nature climate change

ARTICLES

https://doi.org/10.1038/s41558-018-0140-y

Increasing precipitation volatility in twenty-first-century California

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Mediterranean climate regimes are particularly susceptible to rapid shifts between drought and flood—of which, California's rapid transition from record multi-year dryness between 2012 and 2016 to extreme wetness during the 2016–2017 winter provides a dramatic example. Projected future changes in such dry-to-wet events, however, remain inadequately quantified, which we investigate here using the Community Earth System Model Large Ensemble of climate model simulations. Anthropogenic forcing is found to yield large twenty-first-century increases in the frequency of wet extremes, including a more than threefold increase in sub-seasonal events comparable to California's 'Great Flood of 1862'. Smaller but statistically robust increases in dry extremes are also apparent. As a consequence, a 25% to 100% increase in extreme dry-to-wet precipitation events is projected, despite only modest changes in mean precipitation. Such hydrological cycle intensification would seriously challenge California's existing water storage, conveyance and flood control infrastructure.

Mediterranean climate regimes are renowned for their distinctively dry summers and relatively wet winters—a globally unusual combination[1]. Such climates generally occur near the poleward fringe of descending air in the subtropics, where semi-permanent high-pressure systems bring stable conditions during most of the calendar year[2]. Here, the majority of precipitation occurs during the passage of transient storm events during a short rainy season[3]—a distinct seasonality brought about by an equatorward shift in the mid-latitude storm track during winter[4]. The same factors that imbue such regions with their temperate mean climate state, however, are also conducive to dramatic swings between drought and flood[4–6]. Subtle year-to-year jetstream shifts can generate disproportionately large precipitation variability[7]—yielding highly non-uniform precipitation distributions[8] and increasing the intrinsic likelihood of hydroclimatic extremes[4,9]. These effects are often amplified in California, where a combination of complex topography and over 1,000 km of latitudinal extent yield a great diversity of microclimates within the broader 'dry summer' regime[3].

California's rapid shift from severe drought to abundant precipitation (and widespread flooding) during the 2016–2017 winter[10] offers a compelling example of one such transition in a highly populated, economically critical and biodiverse region[11,12]. Immediately following one of the most intense multi-year droughts on record between 2012 and 2016 (refs [13–15]), the state experienced several months of heavy precipitation associated with an extraordinarily high number of atmospheric river storms during November–March 2016–2017 (ref. [10]). While the heaviest precipitation was concentrated in northern Sierra Nevada watersheds, hundreds of roads throughout California were damaged by floodwaters and mudslides (including a major bridge collapse)[16]. In February 2017, heavy runoff in the Feather River watershed contributed to the failure of the Oroville Dam's primary spillway—culminating in a crisis that forced the emergency evacuation of nearly a quarter of a million people[17].

Previous studies focusing on future changes in California precipitation have generally reported modest[18–20] (and/or uncertain) changes in regional mean precipitation[7,20]. More recent work, however, has suggested an increased likelihood of wet years[20–23] and subsequent flood risk[9,24] in California—which is consistent with broader theoretical and model-based findings regarding the tendency towards increasing precipitation intensity[25] in a warmer (and therefore moister) atmosphere[26,27]. Meanwhile, while evidence shows that anthropogenic warming has contributed to an increased risk of California drought via increasing temperatures[28,29] and increased frequency of seasonally persistent high-pressure ridges[8,14,30,31], attribution studies focusing directly on precipitation have yielded mixed results[18,32]. Contributing additional uncertainty are climate model simulations suggesting that the boundary between mean subtropical drying and mid-latitude wetting will probably occur over California[33], potentially yielding strong latitudinal gradients in the precipitation response. Thus, while there is already substantial evidence that climate change will induce regional hydroclimatic shifts, a cohesive picture has yet to emerge—presenting serious challenges to decision-makers responsible for ensuring the resilience of California's water infrastructure[11].

Importance of large ensemble approach

We use specific flood and drought events from California's history as baselines for exploring the changing character of precipitation extremes. Our use of a large ensemble of climate model simulations[34]—the Community Earth System Model Large Ensemble (CESM-LENS)—allows us to directly quantify changes in large-magnitude extremes. This approach offers a substantial advantage over traditional climate model experiments, which yield too small a sample size of statistically rare extreme events to draw robust inferences without making assumptions regarding the underlying precipitation distribution[35]. By selecting a wide range of wet, dry and dry-to-wet transition (that is, 'whiplash') events informed by historical analogues, we aim to provide a comprehensive perspective on the changing risks of regional hydroclimate extremes in a manner directly relevant to climate adaptation and infrastructure planning efforts.

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