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RESEARCH

Historical and Future Relations Between Large Storms and Droughts in California

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ABSTRACT

California precipitation varies more dramatically from year to year than elsewhere in the conterminous United States. This paper analyzes the extent to which contributions of the wettest days to overall precipitation dictate the state's precipitation seasonality and frequent multiyear periods of drought (as precipitation deficit) and plenty is analyzed, historically and in projections of future climates. The wettest 5% of wet days in California contribute about a third of precipitation but about two-thirds of the variance of water-year precipitation. Year-to-year fluctuations in precipitation strongly reflect year-to-year fluctuations of contributions from the largest storms, with the large-storm contributions explaining about twice as much precipitation fluctuation as do contributions from all remaining storms combined. This extreme dominance of large storms is largely unique to California within the United States. In climate-change projections, eight of ten climate models considered here yield increases in precipitation from the largest storms, and when the increases are large, total precipitation follows suit. All of the models project declines in contributions from the smaller storms and models projecting total-precipitation declines reflect this decline. Projected changes in variance of water-year precipitation reflect changes in variance of large-storm contributions. The disproportionately large overall contributions from California's largest storms, and their outsized year-to-year variability, ensure that the state's largest storms dictate the state's regimes of wet and dry spells, historically and in climate-change projections.

KEY WORDS

Drought, storms, extreme events, hydroclimatology of California, effects of global change

INTRODUCTION

Storm and drought dictate so much of the story of water and life in California that hydro-environmental engineering is an almost uniquely difficult proposition in this state. California precipitation varies more dramatically from year to year than anywhere else in the conterminous United States. (Dettinger et al. 2011), with standard deviations of annual precipitation between 30% and 50% of long-term averages, compared to 10% to 30% nearly everywhere else. California's precipitation totals vary widely from year to year—from as little as 50%

to more than 200% of long-term averages, and, on multi-year time scales, between about 80% and 140% of normal for sustained periods (e.g., in 5-year moving averages). At shorter time-scales, California's largest storms have doused its mountain ranges with 3-day precipitation totals that are among the largest in the conterminous U.S., exceeding those anywhere else in the country except in the southeastern U.S. (where tropical storms and landfalling hurricanes unleash tremendous deluges upon occasion) and equaling the size of storms even there (Ralph and Dettinger 2012). When a surfeit of these large storms have been unleashed on California, floods have often been the devastating outcome (Kelley 1998; Dettinger and Ingram 2013).

These hydroclimatic excursions in California are so frequent and extreme that it often seems that there is little middle ground; they rarely yield "normal" conditions. Managers of the state's many water supplies face droughts of frightening depth and persistence, while flood managers throughout the state struggle to anticipate and contain the destructive elements of storms as large as any others in the nation. These two aspects of water management in the state have historically and routinely been at odds (e.g., Ralph et al. 2014) because most major reservoirs in the state, and many of its largest water conveyance systems, are used jointly for flood and supply purposes. Thus, on a regular basis, water users are at risk of summertime water-supply shortfalls if "too little" runoff is captured behind the state's many reservoirs, while the state's people and infrastructures could be placed at risk of extreme and widespread flood damages if "too little" empty space (to capture or dampen flood flows) were maintained in those same reservoirs.

In fact, the number of large storms does not have to be enormous (nor much smaller than normal) to drive the state towards surfeit or drought. The state's extreme precipitation variability arises from the small number of storms that provide most of the state's precipitation each year. In much of California, nearly half of all precipitation falls during just 5 to 10 days per year (Dettinger et al. 2011). If a few large storms happen to bypass California in a given year, precipitation totals are proportionally much reduced, and the state experiences drought (Dettinger and Cayan 2014); a few extra storms can push the state towards surfeit and water logging. In this context, it has been informative and a bit disheartening to discover just how very intimate are the ties between major storms and droughts in California. The state's surfeits (and, eventually, its floods) and droughts are actually inseparable, so that planning and management of floods and droughts may never be completely disentangled.

This paper documents the close relations between droughts and the largest storms in California, identifying the fractions of total precipitation and precipitation variability that are attributable to just the wettest 5% of storm days and contrasting the large-storm contributions to those from the remaining, smaller but much more frequent storms. I compare the special role of large storms in determining California's precipitation variability to precipitation regimes in other parts of the conterminous U.S., to determine whether the strong contributions of largest storms to overall precipitation found in California is unusual. Finally, I compare the observed role of the largest storms in California's overall precipitation variability with precipitation regimes simulated by current global-climate models, and calculate how this role may change under projected climate changes.

DATA

For the most part, the analyses presented in this study are based on sub-regional aggregations of daily precipitation totals from high-resolution, 1/8°-latitude-longitude gridded fields by Hamlet and Lettenmaier (2005, and updates thereto). Initially, the gridded precipitation dailies are aggregated to compute precipitation totals for California north of 35°N (Figure 1) to represent the "California precipitation regime" for the wet parts of the state. The solid black curve is the 5-year moving average of precipitation totals for the Central Valley drainage (Figure 1) based on Abatzoglou et al.'s (2009) reclassified climatic divisions, whereas the thin dashed curve (almost totally obscured by the solid curve) is the corresponding moving average of precipitation over all of California north of 35°N, indicating that either region could have been used. In this analysis, I determine precipitation percentiles from aggregations of the Hamlet and Lettenmaier

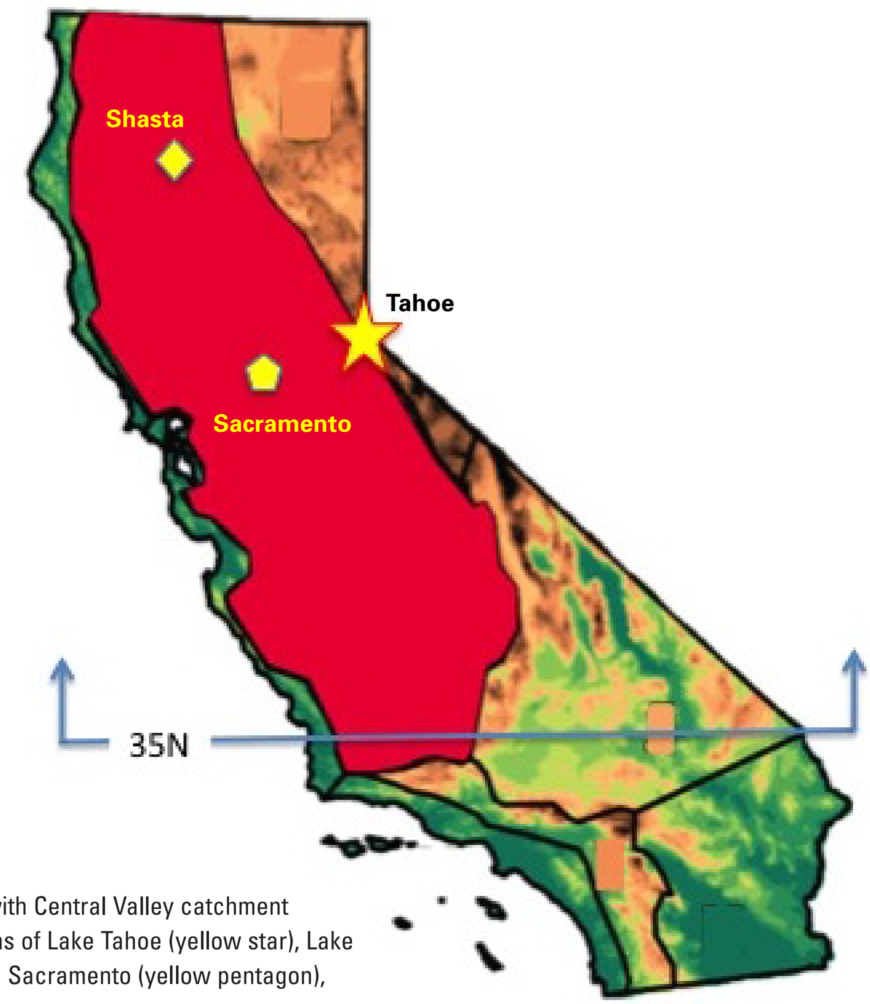

Figure 1 Map of California, with Central Valley catchment indicated in red, with locations of Lake Tahoe (yellow star), Lake Shasta (yellow diamond), and Sacramento (yellow pentagon), along with 35°N latitude

(2005) daily fields over California and, later, on a 1°-latitude–longitude grid over the conterminous U.S., although I also briefly compare analysis results to station-by-station analyses of Summary-of-Day precipitation records from long-term National Centers for Environmental Information cooperative-observer sites; National Weather Service (1989, and updates thereto).

To characterize the relations between storms and droughts, these subregional aggregations are separated here into water-year total contributions from the long-term wettest 5% of wet days and contributions from all remaining wet days. Daily precipitation totals from all wet days in the 1950–1999 period were sorted, so that I could identify the threshold between the wettest 5% and the remaining 95% of wet days. Then, I separated daily precipitation totals for each water year for the entire period of record into those days that exceeded that threshold and those that fell below it, and summed the two sets separately to arrive at the contributions to total precipitation from the wettest 5% of wet days and remaining days.

I then compare the contributions of large and small storms to precipitation totals for: (a) to the water year totals from a longer monthly precipitation time-series for the Central Valley drainage area (Figure 1) based on a recent re-classification of climate divisions in California (Abatzoglou et al. 2009), (b) to numbers of atmospheric-river storms making landfall in the state each year (Dettinger et al. 2011 and updates thereto), (c) to April 1 snow-water contents in the Sierra Nevada and storage in two large reservoirs there, and (d) year-to-year variations of Pacific

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climate modes. Much of the present analysis focuses on northern California, because this is the area within which two-thirds of the precipitation and runoff in California occurs, whereas roughly three-fourths of the population and water demands are in the southern two-thirds of the state. To meet these demands, local, state, and federal agencies have constructed massive storage and conveyance systems that span the state, so that precipitation in northern California contributes to much of the state's overall water supply. I will apply a variety of statistical methods to these components of total precipitation, including moving averages, correlations, regression analyses, and coherency analyses in California, and, briefly, across the conterminous U.S. I will introduce these methods as they enter the discussion.

Finally, a similar disaggregation of water-year precipitation totals into contributions from small and largest storms will be applied to precipitation simulations of historical and future climate conditions by 10 modern global-climate models of 2013 vintage (CCTAG 2015) under two greenhouse-gas emissions scenarios each. The emissions scenarios considered are a scenario in which greenhouse-gas concentrations continue to increase rapidly throughout the 21st century (RCP8.5) and a scenario in which greenhouse-gas concentrations level off at a concentration 4.5/8.5 (53%) as strong as in the RCP8.5 scenario by end of century. I then compare the precipitation regimes the selected models project for late in the 21st century to observations and to historical-climate simulations by the same models, to explore the currently projected future of storm–drought relations in northern California.

CALIFORNIA PRECIPITATION CLIMATOLOGY AND CONTRIBUTIONS

Historically, precipitation in northern California and the Central Valley catchment (Figure 1) has fluctuated widely from year to year (purple bars, Figure 2A). The total-precipitation fluctuations indicated in Figure 2A are large enough, and persistent enough over multiple years, to have considerable practical importance. For example, Figure 3A shows September (and 5-September moving averages of) storage conditions at two of the largest reservoirs in California, where September conditions measure the carryover of storage from water year to water year. At the 5-year moving average scale, September lake levels at Lake Tahoe (Figure 3A) correlate with total precipitation with $r=0.65$, and storage at Lake Shasta correlates with $r=0.61$, with a high-to-low range that amounts to half the average storage in both lakes. A comparison (not shown here) of April 1 snow-water content estimates in the Sierra Nevada (*http://cdec.water.ca.gov/cgi-progs/snowsurvey_sno/COURSES*, where April 1 snowpack more or less dictates streamflows for the rest of water year) to the contributions to total precipitation from the wettest 5% of wet days yields correlations between the unfiltered precipitation contributions and April 1 snowpack, 1950–2013, in the northern, central, and southern Sierra Nevada of 0.68, 0.78, and 0.75 respectively, reinforcing again the practical importance of the precipitation components and variations that I will unpack in the remainder of this paper.

To show the character and some origins of the precipitation variations shown in Figure 2A, the precipitation totals in Figures 2B and 2C are separated into contributions from the long-term wettest 5% of wet days (the upper 95th percentile of wet days; purple bars and red curve, Figure 2B), and contributions from all remaining wet days (purple bars and green curve, Figure 2C). The three panels in Figure 2 comprise the key elements of Figure 1A in Dettinger and Cayan (2014), now expanded to show the full range of time scales of total, wettest-day, and remaining-day precipitation fluctuations better than that earlier summary figure. The wettest days (Figure 2B) contribute an average of 38% of the 1951–2000 total precipitation, with remaining storms contributing 62% of total precipitation (Figure 2C). This 40–60 split in the average contributions to total precipitation from the wettest days versus remaining days is consistent with previous indications that California's primary largest-storms mechanism (atmospheric rivers; to be discussed briefly later) provide between 35% and 50% of all precipitation on long-term average (Guan et al. 2010; Dettinger et al. 2011; Ralph et al. 2014; Rutz et al. 2014).

Although remaining-day contributions make up the majority of precipitation on average, contributions from the wettest 5% of wet days vary more than twice as much as those remaining-day contributions. The wettest-day contributions have a variance that

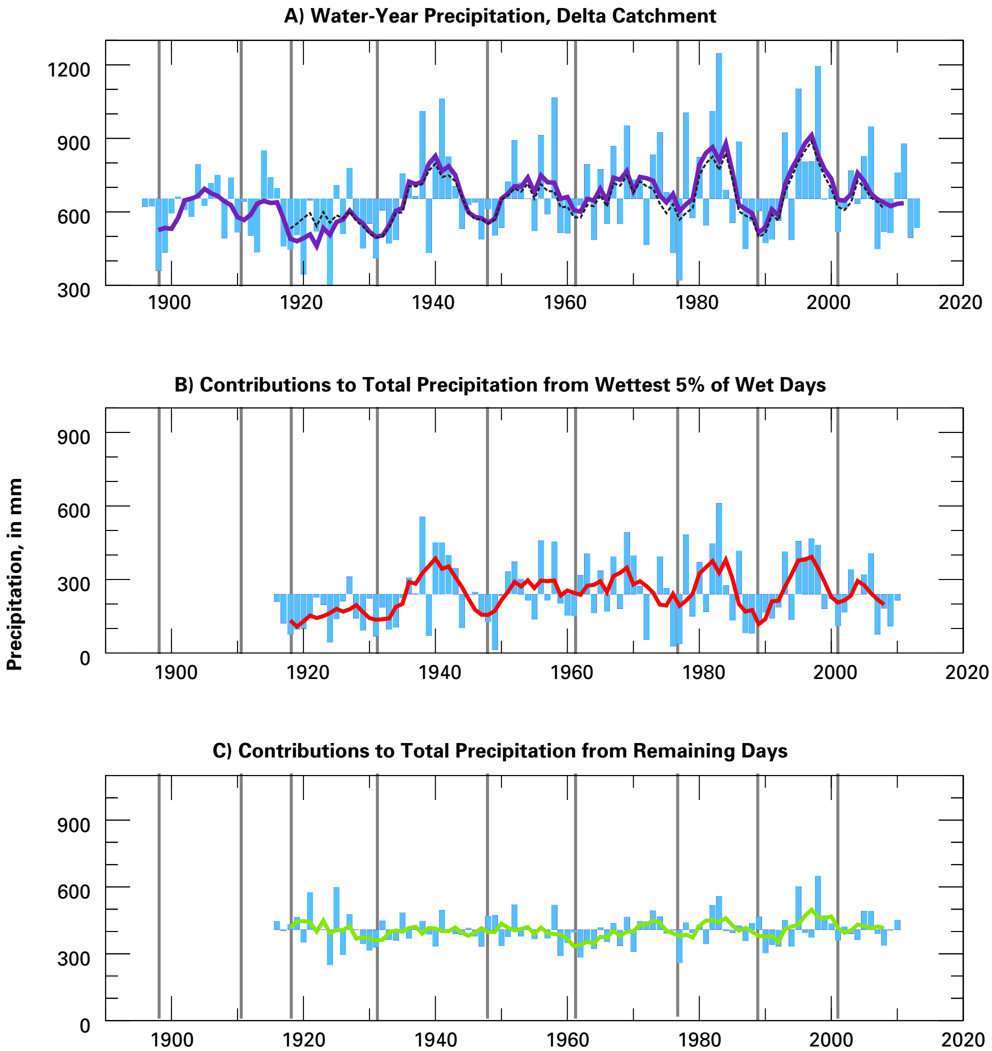

Figure 2 **(A)** Water-year precipitation totals (blue bars—unfiltered, and purple curve—5-year moving averages) in the Central Valley catchment, 1895–2013, based on updated monthly Abatzoglou et al. [2009] data, and total precipitation in California north of 35°N computed from the Hamlet and Lettenmaier [2005] gridded daily precipitation time series, 1916–2011 (thin dashed black curve); **(B)** contributions to these totals from the wettest 5% of wet days (blue bars and red curve); and **(C)** from all remaining wet days (<95th percentile; blue bars and green curve) based on updated daily Hamlet and Lettenmaier [2005] data, 1916–2010, in California north of 35°N. Heavy curves are 5-year moving averages in all frames; vertical grey lines through all panels indicate timing of minima of the heavy purple curve in panel **(A)**.

is 46% as large as the variance of total precipitation, whereas the variance of the contributions from all remaining days combined is only about 20% as large as the variance of total precipitation. Thus, contributions from the largest 5% of storms ultimately provide most of the variance of water-year precipitation totals.

This separation of the variability of total precipitation into wettest-day and remaining-day fractions can be extended to better understand the seasonal cycle as well. California has a Mediterranean precipitation regime, with wettest months in the cool season, centered on January, and also experiences its greatest year-to-year variance of monthly precipitation in the deep-winter months (black curves, Figures 4A and 4B). Precipitation contributions from the wettest 5% of wet days, and from the remaining days, also are largest and most variable in winter (stacked red and green bars, Figures 4A and 4B, respectively). The average contributions from the

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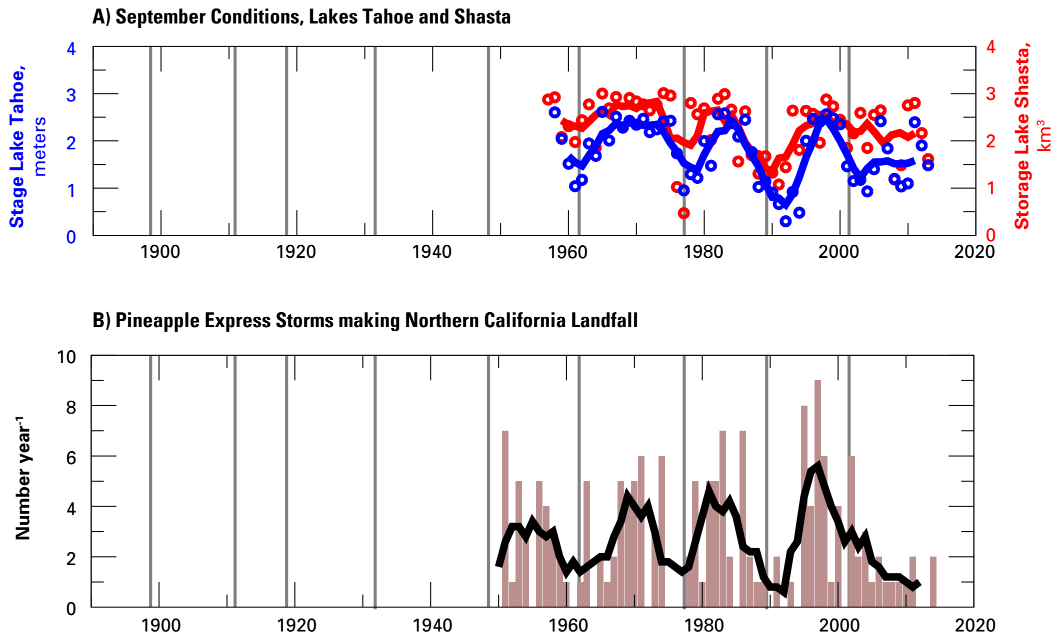

Figure 3 **(A)** September water levels in Lake Tahoe (blue symbols and curve; a 50,000-ha lake, Figure 1) and storage in Lake Shasta (red symbols and curve; a 12,000-ha lake); and **(B)** numbers of pineapple-express storms making landfall between 35°N and 42.5°N per water year (using counts from Dettinger et al. [2011], updated through September 2014). As in Figure 2, heavy curves are 5-year moving averages in all frames; vertical grey lines through all panels indicate timing of minima of the heavy purple curve in Figure 2A.

wettest days are notably even more peaked in the winter months with a narrower "wet" season than either the monthly precipitation totals or the contributions from smaller storms (Figure 4A), which are notably close to uniform from December through March. Consequently, most of the peaked-ness of the seasonal cycle of total precipitation in northern California comes from the briefness of the season when the largest storms arrive.

Monthly variances of the contributions from the wettest 5% of storms are even more seasonally peaked in the winter months (Figure 4B), and the variance of contributions from smaller ("remaining") storms are even more uniform, and small, than in the mean. The total precipitation is the sum of the contributions from the wettest 5% and the remaining wet days, and some algebra applied to the definitions of variance and covariance shows that the variance of total precipitation is:

$$Var(total) = Var(wettest) + Var(remaining) + 2\,Cov(wettest, remaining) \quad (1)$$

where $Var(.)$ is the sample variance and $Cov(.,.)$ is the sample covariance (Benjamin and Cornell 1970). The final term in this equation represents nonlinear constructive or destructive interference of the fluctuations of wettest-day and remaining-day contributions to total precipitation. To the extent that the two contributions vary in phase with each other, they constructively increase the overall variance of total precipitation, whereas if they are out of phase with each other they tend to cancel, reducing the variance of the total. The covariance of the wettest- and remaining-day contributions (blue in Figure 4B) contribute only modestly to the monthly variances of total precipitation. Thus, California's narrow wet-season (on average) and most of its year-to-year precipitation variance derive from the wettest 5% of storms, in winter, rather than from the remainder of storms in winter or otherwise. Notably, the drier 95% of wet days contribute only muted forms of seasonality in terms of either mean seasonality or month-to-month precipitation variance.

By passing the annual fluctuations (in Figures 2A–2C) through 5-year moving averages, multi-year characteristics of the contributions to total precipitation can be readily visualized. The curves in Figure 2A show those moving averages

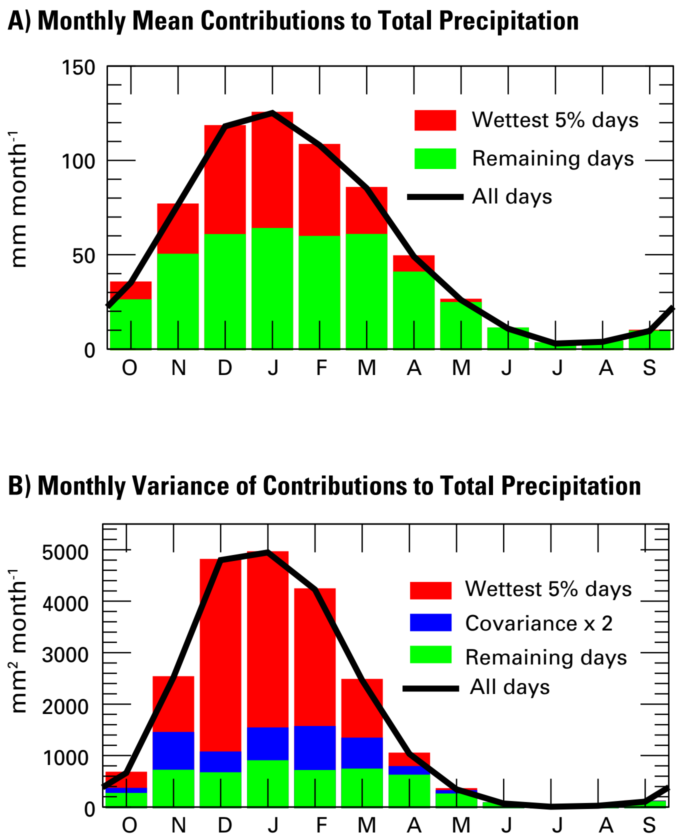

Figure 4 Seasonality of monthly **(A)** means and **(B)** variances of Central Valley catchment's total precipitation and contributions from the wettest 5% of wet days and remaining days, water years 1916–2010

and illustrate the tendency towards long-term, quasi-decadal variations between drought and wet episodes. Nine times since 1900 (vertical grey lines, Figures 2A–2C), northern California precipitation has cycled between wet periods and droughts (e.g., Ault and St. George 2010), with the ongoing (as of 2015) drought arriving more or less "on schedule" at this time-scale. The quasi-decadal time-scale of these fluctuations indicates that they are not expressions (Dettinger and Cayan 2014) of either the El Niño–Southern Oscillation (ENSO) or the Pacific Decadal (PDO) climate modes (Redmond and Koch 1991; Mantua et al. 1997; Cayan et al. 1999; McCabe and Dettinger 2002), and their origins remain uncertain. Reliance on the seeming regularity of these quasi-decadal swings in the late 20th century needs to be tempered by the repeated observations in tree-ring reconstructions that this fluctuation has not been persisted in previous centuries (St. George and Ault 2011; Meko et al. 2014) and by the long periods in the early 20th century when it also flagged. The corresponding curves in Figures 2B and 2C suggest that California's quasi-decadal precipitation variations are also dominated by fluctuations in the largest storms over multi-year periods.

The year-to-year and decade-to-decade correspondences between fluctuations of the red and green, versus black, curves in Figure 2 since 1916 are shown in Figure 5, for unfiltered water-year values (open circles) and for the same 5-year moving averages as shown in Figure 2 (solid circles). Fully 85% of the total-precipitation variance is explained (in terms of r^2 from simple linear regressions) by the water-year contributions from the wettest 5% of wet days (if both are unfiltered; 92% if they are 5-year moving averaged, as in Figure 2). Remaining, smaller storms explain only 46% of total-precipitation variability (unfiltered; 24% if 5-year moving averaged).

Although the moving averages applied in Figure 2 highlight quasi-decadal (roughly 14-year) fluctuations

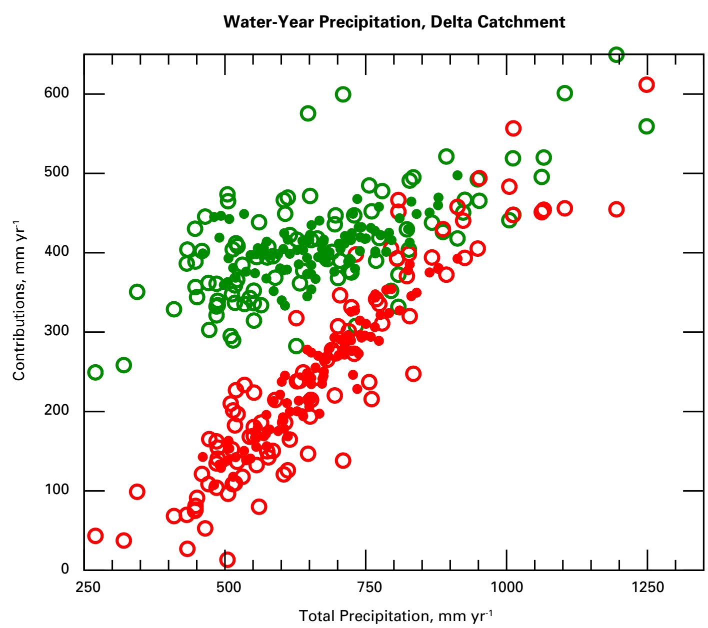

Figure 5 Comparisons of contributions to total Central Valley catchment precipitation from wettest 5% of wet days (red) and remaining wet days (green) with total precipitation, 1916–2010. Solid dots are 5-year moving averages from Figure 2 and open circles are unfiltered water-year values.

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of total precipitation and the contributions from the largest storms, the strong tendency for fluctuations of the largest storms to dictate total-precipitation fluctuations is not restricted to that quasi-decadal time-scale, as illustrated by the wide range of frequencies (time-scales) over which the contributions from largest storms cohere closely to the variations of total precipitation (heavy curves, Figure 6). This coherence spectrum essentially shows r^2 values (fraction of variance explained) between two time-series within each frequency band (time-scale) from year-to-year differences (0.5 cycles yr^{-1}) to multi-decadal variations (e.g., 0.03 cycles yr^{-1}). Coherence varies between zero and one, and the larger the coherence, the more the two time-series fluctuate in parallel at a given time-scale. Figure 6 shows close (>80%) coherence (high explanatory power) between total precipitation and contributions for the wettest days across almost the entire range tested, except around a 3-year time-scale (0.33 cycles yr^{-1}), whereas the coherence between total precipitation and contributions from remaining wet days only rises to large values at a few frequencies. The broadband and extremely close relation between the year-to-year and decade-to-decade fluctuations of the very largest storms and overall precipitation in California indicates that episodes of overall drought and surfeit

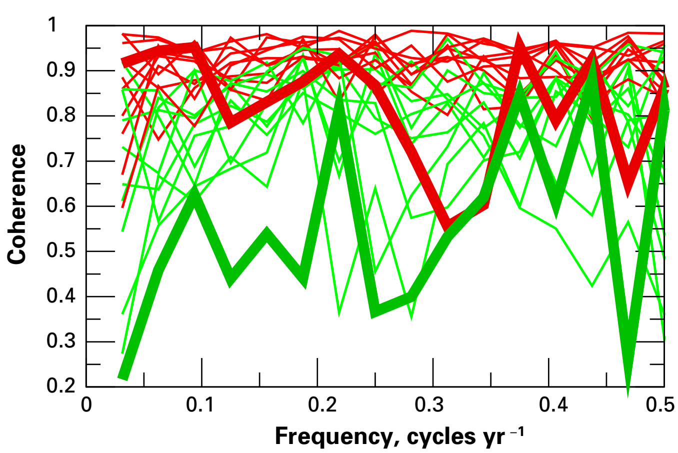

Figure 6 Coherence spectrum between observed fluctuations of total precipitation and contributions from the wettest 5% of wet days (heavy red) or contributions from all remaining days (heavy green), 1916–2011; light curves are corresponding coherence spectra for precipitation series from 10 climate models, 1951–2099. The coherence spectra illustrate the fractions of variance shared by two series as a function of frequency (Granger 1964).

are very much a function of those largest storms across most longer-than-annual time scales in the historical period. This conclusion goes well beyond earlier findings that many historical droughts have ended with the arrival of one or two large storms (Dettinger 2013) to indicate, more generally, that variations between precipitation deficit and surplus in California on all time-scales longer than about 3 years are overwhelmingly a result of the variations in the largest storms. This finding also goes beyond (but complements) previous findings that almost half of the long-term average precipitation in California derives from atmospheric rivers (ARs) (Guan et al. 2010; Dettinger et al. 2011), by showing that large storms dictate an even larger fraction of the annual to multi-decadal fluctuations of total precipitation.

The use of a wettest 5% of wet days as a threshold to separate large storms from the rest in Figures 2 and 5 is fairly arbitrary, as is the application of a 5-year moving average in the figures. Figure 7 shows the percentages of water-year total-precipitation variance explained (as r^2) when various percentile thresholds of wetness are applied to separate between contributions from the 'wettest' and 'remaining' storms, on the vertical axis, and when various levels of smoothing are applied, on the horizontal axis. Until an upper threshold of about the wettest 5% of wet days is reached, little variance of total precipitation is explained; once storms at least this wet are considered, the variance explained increases rapidly. Above this threshold, the choice of how much (if any) smoothing is applied is not very influential.

Given this dominant role of large storms in determining year-to-year precipitation variations in northern California, and together with the growing body of evidence demonstrating that landfalling ARs are sources of the largest storms and floods on the West Coast (e.g., Ralph et al. 2006; Neiman et al. 2008; Dettinger et al. 2011; Neiman et al. 2011; Ralph and Dettinger 2012; Dettinger 2013; Ralph et al. 2014), it is no surprise that the multi-year fluctuations of total precipitation (and of contributions from wettest 5% of wet days) in Figures 2A and 2B closely parallel yearly counts of ARs directly connecting the tropics with northern California ('pineapple expresses,' Figure 3B). The unfiltered AR counts explain about 33% of the

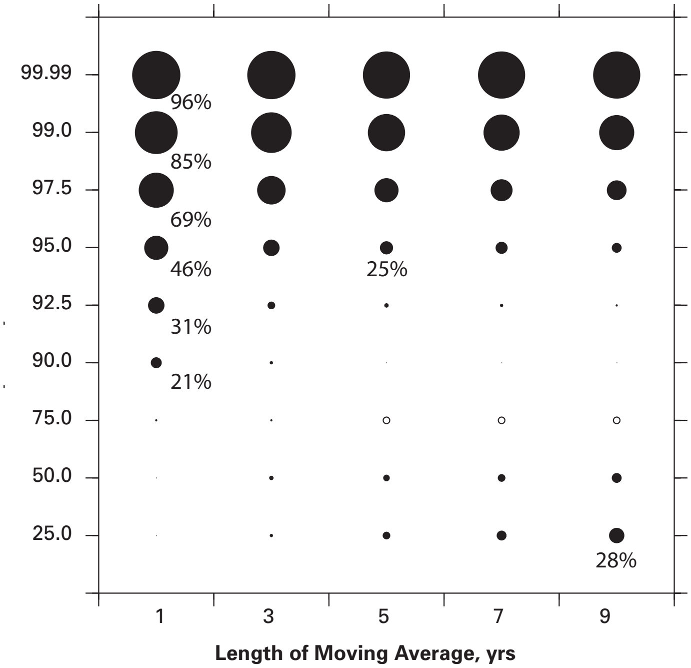

Figure 7 Percentages of water-year total precipitation variance explained (in regression sense) by precipitation contributions from wet days with precipitation less than various percentiles (vertical axis), under various moving averages (horizontal axis), water years 1916–2010. Areas of circles are proportional to correlations squared; open circles indicate negative correlations.

variance of total precipitation, but once 5-yr moving averaged to emphasize multi-year fluctuations, AR counts explain 75% of precipitation variations during the 1948–2014 period when water-year counts of pineapple expresses are available (Dettinger et al. 2011, and updates thereto). Among the wettest days, in the 1998–2008 period covered by the chronology of all AR landfalls in California reported in Dettinger et al. (2011), 48% of the wettest 5% of wet days correspond to occasions with landfalling ARs, despite AR landfalls making up only about 5% of all wet days. Overall then, ARs provide a disproportionate number of the wettest days in California. During sustained periods when the number of ARs that reach California flags, California experiences multi-year drought, and when more than the normal number of ARs reaches the state, wet conditions prevail. Consequently, explaining and anticipating seasonal to multi-year fluctuations in AR landfalls has become a key research need to meet California's future water resources and drought information needs.

U.S. PRECIPITATION VARIABILITY AND CONTRIBUTIONS

This extremely close connection between northern California's largest storms and its droughts is actually quite unusual within the United States. Precipitation contributions from largest storms are important elsewhere, but only rise to the extreme levels indicated above in California's precipitation regimes. To document this, I analyzed 1° aggregates of daily precipitation across the conterminous U.S., as in Figure 2, except that instead of using a wettest-5% threshold, a threshold was chosen for precipitation in each 1°-latitude–longitude grid cell such that only an average of 7 days per year exceed the threshold. This thresholding ensures that similar numbers of wettest days were considered everywhere, regardless of whether a locale had many wet days each year or very few. This threshold approximates the wettest 5% of wet days in California. Resulting variances of total precipitation explained by contributions from wettest (7, on average) days and by contributions from all remaining days are mapped in Figures 8A and 8B, respectively.

Analyzed this way, contributions of wettest days to total precipitation capture >80% of the variations of total precipitation only in California and its immediate environs (Figure 8A). Elsewhere in the conterminous U.S., the contributions of wettest (7, on average) days per year mostly explain between about 40% and 80% of total-precipitation variance (Figure 8C), with wettest days contributing between 50% and 70% at 63% of 1°-grid cells in the conterminous U.S., mostly in the western two-thirds of the country. By contrast, contributions from smaller storms explain much less variance everywhere, including California (Figure 8B), with the variance captured by the smaller storms amounting to between 10 and 30% at 89% of grid cells (Figure 8C). The smaller storms explain the least total-precipitation variances in California, with no California grid cell having small-storm contributions explaining more than 10% of total-precipitation variability (Figure 8C) on this 1° grid. California's comparatively close relation between water-year

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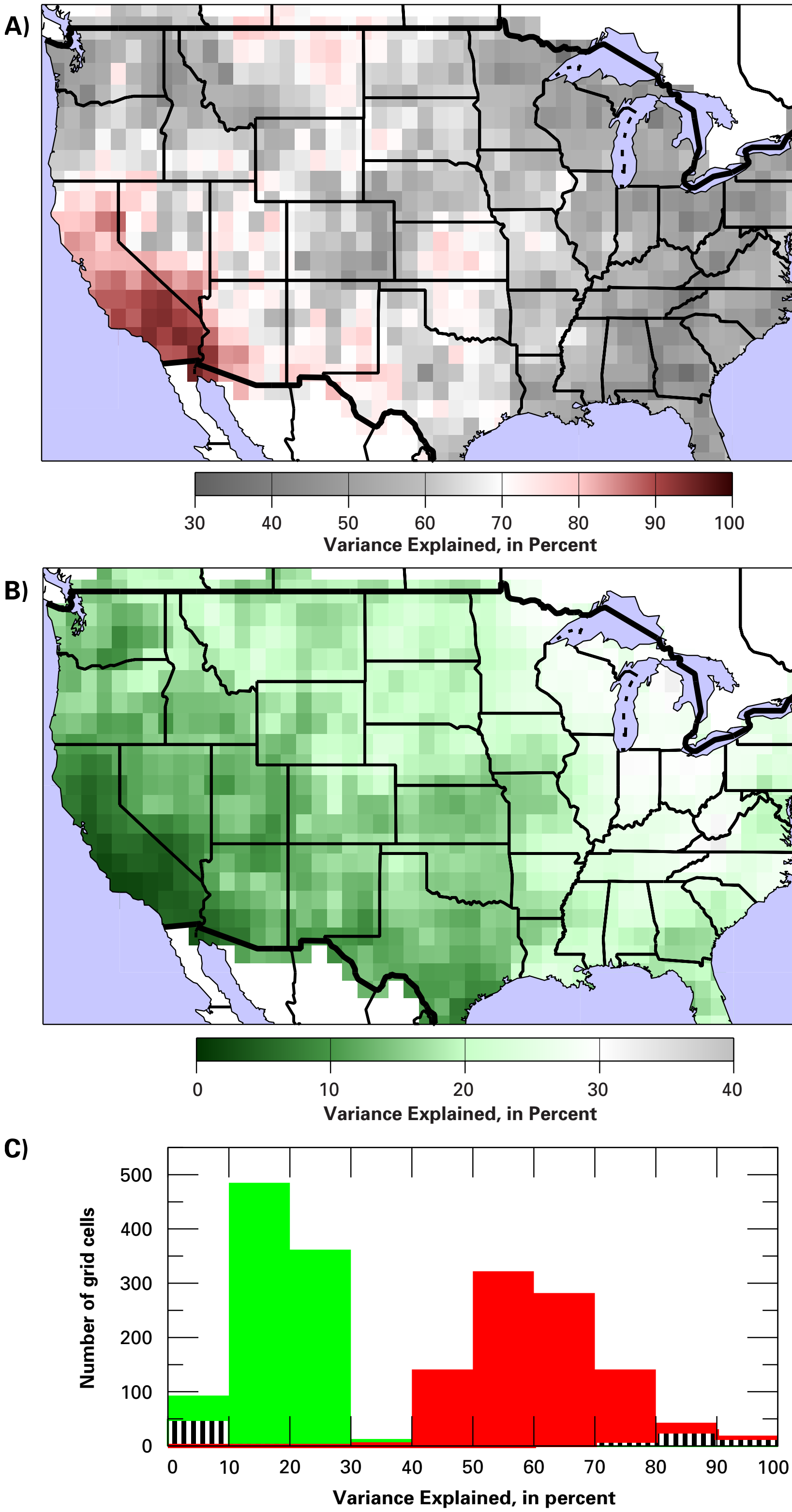

Figure 8 Percentages of total water-year precipitation variance explained by **(A)** precipitation from the wettest days (wetter than a threshold exceeded by an average of 7 days per year at each 1º-latitude–longitude grid cell) and **(B)** precipitation on all remaining days, water years 1951–1999; and **(C)** histograms of the variances explained at all grid cells (red for wettest days, green for remaining days), with histogram contributions from California grid cells marked by vertical hachures. The color bars for **(A)** and **(B)** are chosen to emphasize the grid cells with extremes of most explanatory and least explanatory contributors to total precipitation variance.

precipitation contributions from wettest days and total precipitation is also evident, albeit amidst much more scatter (especially in the south-central U.S.), when the same calculations are made for 3,369 stations in the cooperative weather-observers network (Figure 9).

The extremely close relation between contributions from largest storms and precipitation totals is a result of (a) California's relatively small number of storms per year and the large part of total precipitation those storms contribute on average (Figure 4A), (b) its Mediterranean hydroclimate, which ensures that the season when storms of any size contribute much precipitation is short, and (c) the extreme size of California's largest storms (Ralph and Dettinger 2012). California's precipitation regime is skewed towards a relatively few (compared to total numbers of wet days in many other parts of the U.S.) and absolutely large largest storms, with wet-day precipitation skewness coefficients mostly in the upper half of coefficients nationwide (not shown). This combination of few and large storms yields a precipitation regime that is unusually dependent on those few largest storms at annual and interannual time-scales.

FUTURE PRECIPITATION CONTRIBUTIONS

Given the important role of wettest-day contributions to California's water-year precipitation variability, it is natural to consider (a) whether current global-climate models capture this aspect of the region's precipitation regime and (b) if so, how the contributions are projected to evolve under future climate changes. The historical performances of over 30 climate-models used in the recent Fifth Intergovernmental Panel on Climate Change Assessment (IPCC 2013) were evaluated recently (CCTAG 2015), in

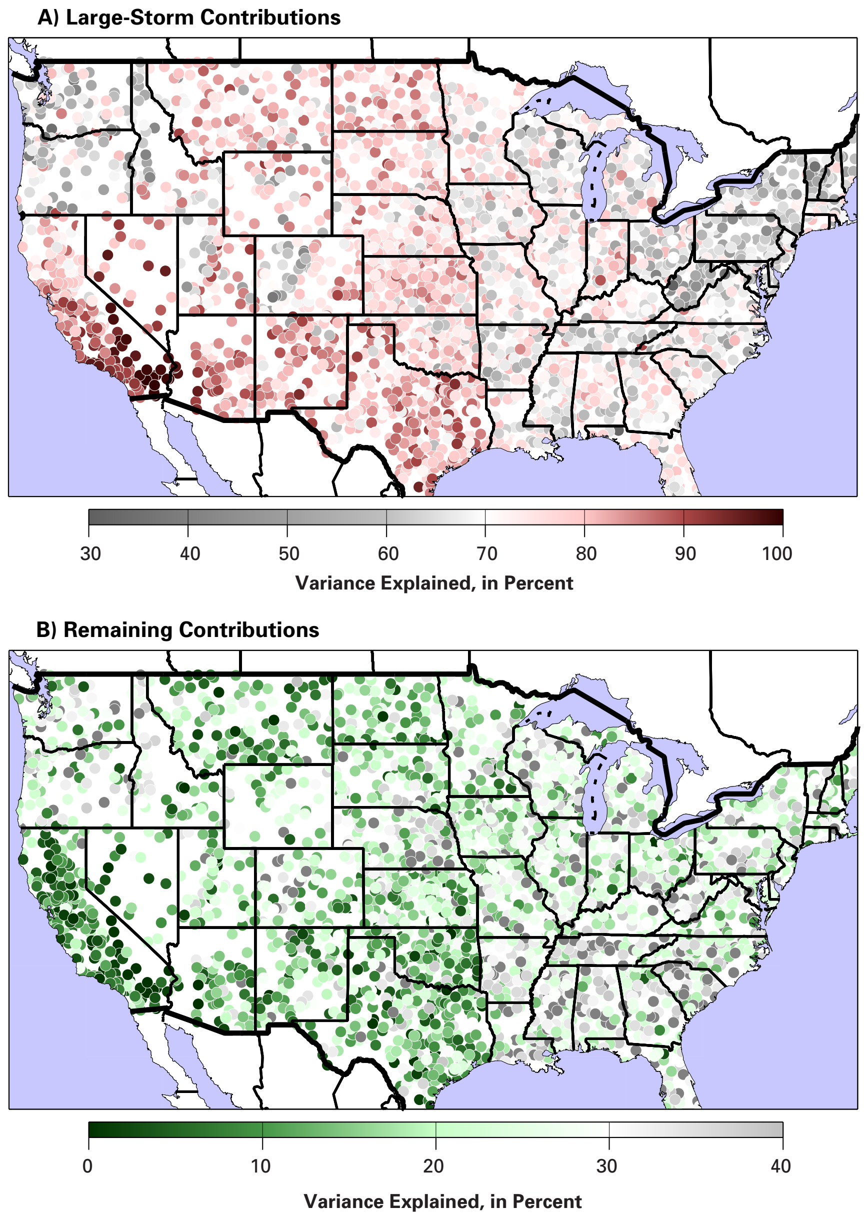

Figure 9 Same as in Figures 8A and 8B, respectively, except for individual cooperative-observer weather stations, water years 1951–2010. Stations shown have at least 48 years of >90%-complete daily precipitation records in this analysis period.

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terms of how well historical climatic metrics were simulated at global scales (Gleckler et al. 2008; Flato et al. 2013), over the southwestern U.S. (using the metrics of Rupp et al. 2013, as computed by Rupp for the southwest; D. Rupp, pers. comm., unreferenced, see "Notes"), and over California (CCTAG 2015). Metrics measured model performance in terms of (a) global radiation fluxes, temperatures, precipitation, and wind patterns; (b) regional mean temperatures and precipitation patterns and seasonality, along with characteristics of interannual to trending temperature and precipitation variability; and, for California, (c) precipitation extremes and simulated El Niño processes. Models that simulated these various metrics least realistically were culled to arrive at a subset of ten models that will be a starting point for California's upcoming (2018) Fourth Climate-Change Assessment and related activities. Those ten models are listed in Table 1. The left half of Table 2 reports the models' abilities to reflect observed mean and variance of the breakdown of water-year precipitation totals into contributions from wettest days and remaining days. The right half of Table 2 describes projected changes in the northern California precipitation regime by the late 21st century under RCP8.5 and RCP4.5 greenhouse-gas emissions scenarios.

Figure 10A shows the mean contributions of the wettest 5% of wet days and remaining days to water-year precipitation in observations (Figure 2) and in simulations of climate under specific historical radiative climate forcings by the ten climate models, from 1951–2000, with corresponding variances in Figure 10B. The ten climate models generally reproduce the observed mean fractional contributions of the wettest days and remaining days to total precipitation. The comparisons of variance contributions are somewhat more scattered. Nonetheless, historical simulations by most of the ten models broadly reflect the observed variance contributions, albeit with some performing especially well in this regard (e.g., ACCESS-1.0, CSSM4, GFDL-CM3, and MIROC5) and others less so (e.g., CMCC-CMS and HadGEM2-ES). Year-to-year precipitation fluctuations explained by the wettest-day and remaining-day contributions also vary considerably, relative to observed relations (Table 2, Figure 11), but again are generally united in having the largest fractions of year-to-year precipitation variability deriving from wettest days in broadly realistic proportions.

Examples of simulated precipitation totals and contributions from largest and smaller storms

Table 1 Global climate models from which climate simulations under historical and RCP8.5 greenhouse-gas conditions are analyzed in this study

Climate model name	Institution	Number of horizontal grid cells	Approximate horizontal resolution
		Longitude x Latitude	
ACCESS1.0	CSIRO (Commonwealth Scientific and Industrial Research Organization) and BOM (Bureau of Meteorology), Australia	192 × 145	1.9° × 1.24°
CCSM4	National Center for Atmospheric Research, United States	288 × 192	1.2° × 0.9°
CESM1BGC	National Science Foundation, Department of Energy, National Center for Atmospheric Research, United States	288 × 192	1.2° × 0.9°
CMCCCMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy	192 × 96	1.9° × 1.9°
CNRMCM5	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique, France	256 × 128	1.4° × 1.4°
CANESM2	Canadian Centre for Climate Modeling and Analysis, Canada	128 × 64	2.8° × 2.8°
GFDLCM3	Geophysical Fluid Dynamics Laboratory, United States	144 × 90	2.5° × 2.0°
HADGEM2CC	Met Office Hadley Centre, United Kingdom	192 × 145	1.9° × 1.2°
HADGEM2ES	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais), United Kingdom	192 × 145	1.9° × 1.2°
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan	256 × 128	1.4° × 1.4°

Table 2 Selected statistics of observed and simulated historical and projected contributions to total precipitation from wettest and remaining days for grid cells close to Sacramento; projected contributions are presented under both RCP8.5 and RCP4.5 (numerals in parentheses) greenhouse-gas emissions. Statistics of observed conditions in dark blue rows; statistics from models that yielded more overall precipitation in both futures in light blue rows. See Table 1 for model information.

Model	Storm sizes	WY 1951–2000				2046–2095 minus 1951–2000					
		Contrib means (%hist mean total)	**Contrib variances** (%hist total var)	**Co-variance** (%hist total var)	**Total variance explained** (%hist total var)	**Change, mean total** (%hist mean total)	**Change, total variance** (%hist total var)	**Change, contrib means** (%hist mean total)	**Change, contrib variances** (%hist total var)	**Change, contrib from covariance** (%hist total var)	**Change, total variance explained**
Observed	Wet 5%	38	46	34	86	Not available					
	Remaining	62	20		68						
ACCESS 1.0	Wet 5%	37	42	32	80	–15 (0)	–39 (–6)	–4 (+4)	–20 (+3)	–10 (–2)	–1 (+1)
	Remaining	63	26		68			–12 (–4)	–8 (–2)		+6 (0)
CCSM4	Wet 5t%	38	42	33	81	+8 (2)	+41 (34)	+12 (6)	+49 (33)	+10 (7)	+5 (8)
	Remaining	62	25		69			–1 (–4)	-4 (–6)		–27 (–9)
CESM1BGC	Wet 5%	38	53	26	82	+12 (7)	+53 (79)	+12 (7)	+21 (39)	+27 (39)	+7 (13)
	Remaining	62	21		55			–1 (0)	+5 (0)		+14 (21)
CMCCCMS	Wet 5%	31	32	37	80	–1 (-7)	–9 (–21)	+6 (–1)	+16 (–5)	–16 (–15)	–4 (–12)
	Remaining	69	31		79			–7 (–6)	–7 (–1)		–29 (–7)
CNRMCM5	Wet 5%	41	58	27	87	+19 (14)	+102 (35)	+22 (16)	+70 (45)	+36 (–6)	+3 (5)
	Remaining	59	16		53			–3 (–2)	+9 (–4)		–5 (–23)
CANESM2	Wet 5%	44	55	28	86	+35 (11)	+255 (57)	+37 (11)	+172 (29)	+74 (23)	+10 (4)
	Remaining	56	17		56			-2 (–1)	+9 (5)		+9 (8)
GFDLCM3	Wet 5%	39	43	36	87	0 (–3)	–3 (4)	+5 (1)	0 (11)	–7 (–5)	–8 (v1)
	Remaining	61	21		72			–5 (–4)	+5 (–2)		–9 (–12)
HADGEM2CC	Wet 5%	44	48	27	78	–7 (4)	+7 (30)	+1 (6)	+19 (29)	+2 (5)	+9 (8)
	Remaining	56	25		59			–8 (–2)	–10 (–4)		–13 (–9)
HADGEM2ES	Wet 5%	37	56	19	77	–11 (–7)	–10 (12)	0 (–1)	–6 (6)	+1 (–1)	+9 (–4)
	Remaining	63	25		47			–11 (–6)	–9 (7)		+8 (0)
MIROC5	Wet 5%	40	49	33	87	–9 (–11)	–25 (–33)	–1 (–3)	–17 (–21)	–3 (–11)	+4 (–7)
	Remaining	60	18		65			–8 (–8)	–5 (–1)		+13 (3)

are shown in Figures 11C and 11D. Although not as persistently as in 20th century observations (Figure 2), occasional quasi-decadal fluctuations are evident in both examples. These fluctuations have played important roles in California's recent hydroclimate but, as illustrated by Figure 6, the close relations between total precipitation and largest storms in California are not restricted to that time-scale. The thin curves in Figure 6 are coherence spectra that relate variations in total precipitation with wettest-day contributions and remaining-day contributions in the ten climate models, and indicate that in the climate models the contributions from largest storms cohere closely to the variations of total precipitation, more closely than do the contributions from remaining storms, but the differences between wettest-day and remaining-day contributions are not as large generally as in the real world (heavy curves, Figure 6). The strong coherence of wettest-day contributions with total precipitation is even stronger than in observations but, as in observations, is not restricted to any single frequency band. Thus, even in models where the quasi-decadal fluctuation is weak or possibly missing, the overall relations between total precipitation and largest storms in climate models (Figure 10)—and the evolution of

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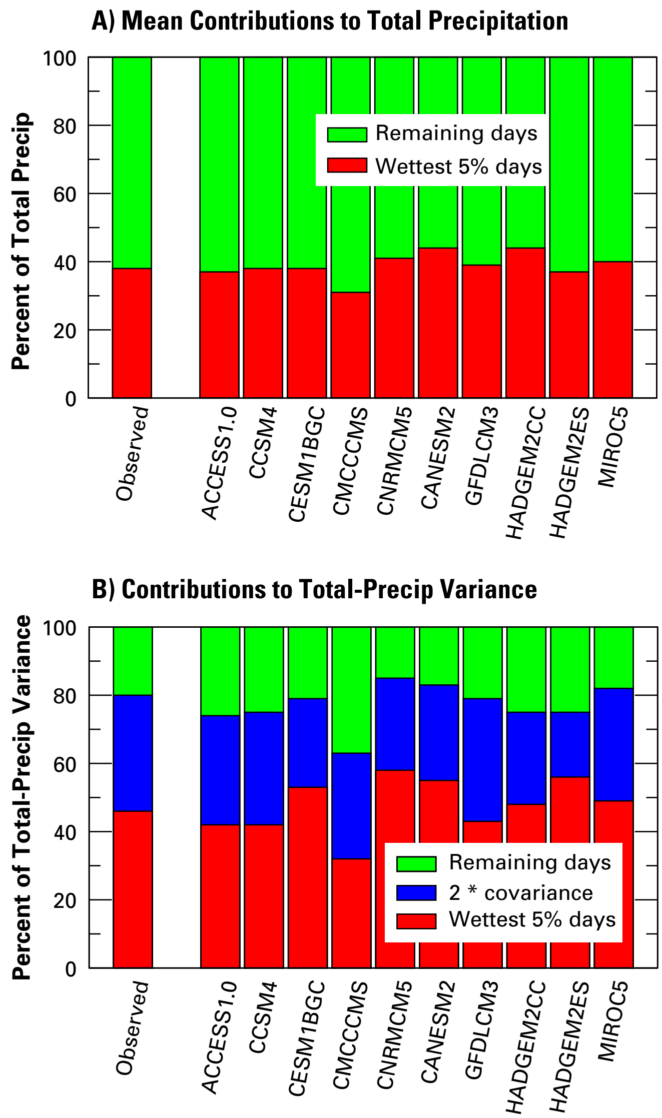

Figure 10 Contributions of wettest 5% of wet days, remaining days, and covariations of the two, to **(A)** mean water-year total precipitation and **(B)** the variance of water-year total precipitation, in observations and in ten global-climate models (see Table 1) under historical greenhouse-gas forcings, water years 1951–2000

those relations under projected climate changes—are of continuing interest.

Comparing projected 2046–2095 precipitation regimes to 1951–2000 simulations under historical climate forcings, the ten climate models yield a wide range of total-precipitation outcomes for the two emissions scenarios considered here. This mixed response in multi-model ensemble projections is a long-recognized feature of climate-change projections for northern California (Dettinger 2006; Cayan et al. 2008; Brekke et al. 2009; Polade et al. 2014; Walsh et al. 2014). In the current ten-model ensemble under RCP8.5 forcings, four models yield wetter conditions by the last half of the 21st century, four yield drier conditions and two yield minimal changes (Table 2). When these total-precipitation changes are broken into changes in contributions from wettest days and remaining days (Figure 11A), the remaining-day contributions are found to decline in all ten models, while wettest-day contributions most often (7 of 10) increase.

The models that project large total-precipitation increases clearly reflect large increases in contributions from the wettest days, much larger than the remaining-day declines. (Note that all variables in Figures 11A and 11B are normalized by their model's historical total-precipitation means so that in absolute terms these wettest-day increases are in fact much larger than the changes in remaining-day contributions.) This large range of projected changes in wettest-day precipitation rates is consistent with previous studies in the region (e.g., Pierce et al. 2013; Polade et al. 2014). Both RCP8.5 and RCP4.5 projections with total-precipitation declines all reflect (relatively) large decreases in remaining-day contributions. RCP8.5 emissions (and greenhouse-gas concentrations) are larger than those under RCP4.5 during the last half of the 21st century, and so the climate-change forcings and responses are larger under RCP8.5. This makes the precipitation-change signals larger and clearer under RCP8.5, although the RCP4.5 projections parallel them in muted form (Figure 11B). The RCP8.5 projections (CMCC-CMS and GFDL-CM3) that yield the smallest total-precipitation changes both reflect a near balance between increases in wettest-day contributions and decreases in remaining-day contributions, as do the RCP4.5 projections (ACCESS1.0 and CCSM4). The much broader ranges of RCP8.5 and RCP4.5 changes in wettest-day contributions—compared to the smaller, universally negative, changes in remaining-day contributions—are evident in Figure 11B.

To illustrate how these precipitation changes emerge, Figures 11C and 11D show the simulated RCP8.5 time-series (corresponding to Figure 2) from the model yielding the largest precipitation increase

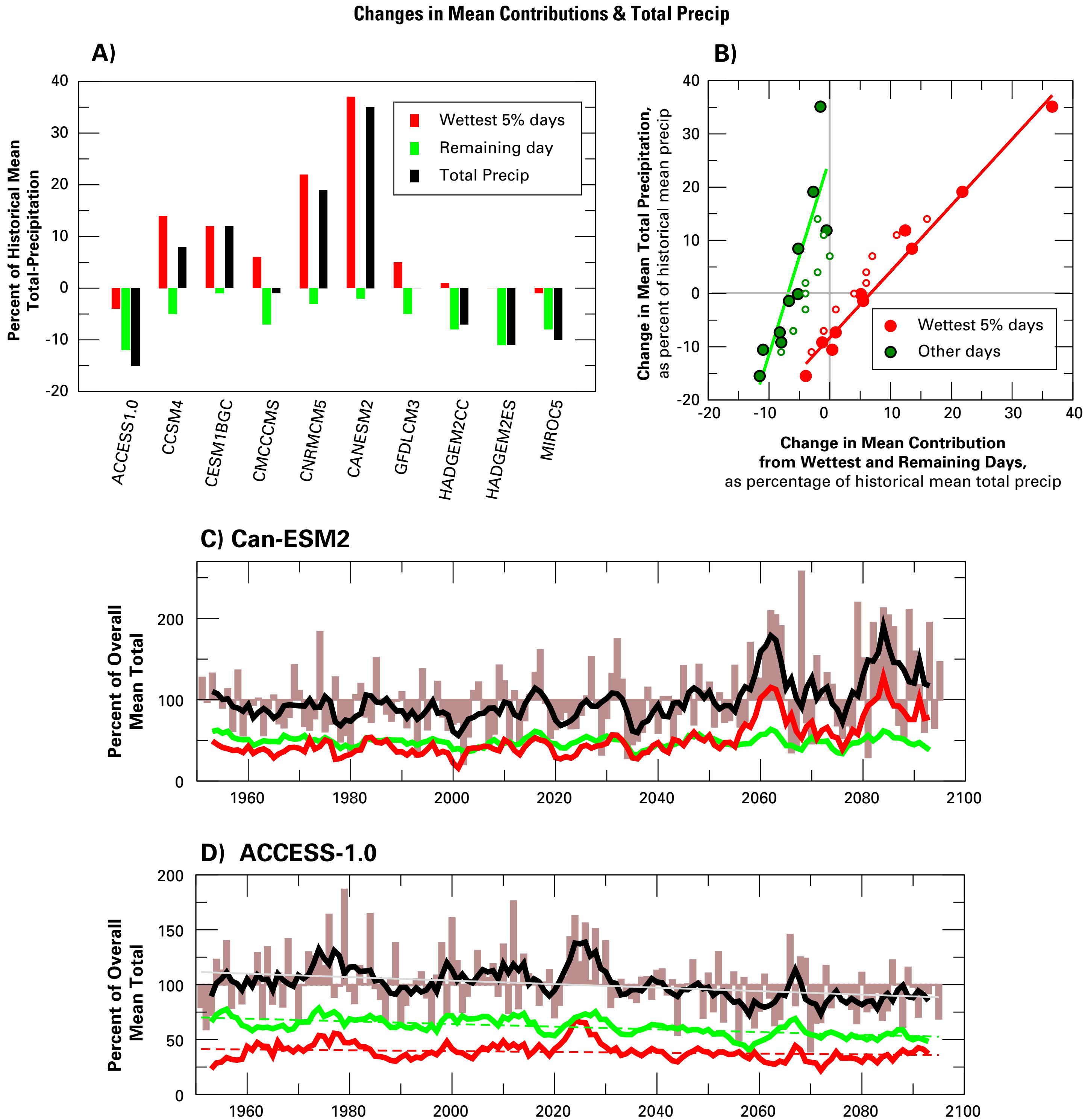

Figure 11 **(A)** Projected RCP8.5 changes in water-year mean contributions of precipitation from the wettest 5% of wet days (red), remaining wet days (green), and total precipitation (black), between 1951–2000 and 2046–2095, in climate-change projections by ten climate models (Table 1); **(B)** a comparison of the mean changes under RCP8.5 (solid dots) and RCP4.5 (smaller, open circles) greenhouse-gas emissions; and **(C)** and **(D)** same as in Figure 2, except for historical and future-climate simulations by the Can-ESM2 and ACCESS-1.0 climate models under RCP8.5 emissions

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(Can-ESM2) and the model yielding the largest precipitation decline (ACCESS-1.0). In the Can-ESM2 projection, all of the total-precipitation change (increase) comes from increased wettest-day contributions; in the ACCESS-1.0 projection, both wettest-day and, especially, the remaining-day contributions decline, yielding a total-precipitation decline of −15%. Considering the ten-model ensemble as a whole, RCP8.5 changes in wettest-day contributions explain (in the r^2 sense) 98% of the change in total precipitation (Figure 11B). This strong dependence of precipitation-change projections on the underlying changes in wettest-day precipitation rates is consistent with previous studies in the region (e.g., Pierce et al. 2013; Polade et al. 2014).

Changes in the variances of total precipitation and of the wettest-day and remaining-day contributions also vary widely from model to model (Table 2), with the CNRM-CM3 and CanESM2 models yielding large RCP8.5 increases in variance of both total precipitation and wettest-day contributions (Figure 12A). Generally (with only one modest exception, from the CMCC-CMS model) the sign of changes in total-precipitation variance mirror those of the changes in wettest-day contribution variance. Figure 12B compares projected changes in the variances of contributions and total precipitation, under both RCP8.5 and RCP4.5 emissions. In this figure, the RCP8.5 changes in variance of wettest-day contributions explain 88% of the change in variance of total precipitation, but much of this explanatory power comes from the very large and outlying Can-ESM2 projection (Figure 11C). When the Can-ESM2 projection is excluded, the explanatory power drops to 53%, a smaller but still a significant-at-95%-confidence-level value. Changes in the variance of remaining-day contributions explain 36% of the RCP8.5 change in total-precipitation

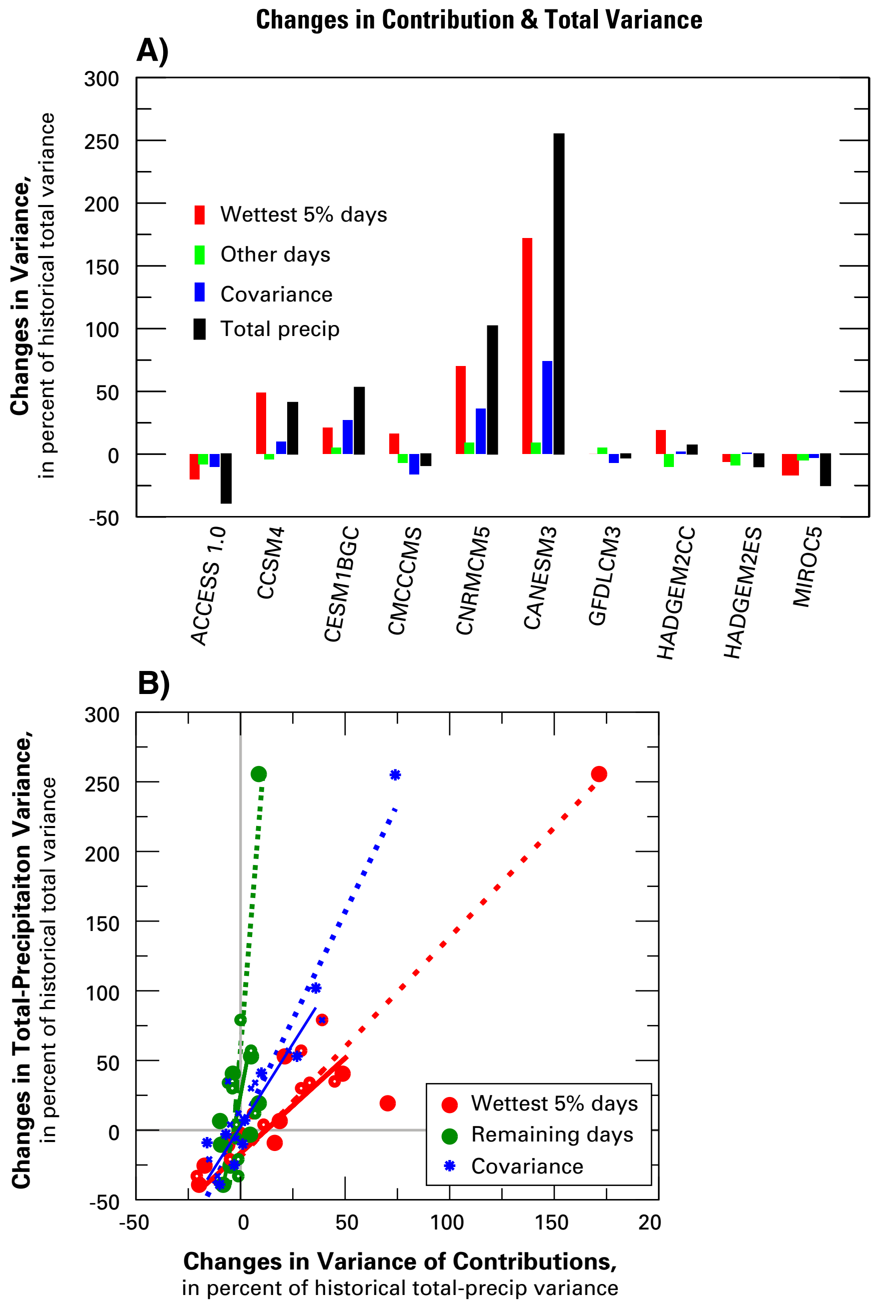

Figure 12 **(A)** Projected RCP8.5 changes in variance of water-year contributions of precipitation from the wettest 5% of wet days, remaining wet days, covariance of the two, and total precipitation (all days), from 1951–2000 to 2046–2095, in climate-change projections by ten climate models (Table 1); and **(B)** a comparison of changes in total-precipitation variance changes in the variance of contributions from wettest days, remaining days, and covariance of the two under RCP8.5 (solid symbols) and RCP4.5 (open symbols) greenhouse-gas emissions. Dashed lines in **(B)** are regression lines fit to all RCP8.5 projections, and solid lines are regression lines when Can-ESM2 changes are omitted.

variance (dropping to 28% when the Can-ESM2 value is excluded).

As with changes in mean precipitation, the models that yield large increases in total-precipitation variance reflect larger increases in the future variances of wettest-day contributions (Table 2). Unlike the changes in the means, the models that yield the (more modest) declines in total-precipitation variance reflect commensurate declines in variance of the wettest-day contributions, so that changes in wettest-day contributions dominate the changes in total-precipitation variance. Contributions to total variance from covarying fluctuations of wettest-day and remaining-day contributions (last term in Equation 1) reflect a combination of the changes in correlations between those two contributions and changes in the variances of each. Changes in the correlation between wettest-day and remaining-day contributions are uniformly small. In 18 of the 20 projections considered here, the changes in r^2 were less than 5%, with only one projection (by the CESM-BGC model under RCP4.5) rising to a 10% change. In most cases (13/20), the correlations increased slightly or stayed the same. Thus, given the greater variance contributions from wettest days overall, changes in the contribution from covariance mostly reflect the changing variance of wettest-day contributions (explaining 84% and 38% of the covariance-contribution changes under RCP8.5 and RCP4.5 emissions, respectively) rather than the changing variance of remaining-day contributions (55% and 5%, respectively). Taken together, these analyses show that the future changes in the variance contributed by the wettest days, and the largest storms dictate future total-precipitation variance.

Finally, the extent to which year-to-year fluctuations of total precipitation are explained (in a regression sense) by fluctuations of wettest-day and remaining-day contributions also changes in the climate-change projections (final column, Table 2). There are no clear

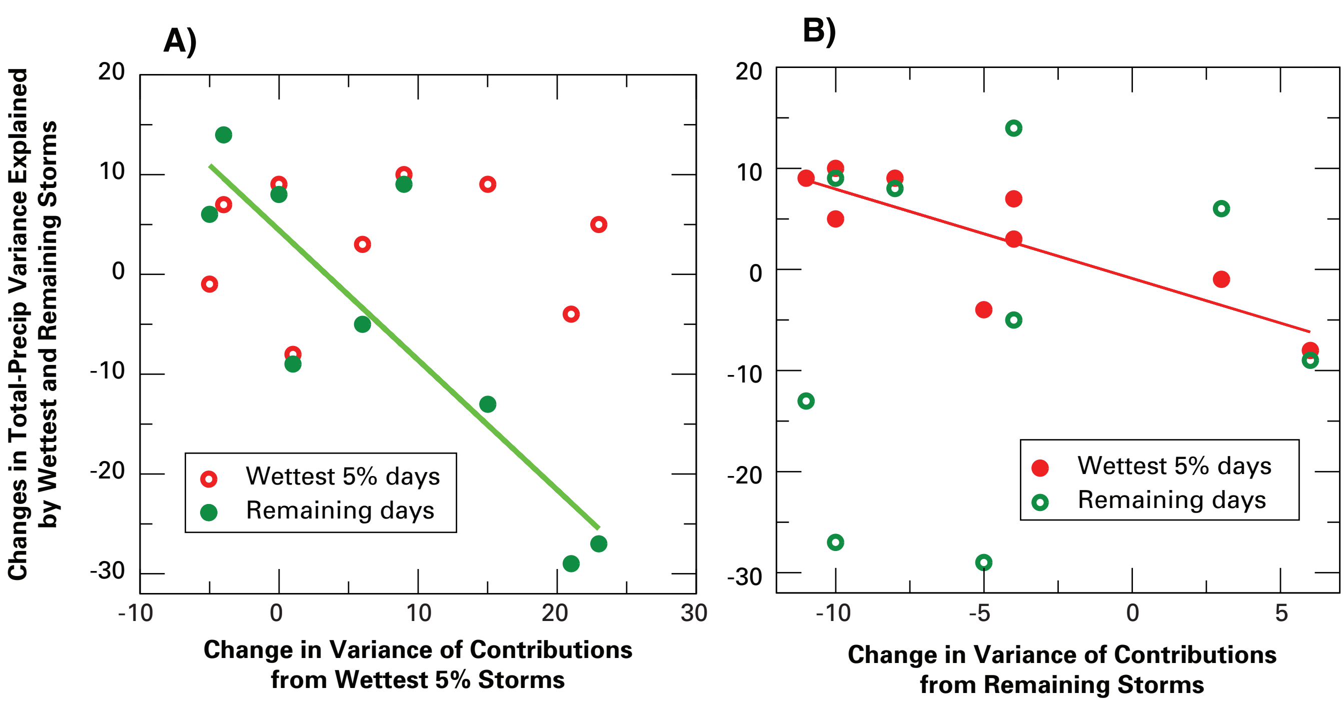

Figure 13 Comparisons of RCP8.5 changes in total-precipitation variance explained (in r^2 sense) by changes in variance of precipitation contributions from **(A)** wettest 5% of wet days and **(B)** remaining days as functions of changes in the variance of those contributions; changes in variance are expressed here as differences between 2046–2095 contribution variances as percentage of 2046–2095 total-precipitation variance minus the 1951–2000 contribution variances as percentage of 1951–2000 total-precipitation variance (to be consistent with variances explained on vertical axes). Solid dots are the contributions with significant (>95% level) explanatory value (regression line shown) in each panel.

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relations between the historical variances explained by the contributions and the climate-changed versions thereof. However, projected changes in the variance of the contributions are significantly related to the changes in total-precipitation variance explained by the 'opposite' contribution. The changes in variance of (A) wettest-day contributions and (B) remaining-day contributions are compared to the changes in total-precipitation fluctuations explained by the contributions in Figure 13. The explanatory value of remaining-day fluctuations declines most in the models in which wettest-day variances increase most (Figure 13A; $r = -0.86$), with no consistent relation indicated between changes in the percentage of total-precipitation fluctuations explained by wettest-day fluctuations and changes in wettest-day variance ($r = 0.04$). Correspondingly, the explanatory value of the fluctuations of wettest-day contributions declines with increases in remaining-day contribution variance (Figure 13B; $r = -0.82$), with no consistent relation to changes in remaining-day variance ($r = 0.15$). Thus, the extent to which total-precipitation fluctuations follow fluctuations of one category of contributions declines with increases in variance of the other category. This is not unexpected, given that increased variance of one category of contribution might be expected to 'force' the total precipitation more, thus competing more with the other category, but the fact that increases in the variance of one category does not consistently increase its own explanatory value is a bit unexpected.

CONCLUSIONS

California precipitation varies more dramatically from year to year than anywhere else in the conterminous U.S., and its droughts historically have been broken by the arrival of a relatively few major storms within a short time. The evaluation here, of how the wettest 5% of wet days (as a largely arbitrary threshold to understand contributions from a relatively few large storms) contribute to overall precipitation variability on year-to-year and on longer time-scales, has uncovered very close connections between variations in the largest storms and the state's frequent multi-year drought and wet periods. These connections include:

- The wettest 5% of wet days in northern California contribute about a third of all precipitation on average, but about two-thirds of the variance of water-year precipitation. Other (less wet) wet days contribute two-thirds of precipitation on average but only about a third as much of the year-to-year variance.
- The wettest days occur almost exclusively in winter months, while the remaining wet days contribute across a broader range of seasons. Notably, the mean contributions from the remaining wet days are fairly uniform from month to month through the November–March or April wet season, so that most of the strong mid-winter peak in California's long-term annual cycle of precipitation comes from the contributions by its occasional large storms.
- Similarly, nearly all of the year-to-year variance in precipitation during winter months comes from these largest storms.
- Year-to-year fluctuations in total precipitation are very much a reflection of the year-to-year fluctuations of contributions from the largest storms, with the large-storm contributions explaining about twice as much of the total-precipitation fluctuations as do the contributions from all remaining storms. Because an important mechanism for the state's largest storms is the arrival of atmospheric-river storms, about three-quarters of the multi-year variability of total precipitation is associated with fluctuations of water-year counts of landfalls of the particular form of atmospheric rivers called 'pineapple expresses.'
- The extreme extent to which large storms control California's extreme seasonal and year-to-year precipitation fluctuations is largely restricted to California and its immediate surroundings within the conterminous U.S. California's precipitation regime, with over 80% of the total-precipitation variance in California explained by year-to-year fluctuations in the contributions from an average of 7 wettest days per year, is notably larger than the 50% to 70% elsewhere in the country. Fluctuations of California's precipitation totals also depend less upon smaller storms than in other parts of the country. (This finding does not

depend on whether lumped, gridded, or station data are used for the comparisons.)

- Projected future precipitation changes (in response to globally increasing greenhouse-gas concentrations) for northern California include declines in the precipitation contributions from days drier than the wettest 5% of wet days in all ten climate models considered here. Most models yield increases in the contributions from the wettest days, and the models that yield substantial precipitation increases (about half of the models) do so as a result of large increases in the wettest-day contributions. Broadly similar relations describe the projected changes in the overall variance of total precipitation, with the variance of contributions from wettest days increasing markedly in several models with attendant large increases in total-precipitation variance in those models.
- Finally, the close explanatory relations between year-to-year fluctuations of total precipitation and contributions from large and small storms are projected to change by the late 21st century by anywhere from +15% to –30% of the total-precipitation variability. In the climate-change projections, as contributions from the largest (or smaller) storms increase, the extent to which total-precipitation fluctuations can be ascribed to the other category of storms declines.

At the heart of each of these relations are the disproportionately large overall contributions from California's largest storms and their outsized year-to-year variability, which raise those largest storms to a dominant role in the state's precipitation regime and in the occurrence of extended wet and, especially, dry spells. Thus, the largest storms in California's precipitation regime not only typically end the state's frequent droughts (Dettinger 2013), but their fluctuations also cause those droughts in the first place. More research is needed to better understand how and why these largest storms tend to vary so widely on multi-year time scales.

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NOTES

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