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Atmospheric Rivers and Floods in California's Changing Hydroclimate

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ABSTRACT

Flooding in the Bay–Delta is most commonly due to runoff from atmospheric river (AR) storms, often enhanced by low-elevation snowmelt. In this paper, we review the current science of ARs and their projected enhancement in a warming climate. We also address the changing state of the Sierra Nevada snowpack. Climate-model projections indicate increasing contributions to extreme precipitation from ARs, and more variable hydroclimate, with increased floods as well as droughts. Observations, meanwhile, do not yet show enhanced precipitation intensity trends. In agreement with climate-model projections, observations do show that, as the climate continues to warm, California's greatest natural freshwater reservoir—its snowpack—continues to erode. This is despite record snowpacks (e.g., 2023) still being possible, and potentially exacerbating flood effects from ARs in a highly variable hydroclimate. Original analysis of extreme historical and projected precipitation events shows events of the magnitude associated with the New Year 1997 floods are expected to become twice as likely by the late 21st century. Moreover, as extreme precipitation events are expected to become wetter, hydrologic modeling suggests that extreme runoff events will be disproportionately enhanced, primarily as the result of a greater fraction of rain vs. snow. We also discuss the mitigating influence of water management on extreme flows, and mention new research results, challenges, and opportunities associated with sub-seasonal and seasonal precipitation predictability. We suggest that—along with infrastructural modernization, as well as maintenance and improvement of observational networks—current and future challenges for water management can be mitigated by better and longer lead-time weather and climate-forecast information.

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KEY WORDS

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INTRODUCTION AND BACKGROUND

In this paper, we first examine the role of Atmospheric Rivers (ARs), floods and the natural volatility of California's hydroclimate. We describe how and why these elements of the hydroclimate are expected to change in a warming world, and reconcile climate-model projections with observations. After an account of observed and projected trends in snow accumulations and snowline elevations in California's snowy mountains during ARs and other storms, we turn to extreme events.

Next, in "Observed and Projected Extreme Precipitation and Runoff Events," we describe a novel mathematical model for estimating the probabilities of precipitation events defined by their duration, maximum intensity and overall magnitude, and use it to estimate the evolving past and future return periods of a specific historic event that led to widespread Bay–Delta flooding. We then examine the evolution of annual maximum extreme precipitation and runoff events into the future, and investigate the physical mechanisms of amplified trends in extreme runoff compared to trends in extreme precipitation.

In "Flood Risks," we consider the observed effect of water management on flow, focusing on extremes. This is followed by a discussion of levee failures and real and perceived flood risks.

"Flood-Mitigation Strategies and Recommendations" focuses on improvements in infrastructure and emergency response, better forecasts, and more flexible reservoir operations—as well as improvements in observational networks.

Last, we present our "Summary and Conclusions."

ARs, Floods, and the Natural Volatility of California's Hydroclimate

California's hydroclimate is exceptionally variable from year to year, as well as on longer time-scales, because of the narrow seasonal window and typically small numbers of storms that contribute to the total precipitation over the water years (Dettinger et al. 2011). A water year with near-normal precipitation is an exception rather than the norm in California, where water supply is more typically either deficient or lavish compared to the statistical annual average (Figure 1A). The closest to an average water year during this century so far was WY[1] 2016, the "Godzilla" El Niño year, when universally wet seasonal forecasts dominated by the canonical El Niño signal (Goddard and Gershunov 2020) provided expectation to widespread desire—fueled by 4 previous years of severe drought—for copious precipitation. California, especially the Sierra Nevada range, receives more than its share of the wettest storms that affect the contiguous United States (Figure 1B). The fact that California's excessive hydroclimate variability is driven by a handful of the largest storms of the year is highlighted in Figure 1C (Dettinger and Cayan 2014; Dettinger 2016). The occurrence or lack of a few (two to four) big storms—typically atmospheric rivers (ARs)—can make the difference between flood and drought years in California.

Atmospheric rivers (ARs) are essentially rivers of water vapor in the sky. They are ephemeral jets of moist air that operate in the lower troposphere. They exist for durations on the order of days, driven by evolving configurations of mid-latitude synoptic high- and low-pressure systems. Globally, several ARs exist simultaneously, moving vast quantities of tropical moisture, and picking up additional evaporation along their meandering eastward and poleward trajectories, primarily over the middle latitudes of the global ocean. Each typically transports two to three times more water vapor instantaneously than the average instantaneous flow of the Amazon—

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[1] October 1–September 30, which aligns with the natural hydrological cycle. WY 2016 refers to October 2015–September 2016. Appendix A includes a glossary of terms and acronyms.

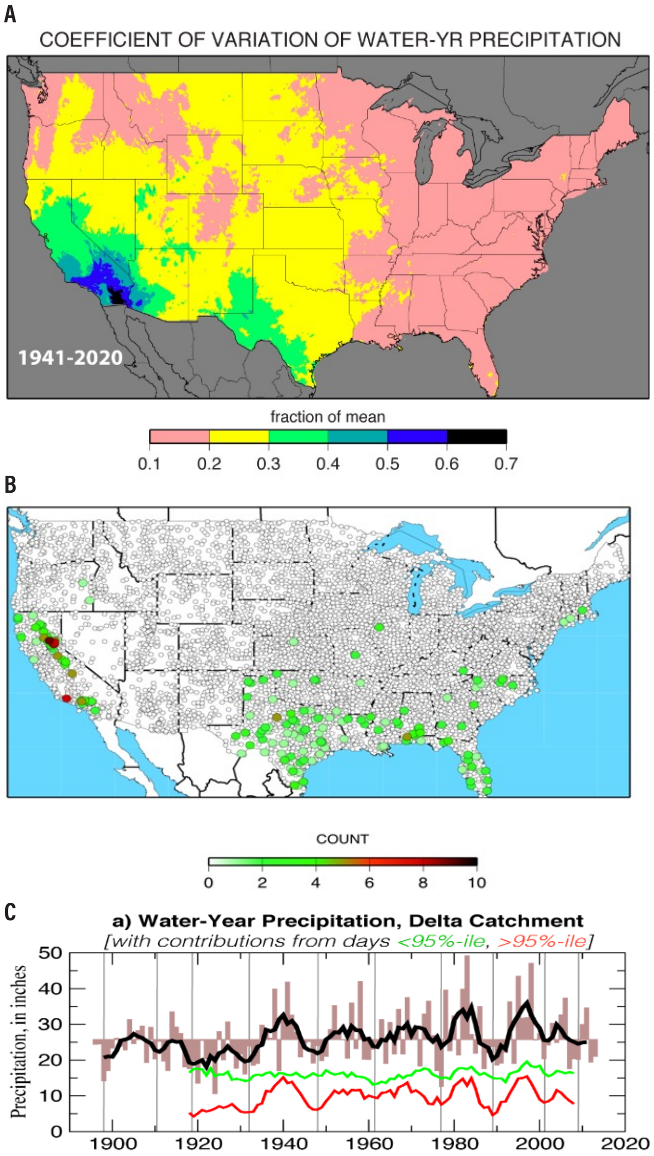

Figure 1 Coefficient of WY precipitation (**A**) update to Figure 2B in Dettinger et al. (2011); count of storms with at least 40 cm accumulations in at most 3 days (**B**), Dettinger et al. (2011); and the dependence of low-frequency annual precipitation variation on the wettest 5% of wet days (**C**) adapted from Figure 1 in Dettinger and Cayan (2014).

the largest river on earth. Transporting tropical moisture to higher latitudes, ARs produce heavy precipitation when they encounter mountains. ARs are historically associated with extreme and strongly orographic precipitation (Ralph et al. 2006; Neiman et al. 2008) along the mountainous west coasts of continents. ARs drive the vast majority of flood damages along the west coast of North America (Corringham et al. 2019), with northern California located in the bullseye of their winter-time landfalling activity (Gershunov et al. 2017). The warm, heavy, orographic precipitation and rain-on-snow events associated with ARs in California (Hatchett et al. 2017) tend to generate much more runoff from topography and associated streamflow in elevated basins than other types of winter storms, especially when associated with snowmelt (Katz et al. 2023). Atmospheric rivers also result in more remote downstream flooding than other colder winter storms (e.g., Konrad and Dettinger 2018). Atmospheric rivers are not associated with El Niño or La Niña events; strong AR effects can potentially occur in any year. Since time immemorial, the Bay–Delta has experienced AR effects that range from beneficial to hazardous.

The most devastating flooding that occurred in recent memory on the Bay–Delta was the 1997 New Year's flood (hereinafter the NY 1997 flood; Rhoades et al. 2024) when nine people lost their lives, 120,000 were displaced, and property damage was estimated at almost $3 billion[2]. The NY 1997 flood was preceded by other destructive floods, notably in 1986, in 1955, and in the Great Flood of 1862. We often associate El Niño—anomalous warming of the tropical Pacific Ocean—with copious precipitation in California (e.g., Goddard and Gershunov 2020). This is part of the so-called "canonical" El Niño signal, i.e., anomalously wet southwest and dry northwest. However, none of the big Bay–Delta floods occurred during El Niño years. In other words, none of these floods occurred during climate states conducive to skillful seasonal climate forecasts of wet winters (e.g., Gershunov and Cayan 2003). In fact, the floods of 1955 and the more recent flooding of 2017 and 2023 occurred during La Niña winters, when dry anomalies are generally expected in California (Luna Niño et al. 2025). All of these floods were triggered by inordinate AR activity during times when significant snowpack had already accumulated over the Sierra Nevada. ARs do not dance to the tune of El Niño–Southern Oscillation (ENSO)—the oscillation of the tropical Pacific

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2. In 2023 USD according to Wikipedia: *https://en.wikipedia.org/wiki/1997_California_New_Years_Floods*

Ocean between El Niño and La Niña states—which makes ARs capable of triggering floods in any winter, even during drought, and without regard to the traditional sources of seasonal climate predictability (Guirguis et al. 2024; Luna Niño 2025).

Damaging AR-driven floods have occurred in the 21st century, all set against a backdrop of California's exceptionally high hydroclimatic variability, exemplified by the recent succession of droughts and wet years. After 5 years of intense drought (2012–2016), water year (WY) 2017 was extremely wet—and dominated by AR activity unprecedented since at least the late 1940s (Gershunov et al. 2017). An anomalously large snowpack accumulated on the Sierra Nevada from an unusually long series of ARs in early midwinter. Then two back-to-back ARs moved over the Feather River basin: the first cold pulse accumulated more snow on February 7, and the second—warm pulse—dumped rain on top of snow. Although not extreme, as far as ARs go, these events produced more runoff than was predicted, primarily as a result of antecedent soil moisture (Haleakala et al. 2023). This overwhelmed Lake Oroville, already in crisis owing to compromised spillways (Vano et al. 2019). Persistent precipitation and runoff overtopped Oroville Dam's emergency spillway, leading to evacuation of 188,000 people downstream, and a billion dollars in damage to the dam and the hill slope beneath it. California then vacillated from floods to drought during WY 2018, and back to floods in the very wet WY 2019. The following 2 years were marked by dry winters and warm summers. By the summer of 2021, the level of Lake Oroville was at a record low, to the point that its hydroelectric plant shut down for the first time since it began operation in 1968. This most recent drought deepened in WY 2022. In WY 2023, a La Niña year, California was treated to extreme precipitation from ARs and widespread flooding—even while the region was still in the grip of drought (DeFlorio et al. 2023)[3]. In addition to extreme precipitation, WY 2023 resulted in unprecedented snowpack accumulation in the central and southern Sierra Nevada, facilitated by anomalously cold temperatures (Guirguis et al. 2024). As the snow melted, Tulare Lake reappeared in the southern Central Valley for the first time in a quarter century.[4] The role of ARs in this extreme volatility illustrates California's changing hydroclimate and motivates this paper.

Expected Change Based on Climate Projections

As climate warms, this natural volatility will be exacerbated by the fact that the frequency of storms is expected to decrease (i.e., dry days will be increased, Figure 3, Polade et al. 2014, Gershunov et al. 2019), especially in the shoulder seasons of fall and spring (Pierce et al. 2013a), while the intensity of extreme storms is expected to increase (Polade et al. 2017; Gershunov et al. 2019; Rhoades et al. 2020; John et al. 2022; Figure 2). These two signals are present with high confidence in nearly all global climate models (GCMs) and together they drive the high-confidence expectation of an increasingly volatile California hydroclimate (Polade et al. 2014, 2017; Dettinger 2016; Gershunov et al. 2019; Douville et al. 2021). Increasing volatility is expected for two related reasons, with both signals contributing: (1) decreasing sample size of storms translates into greater sampling variability, and (2) greater contribution of enhanced extreme storms to the annual total precipitation means that the total increasingly depends on the occurrence (or not) of at least one extreme AR storm in any given year (Gershunov et al. 2019).

Both signals increase the year-to-year variability of the annual total precipitation in climate projections, leading to anticipation of increased floods as well as drought in the warming climate. The expectation for flood from stronger ARs, however, may be somewhat mitigated by the drier soils expected in a warmer environment with fewer storms (Cao et al. 2020; Rhoades et al. 2024) as well as decreased snowpack (Rhoades et al. 2022). However, new hydrologic modeling over the Bay–Delta watershed suggests that extreme runoff events are expected to scale up disproportionately to the projected enhancement

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[3] *https://lofgren.house.gov/2023-winter-storms*

[4] *https://sierranevadaalliance.org/the-resurgence-of-tulare-lake-in-california/*

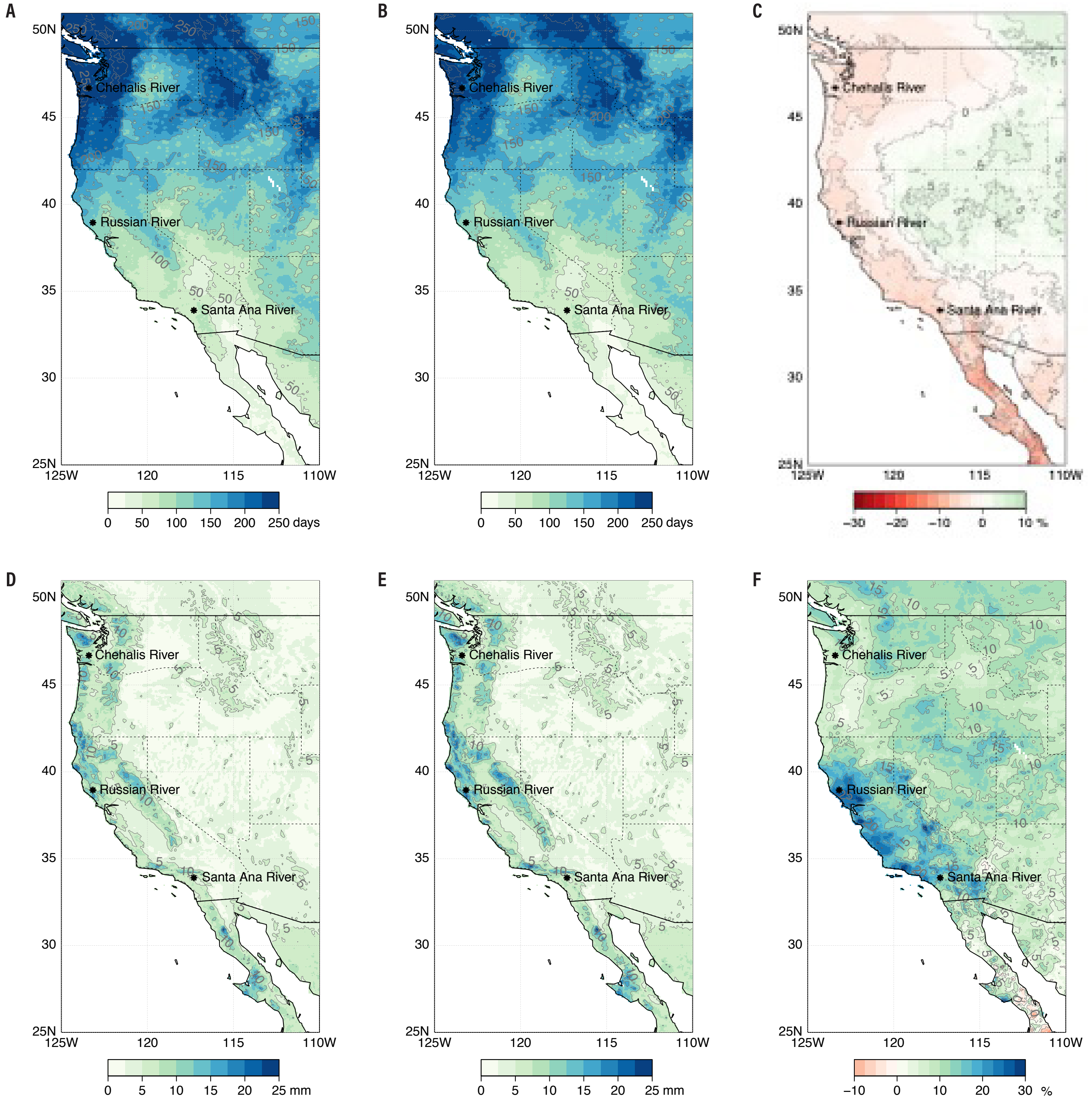

Figure 2 Data from five CMIP5 GCMs considered most realistic for the contribution of AR landfalling activity to total precipitation (Gershunov et al. 2019), statistically downscaled by Localized Constructed Analogs (LOCA; Pierce, Das, et al. 2013). GCM ensemble average of daily precipitation intensity or accumulation during historical (1951–2000, left) and projected (2051–2100, *middle*) water years (July–June) and (*right*) the change (%) of daily precipitation frequency (*top*) and intensity (*bottom*) over the projected period, relative to the historical period, using the Representation Concentration Pathway (RCP) 8.5 "business as usual" forcing scenario. Daily precipitation intensity is defined as the total accumulation over a period (in this case over 50-year time-periods) divided by the frequency or the number of precipitating days. It is a climatological average accumulation on a precipitating day. *Source: Combined from Figures S4 and S5 in Gershunov et al. 2019.*

in extreme precipitation (see results in the "Flood Risk" section).

Projected declines in precipitation frequency are hypothesized to be from changes in atmospheric dynamics—i.e., the widening of the subtropical belt and poleward displacement of the jet stream (Johanson and Fu 2009; Lau and Kim 2015)[5]—while changes in intensity are from thermodynamics, with wetter ARs resulting from the increasing water-vapor holding capacity in a warming atmosphere (Gao et al. 2015; Lavers et al. 2015)—i.e., the ability of air to contain water vapor increases by 7% for every degree C of warming. This thermodynamic effect of warming on precipitation intensity—particularly from near-saturated ARs—is straightforward (i.e., more precipitation from wetter ARs that encounter the same topography), which is why all climate models project increasing precipitation intensity in a warming climate (Dettinger 2016; Gershunov et al. 2019; Williams et al. 2024, Figure 2, bottom panels). The inordinate enhancement of extreme precipitation (Williams et al. 2024), specifically from ARs (Gershunov et al. 2019), drives these changes in projected precipitation intensity.

In the same vein, atmospheric-modeling experiments that simulated the two AR pulses that triggered the Oroville Dam crisis in 2017 under pre-industrial, current, and future levels of global warming were performed by Michaelis et al. (2022). Modeled precipitation for the actual event in 2017 was modeled to be about 11% to 15% heavier over the Feather River basin compared to what would have fallen from the same storm in pre-industrial times; and still greater enhancements were projected for the warmer future. Similarly, dynamical model experiments that re-forecasted in a warmer world the costliest AR-induced flood event in California history (the New Year's flood of 1997), showed enhanced storm total precipitation with strong contribution from short-duration, high-intensity rainfall (Rhoades et al. 2024).

The two projected signals of less frequent but more intense precipitation largely cancel each other out in terms of their contribution to the water year total precipitation, leading to model uncertainty in the total average water year precipitation change for California as a whole. While the trend toward more volatility is challenging for water-resource management, it is preferable to the wholesale drying projected for other Mediterranean climate regions around the world, where decreased frequency of storms is the dominant signal (Polade et al. 2017). In a warmer future, California will likely have to contend with more drought (Cook et al. 2021; Williams, Cook et al. 2022)—particularly snow drought—as the emergence of low-to-no snow conditions in the Sierra Nevada continues (Siirila–Woodburn et al. 2021; Rhoades et al. 2022) along with increased atmospheric evaporative demands (McEvoy et al. 2020; Albano et al. 2022). California will also have to contend with more flooding, resulting in increasing flood damages (Rhoades et al. 2021; Corringham et al. 2022). The projected implication for water resources, tersely distilled, is that California must learn to derive more of its future water resources from less reliable snowmelt, fewer storms, and more punctuated floodwater.

Williams et al. (2024) scrutinized climate-model projections to assess the timing of when trends in precipitation intensity are expected to emerge from natural variability. This time of emergence (TOE) analysis of trends in average precipitation intensities—as well as the intensities of the most extreme storms—provides important timing detail on when enhanced heavy and extreme precipitation should become statistically detectable. Time of emergence analyses were performed over sub-regions of the western US and in individual members of 35 Coupled Model Intercomarison Project (Phase 6) CMIP6 model ensembles and two (mid- and high-level) emissions scenarios: 552 members in total. These statistically rigorous results indicate that the projected increase in precipitation intensity over California should not be expected to detectably emerge (i.e., with statistical confidence) from natural variability until closer to the end of the 21st century.

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[5] A shift in storm types is also expected. Although the number of total storms that affect California is projected to decrease in a warmer future, the number of ARs would increase, as more wet synoptic situations would be promoted to AR status in a warmer and moister atmosphere.

As the precipitation intensity increases while the frequency of precipitation decreases, California's natural hydroclimate volatility is expected to intensify in a warming climate (Gershunov et al. 2019). This is a high-confidence expectation from climate models for all Mediterranean climate regions (Polade et al. 2014), which seems to be already playing out globally as increasing "hydroclimate whiplash," i.e., sharper swings between extremely dry and wet conditions (Swain et al. 2025). The naturally exceptional and projected increasing nature of California's hydroclimate volatility hampers our ability to detect emerging hydroclimatic trends with statistical confidence. The TOE results of Williams et al. (2024) certainly suggest this to be the case. Given these considerations, should we expect ARs to already be boosted by more than 1° C warming that has occurred since pre-industrial times (IPCC 2021)?

Observations vs. Projections

Trends towards more intense precipitation—a key element of hydroclimate change projected over the western US by climate models—have not yet been observed. If anything, in northern California, the most intense daily precipitation accumulation has been trending down (Figure 8A in Lamjiri et al. 2020; Hoerling et al. 2021; Williams et al. 2024), possibly contributing to a decrease in levee breaks observed over recent decades (Rittelmeyer et al. 2025). Far northern California is in the climatological bull's-eye for strong AR landfalls, and where ARs contribute the most —roughly half—of average water year precipitation (Gershunov et al. 2017). Moreover, trends in precipitation frequency have not clearly been observed, though Luković et al. (2021) hint at a delay in the start of winter rains, which is expected from the projected narrowing of the wet season (Pierce, Cayan, et al. 2013a; Swain et al. 2018). This would be important for decreasing the runoff efficiency from storms that do finally arrive in winter. Weakening autumn precipitation can thus affect water resources and even flooding. The observed precipitation timing trends are, however, tenuous at best.

Let us consider trends in precipitation intensity—arguably the variable most directly related to flooding—and highlight the key reasons why the projected increase in extreme precipitation is not seen in observations. The nonlinear dependence of saturation vapor pressure on temperature (i.e., the Clausius–Clapeyron law that describes the water-vapor holding capacity of the atmosphere) dictates that in a warmer climate, saturated air (i.e., air at 100% relative humidity) should carry 7% more water vapor for every 1° Celsius (1.8° Fahrenheit) warming. Near-saturated ARs, therefore, should be wetter in a warmer climate. However, climate change could also alter the atmospheric circulation associated with these storms, and inordinate natural variability as well as other possible issues (see "Caveats" section in Appendix A) can interfere with the thermodynamically driven trends in precipitation intensity and their detection. Moreover, there is evidence for stronger AR scaling and super Clausius–Clapeyron scaling for high-frequency (e.g., hourly and sub-hourly) precipitation (Westra et al. 2014; Najibi and Steinschneider 2023). As far as the observations are concerned, the TOE results of Williams et al. (2024) apply to both average precipitation intensities and the intensities of the most extreme storms, albeit at daily resolution. These results suggest that natural decadal variability is still the main source of observed trends.

Northern California naturally experiences multi-decadal oscillations between wet and dry epochs (e.g., Mantua et al. 1997), although GCMs may traditionally underestimate this low-frequency variability (Ault et al. 2012). The observed climate can be expected to continue on this highly variable trajectory, becoming increasingly variable as extreme ARs increasingly deliver more of the future annual total precipitation. Such a trajectory is in line with model projections. So far, examinations of several re-analysis datasets (Williams et al. 2024; Henny and Kim 2025) indicate that, while moisture transport has increased globally, Pacific moisture transports into California have not increased. This is because decadal trends in atmospheric circulation (dynamics) have negated the expected increases from atmospheric moistening that result from warming alone (thermodynamics).

These dynamical changes likely result mainly from natural decadal climate variability, which may have masked an increasing flood risk (Bass et al. 2022). It is, therefore, possible that strongly enhanced precipitation extremes could emerge, boosting regional hydroclimate extremes sooner than expected (Ombadi et al. 2023). There is also evidence that aerosol emissions have masked wintertime extreme precipitation shifts in the western US induced by anthropogenic climate change (Risser et al. 2024), so that future anticipated decreases in pollution and continued warming can boost precipitation extremes and flood risk sooner than expected. Given California precipitation's strong natural decadal variability (Malamud–Roam 2006; Ault et al. 2013; Howard et al. 2023) and the inherent volatility of our hydroclimate, abrupt shifts of near-future hydroclimate change are possible. Such shifts appear to be consistent with the envelope of possibilities outlined by current climate-model projections (Williams et al. 2024)—an envelope defined by natural variability with a strengthening boost from climate change. This strong natural variability certainly makes it challenging to detect trends with statistical confidence in both models and observations.

For applications to something as important as future damaging floods in the Bay–Delta, however, detection of trends with high statistical significance will occur long after such trends and their effects on society have already emerged. Fundamentally, science needs a better way to detect change beyond worrying when a trend becomes statistically significant. There are options for this, including relaxing the confidence requirements (i.e., lowering the *p*-value for trend detection), that can better inform water management now. Another option is to develop and apply novel probability models tailored to quantify the probabilities of extreme precipitation events—including observed damaging extremes and unprecedented or out-of-sample storms. In the section, "Estimating Probabilities of the Perfect Storm in a Non-Stationary Climate," we apply such a model to quantify the evolving return periods of the NY 1997 Bay–Delta flood.

In summary, although thermodynamics alone should already be increasing the potential for wetter extremes in California, this potential might not clearly manifest in detectable precipitation intensity trends until much deeper into the century. One caveat to the above results is that they do not guarantee that specific storms and water years might not be affected by global warming much earlier, even now. In other words, these results don't mean that warming is not already affecting precipitation extremes and that effects won't manifest before trends are robustly detected. When dynamic negation is weakened or reversed by natural processes, the thermodynamic effect of climate change can prevail to significantly intensify precipitation, particularly from ARs, even before the long-term trends clearly emerge. Another caveat to the above results also needs to be mentioned. We cannot rule out that GCMs are in some ways deficient in their representation of hydroclimate variability in California and other regions (e.g., Dong et al. 2021). When conducting climate projections, it is essential to validate climate models for their ability to realistically simulate the features of global and regional climate salient to the problem being considered. Echoing previous such recommendations and attempts (e.g., Brekke et al. 2009; CDWR 2015; Gershunov et al. 2019; Pierce et al. 2023), we recommend a systematic examination of the realism of climate models as applied to the atmospheric branch of the water cycle, specifically their ability to realistically simulate salient aspects of the hydroclimate, such as controls on water vapor transport by atmospheric circulation, ARs, and other storms.

Precipitation Type (Snow-to-Rain Transition and ARs)

The above concerns apply to precipitation amount, not the type of precipitation, which many observational studies have shown to be clearly changing because of warming. The snow-to-rain transition has been creeping up the slopes of western topography—and California's mountains in particular—over decades now (Mote et al. 2005; Knowles et al. 2006; Barnett et al. 2008; Hatchett et al. 2017; Mote et al. 2018; Shulgina et al. 2023) and is expected to continue into the foreseeable future. This is the first-order effect of global warming with which observations and climate models clearly agree (Siirila–Woodburn et al. 2021). This snowpack loss and the corresponding decline of spring streamflow of about 10% per century have been known since the work of the CDWR's Chief Hydrologist, Maury Roos, in the 1980s (Roos 1987, 2003). Figure 3 (Figure S5 from Shulgina et al. 2023) shows that projected changes in seasonal snow accumulations in the Central Sierra show the largest declines between 2,000 and 3,000 m of elevation, amounting to over 1.5 million acre-feet of snow-water-equivalent (SWE) lost in an average year by the second half of the 21st century.

Much of this snow accumulation decline results from warming, via the snow-to-rain transition, which affects both AR and non-AR storms. Snow loss from AR storms is less affected, however, because AR-related precipitation is expected to increase with wetter ARs, while precipitation from other storms not meeting AR criteria is expected to decline (Figure 2B), becoming less frequent (Gershunov et al. 2019). Snow accumulation from ARs is actually projected to increase above 3,000 m (Figure 3A) where snow accumulation is less threatened by warming, particularly in mid-winter. The snow season in California's mountains is also projected to narrow, however, mainly as the result of continued warming (Shulgina et al. 2023). Though heavy and record snow years such as WY 2023 are still possible, they are expected (with a high degree of confidence) to become rarer. However, at the highest elevations of the Central and Southern Sierra, the wetter ARs we expect in the coming decades (based on thermodynamics and climate-model projections) may make anomalous to unprecedented heavy snowfalls more likely (Shulgina et al. 2023; Figure 3A). Essentially, the competing effects of warming (which decreases the fraction of precipitation falling as snow) and Clausius–Clayperon scaling (which increases precipitation intensity, particularly from ARs), result in a great anticipated decline in median snow-accumulation years, compared to a more modest anticipated decline in heavy snow-accumulation years (Marshall et al. 2024).

The big picture over the Sierra Nevada shows increasing total precipitation from greater AR activity and a coincident decrease in snow accumulation (Figure 3). If, as results of Gershunov et al. (2019) suggest, the greater projected AR precipitation will be at least partially fueled by wetter ARs that lead to more extreme orographic precipitation, then in a warmer future we can expect more frequent and more extreme runoff episodes in winter. A median-dominated snowpack decline can exacerbate such trends, allowing for increasingly occasional intense rain-on-snow runoff events with continued warming. More rain and less snow generally means more winter flows for the same amount of precipitation, and flashier flows, with more wintertime snowmelt events, all of which bolsters extreme runoff, and prepares soils for more flood potential from subsequent storms (e.g., Stewart et al. 2005; Knowles et al. 2006). We show runoff projections later in the "Projected Precipitation and Runoff Extremes" section.

OBSERVED AND PROJECTED EXTREME PRECIPITATION AND RUNOFF EVENTS

Estimating Probabilities of the Perfect Storm in a Non-Stationary Climate

Probability models designed to reflect physical reality can be used to focus on the changes expected in the likelihood of specific events that have lasting, damaging, and expensive effects. An example of such a physically-consistent probabilistic modeling approach is the trivariate event distribution (TED) used to estimate probabilities and return periods of specific precipitation events (Weyant et al. 2025). Trivariate events are defined according to three variables: duration, maximum intensity, and total magnitude of precipitation. The maximum intensity and total magnitude both comprise exceedances over a threshold, which themselves are modeled consistently with peaks-over-threshold (PoT) theory. Peaks-over-threshold theory is typically applied only to the probability distribution of arbitrarily isolated precipitation

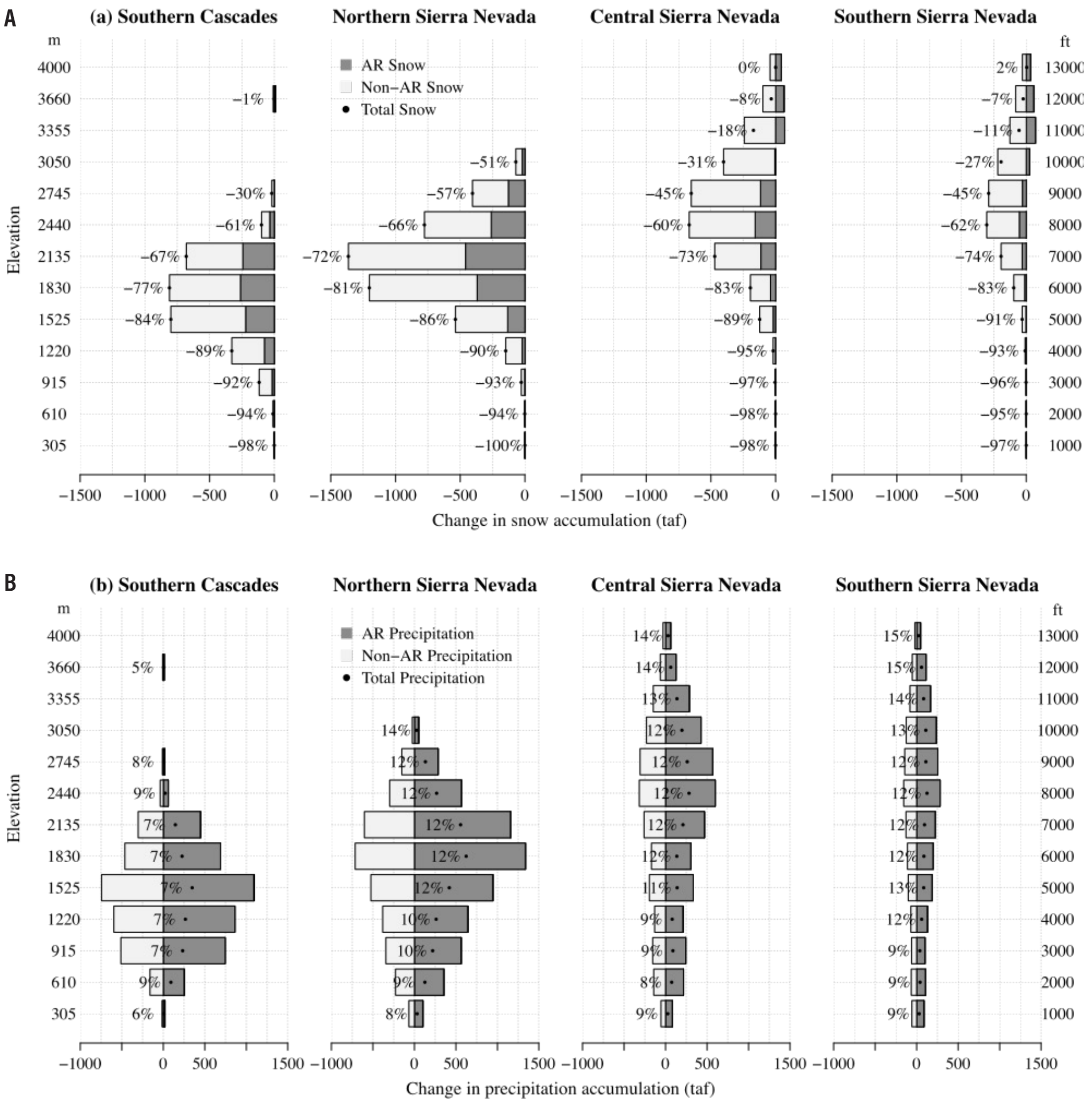

Figure 3 Change in the seasonal snow (**A**) and total precipitation (**B**) accumulations by elevation shown in dots and associated percentages. Contributions from ARs (and other storms) are shown in *dark* (*light*) *bars. Source: Figure S5 from Shulgina et al. 2023.*

accumulations over prescribed durations (such as 1 day or 72 hours). We can now apply it to physical events of random duration. As in Weyant et al. (2025), the threshold is the 75th percentile of the local distribution of daily precipitation accumulations, which accounts for well over half of total annual precipitation at most California locations. Duration is a random variable that represents consecutive days of precipitation exceedances over the threshold. The events thus defined are therefore sequences of relentless or unceasing precipitation, judged (in this analysis) at the daily scale.

This model is flexible to quantify the probability of any precipitation event defined by these three variables. Here, the TED is applied to quantifying the evolving return periods of a damaging historical precipitation event associated with the NY 1997 flood. Specifically, TED is fitted to observed and modeled historical and projected precipitation events over the Yuba River basin (YRB). Table 1 presents the twenty largest observed events according to their total accumulation of precipitation—magnitude above the threshold plus the sub-threshold precipitation—over a record that spanned from 1951 to 2024. Most of these events were associated with Bay–Delta floods that ranged from widespread to localized. According to the SIO-R1 AR Landfalling Catalog (Gershunov et al. 2017), all 20 highest-ranking, upper YRB precipitation events listed in Table 1 were associated with ARs.

The NY 1997 storm that triggered levee failures and severe flooding in the Bay–Delta ranks fourth on the record. Recorded from that storm was precipitation accumulation of 472 mm that fell in 5 consecutive days above the 75th percentile threshold (19.7 mm averaged over the upper YRB), with a maximum of 160 mm in a single day. There have been larger precipitation events in the upper YRB before NY 1997 on this record:

- The December 1955 precipitation event associated with catastrophic floods ranks first, at 660 mm in 7 consecutive days of above-threshold precipitation.
- The February 1986 event associated with the next most recent widespread Bay–Delta flooding ranks second, at 648 mm in 8 days.
- The storm that triggered the Christmas 1964 floods—widespread in the Bay–Delta and more catastrophic further north—ranks third, at 543 mm falling in 6 consecutive days of above-threshold precipitation.

Five 21st-century events ranked in the top 20: January 2017 (6th), October 2021 (10th), November 2012 (11th), February 2017 (14th, the Oroville AR), and December 2002 (18th).

Table 1 The 20 highest-ranking precipitation events averaged over the upper YRB from an observational record from 1951 to 2024 based on the nClimGrid-Daily data set (Durre 2022). The threshold used in the POT set-up is 2 cm in the 75th percentile of upper YRB precipitation. Ranking is relative to the total.

Start date	Duration (d)	Maximum (mm)	Total (mm)
1955–12-18	7	178	659
1986-02-13	8	151	647
1964-12-19	6	177	543
1996-12-30	**5**	**160**	**472**
1962-10-11	4	1 46	448
2017-01-08	4	113	383
1980-01-12	6	122	377
1963-01-30	3	149	366
1969-01-19	4	117	358
2021-10-21	6	154	357
2012-11-29	5	104	353
1980-02-15	7	70	350
1995-01-07	5	106	340
2017-02-06	5	92	331
1991-03-01	5	89	299
1973-11-10	5	102	297
1995-03-09	4	115	294
2002-12-13	5	91	285
1962-02-07	5	120	285
1981-11-12	6	75	284

Below, we assess daily precipitation accumulation associated with NY 1997 by YRB sub-basins (Figure 4). However, we acknowledge that antecedent conditions—as well as the storm's temperature—amplified flood waters. Precipitation accumulation leading to NY 1997 was already about 50% above average over most of the YRB by the time the AR made landfall on December 29, 1996 (Rhoades et al. 2023 and Figure 4B); the soil was saturated, and an anomalous snowpack awaited the storm. Over the upper YRB, precipitation ramped up over several days to a maximum of 160 mm on January 2, 1997 (Figure 4C). On that seventh consecutive day of precipitation (fourth day of the event defined by TED), maximum temperature reached 7 °C at 2,100 m and 3 °C at 2,900 m, promoting major flooding, exacerbated by a ripe snowpack over saturated soils (Rhoades et al. 2023).

To simulate the evolving probability of the NY 1997 storm, TED has also been applied to statistically down-scaled CMIP6 simulations of historical and projected future precipitation extremes under the moderate to high emissions scenario. The down-scaling was done via the Localized Constructed Analogues (LOCA2) methodology (Pierce et al. 2023) and averaged over the upper YRB (Figure 4D). These projections indicate modest increases in daily mean precipitation magnitudes (not shown): about 5%

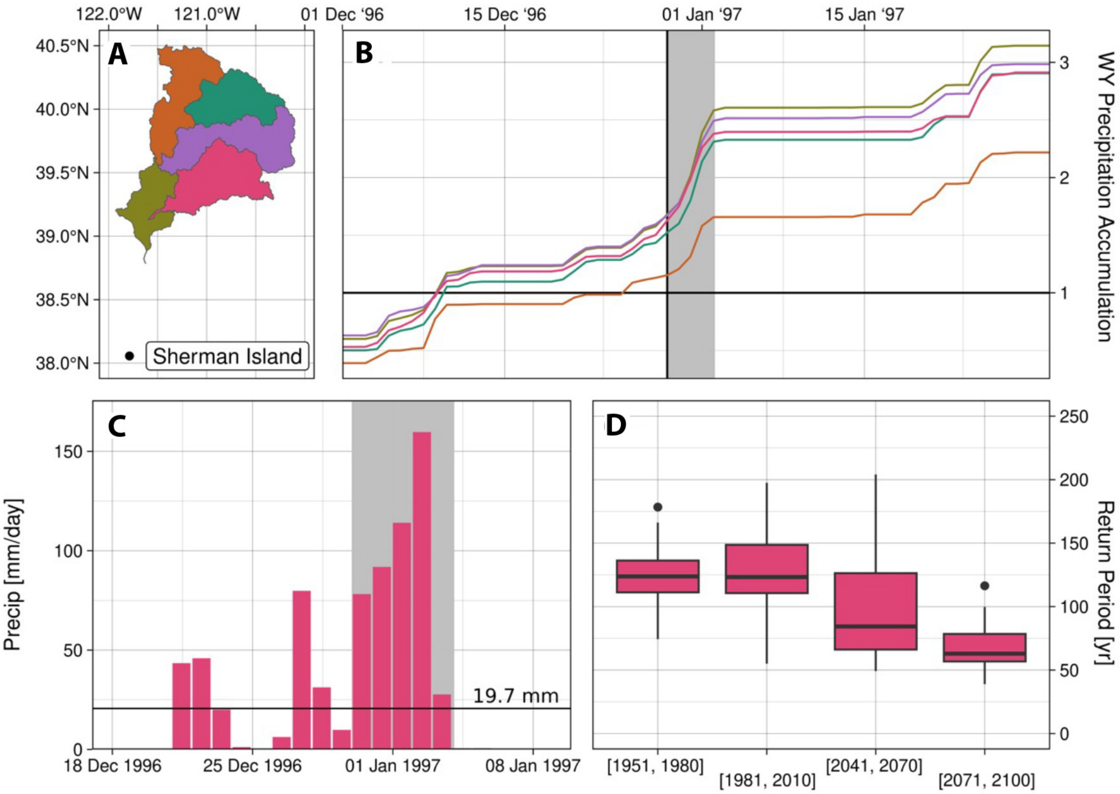

Figure 4 Overview of the NY 1997 precipitation event in observations (nClimGrid) and in climate projections (CMIP6 LOCA2 CA Hybrid), under the moderate to high Shared Socioeconomic Pathway (SSP370, Meinshausen et al. 2020). (**A**) Map of the Yuba–Feather watershed, subdivided at the hydrological unit code 8 (HUC8[6]). (**B**) Progression of WY 1997 in the sub-watersheds; all values are relative to the climatological average precipitation accumulated from the beginning of the water year through the beginning of the NY 1997 event, 1 October through 29 December. (**C**) Observed daily precipitation time-series in the upper Yuba around NY 1997; the event-defining threshold of 19.7 mm/day is plotted as a *horizontal line segment*, and the NY 1997 event has *grey shading* behind it. (**D**) Box plots of estimated return periods of an event total precipitation that exceeded the total observed during the NY 1997 event (472 mm in nClimGrid). In the construction of the box plot, there is one data point per climate model, with 14 GCMs used.

over the historical (1981–2010) in the mid-century (2041–2070), and 10% by the end-of-century (2071–2100). Based on Figure 4D, we can expect an event of NY 1997 magnitude to become about twice as likely in the future, i.e., from a roughly 135-year to a 75-year event by the end of the century. This ensemble median result is robust in that twelve out of the fourteen GCMs considered agreed that event totals this large will be more likely by the end of the century. Much of this change arises from projected changes in precipitation intensity rather than duration.

Projected Precipitation and Runoff Extremes

The largest observed precipitation events do not necessarily lead to the largest floods, though the highest-ranking events listed in Table 1 were associated with flooding in the Bay–Delta, ranging from widespread to localized. The flood effects from any wet storm are determined by factors beyond the duration, maximum intensity, and overall magnitude of the given storm itself. The following elements are all important in conveying precipitation into streamflow: snowline, antecedent soil moisture and snowpack, geographic and geological features of the watershed, engineered infrastructure,

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6. US Geological Survey, National Hydrography Dataset (version USGS National Hydrography Dataset Best Resolution (NHD) for Hydrologic Unit (HU) 8. *https://www.usgs.gov/national-hydrography/access-national-hydrography-products*

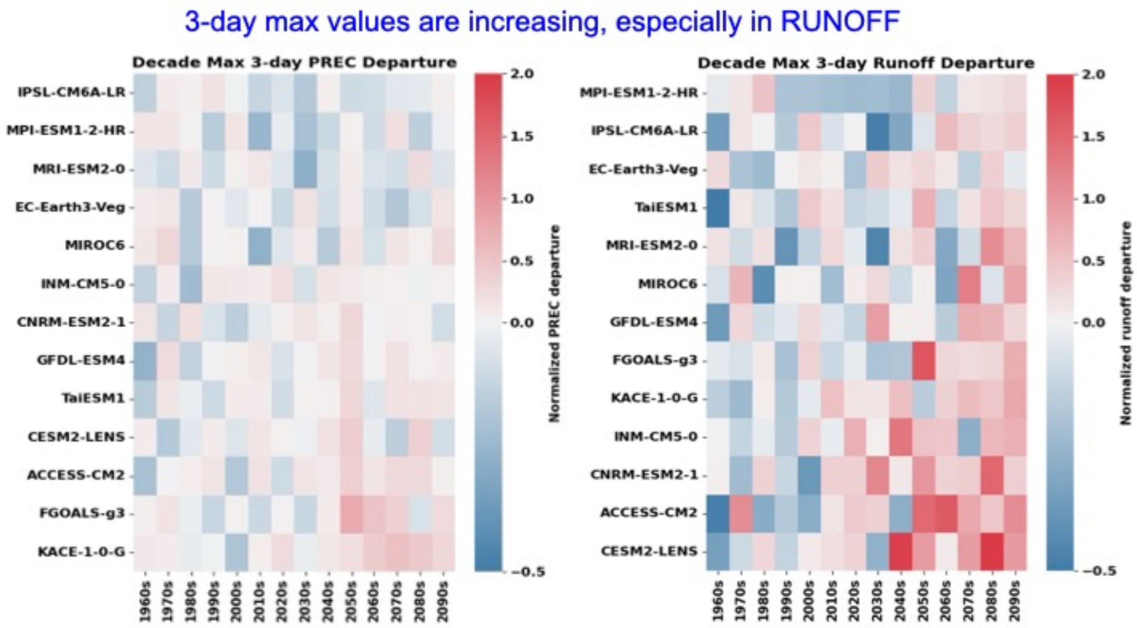

Figure 5 CMIP6 global climate model (GCM)-based projections of the 3-day maximum precipitation (*left*) and runoff (*right*) per year—not necessarily the same 3 days—averaged over each decade, in one realization of each of the LOCA2 (Pierce et al. 2023) down-scaled models, and variable infiltration capacity (VIC)-simulated runoff forced by said down-scaling for the SF Bay Delta watershed. The strength of the trends in precipitation (*left*) and runoff extremes (*right*) determines the ordering of the 13 GCMs along the *y*-axes of the two heat maps.

and management decisions (see "The Observed Effect of Water Management on Flow" section). Thus, insured flood losses are more related to runoff than to precipitation, and the relationship between runoff and damages is not linear—the most extreme runoff events cause the bulk of the damages (Tom Corringham, pers. obs., unreferenced). In a particular watershed, though, bigger storms tend to lead to bigger floods, with the caveats that temperature matters via snowline in snowy basins, and what weather led up to the storm also matters in determining runoff efficiency.

Examinations of how the projected hydroclimate change of decreasing frequency of cool-season precipitation translate into surface hydrology have been carried out for rain-dominated US west-coast basins (Cao et al. 2020). Figure 5 presents projections of the 3-day maximum precipitation (left) and runoff (right) per year averaged over each decade, not necessarily the same 3 days, in one realization of each of the 13 LOCA2 down-scaled CMIP6 global climate models and variable infiltration capacity (VIC) modeled runoff forced by this downscaling (Pierce et al. 202b) for the Bay Delta watershed. A projected change in maximum 3-day precipitation accumulations, amounting to between a zero and 50% increase by the late 21st century, translates into a much larger—up to 2-fold—increase in runoff extremes. Though the order of the models as they are listed on the two panels of Figure 5 differs by the relative rankings of modeled trends in precipitation vs. runoff, there is a general model-to-model correspondence between maximum precipitation and runoff increases. In other words, stronger trends in extreme precipitation generally tend to translate into much stronger trends in extreme runoff.

Figure 5 demonstrates that not all—but a substantial fraction—of the 13 VIC–CMIP6 model projections exhibit a shift toward intensified 3-day runoff during the mid- to late 21st century. Six of the thirteen Delta watershed projections produced 3-day maximum runoff volumes that amounted to 50% or more than historical volumes. Furthermore, as evident from Figure 5, while there are a few outlier models, the intensification signal generally increases over the last half of the 21st century.

Different GCMs amplify the increase in heavy precipitation in runoff to somewhat different extents. According to previous work (e.g., Stewart et al. 2005; Knowles et al. 2006), this can happen via an increasing rain-to-snow ratio, as well as via more frequent wintertime snowmelt events that moisten soils, to produce a much larger increase in extreme runoff compared to extreme precipitation. How this translates into flood potential is a more nuanced story subject to several caveats discussed by Rhoades et al. (2024).

The VIC hydrological modeling employed here reflects such natural considerations and allows for the exploration of the natural mechanisms (see "Flood Risk" section and Figure A1 in Appendix A), which largely corroborates this view. This close interrogation of one of the representative GCMs shown in Figure 5, suggests that the amplified runoff response appears to be mostly attributable to an increase in the proportion of rainfall and corresponding decline in snowfall that is projected to occur during the substantially warmer future period. Some snowmelt is also projected to contribute to the increased future runoff, but to a much lesser degree (Figure A1). Thus, the warmer future period is projected to produce more peak precipitation, a greater fraction of rain instead of snow, a greater increase in soil moisture, and a disproportionately greater increase in runoff over the Sacramento–San Joaquin watershed. The VIC hydrological modeling does not reflect flow modification from water-management infrastructure and its utilization.

FLOOD RISK

The Observed Effect of Water Management on Flow

The major water resources and hazards management activities and infrastructure in the Central Valley and its tributaries considerably modify outflows and floods that occur through and within the Delta. To explore the modifications to the largest outflows, Florsheim and Dettinger (2015) analyzed management influences on the largest historical (1967–1987) weekly Delta outflows, as estimated with and without upstream reservoirs and diversions (Knowles 2002). In Figure 6 (reproduced from Florsheim and Dettinger 2015), solid curves are of the highest 7-day mean flows with upstream-reservoir effects removed (by frequencies, Knowles 2002) from Dayflow estimates of daily potential and actual Delta inflows; *http://www.water.ca.gov/dayflow*) during winters (black solid curve) and springs (gray solid curve), 1967–1987. For each 7-day flow that comprises the solid curves in Figure 6, the black and gray circles are corresponding Dayflow estimates of actual inflow to the Delta, including upstream-reservoir and diversion effects. Clearly, on many occasions historically, managed outflows were larger than the unmanaged flows would have been, because water from various reservoirs and diversions was added to the otherwise lower natural flows for various reasons; on other occasions, water was held back by reservoirs in flood-management mode, or diverted so that managed outflows were less than the unmanaged flows would have been. To determine the long-term effects on the highest outflows under natural conditions, 20-episode moving averages (roughly speaking, averaged over 20 historical peak-flow episodes) were calculated for the black and gray dots in Figure 6 and are shown there by the heavy dashed curves.

A comparison of the solid curves (unmanaged flood frequencies) with the resulting dashed curves (average of corresponding managed floods) in Figure 6 shows that upstream management reduced the largest winter flood flows just enough, on average, so that they correspond to the magnitude of the largest unmanaged springtime outflows instead. By contrast, in springtime, flood management did not reduce outflows (on average) below the corresponding springtime unmanaged outflows. Thus, upstream management has tended to reduce wintertime (AR) floods to the lesser scales of springtime snowmelt pulses. The effect of this influence is uncertain but potentially significant for floodplain and estuarine ecosystems that have evolved under natural conditions to accommodate—and indeed rely upon— occasional deeper, faster, and broader

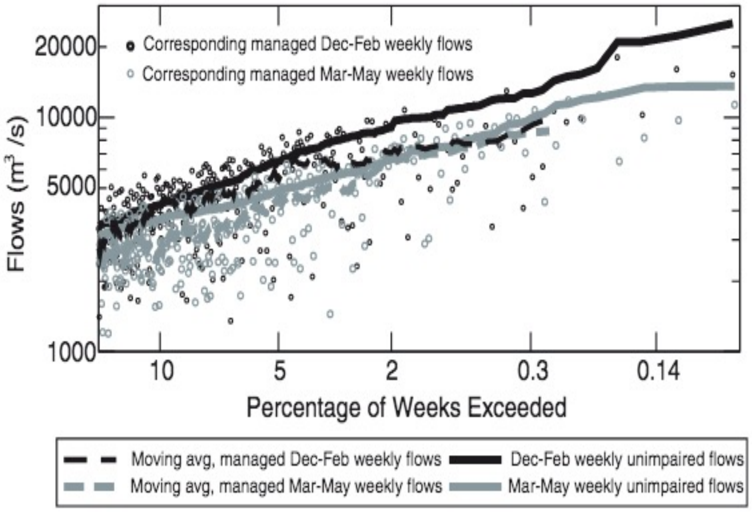

Figure 6 Estimated exceedence probabilities (*solid curves*) of unmanaged 7-day average outflows from the Central Valley, above the Sacramento–San Joaquin Delta, in winters and springs, 1967–1987, with corresponding managed-flow estimates as *circles*, as based on time-series from Knowles 2002. *Dashed curves* are moving averages of *circles*, showing the 20-episode average managed flows around each level of unmanaged flow rate. *Source: Figure 10 of Florsheim and Dettinger 2015.*

wintertime inundations and flows (Sommer et al. 2001). To return to the floodplains and estuary at least some of the ecological and morphological benefits from these occasional floods, some ecologically important floodplains—such as the Yolo Bypass—might benefit from changes to weirs and other controls.

Real and Perceived Flood Risk

In the Bay–Delta, levees protect over 60 low-lying islands, mostly comprising small towns and family-run farms. The Delta is critical for the state's freshwater supply and economy, so its potential to be flooded as the result of levee failures is an issue that affects the safety and well-being of vastly more Californians than solely the residents of the Delta themselves. Most of the islands in the Bay–Delta have experienced at least one levee failure since the early 1900s (URS 2009). There were many levee failures during the 1970s, 1980s, and 1990s, leading to increases in awareness of infrastructural weaknesses. Upstream water management tends to keep fall and winter AR-driven Delta floodwaters in check (Figure 6), and major floods and levee failures have trended down since the 1990s, in part from investments in levee and emergency-management improvements (Rittelmeyer et al. 2025). Levee maintenance and improvements are funded through a cost-share program between local reclamation districts and the state (CDWR 2024). Residents have a nuanced understanding of the conditions under which floods have occurred in the past and the measures to take to prevent them, including daily inspections of the levees and ensuring that barges filled with sandbags are standing by (Rittelmeyer 2020). Nonetheless, even after decades of local, state, and federal collaborative efforts, narratives of flood risk in the Delta range from a problem that is manageable—to one that is not. The local perspective is one of resilience if there is ample and continual funding for levee improvements and maintenance.

FLOOD-MITIGATION STRATEGIES AND RECOMMENDATIONS

Improved Infrastructure and Emergency Response

Planning efforts in California aim to improve resilience to future extreme storms and flooding. These efforts are outlined in planning and programmatic awareness documents (e.g., the Central Valley Flood Protection Plan, the CDWR's Regional Flood Management Planning program, the Flood Managed Aquifer Recharge (Flood-MAR) initiative, and the Delta Plan). These plans and initiatives set the stage for projects to improve flood-management capability, including highlighting state priorities in nature-based solutions and multi-benefit projects. For example, the Central Valley Flood Protection Plan is a comprehensive flood-management strategy focused on reducing flood risk in the Sacramento and San Joaquin river basins. It includes elements such as levee improvements, bypass expansions, and floodplain-restoration projects. Flood-MAR is a complementary example. Working alongside traditional flood-control infrastructure, Flood-MAR can help reduce flood risk in the Bay–Delta by focusing on areas upstream of the Delta. The initiative works by capturing and diverting flood flows onto agricultural lands, working landscapes, and managed natural lands for groundwater recharge, which can help reduce peak flows from reaching the Delta during extreme ARs.

Compounding effects from California's multiple hazards—including sea level rise, earthquakes, and wildland fires—should also be considered. For example, continued increases in the size, frequency, and severity of wildfires in California's mountains temporarily increases runoff ratios across larger contributing areas (Moody et al. 2013; Hallema et al. 2017; Maina and Siirila–Woodburn 2020). In some cases, this could present benefits if the additional runoff is expected and can be accommodated via storage and conveyance systems. In other cases, changes in runoff efficiency as a result of fire-induced alterations in vegetation and the physical properties of soil will increase the frequency and magnitude of floods (Yu et al. 2024) as well as water-quality hazards (Williams, Livneh, et al. 2022). In snow-dominated watersheds, fire-induced loss of canopy and decreased surface albedo from moderate- to high-severity wildfire increases midwinter (Hatchett et al. 2023) and/or spring snowmelt (Koshkin et al. 2022). These land-surface alterations may potentially further alter climate-induced changes in the timing of runoff (Stewart et al. 2005), though additional research is necessary to understand responses in burned areas (Uecker et al. 2020). Together, these changes—combined with expectations for declining snowpack (Siirila–Woodburn et al. 2021) and increased wildfire activity in snowy regions (Hatchett et al. 2024)—provide impetus for the state to prioritize integrated flood risk management and water-supply resilience efforts.

Better Forecasts and More Flexible Reservoir Operations

Given the projections for enhanced precipitation from ARs and the inherent uncertainties associated with projecting extreme precipitation into the changing climate, water-resource management and flood-control efforts can meanwhile directly benefit from improved sub-seasonal and seasonal (S&S) prediction. Existing flood early warning systems are based on weather prediction driving hydrologic models, and typically predict the occurrence of ARs and other extreme weather at a lead-time up of to a week, or possibly 10 days in exceptional cases. Dynamical and statistical approaches have been developed for long-range seasonal outlooks (e.g., North American Multi-Model Ensemble (NMME); Climate Commitment Act (CCA). However, they suffer from various and often common shortcomings. For example, it is becoming clear that ARs do not much care about ENSO—the main source of seasonal predictability in California—and thus ENSO phase does not predict AR-produced precipitation (Luna Niño et al. 2025); consequently, AR precipitation is not well predicted on seasonal time-scales, either dynamically or statistically. We have seen above that some of the most extreme precipitation events leading to some of the most devastating historic floods have occurred in heretical La Niña years when climate forecasts predict deficient precipitation. On sub-seasonal time-scales (2 to 4 weeks out), hybrid dynamical/statistical approaches are most promising for AR effects (Guirguis et al. 2023; Castellano et al. 2023), while at short-range weather prediction time-scales (a week to 10 days out), dynamical models work best. It is possible to develop integrated S&S predictive models to complement short-range weather-prediction systems and help prepare for extreme storms at time-scales and lead times that range from months to days. Seasonal and sub-seasonal prediction models can be combined with probability modeling of events and short-range weather-prediction models into one phased approach for early warning systems to enhance resilience to floods and other extreme weather effects.

Better predictions in terms of both forecast lead time and skill, allowing enhanced anticipation of extreme storms—particularly ARs—will provide additional sources of resilience. Specifically, improvements are needed on S&S lead times and time-scales. California's AR Program and Forecast Informed Reservoir Operations (FIRO), among other efforts, are promoting the improvement of forecasts and facilitating the use of improved forecast information in water- resource management decisions. The AR Program promotes research and monitoring in a comprehensive effort to better understand, predict, and manage ARs, their benefits, and their adverse effects. The program combines advanced monitoring technology—including offshore reconnaissance aircraft and ground-based observations (see below) and sophisticated forecasting models—helping water managers and emergency responders better prepare for both drought-ending rainfall and potential flooding effects. FIRO is an advanced flexible water-management strategy that incorporates modern weather and water forecasting technology to optimize reservoir operations. This system allows reservoir operators to make more informed decisions about water retention and releases, improving both flood control and water supply reliability. FIRO can significantly reduce flood risk via skillful forecasts and improved coordination between reservoir operators and downstream water districts. This has been demonstrated specifically for the Yuba and Feather watersheds affected by historic AR activity (CW3E 2025). Better informed and more flexible reservoir-management strategies in development now are effective adaptation and flood mitigation tools for the future.

The integration of FIRO with Flood-MAR (FIRO-MAR) is particularly critical in mitigating flood risks in the Delta. The Merced River Watershed Flood-MAR Reconnaissance Study (CDWR 2023) demonstrated that leveraging reservoir re-operation strategies in upstream watersheds significantly reduces peak flood flows, lessening the downstream surge into the Delta. Under projected climate conditions, FIRO-MAR strategies were shown to cut peak discharges by up to 50%, reducing the likelihood of levee failures and extensive flood damage in the Delta (CDWR 2023). Additionally, strategic flood diversions enabled by FIRO-MAR provide a controlled mechanism to absorb excess runoff before it reaches the Delta, supporting a more resilient flood-management system. These strategies align with Delta risk-reduction efforts, including the safeguarding of critical water-conveyance infrastructure and agricultural lands. Moreover, the ability to store excess floodwaters in aquifers—rather than allowing them to contribute to Delta flood surges—enhances both water-supply reliability and ecosystem health. Such approaches combining FIRO with Flood-MAR are expected to significantly reduce projected increases in flood risk vulnerability[7]. As Delta flood conditions worsen with rising sea level and bolstered extreme ARs, modernized forecasting tools and flexible reservoir-management approaches such as FIRO-MAR present a practical, science-based solution to balancing flood control, groundwater recharge, and Delta sustainability in California's evolving hydrologic landscape.

Consolidating Existing—and Developing New—Observations

Continued progress in forecasting capabilities and monitoring the success of adaptation strategies rests on our ability to accurately observe California's hydroclimate, especially its extremes, because these are often the most difficult to skillfully forecast and yet the most important to understand. Substantial investments in novel hydrometeorological and long-term climatological observational networks throughout California during the late 20th and early 21st century now provide situational awareness for managers, verification datasets to improve model systems, and help to contextualize extreme events such as ARs (Ralph et al. 2014; Hatchett et al. 2020; White et al. 2013). Surface-based instruments are distributed throughout California, particularly in hydrologically critical watersheds for water-resource management. Relevant instruments

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[7] Substantial flood-management improvements associated with Merced River peak flow, for example, are possible with reservoir re-operation combined with MAR. The reductions of flood risk vulnerability under Lev els 2 and 3 (which both include a FIRO component) Flood-MAR actions are robust, because the expected percentage reductions are similar for 2070 compared with 2040. Level 2 peak flow reduction ranges from 41% to 37% for 2040 and 2070, respectively; Level 3 peak flow reduction ranges from 46% to 50% for 2040 and 2070, respectively (DWR 2024, Section 3.1.2 and Figure 3-2).

include weather and snowpack monitoring stations, stream gages, vertical wind profilers, vertically oriented radars, disdrometers, and soil moisture sensors. Airborne platforms measure atmospheric and land surface conditions during singular flights (e.g., dropsonde data from AR reconnaissance flights and high-resolution LiDAR estimates of snow depth from the Airborne Snow Observatory, which operates over mountain watersheds in the western US). Satellite-based platforms provide continuous (minutes-to-days) observations of atmospheric temperature, moisture, composition, and radiation, as well as land-surface conditions such as soil moisture, snow-covered area, and vegetation health. Uncrewed autonomous vehicles, additional sensor networks that measure diverse phenomena, as well as airborne and spaceborne hyperspectral imagery are areas where technological advancement will support management and research goals.

Community, or participatory science projects represent an emerging frontier in environmental observations to supplement and address gaps in existing observations and to provide verification datasets. These projects harness the ability of the public to provide spatio-temporally distributed data collection in otherwise data-sparse regions. Relevant programs to flooding and water resource management in California include the Community Collaborative Rain, Hail, and Snow program (CoCoRaHS; a rain-gauge network; Reges et al. 2016), the Mountain Rain or Snow project (MRoS; observations of precipitation phase in mountain areas; Arienzo et al. 2021), and the Community Snow Observations effort (CSO; snow depth observations; Crumley et al. 2021). The CoCoRaHS project provides precipitation data to the Global Historical Climate Network Daily (augmenting other long-term climate monitoring; CoCoRaHS). Data from MRoS supports verification of ground- and satellite-based remote sensing (Jennings et al. 2023), land-surface re-analysis products (Yu et al. 2024), and freezing-level forecasts (Heggli et al. 2024). CSO measurements are assimilated into semi-distributed snowpack models (Crumley et al. 2021).

Long-term, consistent data records are paramount to understanding environmental change. Increasingly, novel observational networks initially established in the late 20th and early 21st century now provide sufficient record lengths to evaluate variability and trends in tandem with traditional weather and climate-observation stations. However, to provide high-quality, useable data for applications in research and operations, both well-established and novel observational networks require continued funding support for maintenance, data management, and visualization. Continued support of existing—and investment in new—technologies will enhance our understanding of both the general aspects and the nuances of how California's hydroclimate is changing, how these changes affect its people and environment, and how to monitor the success of mitigation efforts. While model projections paint a broad picture of change and motivate planning efforts to adapt to a range of outcomes, improved forecasting capabilities at seasonal-to-sub-hourly time-scales drive management decisions and the communication of protective actions. In all cases, maintaining and enhancing observational networks remains critical for efforts that range from extreme precipitation forecasting and immediate flash flood warnings to planning for droughts and floods in a warmer world.

SUMMARY AND CONCLUSIONS

Floods impacting the Bay–Delta system are triggered primarily by AR storms. Climate models project enhanced precipitation from wetter ARs in the future warmer climate, but also a decline in snowpack at low-to-middle elevations. Strong model agreement on the future enhancement of precipitation intensity—particularly from the most intense ARs—is mainly from thermodynamics: the nonlinear dependence of the atmosphere's water vapor holding capacity on temperature (i.e., the Clausius–Clapeyron law), which dictates that in a warmer climate, saturated air (i.e., air at 100% relative humidity) should carry 7% more water vapor for every 1 degree Celsius (1.8 degree Fahrenheit) warming. Strong near-saturated ARs, therefore, should be wetter in a warmer climate. So far, natural decadal variability has affected the atmospheric circulation so as to dampen the thermodynamically driven trends in observed precipitation intensity.

The natural volatility of California's hydroclimate is only expected to increase with further warming because of a decrease in the frequency of non-AR storms and an increase in the intensity of strong ARs. This volatility is making emerging hydroclimate trends—including trends in AR intensity—difficult to detect. Although such trends have not yet been detected in observations of extreme precipitation, the balance of evidence points to wetter ARs in the future. Toward the end of the century, extreme storms—on the order of 500 mm (20 inches) of precipitation accumulated over several consecutive stormy days over the Yuba River basin—are expected to become twice as likely. Maximum 3-day precipitation events are, likewise, projected to increase in intensity, while Bay–Delta watersheds are projected to amplify these increases into disproportionately stronger maximum 3-day runoff events. This is primarily from a greater fraction of rain vs. snow in a warmer climate.

Water management has taken the edge off extreme fall and winter AR-driven Delta flows, while levee failures have been rare since the 1990s, as a result of infrastructure investments as well as recent droughts and a delay in the expected anthropogenic enhancement of extreme AR precipitation. In the meantime, California is undertaking several major water-infrastructure initiatives, including modernizing aging dams, levees, and aqueducts; as well as improving flood protection and groundwater recharge through programs such as the Flood-MAR Initiative. This is part of more general plans to improve California's water resilience—e.g., the Water Supply Strategy and the Water Resilience Portfolio—which include goals for recycling more water, capturing stormwater, strengthening conservation, and improving watershed health.

Planning efforts to enhance California's resilience to future extreme storms and anticipated increasing flood risk can benefit from additional investments into modernizing forecasts: particularly improved sub-seasonal and seasonal prediction, as well as continued maintenance and development of observational networks. As the global climate continues to warm—affecting California's hydroclimate, including snowpack and ARs—we highlight the increasing importance of research-to-operations programs, e.g., the AR Research Program and FIRO. Advancing monitoring and forecasting systems for ARs, and facilitating more flexible reservoir operations via FIRO, comprise a cost-effective approach to more intelligently and effectively utilizing existing infrastructure for more successful and resilient water storage and flood management. In the longer run, integration of FIRO with infrastructure improvements via FIRO-MAR will further enhance California's resilience to extreme ARs, floods and water-supply volatility.

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REFERENCES

Albano CM, Abatzoglou JT, McEvoy DJ, et al. 2022. A multidataset assessment of climatic drivers and uncertainties of atmospheric evaporative demand changes. Atmospheric Res. [accessed 2025 Aug 22];23:505-519. *https://doi.org/10.1175/JHM-D-21-0163.1*

Arienzo MM, Collins M, Jennings KS. 2021. Enhancing engagement of citizen scientists to monitor precipitation phase. Front Earth Sci. [accessed 2025 Jul 8];9:617594. *https://doi.org/10.3389/feart.2021.617594*

Ault TR, Cole JE, St. George S. 2012. The amplitude of decadal to multidecadal variability in precipitation simulated by state-of-the-art climate models. Geophys Res Lett. [accessed 2025 Jul 8];39(21):GL053424. *https://doi.org/10.1029/2012GL053424*

Ault TR, Cole JE, Overpeck JT, Pederson GT, St. George S, Otto–Bliesner B, Woodhouse CA, Deser C. 2013. The continuum of hydroclimate variability in western North America during the last millennium. J Clim. [accessed 2025 Jul 8]; 26:5863–5878. *https://doi.org/10.1175/JCLI-D-11-00732.1*

Barnett T, Pierce D, Hidalgo H, Bonfils C, Santer BD, Das T, Bala G, Wood AW, Nozawa T, Mirin AA, et al. 2008. Human-induced changes in the hydrology of the Western United States. Science. [accessed 2025 Jul 8];319:1080–1083. *https://doi.org/10.1126/science.1152538*

Bass B, Norris J, Thackeray C, Hall A. 2022. Natural variability has concealed increases in western US flood hazard since the 1970s. Geophys Res Lett. [accessed 2025 Jul 8];49:e2021GL097706. *https://doi.org/10.1029/2021GL097706*

Brekke LD, Maurer EP, Anderson JD, Dettinger MD, Townsley ES, Harrison A, Pruitt T. 2009. Assessing reservoir operations risk under climate change. Water Resour Res. [accessed 2025 Jul 8];45(4). *https://doi.org/10.1029/2008WR006941*

Cao Q, Gershunov A, Shulgina T, Ralph FM, Sun N, Lettenmaier DP. 2020. Floods due to atmospheric rivers along the U.S. West Coast: the role of antecedent soil moisture in a warming climate. J Hydrometeor. [accessed 2025 Jul 8];21:1827–1845. *https://doi.org/10.1175/JHM-D-19-0242.1*

Castellano CM, DeFlorio MJ, Gibson PB, Delle Monache L, Kalansky JF, Wang J, Guirguis K, Gershunov A, Ralph FM, Subramanian AC, Anderson ML. 2023. Development of a statistical subseasonal forecast tool to predict California atmospheric rivers and precipitation based on MJO and QBO activity. J Geophys Res–Atmos. [accessed 2025 Jul 8];128:e2022JD037360. *https://doi.org/10.1029/2022JD037360*

[CDWR] California Department of Water Resources. 2015. Perspectives and guidance for climate change analysis. [accessed 2025 Jul 9]. Sacramento (CA): CDWR, Climate Change Technical Advisory Group. 142 p. Available from: *https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Climate-Change-Program/Climate-Program-Activities/Files/Reports/Perspectives-Guidance-Climate-Change-Analysis.pdf*

[CDWR] California Department of Water Resources. 2023. Merced River Watershed Flood-MAR reconnaissance study: baseline performance and climate change vulnerability. [accessed 2025 Jul 9]. Sacramento (CA): California Natural Resources Agency, CDWR. 74 p. Available from: *https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Flood-Management/Flood-MAR/TIR-3--Baseline-Performance-and-Climate-Change-VulnerabilityFINAL.pdf*

[CDWR] California Department of Water Resources. 2024. Delta Levees Maintenance Subventions. Sacramento (CA): California Natural Resources Agency, CDWR. Available from: *https://water.ca.gov/Work-With-Us/Grants-And-Loans/Delta-Levees-Maintenance-Subventions*

[CDWR] California Department of Water Resources. 2024. Merced River Watershed Flood-MAR reconnaissance study report. [accessed 2025 Jul 9]. Sacramento (CA): CDWR, Statewide Infrastructure Investigations Branch. 56 p. Available from: *https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Flood-Management/Flood-MAR/230410_Merced-R_FloodMAR-Reconnaissance-Study_Division-Report_v7.pdf*

Cook BI, Mankin S, Williams AP, Marvel KD, Smerdon JE, Liu H. 2021. Uncertainties, limits, and benefits of climate change mitigation for soil moisture drought in southwestern North America. Earth's Future. [accessed 2025 Jul 8];9(9): e2021EF002014. *https://doi.org/10.1029/2021EF002014*

Corringham T, McCarthy J, Shulgina T, Gershunov A, Cayan DR, Ralph FM. 2022. Climate change contributions to future atmospheric river flood damages in the western United States. Sci Rep. [accessed 2025 Jul 8];12:13747. *https://doi.org/10.1038/s41598-022-15474-2*

Corringham, TW, Ralph FM, Gershunov A, Cayan DR, Talbot CA. 2019. Atmospheric rivers drive flood damages in the western United States. Sci Adv. [accessed 2025 Jul 8];5:12. *https://doi.org/10.1126/sciadv.aax4631*

Crumley RL, Hill DF, Wikstrom Jones K, Wolken GJ, Arendt AA, Aragon CM, Cosgrove C, Community Snow Observations Participants. 2021. Assimilation of citizen science data in snowpack modeling using a new snow data set. Community Snow Observations, Hydrol Earth Syst Sci. [accessed 2025 Aug 22];25:4651–4680 *https://doi.org/10.5194/hess-25-4651-2021*

[CW3E] Center for Western Weather and Water Extremes. 2025. Yuba–Feather Forecast Informed Reservoir Operations final viability assessement. [accessed 2025 Jul 8]. La Jolla (CA): UC–San Diego, Scripps Institution of Oceanography. 175 p. Available from: *https://cw3e.ucsd.edu/FIRO_docs/Yuba-Feather_FVA/Yuba-Feather_FVA.pdf*

DeFlorio MJ, Sengupta A, Castellano CM, Wang J, Zhang Z, Gershunov A, Guirguis K, Luna Niño R, Clemesha RES, Pan M, Xiao M. 2023. From California's extreme drought to major flooding: evaluating and synthesizing experimental seasonal and subseasonal forecasts of landfalling atmospheric rivers and extreme precipitation during Winter 2022–2023. Bull Am Meteorol Soc. [accessed 2025 Jul 8];105(1):E84–E104. *https://doi.org/10.1175/BAMS-D-22-0208.1*

Dettinger M. 2016. Historical and future relations between large storms and droughts in California. San Franc Estuary Watershed Sci. [accessed 2025 Jul 9];14(2). *https://doi.org/10.15447/sfews.2016v14iss2art1*

Dettinger M, Cayan DR. 2014. Drought and the California Delta—a matter of extremes. San Franc Estuary Watershed Sci. [accessed 2025 Jul 9];12(2). *https://doi.org/10.15447/sfews.2014v12iss2art4*

Dettinger MD, Ralph FM, Das T, Neiman PJ, Cayan DR. 2011a. Atmospheric rivers, floods and the water resources of California. Water. [accessed 2025 Jul 8];3:445–478. *https://doi.org/10.3390/w3020445*

Dong L, Leung LR, Song F et al. Uncertainty in El Niño-like warming and California precipitation changes linked by the Interdecadal Pacific Oscillation. 2021. Nat Commun [accessed 2025 Aug 22];12:6484. *https://doi.org/10.1038/s41467-021-26797-5*

Douville H, Raghavan K, Renwick J, Allan RP, Arias PA, Barlow M, Cerezo–Mota R, Cherchi A, Gan TY, Gergis J, et al. 2021. Water cycle changes. In: Masson–Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, et al., editors. 2021. Climate change 2021: the physical science basis. Contribution of Working Group I to the sixth assessment report of the Intergovernmental Panel on Climate Change Cambridge (UK): Cambridge University Press. p 1055–1210. [accessed 2025 Jul 9]. Available from: *https://doi.org/10.1017/9781009157896.010*

Durre I, Squires MF, Vose RS, Arguez A, Gross WS, Rennie JR, Schreck CJ. 2022. NOAA nClimGrid-Daily Version 1—daily gridded temperature and precipitation for the contiguous United States since 1951. Asheville (NC): NOAA National Centers for Environmental Information. [accessed 2025 Jul 9]. *https://doi.org/10.25921/c4gt-r169*.

Florsheim J, Dettinger M. 2015. Promoting atmospheric-river and snowmelt fueled biogeomorphic processes by restoring river-floodplain connectivity in California's Central Valley. In: Hudson P, Middelkoop, H. editors. 2015. Geomorphic approaches to integrated floodplain management of lowland fluvial systems in North America and Europe. New York (NY): Springer. [accessed 2025 Jul 9];119–141. Available from: *https://cw3e.ucsd.edu/wp-content/uploads/2015/05/florsheim_dettinger_floodplain_chapter6_2015.pdf*

Gao Y, Lu J, Leung LR, Yang Q, Hagos S, Qian Y. 2015. Dynamical and thermodynamical modulations on future changes of landfalling atmospheric rivers over western North America. Geophys Res Lett. [accessed 2025 Jul 9];42:7179–7186. *https://doi.org/10.1002/2015GL065435*

Gershunov A, Cayan DR. 2003. Heavy daily precipitation frequency over the contiguous United States: Sources of climatic variability and seasonal predictability. J Climate. [accessed 2025 Aug 22];16(16):2752–2765. *https://doi.org/10.1175/1520-0442(2003)016%3C2752:hdpfot%3E2.0.co;2*

Gershunov A, Shulgina TM, Ralph FM, Lavers D, Rutz JJ. 2017. Assessing the climate-scale variability of atmospheric rivers affecting western North America. Geophys Res Lett. [accessed 2025 Jul 9];44(15):7900–7908. *https://doi.org/10.1002/2017GL074175*

Gershunov A, Shulgina TM, Clemesha RES, Guirguis K, Pierce DW, Dettinger MD, Lavers DA, Cayan DR, Polade SD, Kalansky J, Ralph FM. 2019. Precipitation regime change in Western North America: the role of atmospheric rivers. Sci Rep. [accessed 2025 Jul 9];9:9944. *https://doi.org/10.1038/s41598-019-46169-w*

Goddard L, Gershunov A. 2020. Impact of El Niño on weather and climate extremes. In: McPhaden MJ, Santoso A, Cai W, editors. El Niño southern oscillation in a changing climate. Am Geophys Union. [accessed 2025 Jul 9]. *https://doi.org/10.1002/9781119548164.ch16*

Guirguis K, Gershunov A, Hatchett BJ, DeFlorio MJ, Subramanian AC, Clemesha RES, Delle Monache L, Ralph FM. 2023. Subseasonal prediction of impactful California winter weather in a hybrid dynamical–statistical framework. Geophys Res Lett. [accessed 2025 Jul 9];50(23):e2023GL105360 *https://doi.org/10.1029/2023GL105360*

Guirguis K, Hatchett B, Gershunov A, DeFlorio M, Clemesha R, Brand T, Haleakala K, Castellano C, Luna Niño RB, Tardy A, Anderson M, Ralph FM. 2024. Reinterpreting ENSO's role in modulating impactful precipitation events in California. Geophys Res Lett. [accessed 2025 Jul 9];51(14):e2024GL110326. *https://doi.org/10.1029/2024GL110326*

Haleakala K, Brandt WT, Hatchett BJ, et al. 2023. Watershed memory amplified the Oroville rain-on-snow flood of February 2017. Proc Natl Acad Sci–Nexus [accessed 2025 Jul 9];2(1):pgac295. *https://doi.org/10.1093/pnasnexus/pgac295*

Hallema DW, Sun G, Bladon KD, Norman SP, Caldwell PV, Liu Y, McNulty SG. 2017. Regional patterns of postwildfire streamflow response in the Western United States: the importance of scale-specific connectivity. Hydrolog Proc. [accessed 2025 Jul 9];31:2582–2598. *https://doi.org/10.1002/hyp.11208*

Hatchett BJ, Cao Q, Dawson PB, Ellis CJ, Hecht CW, Kawzenuk B, Lancaster JT, Osborne TC, Wilson AM, Anderson ML, et al. 2020. Observations of an extreme atmospheric river storm with a diverse sensor network. Earth Space Sci. [accessed 2025 Jul 9];7:e2020EA001129. *https://doi.org/10.1029/2020EA001129*

Hatchett BJ, Daudert B, Garner CB, Oakley NS, Putnam AE, White AB. 2017. Winter snow level rise in the northern Sierra Nevada from 2008 to 2017. Water. [accessed 2025 Jul 9];9(11):899. *https://doi.org/10.3390/w9110899*

Hatchett BJ, Rhoades AM, McEvoy DJ. 2022. Decline in seasonal snow during a projected 20-year dry spell. Hydrology. [accessed 2025 Jul 9];9(9):155. *https://doi.org/10.3390/hydrology9090155*

Heggli A, Reichel D, Brong B, Hatchett BJ, Hur N, Collins M, Jennings K, Arienzo M. Tonino S. 2024. Mountain rain or snow: enhancing avalanche forecasting with real-time precipitation phase data. Proceedings of the International Snow Science Workshop. Sep 23–27, 2024. [accessed 2025 Jul 9]; p 153–159 Tromsø (Norway): Available from: *https://arc.lib.montana.edu/snow-science/item/3127*

Henny L, Kim KM. 2025. The changing nature of atmospheric rivers. J Clim. [accessed 2025 Jul 9];38:1435–1456. *https://doi.org/10.1175/JCLI-D-24-0234.1*

Hoerling M, Smith L, Guan XW, Eischeid J, Barsugli J, Diaz HF. 2021. Explaining the spatial pattern of US extreme daily precipitation change. J Clim. [accessed 20XX Mmm dd];34:2759–2775. *https://doi.org/10.1175/JCLI-D-20- 0666.s1*

Howard M, Stahle DW, Dettinger MD, Poulsen C, Ralph FM, Torbenson MCA, Gershunov A. 2023. A 440-year reconstruction of heavy precipitation in California from Blue Oak tree rings. J Hydrometeor. [accessed 2025 Jul 9];24(3):463–477. *https://doi.org/10.1175/JHM-D-22-0062.1*

Jennings KS, Arienzo MM, Collins M, Hatchett BJ, Nolin AW, Aggett G. 2023. Crowdsourced data highlight precipitation phase partitioning variability in rain-snow transition zone. Earth Space Sci. [accessed 2025 Jul 9];10: e2022EA002714. *https://doi.org/10.1029/2022EA002714*

Johanson CM, Fu Q. 2009. Hadley cell widening: model simulations versus observations. J Clim. [accessed 2025 Jul 9];22:2713–2725. *https://doi.org/10.1175/2008JCLI2620.1*

John A, Douville H, Ribes A, Yiou P. 2022. Quantifying CMIP6 model uncertainties in extreme precipitation projections. Weather Clim Extremes. [accessed 2025 Jul 9];36:100435. *https://doi.org/10.1016/j.wace.2022.100435*

Katz L, Lewis G, Krogh S, Drake S, Hanan E, Hatchett B, Harpold A. 2023. Antecedent snowpack cold content alters the hydrologic response to extreme rain-on-snow events. J. Hydrometeor. [accessed 2025 Jul 9];24:1825–1846. *https://doi.org/10.1175/JHM-D-22-0090.1*.

Knowles N. 2002. Natural and management influences on freshwater inflows and salinity in the San Francisco Estuary at monthly to interannual scales. Water Resour Res. [accessed 2025 Jul 9];38:25-1–25-11. *https://doi.org/10.1029/2001WR000360*

Knowles N, Dettinger MD, Cayan DR. 2006. Trends in snowfall versus rainfall in the western United States. J Clim. [accessed 2025 Jul 9];19:4545–4559. *https://doi.org/10.1175/JCLI3850.1*

Konrad CP, Dettinger MD. 2017. Flood runoff in relation to water vapor transport by atmospheric rivers over the western United States, 1949–2015. Geophys. Res. Lett. [accessed 2025 Jul 9];44:11456–11462. *https://doi.org/10.1002/2017GL075399*

Koshkin AL, Hatchett BJ, Nolin AW. 2022. Wildfire impacts on western United States snowpacks. Front Water. [accessed 2025 Jul 9];4: 971271. *https://doi.org/10.3389/frwa.2022.971271*

Lamjiri MA, Ralph FM, Dettinger MD, 2020. Recent Changes in United States Extreme 3-Day Precipitation Using the R-CAT Scale. J. Hydrometeor. [accessed 2025 Aug 22];21:1207-1221. *https://doi.org/10.1175/JHM-D-19-0171.1*

Lau WKM, Kim K–M. 2015. Robust Hadley circulation changes and increasing global dryness due to CO2 warming from CMIP5 model projections. Proc Natl Acad Sci. [accessed 2025 Jul 9];112:3630–3635. *https://doi.org/10.1073/pnas.1418682112*

Lavers DA, Ralph FM, Waliser DE, Gershunov A, Dettinger MD. 2015. Climate change intensification of horizontal water vapor transport in CMIP5. Geophys Res Lett. [accessed 2025 Jul 9];42:5617–5625. *https://doi.org/10.1002/2015GL064672*

Luković J, Chiang JCH, Blagojević D, Sekulić A. 2021. A later onset of the rainy season in California. Geophys Res Lett. [accessed 2025 Jul 9];48:e2020GL090350. *https://doi.org/10.1029/2020GL090350*

Luna–Niño R, Gershunov A, Ralph FM, Weyant A, Guirguis K, DeFlorio MJ, Cayan DR, Williams AP. 2025. Heresy in ENSO teleconnections: atmospheric rivers as disruptors of canonical seasonal precipitation anomalies in the southwestern US. Clim Dyn. [accessed 2025 Jul 9];63(115): Available from: *https://link.springer.com/article/10.1007/s00382-025-07583-1*

Maina FZ, Siirila–Woodburn ER. 2020. Watersheds dynamics following wildfires: nonlinear feedbacks and implications on hydrologic responses. Hydrolog Proc. [accessed 2025 Jul 9];34:33–50. *https://doi.org/10.1002/hyp.13568*

Malamud–Roam FP, Ingram BL, Hughes M, Florsheim JL. 2006. Holocene paleoclimate records from a large California estuarine system and its watershed region: linking watershed climate and bay conditions. Quat Sci Rev. [accessed 2025 Jul 9];25:1570–1598. *https://doi.org/10.1016/j.quascirev.2005.11.012*

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC. 1997. A Pacific Interdecadal Climate Oscillation with impacts on salmon production. Bull Am Meteor Soc. [accessed 2025 Jul 9];78:1069–1080. *https://doi.org/10.1175/1520-0477(1997)078%3C1069:APICOW%3E2.0.CO;2*

Marshall AM, Abatzoglou JT, Rahimi S, Lettenmaier DP, Hall A. 2024. California's 2023 snow deluge: contextualizing an extreme snow year against future climate change. Proc Natl Acad Sci. [accessed 2025 Jul 9];121:e2320600121. *https://doi.org/10.1073/pnas.2320600121*

McEvoy DJ, Pierce DW, Kalansky JF, Cayan DR, Abatzoglou JT. 2020. Projected changes in reference evapotranspiration in California and Nevada: Implications for drought and wildland fire danger. Earth's Future. [accessed 2025 Aug 22];8:e2020EF001736. *https://doi.org/10.1029/2020EF001736*

Meinshausen M, Nicholls ZRJ, Lewis J, Gidden MJ, Vogel E, Freund M, Beyerle U, Gessner C, Nauels A, Bauer N, et al. 2020. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geosci Model Dev. [accessed 2025 Jul 9];13:3571–3605. *https://doi.org/10.5194/gmd-13-3571-2020*

Michaelis AC, Gershunov A, Weyant A, Fish MA, Shulgina T, Ralph FM. 2022. Atmospheric river precipitation enhanced by climate change: a case study of the storm that contributed to California's Oroville Dam crisis. Earth's Future. [accessed 2025 Jul 9];10:e2021EF002537. *https://doi.org/10.1029/2021EF002537*

Moody JA, Shakesby RA, Robichaud PR, Cannon SH, Martin DA. 2013. Current research issues related to post-wildfire runoff and erosion processes. Earth–Sci Rev. [accessed 2025 Jul 9];122:10–37. *https://doi.org/10.1016/j.earscirev.2013.03.004*

Mote P, Li S, Lettenmaier D, Xiao M, Engel Ret al. 2018. Dramatic declines in snowpack in the western US. npj Clim Atmos Sci. [accessed 2025 Jul 9];1:2. *https://doi.org/10.1038/s41612-018-0012-1*

Mote PW, Hamlet AF, Clark MP, Lettenmaier DL. 2005. Declining mountain snowpack in western North America. Bull Am Meteor Soc. [accessed 2025 Jul 9];86:39–50. *https://doi.org/10.1175/BAMS-86-1-39*

Ombadi M, Risser MD, Rhoades AM et al. 2023. A warming-induced reduction in snow fraction amplifies rainfall extremes. Nature. [accessed 20205 Aug 22];619:305–310. *https://doi.org/10.1038/s41586-023-06092-7*

Najibi N, Steinschneider S. 2023. Extreme precipitation-temperature scaling in California: the role of atmospheric rivers. Geophys Res Lett. [accessed 2025 Jul 9];50:e2023GL104606. *https://doi.org/10.1029/2023GL104606*

Neiman PJ, Ralph FM, Wick GA, Lundquist JD, Dettinger MD. 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 observation. J Hydrometeor. [accessed 2025 Jul 9];9(1):22–47. Available from: *https://journals.ametsoc.org/view/journals/hydr/9/1/2007jhm855_1.xml*

Pierce DW, Cayan DR, Das T, Maurer EP, Miller NL, Bao Y, Kanamitsu M, Yoshimura K, Synder MA, Sloan LC, et al. 2013. The key role of heavy precipitation events in climate model disagreements of future annual precipitation changes in California. J Clim. [accessed 2025 Jul 9];26:5879–5896. *https://doi.org/10.1175/JCLI-D-12-00766.1*

Pierce DW, Das T, Cayan DR, Maurer EP, Miller NL, Bao Y, Kanamitsu M, Yoshimura K, Synder MA, Sloan LC, et al. 2013. Probabilistic estimates of future changes in California temperature and precipitation using statistical and dynamical downscaling. Clim Dyn. [accessed 2025 Jul 9];40:839–856. *https://doi.org/10.1007/s00382-012-1337-9*

Pierce DW, Rahimi S, Iacobellis S, Cayan DR, Kalansky J. 2023. Data adoption justification memo (for California's Fifth Climate Change Assessment): LOCA version 2 Hybrid Downscaling. CEC-funded agreement: EPC-20-006 Development of climate projections for California and identification of general use projections. [accessed 2025 Jul 9]. Available from: *https://www.energy.ca.gov/media/9329*

Polade SD, Gershunov A, Cayan DR, Dettinger MD, Pierce DW. 2017. Precipitation in a warming world: assessing projected hydro-climate of California and other Mediterranean climate regions. Sci Rep. [accessed 2025 Jul 9];7:10783. *https://doi.org/10.1038/s41598-017-11285-y*

Polade SD, Pierce DW, Cayan DR, Gershunov A, Dettinger MD. 2014. The key role of dry days in changing regional climate and precipitation regimes. Sci Rep. [accessed 2025 Jul 9];4:4364. *https://doi.org/10.1038/srep04364*

Ralph FM, Dettinger M, White A, Reynolds D, Cayan DR, Schneider T, Cifelli R, Redmond K, Anderson M, Gherke F, et al. 2014. A vision for future observations for western U.S. extreme precipitation and flooding. J Contemp Wat Res Educ. [accessed 2025 Jul 9];153:16–32. Available from: *https://cw3e.ucsd.edu/wp-content/uploads/2014/04/Ralph_etal_2014_UCoWR.pdf*

Ralph FM, Neiman PJ, Wick GA, Gutman SI, Dettinger MD, Cayan DR, et al. 2006. Flooding on California's Russian River: role of atmospheric rivers. Geophys Res Lett. [accessed 2025 Jul 9];33(13):282. *https://doi.org/10.1029/2006GL026689*

Reges HW, Doesken N, Turner J, Newman N, Bergantino A, Schwalbe Z. 2016. CoCoRaHS: the evolution and accomplishments of a volunteer rain gauge network. Bull Amer Meteor Soc. [accessed 2025 Jul 9];97:1831–1846. *https://doi.org/10.1175/BAMS-D-14-00213.1*

Rhoades Am, Jones, AD, Srivastava A, Huang H, O'Brien TA, PatricolaCM, Ullrich PA, Wehner M, Zhou Y. 2020. The shifting scales of western U.S. landfalling atmospheric rivers under climate change. Geophys Res Lett. [accessed 2025 Jul 9];47(17): e2020GL089096. *https://doi.org/10.1029/2020GL089096*

Rhoades AM, Hatchett BJ, Risser MD, Collins WD, Bambach ME, Huning LS, McCrary R, Siirila–Woodburn ER, Ullrich PA, Wehner FM, et al. 2022. Asymmetric emergence of low-to-no snow in the midlatitudes of the American Cordillera. Nat Clim Chang. [accessed 2025 Jul 9];12:1151–1159. *https://doi.org/10.1038/s41558-022-01518-y*

Rhoades AM, Zarzycki CM, Hatchett BJ, Inda–Diaz HA, Rudisill W, Bass B, Dennis E, Heggli A, McCrary R, McGinnis S, et al. 2024. Anticipating how rain-on-snow events will change through the 21st century: lessons from the 1997 new year's flood event. Clim Dyn. [accessed 2025 Jul 9];62(9):8615–8637. *http://doi.org/10.1007/s00382-024-07351-7*

Rhoades AM, Zarzycki CM, Inda–Diaz HA, Ombadi M, Pasquier U, Srivastava A, Hatchett BJ, Dennis E, Heggli A, McCrary R, et al. 2023. Recreating the California New Year's flood event of 1997 in a regionally refined earth system model. J Adv Model Earth Syst. [accessed 2025 Jul 9];15(10):e2023MS003793. *http://doi.org/10.1029/2023ms003793*

Risser MD, Collins WD, Wehner MF, O'Brien TA, Huang H, Ullrich PA. 2024. Anthropogenic aerosols mask increases in US rainfall by greenhouse gases. Nat Commun. [accessed 2025 Jul 9];15:1318. *https://doi.org/10.1038/s41467-024-45504-8*

Rittelmeyer P. 2020. Socio-cultural perceptions of flood risk and management of a levee system: applying the Q methodology in the California Delta. Geoforum, [accessed 2025 Jul 9];111:11–23. *https://doi.org/10.1016/j.geoforum.2020.02.022*

Rittelmeyer P, Bowers C, Guan B. 2025. Coupling of atmospheric rivers and levee failure events in California's Sacramento–San Joaquin Delta, 1980–2021. Weather, Clim Soc. [accessed 2025 Jul 9];17:65–77 *https://doi.org/10.1175/WCAS-D-23-0136.1*

Roos M. 1987. Possible changes in California snowmelt runoff patterns. In: Proceedings of the Fourth Annual Pacific Climate (PACLIM) Workshop, Pacific Grove (CA). [accessed 202X Mmm dd]. pp 22-31.

Roos M. 2003. The effects of global climate change on California water resources. Contractors Report. Sacramento (CA): Public Interest Energy Research, California Energy Commission. P500-03-025 (April).

Shulgina T, Gershunov A, Hatchett BJ, Guirguis K, Subramanian AC, Margulis SA, Fang Y, Cayan DR, Pierce DW, Dettinger M, et al. 2023. Observed and projected changes in snow accumulation and snowline in California's snowy mountains. Clim Dyn. [accessed 2025 Jul 9];61:4809–4824. *https://doi.org/10.1007/s00382-023-06776-w*

Siirila-Woodburn ER, Rhoades AM, Hatchett BJ, 2021. A low-to-no snow future and its impacts on water resources in the western United States. Nature Rev Earth Environ. [accessed 2025 Aug 22];2:800-819. *https://www.nature.com/articles/s43017-021-00219-y*

Sommer TR, Nobringa ML, Harrell WC, Batham W, Kimmerer WJ. 2001. Floodplain rearing of juvenile Chinook Salmon—evidence of enhanced growth and survival. Can J Fish Aquat Sci. [accessed 2025 Jul 9];58:325–333. *https://doi.org/10.1139/f00-245*

Stewart I, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. J.Clim. [accessed 2025 Aug 22];18:1136-1155. *https://doi.org/10.1175/JCLI3321.1*

Stewart IT, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. J Clim. [accessed 2025 Jul 9];18:1136–1155. *https://doi.org/10.1175/JCLI3321.1*

Swain DL, Prein AF, Abatzoglou JT et al. 2025. Hydroclimate volatility on a warming Earth. Nat Rev Earth Environ. [accessed 2025 Aug 25];6:35–50. *https://doi.org/10.1038/s43017-024-00624-z*

Swain DL, Langenbrunner B, Neelin JD, Hall A. 2018. Increasing precipitation volatility in twenty-first-century California. Nat Clim Chang. [accessed 2025 Jul 9];8: 427–433. *https://doi.org/10.1038/s41558-018-0140-y*

Uecker TM, Kaspari SD, Musselman KN, McKenzie Skiles S. 2020. The post-wildfire impact of burn severity and age on black carbon snow deposition and implications for snow water resources, Cascade Range, Washington. J Hydrometeor. [accessed 2025 Jul 9];21(8):1777–1792. *https://doi.org/10.1175/jhm-d-20-0010.1*

URS Corporation. 2009. Delta risk management strategy. Sacramento (CA): Prepared by the California Department of Water Resources from documents developed by URS Corporation/Jack R. Benjamin & Associates, Inc. [accessed 2025 Jul 9]. 32 p. Available from: *https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/california_waterfix/exhibits/docs/SJRECWA/sjrecwa_3.pdf*

Vano JA, Miller K, Dettinger MD, Cifelli R, Curtis D, Dufour A, Olsen JR, Wilson AM. 2019. Hydroclimatic extremes as challenges for the water management community: Lessons from Oroville Dam and Hurricane Harvey. Bull Am Meteorol Soc. [accessed 2025 Aug 22];100(1):S9–S14. *https://doi.org/10.1175/BAMS-D-18-0219.1*

Westra S, Fowler HJ, Evans JP, et al. 2014. Future changes to the intensity and frequency of short-duration extreme rainfall. Rev Geophys. [accessed 2025 Aug 22];52:522–555. *https://doi.org/10.1002/2014RG000464*

Weyant A, Gershunov A, Panorska AK, Kozubowski TJ, Kalansky J. 2025. A holistic stochastic model for precipitation events. Sci Rep. [accessed 2025 Jul 9];15:4595. *https://doi.org/10.1038/s41598-024-77031-3*

White AB, Anderson ML, Dettinger MD, Ralph FM, Hinojosa A, Cayan DR, Hartman RK, Reynolds DW, Johnson LE, Schneider TL. 2013. A twenty-first-century California observing network for monitoring extreme weather events. J Atmos Ocean Tech. [accessed 2025 Jul 9];30(8):1585–1603. *https://doi.org/10.1175/JTECH-D-12-00217.1*

Williams AP, Cook BI, Smerdon JE. 2022. Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. Nat Clim Chang. [accessed 2025 Jul 9];12:232–234. *https://doi.org/10.1038/s41558-022-01290-z*

Williams AP, Livneh B, McKinnon KA, Hansen WD, Mankin JS, Cook BI, Smerdon JE, Varuolo–Clarke AM, Bjarke NR, Juang CS. 2022. Growing impact of wildfire on western US water supply. Proc Natl Acad Sci. [accessed 2025 Jul 9];119(10):e2114069119. *https://doi.org/10.1073/pnas.2114069119*

Williams AP, McKinnon KA, Anchukaitis KJ, Gershunov A, Varuolo–Clarke AM, Clemesha RES, Liu H. 2024. Anthropogenic intensification of cool-season precipitation is not yet detectable across the western United States. J Geophys Res– Atmos. [accessed 2025 Jul 9];129:e2023JD040537. *https://doi.org/10.1029/2023JD040537*

Yu G, Jennings KS, Hatchett BJ, Nolin AW, Hur N, Collins M, Heggli A, Tonino S, Arienzo MM. 2024. Crowdsourced data reveal shortcomings in precipitation phase products for rain and snow partitioning. Geophys Res Lett. [accessed 2025 Jul 9]; 51. *https://doi.org/10.1029/2024GL112853*

ADDITIONAL REFERENCES

Cayan DR, DeHaan L, Gershunov A, Guzman–Morales J, Keeley JE, Mumford J, Syphard AD. 2022. Autumn precipitation—the competition with Santa Ana winds in determining fire outcomes in Southern California. Intl J Wildland Fire. [accessed 2025 Jul 8];31(11):1056–1067. *https://doi.org/10.1071/WF22065*

Dettinger M. 2011b. Climate change, atmospheric rivers, and floods in California —a multimodel analysis of storm frequency and magnitude changes. J Am Water Resour Assoc. [accessed 2025 Jul 9];47: 514–523. *https://doi.org/10.1111/j.1752-1688.2011.00546.x*

Gimeno–Sotelo L, Gimeno L. 2022. Where does the link between atmospheric moisture transport and extreme precipitation matter? Weather Clim Extremes. [accessed 2025 Jul 9];39(March 2023):100536 *https://doi.org/10.1016/j.wace.2022.100536*

Guirguis K, Gershunov A, Shulgina TM, Clemesha RES, Ralph FM. 2018. Atmospheric Rivers impacting Northern California and their modulation by a variable climate. Clim Dyn. [accessed 2025 Jul 9]; *https://doi.org/10.1007/s00382-018-4532-5*

Guirguis K, Gershunov A, Shulgina T, Subramanian AC, Clemesha RES, Ralph FM. 2018. Circulation drivers of atmospheric rivers along the North American West Coast. Geophys Res Lett. [accessed 2025 Jul 9]; 45. *https://doi.org/10.1029/2018GL079249*

Ralph FM, Dettinger MD. 2011. Storms, floods, and the science of atmospheric rivers. Eos Trans. AGU. [accessed 2025 Jul 9];92:2009–2011. *https://doi.org/10.1029/2011EO320001*

Ralph FM, Dettinger MD. 2012. Historical and national perspectives on extreme West Coast precipitation associated with atmospheric rivers during December 2010. BAMS. [accessed 2025 Jul 9]; *https://doi.org/10.1175/BAMS-D-11-00188.1*

Yu G, Liu T, McGuire LA, Wright DB, Hatchett BJ, Miller JJ, Berli M, Giovando J, Bartles M, Floyd IE. 2023. Process-based quantification of the role of wildfire in shaping flood frequency. Water Resour Res. [accessed 2025 Jul 9]; 59. *https://doi.org/10.1029/2023WR035013*

Zhang L, Zhao Y, Cheng TF, Lu M. 2024. Future changes in global atmospheric rivers projected by CMIP6 models. J Geophys Res–Atmos. [accessed 2025 Jul9];129(3). *https://doi.org/10.1029/2023JD039359*