Anthropogenic Warming Impacts on California Snowpack During Drought

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ABSTRACT

Sierra Nevada climate and snowpack is simulated during the period of extreme drought from 2011 to 2015 and compared to an identical simulation except for the removal of 20th century anthropogenic warming. Anthropogenic warming reduced average snowpack levels by 25%, with mid-to-low elevations experiencing reductions between 26-43%. In terms of event frequency, return periods associated with anomalies in 4-year April 1 SWE are estimated to have doubled, and possibly quadrupled, due to past warming. We also estimate effects of future anthropogenic warmth on snowpack during a drought similar to that of 2011 – 2015. Further snowpack declines of 60-85% are expected, depending on emissions scenario. The return periods associated with future snowpack levels are estimated to range from millennia to much longer. Therefore, past human emissions of greenhouse gases are already negatively impacting statewide water resources, and much more severe impacts are likely to be inevitable.

1. Introduction

California recently experienced an epic 4-year (2011/12 – 2014/15) drought, with extremely warm temperatures and low precipitation throughout the state (e.g. Swain et al. 2014, AghaKouchak et al. 2014). The drought manifested itself in record-breaking dry soils (Griffin and Anchukaitis 2014, Williams et al. 2015, Robeson 2015) and has led to significant agricultural damage (Howitt et al. 2014) alongside rapid depletion of groundwater resources (Famiglietti et al. 2014). The precipitation deficit driving the drought can be primarily understood through natural variability (Seager et al. 2015). While recent multi-year low precipitation totals are extreme, there is no evidence that historical California precipitation exhibits any negative trend (Berg et al. 2015, Seager et al. 2015). Future precipitation is also expected to increase somewhat over California (e.g. Neelin et al. 2013), lending further support to the notion that anthropogenic precipitation changes have likely not influenced the recent drought. Anthropogenic temperature changes, on the other hand, have repeatedly been invoked to explain the severity of record dry soils across California (Griffin and Anchukaitis 2014, Williams et al. 2015, Shukla et al. 2015, Cheng et al. 2016).

Snow is another hydrologic variable influenced by warming. In 2015, April 1 snow water equivalent (SWE) in the Sierra Nevada reached a low unprecedented within the past 500 years (Belmecheri et al. 2015), coinciding with the warmest California winter on record (http://www.ncdc.noaa.gov/sotc/national/201503). This alarming statistic begs the question: how have anthropogenic temperature changes influenced California snowpack during the 4-year drought? Addressing this question is a focus here, building on two prior studies. Shukla et al. (2015) find that the ranking of the 2013/14 Sierra Nevada snowpack was below the 2nd percentile for the 1916 – 2012 period. They also show that if 2013/14 temperatures had resembled any prior historical year, there is a 90% chance that 2013/14 SWE would have ranked above the 2nd percentile. So the unusual warmth of 2013/14 (the second warmest winter on record behind 2014/15, http://www.ncdc.noaa.gov/sotc/national/201403) likely contributed to the low snowpack conditions of that year. Mao et al. (2015) also analyze the role of anthropogenic temperatures on 2012-2014 April 1 SWE over the Sierra Nevada by simulating snowpack conditions when daily minimum temperature trends across the cold-season (November-March) and warm-season (April-October) are removed from the forcing data. Their results suggest that recent warming more than doubled the return period of the 3-year 2012-2014 average April 1 SWE over the Sierra Nevada.

This study advances these prior results in two respects. First, we include observed and simulated 2014/15 snowpack totals in our analyses, providing for a more comprehensive assessment of the role of past anthropogenic temperature change in the low Sierra Nevada snowpack during the entire 4-year drought. Second, we also examine effects on snowpack if the drought had unfolded under the much more severe warming occurring at the end of the 21st century under enhanced anthropogenic forcing. This is accomplished by performing a series of experiments simulating 2011/12 – 2014/15 snowpack levels when subjected to future conditions derived from downscaled regional climate projections. We explore the full range of plausible greenhouse gas forcing scenarios, allowing for an assessment of the inevitability of snowpack change during future drought conditions.

2. Data and Methods

2a. Coupled WRF-NoahMP simulation

To quantify the role of anthropogenic warming in the record-setting low 2011/12 – 2014/15 California snowpack, we perform regional climate simulations using version 3.5 of the Weather Research and Forecast model (WRF, Skamarock et al. 2008) and the Noah land surface model with multiparameterization options (NoahMP, Niu et al. 2011) in both coupled and uncoupled (or offline) frameworks. A January 1980 – June 2015 baseline climatology is first simulated in coupled mode. The coupled baseline simulation is also used to drive offline simulations described in Section 2b. The coupled simulation uses two domains (Fig. 1a), D01 (27 km) and

D02 (9 km), to resolve California's Sierra Nevada topography and relevant fine-scale climatic features (e.g. snow albedo feedback, land-sea breeze). Boundary conditions for the coupled baseline simulation are supplied by 6-hourly North American Regional Reanalysis output (Mesinger et al. 2006). Multiple parameterization packages were tested and the optimal configuration was shown to accurately simulate spatial and temporal patterns of observed Sierra Nevada SWE (c.f. Fig. S2 in Sun et al. 2016). Additional information on the coupled model configuration can be found in Section S1. Its performance in simulating California hydrology is further detailed in Walton et al. 2016, Sun et al. 2016, and Schwartz et al. 2016.

2b. Uncoupled WRF-NoahMP simulations

We next create an uncoupled version of the January 1980 – June 2015 baseline land surface conditions. This is achieved by forcing the offline NoahMP model with 3-hourly outputs of 2 m air temperature, surface pressure, shortwave and longwave radiation, 10 m wind speed, 10 m wind direction, precipitation, and relative humidity from the aforementioned 9 km (D02) coupled baseline simulation. For computational efficiency, only grid cells in D02 that experience over 10 mm of 1980 – 2015 annual-mean SWE are simulated (Fig. 1b). Evaluation of simulated SWE from this offline "reference" experiment is found in Section 2c.

Following the reference experiment, five additional experiments, each spanning June 2011 – June 2015, are executed where temperature inputs to the offline model are perturbed by various amounts. First, a "natural" experiment is performed where the monthly warming that has arisen over the past century is removed at each time step in a given month. This experiment estimates how 2011/12 – 2014/15 snowpack totals would have evolved in the absence of past warming.

Warming is computed from two observational products, the 2°x2° GISS Surface Temperature Analysis spanning January 1880 – May 2015 (Hansen et al. 2010, available at http://data.giss.nasa.gov/gistemp/) and the 5°x5° Climatic Research Unit temperature database spanning January 1850 – May 2015 (Jones et al. 2012, available at http://www.cru.uea.ac.uk/cru/data/temperature/#sciref). For each month, 1880 – 2015 (or 2014 for months June – December) time series of temperature anomalies with respect to 1880 – 1919 are averaged across California grid cells within each data set. Warming for a given month is then calculated as the difference between two 35-year averages, a recent climate of 1981 – 2015 (or 1980 – 2014 for months June through December) minus a past climate of 1880 – 1914. Averaged across the two data sets, this yields monthly warming (units °C) of 1.33 (January), 1.30 (February), 1.24 (March), 0.73 (April), 1.11 (May), 1.11 (June), 1.0 (July), 0.95 (August), 1.46 (September), 1.12 (October), 0.37 (November), and 0.27 (December). Very similar values are obtained with different averaging periods and through trend analysis (Section S2, Table S1). Also note that global climate models (GCMs) on average estimate that anthropogenic forcings have contributed to around 1°C annual warming by the start of the 21st century over North America (c.f. Fig. 10.7, Bindoff et al. 2013), reasonably consistent with the above values. Thus we interpret the "natural" experiment as representing a regional climate state that is identical to that of 2011/12 – 2014/15, but without anthropogenic forcing.

Finally, we analyze how 2011/12 – 2014/15 snowpack responds to end-of-21st century projected temperature increases with four future experiments corresponding to the Representative Concentration Pathway (RCP) emissions scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) used in the IPCC Fifth Assessment Report (Van Vuuren et al. 2011). In these future experiments, we rely on a hybrid downscaling framework to generate end-of-century monthly warming values at 3 km resolution for all available GCMs and emissions scenarios over the Sierra Nevada (Walton et al. 2016). The GCM-mean downscaled projection is computed for each scenario and then coarsened to 9 km to match the resolution of the offline grid dimensions used in this study (Fig. 1). For each grid cell in the offline simulations, we increase temperatures by month according to its ensemble-mean change at the nearest grid cell in the 9 km downscaled projection.

2c. Uncoupled model evaluation of SWE

Here we evaluate simulated Sierra Nevada SWE from the reference experiment based on a collection of 93 in-situ stations (red dots Fig. 1b) that recorded April 1 SWE from 1930 – 2015. Data is provided by the California Department of Water Resources (CDWR, available at http://cdec.water.ca.gov/snow/current/snow/index.html) and the National Resources Conversation Service (NRCS, available at http://www.wcc.nrcs.usda.gov/snow/). Figure 2 compares time series of the observed station-average April 1 SWE and simulated values averaged across grid cells nearest to the 93 station locations for the overlapping period of 1980 – 2015. Simulated output in this comparison has already been adjusted for the grid-to-point elevation mismatch (Section S3, Figures S1, S2). Simulated climatological April 1 SWE is 696.6 mm, nearly equal to the average observed value of 690.4 mm. Standard deviations for the simulated and observed time series are 333.6 and 324.0 mm, respectively. These very small biases, indicates that WRF-NoahMP quite accurately simulates Sierra Nevada SWE compared to observed data.

3. Past and future anthropogenic warming impacts

3a. Elevational dependency

Figure 3 compares September 2011 – June 2015 time series of daily SWE from the six offline experiments averaged across grid cells in various elevation categories: all elevations (Fig. 3a), high elevations (>2500 m, Fig. 3b), mid elevations (1500-2500 m, Fig. 3c), and low elevations (<1500 m, Fig. 3d). Results are further summarized in Table 1. Focusing on the 4-snow year (November – June) average, anthropogenic warming reduced 2011/12 – 2014/15 average annual snowpack levels by 17.2 mm (25%) across all elevations and by 9.2 mm (10%), 19.7 mm (26%), and 16.4 mm (43%) for the high, mid, and low elevations, respectively. Hence, snowpack at mid-to-low elevations is much more affected by recent warming trends than snowpack at the highest elevations.

Strong impacts to the mid elevations (also discussed in Sun et al. 2016) are particularly noteworthy given that the mid-elevations encompass over 60% of the entire domain. In terms of volumetric SWE (i.e. SWE multiplied by area), mid-elevations also dominate. The reference 4-snow year average equals 0.357 km^3 over all elevations and 0.230 km^3 in just the mid elevations (Fig. 3a,c). In the natural experiment, the corresponding values are 0.473 km^3 over all elevations and 0.313 km^3 for the mid elevations (Fig. 3a,c). Thus, 0.116 km^3 (94 kAf) of additional total snowpack would have resulted if anthropogenic warming had not occurred, 71% of which would be found in mid-elevations. For perspective, 94 kAf of water is roughly twice the current annual residential water demands for the city of San Francisco (~46 kAf, SFPUC 2014)

Projected 21st century warming applied to this recent period would diminish snowpack levels even further. Under the least aggressive emission scenario of RCP2.6 (dark blue line, Fig. 3), 4-

year average snowpack levels are significantly reduced from the levels of the reference experiment by 24.6 mm (47%) across the entire domain. However, estimates of recent global greenhouse gas emissions (Le Quéré et al. 2015) show that RCP2.6 involves emissions reductions that have not occurred since the RCP forcing scenarios were created in 2005. The significant reductions associated with RCP2.6 in the coming decades are likewise unlikely to occur. Thus we only consider RCP4.5, RCP6.0, and RCP8.5 to be the plausible forcing scenarios. RCP4.5, which also involves emissions reductions over the coming decades, may be the most realistic "mitigation" scenario. Under this scenario (light blue line, Fig. 3), total snowpack is reduced by 31.9 mm or 60%. RCP8.5 is the scenario emissions have been tracking over the past 10 years, and will continue to track if emissions keep increasing at the same pace, and can be considered a "business-as-usual" scenario. Under RCP8.5 (red line, Fig. 3), total snowpack is reduced by 45.2 mm or 85%, and even high elevations become susceptible to large declines of 55.3 mm (67%). Nearly all snowpack is lost at mid and low elevations, with reductions exceeding 90% for each category. Volumetric SWE declines by 0.305 km^3 (over 247 kAf) between the reference and RCP8.5 simulations, over five times the annual residential usage in San Francisco.

3b. Event frequency

We next quantify how return periods of simulated 4-year average (2012-2015) April 1 snowpack levels change under current and future anthropogenic warming in Figure 4. Observed April 1 return periods of 4-year events are first computed using the 93 CDWR/NRCS station-average data set. To minimize possible biases due to anthropogenic trends in the station data, we only consider the first half of the observed time series, 1930-1970, when computing observed return periods. These return periods are simply equal to the observed length of the sample size plus one (i.e. 42 years) divided by the rank of the sorted running 4-year 1930-1970 SWE averages from lowest to highest (grey triangles, Fig. 4). A normal distribution is then fitted to the set of observed 4-year averages and corresponding fitted return periods are computed (black line). Several distribution types were tested and the normal distribution proved to be the best fit. 95% confidence intervals are obtained via a bootstrap-resampling technique (black dashed lines, details in Section S4). 4-year average SWE from the six offline simulations are placed on the fitted curve to estimate their return periods (colored dots, Fig. 4). Finally, the observed 2012-2015 average is noted by a magenta dash-dot line.

The observed 2012 – 2015 station-average of 270.4 mm (magenta dash-dot line in Fig. 4) is by far the lowest 4-year average on record (including 1971-2015, not shown). This very low 4-year snowpack is matched by the "reference" WRF-NoahMP experiment, when model and observational uncertainty are considered. (See Section S3 and Fig. S2 for details on the calculation of these error bars.) For the longer return periods, the associated 95% confidence level uncertainty is large, making it difficult to make precise statements about the return periods of any individual SWE value when that value is very low. However, relative values may be meaningful. For example, comparing the natural to the reference experiment, the return period is roughly two to four times longer with anthropogenic warming than without.

Using output from the future warming experiments, we also provide estimates of the event frequency of 2012 – 2015 snowpack levels when subjected to end-of-century warming. The results are shown as dark blue (RCP2.6), light blue (RCP4.5), orange (RCP6.0), and red

(RCP8.5) dots in Fig. 4. Examining the plausible forcing scenarios (RCP4.5, RCP6.0 and RCP8.5), it is evident that any additional warming applied to the already thin 2012 – 2015 snowpack yields almost incalculable return periods, from millennial time scales to much longer. While future snowpack will likely be shaped by factors beyond just warming, our idealized experiments suggest that a future 4-year period with precipitation characteristics like 2012 – 2015 would yield snowpack levels that cannot be reconciled with the snowpack statistics of the historical record, no matter which plausible forcing scenario is chosen.

4. Summary and Discussion

Offline simulations reveal that observed century-scale warming exacerbated Sierra Nevada snowpack loss significantly during 2011/12 – 2014/15. Across the region, warming reduced 4-year average snowpack levels by 25%, with even greater relative losses concentrated in the mid and low elevations. In terms of event frequency, warming has at least doubled, and perhaps quadrupled, estimated return periods of the 2011/12 – 2014/15 4-year average April 1 snowpack. While absolute values of the return periods are different, Mao et al. (2015) also found over a doubling of return periods for 3-year (2012-2014) April 1 SWE events due to anthropogenic warming. And while a period exactly like 2011/12 – 2014/15 will obviously not recur, droughts like it surely will, and end-of-century anthropogenic warming applied to this time span results in snowpack declines of 60-85% and estimated 4-year return periods range from millennial to much longer time scales, no matter which realistic forcing scenario is chosen. In other words, when it comes to snowpack, future drought will have no analog in the historical record.

These results corroborate recent findings of a clear link between anthropogenic warming and the ongoing drought's severity (e.g. Griffin and Anchukaitis 2014, Williams et al. 2015). While consecutive years of low precipitation lie at the origin of recently depleted snowpack levels (Mao et al. 2015), this study suggests that California's water situation (Brown 2015) would not have been so dire had anthropogenic warming not occurred. Moreover, we find that even with significant emissions reductions, such as those of the RCP4.5 forcing scenario, future Sierra Nevada-based water resources are expected to further diminish due to additional warmth. Going forward, it is likely to become more difficult to satisfy municipal, agricultural, and ecological water needs within a warmer climate, and clearly water will have to be managed very differently during periods of extreme drought.

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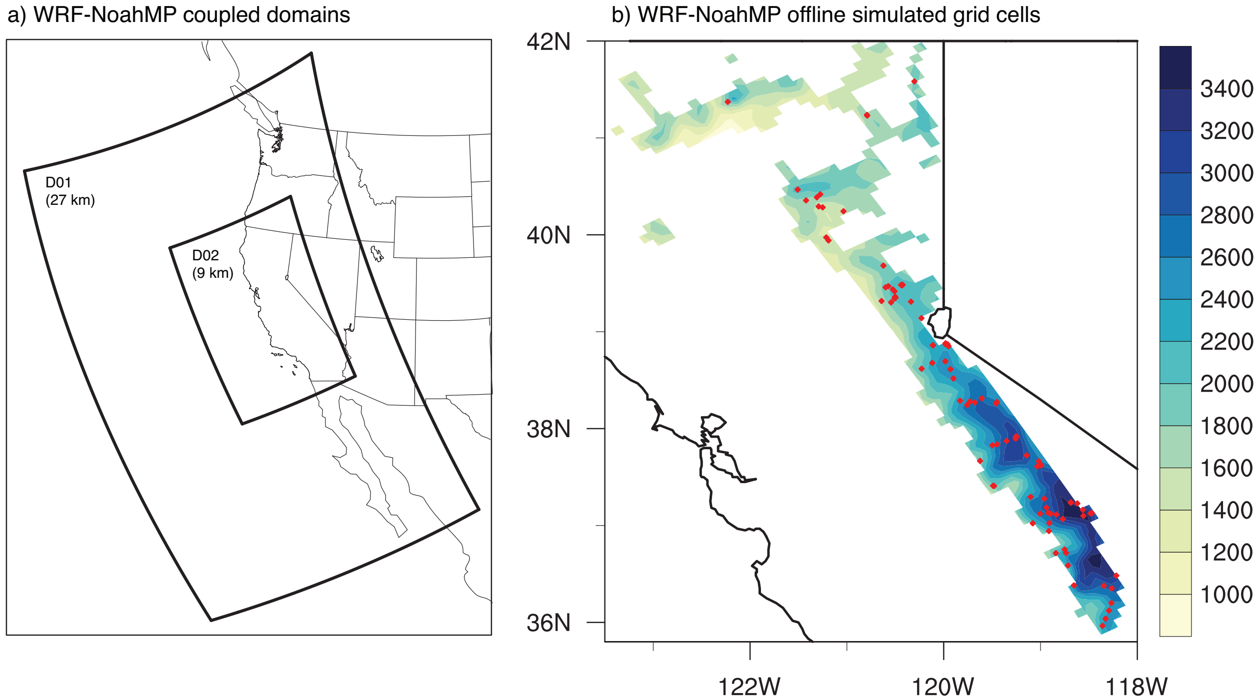

FIG 1. (a) Location of nested WRF-NoahMP coupled domains: D01 (27 km resolution) – D02 (9 km resolution). (b) 9 km resolution grid cells (750 total) selected for WRF-NoahMP offline simulations, as they experience over 10 mm of annual SWE averaged across 1980 – 2015. Grid cell elevation (unit m) is shaded according to the legend on the right. Locations of 93 CDWR/NRCS snowpack observations are overlaid as red dots.

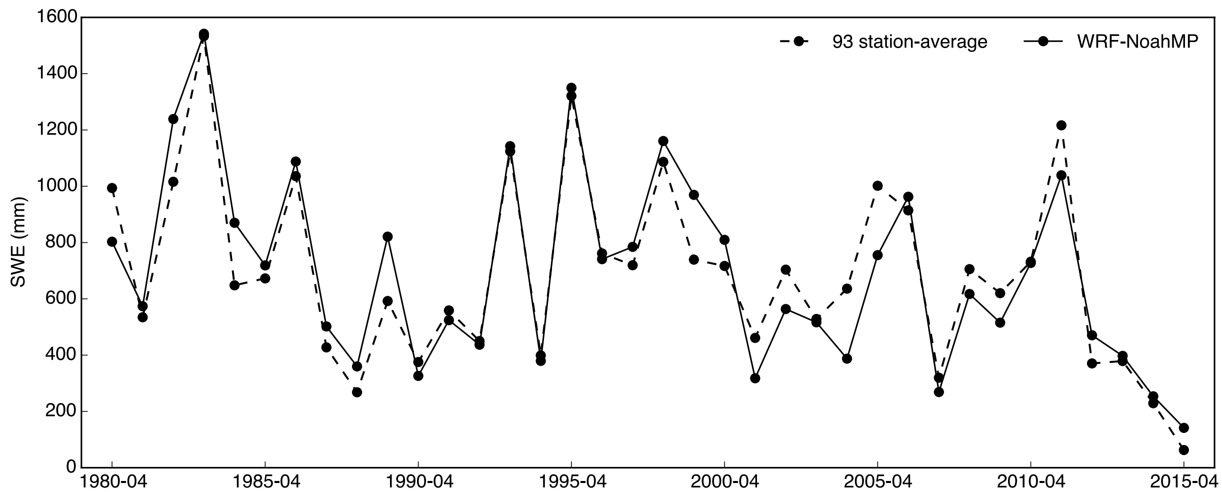

FIG 2. April 1 SWE (unit mm) according to the 93 station-averaged observations (dashed) and the average of the nearest grid cells to the 93 stations in the WRF-NoahMP reference simulation (solid) for the overlapping period of 1980 – 2015. Simulated output is corrected for grid-to-station elevation mismatch.

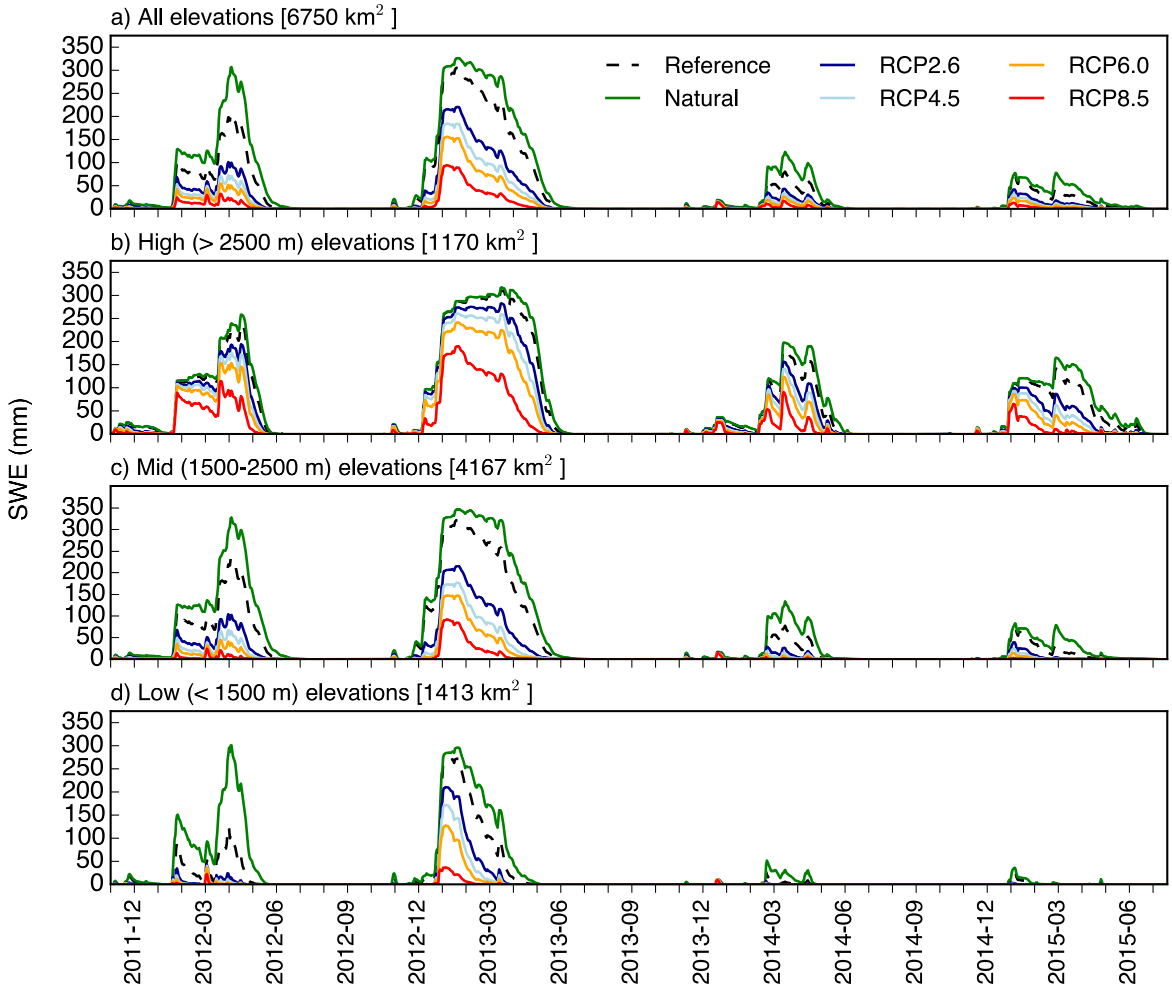

FIG 3. September 2011 – June 2015 daily SWE (unit mm) according to the reference (black dashed), natural (green), RCP2.6 (dark blue), RCP4.5 (light blue), RCP6.0 (orange), RCP8.5 (red) simulations averaged over (a) all grid cells, (b) grid cells with elevations greater than 2500 m, (c) grid cells with elevations between 1500-2500 m, and (d) grid cells with elevations lower than 1500 m. The area of each elevation category is noted in the brackets.

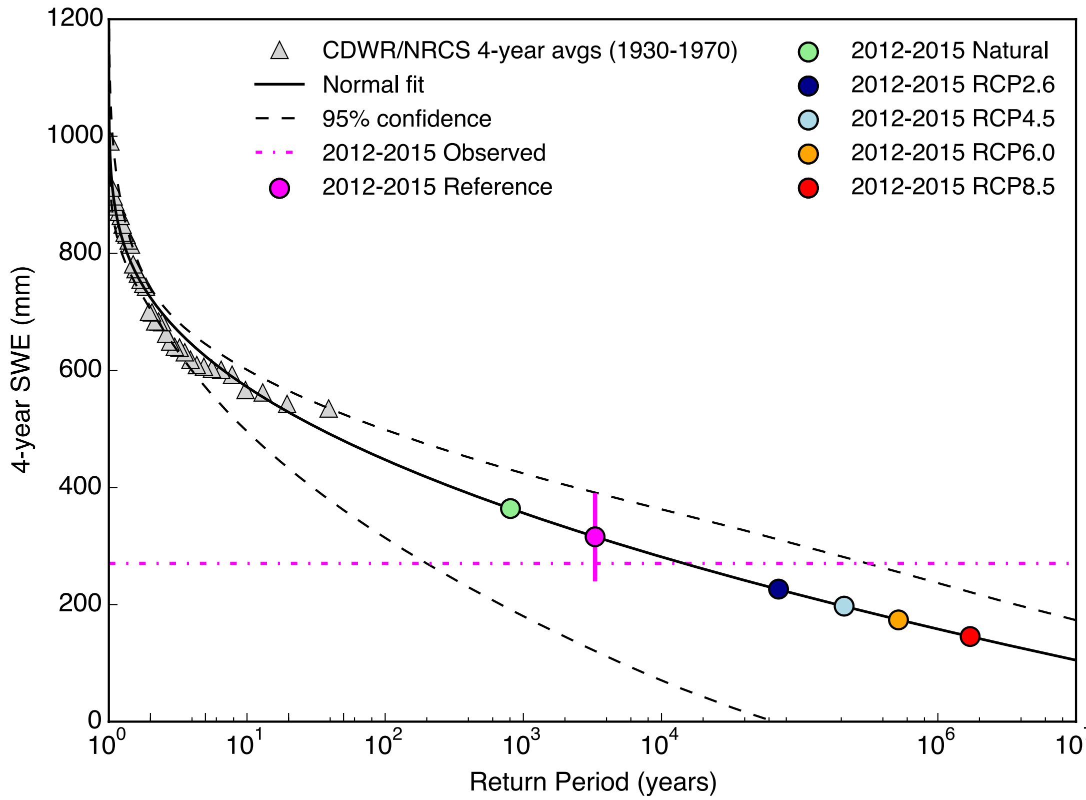

FIG 4. Observed (1930-1970) return periods of 4-year averaged 93 CDWR/NRCS station-averaged April 1 SWE (grey triangles) and estimated return periods of corresponding simulated values (colored dots) using a normal fitted distribution (black line, 95% confidence intervals in black dashes). The observed 2012-2015 average April 1 SWE amount is shown in magenta dash-dot line. Error bars on the 2012-2015 simulated “reference” experiment (solid magenta line) are based on results in Figure S2a.

	Reference	Natural	RCP2.6	RCP4.5	RCP6.0	RCP8.5
All elevations	52.9	70.1	28.3	21.0	15.8	7.7
High elevations	82.0	91.2	65.0	56.3	46.9	26.7
Mid elevations	55.3	75.0	24.4	16.1	11.0	4.7
Low elevations	21.7	38.1	9.6	6.5	4.2	1.1

TABLE 1. Simulated 2011/12 – 2014/15 snow-year (November – June) average SWE (unit mm) across all elevations, high elevations (> 2500 m), mid elevations (1500-2500 m), and low elevations (< 1500 m) for each experiment. Data corresponds to time series in Figure 3.