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COMMENTARY
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Key Points:
- Extreme precipitation is increasing with rising temperatures
- Flood magnitudes, however, are decreasing at the same time
- However, this is not a complete story; very rare floods are rising while frequent floods are reducing; reasons for this are explored

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If Precipitation Extremes Are Increasing, Why Aren't Floods?

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Abstract Despite evidence of increasing precipitation extremes, corresponding evidence for increases in flooding remains elusive. If anything, flood magnitudes are decreasing despite widespread claims by the climate community that if precipitation extremes increase, floods must also. In this commentary we suggest reasons why increases in extreme rainfall are not resulting in corresponding increases in flooding. Among the possible mechanisms responsible, we identify decreases in antecedent soil moisture, decreasing storm extent, and decreases in snowmelt. We argue that understanding the link between changes in precipitation and changes in flooding is a grand challenge for the hydrologic community and is deserving of increased attention.

Plain Language Summary It is now well established that rising temperatures are increasing precipitation extremes. This has led many to believe that flood magnitude and hence risk are also increasing, while observational evidence suggests otherwise. This commentary outlines the reasons for this dichotomy and presents mechanisms that may be contributing to it. The implications of increasing precipitation extremes leading to reducing flood magnitudes are discussed, and an argument is made that understanding this changing link between the two is deserving of increased attention.

1. A Dichotomous Relationship

Since the proclamation that "stationarity is dead" (Milly et al., 2008), considerable effort has been dedicated to understanding and planning for changes in hydrological extremes. While significant advances have been made (O'Gorman, 2015), observed increases in precipitation extremes (Alexander et al., 2006; Donat et al., 2013; Groisman et al., 2005; Wentz et al., 2007; Westra et al., 2013) do not appear to have translated to observed increases in flooding. Despite attribution of climate change to flooding, for example, by Pall et al. (2011), a long list of studies shows little or no evidence of increased flood magnitudes, with some studies finding more evidence of decreases than increases (e.g., Archfield et al., 2016; Blöschl et al., 2017; Do et al., 2017; Groisman et al., 2001; Hall et al., 2014; Hodgkins et al., 2017; Lins & Slack, 1999; McCabe & Wolock, 2002; Zhang et al., 2016).

Why, on average, rainfall extremes are increasing (and are expected to continue increasing) can be summarized by a simple conceptualization. If temperature increases, in accordance with the Clausius-Clapeyron relationship, so does the saturation vapor pressure of the atmosphere, at a rate of approximately 7% per degree centigrade (Trenberth, 2011; Trenberth et al., 2003). The result is that the atmosphere is able to *hold* more moisture, and, if there is more moisture in the atmosphere, then in an extreme event, more precipitation results. This mechanism is represented in weather and climate models (Bao et al., 2017; Collins et al., 2013; Kharin et al., 2013; Prein, Rasmussen, et al., 2017) and is supported by observational evidence that shows average increases in observed precipitation extremes consistent with the Clausius-Clayepron relationship (Asadieh & Krakauer, 2015; Barbero et al., 2017; Seth Westra et al., 2013). Notwithstanding, qualifiers exist, such as possible greater precipitation increases due to storm invigoration (Lenderink & van Meijgaard, 2008; Trenberth, 2011; Wasko et al., 2016); longer storm durations among other factors (Prein, Liu, et al., 2017), where moisture may be external to the atmospheric column (Trenberth, 1998); and changes in extremes due to changed atmospheric circulations at both regional (Steinschneider & Lall, 2015) and global scales (Mitas & Clement, 2005; Seidel et al., 2008).

Although simplified, increases in precipitation have been used extensively (Bates et al., 2008; Kundzewicz et al., 2014; Seneviratne et al., 2012; Westra et al., 2014) as the basis for explaining why flooding may increase as temperatures rise with climatic change. However, as extreme precipitation does not always lead to

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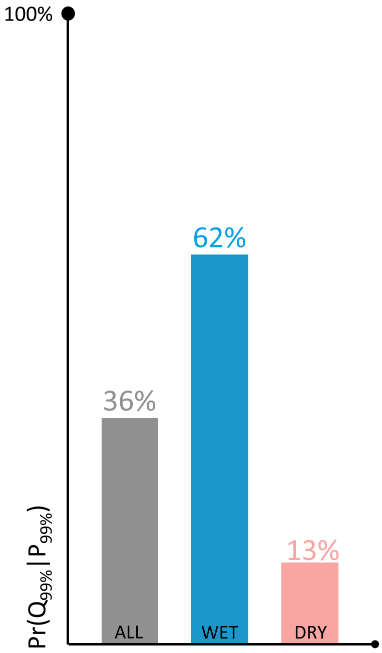

Figure 1. The probability of an upper 99th percentile discharge event ($Q_{99\%}$) being associated with an upper 99th percentile precipitation event ($P_{99\%}$) across the contiguous United States. Wet (antecedence) is defined as a soil moisture wetness above the median, and dry (antecedence) is defined as below the median. Reproduced from Ivancic and Shaw (2015).

flooding, this argument clearly must be flawed at some level. Across all regions in the contiguous United States (Figure 1) the probability of observing extreme discharge given extreme precipitation is much less than unity. Aggregated across all sites only 36% of extreme precipitation events (in a probabilistic sense) lead to a corresponding extreme discharge (Ivancic & Shaw, 2015). When the precipitation is conditioned on the catchment being wet before the start of the event, this number increases to 62% (blue bar), as contrasted with only 13% when the moisture conditions before the storm are dry (pink bars). Clearly, as should be no surprise to hydrologists, soil moisture modulates the flood response. Increases in precipitation do not have to translate to increases in flooding, and drying soil moisture conditions will reduce flood magnitudes.

2. Mechanisms

The primary problem in the conceptualization that precipitation increases lead to increased flooding is that it assumes that catchment specific conditions are invariant and streamflow is generated from precipitation alone. In fact, floods are influenced by the location, pattern, duration and rarity of precipitation, as well as the wetness state of the catchment prior to the event, with the streamflow response dependent on the hydraulic characteristics of the catchment, among other factors (Andrés-Doménech et al., 2015; Johnson et al., 2016). Additionally, there exist multiple flood types, with many of these (such as coastal floods) attributable to factors independent of precipitation change (Zheng et al., 2013).

There is evidence that increasing temperatures result in increased periods of drought (Dai, 2012) and drier soils (Jung et al., 2010; Sheffield & Wood, 2008), reducing soil moisture at the onset of extreme precipitation events. This would tend to decrease the flood magnitude (or lead to nonflood streamflow even given extreme precipitation). Decreasing flooding in larger catchments may also be coupled with a shift to more frequent, higher intensity but shorter convective storms (Lenderink & van Meijgaard, 2008; Molnar et al., 2015; Wasko & Sharma, 2015), which may have smaller spatial extents (Peleg et al., 2018; Wasko et al., 2016). Any shift in atmospheric circulation will result in changes in the dominant storm mechanism or frequency of events, changing persistence characteristics, which will correspondingly change precipitation extremes and antecedent conditions causing changes in flood magnitude as well (Hirsch & Archfield, 2015; Lu et al., 2013; Mallakpour & Villarini, 2015; Wasko, Pui, et al., 2015), a point which imparts large uncertainty in climate model simulations (Shepherd, 2014). Any of the above listed changes will affect flooding irrespective of the temporal or spatial scale considered (Pathiraja et al., 2012; Saft et al., 2016; Stephens et al., 2018).

Furthermore, warmer temperatures are causing earlier snowmelt (Blöschl et al., 2017; Trenberth, 2011), which, coupled with decreased snowpack (Hamlet & Lettenmaier, 2007), appear to be associated with decreases in flood magnitude (Vormoor et al., 2016). There is also evidence of rain on snow events changing in their behavior, resulting in changed flood characteristics depending on elevation (Musselman et al., 2018). Warmer temperatures have contributed to shifts in flood timing; for example, earlier seasonal peaks of soil moisture are correlated to earlier seasonal flooding (Blöschl et al., 2017).

Changes in catchment characteristics can also reduce the streamflow response to a given precipitation event. Increases in temperature can increase canopy storage capacity (Klamerus-Iwan & Błońska, 2018). Changes in land cover (Liu et al., 2015) may lead to increased evapotranspiration (Huntington, 2006) in nonmoisture limited environments (Huntington, 2006; Johnson & Sharma, 2010) and change the surface properties of the catchment changing the conveyance of rainfall through the catchment. Urbanization not only changes precipitation characteristics (J. M. Shepherd et al., 2002) but also changes catchment imperviousness and roughness and hence the response to rainfall, which may lead to changes in flooding in a future climate. For instance, in a study of changing flood response of over 14,000 U.S. catchments (Vogel et al., 2011), while

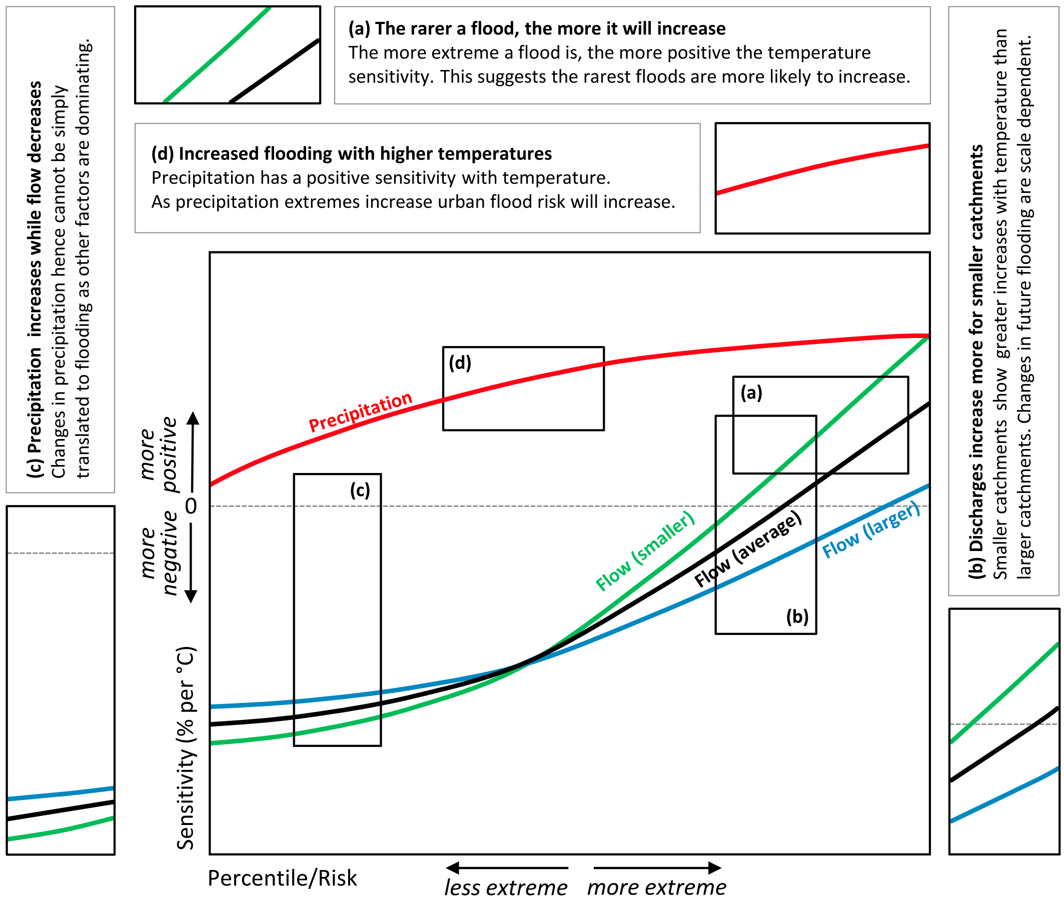

Figure 2. Conceptualized sensitivity of precipitation and streamflow to changes in temperature for undeveloped catchments. Streamflow sensitivity for smaller catchments is in green, for larger catchments in blue, and the average is in black. The sensitivity of precipitation is shown in red. Insets (a–d) represent four broad observations detailed in sections 3.1–3.3 below. This figure is adapted from Wasko and Sharma (2017b), which analyzed streamflow from the Global Runoff Data Centre (GRDC, 2015) to arrive at the general patterns indicated above.

the overall fraction of statistically significant sites showing flood magnification was modest (about 10%), among those catchments showing changes there was a clear predominance of urban catchments.

3. Expected Changes

What then are the possible changes that we can expect to flood magnitudes in the future? The pattern of precipitation and streamflow sensitivities with temperature observed across many major regions throughout the world is shown in Figure 2 (from Wasko & Sharma, 2017b). These sensitivities can be expressed as $\frac{\partial E}{\partial T}$, where a variable E denotes extremes such as flood or storm peaks that exhibit significant variations in time (t) and T represents temperature. A positive or negative sensitivity is equivalent to a corresponding positive or negative trend in the variable, as

$$\frac{\partial E}{\partial t} = \frac{\partial E}{\partial T} \times \frac{\partial T}{\partial t}, \tag{1}$$

and the temperature trend, $\frac{\partial T}{\partial t}$, is positive and expected to remain so for the rest of the century (Raftery et al., 2017). Despite the possible use of different surrogate variables, temperature remains a strong candidate to express this change (Agilan & Umamahesh, 2017; Lenderink & Attema, 2015; Wasko & Sharma, 2017a; Westra et al., 2012), given its direct linkage with the global energy balance.

3.1. Dependence of Extreme Floods on Storm Magnitude

As the rarity of a flood event increases, the positive relationship between streamflow and temperature increases (Figure 2a), although the (fractional) increase in streamflow remains less than the (fractional) increase in precipitation. During a flood event, some precipitation contributes to increasing the soil moisture storage or undergoes evapotranspiration, with the remaining precipitation contributing to the observed streamflow. While this relationship depends on the precipitation duration and catchment size, in general, the more extreme an event is, the greater is the precipitation intensity and the more likely the catchment is to become saturated, with a greater proportion of the (subsequent) precipitation contributing to streamflow. Hence, flood response in a future (warmer) climate will be dependent on how rare the event is, and the rate at which precipitation increases (Westra et al., 2013). Increase in precipitation intensity are hypothesized to be greatest at smaller durations (Hardwick Jones et al., 2010; Panthou et al., 2014; Wasko, Sharma, et al., 2015), but increases in precipitation are observed at durations of up to 5 days (Donat et al., 2013). The rarest floods are expected to increase (Knox, 2000; Milly et al., 2002), while less extreme events, particularly in larger catchments (Figure 2c), are more likely to decrease on the whole (Do et al., 2017), to the extent that the largest flood magnitudes lead to spills in many storage reservoirs, thereby assuming lower significance from a water supply perspective, while decreases in the more frequent flow events imply greater water insecurity with potentially reduced supply to farmers or communities experiencing greater demand due to higher temperatures (Milly et al., 2018).

3.2. Catchment Scale Sensitivity of Flood Response

The sensitivity of discharge to temperature is greater for smaller catchments (Figure 2b). With a smaller spatial extent, there is an increased likelihood that a storm will cover the entire catchment and hence lead to soil moisture saturation, with more of the precipitation contributing to the streamflow response. Do et al. (2017) show that observed increases in flood magnitude are more likely for smaller catchments, with larger catchments being more prone to decreasing flood peaks. This suggests that changes in future flooding will be scale dependent. The influence of changes in soil moisture storage and evaporative losses are more important in larger catchments (Ivancic & Shaw, 2015). Changes in the size of storm events, which have been shown to be decreasing in general (Chang et al., 2016; Wang & Kotamarthi, 2015; Wasko et al., 2016), will also change flood response with a smaller portion of the catchment experiencing rainfall. This will interact with changes in storm type or the mix of alternate storm types (Feng et al., 2016; Li et al., 2018; Prein, Liu, et al., 2017). Changes in vegetation, land cover, and permeability with greater greenhouse gas concentrations will additionally impact catchment response and are spatial scale dependent.

3.3. Increased Urban Flood Risk

Precipitation intensities are positively correlated with temperature (Figure 2d). Urban catchment flooding is primarily precipitation driven, with low storage and hence ability to attenuate flood peaks. It can be expected that the flood peaks resulting from frequent to extreme storms will increase as temperatures rise. With developed areas more likely to have positive flood trends (Vogel et al., 2011), further urbanization will result in increased flood magnitudes (Shuster et al., 2005; Villarini et al., 2009), and the sensitivity of urban flood increases to temperature is likely to be higher (closer to precipitation sensitivities) than for nonurban catchments. Storm intensification will further compound this increase as more rain falls in a shorter period of time, at least for small urban catchments (Fadhel et al., 2018; Hettiarachchi et al., 2018; Wasko & Sharma, 2015).

4. What Is Missing?

There is a clear dichotomy between observed increases in precipitation extremes and the lack of corresponding increases in floods, with reduced flood magnitudes observed in many cases. Despite the conceptual arguments we've made, there remains a good deal of uncertainty in the relationships between changes in precipitation and flood magnitude across the spectrum of catchment, storm, and antecedent hydrologic conditions. Although changes in flood magnitude are unlikely to be explainable by precipitation changes alone, this has largely been the focus to date in the climate literature. Moving forward, along with a better characterization of changes in floods not directly driven by precipitation increases, we argue for a focus on the complexity of the relationships among the entire suite of variables (including precipitation extremes) that lead to the generation of flood extremes. In our view, the foremost among these are as follows:

1. Changes to antecedent hydrologic conditions and their impact on flood response;
2. Changes in the proportion and persistence of storms arising from different causative mechanisms, such as an increased proportion and frequency of convective extremes;
3. Interaction among catchment size and geometry and changing storm characteristics including extent, intensity, and duration;
4. Snow cover and snow volume changes and their changing contributions to flood extremes in a warmer climate;
5. The role of land cover change (especially, but not only, urbanization) and the interaction of land cover change with climatic factors.

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