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Key Points:
- We estimate that 53% of the total runoff in the western U.S. originates as snow, despite only 37% of the precipitation falling as snow
- Snowmelt produces 70% of the total runoff in mountainous areas in the West
- The ratio of snow-derived runoff to the total runoff will reduce by one third by 2100 in a business-as-usual climate scenario

Supporting Information:
- Supporting Information S1

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How much runoff originates as snow in the western United States, and how will that change in the future?

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Abstract In the western United States, the seasonal phase of snow storage bridges between winter-dominant precipitation and summer-dominant water demand. The critical role of snow in water supply has been frequently quantified using the ratio of snowmelt-derived runoff to total runoff. However, current estimates of the fraction of annual runoff generated by snowmelt are not based on systematic analyses. Here based on hydrological model simulations and a new snowmelt tracking algorithm, we show that 53% of the total runoff in the western United States originates as snowmelt, despite only 37% of the precipitation falling as snow. In mountainous areas, snowmelt is responsible for 70% of the total runoff. By 2100, the contribution of snowmelt to runoff will decrease by one third for the western U.S. in the Intergovernmental Panel on Climate Change Representative Concentration Pathway 8.5 scenario. Snowmelt-derived runoff currently makes up two thirds of the inflow to the region's major reservoirs. We argue that substantial impacts on water supply are likely in a warmer climate.

1. Introduction

The seasonal snowpack in the western U.S. is a natural water tower: snow stores winter precipitation and releases it in spring. Snowmelt replenishes groundwater and reservoir storage critical to the region's ecosystems, urban centers, agricultural irrigation, and hydroelectric power production [*Barnett et al.*, 2005; *Bales et al.*, 2006; *Knowles and Cayan*, 2004; *Cayan et al.*, 2001; *Mote et al.*, 2005]. Anomalously low spring snowpacks can lead to water scarcity, groundwater overdrafts, tree mortality, insect outbreaks, and increased wildfire risk, all of which can significantly undermine the socio-economic well-being of the region [*Diffenbaugh et al.*, 2015]. Western U.S. snowpacks are highly variable in both time [*Mote*, 2003; *Cayan*, 1996] and space [*Bales et al.*, 2006; *Margulis et al.*, 2016a]. Climate warming augments these variations and has generated a steady trend of declining spring snow storage [*Mote*, 2003; *Groisman et al.*, 1994], earlier melt onset [*Cayan et al.*, 2001; *Stewart et al.*, 2004, 2005], and reduced warm-season streamflow [*Stewart et al.*, 2004, 2005; *Regonda et al.*, 2005]. These snow climatologic trends have been projected to continue throughout the 21st century for the region [*Gergel et al.*, 2017]. In addition, most of the reservoirs and dams in the western U.S. were designed for both flood control and water supply, but these designs are based on the climate of many decades ago. With the earlier shift in snowmelt timing and stronger and more frequent hydrologic extremes, the reservoirs have to release part of the meltwater early in the season due to flood control requirements and finite reservoir capacity [*Barnett et al.*, 2005; *Knowles et al.*, 2006]. Thus, it is increasingly challenging for the current infrastructure to fulfill its designed water storage functions, which further increases the region's water resources vulnerability [*Vicuna and Dracup*, 2007].

The ratio of the snow-derived runoff to the total runoff (referred to as $f_{Q,\text{snow}}$ hereafter) is a metric often cited in research articles and media reports, among other sources (e.g., the webpage of many agencies and organizations), to highlight the importance of snow to water supply and to the water cycle. However, to our knowledge, a detailed study of the contribution of snow to the runoff over the western U.S. has not been conducted. Indeed, numerous studies have approximated $f_{Q,\text{snow}}$ with indirect metrics such as the total snowfall as a fraction of total precipitation, total snowfall as a fraction of total runoff, or melt season runoff as a fraction of total annual runoff. As pointed out by *Serreze et al.* [1999], these approximations provide a useful basis for estimating $f_{Q,\text{snow}}$, but they neglect the physical processes that affect the transformation from snow to

Table 1. Summary of Literature That Has Reported the Contribution of Snow to Runoff Over the Western U.S. by Approximations or by Citing Other Literature

Literature	Value of $f_{Q,\text{snow}}$	Method	Source
Barnett et al. [2005]	60% to 90%	Snowfall/total runoff	–
Serreze et al. [1999]	34% to 80%	SWE/precipitation	–
Kapnick and Delworth [2013]	40% to 60%	Snowfall/total precipitation, snowfall/total runoff	–
Mankin et al. [2015]	–	Snowmelt/total precipitation	–
Barnett et al. [2005]	60% to 90%	Snowfall/total runoff	–
Stewart et al. [2004]	50% to 80%	Melt season runoff/total annual runoff	–
Palmer [1988]	75%	–	–
Hamlet et al. [2005]	Over 70%	–	–
Daly et al. [2000]	70% to 80%	–	–
Pagano and Garen [2006]	80%	–	–
Doesken and Judson [1996]	60% to 75%	Snowfall/total precipitation	–
Clow et al. [2012]	70% to 80%	–	*Doesken and Judson* [1996]
Balk and Elder [2000]	75%	–	*Doesken and Judson* [1996]
Fassnacht et al. [2003]	70% to 80%	–	*Doesken and Judson* [1996]
Vuyovich et al. [2014]	75%	–	*Doesken and Judson* [1996] and *Daly et al.* [2000]
Sexstone and Fassnacht [2014]	60% to 75%	–	*Doesken and Judson* [1996]
Chang and Li [2000]	75%	–	*Palmer* [1988]
Simpson and McIntire [2001]	75%	–	*Palmer* [1988]
Cowles et al. [2002]	75%	–	*Palmer* [1988]
Powell et al. [2011]	75%	–	*Palmer* [1988]
Cayan [1996]	75%	–	*Palmer* [1988]
Pagán et al. [2016]	75%	–	*Palmer* [1988]
Franz et al. [2003]	75%	–	*Palmer* [1988]
Welch et al. [2016]	75%	–	*Palmer* [1988] and *Cayan* [1996]
Tang and Lettenmaier [2010]	75%	–	*Palmer* [1988]
Gillan et al. [2010]	60% to 75%	–	*Serreze et al.* [1999], *Cayan* [1996], and *Palmer* [1988]
Rice et al. [2011]	80%	–	*Daly et al.* [2000]

runoff, e.g., evapotranspiration, sublimation, infiltration, and rainfall. Partly due to the differences among the methods by which $f_{Q,\text{snow}}$ has been approximated, large variations exist in the estimates. Other studies reported $f_{Q,\text{snow}}$ by citing existing literature. Earlier studies have also reported $f_{Q,\text{snow}}$ but contain no supporting analysis or references for the claimed ratio. A list of literature we reviewed that reported $f_{Q,\text{snow}}$ values is summarized in Table 1.

In this study we develop explicit quantification of the historical and future $f_{Q,\text{snow}}$ over the western U.S. We quantify $f_{Q,\text{snow}}$ by tracking the fate of snowmelt in modeled hydrologic fluxes. Modeling is arguably the only realistic way to compute $f_{Q,\text{snow}}$, as it provides a full suite of spatiotemporally continuous hydrologic estimates over a large domain that are not readily available from in situ observations or remote sensing. Land surface models simulate physical snow hydrologic processes including snow accumulation, sublimation, infiltration, evapotranspiration, runoff, and base flow. In calculating $f_{Q,\text{snow}}$, we develop a snowmelt tracking system that disentangles the snow-derived water from rainfall-derived water in simulated surface and subsurface runoff fluxes, and accounts for the losses and exchanges from snowmelt before it flows into river channels. We perform our analysis over the contiguous U.S. west of 103°W, based on model runs for the period of 1960 to 2100. We evaluate the accuracy and uncertainty of our $f_{Q,\text{snow}}$ estimates from the tracking and analyze the impact of the future hydrologic cycle changes on regional water resource availability and their implications to effective water management in the future.

2. Methods

In this study, we used simulation results over the western U.S. from the Integrated Scenarios Project (ISP) described by *Gergel et al.* [2017] and archived as indicated in the Acknowledgments section. ISP simulated snow accumulation and ablation and other hydrologic processes across the western U.S. using the Variable Infiltration Capacity (VIC) model [*Liang et al.*, 1994]. ISP used downscaled and bias-corrected forcings to the VIC model taken from 10 global climate models (GCMs) archived for Phase 5 of the Coupled Model

Inter-comparison Project. The 10 GCMs included Hadley Centre Global Environmental Model version 2 (HadGEM2)-CC365, Beijing Climate Center Climate System Model version 1.1-M, Centre National de Recherches Météorologiques Coupled Global Climate Model version 5, Norwegian Earth System Model version 1, Institut Pierre-Simon Laplace-Climate Model version 5A-medium resolution, Canadian Earth System Model version 2, Commonwealth Scientific and Industrial Research Organisation Mark version 3. 6. 0, HadGEM2 Earth System 365, Model for Interdisciplinary Research on Climate version 5, and Community Climate System Model version 4. These 10 GCMs were selected from a larger group as having the best reproduction of historical storm track and other precipitation-related information along the U.S. west coast [*Rupp et al.*, 2013]. The output of each GCM was downscaled using the Multivariate Adaptive Constructed Analogs statistical method reported in *Abatzoglou and Brown* [2012] and was trained to the Livneh gridded surface observation data set [*Livneh et al.*, 2013] for bias correction. Downscaling and bias correction to the Livneh et al. data, and in turn simulation with the VIC model, resulted in 10 ensembles of simulated hydrologic variables over the West.

The VIC modeling in ISP was conducted at the same 1/16° (~6.5 km N-S) spatial resolution as in *Livneh et al.* [2013], at a 3 h time step. In the ISP archive, the 3 h hydrologic fluxes were aggregated to daily resolution, which we used. The VIC modeling includes a historical time period from 1950 to 2005 and a projected period, which was defined herein as the "future" period, from 2006 to 2100. For the future period, the hydrologic simulation was conducted in two climate change scenarios: Intergovernmental Panel on Climate Change Representative Concentration Pathway (RCP) 4.5 and RCP8.5. By the end of the 21st century, global mean temperature is projected to rise by 1.1°C to 2.6°C in RCP4.5 and by 2.6°C to 4.8°C in RCP8.5 [*Intergovernmental Panel on Climate Change*, 2014]. These two scenarios were selected partly because RCP4.5 represents an intermediate warming case, in which the temperature rise is consistent with the international goal of limiting the long-term temperature rise to 2°C, while RCP8.5 effectively represents "business as usual." It should be noted that the RCP8.5 scenario does not represent an upper boundary of the warming regime in the future; the real condition could be worse than business as usual, for example, if more countries develop or transition to more fossil fuel-dependent economies. It is also important to note that for the historical period, the 10 sets of ISP snow water equivalent (SWE) simulations are similar to those produced in the *Livneh et al.* [2013] data set in a statistical sense, but they do not match on a year-by-year basis, because the similarity in the historical past is only to global greenhouse gas emissions. We used this approach rather than using the archived SWE directly from *Livneh et al.* [2013] because the ensemble simulations provide a greater variability in conditions than is encapsulated in the (simulated) historical record.

Our snowmelt tracking algorithm calculates $f_{Q,\text{snow}}$ from the modeled hydrologic fluxes, meteorological model inputs, and water balance equations. The details of the derivation, validation and the uncertainty assessment of the tracking algorithm are included in sections S1–S3 in the supporting information. In general, the tracking algorithm traces moisture originating as snowmelt in the soil, surface water, and the atmosphere and accounts for the exchanges among the three. Snowmelt contributes to the total runoff in two ways: direct surface runoff and base flow. Since rainfall also contributes to the same quantities, the snowmelt tracker operates at every time step to disentangle the snow-derived runoff from total surface runoff and base flow and to calculate $f_{Q,\text{snow}}$. We conducted the tracking using an ensemble of the 10 VIC modeling outputs, and we report the mean of the 10 tracking results. We computed the historical $f_{Q,\text{snow}}$ from the modeling estimates from 1960 to 2005 and predicted the future $f_{Q,\text{snow}}$ using the modeling estimates from 2006 to 2100 for RCP4.5 and RCP8.5 scenarios. The model output from 1950 to 1960 was used to "spin up" the tracking calculations, and thus that period is not included in the long-term average. We evaluated only the mean contribution of snowmelt to runoff over the historical period 1960–2005 and a future period at the end of the 21st century (2080–2100); we did not assess the interannual variability of $f_{Q,\text{snow}}$ in the analysis.

To evaluate the contribution of snowmelt to runoff in the western U.S., we calculated weighted average $f_{Q,\text{snow}}$ for the entire region, for the mountainous areas, and for the drainage area of the largest reservoirs in the region, using the runoff at each pixel in the area as weights. The runoff includes both surface runoff and base flow. Since both $f_{Q,\text{snow}}$ and runoff are spatially variable, from the water resource point of view, an area with low $f_{Q,\text{snow}}$ and high runoff could yield more water and outweigh another area with high $f_{Q,\text{snow}}$ but low runoff. The runoff-weighted average $f_{Q,\text{snow}}$ thus allowed us to account for the spatial variability of runoff and to evaluate the actual amount of the snowmelt-derived water in different areas. Following the criteria of

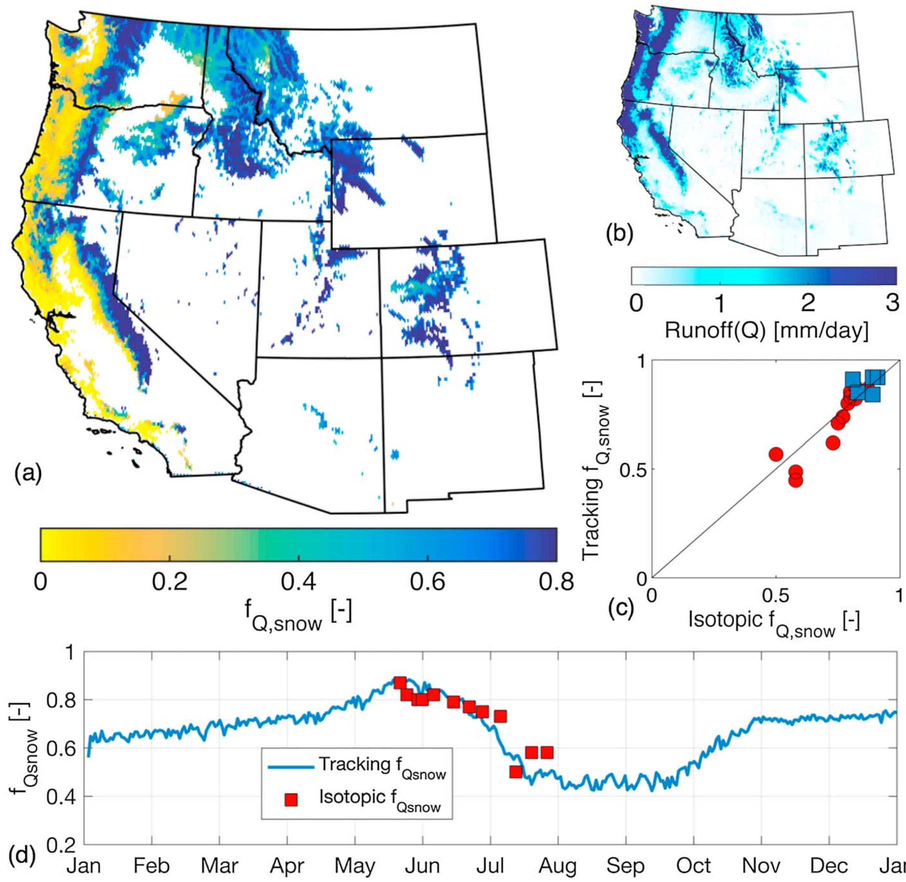

Figure 1. (a) Historical long-term average $f_{Q,\,snow}$; 25% of the area produces 90% of the total runoff across the western U.S.; values of $f_{Q,\,snow}$ are only shown for this subset of pixels. (b) Historical mean annual runoff over the western U.S. (c) The scatterplot shows the validation of the tracking $f_{Q,\,snow}$ against the $f_{Q,\,snow}$ from the isotopic measurements in the Rockies (red circles) and the Sierra Nevada (blue squares); the tracking $f_{Q,\,snow}$ has an overall root-mean-square error of 0.05. (d) The time series mean seasonal $f_{Q,\,snow}$ agrees well the isotopic $f_{Q,\,snow}$ measured during the melt season at Niwot, CO.

defining mountainous terrain in *Kapos et al.* [2000], we delineated the extent of the mountains in the western U.S. based on elevation, slope, and the magnitude of their spatial variabilities (details in section S5). The reservoir drainage areas discussed in section 3.1 were obtained through hydrologic analysis of GTOPO30 digital elevation model in ArcGIS (details in section S6); the boundaries of the drainage area from the delineations agree closely with the watershed boundaries in the U.S. Geological Survey (USGS) published 8-digit hydrologic unit data set (U.S. Geological Survey Watershed Boundary Dataset, https://water.usgs.gov/GIS/huc.html).

To increase the accuracy of the large-scale snow modeling, the VIC model performs a separate energy balance to model the snow accumulation and ablation on canopy and ground [*Andreadis et al.*, 2009]. Each 1/16° modeling grid cell is divided into up to five snow bands to capture the effects of the subgrid heterogeneity (e.g., elevation and land cover) on snow. *Feng et al.* [2008] found that with these model settings, the snow states from VIC predictions agreed well with those from other state-of-the-art snow models with higher complexity. In addition, the precipitation in the Livneh training data has been corrected for orographic effects, which improves the accuracy of both snow and runoff estimates, especially in mountain areas [*Livneh et al.*, 2013, 2015]; the combined application of the VIC model and the Livneh data is desirable for the macroscale snow and hydrologic estimates in this study. We evaluated the SWE simulated by the VIC model in comparison with a recent SWE reanalysis product [*Margulis et al.*, 2016a, 2016b]. We found that the peak SWE volume and the timing of the peak SWE from the VIC modeling agreed well with those calculated from the reanalysis SWE (see section S2.3).

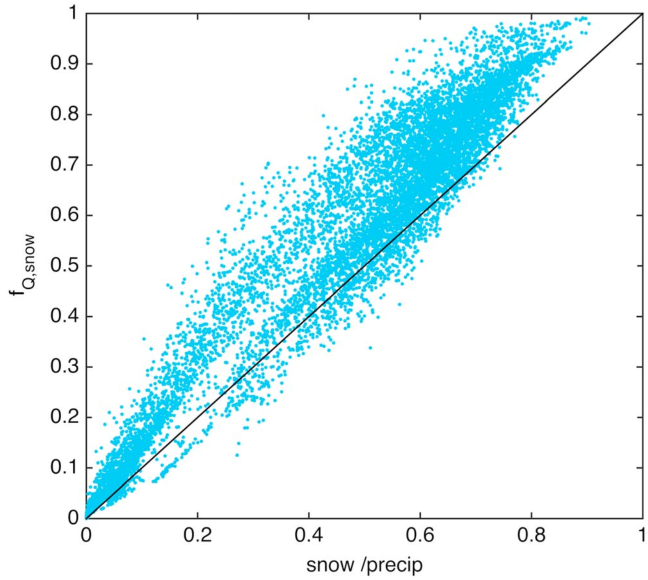

Figure 2. Comparison of historical $f_{Q,\mathrm{snow}}$ with the snowfall ratio (snowfall/precipitation) for the pixels that contribute to 90% of the runoff over the western U.S. The comparison indicates that (1) snowfall is more efficient than rainfall in runoff generation in the western U.S. and (2) hydrologic processes such as evaporation, infiltration, and sublimation significantly impact $f_{Q\,,\,\mathrm{snow}}$.

3. Results and Discussions

3.1. Historical Case

Across the West, we find that the long-term average $f_{Q\,,\,\mathrm{snow}}$ ranges from 0 to as much as 0.99, with higher values in mountainous regions and lower values along the coast (Figure 1). Runoff production is highly variable in space; 25% of the total area of the western U.S. (colored in Figure 1) produces 90% of total annual runoff on average. Across the western U.S., 53% of the total runoff on average is derived from snow, according to our estimates, despite the fact that snowfall makes up 37% of the total precipitation. In the mountainous regions of the western U.S. (as defined in section S5), 71% of the annual average runoff originates as snowmelt. In the Rockies, the Sierra Nevada, and the Cascades, snow comprises 74%, 73%, and 78% of the total annual average regional runoff, respectively. Although available snow isotope data in the western U.S. are scarce, we found $f_{Q\,,\,\mathrm{snow}}$ from snow isotope measurements for both maritime snow [*Huth et al.*, 2004] and continental snow [*Williams et al.*, 2009], which are broadly representative of two of the major types of snowpack in the western U.S. [*Sturm et al.*, 1995] We validated the $f_{Q\,,\,\mathrm{snow}}$ from the tracking through the comparison with the isotopically measured $f_{Q\,,\,\mathrm{snow}}$ (details in section S2.2). The overall root-mean-square error (RMSE) of the tracking $f_{Q\,,\,\mathrm{snow}}$ is 0.05, based on the in situ measured snow isotope data. The temporal pattern of the tracking $f_{Q\,,\,\mathrm{snow}}$ also agreed well with that of the isotopic $f_{Q\,,\,\mathrm{snow}}$ in the time series comparison.

Reservoir storage is critical for water supply, power generation, and the ecological balance of the downstream aquatic systems [*Adam et al.*, 2009; *Kapnick and Delworth*, 2013; *Barnett et al.*, 2005]. There are 2326 natural and artificial reservoirs in the western U.S., 21 of which have a storage capacity larger than 2 km^3; the integrated capacity of these 21 reservoirs is larger than that of the remaining 2300+ reservoirs of the region [*The National Inventory of Dams*, 2013]. We found that 67% of the storage in these largest 21 reservoirs is snowmelt-derived, and for the three largest reservoirs in the West, i.e., Lake Mead, Lake Powell, and Fort Peck Lake (which collectively have 30% of the total reservoir capacity in the western U.S.), 70% of storage is from snowmelt. The details and the $f_{Q\,,\,\mathrm{snow}}$ for the 21 largest reservoirs are summarized in section S6.

Figure 2 compares $f_{Q\,,\,\mathrm{snow}}$ with the ratio of snowfall to the total precipitation (snowfall ratio hereafter). Our results show that $f_{Q\,,\,\mathrm{snow}}$ is generally larger than the snowfall ratio, partly due to the loss of most summer rainfall to the atmosphere, as available energy is larger in spring and summer when rainfall dominates. Another explanation is that the magnitude and timing of typical snowmelt events more frequently overwhelm soil storage than do rainfall events [*Barnhart et al.*, 2016]. The results shown in Figure 2 imply that over the western U.S., snowfall is more efficient than rainfall in generating runoff, which is consistent with the conclusion of *Berghuijs et al.* [2014]. Given the same amount of rainfall and snowfall, snowfall generally leads to more seasonal runoff. Also, the comparison in Figure 2 has a relative RMSE of 28.7%; indicating the hydrologic processes such as evaporation, infiltration have a significant impact on the quantity of snowmelt that eventually transforms to runoff.

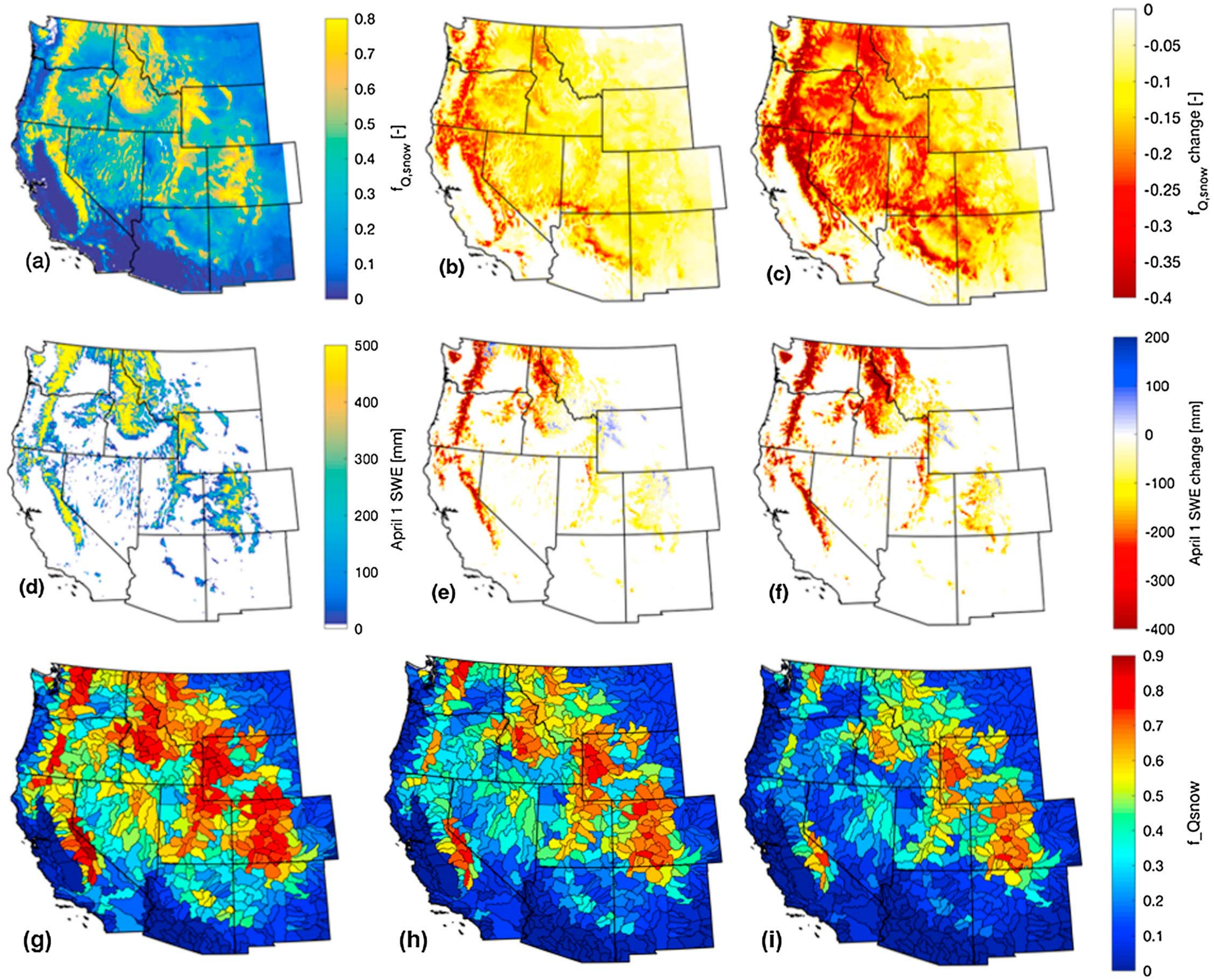

Figure 3. (a) Mean historical $f_{Q,snow}$ and $f_{Q,snow}$ changes in the (b) RCP4.5 and (c) RCP8.5 future climate scenarios across the western U.S. (d) Mean historical 1 April SWE and 1 April SWE changes in (e) RCP4.5 and (f) RCP8.5 scenarios. (g) The runoff-weighted average historical $f_{Q,snow}$ of each 8-digit hydrologic basin, and the future runoff-weighted average $f_{Q,snow}$ of each basin in the (h) RCP4.5 and (i) RCP8.5 scenarios.

3.2. Future Cases

Climate change will impact the future contribution of snow to runoff generation, and thus, regional runoff. Our simulations show that snow's contribution to runoff across the West will be reduced substantially in both RCP4.5 and RCP8.5 scenarios. As shown in Figure 3, by the end of the 21st century, $f_{Q,snow}$ across the entire western U.S. would fall from 53% to 39.5% and 30.4% in the RCP4.5 and RCP8.5 cases, respectively. For mountainous areas in the West, $f_{Q,snow}$ would fall from 71% to 57% and to 46%. In both scenarios, the largest $f_{Q,snow}$ decrease is in the Sierra Nevada and the Cascades, which are lower and warmer than the other western U.S. mountainous areas; the $f_{Q,snow}$ in the Sierra Nevada and the Cascades is predicted to decline from 73% to 38% and from 78% to 44% by 2100, respectively, for RCP8.5. Figure 3 also shows the average historical $f_{Q,snow}$ and future $f_{Q,snow}$ for the USGS 8-digit hydrologic units in the West. Those basins in the southern Cascades and the northern Sierra Nevada will experience the most significant snow water resource declines in the future. Although 1 April SWE does not, in general, correspond to annual maximum accumulation, it is a

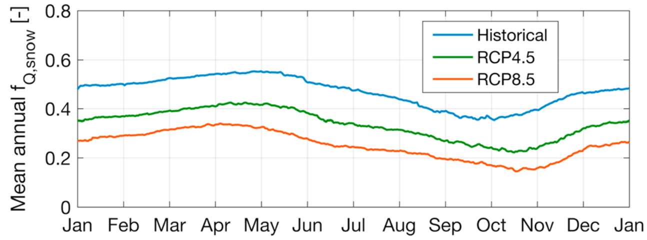

Figure 4. The mean seasonal $f_{Q,\text{snow}}$ for the historical case and the RCP4.5 and RCP8.5 future climate scenarios. The length of the period between the annual peak $f_{Q,\text{snow}}$ and the annual lowest $f_{Q,\text{snow}}$ is prolonged due to the warmer climate, which shifts the snowmelt earlier and delays the start of the snow season. The earlier snowmelt onset and the overall declines in snow accumulation reduce the amount of the available snow water resources on which large areas in the West depend for water supply.

commonly used climatic metric to infer the water availability in the succeeding summer and fall. Based on the modeling estimates, the total historical 1 April SWEs in the Sierra Nevada, the Cascades, and the Rockies are 22 km^3, 60 km^3, and 163 km^3, respectively. By 2100, in these mountain ranges the total 1 April SWEs will be reduced to 8 km^3, 25 km^3, and 89 km^3 in the RCP8.5 scenario, corresponding to a decrease of the historical 1 April SWE between 50% and 65%, in spite of increased total precipitation in many areas [e.g., *Howat and Tulaczyk*, 2005]. The future $f_{Q,\text{snow}}$ decrease in the Rockies is not as large as in the Sierra Nevada or the Cascades, because on average, snowpack accumulates at higher (and colder) areas in the Rockies than the other two mountain ranges; the iso-50%-$f_{Q,\text{snow}}$ line in the Sierra Nevada has a mean elevation of 1282 m, while in the Rockies the elevation of the iso-50%-$f_{Q,\text{snow}}$ line is at 1986 m. Our findings are consistent with other studies: snow at elevations lower than 2000 m is most sensitive to temperature increases [*Knowles and Cayan*, 2004; *Stewart et al.*, 2005; *Lundquist et al.*, 2004]. The future snow declines we project show significant "warm snow drought" characteristics, in the terminology of *Harpold et al.* [2017]. Based on our model forcings and output, it is clear that while total future precipitation is close to historical values, a substantial portion of the winter precipitation transitions from snow to rain in the low and middle elevations of those areas that historically have accumulated substantial winter snowpacks. This snow-to-rain transition is noticeable especially in the northern Sierra Nevada and in the Cascades, the lowest elevation portions of our mountainous domain. Maps of watershed-wide runoff-weighted average historical $f_{Q,\text{snow}}$ and the future $f_{Q,\text{snow}}$ over the West in Figure 3 show that the largest $f_{Q,\text{snow}}$ decreases will occur in the Sacramento-San Joaquin basins, which are a major water source for the 25 million California residents living downstream and for the 3 million acres of agriculture land in the Central Valley which produces two thirds of fruits and nuts and one third of vegetables for the entire country [*California Agricultural Exports*, 2015–2016].

Snow plays a key role in sustaining dry season runoff in the western U.S. In the areas that contribute 90% of the West's total runoff, the historical mean $f_{Q,\text{snow}}$ from July to October is 41%. This ratio is projected to decrease to 28% and 20% by 2100 in the RCP4.5 and RCP8.5 scenarios, respectively (details in section S7). The most significant dry-season $f_{Q,\text{snow}}$ decrease occurs also for the Cascades and the Sierra Nevada (Figure S6 in the supporting information), which have strongly winter-dominant precipitation. The decrease in the fraction of the snow-derived runoff in the dry season is a combined effect of declining snow storage and a prolonged dry season, which results from warmer temperatures melting the snow earlier and delaying winter snowfall events. Figure 4 shows that historically, the average $f_{Q,\text{snow}}$ across the western U.S. peaks around 2 May. By the end of the 21st century, the peak $f_{Q,\text{snow}}$ shifts earlier by 1.5 weeks in RCP4.5 scenario and by 4 weeks in the RCP8.5 scenario. The $f_{Q,\text{snow}}$ increases after its seasonal low in late fall, indicating that the snow-released water replenishes the runoff and starts to alleviate the low flow of the dry season. At the end of the 21st century, the lowest $f_{Q,\text{snow}}$ is projected to be delayed by around 2 weeks and 4 weeks in the RCP4.5 and RCP8.5 scenarios relative to the lowest seasonal $f_{Q,\text{snow}}$ in the historical case. Since the western U.S. heavily relies on snowmelt stored in reservoirs to meet demands for water in the low flow season, reduced spring snowpack and earlier melt onset will likely put significant pressure on water supply in the late summer and fall.

4. Conclusion

We quantified the contribution of snowmelt to the total runoff over the western U.S. in the past and in the future. We found that from 1960 to 2005, snowmelt accounted for 53% of the total runoff over the entire West. For the three major mountain ranges in the western U.S., i.e., the Rockies, the Sierra Nevada, and the

Cascades, snow comprises 74%, 73%, and 78% of the total regional runoff, respectively. Snow's contribution to the total runoff will decrease in the future. By 2100, the snow-derived runoff in the total runoff across the entire western U.S. is projected to decline from 53% to 39.5% and 30.4% in the RCP4.5 and RCP8.5 cases, respectively. For streams draining the major mountain ranges of the West, the overall contribution of snow will fall from 71% in the historical case to 57% in the RCP4.5 scenario and to 45% in the RCP8.5 scenario.

Taken together, our analysis sheds light on expected future runoff and water supply changes over the western U.S. in a warming climate. Future runoff will be driven more by rainfall than snowmelt. On average, snowmelt produces more runoff than does rainfall. Thus, future runoff across the western U.S. is expected to decrease, though a thorough description of this decrease is outside the scope of this manuscript. Snowmelt-derived runoff is stored and redistributed by reservoirs and is essential to meeting the peak water demands for the regions' major population centers, irrigation, power generation, recreation, and fisheries populations in the following summer and fall. A decrease of the total snow storage in winter and the reduced contribution of snow to runoff would likely exacerbate the dry-season water scarcity in the future. In addition, the earlier snowmelt will strain storage capacity of the hydrologic infrastructure and further reduce the water availability in the prolonged dry season. We predict a reduced role of snowmelt in producing western U.S. runoff in the future. Indeed, future runoff is also affected by other factors in addition to snow, such as land surface and land use changes, CO_2 fertilization, water use efficiency, and water policy. However, due to the profound reliance on snow as water resources, future declines in snow accumulations in the West will pose a first-order threat directly on the regional water supply, especially in the late summer and fall when water demands peaks. All these factors potentially have significant impact on regional water supply.

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