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The 1991 California "Miracle March": Precipitation Myth or Miracle?

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Abstract

The term "Miracle March" is colloquially used in California to describe an anomalously wet spring that alleviates drought conditions caused by a winter precipitation deficit. This study centers on the influential water year 1991, which is the standard reference point for this phenomenon. The spring precipitation impact on water year totals and the geographic extent of the spring precipitation anomaly during the 1991 "Miracle March" (MM91) is without equal in the observational record. This exceptional precipitation episode was initiated by a week-long sequence of extreme atmospheric rivers that started landfalling on February 27th. To this day, MM91 is routinely referenced as a basis for hope of drought alleviation in California water management. MM91 demonstrates the role that an exceptional spring precipitation season can play in determining the cessation of drought, but a historical analysis also shows just how unusual such conditions are.

Keywords: California, drought, water management, seasonal precipitation, extremes, atmospheric rivers

1. Introduction

In February of 1991, California and a large part of the western contiguous United States (the West) was in a state of significant winter drought (Dziegielewski et al., 1993). To make matters worse, the dry winter conditions of water year 1991 (October 1st, 1990 – September 30th, 1991) were a continuation of one of the worst multi-year droughts (1987-1992) in California since the early part of the 20th century (Jones et al., 2015). As a result of the extended drought period and dry winter, the statewide runoff during water year 1991 was the lowest of the 6-year drought and ranked as the 5th lowest from water years 1900-2014 (Dziegielewski et al., 1993; Jones et al., 2015). The extended drought significantly impacted all parts of the state, with the City of San Francisco's water storage dropping to only 25% of its capacity in 1991 (Jones et al., 2015). The California Department of Water Resources (DWR) estimated that, in the years 1990 and 1991 respectively, there were $220 million and $250 million gross revenue losses by farms. Based on surveys of commercial and industrial users, DWR estimated losses of $460 million in gross revenues and 5,600 full-time jobs in 1991 due to cutbacks in residential and institutional landscaping (Department of Water Resources, 1994). However, anomalously wet conditions began at the end of February and continued for the rest of spring weakening the winter meteorological drought without a complete reversal in conditions (drought alleviation) across California and the West. California statewide reservoir storage increased by 10% of its capacity due to the anomalous March precipitation (Dziegielewski et al., 1993). Folsom Lake reservoir saw an increase from 17% of total capacity on February 28th, 1991 (34% of historical average for this date) to 76% of total capacity on May

31st, 1991 (93% of historical average for this date) (California Department of Water Resources, 2024). Drought in California was not entirely terminated by the anomalous spring precipitation, but it made the drought conditions manageable entering the summer of 1991 (Dziegielewski et al., 1993). The term "Miracle March" was thus coined through public discourse.

El Niño Southern Oscillation (ENSO), the main source of seasonal precipitation predictability in California (Gershunov & Cayan, 2003), was in its neutral phase for most of winter and spring. The only exception is that in January, ENSO transitioned into a weak El Niño phase (0.51 ºC SST anomaly) but quickly transitioned back to neutral in February. The March 1991 Niño 3.4 sea surface temperature anomaly was 0.10 ºC indicating ENSO was not active during the "Miracle March" precipitation event (NOAA Physical Science Laboratory Niño 3.4 index; Rayner et al., 2003). The canonical ENSO precipitation pattern in California is anomalous wetness, particularly in Southern California, during El Niño and vice versa for La Niña (Cayan et al., 1999; Gershunov, 1998; Gershunov & Cayan, 2003). In recent years the canonical ENSO Western US precipitation teleconnection has been less predictable attributed to internal variability and the influence of other climate modes (Singh et al., 2018). Moreover, Guirguis et al. (2024) has provided a novel perspective that ENSO influences the charcter of wet weather patterns reaching California, but it does not impact the seasonal frequency of these patterns. Adding more nuance to using ENSO in seasonal prediction is the realization that atmospheric rivers (ARs; Ralph et al., 2018), the storms that deliver the heaviest precipitation events to California, do not much care about ENSO phase, introducing heresy to ENSO teleconnections and a major source of uncertainty to seasonal forecasting (Luna-Niño et al., 2025). Indicated herein, ENSO may not be a key to determining the predictability of future "Miracle March" events. It will be necessary to investigate other aspects of the regional and global climate during the 1991 "Miracle March" and atmospheric rivers, as we shall see, emerge as key contributors.

A recent publication by Pokharel et al. (2024), through a co-production research process with local water managers, characterized spring precipitation "miracles" in the Colorado River Basin (CRB) as an event where three consecutive wet months succeed four consecutive winter dry months eliminating drought conditions. The characterization was used to quantify the frequency of spring "miracles" in the observational record and how they might change under a warming climate. Pokharel et al. (2024) found spring "miracles" will be less common in the future and occur about 10% of the years in the upper CRB, highlighting the keen interest of western water managers in "miracle" spring precipitation and the benefits of rigorous climatological analysis focused on water management applications. In addition, the authors note the challenge of defining a precipitation "miracle" due to the high spatial dependency of impacts and "fuzzy phenomenon" characteristics. The authors abate this issue with local water manager insight. In this study, we conduct a climatological analysis on a few "Miracle March" definitions to present a methodological variability and provide a foundation for situational applications.

Following a dry early-to-mid winter, water managers are faced with difficult decisions based on what to expect for spring precipitation and runoff. They typically look to the snowpack, weather forecasts, and seasonal to subseasonal outlooks to help inform their decisions. In addition, they often draw from past experiences, including the example of March 1991, which can offer some hope of recovery from a dry winter. However, there has not been a published scientific study analyzing the climatological context of the California 1991 "Miracle March" (MM91) but the term was briefly discussed in Howard et al. 2024. This study investigates 1) the temporal and spatial signature of MM91 as compared with other water years, 2) the historical instances in California where spring precipitation abated a winter meteorological drought, and 3) the role of a sequence of landfalling atmospheric rivers in this anomalously wet spring season.

2. Materials, Methods, and Data

For the following analyses, we define the "wet season" as October-May, "winter" as October-February, "spring" as March-May, and "water year" as October(Year)–September(Year+1). Winter and water year are assigned the calendar year where the period ends. Northern, Central, and Southern California, as used herein, are shown in Figure 1a. MM91 is mostly discussed as a California phenomenon, but the domain used in this analysis is broad enough to show the extent of spring drought alleviation across the West.

2.1 Precipitation Data

Parameter-elevation Regressions on Independent Slopes Model (PRISM) monthly 4 km gridded precipitation data (water year 1900-2023) is used for the spatial analysis of the "Miracle March" phenomenon (Daily et al., 2008; PRISM Climate Group, 2024). To study the magnitude of precipitation changes during MM91 the climatological median is used instead of climate normals (mean) to reduce the impacts of precipitation extremes. The differences between the precipitation mean and median are greatest in arid and semi-arid regions with fewer storms and low precipitation totals such as Southern California or the Southwest. Livneh daily 6 km gridded precipitation data (water year 1916-2021, Livneh et al., 2013, 2015) is used to compare water year 1991 to an extended record of daily precipitation that isn't available in the PRISM dataset. The two data sets are both interpolated precipitation products from similar station data, but the data sets have some differences at finer scales and over complex terrain (Behnke et al., 2016; Henn et al., 2018). The two datasets show that MM91 is an extreme (compared to the rest of the record) example of winter drought alleviation by spring. To avoid overreliance on the PRISM and Livneh interpolation algorithms in California, the Northern Sierras 8-station precipitation index (1920-2023), the Central Sierras 5-station precipitation index (CS5, 1913-2023), and the Southern Sierras 6-station precipitation index (SS6, 1923-2023) from the California Department of Water Resources are also analyzed (California Department of Water Resources, 2024). These indices are averages of high elevation precipitation records from long-term stations in the various regions of the Sierra Nevada Mountains.

2.2 Atmospheric rivers and associated meteorology

The ocurrence of atmospheric rivers (ARs) during the 1991 "Miracle March" was determined by searching the Scripps Institution of Oceanography (SIO)-generated AR catalog (SIO-R1 catalog), which applies the Gershunov et al. (2017) AR detection methodology, for events that made landfall during our period of interest. NASA's Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2, Gelaro et al., 2017) vertically-integrated water vapor transport (IVT $= \frac{1}{g}\int_{p_{sfc}}^{p_{top}} q\mathbf{V}dp$, where g is gravity, q is the specific humidity, **V** is the wind velocity, Ralph et al., 2017) with 0.5º lattiude by 0.667° longitude spatial resolution was used to evaluate the temporal and spatial signature of the impactful AR sequence. Some general synoptic and mesoscale features that helped form this AR sequence are identified with 2.5º gridded 850 hPa wind speed anomalies and 500 hPa geopotential height anomalies from the NCEP/NCAR Reanalysis (Kalnay et al., 1996).

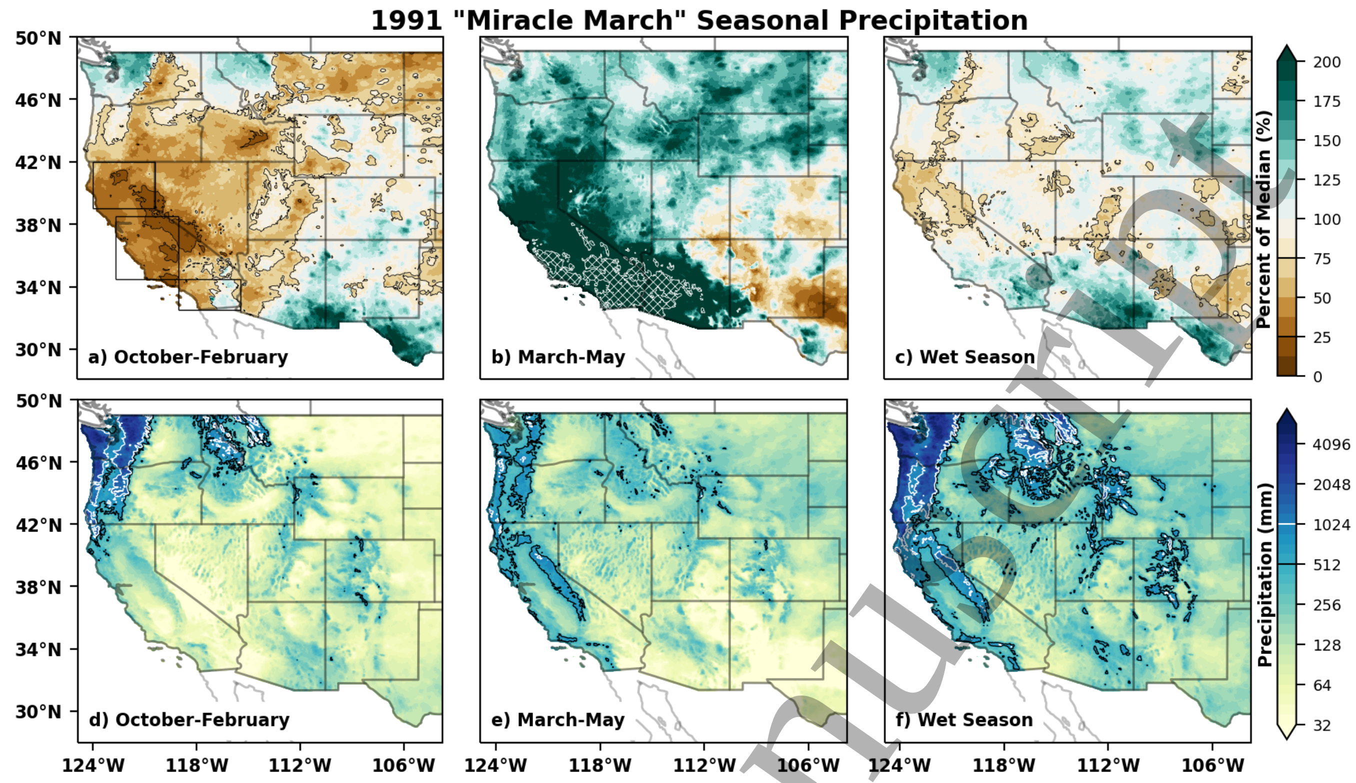

Figure 1. Percent of median precipitation ((precipitation total / climate median) *100) for a) winter, b) spring, and c) the wet season (Oct-May), and cumulative daily precipitation for the same seasons (d-f), with (a-c) using the 1900-2023 climate median for each season. White hatches in (b) represent regions above 300% of the median. Black contours in (a, c) denote the 75% and 25% of the median contour. In panels d-f, black (white) contours denote regions of precipitation greater than 512 (1024) mm. Black boxes in (a) demarcate the boundaries for Southern, Central, and Northern California.

3. Results

3.1 The "Miracle March" of 1991

The precipitation in MM91 was so significant in the Northern Sierra Nevada that it was touted as saving the ski industry from a disastrous ski season (Bourelle, 2001; Parsons, 2008). 1991 ranks as the fourth, third, and second wettest March in the instrumental record for the Northern Sierra 8 station, Central Sierra 5 station, and the Southern Sierra 6 station precipitation indices respectively (456, 482, and 382 mm). What made MM91 a "miracle" was that the anomalous March precipitation followed the driest winter on record for the Northern Sierra 8 station and Central Sierra 5 station precipitation indices (41 and 34 mm) and the third driest for the Southern Sierra 6 station precipitation index (28 mm). Despite the extremely anomalous 1991 spring, the California averaged 1991 wet season total still fell below the median (Figure 1c). However, the California drought was substantially alleviated by MM91 but the drought wasn't declared over until water year 1993 (Dziegielewski et al., 1993).

Most of California's 1991 winter-total precipitation was below 40% of median precipitation, with the eastern Sierras receiving 20% or less of the median and most of the West seeing a >25% precipitation deficit (Figure 1a). The 1991 spring precipitation was highly anomalous across the West with precipitation totals across California >200% of the median and southern California >300% of the median (Figure 1b). The largest deviation from median spring precitation is an area in the Southern California deserts east of Mount San Jacinto and Mount San Gorgonio where spring precipitation values reached >500% of median precipitation. For all of California March 1991 was the third wettest but in Central, and Southern Claifornia it is ranked #1 out of the 124-yr record (Table S1). A widespread improvement in drought conditions resulted, as indicated by decreases from the end of February to the end of May in the West-wide area with 75% of median or less precipitation (Figure 1a and 1c). Most of California received <250 mm (10 inches) of accumulated precipitation during the five winter months (Figure 1d). In three spring months, though, most of the coastal and mountainous regions received >250 mm of precipitation (Figure 1e), rising to >500 mm (Figure 1e) in the Sierra Nevada. Across California, spring 1991 far exceeded the amount of precipitation that fell in winter 1991. Considering how much worse the continuing drought could have been in the absence of these strong March precipitation totals, spring 1991 provided a much-welcomed reprieve to a state that was gripped by drought, even though the large precipitation totals did not entirely end the drought with Northern and Central California still falling below median for the 1991 wet season (Figure 1c).

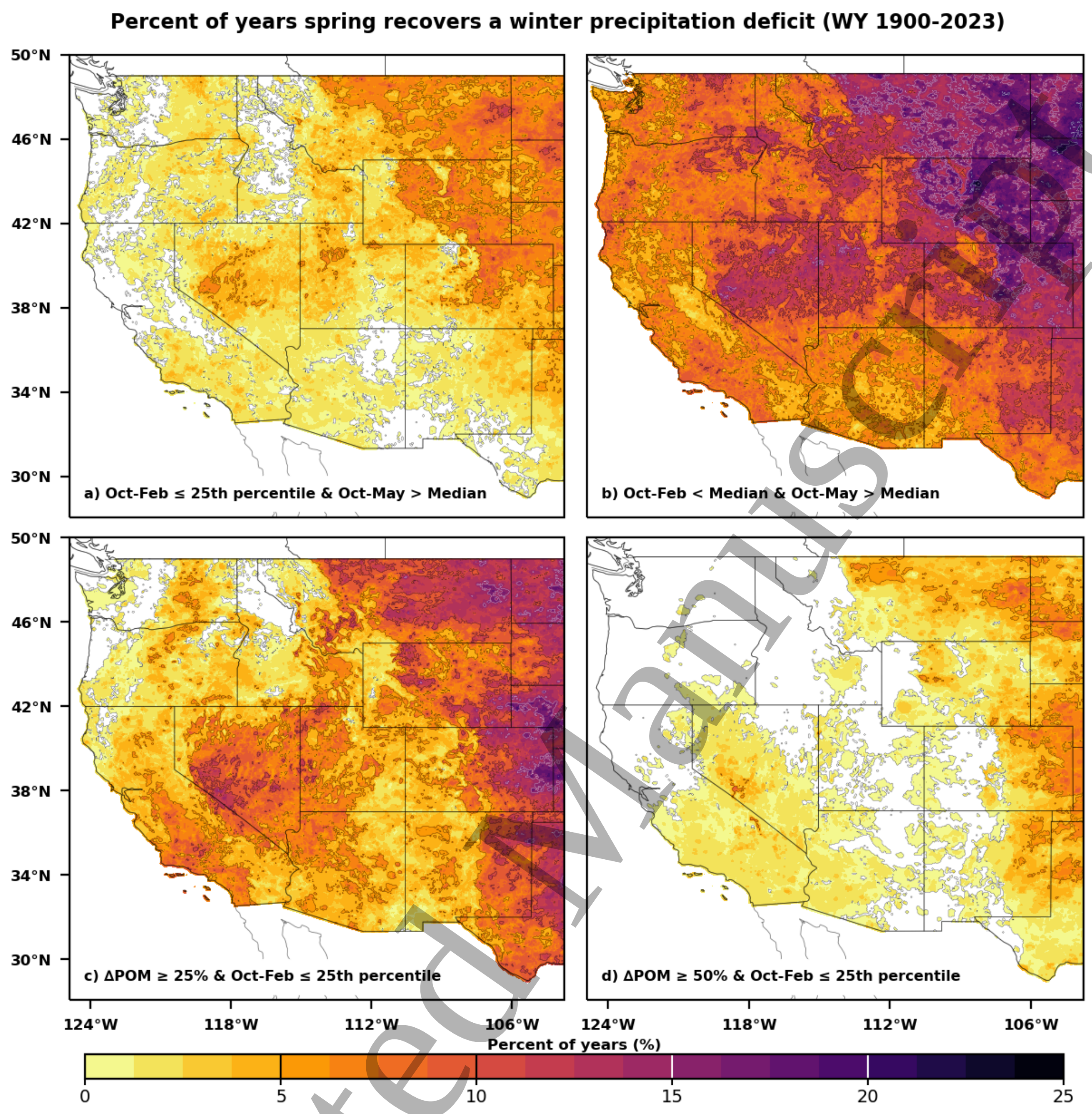

Figure 2. Empirical probabilities, based on climatology, that the wet season total precipitation will be above median when winter precipitation was (a) less than or equal to the 25th percentile and (b) less than median, and probabilities that change in percent of median (ΔPOM, percent of median(wet-season precipitation) – percent of median(winter precipitation)) is greater than or equal to (c) 25% and (d) 50% when winter precipitation is less than or equal to the 25th percentile.

3.2 The Realities of 1991

To historically contextualize MM91 and the "Miracle March" phenomenon, gridded precipitation is used to empirically assess the number of water years that fulfill different definitions of "Miracle March" in the West (Figure 2). "Miracle March" can be defined as spring precipitation that has overcome a deficit in winter precipitation totals falling in the lower quartile (25th percentile, Figure 2a) so as to raise overall wet-season totals above the median. Most of the West fulfilled this condition in <5% of the 124-year record (1900-2023) and regionally, water year 1991 only fulfilled this criterion in Southern California (Figure S1). To test the impact of the definition of winter drought on “Miracle Marches” the drought threshold is reduced to precipitation below the median, although this only increased the empirical probability to ~10% of water years (Figure 2b). A still less restrictive criterion would be to count the number of water years when spring precipitation improved conditions at all, regardless of whether the wet season total ends above the median. The statistic defined to look at these more general cases is the change in percent of median. Given winter totals in the lower quartile and relaxing the “Miracle March” criterion to a 25% improvement in precipitation conditions (Figure 2c) only provides a marginal increase in the number of “Miracle March” years (relative to Figure 2a). For a 50% improvement in precipitation conditions (Figure 2d) the number of years drastically decreases across the West. The small number of years associated with these varying “Miracle March” thresholds highlights the reality that for most of the West the onset of drought during winter will persist through spring.

To compare daily changes in water year 1991 to an extended record of 20th century daily precipitation, cumulative daily precipitation totals are plotted for three regions of California for all years when the winter total was below normal (Figures 3a-c). MM91 (red line) is highly anomalous given how dry conditions were throughout winter, but a series of atmospheric rivers beginning on February 27th dramatically raised wet-season totals across California (Figure 3). By the end of May, Southern California changed from 61% of normal for winter to 112% of normal for the wet season, the largest increase (for these seasons) in the Livneh instrumental record. Similarly, dramatic increases were present in Central and Northern California though the spring totals were not large enough to overcome one of the driest winters on record in these regions. The magnitude and extent of drought alleviation are notable for water year 1991 even when compared with recent “Miracle March” years that are part of the California water lexicon (water year 2012, 2018, 2020). Water year 1991 is unique among these recent “Miracle Marches” in that it’s one of the only times in the instrumental record when all of California experienced significant drought relief because of spring precipitation (Figure S1).

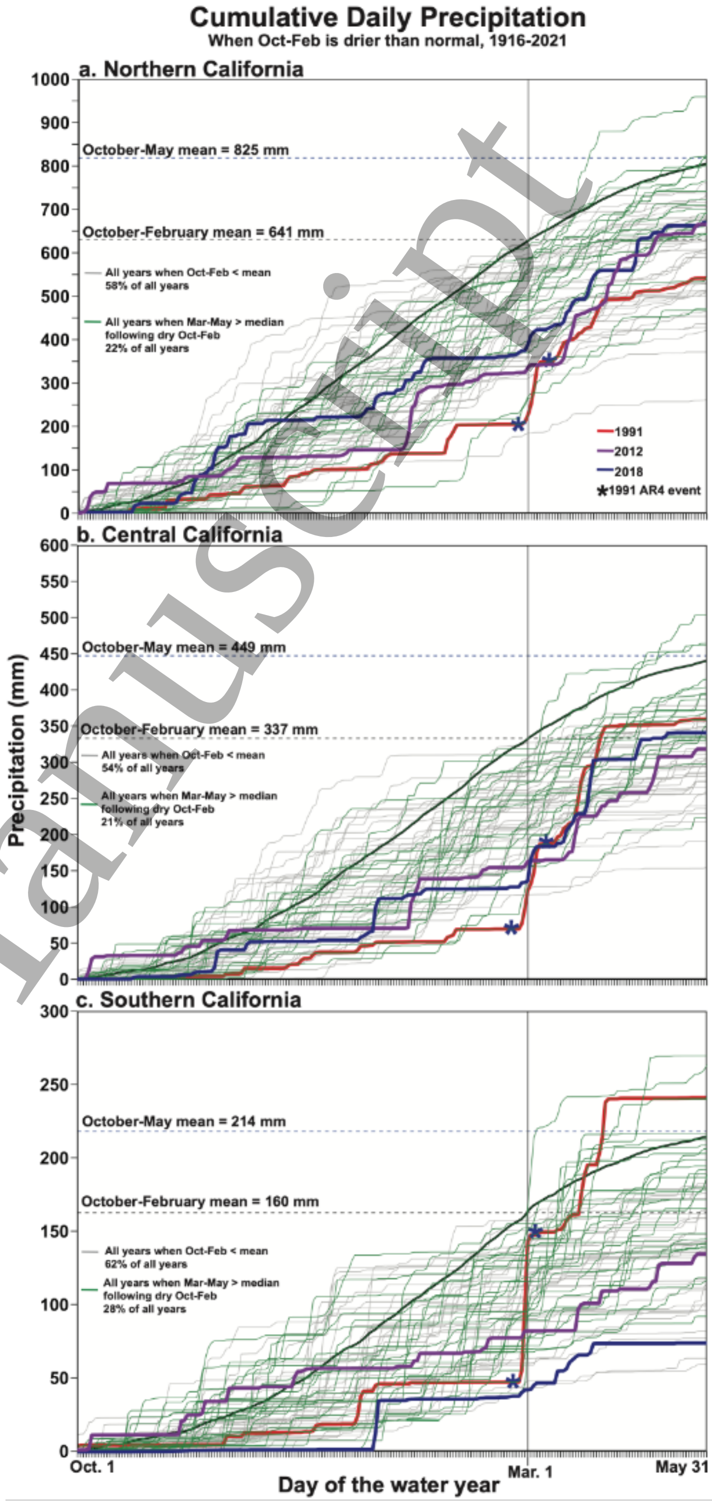

Figure 3. Cumulative daily precipitation totals for (a) Northern, (b) Central, and (c) Southern California are plotted for all years when the winter total was below the long-term mean. Years when the spring precipitation total was above normal following a dry winter are plotted as green. In each panel, the black asterisks denote the start and end date of a landfalling atmospheric river (AR4) during the early spring of 1991. The smooth black curves represent the average accumulated daily precipitation for each region (1916-2021).

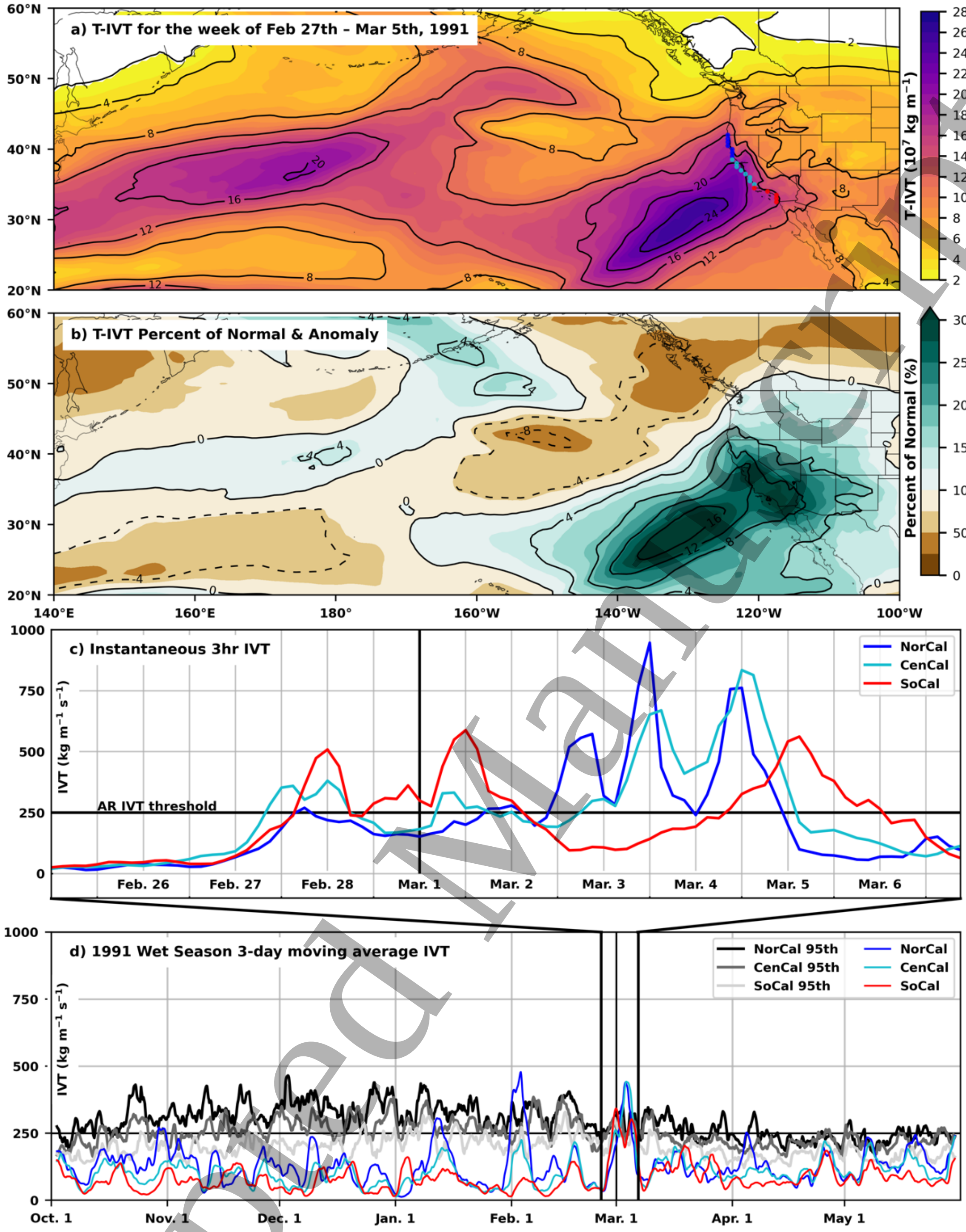

Figure 4. (a) Time integrated IVT (T-IVT, 10^7 kg m^{-1}) for the Atmospheric River sequence February 27th - March 5th, 1991. (b) T-IVT anomaly (contours) and precent of normal (color shading) based on the weekly climatological mean of February and March T-IVT for the period of 1980-2023. Instantaneous 3-hourly IVT (kg m^{-1} s^{-1}) during the (c) AR sequence and (d) 1991 wet season 3-day moving average and 95th percentile (water year 1981-2023, 2nd highest IVT value for each 3-day period) at landfall for the three domains Northern, Central, and Southern California. Dots in panel (a) highlight the landfall locations used for the three domains.

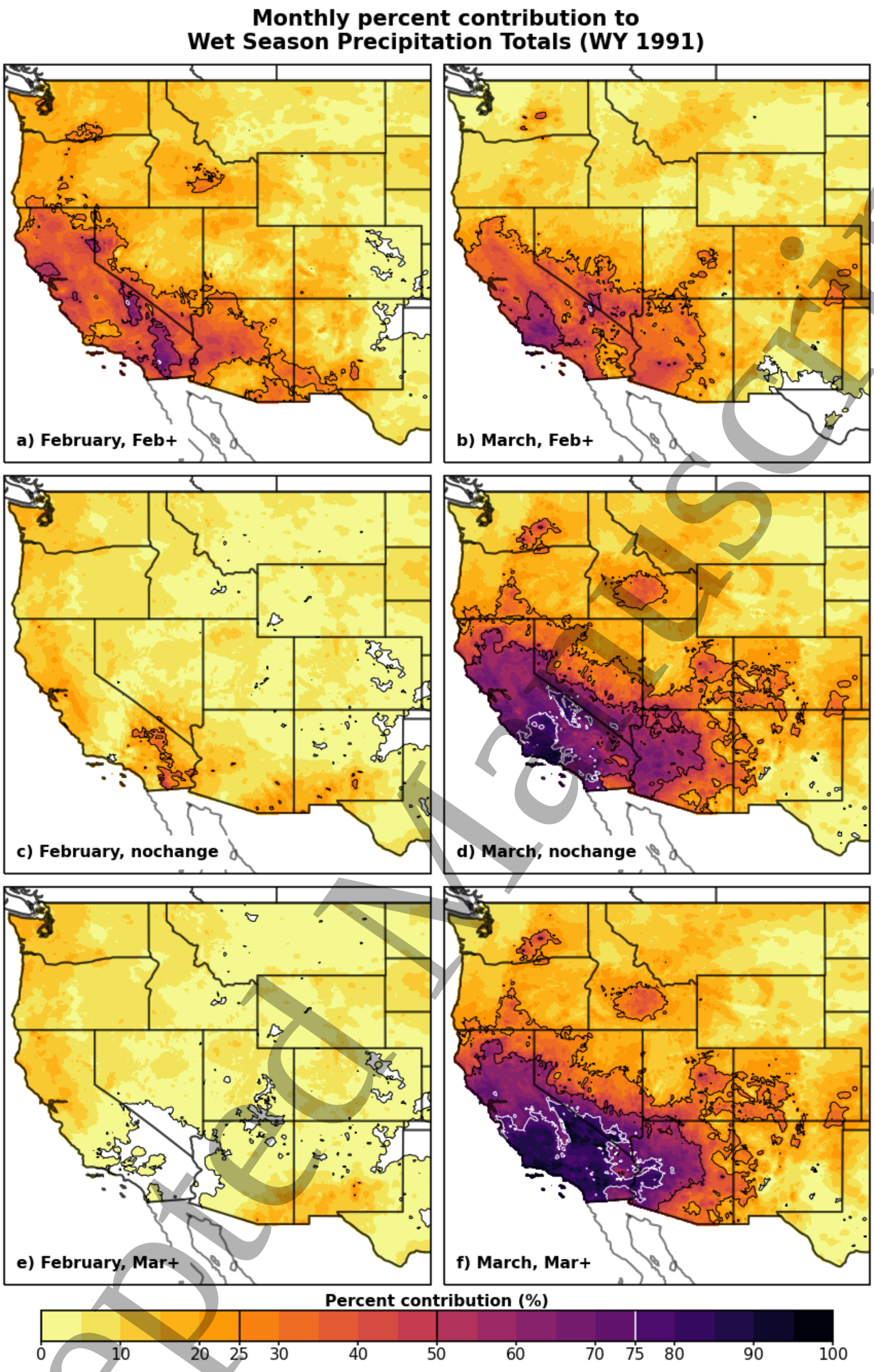

Figure 5. February 27th - March 5th precipitation impacts on monthly percent contribution to 1991 wet-season precipitation totals ((monthly precipitation total / wet season precipitation total)*100) for February (a) and March (b) with the daily precipitation totals from March 1st - March 5th moved to February (Feb+), February (c) and March (c) with daily precipitation totals kept in their respective months (nochange), and February (e) and March (f) with daily precipitation totals from Feb 27th and 28th moved to March (Mar+). Black (white) contours highlight regions with 25 and 50 (75) monthly percent contribution to wet-season totals. White grid cells represent zero precipitation.

3.3 Precipitation contribution and AR conditions, "Miracle March" episode

On February 27th, an AR made landfall in California, and began a week-long sequence of AR arrivals that provided anomalous AR precipitation (Figure S2) and IVT (Figure 4) across the West for this time of year. The essentially unbroken period of California AR-landfall conditions (Figure 4c) was labeled a single event by the SIO-R1 catalog and ranked as an AR4 (extreme AR) event based on the AR Scale introduced by Ralph et al. (2019). The AR-landfall conditions were associated with a stationary low-pressure center located south of Alaska that persisted for the entirety of the sequence and spun off several individual ARs in quick succession (Figure S3). Weekly time-integrated IVT (T-IVT) for the AR4 sequence highlights the southwesterly orientation and magnitude of the California focused water vapor transport (Figure 4a). The core of the T-IVT reached values above 250% of the February and March weekly T-IVT normal (1980-2023) with some regions receiving 300% of normal (Figure 4b). The percent of normal calculations highlight how broad and influential the IVT anomaly was during this week with the entirety of the western US experiencing above normal fluxes.

The landfall timing of the central AR sequence to the precipitation of MM91 lead us to question if the historical transition in precipitation conditions of 1991 was justly named a March "miracle". To try and answer this question, 1991 February (Figure 5c) and March (Figure 5d) percent contribution to wet-season precipitation totals are compared to hypothetical situations where the Feb 27th-Mar 5th precipitation totals (Figure S4) are added to February (Figure 5a) or March precipitation totals (Figure 5f). If the precipitation during the AR sequence occurred in February alone, it is unlikely that the term "Miracle March" would have been coined because precipitation contributions would have been equally split between the two months (Figure 4a-b); that is, the period during the AR sequence in question provided between 40-50% of the March totals for most of California (Figure S5). On the other hand, if the AR sequence had made landfall two days later, the March 1991 total would have been increasingly anomalous with Central and Southern California receiving more than 75% of the 1991 wet-season precipitation totals (Figure 4f). If the contributions of AR (Figure S6) and non-AR (Figure S7) precipitation to March 1991 precipitation totals are separated, we see that ARs were more important to California coastal precipitation during this period. Alternatively, non-AR precipitation contributed a larger fraction of precipitation in the Sierra Nevada mountains, except during the extreme sequence of ARs (Figure S2). This suggests that for March 1991 other precipitation mechanisms, such as post-cold frontal convective precipitation, also played a importtant role in the MM91 precipitation in the Sierra Nevada. This analysis highlights the unique challenge atmospheric rivers present when studying seasonal precipitation due to their ability to produce a large fraction of a water years' precipitation in a few days (Dettinger et al., 2011) and depending on when the storms occur it can make or break a "Miracle March". Thus, these results underscore the need to determine the role of other precipitation mechanisms in producing spring precipitation extremes.

4. Discussion and Conclusion

In water year 1991, unusually prolific springtime precipitation totals dramatically improved the state of California's water-supply situation at the start of its Mediterranean dry summer. This episode has left many in the state with an inflated belief in the possibility that a wet spring "often" raises the overall wet season out of a severe wintertime precipitation deficit. Even though March 1991 set precipitation records across California, it still only improved wet-season precipitation totals to above the median in the Southern part of the state (Figure 1). The infrequency of precipitation "miracles" is corroborated by Pokharel et al. (2024) which found that in the upper CRB they only occur about 10% of years. Even the AR event that commenced the anomalous precipitation transition was a rare phenomenon (Figure 4d), especially for spring when AR activity typically declines (Gershunov et al., 2017). The challenge with the concept of a "Miracle March" is that the seasonal cycle of precipitation in California is dominated by winter. Thus, a lack of precipitation in this season leaves a deficit that is almost always unrecoverable by spring storms. In addition, the interseasonal correlation between winter and spring across the 124-year record is weakly positively correlated with some regions of statistically significant correlation (Figure S8). The weak positive correlation further indicates a tendency in the California climate for precipitation conditions to persist from winter to spring.

We show here that the MM91precipitation was very rare (order of <1% to <2% of water years in California) but, despite the rarity of that event, there is still a collective memory of the phenomenon, so an exceedingly unrealistic hope lingers in years with dry winters. We recognize that this analysis relies on the observational record which is limited to one instance of the historical climate and might not capture the full envelope of variability. One method to abate this issue and add statistical robustness to estimating climate extremes is to apply dynamical models to produce an ensemble of climate realizations (Fischer et al., 2023; Thompson et al. 2017). Another method to better represent the extent of climate variability is to extend the observational record with reconstructions of past seasonal precipitation totals such as in Howard et al. (2023). To bolster our confidence on the return interval of an event like MM91, or something more extreme, it will be necessary to expand this work by applying these appraoches to better resolve the climate variability. Albeit MM91 is unique to California, it is a useful example of how applying historical climate data to carefully diagnose climate extremes, that have policy and management implications, can help dispel the influence of recency or other cognitive biases on the management of water risk inherent in variable hydroclimates. Remarkably, during the final edits on this paper, mother nature presented an illustrative case in Spain where the first 18 days of March 2025 received record breaking rainfall which ended an extended drought period while simultaneously causing severe flooding. This demonstrates the potential relevance of the California analysis to other regions of the globe with Mediterranean climates. Furthermore, the Spanish floods exemplify how precipitation "miracles" may quickly turn into disasters.

Under future global warming, Pokharel et al. (2024) found that precipitation "miracles" are likely to decrease in frequency and strength in the CRB. Granted, the seasonal cycles and meteorology of the CRB and California have different flavors, but this indicates that an already rare phenomenon might become rarer in a warming climate. Improved understanding of spring precipitation and its consequences will be necessary to increase resilience to future-climate changes in precipitation seasonality wherein wet-season variability is projected to increase (Gershunov et al., 2019) even as the total precipitation in shoulder seasons, like spring, is projected to decline (Diffenbaugh et al., 2015; Pierce et al., 2013; Swain et al., 2018).

California water managers in spring are tasked with making complex decisions about the future of water entering the dry season at the same time as seasonal forecast skill begins to degrade (Gershunov & Cayan, 2003). In this regard, we show that March 1991 was aptly named a "miracle", or a profoundly uncommon event, and should be considered as such when making operational decisions during a winter drought. A more optimistic interpretation of our analysis is that weather forecast models (up to 10 days) are continuing to garner forecast skill for extreme storms like the AR that triggered the MM91 transition in precipitation conditions. This could indicate that the improvement of weather forecasts could aid in our ability to predict transitions in seasonal precipitation, particularly from dry to wet, alongside improvements in subseasonal forecast methods such as in Guirguis et al., 2023. All in all, in the absence of improvements in seasonal to subseasonal forecast skill, it is ill advised to plan for a "Miracle March".

Data availability statement

The gridded precipitation data set used in this study is publicly available from PRISM Climate Group (2024). The daily precipitation data used in Figure 3 is from Livneh et al. (2013, 2015). The Sierra station indices are available from California Department of Water Resources (2024). The SIO-R1 catalog is from Gershunov et al. (2017). The MERRA-2 grided amtopsheric water vapor and winds used to compute the grided Integrated Vapor Transport (IVT) data is from Gelaro et al. (2017). The NCEP/NCAR reanalysis data is from Kalnay et al. (1996). The data, code set, and figures used in this publication will be openly available at the UCSD digital archives (Poulsen et al., 2024) .

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References

[1] Behnke, R., Vavrus, S., Allstadt, A., Albright, T., Thogmartin, W. E., & Radeloff, V. C. (2016). Evaluation of downscaled, gridded climate data for the coterminous Unitied States. *Ecological Applications*, *26*(5), 1338–1351.

[2] Bourelle, A. (2001). Memories of "Miracle March" | TahoeDailyTribune.com. *Tahoe Daily Tribune*. Retrieved from https://www.tahoedailytribune.com/news/memories-of-miracle-march/

[3] California Department of Water Resources, C. (2024). CDEC [Dataset]. Retrieved May 1, 2024, from https://cdec.water.ca.gov/

[4] Cayan, D. R., Redmond, K. T., & Riddle, L. G. (1999). ENSO and hydrologic extremes in the western United States. *Journal of Climate*, **12**(9), 2881–2893. https://doi.org/10.1175/1520-0442(1999)012<2881:eaheit>2.0.co;2

[5] Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., Curtis, J., & Pasteris, P. P. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology*, *28*(15), 2031–2064. https://doi.org/10.1002/JOC.1688

[6] Department of Water Resources. (1994). *Bulletin 160-93, the California Water Plan Update*. Retrieved from https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/wq_control_plans/1995wqcp/admin_records/part05/328.pdf

[7] Dettinger, M. D., Ralph, F. M., Das, T., Neiman, P. J., & Cayan, D. R. (2011). Atmospheric Rivers, Floods and the Water Resources of California. *Water 2011, Vol. 3, Pages 445-478*, *3*(2), 445–478. https://doi.org/10.3390/W3020445

[8] Diffenbaugh, N. S., Swain, D. L., Touma, D., & Lubchenco, J. (2015). Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(13), 3931–3936. https://doi.org/10.1073/PNAS.1422385112/SUPPL_FILE/PNAS.201422385SI.PDF

[9] Dziegielewski, B., Garbharran, H. P., & Langowski, J. F. Jr. (1993). Lessons Learned from the California Drought (1987–1992): National Study of Water Management during Drought.

[10] Fischer, E. M., Beyerle, U., Bloin-Wibe, L., Gessner, C., Humphrey, V., Lehner, F., Pendergrass, A. G., Sippel, S., Zeder, J., & Knutti, R. (2023). Storylines for unprecedented heatwaves based on ensemble boosting. *Nature Communications*, *14*(1). https://doi.org/10.1038/s41467-023-40112-4

[11] Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., et al. (2017). The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) [Dataset]. *Journal of Climate*, *30*(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

[12] Gershunov, A. (1998). ENSO influence on intraseasonal extreme rainfall and temperature frequencies in the contiguous US: Implications for long-range predictability. *Journal of Climate*, **11**(12), 3192–3203. **https://doi.org/10.1175/1520-0442(1998)011<3192:eioier>2.0.co;2**

[13] Gershunov, A., & Cayan, D. R. (2003). Heavy Daily Precipitation Frequency over the Contiguous United States: Sources of Climatic Variability and Seasonal Predictability. *Journal of Climate*, *16*(16), 2752–2756. https://doi.org/10.1175/1520-0442(2003)016<2752:HDPFOT>2.0.CO;2

[14] Gershunov, A., Shulgina, T., Clemesha, R. E. S., Guirguis, K., Pierce, D. W., Dettinger, M. D., et al. (2019). Precipitation regime change in Western North America: The role of Atmospheric Rivers. *Scientific Reports*, *9*(1), 1–11. https://doi.org/10.1038/s41598-019-46169-w

[15] Gershunov, A., Shulgina, T., Ralph, F. M., Lavers, D. A., & Rutz, J. J. (2017). Assessing the climate-scale variability of atmospheric rivers affecting western North America [Dataset]. *Geophysical Research Letters*, *44*(15), 7900–7908. https://doi.org/10.1002/2017GL074175

[16] Guirguis, K., Gershunov, A., Hatchett, B. J., DeFlorio, M. J., Subramanian, A. C., Clemesha, R., et al. (2023). Subseasonal Prediction of Impactful California Winter Weather in a Hybrid Dynamical-Statistical Framework. *Geophysical Research Letters*, *50*(23), e2023GL105360. https://doi.org/10.1029/2023GL105360

[17] Guirguis, K., Hatchett, B., Gershunov, A., DeFlorio, M., Clemesha, R., Brandt, W. T., Haleakala, K., Castellano, C., Niño, R. L., Tardy, A., Anderson, M., & Ralph, F. M. (2024). Reinterpreting ENSO's Role in Modulating Impactful Precipitation Events in California. *Geophysical Research Letters*, *51*(14), e2024GL110326. https://doi.org/10.1029/2024GL110326

[18] Henn, B., Newman, A. J., Livneh, B., Daly, C., & Lundquist, J. D. (2018). An assessment of differences in gridded precipitation datasets in complex terrain. *Journal of Hydrology*, *556*, 1205–1219. https://doi.org/10.1016/j.jhydrol.2017.03.008

[19] Howard, I. M., Stahle, D. W., Torbenson, M. C. A., Granato–Souza, D., & Poulsen, C. (2023). The Flood Risk and Water-Supply Implications of Seasonal Precipitation Reconstructions in Northern California. *San Francisco Estuary and Watershed Science*, *21*(1). https://doi.org/10.15447/SFEWS.2023V21ISS1ART2

[20] Luna-Niño, R., Gershunov, A., Ralph, F. M., Weyant, A., Guirguis, K., Deflorio, M. J., Cayan, D. R., & Williams, A. P. (2025). Heresy in ENSO teleconnections: atmospheric rivers as disruptors of canonical seasonal precipitation anomalies in the Southwestern US. *Climate Dynamics, 63*(2), 1–11. https://doi.org/10.1007/S00382-025-07583-1

[21] Jones, J., Anderson, M., Chung, F., Islam, N., Juricich, R., Kofoid, J., et al. (2015). California's Most Significant Droughts: Comparing Historical and Recent Conditions. *State of California, California Department of Water Resources* . Retrieved from https://cawaterlibrary.net/wp-content/uploads/2017/05/CalSignficantDroughts_v10_int.pdf

[22] Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40-Year Reanalysis Project [Dataset]. *Bulletin of the American Meteorological Society*, *77*(3), 437–371. https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2

[23] Livneh, B., Bohn, T. J., Pierce, D. W., Munoz-Arriola, F., Nijssen, B., Vose, R., et al. (2015). A spatially comprehensive, hydrometeorological data set for Mexico, the U.S., and Southern Canada 1950-2013 [Dataset]. *Scientific Data*, *2*. https://doi.org/10.1038/sdata.2015.42

[24] Livneh, B., Rosenberg, E. A., Lin, C., Nijssen, B., Mishra, V., Andreadis, K. M., et al. (2013). A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions [Dataset]. *Journal of Climate*, *26*(23), 9384–9392. https://doi.org/10.1175/JCLI-D-12

[25] Parsons, T. (2008). Miracle March saved ski season, helped battle seven-year drought | TahoeDailyTribune.com. *Tahoe Daily Tribune*. Retrieved from https://www.tahoedailytribune.com/news/miracle-march-saved-ski-season-helped-battle-seven-year-drought/

[26] Pierce, D. W., Cayan, D. R., Das, T., Maurer, E. P., Miller, N. L., Bao, Y., et al. (2013). The Key Role of Heavy Precipitation Events in Climate Model Disagreements of Future Annual Precipitation Changes in California. *Journal of Climate*, *26*(16), 5879–5896. https://doi.org/10.1175/JCLI-D-12-00766.1

[27] Pokharel, B., Jagannathan, K. A., Wang, S.-Y. S., Jones, A., LaPlante, M. D., Buddhavarapu, S., et al. (2024). Can we rely on drought-ending "miracles" in the Colorado River Basin? *JAWRA Journal of the American Water Resources Association*, *00*, 1–12. https://doi.org/10.1111/1752-1688.13204

[28] Poulsen, Cody D.; Clemesha, Rachel E. S.; Howard, Ian M.; Gershunov, Alexander; Dettinger, Michael D.; Zhang, Zhenhai; Stahle, David W.; Ralph, F. Martin (2024). Data from: The 1991 California "Miracle March": Precipitation Myth or Miracle? [Dataset]. UC San Diego Library Digital Collections. https://doi.org/10.6075/J0DR2VRQ

[29] PRISM Climate Group, O. S. U. (2024). PRISM Precipitation data [Dataset]. Retrieved December 31, 2023, from https://prism.oregonstate.edu

[30] Ralph, F. M., Dettinger, M. C. L. D., Cairns, M. M., Galarneau, T. J., & Eylander, J. (2018). Defining "Atmospheric river" : How the glossary of meteorology helped resolve a debate. *Bulletin of the American Meteorological Society*, *99*(4), 837–839. https://doi.org/10.1175/BAMS-D-17-0157.1

[31] Ralph, F. M., Iacobellis, S. F., Neiman, P. J., Cordeira, J. M., Spackman, J. R., Waliser, D. E., Wick, G. A., White, A. B., & Fairall, C. (2017). Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers. *Journal of Hydrometeorology*, *18*(9), 2577–2596. https://doi.org/10.1175/JHM-D-17-0036.1

[32] Ralph, F. M., Rutz, J. J., Cordeira, J. M., Dettinger, M., Anderson, M., Reynolds, D., et al. (2019). A scale to characterize the strength and impacts of atmospheric rivers. *Bulletin of the American Meteorological Society*, *100*(2), 269–289. https://doi.org/10.1175/BAMS-D-18-0023.1

[33] Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. v., Rowell, D. P., Kent, E. C., & Kaplan, A. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research: Atmospheres*, *108*(D14). https://doi.org/10.1029/2002JD002670

[34] Singh, D., Ting, M., Scaife, A. A., & Martin, N. (2018). California Winter Precipitation Predictability: Insights From the Anomalous 2015–2016 and 2016–2017 Seasons. *Geophysical Research Letters*, *45*(18), 9972–9980. https://doi.org/10.1029/2018GL078844

[35] Swain, D. L., Langenbrunner, B., Neelin, J. D., & Hall, A. (2018). Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change 2018 8:5*, *8*(5), 427–433. https://doi.org/10.1038/s41558-018-0140-y

[36] Thompson, V., Dunstone, N. J., Scaife, A. A., Smith, D. M., Slingo, J. M., Brown, S., & Belcher, S. E. (2017). High risk of unprecedented UK rainfall in the current climate. *Nature Communications*, *8*(1). https://doi.org/10.1038/s41467-017-00275-3