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# Climate Extremes and Compound Hazards in a Warming World

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## Keywords

compound events, cascading hazards, climate extremes, climate change, risk, hydrology

## Abstract

Climate extremes threaten human health, economic stability, and the well-being of natural and built environments (e.g., 2003 European heat wave). As the world continues to warm, climate hazards are expected to increase in frequency and intensity. The impacts of extreme events will also be more severe due to the increased exposure (growing population and development) and vulnerability (aging infrastructure) of human settlements. Climate models attribute part of the projected increases in the intensity and frequency of natural disasters to anthropogenic emissions and changes in land use and land cover. Here, we review the impacts, historical and projected changes, and theoretical research gaps of key extreme events (heat waves, droughts, wildfires, precipitation, and flooding). We also highlight the need to improve our understanding of the dependence between individual and interrelated climate extremes because anthropogenic-induced warming increases the risk of not only individual climate extremes but also compound (co-occurring) and cascading hazards.

- Climate hazards are expected to increase in frequency and intensity in a warming world.
- Anthropogenic-induced warming increases the risk of compound and cascading hazards.
- We need to improve our understanding of causes and drivers of compound and cascading hazards.

## INTRODUCTION

Over the course of human history, climate extremes have threatened human health, economic growth, and the longevity of natural and built environments around the globe. From 1980 to 2017, extremes resulted in more than USD 1.537 billion losses and 9,985 deaths in the United States alone (NCDC 2018). In 2017, natural disasters resulted in USD 306 billion in losses, setting the record as the costliest disaster year in the United States. Many regions around the world have also experienced a rising number of costly disastrous events (Fischer & Knutti 2015, Idier et al. 2017, IPCC 2012, Seneviratne et al. 2016, Wallemacq & House 2018). The observed increase in the impacts of extreme events directly reflects increases in exposure to natural hazards (i.e., due to population growth and development), vulnerability of existing infrastructure systems (IPCC 2012, Neumann et al. 2015, Willis et al. 2016), and climate change and variability (IPCC 2012).

Climate models project increases in the intensity and frequency of extreme climatic events, attributed in part to changes in anthropogenic emissions, land use, and land cover (Christidis et al. 2011, Das et al. 2011, Neumann et al. 2015, Reidmiller et al. 2018). Higher temperatures can increase the frequency of heat waves and alter the global water cycle by increasing the number of heavy precipitation events and even intense hurricanes (Fischer & Knutti 2015, 2016; IPCC 2013; Patricola & Wehner 2018; Scoccimarro et al. 2013; Trenberth 2008, 2011). In turn, heavier precipitation events exacerbate the risk of flooding, debris flows, and rainfall-triggered landslides (Gariano & Guzzetti 2016). Increased flood risk in coastal regions is further amplified by sea level rise (Buchanan et al. 2017, Jongman et al. 2012, Vitousek et al. 2017), threatening the integrity of coastal infrastructure systems and assets (Hallegatte et al. 2013, Neumann et al. 2015, Willis et al. 2016). Population and development projections show a continued trend of rapidly expanding urbanization, particularly in coastal zones, which increases both vulnerability and exposure to extremes (Hauer et al. 2016, Neumann et al. 2015).

Rising temperatures have also increased the occurrence, severity, and duration of heat waves and droughts, which in turn have increased the risk of wildfires. In recent decades, the frequency and severity of wildfires have increased substantially in many regions of the world (IPCC 2012, Westerling 2016), exacerbating the vulnerability of charred landscapes to flooding, landslides, and debris flows and increasing the exposure of humans and built environments to wildfires and other extremes such as debris flows (Radeloff et al. 2018).

Droughts, heat waves, wildfires, and floods often result from interactions between various physical processes that in isolation might not be considered extreme but when combined result in significant impacts. These types of events are referred to as compound events (Zscheischler et al. 2018)—for example, concurrent drought and heat wave conditions or the combination of storm

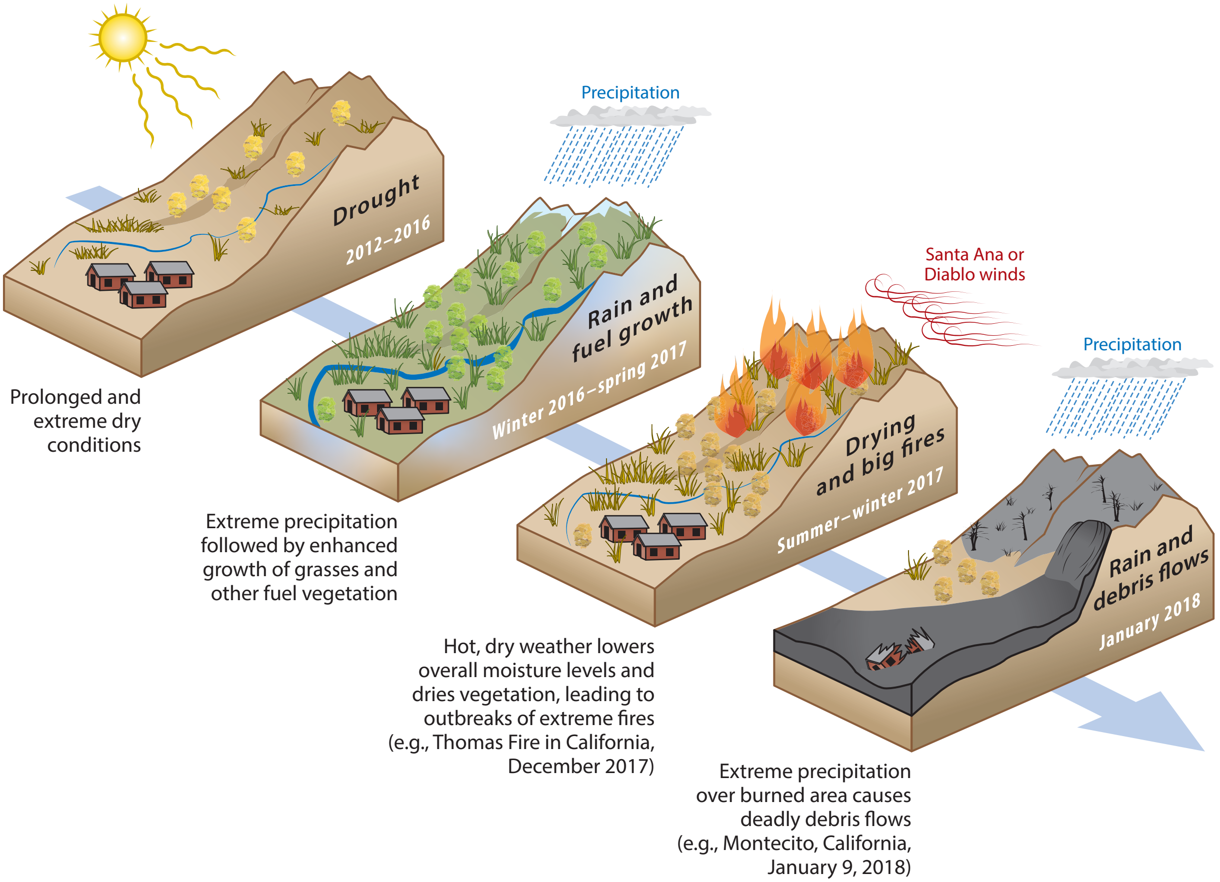

**Figure 1**

The following set of consecutive events resulted in significant human health and economic impacts in Southern California: a prolonged extreme drought from 2012 to 2016; extreme precipitation during the winter of 2017, enhancing growth of fuels such as shrubs and grasses; a very dry, warm spring and summer, reducing moisture levels and drying existing vegetation; record-setting Santa Ana winds (for sustained wind and low humidity); extreme fires occurring shortly thereafter (e.g., the Thomas Fire in December 2017); and extreme rainfall over the burned area in January 2018, leading to an extreme debris flow event in Montecito, CA.

surge and fluvial flooding in coastal areas caused by a hurricane. A cascading hazard is a specific type of compound event in which consecutive events lead to major societal impacts (AghaKouchak et al. 2018). For instance, the following set of consecutive events resulted in significant human health and economic impacts in California: (*a*) a prolonged extreme drought from 2012 to 2016; (*b*) extreme precipitation during the winter of 2017, enhancing growth of fuels such as shrubs and grasses; (*c*) a very dry, warm spring and summer, reducing moisture levels and drying existing vegetation; (*d*) record-setting Diablo (Northern California) and Santa Ana (Southern California) winds (for sustained wind and low humidity); (*e*) extreme fires occurring shortly thereafter (e.g., the Thomas Fire in December 2017); and (*f*) extreme rainfall over the burned area in January 2018 in Montecito, CA (**Figure 1**). These events cascaded to create the deadliest debris flow event in California's history that killed 23 people and damaged more than 400 homes.

Traditional risk assessment frameworks cannot adequately describe the risk associated with such compounding events, especially cascading events that involve independent hazards (e.g., extreme rain over burned areas one or two years after a major wildfire). Most existing design concepts or risk assessment methods consider one hazard at a time, which can lead to an underestimation of the actual risks (Moftakhari et al. 2019, Sadegh et al. 2018). A better understanding of compound and cascading hazards is critical, as many drivers of extreme events including heat waves, extreme precipitation, and wildfires are projected to intensify in the future (Perkins et al. 2015, Ragno et al. 2018, Reidmiller et al. 2018).

In this article, we review observed and projected changes in different climatic hazards (heat waves, droughts, wildfires, extreme precipitation, and flooding) and their interactions, including different types of compound and cascading hazards. We also identify major research gaps regarding compound and cascading events that require bridging a variety of disciplines, including climate science, engineering, social science, economics, ecology, and policy (Zscheischler et al. 2018). Through our review, we highlight key findings and identify important future research directions that will serve to improve our understanding of extreme events in a warming climate.

## HEAT WAVES

A heat wave is defined as a series of consecutive hot days and can have significant impacts on human health, agricultural yield, water resources, energy consumption, and the environment (Easterling 2000, Perkins et al. 2015, Santer et al. 2017, Tebaldi & Lobell 2018). The 2010 Russian heat wave and 2003 European heat waves killed more than 56,000 and 70,000 people, respectively (Beniston 2003, Rahmstorf & Coumou 2011). A recent study showed that in India, an increase of 2 heat wave days (6 days versus 8 days) raised the probability of mass heat-related mortality events by 78% between 1978 and 2006, highlighting that incremental changes in heat waves can have devastating impacts (Mazdiyasni et al. 2017).

High temperatures can desiccate the soil, heightening plant stress, irrigation rates, and water use (Dai et al. 1999, Flanagan & Johnson 2005). Heat waves also strain the electric grid by increasing electricity demand and reducing efficiency. Urbanization further intensifies heat waves since urban structures generate heat as they reradiate solar radiation, causing an increase in energy consumption and greenhouse gases (Rizwan et al. 2008). For instance, during the 2003 European heat wave, France cut power exports by more than half (De Bono et al. 2004) due to the unprecedented demand on its domestic energy infrastructure. As global temperatures rise and urban areas increase in size and density, scientists expect greater increases in water and energy use; however, there is still a gap in understanding the extent to which rising temperatures will affect consumption rates and increase peak energy load in the future. Across the United States, peak energy load is projected to increase by 7.2% [moderate emission scenario: Representative Concentration Pathway (RCP) 4.5] to 18% (high emission scenario: RCP 8.5) by the end of this century (Auffhammer et al. 2017). The RCPs represent various future possible emissions and land use/land cover scenarios (Moss et al. 2010). Also, increased urbanization will play a major role in local temperature extremes due to the urban heat island effect, and further research must be performed to understand projected interactions between society and local climate extremes.

Heat waves have increased in intensity, frequency, and duration globally (Meehl & Tebaldi 2004). The 2011 and 2012 heat waves in Texas and the midwestern United States shattered the monthly extreme temperature records set in the 1930s (Karl et al. 2012). California continues to break extreme temperature records, contributing to severe droughts and enhanced wildfire risks (AghaKouchak et al. 2014, 2018). High temperature records continue to be broken at higher rates compared to low temperature records (Meehl et al. 2009). In addition, minimum daily temperatures are rising at a faster rate than maximum temperatures (Alexander et al. 2006, Donat & Alexander 2012), which can reduce nighttime cooling (Perkins et al. 2012) and the human body's

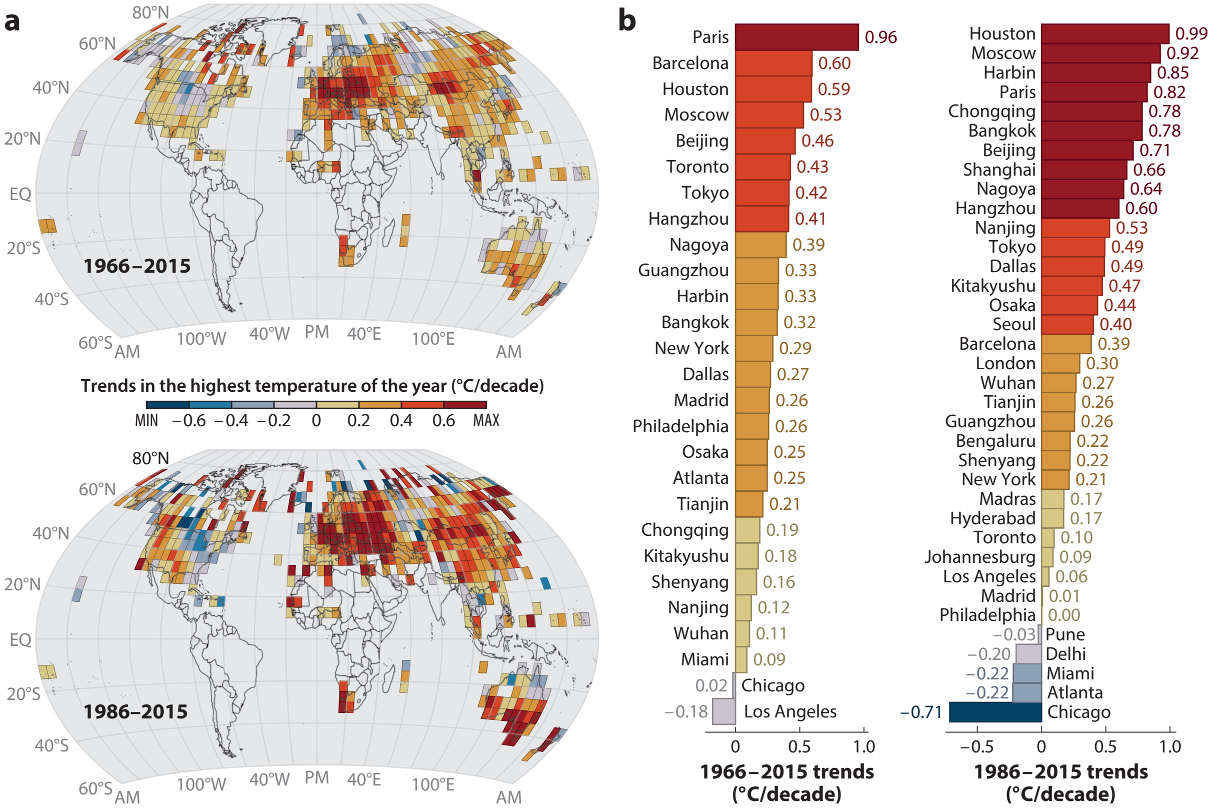

**Figure 2**

(*a*) Observed temperature trends (°C/decade) in the highest temperature of the year for 50- and 30-year periods ending in 2015 (baseline period: 1970–1989). (*b*) Observed temperature trends (°C/decade) in the highest temperature of the year in large (5–10 million) and mega (>10 million) cities for the same periods. Figure adapted from Papalexiou et al. (2018b).

ability to cool down during a heat wave, thereby translating into higher risks for heat-related illnesses and deaths. A recent global analysis by Papalexiou et al. (2018b) on the highest temperature of the year, based on 8,848 stations worldwide, revealed strong increasing trends in a large region of Eurasia (**Figure 2*a***). Yet the most alarming finding of this study regards increasing trends in high temperatures in megacities where most of the human fatalities occur (**Figure 2*b***). These trends were found to be highly unlikely under natural climate variability.

Heat waves are projected to continue to increase over the next century (Fischer & Knutti 2015, Meehl & Tebaldi 2004). Although international efforts aim to limit global warming by 2100 to 1.5 or 2°C, local temperature extremes are expected to vary by region (Seneviratne et al. 2016). For example, annual minimum temperatures in the Arctic are projected to increase by 5.5°C with respect to preindustrial climate, and maximum temperatures over much of the Northern Hemisphere, Central America, and South Africa are expected to rise by at least 3°C by the end of the century (Seneviratne et al. 2016). Climate models project increases of more than 30 heat wave days per degree Celsius of temperature rise across the tropics and ∼10–15 days per degree Celsius in the mid to high latitudes (e.g., North America, Europe, and Russia) (Perkins & Gibson 2017). Soil moisture-temperature feedbacks and the interannual variability of physical conditions are part of the underlying processes that result in more extreme heat waves as global temperatures rise (Perkins et al. 2015, Vogel et al. 2017). However, the impacts of global warming on the duration and intensity of local extreme heat events have high uncertainty and warrant further study.

Most heat wave studies use univariate heat indicators, neglecting the interdependence between multiple characteristics of heat waves (e.g., intensity and duration). However, since such characteristics are often interrelated, it is important to investigate them simultaneously. In addition, other factors, including humidity, air movement, and solar radiation, can exacerbate their impacts and cause heat stress (a measure of what hot weather feels like due to air temperature, humidity, and wind speeds), which has ramifications on the human body. This is an especially important public health consideration for vulnerable populations. Moreover, the cumulative impacts of extremely high temperatures and heat stress over several days on human health are poorly understood.

Detection and attribution studies have attributed the most extreme heat waves and the increasing likelihood of heat waves occurring in the past several decades to anthropogenic influences and warming (Easterling et al. 2016, Stott et al. 2004, Sun et al. 2017, Trenberth et al. 2015). In fact, anthropogenic emissions have increased the likelihood of the strongest events by 10 times in some locations (Sun et al. 2017). However, few attribution studies exist, necessitating further research to quantify the impacts of human activities on extreme heat events, as well as the impact of anthropogenic warming on multifeature changes in heat waves (e.g., duration and intensity).

Rising extreme temperatures due to a warming climate often have a cascading effect, exacerbating other extreme events, such as droughts or wildfires. Heat waves and droughts, for example, have a positive feedback loop, where heat waves intensify drought conditions and extreme droughts increase the likelihood of more intense heat waves. The related compound and cascading hazards are discussed in the section titled Compound and Cascading Hazards.

## DROUGHTS

It has been difficult to ascribe a standard definition to the phenomenon of drought, with different drought indices serving to represent different aspects of water availability (Dracup et al. 1980, Gumbel 1963, IPCC 2012, Palmer 1965, Van Loon et al. 2016). As the effects of anthropogenic climate change grow more apparent, research efforts in recent decades have shifted toward characterizing and understanding droughts in a warming world (IPCC 2012, 2013). Such studies have already documented changes in regional precipitation rates and snow cover (e.g., timing, duration, extent) and predict a redistribution of global precipitation, which may have serious implications for transitional regions sensitive to changes in soil moisture (IPCC 2013, Seneviratne et al. 2006, Trenberth 2011). Due to changes in global climate patterns, there is evidence that these transitional zones will be shifting, resulting in changes in the influence of land surface moisture on local drought events (Seneviratne et al. 2006). As new transitional zones emerge, regional studies will be crucial for understanding how localized feedbacks and processes will respond to changes in surface moisture.

Due to differences in observational data sets and methods accounting for natural climate patterns such as the El Niño–Southern Oscillation, studies have not reached a consensus regarding how drought events have changed. For instance, Dai (2013) concluded that droughts have experienced an 8% increase in global land area between the 1980s and the 2000s, while Sheffield et al. (2012) could not find an observable global drought trend in recent history. This uncertainty highlights the need for more consistency among drought indices and observational data for independent studies to arrive at similar conclusions (Dai 2013, IPCC 2012, Sheffield et al. 2012, Trenberth et al. 2014). In addition, new drought characterizations must still be developed to account for different aspects of dry conditions [e.g., snow droughts or snow water equivalent (SWE) deficits]. Snow droughts have become increasingly relevant given the observed and projected

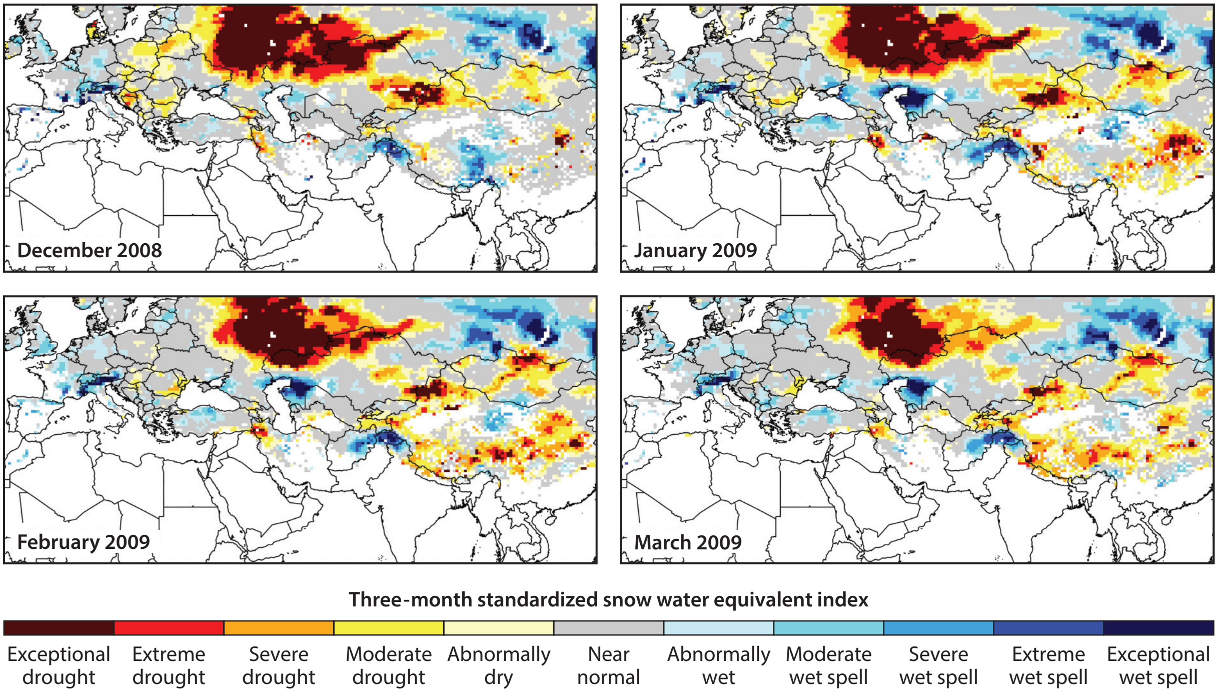

**Figure 3**

Three-month standardized snow water equivalent index dry/wet classification showing the winter 2008/2009 snow drought in western Russia.

declining snowpack in regions such as the western United States (e.g., Mote et al. 2018). For instance, Huning & AghaKouchak (2018) found that, historically, 1 to 2°C of winter warming increased the likelihood of having below-average April 1 SWE volumes from 20 to 40%, respectively, from 1985 to 2016 across the Sierra Nevada in the United States. In particular, regions that are sensitive to temperature changes and prone to snow drought conditions should be monitored for drought conditions. Therefore, global frameworks and indicators for monitoring and characterizing snow droughts must still be developed to prepare for a warmer future climate (Huning & AghaKouchak 2019). **Figure 3** shows the development of a snow drought during winter 2008/2009 across western Russia. The below-average SWE may have contributed to low soil moisture leading into the 2010 Russian heat wave and drought that resulted in a ban on grain exports.

Furthermore, the relative contributions of natural variability and anthropogenic warming are still not well defined. Therefore, studies improving our understanding of droughts and natural variability would increase our understanding of historical and projected drought trends (IPCC 2012). We must also broaden our efforts to characterize the effects of human activities (such as agriculture, deforestation, and increasing human water use) on the occurrence and severity of drought events (Mehran et al. 2015). AghaKouchak et al. (2015) highlighted the lack of studies researching the impacts of human activities on water stress and emphasized the importance of understanding the roles that human activities play in determining water availability. Van Loon et al. (2016) also called attention to the need to incorporate the role of humans in exacerbating (and alleviating) drought conditions. To improve regional and global drought management, we must improve our understanding of the relative contributions of human activity, natural variability, and climate change on droughts.

Using a global multimodel ensemble, Sheffield & Wood (2008) predicted that soil moisture drought events will become more common and more severe and will cover twice as much land area under moderate [the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report's simulations with $CO_2$ concentrations peaking at 720 ppm) and high emissions scenarios (peaking at 850 ppm) at the end of the twenty-first century relative to the twentieth century. Global aridity (i.e., precipitation minus potential evapotranspiration) is expected to increase by 3.4% per degree Celsius increase in temperature over land, which will have negative ramifications on water availability as we move to a drier land state (Fu & Feng 2014). Under a warming climate, we also anticipate a 10–23% expansion of global drylands between 1961–1990 and 2071–2100, increasing total dryland coverage to 50–56% of the global land surface (Huang et al. 2016). Increasing aridity and expanding drylands are projected to significantly increase the number of communities living in prolonged water stress (Huang et al. 2016). Projected increases in aridity and drought-prone regions will likely increase the occurrence of dust events (Prospero & Lamb 2003), which can cause human health problems and modify the hydrology of nearby (and remote) regions. For example, the radiative forcing of dust deposited on/within snow or ice can alter land-atmosphere feedbacks and the timing and rate of melt (Skiles et al. 2018).

The projected increase in global aridity and dryland coverage is influenced by land-atmosphere and biosphere-atmosphere feedbacks. Berg et al. (2016) highlighted the projected contribution of land-atmosphere interactions to the expected doubling in aridity by isolating the influence of long-term soil moisture trends on precipitation, relative humidity, and temperature under a warming climate. In addition, increased dryland coverage and drought occurrences will degrade the ability of soils and vegetation to store carbon, feeding back to atmospheric concentrations of $CO_2$ and leading to further desertification (Huang et al. 2016). Large-scale deforestation, especially in tropical regions, may also influence the occurrence and severity of droughts (Spracklen et al. 2012).

While global models offer information regarding possible climate futures, comparisons of historical and historical natural-only climate scenarios (historical simulations with and without the influence of anthropogenic emissions—i.e., natural variability—respectively) have also improved our understanding of how anthropogenic climate change has contributed to changes in the water cycle, such as the intensification of precipitation events (Diffenbaugh et al. 2015). However, we lack attribution studies focused on drought events and stand to benefit from studying the impact of anthropogenic climate change on drought to reframe how we interpret historical observations. This will, in turn, improve modeling efforts for future projections. **Figure 4** provides an example of examining climate change impacts on drought by displaying the probability ratio of droughts occurring in historical relative to historical natural-only climate simulations. **Figure 4** shows a greater probability of drought occurrences in many regions in the Americas, Europe, Africa, and Asia that can be attributed to anthropogenic climate change.

We must also continue to ask important questions regarding the expected changes in the vulnerability of human communities to droughts. Similar to heat waves, future drought events will challenge the energy sector, influencing future hydropower energy portfolios and powerplant operations (Tarroja et al. 2018). We will need many more studies on the range and magnitude of impacts that drought events will have in the future (e.g., on the agricultural industry and food security), as well as the cascading feedbacks that will result on local and global scales.

## WILDFIRES

Hot and dry conditions can increase the risk of wildfires over vegetated and forested regions. Wildfires act as an integral component of the global ecosystem (Bowman et al. 2009) by modulating the structure and distribution of ecological communities (e.g., clearing dead plant

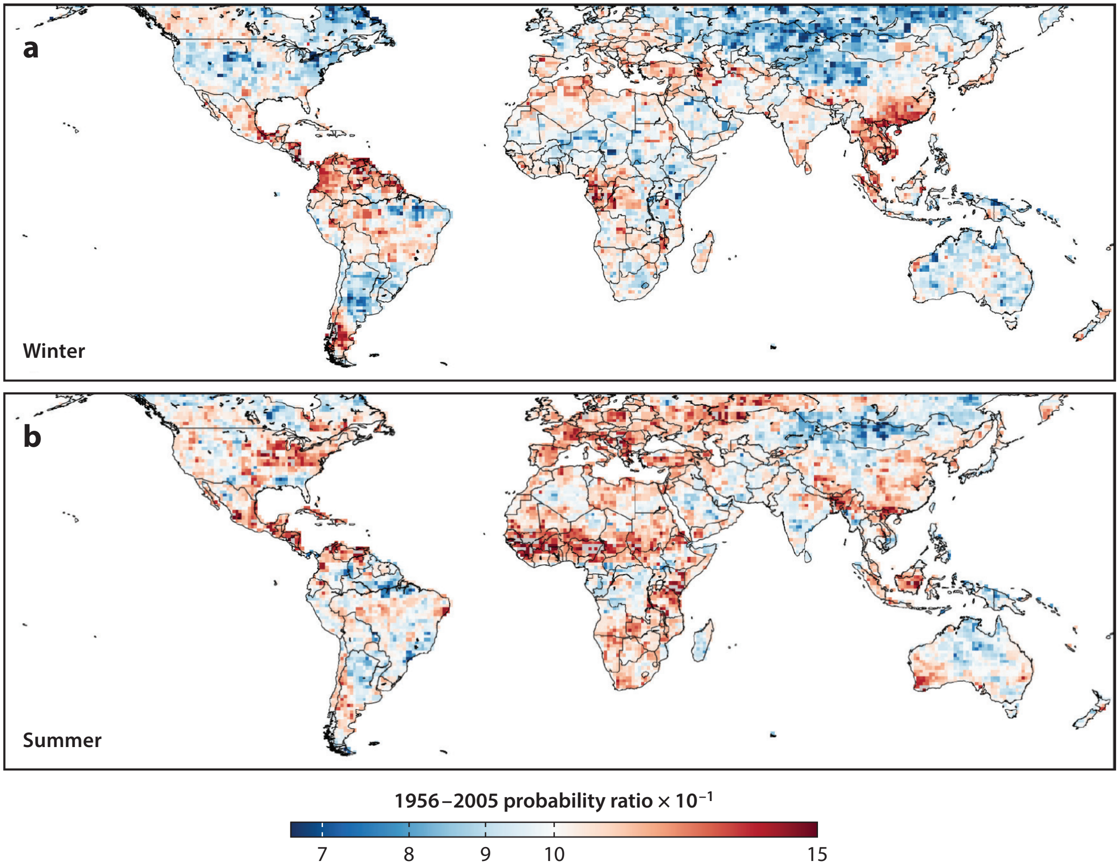

**Figure 4**

Probability ratio (PR) in (*a*) February and (*b*) August [based on 1956–2005 Coupled Model Intercomparison Project Phase 5 (CMIP5) models]. PR is derived from three-month Standardized Precipitation Index (SPI) values, with historical natural-only SPI less than −1.5 as the threshold for a drought occurrence. Values over 1 indicate a greater probability of droughts occurring in the historical climate relative to the historical natural-only climate, while values less than 1 indicate a lower probability of droughts occurring in the historical climate.

litter and reintroducing nutrients to soil, enabling the growth of new vegetation). However, they can also be incredibly destructive. For instance, between 2017 and 2018, eight California wildfire events destroyed 31,444 structures and took 143 lives, despite fire management and control efforts.

Fire controls include topography, climate, weather, fuel (e.g., flammability, load, depth, mass, density, connectedness), ignition, and human activities (Flannigan et al. 2009, Moritz et al. 2005). These controls are complex and interdependent across varying spatiotemporal scales, many of which are influenced by anthropogenic emissions (Abatzoglou & Williams 2016). Global warming has boosted climate and weather drivers of fire across much of the globe (Flannigan et al. 2009). Fire-weather season (conducive to large fires) extended across 25.3% of Earth's vegetated surface between 1979 and 2013, which translates to an increase of 18.7% in the global mean fire-weather season length (Jolly et al. 2015). Numerical studies generally predict that by the end of the century, much of the globe and, in particular, the forested western United States will experience an increase in the number of days with conditions conducive to extreme wildfire events;

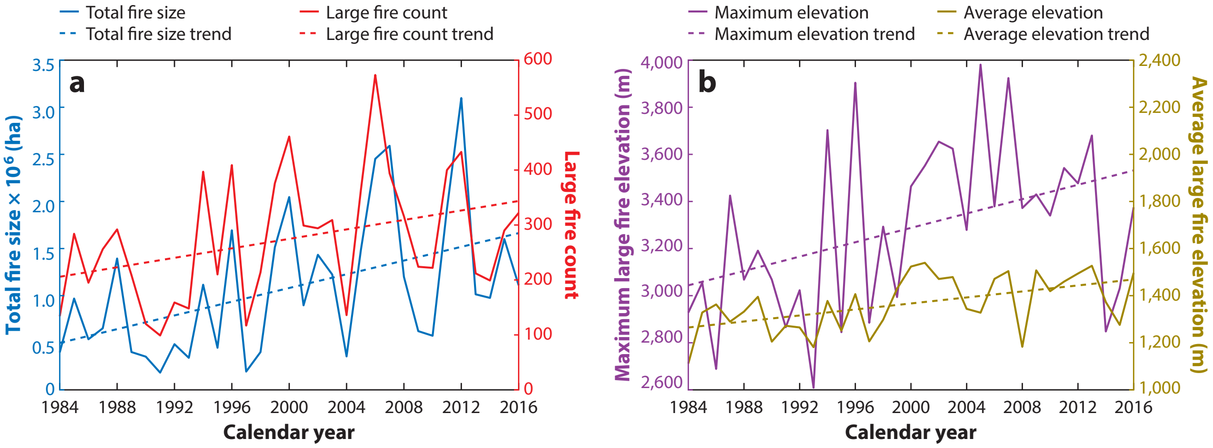

**Figure 5**

The frequency, severity, and elevation of wildfires have increased substantially over the past decades. (*a*) Total cumulative fire size and large wildfire (>405 ha) counts and (*b*) maximum and average large wildfire elevations over the western United States. Fire elevations correspond to the centroid of wildfire perimeters. Data from **https://MTBS.gov**.

however, fuel availability is expected to place an upper limit to this trend (Hurteau et al. 2019). Further research needs to be conducted to accurately project fire-vegetation feedbacks.

Over the western United States, longer and more intense droughts and heat waves have increased tree mortality rates (Allen et al. 2010), which—along with higher fuel aridity due to earlier snowmelt and changing precipitation patterns as well as increased lightning frequency and ignition efficiency—increased the total burned area (Abatzoglou & Kolden 2013, Holden et al. 2018, Littell et al. 2009, Westerling 2016) (**Figure 5**). Humans have also increased fire activity over the United States through aggressive suppression policies and wildfire ignition (Pechony & Shindell 2010). Humans ignited 84% of all wildfires throughout the conterminous United States between 1992 and 2012, fostering a human-started fire season that is three times longer than its lightning-started counterpart (Balch et al. 2017). However, lightning-started fires constitute the majority of the total area burned over the conterminous United States (Balch et al. 2017) and account for the majority of the increase in burned area over the western United States (Barbero et al. 2015).

Between 1984 and 2011, the western United States experienced an increase of seven large fires (>405 ha) per year, with the total burned area increasing by more than 350 km$^2$/year (Dennison et al. 2014). The wildland-urban interface has also grown rapidly in recent decades over the conterminous United States. From 1990 to 2010, the construction of 12.6 million new homes (41% growth) and the urban development of 189,000 km$^2$ of land (33% growth) (Radeloff et al. 2018) collectively increased the wildland-urban interface and escalated the cost of wildfires. In 2018, the US Forest Service and Department of Interior spent more than USD 3.1 billion fighting fires.

Wildfires are associated with myriad short- and long-term adverse impacts as they ravage natural and developed land. Wildfire-related hazards propagate through time, disrupting ecosystem services and threatening human livelihood for months to years after the wildfire event (Nelson et al. 2013). Wildfires consume vegetation, plant litter, and soil organic matter, thereby decreasing canopy interception and forming water-repellent soils, which collectively diminish the infiltration rate and enhance the overland flow of water and runoff in channels. Enhanced direct runoff and reduced vegetation obstruction, along with lowered critical soil shear stress, significantly increase erosion rates over land surfaces and along channel beds and banks, potentially leading to destructive debris flow events (Shakesby 2011, Shakesby & Doerr 2006). Wildfires also disrupt nitrogen and carbon cycling (DeLuca et al. 2006) and plant-fungal interactions, potentially triggering biome shifts (Scholze et al. 2006), deteriorating water quality (Hohner et al. 2016), and prompting geomorphological change through rock weathering (Shakesby & Doerr 2006). In snow-covered regions, the loss of canopy modifies the accumulation, distribution, and melt of the snowpack during subsequent seasons. The increasing elevation of wildfires into snow-covered regions (AghaKouchak et al. 2018) (**Figure 5**) highlights a need for further study of interactions between wildfires and snow.

As climate continues to change, traditional approaches of fuel management, fire suppression, and restoration of burned areas will no longer be sufficient. We need to promote adaptive resilience through the restructuring of human establishments and the management of natural ecosystems to decrease our vulnerability to increasing wildfire risk (Schoennagel et al. 2017).

## EXTREME PRECIPITATION

Precipitation extremes do not have a universal definition; therefore, several definitions and indices have been formulated. For example, some indices proposed by the Expert Team on Climate Change Detection and Indices (**https://www.climdex.org/**) consider the monthly maximum 1-day precipitation, daily precipitation larger than 10 or 20 mm, and so on. In hydroclimatology, analyses on extreme precipitation typically deal with annual maxima or peaks over threshold (see, e.g., Katz et al. 2002, Papalexiou et al. 2018a, Westra et al. 2012).

Precipitation extremes impact ecosystems and societies in many ways. For example, extremes cause waterborne disease outbreaks, stress sewage networks, trigger landslides, wreck homes and buildings, damage crops and affect agricultural production, impact traffic conditions, and—most importantly—lead to heavy and deadly flooding. Anthropogenic activities have altered the global water cycle (IPCC 2013), resulting in an overall increase in extreme precipitation events in both wet and dry regions globally since 1960. Increases in extreme precipitation are an anticipated effect of a warming climate since a warmer atmosphere can hold more water vapor (Allan & Soden 2008, Fowler & Hennessy 1995, O'Gorman & Schneider 2009, Trenberth 2011). This is reflected in physical laws, and more specifically, the Clausius–Clapeyron relation indicates that the atmosphere can hold 7% more water for every 1°C temperature increase (e.g., Pall et al. 2007, Wang et al. 2017); this increase, however, is not expected to be uniform across the globe. Wang et al. (2017) have shown that extreme precipitation and high temperatures can exhibit a negative relationship after exceeding a given temperature threshold. Also, while climate model outputs indicate potential increases in rainfall extremes under global warming (Wentz et al. 2007), modeled and observed precipitation are not always in agreement. For example, it is well accepted that low-resolution climate models show significant biases in modeling precipitation extremes at subdaily timescales (Prein et al. 2015); this has led to the increasing popularity of convection-permitting climate models that allow explicitly simulated deep convection (Kendon et al. 2016, Prein et al. 2017).

Several global studies based mainly on gridded data (e.g., Alexander et al. 2006, Donat et al. 2013) have analyzed different extreme precipitation indices based on event intensity, frequency, and/or duration, with results indicating expected changes in Eurasia and regions of the United States. For example, analysis of gridded data on the frequency of daily precipitation $\geq$10 mm indicates changes over Europe and Asia (e.g., Donat et al. 2016). These studies also show that the observed patterns of change can differ based on the data set and period analyzed. In a recent global study, Papalexiou & Montanari (2019) showed significant changes in the frequency of precipitation extremes at the station level as well as at regional and global scales between 1964 and 2013 (**Figure 6**).

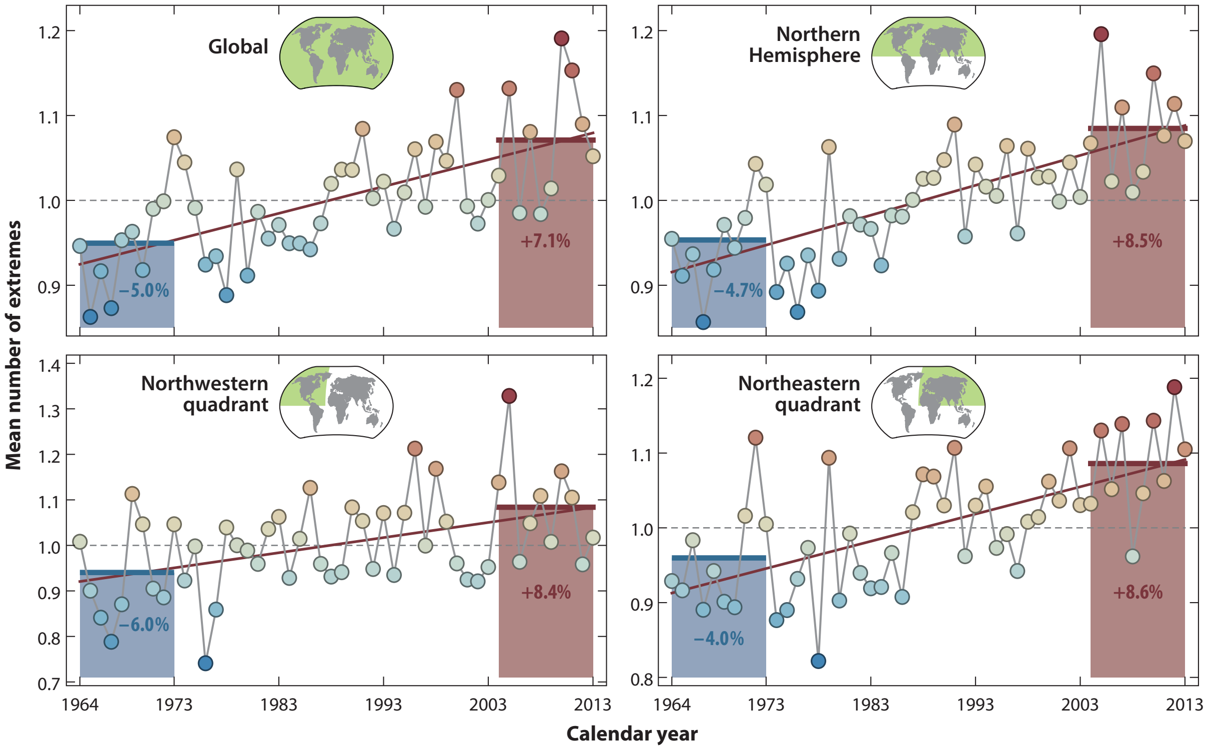

**Figure 6**

Observed number of daily precipitation extremes over the 1964–2013 period when global warming accelerated. Panels show number of extremes versus time, normalized to the average and for four large regions (small maps highlighted in *green*). If the *N* largest precipitation extremes are analyzed in *N*-year records, then under the assumption of stationarity, we expect to observe on average one of these extremes per year. Analysis of 8,730 records from all over the globe shows that recent decades have more extremes than the expected number. For example, globally, over the first and last decade of the study period we observe, respectively, 5.0% less and 7.1% more extremes than the expected number (highlighted by the *vertical bars*). Figure adapted from Papalexiou & Montanari (2019).

Changes in extreme precipitation depend on the interaction of large- and regional-scale processes. The complexity of fully capturing these (often nonlinear) interactions leads to uncertainty in dynamical models of extreme precipitation (Shepherd 2014), since regional-scale processes (e.g., orographic effect, vertical wind velocity) play a key role in either amplifying or weakening local responses (Pfahl et al. 2017, Trenberth et al. 2015, Westra & Sisson 2011). Additionally, large-scale atmospheric circulation patterns that drive storm tracks are highly influenced by Arctic warming at rates that are at least twice as fast as the rest of the Northern Hemisphere (i.e., Arctic amplification) (Coumou et al. 2018, Francis & Vavrus 2012). Storms are becoming more intense and spatially concentrated, increasing the contribution of extreme storms to total precipitation over land (Hawcroft et al. 2018, Wasko et al. 2016). The frequency of the most intensely precipitating extratropical cyclones (>99th percentile) is projected to more than triple in Europe and North America by the end of the century, based on RCP 8.5, although the overall number of extratropical cyclones is expected to decrease (Hawcroft et al. 2018). Marvel & Bonfils (2013) also linked the slowing and strengthening of storms to large-scale dynamical processes (e.g., atmospheric circulation patterns) that affect the horizontal and vertical transport of water vapor. Despite the complex interplay between physical processes that make predicting future changes challenging, general circulation models indicate a seasonally dependent jet stream shift poleward

(Shaw et al. 2016). The poleward shift is projected to increase the frequency of atmospheric rivers, which are responsible for 90% of water vapor transport in the midlatitudes (Zhu & Newell 1998), up to six times along the North American West Coast and doubling in Europe where integrated horizontal vapor transport is expected to intensify (Gao et al. 2015, 2016; Lavers et al. 2013; Papalexiou & Montanari 2019).

The response of daily snowfall extremes to warming varies by region and elevation. For instance, O'Gorman (2014) found that in some regions of the Northern Hemisphere (e.g., those with elevations <1,000 m), snowfall extremes are less sensitive to warming than mean snowfall. Zarzycki (2018) showed that, although there is a projected overall decline in snowstorm frequency in the northeastern United States with a warmer atmosphere, the decrease is less significant when large, high-impact events are considered (i.e., strong wintertime extratropical cyclones occurring over populated regions). This decline occurs despite a projected increase in cumulative precipitation associated with cyclones over this region. While Zarzycki (2018) linked changes in snowstorms with societal impacts and hazards, additional work is needed in this area, since snowstorms can cause loss of life and property and disrupt transportation and communication systems.

Hailstorms are another extreme precipitation phenomenon that require further study since they can cause extensive property damage and result in the loss of human life, livestock, and crops. Increases in the frequency of hailstorms have been observed in the United States and southwest Germany (Changnon 2009, Kunz et al. 2009). Hailstorm-related property damage has risen with growing population density and wealth across the globe (Prein & Holland 2018). Numerical weather prediction models struggle to predict hailstorms even at short lead times (minutes to hours) since microphysical processes are still poorly understood, and there is a need to gather more relevant observational data (Martius et al. 2018). Large uncertainties exist regarding how changes in freezing levels will impact hailstorms. One study that examined future hailstorms projected that a warmer atmosphere will increase the melting level, causing hailstorms across Colorado's mountainous regions to become nearly nonexistent in the future, despite the formation of hailstones in the atmosphere and more intense future storms (Mahoney et al. 2012). However, large uncertainties and unknowns related to changes in hailstorms across many regions remain, and gaining better insight into such phenomena will help improve the understanding of potential damage and flooding risks.

Regional analyses of extreme precipitation, especially for design and risk assessment applications, often rely on statistical methods. In some regions, extreme precipitation statistics have shifted over time, necessitating time-varying (nonstationary) analyses (e.g., Rosner et al. 2014, Steinschneider & Lall 2015). Cheng & AghaKouchak (2014) found that overlooking nonstationarity could result in significant underestimations of subdaily precipitation intensity (e.g., by 32% for 10-year 1-h events and by 62% for 2-year 2-h events). Beyond the underestimation of subdaily precipitation, another major source of underestimation is the use of light-tailed distribution models. A recent analysis of more than 4,000 hourly precipitation records across the United States showed that hourly tails are heavier than those typically used, which results in underestimating the frequency and magnitude of hourly extremes (Papalexiou et al. 2018a). Statistical analyses have also been combined with global climate models (GCMs) to project future changes in extreme events. For southern Quebec, Mailhot et al. (2007) projected a greater increase in the frequency of subdaily events relative to daily and longer duration events, despite an overall increase in the frequency of both short- and long-duration events. In the United States, Ragno et al. (2018) estimated that extreme precipitation may experience up to a 20% increase in intensity and become twice as frequent in highly populated urban areas in the future (2050–2099) relative to the past (1950–1999) (**Figure 7**). Overall, many regions are experiencing a shift to shorter duration, higher intensity, and more frequent extreme precipitation events.

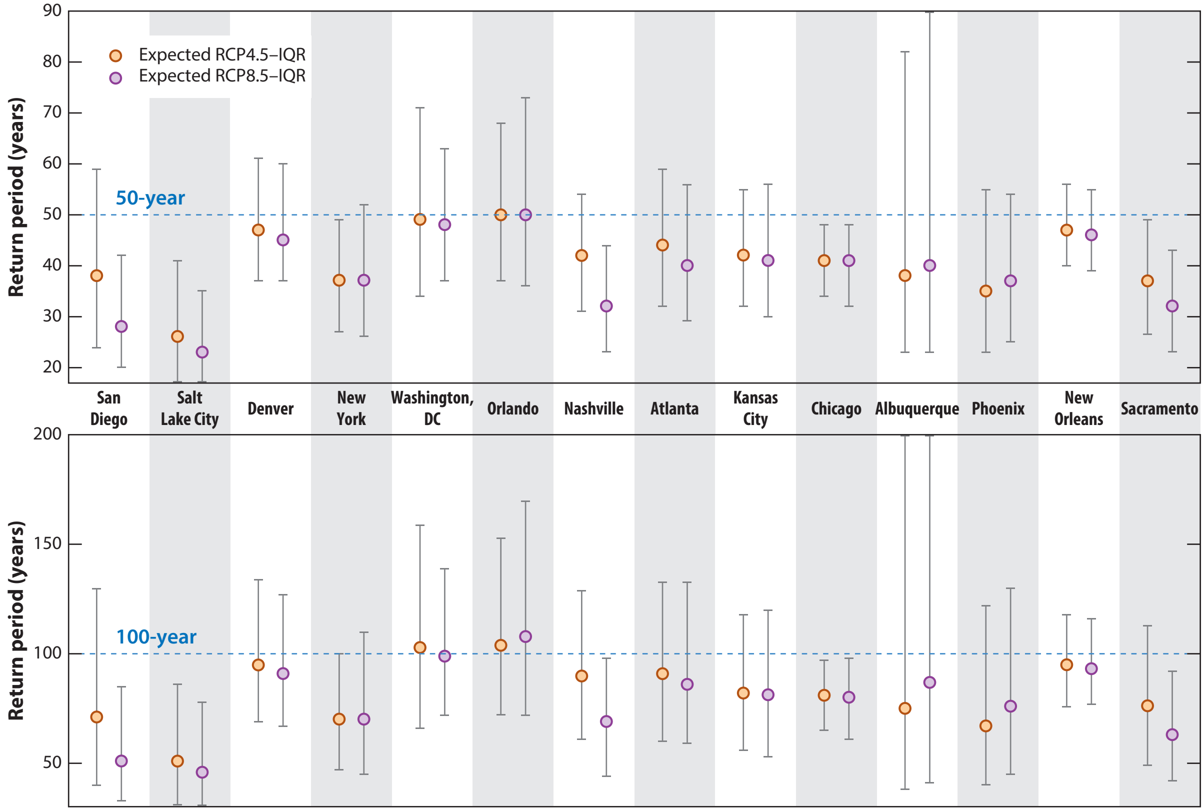

**Figure 7**

Expected future return periods of events currently associated with return periods of 50 and 100 years in urban locations across the United States; expected projected return periods [*orange dots* based on Representative Concentration Pathway (RCP) 4.5 and *purple dots* based on RCP 8.5] along with interquartile range (IQR) (*gray lines*). Figure adapted from Ragno et al. (2018).

A high proportion of extreme precipitation in various coastal regions of North and Central America, East Asia, and Australia can be attributed to tropical cyclone (TC) activity (Khouakhi et al. 2017). The complexity of modeling TC formation at a resolution that accounts for regional-scale processes has led to conflicting results regarding projected changes in their frequency. While several studies using coarse resolution GCMs project global decreases in TC frequency (Walsh et al. 2016), studies that include higher resolution models, relative sea surface temperatures, and/or ocean heat content find that TC frequency remains constant or experiences a small increase in the future (Bhatia et al. 2018, Trenberth et al. 2015). Using downscaled information from GCMs, Emanuel (2013) estimated a 40% global increase in TC frequency of category 3 or higher storms over the twenty-first century, with most of the increase occurring in the North Pacific, North Atlantic, and South Indian Oceans. Attribution studies for recent landfalling hurricanes and tropical storms in the US Gulf Coast region also indicate a TC-associated increase in extreme precipitation probability due to a warming climate, as events such as the 2017 Hurricanes Harvey, Irma, and Maria become significantly more likely relative to historical observations (Trenberth et al. 2018, van Oldenborgh et al. 2017, Wang et al. 2016). Emanuel (2017) projected that the 500 mm of areal averaged rainfall associated with Hurricane Harvey shifts from a 2,000-year event for the period of 1981–2000 to a 100-year event for 2081–2100. Similar to atmospheric rivers, TCs are also expected to experience a poleward shift under climate change. Bhatia et al. (2018) found that favorable areas for TC formation are expanding and increases in TC rapid intensification before landfall are likely to occur.

One important gap is the lack of early warning systems for extreme precipitation resulting from the combination of not-so-extreme events, such as the storm that hit Louisiana in the US Gulf Coast in 2016. The event was the combined result of a weak tropical disturbance and an eastward baroclinic trough to the north with its associated cyclone, which stalled and produced extreme rainfall for 4 days—the same length of time Hurricane Harvey inundated Houston, Texas, the following year (Wang et al. 2016, 2018). In addition, most literature that considers climate change scenarios and the projected impact on snow processes generally focuses on seasonal mean snowfall or peak SWE (e.g., Diffenbaugh et al. 2013, Krasting et al. 2013) rather than on extreme snow/ice events (snow drought, snowstorms, hailstorms, ice jams, etc.). Therefore, additional studies investigating future snow and ice-related extreme events are required to understand how they are changing (i.e., intensity, duration, and frequency) since such changes will influence the size, timing, and extent of flooding across many regions of the globe.

## FLOODING

Floods are the most common natural hazards in the world (e.g., Kundzewicz et al. 2014), affecting more than two billion people globally between 1998 and 2017 (Wallemacq & House 2018). During this period, 3,148 reported flooding incidents caused USD 656 billion in economic damages and killed more than 142,000 people worldwide (Wallemacq & House 2018). Several studies have shown that flood damages have been increasing over the past 60 years (e.g., Downton et al. 2005, Kundzewicz et al. 2018) and attributed this to changes in climate and human settlement and activities in flood-prone regions (Dottori et al. 2018). Despite an evident increase in flooding damages and extreme precipitation in many regions worldwide (e.g., Kunkel et al. 2013), finding changes in the magnitude and/or frequency of flood events on a global scale remains highly elusive (IPCC 2013, Kundzewicz et al. 2014, Sharma et al. 2018).

Recent studies observed contrasting changes in flood characteristics (e.g., Berghuijs et al. 2017, Do et al. 2017, Mallakpour & Villarini 2015, Slater & Villarini 2016). Mallakpour & Villarini (2015) found an increase in the frequency of flood events between 1962 and 2011 in the central United States; however, flood magnitudes did not reveal a pronounced change. Slater & Villarini (2016) showed that the frequency of flood events has increased over the central United States but decreased in California and the southeastern United States. In a recent study, Blöschl et al. (2019) pointed to an increase in flood discharges in northwestern Europe, while most of the stream gauges over southern and eastern Europe showed a deceasing trend. Do et al. (2017) observed increasing trends in the magnitude of maximum daily streamflow across eastern North America, parts of South America and Europe, and southern Africa while decreasing trends in western North America and Australia. Berghuijs et al. (2017) found an overall increasing trend in the magnitude and frequency of floods between 1980 and 2009, with the largest changes in Europe and the United States. Flood timing has also changed in different regions of the world (Blöschl et al. 2017). For instance, Blöschl et al. (2017) showed that relative to 1960, flood events are occurring earlier in northeastern and western Europe. They attributed this shift to earlier snowmelt and soil moisture maxima. They also indicated that delays in winter storms have caused flooding events to occur later in the season for the North Sea and the Mediterranean coast. However, the detection of changes in flood characteristics remains an ongoing research challenge for the scientific community. Traditionally, statistical methods have been employed to identify possible changes in flooding based on observed streamflow records. However, due to the relatively short length of record, the highest confidence in the change of flood characteristics does not extend past 1950 (Hoegh-Guldberg et al. 2018). This also leads to the question of long-term persistence, wherein short-term records (a century or less) may suggest trends that are, in actuality, part of oscillatory behavior in longer records (e.g., paleoflood records) of streamflow (Hirsch & Archfield 2015).

While the detection of changes in historic flood records is important, it is also imperative to go beyond the detection of changes in flood characteristics and start investigating the causes of changes (Villarini & Slater 2017). Attribution studies can help us attain vital insights into changes in flood patterns as the associated drivers evolve in a warming climate (e.g., Hamlet & Lettenmaier 2007, Harrigan et al. 2014). Factors that contribute to changes in inland flooding include the timing, type, duration, and intensity of precipitation; river morphology; topography; soil moisture; land use and land cover; sea level rise; and human modifications of watersheds (e.g., Sharma et al. 2018, Slater & Villarini 2017). Therefore, changes in regional flooding behavior can reflect the combined influence of climate, anthropogenic modifications, stream dynamics, and watershed characteristics (Mallakpour & Villarini 2015). In general, climate conditions are the triggering mechanisms of flood events, and basin characteristics and human modifications shape the occurrence of flood events (Garner et al. 2015).

Climate models project increasing trends in the intensity and frequency of flooding events under a warmer climate (e.g., Kundzewicz et al. 2018, Milly et al. 2005, Winsemius et al. 2016). Without taking measures to mitigate against floods, Winsemius et al. (2016) projected that flood hazards could be amplified by a factor of 20 by the end of the twenty-first century, especially for vulnerable regions such as Southeast Asia and Africa. Recent studies have focused on potential changes in flooding under different climate warming scenarios (e.g., Alfieri et al. 2017). The 2018 IPCC report on the impacts of global warming on natural and human systems stated that flood hazard will likely increase over larger areas under 1.5 and 2°C warming relative to the preindustrial climate (Hoegh-Guldberg et al. 2018). As was mentioned in previous sections, a warmer climate is expected to influence wet and dry weather patterns, which is anticipated to change flood characteristics in the future (Salman & Li 2018).

Moreover, a warmer atmosphere leads to changes in the partitioning of precipitation (from snowfall toward rainfall) and the timing of snowmelt, which may change the seasonality of flooding (e.g., Blöschl et al. 2017, Harpold et al. 2017). Increases in heavy precipitation, especially in the form of rainfall, are most likely to cause flooding if the increase occurs during wet periods of cold seasons (Ivancic & Shaw 2015). A warmer climate may lead to more flooding problems emerging from rain-on-snow (ROS) events, rain falling on frozen ground, ice jam flooding, and glacial lake outburst flood events in regions that are ill-prepared for such events (Frey 2017, Harrison et al. 2018, Rokaya et al. 2018).

ROS events can accelerate snowmelt, increasing runoff and flood risks. Jeong & Sushama (2018) showed that projections of ROS runoff amounts are often expected to increase more than ROS rainfall amounts, especially across northeastern North America. However, not all elevations may experience similar ROS trends. Across western North America, ROS events at lower elevations are projected to be less likely in a warmer climate, due to reductions in the seasonal snowpack, than at higher elevations where the snowpack persists (Musselman et al. 2018). Musselman et al. (2018) showed that future increases in the ROS volumes are driven by the increased spatial extent of the largest 10 events rather than increases in the intensity of the largest events.

In addition, heavy and relatively warmer rainfall over frozen water bodies has the potential to mobilize ice and create natural dams (or ice jams) composed of large chunks of ice that can cause water to inundate adjacent drylands, a phenomenon known as ice jam flooding (Frey 2017). A warmer climate can lead to more frequent ice jam flooding in regions that rarely experience such flood events (Rokaya et al. 2018). Additional global studies are critically important for mitigating snow- and ice-related flood risks and better assessing changes in human exposure to such events and their resulting socioeconomic and water management implications across a variety of snow regimes. Hence, understanding the physical drivers of floods and characterizing spatiotemporal characteristics of changes in floods are important for developing flood mitigation strategies to cope with potential changes in flooding events and associated societal impacts.

## COMPOUND AND CASCADING HAZARDS

In the above sections, we highlighted the state of knowledge regarding individual extremes and their associated impacts. Although individually occurring extremes can produce severe impacts, the interconnected nature of our climate system implies that compounding hazards can be associated with even more devastating impacts, especially as temperatures continue to rise. The concept of compound events was first briefly discussed in the IPCC special report on climate extremes (IPCC 2012). Hao et al. (2013) offered a global analysis of change in compound warm-dry, warm-wet, cold-dry, and cold-wet conditions. Leonard et al. (2014) further developed the notion of a compound event as an extreme-impact event with dependent variables. Zscheischler et al. (2018) ultimately formalized the definition of compound weather/climate events as the combination of two or more climate drivers or hazards that have implications on natural and/or human systems, providing a clear, generalized framework for further research in this area of climate extremes. In this definition of compound events, climate drivers can be taken as temperature, precipitation, river flow, and other climate variables, while hazards can be defined as drought or heat. We can view multiple drivers or hazards, such as drought and heat wave events, occurring concurrently as compound events. As many drivers and hazards are interdependent, the study of compound events is important for accurately assessing the probability of risk (Zscheischler et al. 2018).

Compound events may become more common in a warming climate, which makes the study of compound events even more vital for preparing for future climate extremes. Recent studies documented that concurrent droughts and heat waves have become more frequent in the twentieth century (e.g., Diffenbaugh et al. 2015, Mazdiyasni & AghaKouchak 2015). In California, Diffenbaugh et al. (2015) attributed an increased risk of concurrent warm and dry events to anthropogenic warming and projected that the increased risk of extreme warm and dry concurrences will continue throughout the twenty-first century. One key mechanism responsible for increases in compound drought and heat waves is land-atmosphere interactions. Moisture deficit during droughts limits land evaporation, which in turn increases the sensible heat to latent heat ratio, leading to a warming of the local area (Chiang et al. 2018). Historical observations already show amplified warming of droughts in some regions of the United States, and Coupled Model Intercomparison Project Phase 5 (CMIP5) model projections show this continuing into the future (Chiang et al. 2018).

Compounding effects of droughts and heat waves can intensify wildfires. However, wildfires can trigger other cascading hazards, turning otherwise moderate events into disasters (AghaKouchak et al. 2018), such as the 2018 debris flow in Montecito, California, described in the Introduction. Wildfire-related hazards (e.g., smoke) extend beyond the burned and immediate surrounding area, propagating thousands of kilometers and impacting distant populations. Wildfire smoke is associated with increased mortality rates and can aggravate respiratory, cardiovascular, mental, and perinatal health issues (Reid et al. 2016). It is estimated that exposure to landscape fire (e.g., wildfires, agricultural burn) smoke increases annual mortality rates globally by 339,000 deaths (Johnston et al. 2011). In the United States alone, short- and long-term exposure to wildfire smoke in the period 2008–2012 imposed an estimated economic toll of USD 63 billion and USD 450 billion (net present value in 2016), respectively (Fann et al. 2018). Wildfire smoke and ash also leave a daunting hydrological impact as the radiative properties of black carbon and its deposition on/within the snowpack can increase melt rates, alter the timing of runoff, and even create snow-driven flooding (Flanner et al. 2007). Currently, we do not have robust methodological frameworks for evaluating the risk of cascading hazards, especially when the main drivers are not statistically dependent (e.g., extreme rain over burned area a year after wildfire). We note that for cascading hazards with independent drivers, we cannot simply multiply the probabilities of the hazard drivers. The reason is that the events are physically related, primarily through the actual impact (e.g., debris flow as a result of rain over burned area); however, the relationship cannot be simply described using the commonly used statistical metrics. More research should focus on developing methods for characterization of such events.

Flooding in low-lying coastal regions [land less than 10 m above mean sea level (MSL)] often involves multiple drivers and hence is considered another type of compound event (Moftakhari et al. 2017a, Santiago-Collazo et al. 2019). The primary drivers of coastal flooding include fluvial (terrestrial) flows, ocean flooding, and pluvial flooding (resulting from direct rainfall). The risk stemming from oceanic drivers is changing continuously because of rising sea levels that also interact with the fluvial compound flooding. The rising sea levels will change the gradient of flow in coastal areas and impact sea interactions with fluvial flows (Moftakhari et al. 2017b, Wahl et al. 2017), making future coastal flooding more impactful even if fluvial flows remain unchanged. Many papers have provided robust evidence of increased coastal flooding due to sea level rise (Moftakhari et al. 2015, Vitousek et al. 2017, Woodruff et al. 2013). For example, projections of tidal high water in Los Angeles, California, exceed historic flooding thresholds. **Figure 8** indicates that it is unlikely for the 10-year flooding threshold associated with tidal high waters to be exceeded in 2030; however, there is a 5% and 50% chance that this threshold will be surpassed by 2070 and 2100, respectively, under high emission scenarios. Using New York tidal records dating back to 1844, Talke et al. (2014) also concluded that between the mid-nineteenth and early twenty-first centuries, the annual probability of exceeding the local seawall increased from less than 1% to 20–25%. The rate of exposure to coastal flooding may depart from rising sea level rates due to local patterns of topography and development. Therefore, projected increases in coastal flooding risk can be partially explained by elevated exposure due to population and economic growth (Curtis & Schneider 2011, Hallegatte et al. 2013, Hinkel et al. 2014, Kulp & Strauss 2017).

In addition to sea level rise, large-scale annual sea level fluctuations also significantly contribute to extreme compound coastal flooding and will likely dominate over the contribution of long-term sea level rise for the next few decades (Wahl & Chambers 2016). Interannual climate variability and local weather patterns may also modulate components that contribute to the extreme total water level—for example, unprecedented extreme coastal water levels in the southeast United States in 2008–2009 were linked to incident Atlantic Rossby waves (Calafat et al. 2018), large-scale dynamical response of ocean to the wind and buoyancy forcing (Chelton & Schlax 1996). This indicates that large-scale oceanic or atmospheric patterns such as El Niño and Rossby waves can lead to or intensify coastal flooding events.

The concurrence of heavy precipitation and storm surge can also be considered a compound event in low-lying coastal regions (van den Hurk et al. 2015, Wahl et al. 2015). Storm surges prevent water from discharging into the open sea, while heavy local precipitation results in excessive water levels in inland areas (van den Hurk et al. 2015). Moreover, terrestrial processes can combine with oceanic processes to contribute to the extreme coastal water level. In a warmer climate, the globally averaged intensity of TCs is expected to shift toward stronger storms (2–11% by 2100) (Bender et al. 2010, Emanuel 2013, Knutson et al. 2010), leading to enhanced extreme precipitation and more severe river flooding (Alfieri et al. 2017, Winsemius et al. 2016). Rivers delivering freshwater and sediment to the coast contribute to regional rates of sea level variability/change

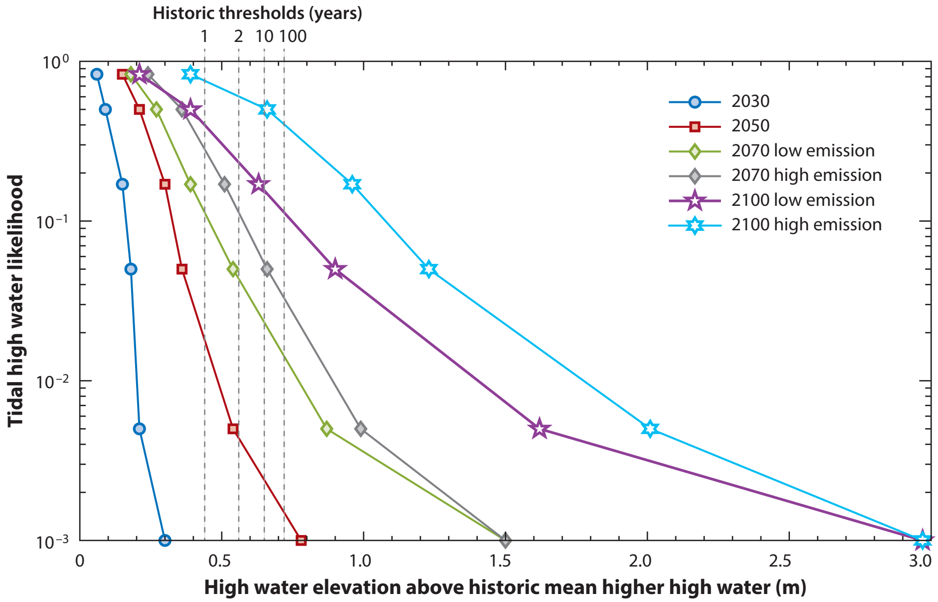

**Figure 8**

Probability of projected tidal high waters exceeding historic flooding thresholds in a warmer climate for Los Angeles, California. Dashed vertical lines represent the historic flooding thresholds associated with 1-, 2-, 10-, and 100-year return periods. Data from the National Oceanic and Atmospheric Administration tide record for Los Angeles (Station ID 9410660). Curves show the likelihood that an extreme coastal water level goes beyond these historic thresholds, based on coastal water-level projections from the Coastal Storm Modeling System (CoSMoS; Barnard et al. 2015), which makes detailed predictions of storm-induced coastal flooding along the coast of California.

(Kopp et al. 2014; Piecuch et al. 2018; Syvitski et al. 2005, 2009) and modulate tides yielding change in extreme coastal water level regime through nonlinear frictional effects (Hoitink & Jay 2016, Jay 1991, Jay & Flinchem 1997). Omitting this interaction could lead to a mischaracterization of the risk of extreme coastal water levels (Moftakhari et al. 2017b, 2019).

Many examples of compound events with devastating impacts can be found in the recent past. For instance, Hurricane Harvey hit the coast of Texas in August 2017, causing widespread flooding and extensive damage in Houston. Flooding resulted from the combination of (*a*) warm water in the Gulf of Mexico, which led to an intensification of the precipitation; (*b*) slowness of the storm, which stalled 100 km inland for 4 days; and (*c*) storm surge, which elevated the nearby Galveston Bay and blocked the discharge of inland water into the open sea. An additional example of a compound event took place in the United Kingdom during the winter of 2013/2014, wherein several successive flooding events occurred along an extended section of coastline as a sequence of storms made landfall in close succession over the region (Haigh et al. 2016). In fact, depending on how the same number of extreme events distributed within a season (i.e., randomly, at regular intervals, or in clusters), the consequences of extreme events will be different (Mallakpour et al. 2017). From these examples, we highlight that temporal clustering of events can greatly amplify flooding damage and slow the recovery process.

## DISCUSSION AND FUTURE PROSPECTS

This review summarizes evidence of change in extreme events including droughts, heat waves, floods, precipitation, and wildfires due to climate change and variability. In addition to individual extremes, we discuss how compound events, broadly defined as the combination of two or more weather or climate drivers or hazards leading to significant impacts on natural and/or human systems (e.g., fluvial-ocean flooding, drought-heat waves), are expected to change in a warming climate. Quantifying and understanding concurrent and compound extremes will become more important as our complex global climate continues to change (Zscheischler et al. 2018). Consecutively occurring or cascading hazards can also magnify the impacts experienced in a region, which fall under the more general definition of compound extremes. Outside of climate change research, cascading disasters have also been used to refer to the cause-and-effect connection between primary disasters and secondary disasters (Franchina et al. 2011, Pescaroli & Alexander 2015). However, cascading events are even more challenging to study, as chains of cascading events are complex, and often nonlinear, and they may be separated by space and time (Pescaroli & Alexander 2015).

Chains of cascading events can interact with the primary event or events, which can create feedbacks that are difficult to model. An additional challenge in studying and modeling cascading events resides in the (in)ability to identify these events in historical observations. For example, extreme rain over burned areas or shifts from extreme high temperature and low soil moisture to extreme rainfall (a drought-flood shift) can trigger catastrophic landslides (Robinson et al. 2017). The accuracy of predicting consequences of cascading extremes will depend on improving data availability and characterizing the potential influence of increased human activities (Gariano & Guzzetti 2016). Although extreme events have been studied extensively from a univariate perspective, as climate change progresses, we will need additional knowledge and understanding of the connections and interdependence of extreme events because some of the key drivers are changing rapidly (e.g., extreme temperatures, rising sea levels). Further, there is evidence that the relationship between drivers of extremes has changed in the historical period (e.g., Sarhadi et al. 2018). For this reason, it is vital to focus more effort into characterizing interrelated extremes and understanding their physical causes. Some key research questions include the following:

- How will the risk of concurrent extremes (e.g., drought-heat waves) change for different levels of warming in the future?
- How do land-atmosphere interactions and feedbacks influence compound climate extremes?
- How will feedbacks intensify or change in the future under warming temperatures?
- How will these extremes translate into impacts on the environment, society, and infrastructure?
- How will human activities (e.g., urbanization, deforestation) alter the risk of compound events?
- How, and to what extent, are cascading events changing in the future?
- How can we track cascading events and quantify their impacts when they are separated across large periods of time?

Human activities (deforestation, urbanization, water management infrastructure) may also regionally modulate extreme events including cascading hazards (Familkhalili & Talke 2016, Talke et al. 2018). For example, water level records dating back to 1868 show that human interventions (e.g., navigational channel modification, wetland reclamation, and river flow regulations) have more than doubled the tidal amplitude near the head of tides in the Hudson River (Ralston et al. 2019). Inland land-use and land-cover change (e.g., urbanization and deforestation) can intensify fluvial flooding and worsen compound coastal flooding. Water transfer projects can enhance vulnerability of a region to extreme droughts (Di Baldassarre et al. 2018). While the role of anthropogenic alterations on extreme events is well understood, modeling and quantifying the effects of human activities on compound events is a challenging task. In general, development, which typically involves more greenhouse gas emissions, leads to not only direct impacts on the land surface (e.g., urbanization) but also feedback on atmospheric, oceanic, and terrestrial extremes (e.g., more frequent heat waves, rising sea levels, higher overland flows). For example, planned actions in response to more frequent extremes involve further development (e.g., building larger dams, water transfer projects, constructing sea walls, increased energy generation for cooling purposes). However, these reactions often lead to even more emissions and impacts on local-regional extreme events. We still need to develop frameworks to track cascading events and feedbacks including human activities on local-regional extremes and their associated risks to humans, infrastructure, ecosystems, and so on.

Given the observed increase in individual and compound extreme events and their projected changes, we need to update infrastructure design guidelines and risk assessment frameworks to account for changing risks and uncertainties. However, there are significant knowledge and methodological gaps related to the characterization of changing hazards. For example, accelerated sea level rise not only shifts tidal ranges to higher elevations but also impacts wave and tide characteristics (Devlin et al. 2017, 2019), thereby amplifying design heights and introducing additional uncertainty when calculating flood risk allowances (Arns et al. 2017, Buchanan et al. 2016, Idier et al. 2017, Pickering et al. 2017). Nonstationarity in tidal fluctuations and dynamic interactions with the coastline must be incorporated into coastal flooding projections (Barnard et al. 2019). To predict sea level rise impacts accurately, we need to factor in the dynamic nonlinear interactions between extreme water level components, including MSL, tides, surge, and waves (Serafin & Ruggiero 2014, Wahl 2017). Similar methodological gaps exist for other extremes that are also projected to change over time. In recent years, several methods have been developed to address nonstationarity in observations (e.g., Ragno et al. 2019). More in-depth research is needed to understand how temporal changes in one extreme event will alter interrelated hazards. We hope that with more coordinated research in this area, we can become better prepared for a wide range of plausible extremes and compound events in a warming world.

## DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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