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Environmental Research Letters

LETTER

Extreme hydrological changes in the southwestern US drive reductions in water supply to Southern California by mid century

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Abstract

The Southwestern United States has a greater vulnerability to climate change impacts on water security due to a reliance on snowmelt driven imported water. The State of California, which is the most populous and agriculturally productive in the United States, depends on an extensive artificial water storage and conveyance system primarily for irrigated agriculture, municipal and industrial supply and hydropower generation. Here we take an integrative high-resolution ensemble modeling approach to examine near term climate change impacts on all imported and local sources of water supply to Southern California. While annual precipitation is projected to remain the same or slightly increase, rising temperatures result in a shift towards more rainfall, reduced cold season snowpack and earlier snowmelt. Associated with these hydrological changes are substantial increases in the frequency and the intensity of both drier conditions and flooding events. The 50 year extreme daily maximum precipitation and runoff events are 1.5–6 times more likely to occur depending on the water supply basin. Simultaneously, a clear deficit in total annual runoff over mountainous snow generating regions like the Sierra Nevada is projected. On one hand, the greater probability of drought decreases imported water supply availability. On the other hand, earlier snowmelt and significantly stronger winter precipitation events pose increased flood risk requiring water releases from control reservoirs, which may potentially decrease water availability outside of the wet season. Lack of timely local water resource expansion coupled with projected climate changes and population increases may leave the area in extended periods of shortages.

1. Introduction

Between 60% and 70% of Southern California's water supply originates from imported sources, primarily the San Joaquin River and Tulare Lake basins (SJRB-TLB), Sacramento River basin (SRB), Mono Lake and Owens Valley basin (ML-OVB), and Colorado River basin (CRB) (figure S1) (Pulido-Velazquez *et al* 2004, Freeman 2008). More importantly, approximately 75% of water discharge from these imported sources comes from spring snowmelt, which is highly sensitive to changes in precipitation (P) and temperature (T) (Palmer 1988). The SRB and SJRB-TLB feed into the Sacramento San-Joaquin Delta which provides water for the federally owned Central Valley Project (CVP) and state owned State Water Project (SWP). The CVP primarily serves agricultural users while the SWP serves urban users in the southernmost areas of the state. Combined, these basins provide over 80% of runoff (Q) in California supporting 25 million people

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and the multi-billion dollar agricultural industry (Gleick and Chalecki 1999, Cloern *et al* 2011). Similarly, the ML-OVB provides water exclusively to the 4 million residents in the city of Los Angeles and is critical in supporting its large economy (Costa-Cabral *et al* 2013). Likewise, the Colorado River Aqueduct transports water from the CRB to seven states plus Mexico serving over 30 million people (Christensen *et al* 2004, Ficklin *et al* 2013a).

Each basin that provides water to Southern California currently has limitations on the amount of water that is available for export. For instance, the Sacramento San-Joaquin Delta is the largest estuary in the Western United States (WUS) making it a critical ecosystem (Kibel 2011). Because endangered species such as the delta smelt are disrupted by pumping from the Delta, water diversions at the Delta have been reduced or completely halted. Similarly, due to excessive diversions from the Owens River, Owens Lake is now considered a dry lakebed, and hazardous levels of mineral dust emissions have led to respiratory illnesses, resulting in state mandates to limit water exports (Fuller and Harhay 2010). Moreover, the Colorado River water allocation system is based on early 20th century climate conditions, which were much wetter than prevailing conditions causing the Colorado River to be severely over allocated (Woodhouse *et al* 2006). Lastly, rising populations across all of these imported basins and the regions they serve have exacerbated water supply security issues.

At regional scales, many previous studies evaluating climate change impacts over the Western United States (WUS) and Southwestern United States (SWUS) have projected increased drying by the end of the 21st century driven by declines in P minus evaporation (E) (Seager and Vecchi 2010, Seager *et al* 2013, Cook *et al* 2014, Gao *et al* 2014). However, projected directional changes in P are quite uncertain in the near-term over the SWUS (Leung *et al* 2004, Cayan *et al* 2008, Cayan *et al* 2010) and at the basin-scale (Brekke *et al* 2004, Knowles *et al* 2006, Christensen and Lettenmaier 2007, Costa-Cabral *et al* 2013, Ficklin *et al* 2013a, Ficklin *et al* 2013b, Vano *et al* 2014). Despite such uncertainties in projected P changes, warmer surface T is expected to accelerate snowmelt and reduce snowfall thus shifting Q timing, which can pose flood management risks for reservoirs (Lettenmaier and Gan 1990, Cayan 1996, Miller *et al* 2003, Barnett *et al* 2004, Stewart *et al* 2004, Stewart *et al* 2005, Mote 2006, Rauscher *et al* 2008, Abatzoglou 2011, Ashfaq *et al* 2013, Diffenbaugh *et al* 2013). The heavy reliance on snowmelt driven imported sources of water makes the SWUS more susceptible to climate change impacts (Roos 1989, Diffenbaugh *et al* 2005, Christensen and Lettenmaier 2007, Rauscher *et al* 2008). During the past century, 0.5°C–1.5 °C of surface warming has been observed over the SWUS, exceeding the global land average (IPCC 2014). Continued warming is expected to drive a decrease in snowpack by 33%–70% in the Sierra Nevada (Knowles 2002, Leung *et al* 2004) and by 20%–29% in the Rocky Mountains (Christensen *et al* 2004, Leung *et al* 2004, Christensen and Lettenmaier 2007) by mid-century, which can potentially reduce annual flows to reservoirs across the region (e.g. Christensen *et al* 2004, Vanrheenen *et al* 2004, He *et al* 2013). Furthermore, in a region like California where climate is highly variable year-to-year, understanding changes to extreme events is necessary for a comprehensive assessment of water supply reliability. While regional-scale cold season daily P is projected to intensify across the WUS, basin-scale changes and impacts are still unknown (Kim *et al* 2002, Kim 2003, Leung *et al* 2004, Diffenbaugh *et al* 2005).

The hydrological basins serving the water supply needs for SWUS exhibit strong spatial heterogeneity and complex topography, which necessitates the need for high-resolution process-based modeling to fully understand fine-scale hydrological respsonses to future increases in radiative forcing. While there is no dearth of scientific studies to understand climate change and its impacts over the WUS, most of these studies are based on coarse resolution climate model data (e.g. Seager and Vecchi 2010, Seager *et al* 2013, Cook *et al* 2014), and therefore lack the regional to local scale details needed for more accurate estimates of future climate change and associated impacts. Moreover, earlier studies do not account for basin-scale changes in extreme hydrological events that can critically influence water resource management (Dettinger *et al* 2004, Hayhoe *et al* 2004, Cayan *et al* 2008). Additionally, many earlier studies do not make use of large ensembles of climate projections (e.g. Christensen *et al* 2004, Dettinger *et al* 2004, Cayan *et al* 2008, Cayan *et al* 2010, Cloern *et al* 2011), which is crucial for understanding the spectrum of uncertainty for all hydrologic parameters and subsequent impacts to water resources (Vano *et al* 2014). In order to improve on these limitations, this study uses a very high-resolution (4 km) multi-ensemble hierarchical modeling framework to (1) resolve and represent complex regional to local scale physical processes, particularly those associated with snow hydrology, and (2) to investigate potential atmosphere-ocean global climate model (AOGCM) based uncertainties in the future hydrological responses. In terms of the number of ensembles, horizontal grid spacing, and the length of simulations, the hydroclimate modeling in this study is perhaps one of the largest modeling efforts over the SWUS to date. Using these simulations, we present analyses focused on changes in extreme hydrological one-day and cumulative annual maxima and minima events. These deviations in extremes are coupled with mean annual and monthly changes to investigate water supply security over the SWUS. Furthermore, we highlight parallels to the recent 2012–2016 SWUS drought with our findings and explore the current limitations to local supply expansion.

2. Methods

2.1. Experimental design

A hierarchal modeling framework to downscale 10 coupled AOGCMs from the Coupled Models Intercomparison Project Phase 5 (CMIP5) (Taylor *et al* 2012) is used to form an ensemble of high-resolution hydrological simulations at a 4 km horizontal grid spacing. The AOGCM simulations are dynamically downscaled at 18 km horizontal grid spacing using the International Center for Theoretical Physics (ICTP) Regional Climate Model version 4 (RegCM4) (Giorgi *et al* 2012) over a domain covering the continental United States (CONUS) and parts of Canada and Mexico. The selection of AOGCMs is largely based on the availability of sub-daily three-dimensional atmospheric fields that are required for dynamically downscaling (table S1). For each of the 10 AOGCMs, RegCM4 is configured for a historical period (1965–2005) and future period (2010–2050) under the Representative Concentration Pathway (RCP) 8.5 (Meinshausen *et al* 2011). These simulations are described in more detail in Ashfaq *et al* (2016). While RCP 8.5 represents the highest greenhouse gas (GHG) concentrations pathway, it matches the current trajectory of GHGs (Fuss *et al* 2014). Moreover, substantial differences between RCP 8.5 and other RCPs only appear after 2030 (IPCC 2013). Within this context, it should be noted that projected changes in P and T in the RegCM4 RCP 8.5 ensemble members are not biased towards a particular magnitude and/or sign and fall near the median when compared with a large ensemble of CMIP5 GCMs representing multiple RCPs (2.6, 4.5, 6.0 and 8.5) (Brekke *et al* 2014) (figure S2).

Daily minimum T, maximum T and P from each of the RegCM4 ensemble members are bias corrected using a quantile based bias correction technique (Wood *et al* 2004, Ashfaq *et al* 2010) (see supplementary section S3). Subsequently, the bias corrected RegCM4 outputs along with 10 m winds from each ensemble member are used to drive the Variable Infiltration Capacity (VIC) model (Liang *et al* 1994) version 4.1.1 for the entire conterminous US at a 1/24° grid cell spacing with the 3 hourly time step. To account for subgrid variability in topography and P, five elevation bands are used within each grid cell of the VIC model. Further details of the 4 km VIC model configuration, calibration and validation are described in Oubeidillah *et al* (2014) and Naz *et al* (2016).

2.2. Analyses

Potential hydrologic changes are assessed by analyzing P, evapotranspiration (ET), Q (sum of baseflow and surface runoff in VIC), snow water equivalent (SWE), snow depth, soil moisture, T and albedo. To assess the impacts of mid-century climate change on SWUS water resources, two 30 year periods are evaluated: baseline (1976–2005) and future RCP 8.5 (2021–2050). The Mann-Kendall statistical test (MK test), with a significance level of 5%, is used to identify any trends in the data specifically for snowmelt and Q timing (Mann 1945, Kendall 1955).

The generalized extreme value (GEV) distribution is fit to both maximum annual one-day P and Q events and cumulative water year (October 1 through September 30) minimum and maximum Q to evaluate reverse return period changes (Jenkinson 1955, Jenkinson 1969, Kao and Ganguly 2011) for 10, 25, 50 and 100 year events. Reverse return periods are the corresponding reoccurrence intervals under the future scenario equivalent to the baseline P and Q volumes, calculated for each grid point within the basin and at the basin-scale using the GEV distribution. If the frequency and intensity of extremes are projected to increase in the future, the reverse return period in the future will be lower than the baseline return period (and vice versa). The Kolmogorov–Smirnov (KS) and Cramer-von Mises (CM) tests are used to evaluate the goodness-of-fit for the GEV distribution across all RegCM4 ensemble members for extreme events. The two-sample KS goodness-of-fit hypothesis test is used to determine whether or not significant changes occur from baseline to RCP 8.5 for extreme events at a 5% significance level (see supplementary section S4).

3. Results and discussion

3.1. Mean hydrological changes

The simulated ensemble average T is projected to increase up to an additional 2 °C under RCP 8.5 for the period 2021–2050 over the SWUS region (figure 1(a); table 1). These increases are smaller at the beginning of the period and greater at the end due to increases in GHG forcing with time. Notably, high elevation regions in major mountain ranges, including the Sierra Nevada and Rocky Mountains, exhibit greater increases (>1.7 °C) in T than the lower elevations likely due to the snow-albedo feedback consistent with previous findings (Leung *et al* 2004, Rauscher *et al* 2008, Diffenbaugh *et al* 2013). The T increases result in decreased daily snow depth for the greatest snow producing months of January through April (JFMA) (figure 1(b); table 1; figure S4) due to increased snowmelt and decreased snow to P ratio. Less snowpack in turn drives reductions in the average daily JFMA albedo for each basin, which decreases most significantly during winter and spring (figure 1(c); table 1). Decreased albedo feedbacks in the form of increases in absorbed insolation further increases T and exacerbates reductions in snowpack.

Ensemble average annual P shows insignificant increases over most of the SWUS (figure 1(d); table 1). However, at the basin-scale, changes in annual and seasonal P vary widely among the ensemble members, which is consistent with previous studies (Leung

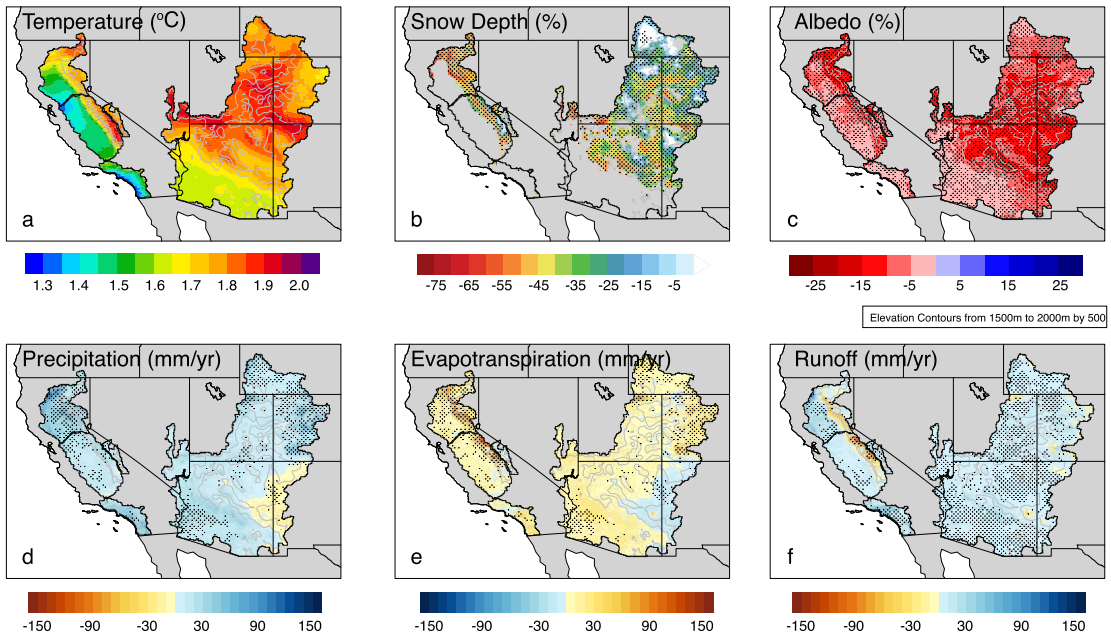

Figure 1. Ensemble mean change in average daily (a) surface temperature (°C) (b) JFMA snow depth (mm d^{-1}) (c) JFMA albedo (%) in 2021–2050 with reference to 1976–2005. Snow depth is masked for any grid point averaging less than 15 mm $month^{-1}$ for baseline. Ensemble mean change in water year (d) precipitation (mm yr^{-1}), (e) evapotranspiration (mm yr^{-1}) and (c) runoff (mm yr^{-1}) with reference to 1976–2005. Stippling indicates 70% or more ensemble agreement for positive or negative changes. All ensemble members agreed on increasing temperatures therefore stippling was not included.

et al 2004, Christensen and Lettenmaier 2007, Costa-Cabral *et al* 2013) (figures 2; S5(a)). In the CRB, ensemble mean *P* is skewed due to the presence of an outlier ensemble member (FGOALS driven RegCM4) that projects a 21% increase in annual *P* while the remaining ensemble members project −4% to +8%. Overall *P* becomes more seasonal, with increases in winter months and decreases in spring months (figure S6).

Annual ET generally increases over the study area with greatest increases in the Sierra Nevada and Rocky Mountain ranges (figure 1(e); table 1). Seasonally, ET increases during winter and spring due to greater water availability and increases in potential ET (PET) (figure 2). The competing effects of changing *P* and ET result in a mixed response of mean annual *Q* at the basin scale ranging from −30% in the SRB to +50% in the CRB for the ensemble members showing greatest change. In the higher elevation mountainous regions there is model agreement denoted with stippling of increasing *P* and increasing ET. However, spatial variations exist in regards to whether or not *P* exceeds ET, or ET exceeds *P*, which impacts the directional changes to *Q*. The magnitude of *P* increases can exceed the ET increases causing *Q* to increase and vice versa. *Q* is dependent upon the magnitude of change, not direction. Generally, *T* driven ET increases exceed any increases in *P* over the mountains, causing ensemble average *Q* to decrease over the Sierra Nevada but not with 70% or more model agreement (figure 1(f); table 1).

Despite increasing *P*, SWE declines during the winter and spring months due to warmer *T*, which increases the fraction of *P* falling as rain rather than snow and accelerates snowmelt (figure 2). Consequently, projected *Q* shows significant increasing trends during the winter and early spring months and decreasing trends (except ML-OVB) during late spring and summer, suggestive of earlier snowmelt (figures 2; S7). Hydrologic shifts of 6–11 days earlier across all basins are also evident in the center of mass date (CMD), defined as the Julian day of the water year when 50% of annual *Q* occurs (figure S8(a)). While an annual average shift of one to two weeks may seem insignificant, these projections are near-term (2050) and *Q* responses are nonlinear meaning more pronounced changes are expected by the end of the century.

3.2. Extreme hydrological changes

Increases in atmospheric moisture content can alter both the quantity and the intensity of *P* events (Hennessy *et al* 1997, Trenberth 1999, Pal *et al* 2004). Many earlier studies show that mid-latitudes regions like the SWUS experience higher intensity *P* events during winter (Gao *et al* 2006, Cayan *et al* 2008, Diffenbaugh *et al* 2013). In our analysis, basin-scale peak extreme daily *P* and *Q* volumes and reverse return periods are projected to decrease for the 10, 25, 50 and 100 year events across all basins, indicating an increase in extreme hydrological events (figure 3; tables 1; S2, S3). It should be noted that while analyses are carried out for multiple return periods (figures S9–S12),

Table 1. Ensemble mean annual change on a basin-scale with ensemble range in italics for temperature (°C), JFMA snow depth (%), JFMA albedo (%), precipitation (%), evapotranspiration (%) and runoff (%) in 2021–2050 with reference to 1976–2005. Annual daily and cumulative extreme 50 year event volume changes (%) are shown with reverse return period in italics.

	Colorado River Basin	Mono Lake—Owens Valley Basin	Sacramento River Basin	San Joaquin—Tulare Lake Basin
Temp.	1.4 °C (0.9 °C to 1.8 °C)	1.4 °C (0.7 °C to 1.7 °C)	1.5 °C (0.8 °C to 1.7 °C)	1.5 °C (0.8 °C to 1.7 °C)
JFMA snow depth	−20% (−35% to −3%)	−22% (−39% to +16%)	−44% (−68% to −2%)	−25% (−41% to +4%)
JFMA albedo	−9% (−12% to 0%)	−10% (−15% to +2%)	−12% (−17% to −6%)	−7% (−10% to −1%)
Precipitation	+3% (−4% to +21%)	+3% (−10% to +16%)	+4% (−13% to +12%)	+2% (−11% to +15%)
Evapotranspiration	+2% (−4% to +19%)	−1% (−7% to +6%)	+4% (−2% to 7%)	+3% (−3% to +7%)
Runoff	+9% (−3% to +50%)	+9% (−13% to +35%)	+2% (−30% to +22%)	−1% (−27% to +30%)
Ann. daily max precipitation	+55% (8 year)	+13% (27 year)	+7% (28 year)	+15% (18 year)
Ann. daily max runoff	+118% (8 year)	+49% (22 year)	+13% (31 year)	+22% (26 year)
Ann. cumulative max runoff	+20% (14 year)	+10% (26 year)	+3% (42 year)	+6% (38 year)
Ann. cumulative min runoff	−3% (38 year)	+4% (69 year)	−13% (29 year)	−10% (36 year)

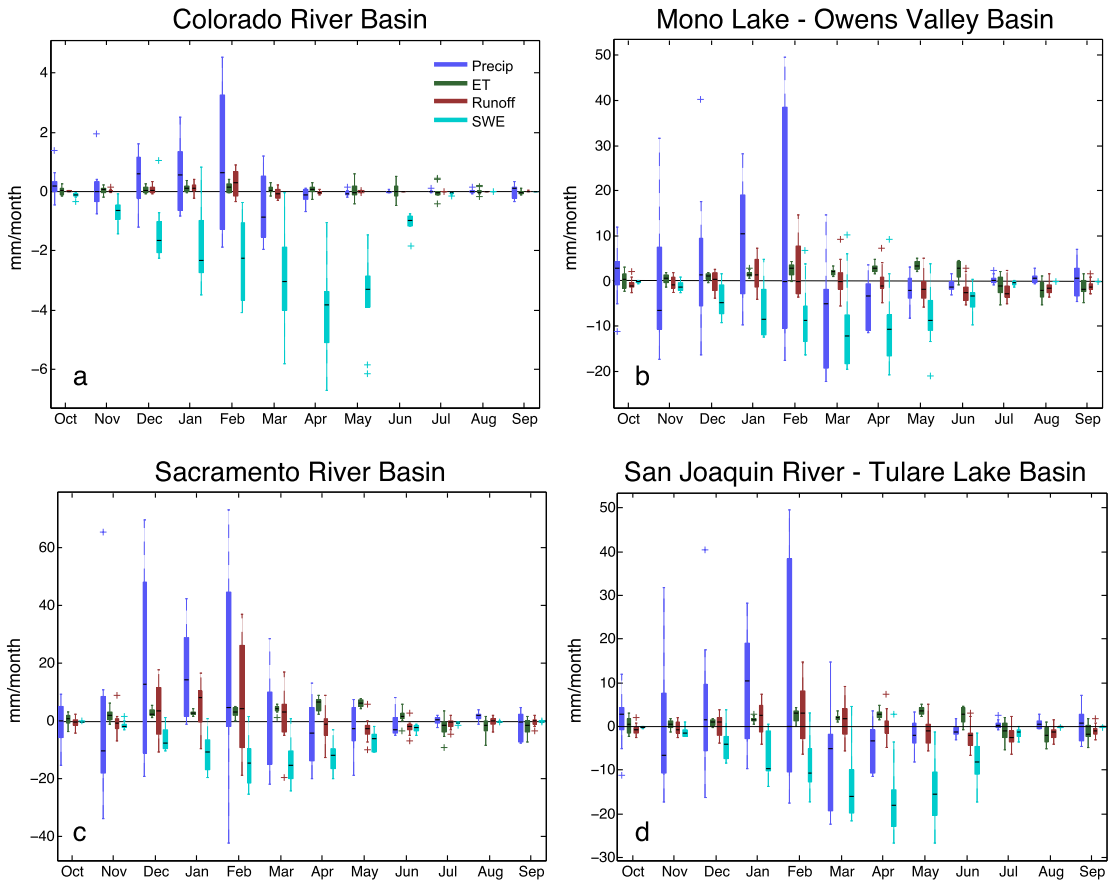

Figure 2. Average 30-year monthly precipitation, evapotranspiration, runoff and snow water equivalent changes (mm month^{-1}) from baseline to RCP 8.5 for (a) Colorado River Basin, (b) Mono Lake—Owens Valley Basin, (c) Sacramento River Basin and (d) San Joaquin—Tulare Lake Basin. Boxplots represent model spread where the central mark is the median model and edges of the box are the 25th and 75th percentiles. Whisker length is 1.5 corresponding to +/−2.7 standard deviations with plusses indicating outliers. Precipitation increases during the winter months and decrease in spring months. SWE declines throughout the winter and spring due to the higher fraction of precipitation falling as rain. Consequently increasing trends in winter and spring runoff coupled with decreasing trends in the summer months indicate a shift in runoff. Evapotranspiration increases during winter and spring due to warmer temperatures and greater water availability.

discussion throughout the results section is centered around the 50 year reverse return periods and associated volumetric changes. We find that results are generally consistent across different return periods. The one-day maximum *P* 50 year event becomes the 8–28 year event depending on the basin. The one-day maximum 50 year *Q* event becomes more frequent in all of the basins ranging from 8 year in the CRB (6 times more likely) to 31 year in the SRB (1.6 times more likely). Volumetrically, the one-day *P* and *Q* events increase by 7%–22% for the SRB and SJRB-TLB regions. The ML-OVB region, however, exhibits a 13% volumetric increase in maximum one-day *P* but a much greater 49% volumetric increase in *Q*. One possible explanation for the incongruent *P* and *Q* increases is the lower surface elevations in the ML-OVB region, which are more susceptible to increases in *T* causing a greater fraction of *P* as rain than snow and consequently more concentrated *Q* during these extreme *P* events. Similar to the ML-OVB, but in much greater magnitude, the CRB one-day maximum *P* event results in a 55% volumetric increase but a 118% volumetric increase in one-day maximum *Q*. Urban areas like the Southern Coast hydrologic region project similar increases in extreme events.

Cumulative annual *Q* represents the total water year *Q* generated from each basin which feeds into streamflow for water supply. Therefore, evaluating changes in the variability of cumulative annual *Q* are critical when assessing climate change impacts on water supply availability and reliability. On the basin-scale, volumes of annual cumulative maximum *Q* for the 10, 25, 50 and 100 year return periods are projected to increase although sub-basin variability is observed. For example, within the SRB portion of the Sierra Nevada mountain range, annual *Q* exhibits decreases in contrast to lower elevation regions of the same basin. Volumetrically, the basin-scale 50-year annual cumulative maximum *Q* increases considerably for the CRB (+20%) but less for the ML-OVB (+10%), SRB (+3%) and SJRB-TLB (+6%) regions. In contrast, cumulative annual minimum *Q* volumes decrease in all basins with the exception of the ML-OVB and with considerable regional variability

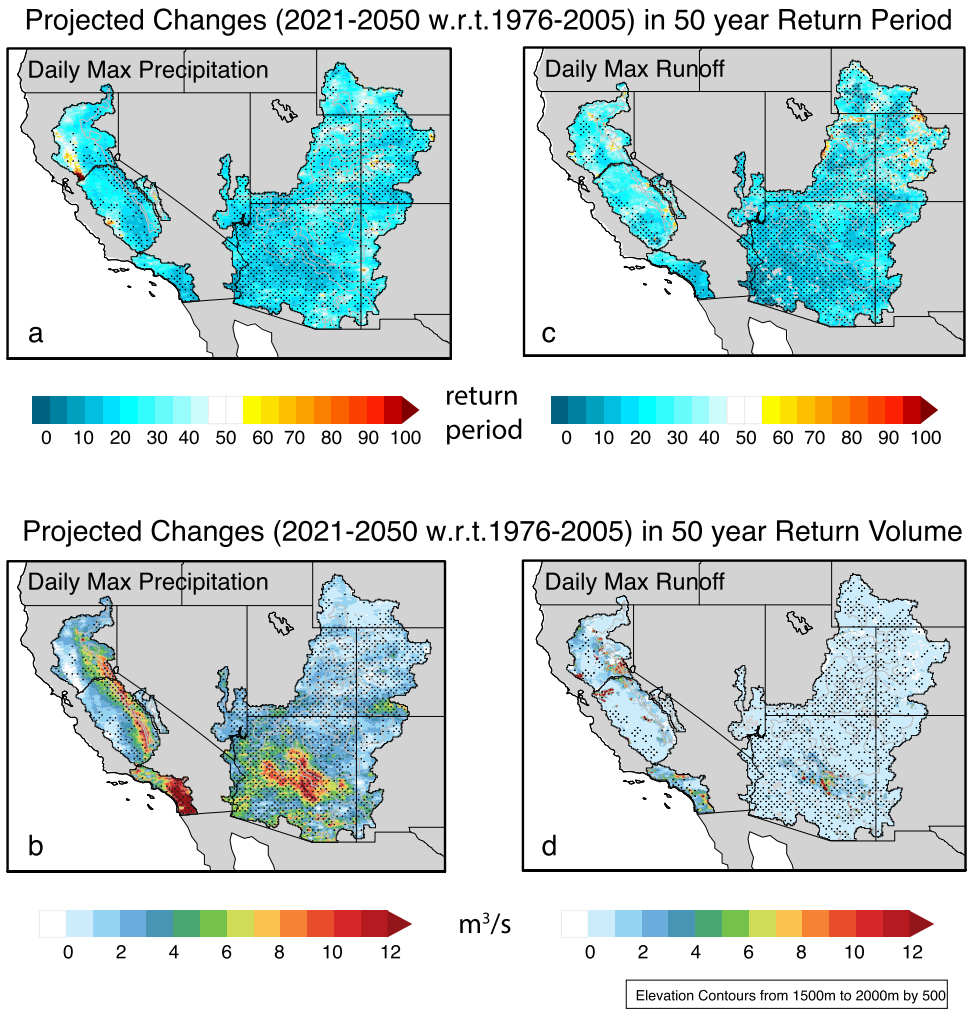

Figure 3. Projected (a) annual daily maximum precipitation return period in 2021–2050 corresponding to a 50 year event estimated in 1976–2005 baseline period and (b) volume change (m^3 s^{-1}). Projected (c) annual daily maximum runoff return period for baseline 50 year event and (d) volume change (m^3 s^{-1}). Annual daily maximum runoff increases in the Sierra Nevada, Rocky Mountains and Southern Coastal hydrologic region, which can result in flooding. Hatchings indicate points of significant changes in volumes of extreme events using the two-sample KS goodness-of-fit test at a 5% significance level.

resulting in possible further strains to water reliability (figures 4(c) and (d); table 1). Volumetrically, the 50-year annual cumulative minimum Q decreases minimally for the CRB (−3%) but substantially for the SRB (−13%) and SJRB-TLB (−10%) while the ML-OVB exhibits a slight increase (+4%). Overall, greater annual drying is projected over mountainous regions where the majority of Q and consequently water supply originates.

3.3. Parallels to the recent drought

California is currently amidst the reportedly most severe multi-year short term (2012–2016) drought in a millennia, experiencing the lowest 12 month and calendar year P in the observed 119 year record (Griffin and Anchukaitis 2014, Swain *et al* 2014). In addition to extremely dry conditions, the region has exhibited elevated T, which increases evaporative demands and decreases the fraction of P falling as snow, exacerbating the drought (Weiss *et al* 2009). Between 2010–2016, SWP allocations have averaged approximately 45%, with a low in 2014 of just 5% (CADWR 2016). Due to the co-occurrence of heightened T and below average P, Sierra Nevada April 1st snow depth was just 33% of average in 2014 and 5% in 2015 (CDEC 2015). Subsequent July major reservoir levels during the recent drought ranged from 37–79% of historical average in 2014 and 18–62% in 2015. (CDEC 2016a). Despite above average P in early 2016, Margulis *et al* (2016) found that full recovery from this long term snow deficit may take an additional four years. This has direct impacts on water resources throughout the state as the Governor of California issued an Executive Order requiring urban per capita water use to be reduced by 25%. Flows from the CVP were restricted to meet environmental needs, limiting water available for agricultural users. Historically, reservoir water levels in Northern California are kept low for flood control purposes due to the region's susceptibility to wintertime flooding (Dettinger *et al* 2004, Hayhoe *et al* 2004, Cayan *et al* 2008). Early 2016 storms and warmer T have resulted in above

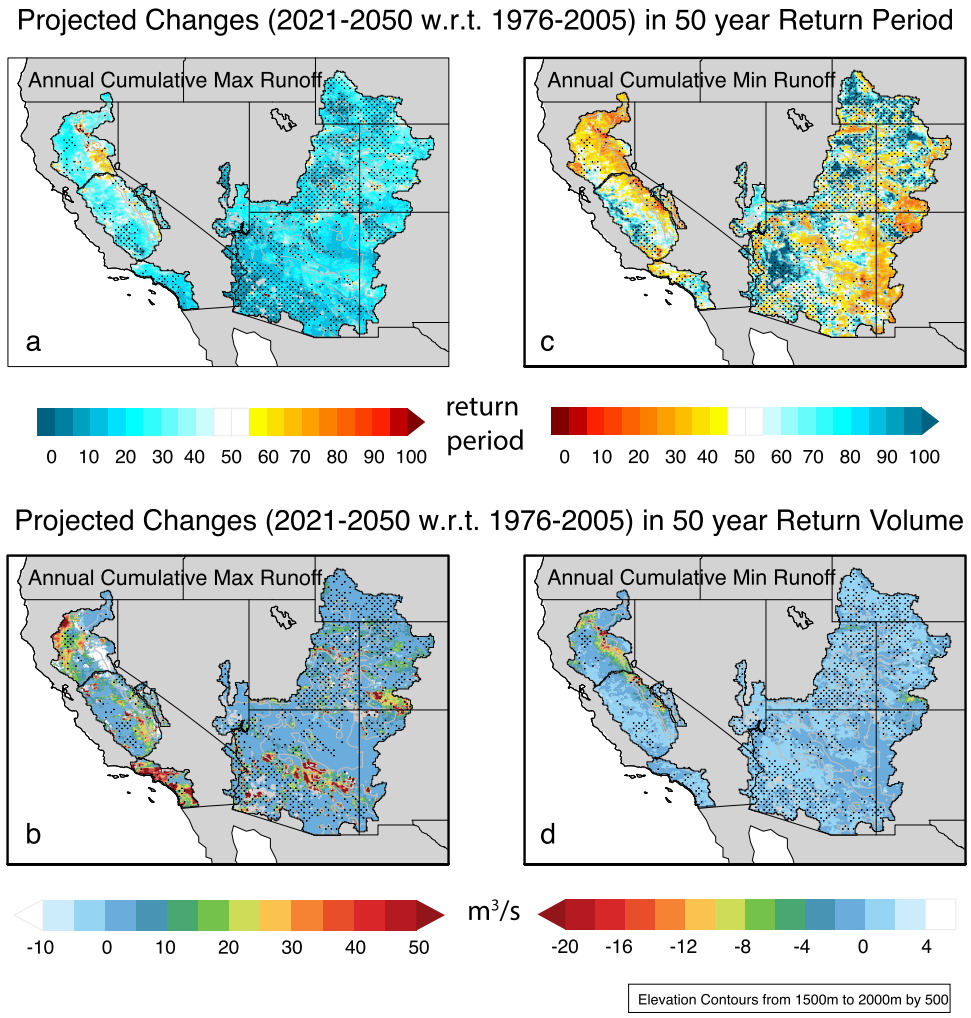

Figure 4. Projected (a) annual cumulative maximum runoff return period in 2021–2050 corresponding to a 50 year event estimated in 1976–2005 baseline period and (b) volume change (m^3 s^{-1}). Projected (c) annual cumulative minimum runoff return period for baseline 50 year event and (d) volume change (m^3 s^{-1}). Changes to cumulative annual maximum and minimum runoff highlights increased frequency of both extreme wet and dry periods leaving the region more susceptible to both droughts and floods. The northern Sierra Nevada exhibits runoff deficits in wet and dry years. Hatchings indicate points of significant changes in volumes of extreme events using the two-sample KS goodness-of-fit test at a 5% significance level.

average Q causing some reservoirs to fill too early in the year. For flood control purposes, water from the Lake Natoma Dam (fed by Folsom Lake), for example, was released during the first two weeks of February 2016 despite persistent drought conditions throughout the state (CDEC 2016b). We project clear shifts in Q timing regardless of increases or decreases in P due to exceptional declines in snowpack, consistent with the recent California drought. It is well understood that decreases in average P will further strain water resources in the SWUS, however, increases in the frequency and the magnitude of extreme P events, as projected in this study, may also lead to decreases in the water supply as observed under the present climate.

3.4. Local supply limitations

Demand for water in Southern California is expected to rise in concurrence with extensive population growth. SCAG (2012) estimates the 2015 population of 18.8 million people in the region to increase by 27%–23.8% million by 2050. Expansion of local water resources is an obvious solution to mitigate climate change impacts and rising populations. However, a variety of constraints exist for each of the potential options including conservation, stormwater capture, recycled water, groundwater and desalination. For instance, urban conservation efforts often focus on per capita water use like California's Senate Bill 7 × 7, which requires a 20% reduction in per capita urban water use by 2020 or the aforementioned Governor's Executive Order in response to the current drought. However, significant projected population increases may eclipse per capita water use reductions, resulting in a net gain of water consumption (State of California, Department of Finance 2014). Similarly, in metropolitan regions, any potential increases in P are restricted to winter and spring months (figure S6). Without new or upgraded infrastructure for water storage, such as storm water capture facilities, additional P as a local

supply may not offset demand. To this end, recycled water only accounts for a small fraction of the region's water supply. Public aversion to using highly treated wastewater for potable use has limited the majority of recycled water use to outdoor irrigation. Therefore, expansion of recycled water involves costly additions to infrastructure as it cannot flow through the same existing potable water pipelines. Furthermore, as PET is projected to rise (figure 1(e)) due to warmer T, irrigation demands are expected to increase for agriculture and urban landscapes. Moreover, local groundwater also exhibits limitations as it requires recharge to prevent over pumping. Groundwater in certain regions of Southern California is severely polluted and cannot be extracted without costly clean up efforts. Also, substantial energy requirements make desalination a currently cost-ineffective option for many water agencies. In regards to expanding imported water supplies, pumping restrictions in the Sacramento-San Joaquin Delta already exist to protect endangered fish species. There is a longstanding debate on the environmental benefits versus consequences of constructing additional infrastructure to aid in the transport of imported water such as the currently proposed twin tunnel project which would divert flow under the Delta. However, both the political situation and environmental concerns in California have prevented the construction of additional reservoirs or increasing current reservoir capacity. Traditional value cost-benefit analyses utilized by many water managers cannot lead to wise decisions if the benchmark for moving forward with a water project is the current cost of imported water alone. Benefits and costs are no longer appropriately defined without incorporating potential reductions of imported water supply as a result of climate change.

4. Conclusions

In this study, we investigate potential mean and extreme changes to the hydrological cycle resulting from climate change across SWUS's major imported water supply basins. Water supplies for Southern California are expected to diminish as a result of more extreme hydrological events, warmer T, declining snowpack, rising populations and insufficient local supply expansion. On the demand side, rising T is projected to increase irrigation demands for both residential and agricultural uses as well as evaporative losses from reservoirs. While projected changes in the direction of total annual P and Q are not consistent, a clear increasing trend is exhibited in the intensity and occurrence of extreme one-day maximum P and Q events. These one-day extremes, coupled with greater fractions of P as rain and a shift in Q timing, will likely require increases in winter reservoir releases and flood channel capacities for flood protection. The inability to capture and store winter and spring Q could lead to shortages during the summer months. In the heavily populated South Coast hydrologic region, an increase in extreme hydrologic events also introduces an increased flood risk in the highly urbanized areas. Our projections suggest that wet years will become wetter and dry years drier with the exception of the Sierra Nevada, which exhibits significant Q deficits during wet and dry years.

We note a number of limitations in the modeling and analysis framework of this study. For instance, the use of a single RCM and hydrological model does not fully encapsulate the spectrum of uncertainty in the potential hydrological changes in this region. Similarly, the implementation of VIC at high resolutions has been known to over-simplify horizontal water and energy exchanges amongst grid cells especially in regions where this horizontal exchange is significant (Naz *et al* 2016). Moreover, this study does not use a water management model to identify the impacts on a local scale. Use of a water management model would provide more detailed quantifications of the changes needed to mitigate increased flooding, including reservoir release timing and volumes in addition to enumerating subsequent potential water supply deficits. Despite these limitations, this study provides new insights regarding increased flood and drought risk to aid water managers in better adaptation planning under a changing climate. The majority of mitigation strategies to increase water supply reliability are primarily based on large infrastructure upgrades, which are time and cost intensive. Overall, near future projected increases in the frequency and intensity of flood and drought events pose potentially severe challenges to water supply in the SWUS and necessitate immediate actions to begin adapting to climate change.

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Author contributions

BRP and JSP led the conception and development of this study. BRP led the analysis and writing of the manuscript. MA designed the modelling framework. DR, MA, RM, KSC and BSN performed the experiments. MA and DR contributed in the overall analysis and DRK with the statistical analysis. All authors contributed to the discussion and writing of the manuscript.

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