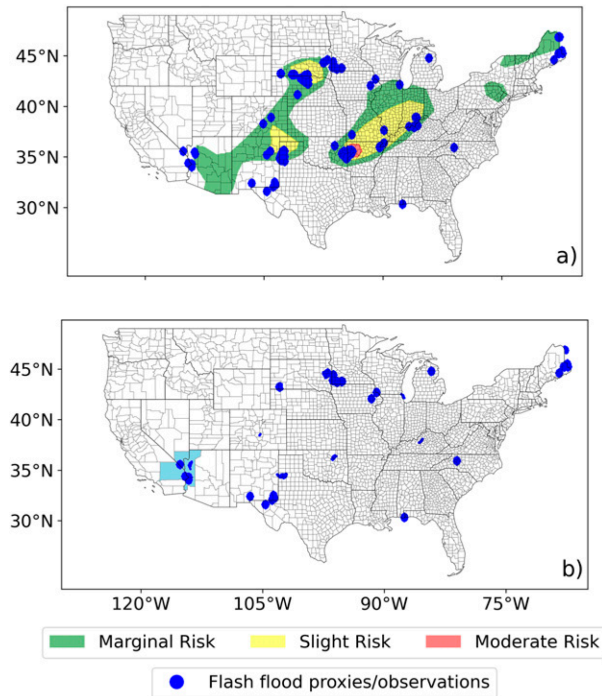

FIG. 1. 1200 UTC 15 Aug 2018–1200 UTC 16 Aug 2018: (a) Day 1 ERO with flash flood proxies and observations from the UFVS and (b) missed flash floods and damages. Light blue shading represents counties with missed damages.

counties with missed flash flood damages. Missed damages were aggregated by county and RFC (see Fig. 2), which are commonly used to study extreme precipitation, QPF, and flash flood regionality (e.g., Ralph et al. 2010; Sukovich et al. 2014). Because RFCs bisect county lines, an RFC was assigned to each county based on location of each county's centroid to ensure that county damages were assigned to only one RFC. Last, for both this and the subsequent risk category analysis, meteorological causes of damages were assigned using the Storm Events Database's flood cause and event narrative categories, which describe the cause and impacts of flash flood events. Populations affected by flash flood damages were determined at the county level for both analyses.

Spatial distributions of ERO risk categories (Marginal, Slight, Moderate, High) were determined at the county level to connect ERO categories to county-level damage data. For every Day 1 ERO, the risk category with the most grid points in each county was assigned to that respective county. If two or more risk categories were tied for the highest number of grid points, the highest risk category was assigned to that county. Flash flood damages were assigned to ERO risk categories based on the category of the county.

Damages from Hurricane Harvey were excluded from this analysis. Hurricane Harvey caused catastrophic flash flooding in 2017 and accounted for 93% of flash flood damages in the Storm Events Database during our study period. The decision to remove damages from Hurricane Harvey is supported by Carbin and Lamers (2019), which removed Hurricane Harvey

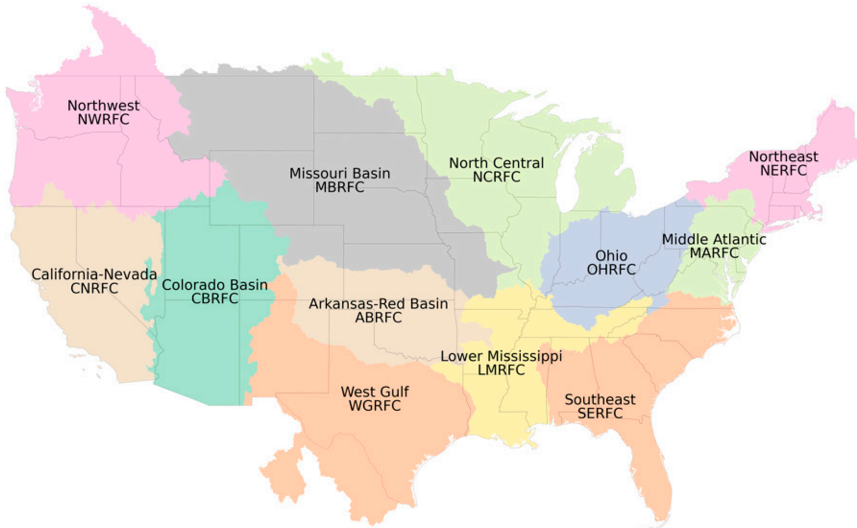

FIG. 2. Map of River Forecast Centers (RFC).

in their analysis of flash flood damages for High Risk issuances. Flash flooding from dam/levee breaks were also excluded from this analysis. The ERO does not explicitly consider flash flooding caused by dam/levee breaks, in part because dam/levee breaks can lead to flash floods days after the causative rain event.

3) Caveats

It is important to note that EROs are not meant to capture every flash flood event (e.g., as represented in the UFVS), and are particularly not meant to capture isolated flash floods (WPC 2020). All UFVS data are included in this analysis to provide a full understanding of potential flash floods missed by EROs. If an area repeatedly incurs flash floods, regardless of whether they are isolated, an investigation into the meteorological and physical causes could be performed to better understand the reason for unexpected but frequent flash flooding, particularly if there are damages.

Additionally, the UFVS defined in Erickson et al. (2019, 2021) utilizes both flash flood observations and proxies. While it is understood that LSRs and USGS river gauge observations do not represent the full scope of flash flood frequency, it is also likely that a flash flood does not occur with every 5-year ARI or FFG exceedance. In this instance, the UFVS can be thought of isolating those regions that experience excessive rain, but not necessarily flash flooding. Therefore, flash flood proxies and observations from the UFVS that were not covered by an ERO may overestimate missed flash floods.

Finally, although the Storm Events Database is comprehensive, severe weather events are likely underreported, particularly in more sparely populated areas (Curran et al. 2000; Ashley and Ashley 2008). Damage cost estimates for small flood events may be inaccurate to the dollar amount, but there is no evidence that they are positively or negatively biased (Downton and Pielke 2005).

3. Results and discussion

a. Missed flash floods

The number of days in which there was a flash flood outside a Day 1 ERO is shown by season in Fig. 3. Missed flash floods occur most frequently in the summer, particularly east of the Rocky Mountains and in the U.S. Southwest (Fig. 3b). In contrast, missed flash floods occur least frequently in winter months, and are concentrated in the Cascade Range in the Pacific Northwest and in the Sierra Nevada in California, as well as in the Appalachian Mountains in the eastern United States (Fig. 3d). Flash floods outside an ERO in the spring and fall are widely dispersed across CONUS (Figs. 3a,c), occurring less frequently than in summer but more frequently than in winter.

Flash floods occur most frequently in the summer and least frequently in winter (Schumacher and Johnson 2006; Dougherty and Rasmussen 2020). Therefore, the number of missed flash floods in the summer is expected to be highest because there are more flash floods for the ERO to capture, which is consistent with our results (Fig. 3b, Table 1). However, there are likely other contributors to the high number of missed flash floods in the summer. The ERO is primarily based on QPF, which has seasonally varying skill. In the summer, QPF tends to exhibit the lowest skill, likely due to the prevalence of convection and other small-scale processes (Olson et al. 1995; Mullen and Buizza 2001; Fritsch and Carbone 2004; Sukovich et al. 2014). Summer precipitation amounts in particular tend to be underforecast by QPF because models are not necessarily able to simulate the complete physical properties of convection, such as the location, structure, movement, propagation, and regeneration that influence its life cycle (Fritsch and Carbone 2004; Schumacher and Davis 2010). In the Southwest, specifically, summer precipitation forecasting is challenged by model representation of the North American monsoon (NAM) (Maddox et al. 1995; Adams and Comrie

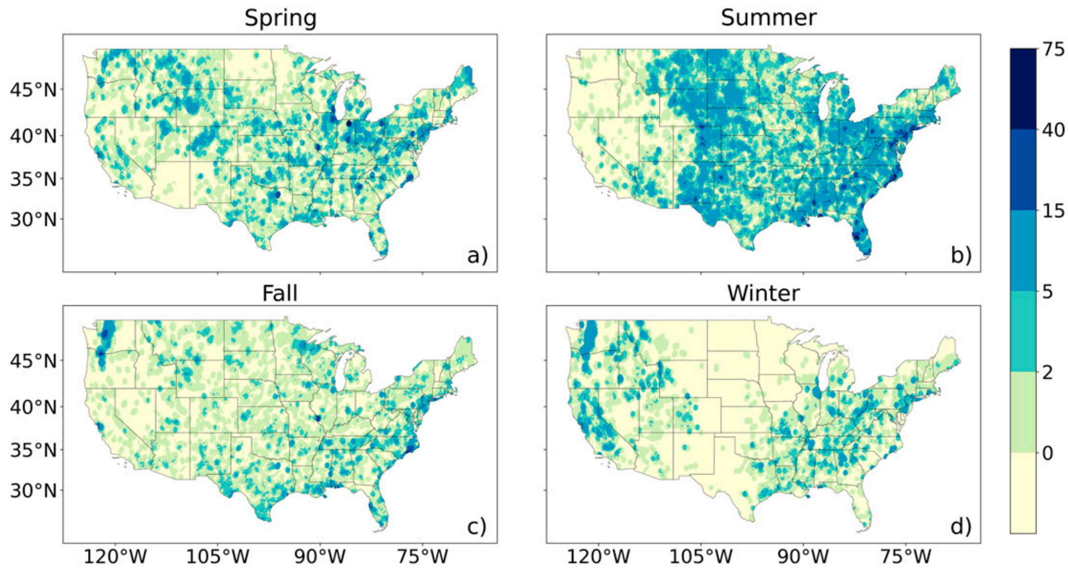

FIG. 3. Number of days with flash floods missed by an ERO in (a) spring, (b) summer, (c) fall, and (d) winter.

1997; Grantz et al. 2007; Carlaw et al. 2017; Rogers et al. 2017; Yang et al. 2017), which is the region's primary driver of flash floods (Ashley and Ashley 2008; Kunkel et al. 2012; Saharia et al. 2017a; Yang et al. 2017). Under-forecasting precipitation amounts associated with convection could reduce the spatial extent of an ERO, which could further explain the comparatively high number of missed Day 1 flash floods in the summer.

In winter, QPF exhibits the highest skill and flash floods are least frequent (Sukovich et al. 2014; Dougherty and Rasmussen 2020). Extreme winter precipitation is dominated by synoptic scale events, which are correlated with better QPF (Sukovich et al. 2014). The combination of fewer winter flash floods and better QPF skill points to fewer missed flash floods in the winter, which is consistent with our results (Fig. 3d). There are fewer winter flash floods outside of an ERO across CONUS compared to other seasons. Missed flash floods that do exist are concentrated throughout the West Coast (Fig. 3d), where atmospheric rivers dominate extreme winter precipitation and are the primary driver of winter flash floods (Neiman et al. 2008; Ralph et al. 2010; Dettinger et al. 2011; Smith and Smith 2015; Young et al. 2017; Dougherty and Rasmussen 2020). Although atmospheric rivers are not necessarily difficult to model, Ralph et al. (2010) found that models have lower skill predicting heavy precipitation produced by atmospheric rivers compared to weaker precipitation, which could contribute to missed winter flash flood events in the western United States.

Although missed flash floods tend to occur frequently in mountainous, less populated regions (Fig. 3), population growth in the mountainous West is outpacing population growth across much of CONUS (Rosewicz et al. 2019). Flash floods in mountainous areas are often associated with landslides and debris flow, which can cause devastating effects on infrastructure (Destro et al. 2018). The complex nature of mountainous terrain and problems detecting precipitation at high altitudes cause difficulties forecasting extreme rainfall associated with flash floods, which impacts the accuracy of EROs (National Research Council 2005; Tao and Barros 2013). Improving EROs will be important for protecting the growing population and infrastructure from flash floods in the mountainous West.

b. *Damages from missed flash floods*

1) COUNTY-LEVEL DAMAGES

Figure 4 depicts the number of damaging flash flood events outside of an ERO in each county. Damaging flash floods are

TABLE 1. Seasonality and characteristics of damaging missed flash flood events.

	Percent of counties with damaging events	Percent of counties in column 1 with damage from one single event	No. of counties with damages	Total damages ($1,000,000)	Average damage per county ($1,000,000)
Spring	29	87	148	98.5	0.67
Summer	39	80	319	136.8	0.43
Fall	19	86	88	11.4	0.13
Winter	11	79	27	9.5	0.35

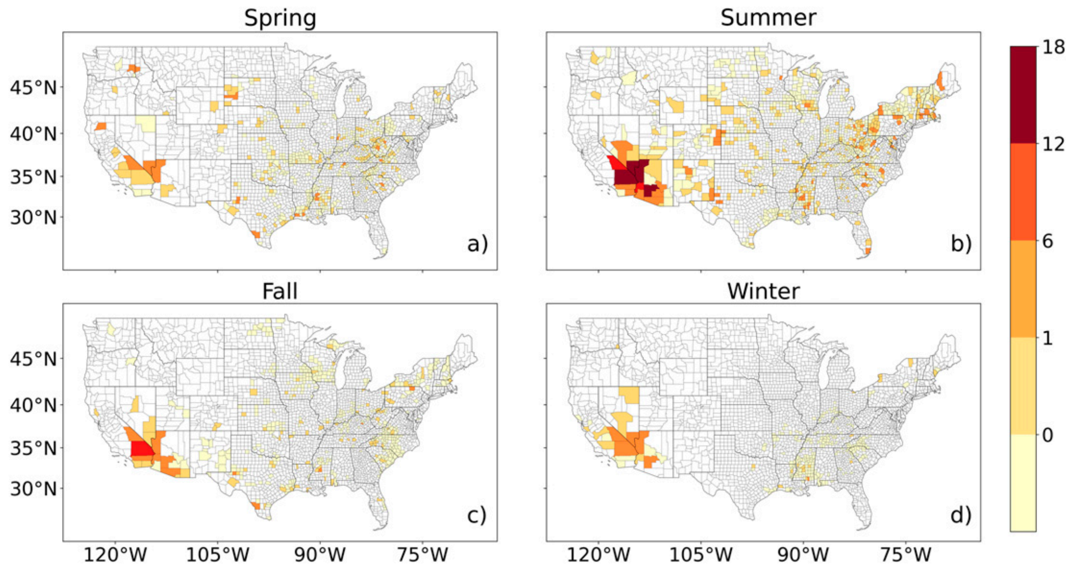

FIG. 4. Number of days with damaging flash floods missed by an ERO in (a) spring, (b) summer, (c) fall, and (d) winter. Unshaded counties did not incur damages from flash floods covered by or outside of a Day 1 ERO.

missed across all seasons but are most widespread and most frequent in the summer (Fig. 4b, Table 1). Among counties that incur flash flood damages, the majority do not incur damages from missed flash flood events (Table 1). 39% percent of counties incur damages from flash floods outside an ERO in the summer, compared to 11% in the winter (Table 1). Among counties that incur missed flash flood damages, more than 75% of counties experience only one missed damaging event across all seasons over four years (Table 1). However, in contrast to the rest of CONUS, multiple counties in the Southwest experience numerous days across all seasons in which there were flash flood damages outside of an ERO (Fig. 4).

The high percentage of counties with zero or one missed damaging flash flood over this sample period suggests that damaging flash floods usually fall within an ERO. Furthermore, excluding the Southwest, EROs do not appear to frequently miss damaging flash floods in any particular region. Singular missed damaging flash floods in a county could be attributed to isolated flash flood events, which EROs are not designed to forecast (WPC 2020). These could also be attributed to ERO placement, in which an ERO is drawn near but not over a missed flash flood. Inaccuracies in forecasting the location of extreme precipitation could lead to inaccuracies in forecasting damaging flash floods (Sharma et al. 2017; Erickson et al. 2021). Overall, 23.2% of damaging flash flood events are missed, which account for only 9.2% of total damages in our study period (Table 2). Based on these findings, we conclude that EROs are generally accurate in their delineation of the spatial risk of damaging flash floods at the initial Day 1 lead time.

2) DAMAGES ACROSS RFCS

Missed flash flood total monetary damages are highest in the North Central RFC (NCRFC), Ohio RFC (OHRFC), and Northeast RFC (NERFC) at $73.1 million, $50.6 million, and $48.3 million, respectively (Table 2, Fig. 5). The California–Nevada RFC (CNRFC), which contains the fourth highest missed damages, incurs only $23.8 million of missed damages (Table 2). The NCRFC, OHRFC, and NERFC also contain the four most damaging missed events located in Wayne County, Michigan ($64 million, event ID: 824344), Cuyahoga County, Ohio ($30 million, event ID: 846841), and Norfolk County, Massachusetts ($25 million, event ID: 897824), and Washington County, New York, respectively ($16 million, event IDs: 915030, 915031, 915029, 915337, 915032). The first three counties have high population densities and contain Detroit, Cleveland, and the Boston suburbs, respectively, which is where the damages occurred according to the Storm Events Database. In contrast, Washington County, New York, has a low population density but incurred severe damage to a local high school, businesses, and roads. Urban areas, because of their expansive infrastructure, tend to incur more damages from flood events, although flash floods can also cause severe damages in rural areas if they affect critical or expensive infrastructure.

To assess the impact of flash floods outside an ERO, it is necessary to look at different metrics. The NCRFC, the OHRFC, and the NERFC have the three highest missed damages per missed flash flood event, but not the highest missed damages per capita or the highest percentage of missed flash flood damages, although they are in the top half of RFCs for these categories (Table 2, Fig. 5). The area covered by the Northwest RFC (NWRFC) has the fewest missed flash flood events and the third fewest missed flash flood damages, but the highest percentage of missed flash flood damages, and the second highest percentage of missed damaging events and missed flash flood damages per capita (Table 2). The Storm Events Database shows that 5 out of 11 damaging flash flood events (event IDs: 818099, 896233, 818423, 758571, 818104) and the majority of flash flood damages occurred in the adjacent counties of Latah County,

TABLE 2. Missed flash flood damages and events for all RFCs. Missed flash flood damages are also expressed as missed damages per missed flash flood event, as a percentage of all flash flood damages, and as missed damages per capita.

River Forecast Center (RFC)	Missed damages ($1,000,000)	Missed damaging events	Percent of damages missed by the ERO	Percent of damaging events missed by the ERO	Missed damages ($100,000) per event	Missed damages ($) per capita
Arkansas–Red basin	1.8	26	8.5	16.5	0.7	1.1
Colorado basin	10.1	103	22.9	43.1	1.0	1.0
California–Nevada	23.8	83	18.5	61.5	2.9	1.9
Lower Mississippi	11.4	112	5.8	17.4	1.0	2.5
Mid-Atlantic	1.4	30	0.9	21.3	0.5	0.3
Missouri basin	10.5	53	9.7	29.0	2.0	5.3
North-central	73.1	39	15.2	12.2	18.7	7.1
Northeast	48.3	41	43.9	25.0	11.8	5.1
Northwest	2.1	11	80.3	50.0	1.9	6.0
Ohio	50.6	168	40.5	21.5	3.0	3.4
Southeast	11.9	80	5.2	16.2	1.5	0.8
West Gulf	11.3	62	1.0	30.0	1.9	0.8
All RFCs	256.2	808	9.2	23.2	3.2	2.6

Idaho and Whitman County, Washington. on four different days during the spring. As mentioned previously, difficulties forecasting extreme precipitation can cause difficulties forecasting flash floods in mountainous regions which is relevant to this area.

Examining flash floods beyond the total amount of damage caused is also advised by local WFOs (Schroeder et al. 2016). WFOs have expressed concern about determining flash flood severity on damages alone because the significance of the damage depends on the population affected and the resources (e.g., emergency services, recovery aid) available for a population (Schroeder et al. 2016). When describing the damages that occurred in Latah County, the Storm Events Database states that the Nez Perce Reservation incurred flash flood damages during one missed flash flood. Notably, however, tribal nations are not guaranteed access to disaster funds awarded to counties by the federal government and could not ask for a presidential disaster declaration until 2013 (Wimsatt 2017). Flash floods that

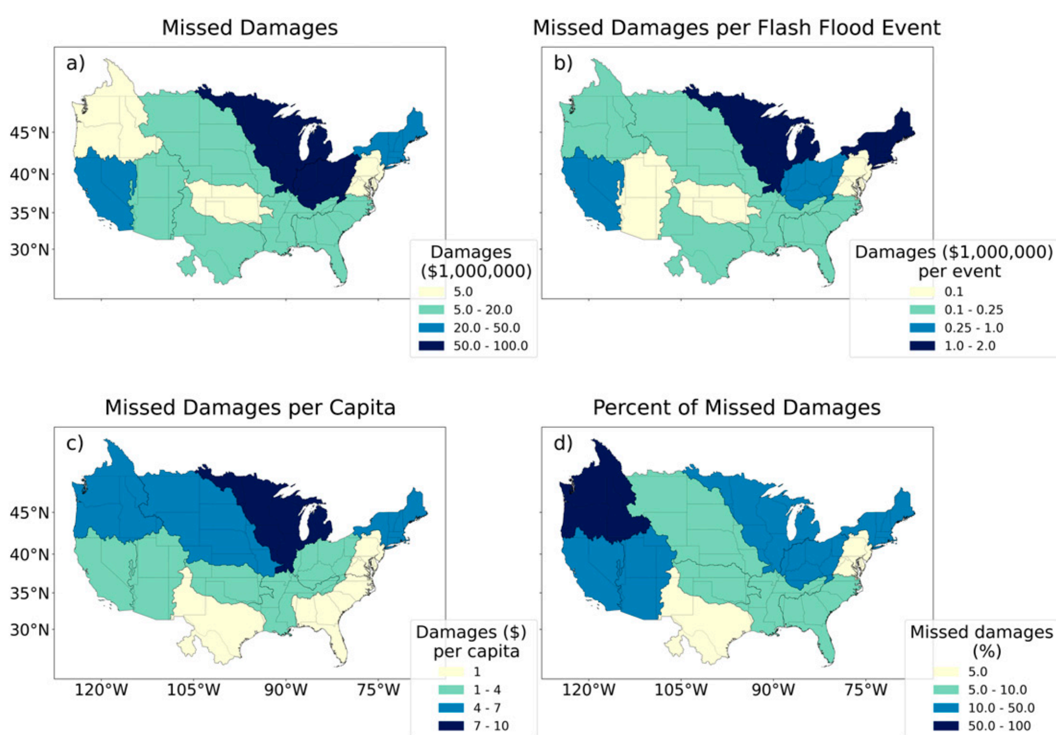

FIG. 5. Across RFCs: (a) missed damages, (b) missed damages per flash flood event, (c) missed damages per capita, and (d) percent of missed damages.

TABLE 3. Missed and forecasted damaging flash floods in the Southwest by meteorological cause. Damaging missed and forecast flash flood events are expressed as a percentage of all damaging flash flood events and by event total. Missed and forecast flash flood damages are expressed as a percentage of all flash flood damages in the Southwest and in U.S. dollar amount.

	Southwest river forecast centers (CBRFC and CNRFC)							
	Missed				Forecast			
	Events (%)	No. of events	Damages (%)	Damages ($1,000,000)	Events (%)	No. of events	Damages (%)	Damages ($1,000,000)
Atmospheric rivers	1.3	5	3.0	5.2	2.7	10	59.6	102.7
North American monsoon	31.0	116	12.3	21.2	29.7	111	15.6	26.9
Tropical systems	3.5	13	1.9	3.2	7.2	27	3.0	5.2

are poorly forecast in socially vulnerable areas may be more impactful than poorly forecast flash floods in well-resourced areas.

3) THE SOUTHWEST

The Southwest contains numerous counties with damaging flash flood events outside an ERO, and thus we focus on this region for further analysis. To better examine the meteorological causes of these events and their associated damages, the Southwest was defined using two RFCs: the Colorado Basin RFC (CBRFC)—which contains Arizona, Utah and parts of Colorado, Nevada, and New Mexico—and the CNRFC—which contains most of California and Nevada. Missed events account for $33.9 million (Table 2), or 19.6% of all flash flood damages in the region. This is higher than the overall percentage of missed flash flood damages across CONUS which is only 9.2% of all damages (Table 2).

Using the Storm Events Database narratives, we found that the NAM was the meteorological driver of over 60% of damaging flash flood events and nearly 30% of damages in the Southwest (Table 3). Atmospheric rivers, despite causing less than 5% of flash floods, cause over 60% of flash flood damages, while tropical systems contribute to few events and damages (Table 3). The remaining missed and forecast damaging flash flood events are broadly attributed to Pacific storm systems and winter storms.

The NAM is the primary driver of flash floods in portions of the southwest (Ashley and Ashley 2008; Kunkel et al. 2012; Saharia et al. 2017a; Yang et al. 2017), which typically begins at the end of June and can last until the end of September (Maddox et al. 1995; Adams and Comrie 1997). Correspondingly, our results show that the NAM drives the majority of damaging flash flood events (Table 3). Furthermore, the proportion of missed damaging events to forecast events with the NAM is nearly 50–50 (Table 3). This even split in forecast and missed damaging events highlights the challenges associated with forecasting flash floods associated with this monsoon system. The topographic features of the Southwest, the complexity of the NAM's moisture source and transport mechanism, and ties to synoptic-scale patterns, make convection and precipitation associated with the NAM contribute to QPF error, particularly at lead times longer than several hours (Maddox et al. 1995; Adams and Comrie 1997; Grantz et al. 2007; Carlaw et al. 2017; Rogers et al. 2017; Yang et al. 2017).

To better understand the regional meteorological and hydrologic context of this region, we discussed our findings with local NWS forecast hydrologists in Las Vegas, Nevada, and Phoenix, Arizona. The role of local forecasters as experts of their domains and their flooding triggers was evident. EROs as a national product are drawn by forecasters who would likely benefit from local WFO knowledge. In the case of the NAM, it is clear to WFOs in the Southwest that monsoon precipitation will occur, but it is less clear when, where, and what the precipitation rate will be (D. Berc 2021, personal communication; L. Hopper 2021, personal communication). At the 2017 Flash Flood and Intense Rainfall Experiment (FFaIR), a yearly experiment that has existed since 2012 which brings together forecasters and other members of the meteorological community to explore tools for improving operational flash flood forecasting and EROs, Southwest forecasters tended to draw EROs more frequently for the Southwest due to their knowledge of local meteorology and terrain (L. Hopper 2021, personal communication). Accordingly, the Southwest was identified as a flash flood hotspot by the operational ERO and the FFaIR experimental ERO, largely due to the NAM (Erickson et al. 2019). The experimental ERO increased Marginal Risks for the Southwest by a factor greater than 4. Slight Risks likewise increased in the Southwest using the experimental ERO. Higher issuances of both risk categories were more consistent with the observed flash flood proxy and observation coverage (Erickson et al. 2019). Even after the 2017 FFaIR, in which monsoon activity in the Southwest was identified as problematic for accurate EROs, Erickson et al. (2021) and internal verification by the WPC found that Slight Risk placement in Arizona was underforecast (overforecast) in lower (higher) terrain. The combination of too few risks issued for the Southwest by operational EROs, ERO placement, insufficient local knowledge, and inaccurate QPF likely contribute to the high miss rate for monsoon-driven flash floods (Tables 2 and 3).

WFOs and the WPC have increased collaboration on EROs and daily QPF in recent years, and WFOs use EROs as a tool for issuing flash flood watches (Brost et al. 2020, D. Berc 2021, personal communication). Better flash flood preparation through more accurate EROs could help individuals and emergency managers better mitigate potential flash flood damages. Overall, damages from monsoon-driven flash floods account for $48 million, or nearly 30% of all flash flood

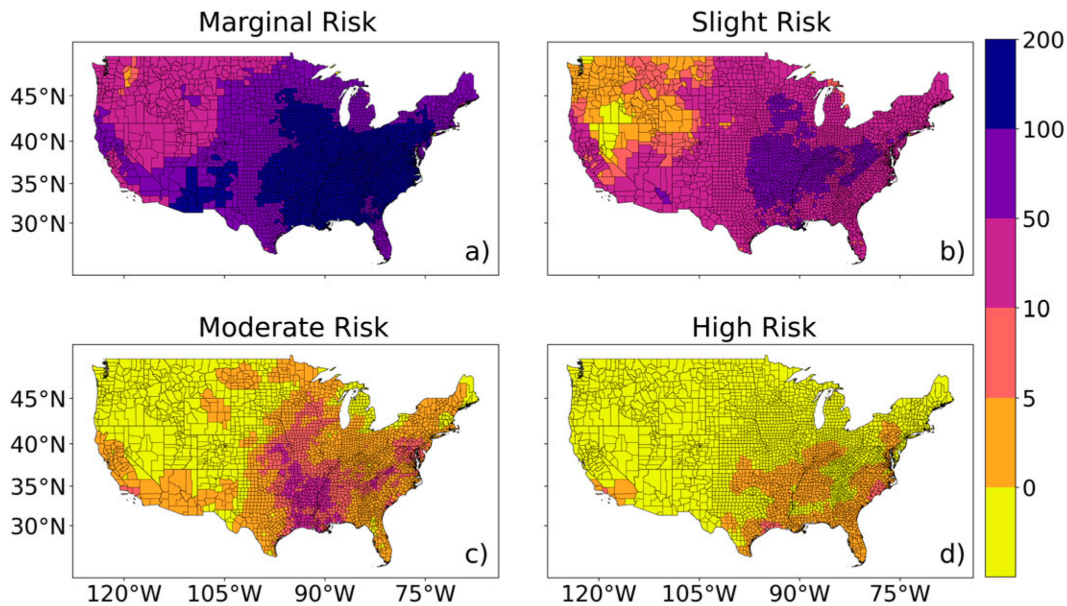

FIG. 6. Number of days in which (a) Marginal Risk, (b) Slight Risk, (c) Moderate Risk, and (d) High Risk ERO categories were issued for counties across CONUS.

damages in the Southwest (Table 3). Although fatalities were not analyzed in this research, it is important to note that flash floods cause high fatalities in the Southwest compared to other regions across the United States (Ahmadalipour and Moradkhani 2019). Improving EROs for the Southwest during the NAM season could better inform Southwest WFOs and the public about where damaging and potentially fatal monsoon-driven flash floods will be located.

Atmospheric rivers do not occur frequently in the Southwest but produce a large fraction of their annual precipitation (Rutz et al. 2014; Payne et al. 2020) and damages (Ahmadalipour and Moradkhani 2019; Corringham et al. 2019). Atmospheric rivers cause few missed or forecast damaging flash floods but the vast majority of damages (Table 3). Counties that incurred more than $1 million in damages from atmospheric river driven flash floods include Riverside County, San Bernardino County, and Mariposa County, California. San Bernardino and Riverside Counties incurred damages caused by an atmospheric river on 14 February 2019, but only the flash flood damages in Riverside County were encompassed by an ERO, indicating that an ERO was issued for the region but was slightly misplaced. Tuolumne and Mariposa Counties likewise incurred flash flood damages from a single atmospheric river on 3 March 2018, but neither county contained flash flood damages that fell inside an ERO. The ERO was similarly slightly misplaced, positioned west of where damages occurred (not shown). Despite incurring high damages, Tuolumne and Mariposa Counties are in the bottom third of densely populated counties in California. Roads, including state highways, were damaged from debris flow and soil erosion, sewer systems were inundated, and the Moccasin Dam was badly damaged. Although Riverside and San Bernardino Counties are more densely populated, the Storm Events Database preparer attributed damages to roads in the eastern, less populated areas, noting that damages were exacerbated by burn scars. Corringham et al. (2019) found that areas most affected by damaging atmospheric river-driven floods were in less densely populated regions but with vulnerable assets, which is consistent with our results. Considering that damages in sparsely populated areas tend to be less well reported than their more populated counterparts (Downton and Pielke 2005), it is possible that flash flood damages from atmospheric rivers, although already a large proportion of all flash flood damages, are underreported.

The Storm Events Database does not provide orientations for atmospheric rivers, which can be a large determinant of how much precipitation they produce in the Southwest. Atmospheric rivers with southerly orientation produce larger amounts of precipitation because they pass over low mountains in southern Baja California (Hughes et al. 2014). Conversely, southwesterly and westerly atmospheric rivers that pass over multiple mountain ranges in Southern California and northern Baja California produce less precipitation (Hughes et al. 2014). As climate changes, atmospheric rivers are expected to contain more moisture which will increase the intensity of precipitation and thus flash floods (Payne et al. 2020). Considering that flash floods driven by atmospheric rivers are very damaging (Table 3), knowing the location and severity of potential flash floods driven by atmospheric rivers is vital for forecasting where impacts to people and infrastructure will be concentrated.

c. ERO risk categories and damages

The spatial distribution of ERO risk categories by county is shown in Fig. 6. Risk outlooks are most frequent at the lowest categories and least frequent at the highest. Marginal, Slight, and Moderate Risks are issued most frequently east of the Rocky Mountains, as well as the interior Southwest and California.

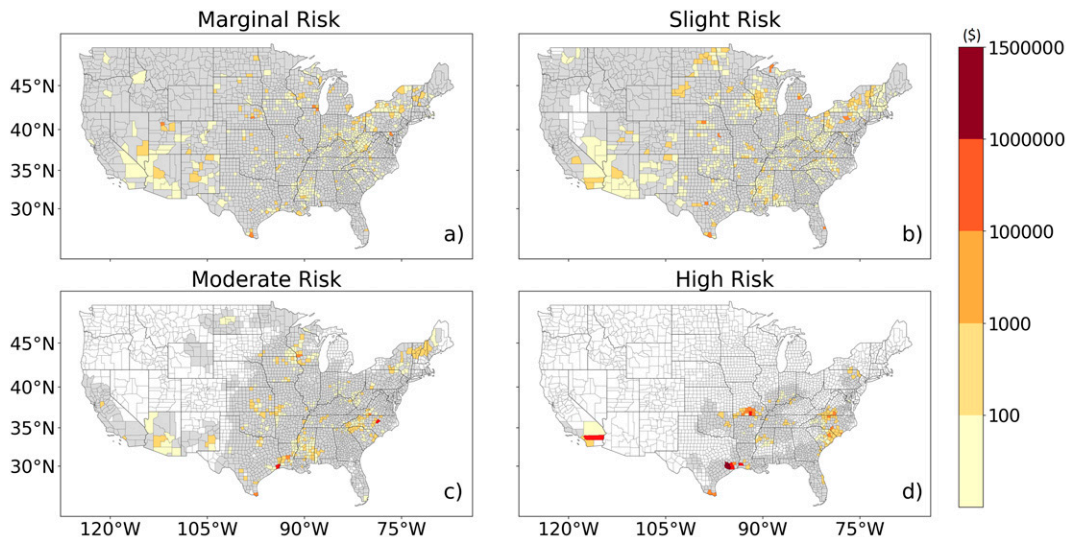

FIG. 7. Damages (U.S. dollars) per flood report for (a) Marginal Risk, (b) Slight Risk, (c) Moderate Risk, and (d) High Risk ERO categories. Gray-shaded counties show where ERO risk categories were issued.

Slight and Moderate Risks are more frequent across the Appalachian Mountains and Mississippi River Valley. Marginal, Slight, and Moderate Risks can be attributed to a wide array of atmospheric events including tropical, monsoonal, mesoscale convective, and synoptic systems (Erickson et al. 2021). High Risks are primarily confined to the Gulf of Mexico, Atlantic Coast, and Mississippi River Valley. Tropical systems are the main cause of High Risks (Erickson et al. 2021).

Although High Risks damages occurred the least frequently and had the smallest spatial extent compared to other risk categories (Fig. 7), damages associated with High Risks were greater than other risk categories. Across CONUS, High Risk counties reported damages of nearly $5 million per flash flood report on average (Table 4). Damages per flash flood event decrease as the risk of flash flooding decreases: Moderate Risk counties incur $1.1 million per event, Slight Risk incur $0.7 million per event, and Marginal Risk incur $0.2 million per event. Damages per capita follow the same pattern (Table 4). In addition to the risk of flash floods, ERO categories are correlated to the average monetary damages associated with such events. That is, counties issued a higher risk category can expect to experience more damaging flash floods than counties issued a lower risk category. Notably, Marginal Risk damages per flood report and damages per capita are slightly lower than missed damages per flood report and damages per capita, indicating that there is potentially room for improvement when placing Marginal Risks versus negligible risks (Table 4).

High and Moderate Risk damages can primarily be attributed to heavy rains from tropical systems. Tropical systems and their associated precipitation tend to be well forecast by weather models resulting in accurate QPF forecasts and, thus, are high-confidence events, which could explain why flash flood damages from tropical systems are rarely missed (Fig. 8). The only missed damages from a tropical system stem from Hurricane Rosa in 2018 on the West Coast. It is likely that flash flood damages from Hurricane Rosa outside the ERO were an issue of ERO placement rather than unanticipated heavy precipitation (e.g., Erickson et al. 2021).

Slight Risk, Marginal Risk, and missed flash floods are primarily driven by heavy rain events (Figs. 8 and 9). Although the WPC already takes into account burn scars when drawing EROs, and damages incurred from heavy rain on burn areas are low across missed and forecast flash flood damages (Figs. 8 and 9), flash floods associated with burn scars may become more frequent as wildfire prevalence increases across the United States, altering the hydrological response of watersheds (Versini et al. 2013; Westerling 2016). Flash floods associated with rain-on-snow events similarly make up a small percentage of damages, but rain-on-snow events leading to flash floods in the western United States are expected to

TABLE 4. Damages, flash flood events, population, damages per flood report, and damages per capita for flash flood events that are missed and at different ERO risk categories.

Risk category	Damages ($1,000,000)	No. of flash flood events	Population (1 000 000 people)	Damages per flood report ($1,000,000)	Damages per capita ($)
Marginal	168.2	745	88.4	0.2	1.9
Slight	837.4	1200	115.6	0.7	7.2
Moderate	551.5	485	52.7	1.1	10.5
High	889.6	188	33.4	4.7	26.6
Missed	256.2	808	100.7	0.3	2.6

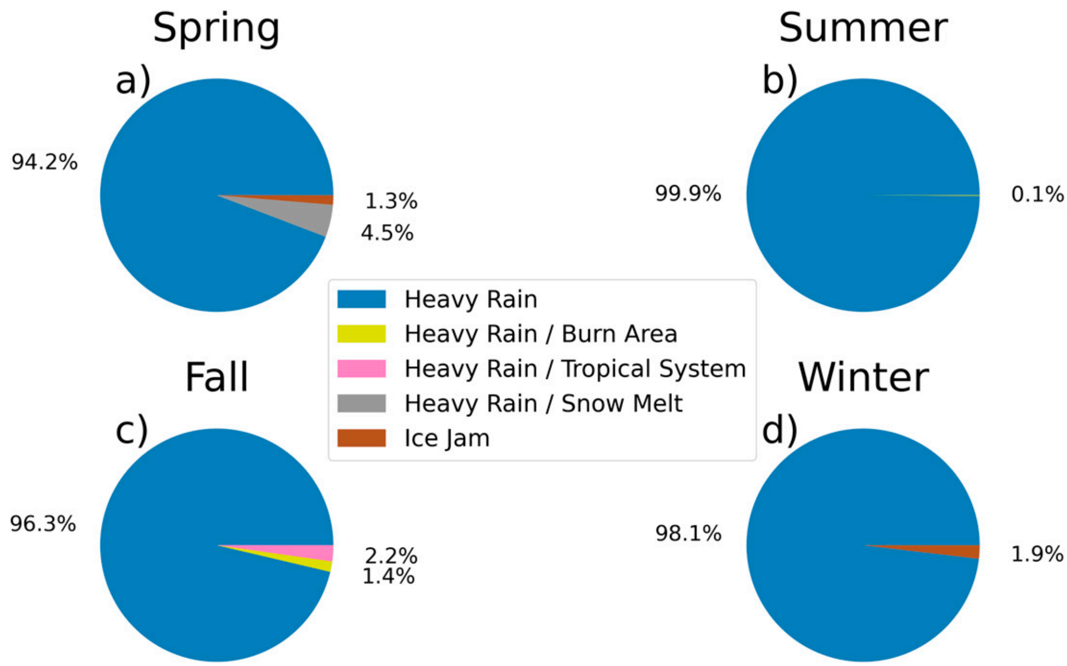

FIG. 8. The proportion of missed damages attributed to different types of heavy precipitation in (a) spring, (b) summer, (c) fall, and (d) winter.

decrease as temperatures warm and decrease snowpack (McCabe et al. 2007).

4. Conclusions

Flash floods are one of the most damaging and deadly weather-related phenomena in CONUS. Consequently, it is important that flash floods are well forecast to prevent fatalities and injury and to protect infrastructure. Across CONUS, only 9.2% of monetary damages are missed by EROs, although 23.2% of damaging flash flood events are missed. Notably, counties with damages from flash floods outside an ERO infrequently experience more than one missed damaging event, indicating that the ERO does not

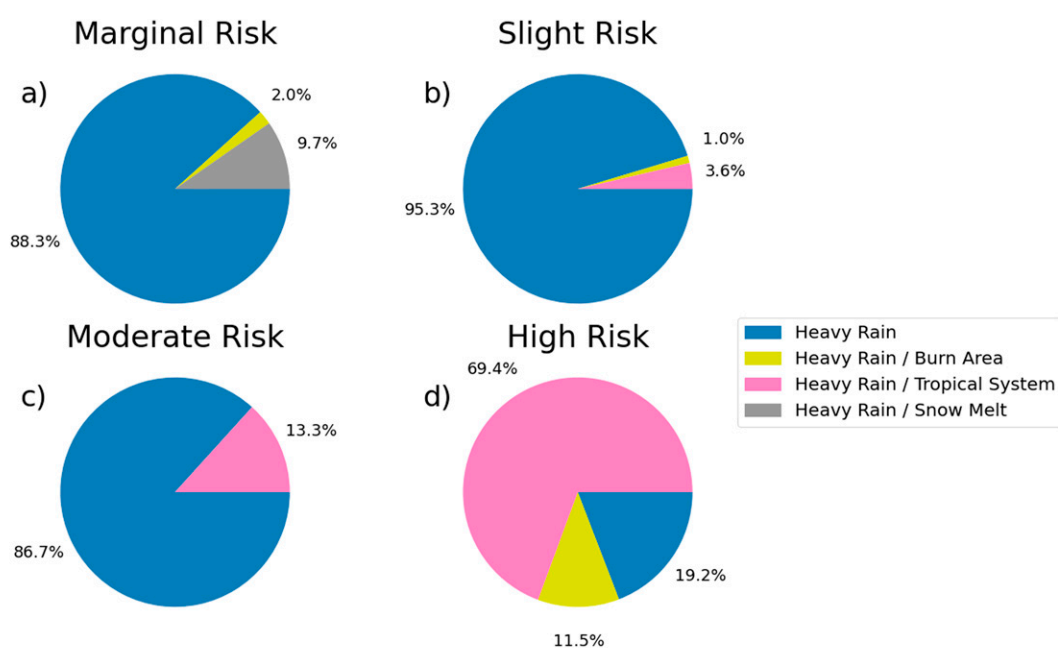

FIG. 9. The proportion of damages attributed to different types of heavy precipitation for (a) Marginal Risk, (b) Slight Risk, (c) Moderate Risk, and (d) High Risk ERO categories.

systematically miss certain regions or counties. The Southwest is an exception, which has a high number of counties that have had repetitive damaging events associated with the NAM and atmospheric rivers and their likely interaction with static terrain features. Flash floods associated with the NAM are not well captured by the ERO and missed damages attributed to the NAM account for nearly 30% of all flash flood damages and over 60% of damaging events in the Southwest. Flash flooding caused by atmospheric rivers occurs infrequently and is well-captured in the ERO but is very damaging when they do occur. Across CONUS, characteristics of missed flash flood damages are difficult to generalize in part because there is little regionality to missed flash flood events. When examining urban and rural counties, damages in urban areas tend to incur higher costs because there is more infrastructure to damage, but rural areas can likewise incur high costs when roads and critical infrastructure are damaged. Overall, our findings indicate that the ERO does not miss many damaging flash floods and, outside of the Southwest, events outside an ERO do not have a distinct regionality.

Although missed flash flood damages are difficult to generalize, damages associated with ERO risk categories appear to validate that they are reasonably well calibrated. Damages per flash flood event and damages per capita are lowest for Marginal Risks, followed by Slight Risks, Moderate Risks, and High Risks, indicating that the risk of flash flooding corresponds to the severity of flash flood damages in a region. This correlation could help forecasters and emergency managers better convey the severity of a potential flash flood event.

It is important to note several limitations with this study. The ERO is not meant to capture isolated flash flood events, meaning that missed flash flood events and damages may be overestimated per the definition of the ERO. Flash flood damages may also be underestimated due to documented underreporting in rural areas.

Future work could investigate the meteorological, hydrological, and topographical causes of damaging missed flash floods in the Southwest and across CONUS to identify patterns that frequently cause flash floods outside of an ERO. Missed flash floods and damages could also be examined across time to see if ERO placement has improved. The relationships between numerous factors such as the orientation of extreme precipitation associated with atmospheric rivers, the NAM, ERO placement, and damages could be assessed to ensure that the ERO becomes more accurate as heavy precipitation, urbanization, and flash flood damages increase. Finally, building off the work of Ahmadalipour and Moradkhani (2019) and Khajehei et al. (2020) in which the intersection of socioeconomic vulnerability and flash flood hazards was investigated, missed flash floods could be analyzed to determine if there are socioeconomically vulnerable regions repeatedly being missed by the ERO.

Acknowledgments. This work was supported by Dr. Esther Mullens' startup grants from the University of Florida. Thanks to the developers of ERO data and the Storm Events Database, NWS forecasters L. Hopper and D. Berc for their insight into the meteorological conditions and local forecast processes in the Southwest, and P. Burke for their insight into the current state of ERO and property damage research.

Data availability statement. The authors will provide all data and Python scripts used in this article upon request. Please contact meirahw@illinois.edu for more information.

APPENDIX

Flash Flood Guidance across River Forecast Centers

Flash flood guidance (FFG) is defined as the amount of rainfall over a given area and time duration that will cause flooding on small streams. These estimates are typically based on the soil moisture and streamflow conditions present in a region. FFG is produced by 12 River Forecast Centers (RFCs) across CONUS. Several different methods are used to generate FFG values: the Arkansas–Red Basin, Lower Mississippi, Southeast, and West Gulf RFCs use gridded flash flood guidance (GFFG); the California–Nevada, Colorado Basin, and Northwest RFCs use flash flood potential index (FFPI); the Middle Atlantic RFC uses distributed flash flood guidance (DFFG); and the Missouri Basin, North Central, Northeast, and Ohio RFCs use lumped flash flood guidance (LFFG) (Clark et al. 2014).

FFPI is useful for regions where flash flooding is not primarily caused by overtopping streams. Soil characteristics, vegetation cover, slope, land use, and seasonal effects are used to determine the likelihood of flash flooding in an area. LFFG is primarily concerned with soil moisture and threshold runoff. GFFG and DFFG are similar to LFFG but use different hydrologic models to assess the soil moisture portion of FFG and have a higher spatial resolution for FFG (Clark et al. 2014).

Although FFG is crucial for the ERO, there are several limitations, particularly along RFC boundaries. FFG values along boundaries may be absent, have multiple overlapping values, or have sharp gradients. These errors are likely due to different methods of generating FFG values and software limitations (Clark et al. 2014). A filter was applied by the WPC to rectify instances of Stage IV rainfall exceeding FFG in the UFVS but spurious instances still exist, particularly in coastal Florida and North Carolina (M. Erickson 2021, personal communication).

REFERENCES

Adams, D. K., and A. C. Comrie, 1997: The North American monsoon. *Bull. Amer. Meteor. Soc.*, **78**, 2197–2214, https://doi.org/10.1175/1520-0477(1997)078<2197:TNAM>2.0.CO;2.

Ahmadalipour, A., and H. Moradkhani, 2019: A data-driven analysis of flash flood hazard, fatalities, and damages over the CONUS during 1996–2017. *J. Hydrol.*, **578**, 124106, https://doi.org/10.1016/j.jhydrol.2019.124106.

Ashley, S. T., and W. S. Ashley, 2008: Flood fatalities in the United States. *J. Appl. Meteor. Climatol.*, **47**, 805–818, https://doi.org/10.1175/2007JAMC1611.1.

Barthold, F. E., T. E. Workoff, B. A. Cosgrove, J. J. Gourley, D. R. Novak, and K. M. Mahoney, 2015: Improving flash flood forecasts: The HMT-WPC flash flood and intense rainfall experiment. *Bull. Amer. Meteor. Soc.*, **96**, 1859–1866, https://doi.org/10.1175/BAMS-D-14-00201.1.

Brost, J. J., D. C. Young, and S. F. Piltz, 2020: On a collaborative forecast process in the United States National Weather Service. *Eighth Symp. on Building a Weather-Ready Nation: Enhancing Our Nation's Readiness, Responsiveness, and Resilience to High Impact Weather Events*, Boston, MA, Amer. Meteor. Soc., 2.6, https://ams.confex.com/ams/2020Annual/webprogram/Paper367442.html.

Carbin, G., and A. Lamers, 2019: Applying WPC excessive rainfall outlooks in decision support. FEMA Informational Webinar, accessed 20 August 2019, https://wxvu.net/wpc/ERO/FEMA-Informational-Webinar-2019-08-15.mp4.

Carlaw, L. B., A. E. Cohen, and J. W. Rogers, 2017: Synoptic and mesoscale environment of convection during the North American monsoon across central and southern Arizona. *Wea. Forecasting*, **32**, 361–375, https://doi.org/10.1175/WAF-D-15-0098.1.

Chen, A. S., M. J. Hammond, S. Djordjević, D. Butler, D. M. Khan, and W. Veerbeek, 2016: From hazard to impact: Flood damage assessment tools for mega cities. *Nat. Hazards*, **82**, 857–890, https://doi.org/10.1007/s11069-016-2223-2.

Clark, R. A., J. J. Gourley, Z. L. Flamig, Y. Hong, and E. Clark, 2014: CONUS-wide evaluation of National Weather Service flash flood guidance products. *Wea. Forecasting*, **29**, 377–392, https://doi.org/10.1175/WAF-D-12-00124.1.

Cooley, D. S., 1978: The excessive rainfall potential outlook. NOAA/NWS Tech. Procedures Bull. 239, 7 pp.

Corringham, T. W., F. M. Ralph, A. Gershunov, D. R. Cayan, and C. A. Talbot, 2019: Atmospheric rivers drive flood damages in the western United States. *Sci. Adv.*, **5**, eaax4631, https://doi.org/10.1126/sciadv.aax4631.

Curran, E. B., R. L. Holle, and R. E. López, 2000: Lightning casualties and damages in the United States from 1959 to 1994. *J. Climate*, **13**, 3448–3464, https://doi.org/10.1175/1520-0442(2000)013<3448:LCADIT>2.0.CO;2.

Destro, E., W. Amponsah, E. I. Nikolopoulos, L. Marchi, F. Marra, D. Zoccatelli, and M. Borga, 2018: Coupled prediction of flash flood response and debris flow occurrence: Application on an alpine extreme flood event. *J. Hydrol.*, **558**, 225–237, https://doi.org/10.1016/j.jhydrol.2018.01.021.

Dettinger, M. D., F. M. Ralph, T. Das, P. J. Neiman, and D. R. Cayan, 2011: Atmospheric rivers, floods and the water resources of California. *Water*, **3**, 445–478, https://doi.org/10.3390/w3020445.

Dougherty, E., and K. L. Rasmussen, 2020: Changes in future flash flood–producing storms in the United States. *J. Hydrometeor.*, **21**, 2221–2236, https://doi.org/10.1175/JHM-D-20-0014.1.

Downton, M. W., and R. A. Pielke, 2005: How accurate are disaster loss data? The case of U.S. flood damage. *Nat. Hazards*, **35**, 211–228, https://doi.org/10.1007/s11069-004-4808-4.

——, J. Z. B. Miller, and R. A. Pielke Jr., 2005: Reanalysis of U.S. National Weather Service flood loss database. *Nat. Hazards Rev.*, **6**, 13–22, https://doi.org/10.1061/(ASCE)1527-6988(2005)6:1(13).

Erickson, M. J., and J. A. Nelson, 2018: Verifying, calibrating, and redefining the excessive rainfall outlook at the Weather Prediction Center. *Eighth Conf. on Transition of Research to Operations*, Austin, TX, Amer. Meteor. Soc., 7.5, https://ams.confex.com/ams/98Annual/webprogram/Paper327404.html.

——, J. S. Kastman, B. Albright, S. Perfater, J. A. Nelson, R. S. Schumacher, and G. R. Herman, 2019: Verification results from the 2017 HMT–WPC flash flood and intense rainfall experiment. *J. Appl. Meteor. Climatol.*, **58**, 2591–2604, https://doi.org/10.1175/JAMC-D-19-0097.1.

——, B. Albright, and J. A. Nelson, 2021: Verifying and redefining the Weather Prediction Center's excessive rainfall outlook forecast product. *Wea. Forecasting*, **36**, 325–340, https://doi.org/10.1175/WAF-D-20-0020.1.

Fritsch, J. M., and R. E. Carbone, 2004: Improving quantitative precipitation forecasts in the warm season: A USWRP research and development strategy. *Bull. Amer. Meteor. Soc.*, **85**, 955–966, https://doi.org/10.1175/BAMS-85-7-955.

Grantz, K., B. Rajagopalan, M. Clark, and E. Zagona, 2007: Seasonal shifts in the North American monsoon. *J. Climate*, **20**, 1923–1935, https://doi.org/10.1175/JCLI4091.1.

Herman, G. R., and R. S. Schumacher, 2018: Flash flood verification: Pondering precipitation proxies. *J. Hydrometeor.*, **19**, 1753–1776, https://doi.org/10.1175/JHM-D-18-0092.1.

Hughes, M., K. M. Mahoney, P. J. Neiman, B. J. Moore, M. Alexander, and F. M. Ralph, 2014: The landfall and inland penetration of a flood-producing atmospheric river in Arizona. Part II: Sensitivity of modeled precipitation to terrain height and atmospheric river orientation. *J. Hydrometeor.*, **15**, 1954–1974, https://doi.org/10.1175/JHM-D-13-0176.1.

Khajehei, S., A. Ahmadalipour, W. Shao, and H. Moradkhani, 2020: A place-based assessment of flash flood hazard and vulnerability in the contiguous United States. *Sci. Rep.*, **10**, 448, https://doi.org/10.1038/s41598-019-57349-z.

Kunkel, K. E., D. R. Easterling, D. A. R. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2012: Meteorological causes of the secular variations in observed extreme precipitation events for the conterminous United States. *J. Hydrometeor.*, **13**, 1131–1141, https://doi.org/10.1175/JHM-D-11-0108.1.

Maddox, R. A., D. M. McCollum, and K. W. Howard, 1995: Large-scale patterns associated with severe summertime thunderstorms over central Arizona. *Wea. Forecasting*, **10**, 763–778, https://doi.org/10.1175/1520-0434(1995)010<0763:LSPAWS>2.0.CO;2.

McCabe, G. J., M. P. Clark, and L. E. Hay, 2007: Rain-on-snow events in the western United States. *Bull. Amer. Meteor. Soc.*, **88**, 319–328, https://doi.org/10.1175/BAMS-88-3-319.

Mullen, S. L., and R. Buizza, 2001: Quantitative precipitation forecasts over the United States by the ECMWF ensemble prediction system. *Mon. Wea. Rev.*, **129**, 638–663, https://doi.org/10.1175/1520-0493(2001)129<0638:QPFOTU>2.0.CO;2.

National Research Council, 2005: *Flash Flood Forecasting over Complex Terrain: With an Assessment of the Sulphur Mountain NEXRAD in Southern California*. The National Academies Press, 206 pp., https://doi.org/10.17226/11128.

Neiman, P. J., F. M. Ralph, G. A. Wick, J. D. Lundquist, and M. D. Dettinger, 2008: Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the West Coast of North America based on eight years of SSM/I satellite observations. *J. Hydrometeor.*, **9**, 22–47, https://doi.org/10.1175/2007JHM855.1.

NWS, 2021: Storm data preparation: Performance and evaluation. NWSPD 10-16, NOAA/NWS, 110 pp.

Olson, D. A., N. W. Junker, and B. Korty, 1995: Evaluation of 33 years of quantitative precipitation forecasting at the NMC. *Wea. Forecasting*, **10**, 498–511, https://doi.org/10.1175/1520-0434(1995)010<0498:EOYOQP>2.0.CO;2.

Payne, A. E., and Coauthors, 2020: Responses and impacts of atmospheric rivers to climate change. *Nat. Rev. Earth Environ.*, **1**, 143–157, https://doi.org/10.1038/s43017-020-0030-5.

Ralph, F. M., E. Sukovich, D. Reynolds, M. Dettinger, S. Weagle, W. Clark, and P. J. Neiman, 2010: Assessment of extreme quantitative precipitation forecasts and development of regional extreme event thresholds using data from HMT-2006 and COOP observers. *J. Hydrometeor.*, **11**, 1286–1304, https://doi.org/10.1175/2010JHM1232.1.

Rogers, J. W., A. E. Cohen, and L. B. Carlaw, 2017: Convection during the North American monsoon across central and southern Arizona: Applications to operational meteorology. *Wea. Forecasting*, **32**, 377–390, https://doi.org/10.1175/WAF-D-15-0097.1.

Rosewicz, B., J. Biernacka-Lievestro, and D. Newman, 2019: Western, southern states gain residents the fastest. Pew Charitable Trusts, accessed 27 April 2021, https://www.pewtrusts.org/en/research-and-analysis/articles/2019/02/27/western-southern-states-gain-residents-the-fastest.

Rutz, J. J., W. J. Steenburgh, and F. M. Ralph, 2014: Climatological characteristics of atmospheric rivers and their inland penetration over the western United States. *Mon. Wea. Rev.*, **142**, 905–921, https://doi.org/10.1175/MWR-D-13-00168.1.

Saharia, M., P.-E. Kirstetter, H. Vergara, J. J. Gourley, and Y. Hong, 2017a: Characterization of floods in the United States. *J. Hydrol.*, **548**, 524–535, https://doi.org/10.1016/j.jhydrol.2017.03.010.

——, ——, ——, ——, ——, and M. Giroud, 2017b: Mapping flash flood severity in the United States. *J. Hydrometeor.*, **18**, 397–411, https://doi.org/10.1175/JHM-D-16-0082.1.

Schroeder, A. J., and Coauthors, 2016: The development of a flash flood severity index. *J. Hydrol.*, **541**, 523–532, https://doi.org/10.1016/j.jhydrol.2016.04.005.

Schumacher, R. S., and R. H. Johnson, 2006: Characteristics of U.S. extreme rain events during 1999–2003. *Wea. Forecasting*, **21**, 69–85, https://doi.org/10.1175/WAF900.1.

——, and C. A. Davis, 2010: Ensemble-based forecast uncertainty analysis of diverse heavy rainfall events. *Wea. Forecasting*, **25**, 1103–1122, https://doi.org/10.1175/2010WAF2222378.1.

Sharma, S., and Coauthors, 2017: Eastern U.S. verification of ensemble precipitation forecasts. *Wea. Forecasting*, **32**, 117–139, https://doi.org/10.1175/WAF-D-16-0094.1.

Sisson, P. A., and J. R. Gyakum, 2004: Synoptic-scale precursors to significant cold-season precipitation events in Burlington, Vermont. *Wea. Forecasting*, **19**, 841–854, https://doi.org/10.1175/1520-0434(2004)019<0841:SPTSCP>2.0.CO;2.

Smith, B. K., and J. A. Smith, 2015: The flashiest watersheds in the contiguous United States. *J. Hydrometeor.*, **16**, 2365–2381, https://doi.org/10.1175/JHM-D-14-0217.1.

Špitalar, M., J. J. Gourley, C. Lutoff, P.-E. Kirstetter, M. Brilly, and N. Carr, 2014: Analysis of flash flood parameters and human impacts in the US from 2006 to 2012. *J. Hydrol.*, **519**, 863–870, https://doi.org/10.1016/j.jhydrol.2014.07.004.

Sukovich, E. M., F. M. Ralph, F. E. Barthold, D. W. Reynolds, and D. R. Novak, 2014: Extreme quantitative precipitation forecast performance at the Weather Prediction Center from 2001 to 2011. *Wea. Forecasting*, **29**, 894–911, https://doi.org/10.1175/WAF-D-13-00061.1.

Tao, J., and A. P. Barros, 2013: Prospects for flash flood forecasting in mountainous regions—An investigation of Tropical Storm Fay in the Southern Appalachians. *J. Hydrol.*, **506**, 69–89, https://doi.org/10.1016/j.jhydrol.2013.02.052.

Terti, G., I. Ruin, S. Anquetin, and J. J. Gourley, 2017: A situation-based analysis of flash flood fatalities in the United States. *Bull. Amer. Meteor. Soc.*, **98**, 333–345, https://doi.org/10.1175/BAMS-D-15-00276.1.

Versini, P.-A., M. Velasco, A. Cabello, and D. Sempere-Torres, 2013: Hydrological impact of forest fires and climate change in a Mediterranean basin. *Nat. Hazards*, **66**, 609–628, https://doi.org/10.1007/s11069-012-0503-z.

Westerling, A. L., 2016: Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. *Philos. Trans. Roy. Soc.*, **B371**, 20150178, https://doi.org/10.1098/rstb.2015.0178.

Wimsatt, M. A., 2017: Cross-jurisdictional sharing for emergency management-related public health: Exploring the experiences of tribes and counties in California. *Front. Public Health*, **5**, 254, https://doi.org/10.3389/fpubh.2017.00254.

WPC, 2016: WPC's what's new page. NOAA/WPC, accessed 4 March 2021, https://www.wpc.ncep.noaa.gov/html/whats_new.shtml.

——, 2020: Product information. NOAA/WPC, accessed 27 April 2021, https://www.wpc.ncep.noaa.gov/html/fam2.shtml.

Yang, L., J. Smith, M. L. Baeck, E. Morin, and D. C. Goodrich, 2017: Flash flooding in arid/semiarid regions: Dissecting the hydrometeorology and hydrology of the 19 August 2014 storm and flood hydroclimatology in Arizona. *J. Hydrometeor.*, **18**, 3103–3123, https://doi.org/10.1175/JHM-D-17-0089.1.

Young, A. M., K. T. Skelly, and J. M. Cordeira, 2017: High-impact hydrologic events and atmospheric rivers in California: An investigation using the NCEI storm events database. *Geophys. Res. Lett.*, **44**, 3393–3401, https://doi.org/10.1002/2017GL073077.

Zevin, S. F., 1994: Steps toward an integrated approach to hydrometeorological forecasting services. *Bull. Amer. Meteor. Soc.*, **75**, 1267–1276, https://doi.org/10.1175/1520-0477-75.7.1267.