AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL075421

Key Points:
- Climate change interacts with land surface properties to affect the amount of recharge that occurs in the future
- Southern portions of the western U.S. are expected to get less and northern portions more recharge in the future
- The large variability in projected recharge across the GCMs is associated with variability in projected precipitation

Supporting Information:
- Supporting Information S1

Correspondence to:
R. Niraula,
rewatin@email.arizona.edu

Citation:
Niraula, R., Meixner, T., Dominguez, F., Bhattarai, N., Rodell, M., Ajami, H., Gochis, D., & Castro, C. (2017). How might recharge change under projected climate change in the western U.S.?. *Geophysical Research Letters*, *44*. https://doi.org/10.1002/2017GL075421

Received 24 AUG 2017
Accepted 12 OCT 2017
Accepted article online 16 OCT 2017

How Might Recharge Change Under Projected Climate Change in the Western U.S.?

R. Niraula[1], T. Meixner[1], F. Dominguez[2], N. Bhattarai[3], M. Rodell[4], H. Ajami[5], D. Gochis[6], and C. Castro[1]

[1]Department of Hydrology and Atmospheric Sciences, University of Arizona, Tucson, AZ, USA, [2]Department of Atmospheric Sciences, University of Illinois, Urbana, IL, USA, [3]School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, USA, [4]Hydrological Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD, USA, [5]Environmental Sciences, University of California, Riverside, CA, USA, [6]NCAR HR Regional Modelling, Boulder, CO, USA

Abstract Although groundwater is a major water resource in the western U.S., little research has been done on the impacts of climate change on groundwater storage and recharge in the West. Here we assess the impact of projected changes in climate on groundwater recharge in the near (2021–2050) and far (2071–2100) future across the western U.S. Variable Infiltration Capacity model was run with RCP 6.0 forcing from 11 global climate models and "subsurface runoff" output was considered as recharge. Recharge is expected to decrease in the West (−5.8 ± 14.3%) and Southwest (−4.0 ± 6.7%) regions in the near future and in the South region (−9.5 ± 24.3%) in the far future. The Northern Rockies region is expected to get more recharge in the near (+5.3 ± 9.2%) and far (+11.8 ± 12.3%) future. Overall, southern portions of the western U.S. are expected to get less recharge in the future and northern portions will get more. Climate change interacts with land surface properties to affect the amount of recharge that occurs in the future. Effects on recharge due to change in vegetation response from projected changes in climate and CO_2 concentration, though important, are not considered in this study.

1. Introduction

Climate change is projected to reduce renewable surface water and groundwater resources in most dry subtropical regions and other already arid regions, intensifying competition for water among sectors (Intergovernmental Panel on Climate Change, IPCC, 2014). The strategic importance of groundwater for global water and food security will likely intensify under climate change as more frequent and intense climate extremes (droughts and floods) result in increased variability in precipitation, soil moisture, and surface water (Taylor et al., 2013).

Climate variability and change influences groundwater systems both directly through replenishment by recharge (Green et al., 2011; Stonestorm et al., 2007) and indirectly through changes in groundwater use with changes in water demands. Climate change and variability have numerous effects on recharge rates and mechanisms (Aguilera & Murillo, 2009; Green et al., 2011; Kundzewicz et al., 2007; Vaccaro, 1992). Many climate change studies have predicted reduced recharge (e.g., Herrera-Pantoja & Hiscock, 2008). However, the effects of climate change on recharge may not necessarily be negative or decrease in all regions over the world (Döll, 2009; Gurdak & Roe, 2010; Jyrkama & Sykes, 2007). Groundwater recharge is projected to increase in northern latitudes, but recharge is projected to decrease strongly, by 30–70% or even more than 70%, in some currently semiarid zones (Döll & Fiedler, 2008).

Groundwater withdrawals represent 25% of total freshwater withdrawals in the U.S. (Maupin et al., 2014). It is the source of drinking water for 50% of the population and as much as 90% of the population in rural areas, especially in the western U.S. (Anderson & Woosley, 2005). Reduced reliability of surface water supplies in the western U.S. with projected increases in evaporative demand and uncertain changes in annual precipitation (Rasmussen et al., 2011, 2014) may increase groundwater use (Scanlon et al., 2005). Many areas of the western U.S. are already experiencing groundwater depletion caused by sustained groundwater pumping (Castle et al., 2014; Faunt, 2009; Konikow, 2013). Recharge from precipitation is the major source of groundwater replenishment. However, research efforts on the impacts of climate change on water resources have focused predominantly on surface water systems (Overpeck & Udall, 2010; Seager et al., 2013; Vano et al., 2014) with limited studies on groundwater recharge projections (Meixner et al., 2016).

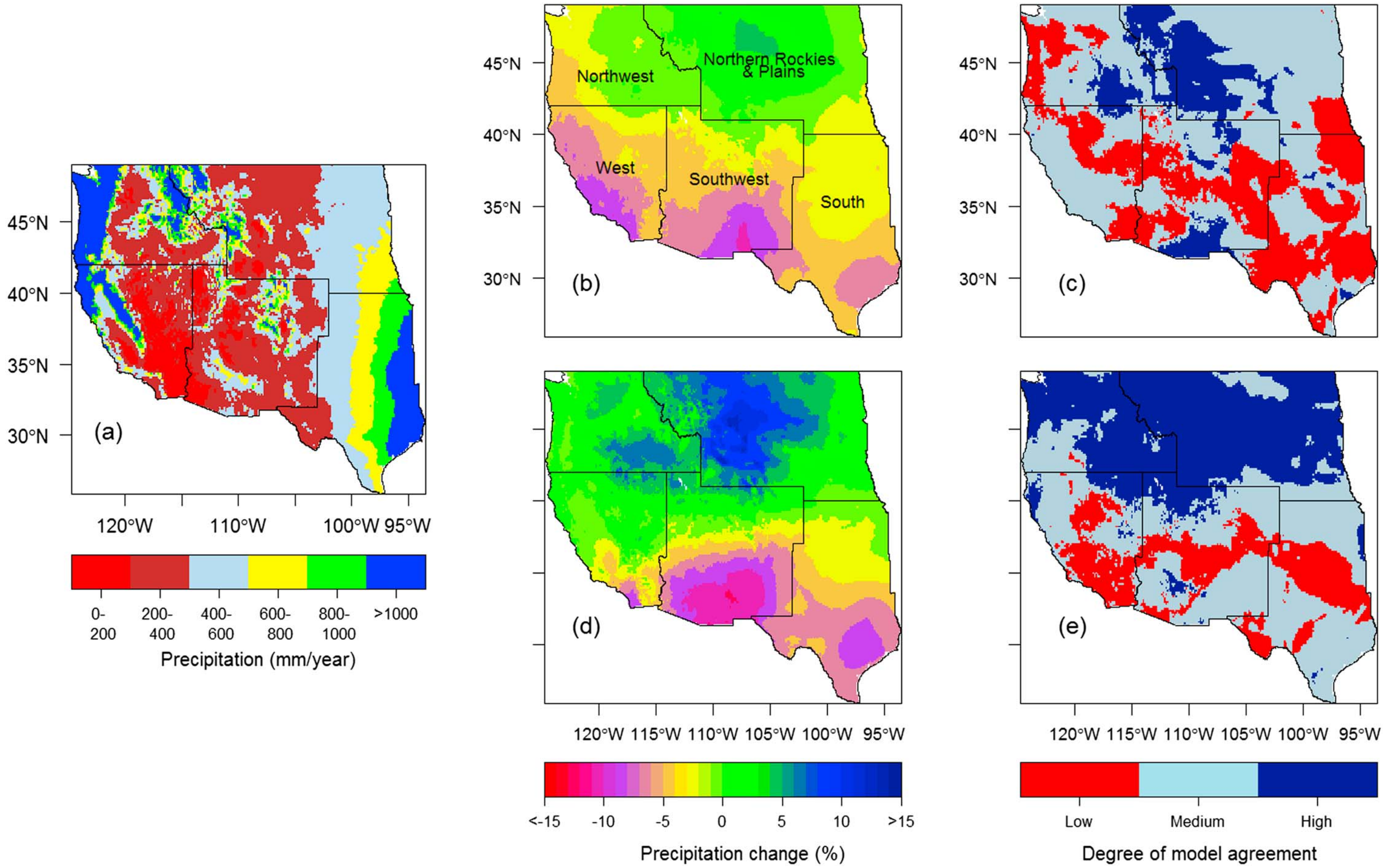

Figure 1. (a) Historic precipitation and relative change in precipitation for the (b) near and (c) far future compared to historic period along with the degree of agreement in the direction of those changes for the (d) near and (e) far future.

Groundwater is often relied upon to make up for shortfalls in surface water resources during times of drought (Dettinger & Earman, 2007). Although there are some local studies for individual basins (Ajami et al., 2012; Anderson et al., 1992; Crosbie et al., 2013; Flint & Flint, 2014; Serrat-Capdevila et al., 2007; Vacarro, 1992), the cumulative effect of climate change on recharge over the western U.S. is not well understood. It is unknown whether overall recharge will increase, decrease, or stay the same in the western U.S. (Dettinger & Earman, 2007). Thus, efforts to estimate potential recharges under projected climate change are needed throughout the western U.S. Since groundwater recharge projections are closely related to highly uncertain projected changes in climate (Bates et al., 2008; Cook & Seager, 2013; Crosbie et al., 2011, 2012, 2013; IPCC, 2014; Taylor et al., 2013), it is important to analyze multiple GCMs when projecting recharge associated with climate change.

Considering that past climate changes significantly impacted groundwater resources (McMahon et al., 2006; Scanlon et al., 2012) and have the potential for more impacts in the future, quantitative predictions of climate change on groundwater recharge may be valuable for effective management of water resources (Crosbie et al., 2013) in the western U.S. Although recharge is a local process, how it is affected by climate change in different environmental settings is better understood through regional studies and provides an opportunity for integrated regional groundwater management in conjunction with available surface water resources (Gorelick & Zheng, 2015). Thus with this study, we attempt to address the following two questions:

1. What is the effect of projected climate change on average annual groundwater recharge in the western U.S.?
2. How does the effect of climate change on recharge vary across the different hydro-climatic regions (South, Southwest, West, Northwest, and Northern Rockies, and Plains; Figure 1)?

2. Methods

2.1. Background on the Western U.S.

The western U.S. (Figure 1), which covers more than half of the land area of the contiguous U.S., is geographically and climatically diverse. Parts of the region receive high amounts of precipitation (~5,000 mm), and other parts are true deserts and receive little precipitation (~58 mm/yr). With high topographic variability (elevation varies between −86 m and 4402 m), the western U.S. is composed of grassland or shrubland (59%), forest (28.1%), agriculture (6.3%), developed (1.5%), and barren (1.9%) lands (Sleeter et al., 2012).

2.2. Sources of Hydrologic Projections From Previous Models

For projecting changes in recharge from future climate change, we used "subsurface runoff" (drainage from the bottom layer) outputs from the Variable Infiltration Capacity (VIC; Liang et al., 1994, Text S1 in the supporting information) model which have been archived by the Bureau of Reclamation (Reclamation, 2014). These simulations are based on Coupled Model Inter-comparison Project Phase 5 (CMIP5) climate projections that were first downscaled into localized climate projections (at grid scales of 1/8°, ~12 km on a side) across the contiguous U.S. using the Bias-Correction and Spatial Disaggregation (BCSD) technique (Wood et al., 2002) and then translated into hydrologic projections over the contiguous U.S. using the VIC model. Through an examination of the dynamics of observed groundwater storage, Li et al. (2015) showed that subsurface runoff simulated by VIC is a suitable substitute for recharge data.

The VIC model has been widely used in climate change impact and hydrologic variability studies (Beyene et al., 2009; Cuo et al., 2009; Hamlet & Lettenmaier, 1999; Lee et al., 2015; Leng et al., 2015; Nijssen et al., 2001; Munoz-Arriola et al., 2009; Parr et al., 2015). Previously, the VIC was found to make reasonable estimates of recharge in the western U.S. (Niraula et al., 2016) and Northeastern U.S. (Li et al., 2015).

Outputs from RCP 6.0 emission scenario-based predictions were selected for this study since this scenario is consistent with the application of a current range of technologies and strategies for reducing greenhouse gas emissions (IPCC, 2014). Outputs from 11 GCMs *(BCC-CSM1-1, CCSM4, CESM1-CAM5, CSIRO-MK3-6-0, FIO-ESM, GFDL-ESM2M, GISS-E2-R, HADGEM2-ES, IPSL-CM5A-MR, MIROC5,* and *NorESM1-M*; Text S2 and Table S1) for this scenario were selected based on data availability and analyzed to incorporate the uncertainty associated with climate and recharge projections. Recharge estimates for the near future (2031–2050) and the far future (2071–2100) are compared with the baseline recharge estimates of the recent past (1971–2000). For these projections, the VIC model was run at a 0.125° spatial resolution at a daily temporal scale.

2.3. Relative Change and Uncertainty Analysis:

Using historical (1971–2000) recharge from VIC as the base scenario (Figure 2a), estimates of relative changes in recharge (mean ± standard deviation, SD) were made at each grid location over the western U.S. for the near (2021–2050) and far (2071–2100) future. The uncertainty analysis on directions and magnitude of those relative changes is then analyzed for each grid based on the number of models that agree on the direction of change and the direction and magnitude of mean ensemble change. In this study, we considered the model agreement on the direction of change to be "high" if $>$80% of the models agree ($>$8 out of 11 models in this study), "medium" if 60%–80% of the models agree (7–8 out of 11), and "low" if $<$60% of the models agree ($<$7 out of 11) on the direction of mean ensemble change. Furthermore, to understand how much recharge (R) variance is explained by changes in precipitation (P) and temperature (T), we employed a partial least squares regression (PLSR) on the percent changes in R using percent changes in P and T as explanatory variables. By using regression on the percentage differences (both in NF and FF periods), we aimed to control for unobserved biases from all time invariant factors that may have influence on R and allow us to attribute the amount of R variability not explained by P and T combined.

3. Results and Discussions

3.1. Baseline (1971–2000) Recharge Estimates

Over the whole domain, the average annual R (Figure 3a) is estimated to be 83 mm/yr (15% of P, Table 1) and ranged between 0 mm/yr and 2291 mm/yr. The average baseline recharge is estimated to be the lowest in the Southwest (27 mm/yr) and highest for the Northwest (256 mm/yr) region (Table 1). Relatively higher evapotranspiration (ET) in the South, Southwest, and the Northern Rockies resulted in

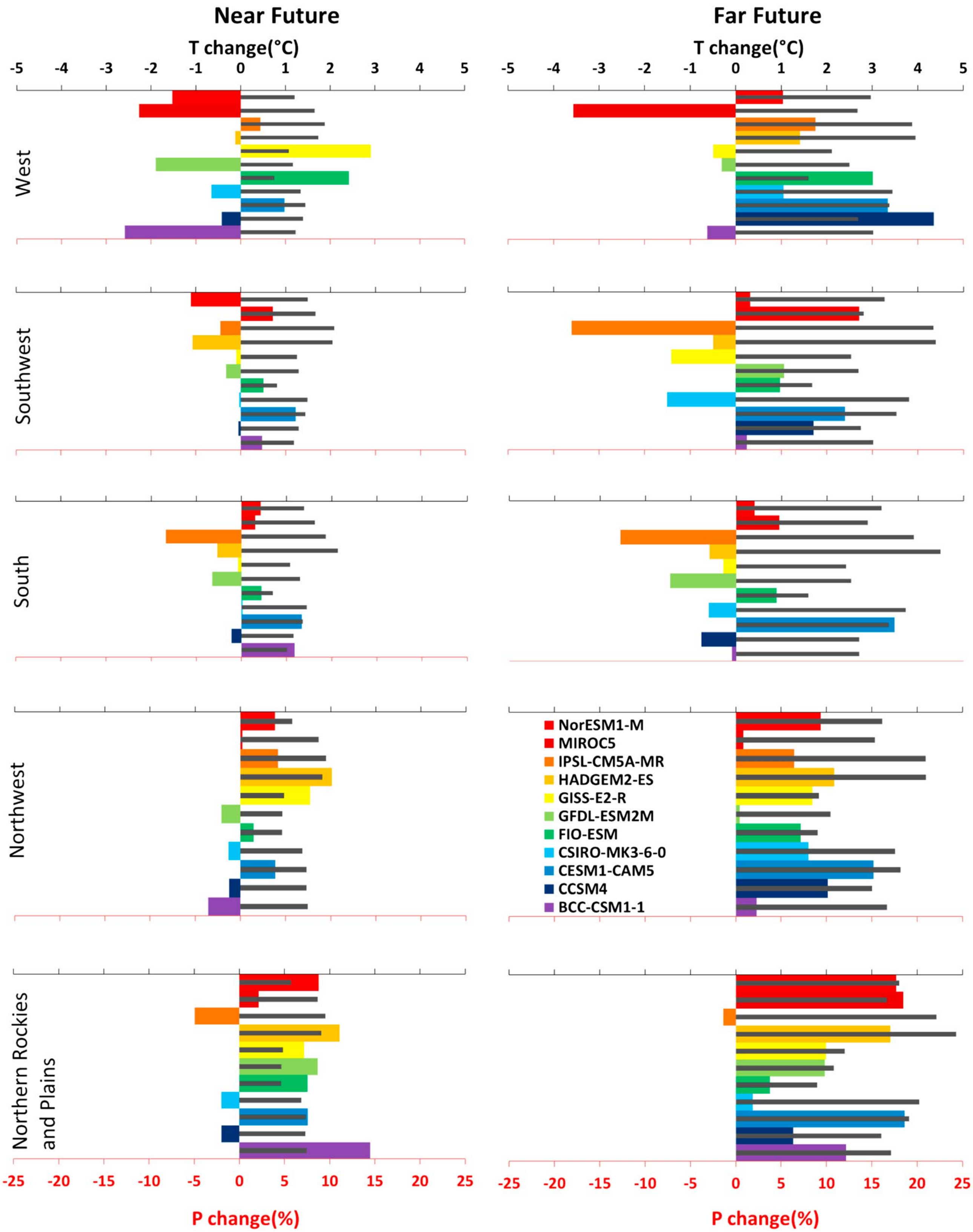

Figure 2. Variability in the relative changes in climate (*P* and *T*) due to GCMs for five climatic regions in the western U.S. in (left column) near and (right column) far future. Each color-coded bar represents the relative change in precipitation based on the GCMs, and the overlying gray bars represent the change in temperature associated with the particular GCMs.

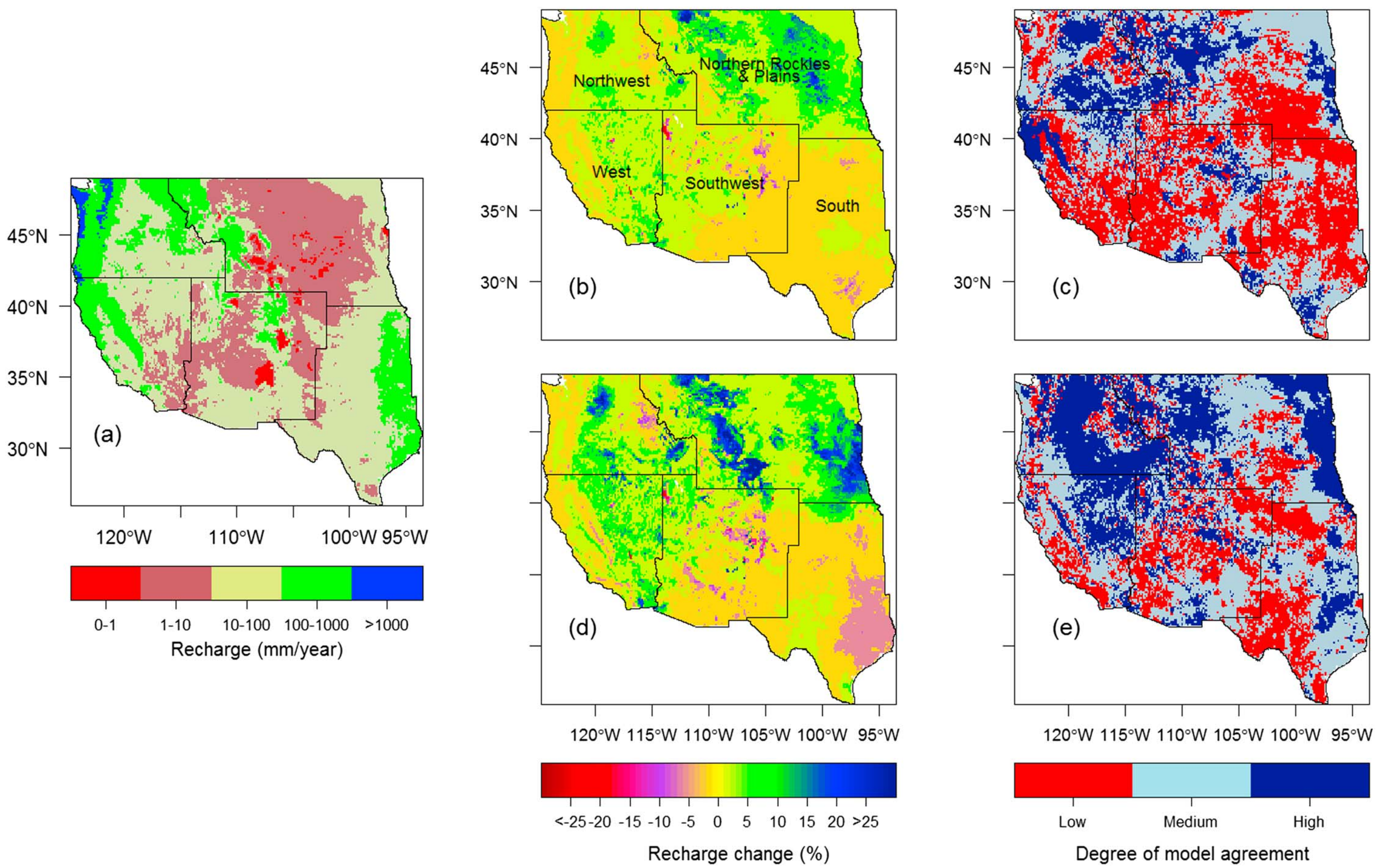

Figure 3. (a) Historical recharge, ensemble average relative change in recharge for the (b) near and (c) far future compared to historic period along with the degree of agreement in the direction of those changes for the (d) near and (e) far future.

lower recharge ratios (*R*/*P*) (≤9%) in these regions (Table 1). The soils of the Rocky Mountains are minimally permeable and thus resulted in minimal recharge.

3.2. Projected Changes in Climate

3.2.1. Projected Change in Ensemble Mean Climate

Average *P* is expected to increase in some locations and decrease in others, with a slight increase when averaged over the domain (+1.6 ± 2.9% and +4.7 ± 5.1% in the near and far future, respectively). In general, *P* is expected to decrease in southern and increase in northern portions of the study area (Figure 1). The winter jet stream and storm track are expected to move northward, resulting in more precipitation north of approximately 40° latitude and less precipitation south of this latitude (Dominguez et al., 2012). Higher change and higher variability in *P* is expected for the far future compared to the near future (Figure 1) which is minimal (<2.1 ± 4.3%) for all the regions except for the Northern Rockies and Plains (+5.3 ± 4.3%) (Table 1). The change in *P* is expected to be minimal for the South (−0.3 ± 7.7%) and maximum for the Northern Rockies and Plains (+10.4 ± 7.1%) for the far future (Table 1). It should be noted that SD > mean in most of the changes in *P* is due to large variability in the projected *P* changes among the models. *P* will increase in the Northern Rockies and Plains for both the near and far future (high agreement, Figures 1 and 2). *P* is also expected to increase in the Northwest region for the near future (medium agreement) and far future (high agreement). However, *P* will decrease in near future and increase in far future (Figure 1) for the West and Southwest regions (medium agreement).

The average *T* is expected to increase (high agreement) in both the near (1.4 ± 0.4°C) and far future (3.2 ± 0.8°C) throughout the western U.S. (Table 1) but vary spatially. While slightly higher increases in *T* are projected for the Northern Rockies, slightly lower *T* increases are projected for the West region (Table 1).

Table 1
Current Conditions of Climate and Recharge, and Projected Change in Climate and Recharge in the Western U.S.

	Current conditions				Projected climate change (mean ± SD)				Projected recharge change (mean ± SD)			
Region	*P* (mm)	Recharge (mm)	*T* (°C)	Recharge ratio (%)	% *P* change (NF)	% *P* change (FF)	*T* change (°C) (NF)	*T* change (°C) (FF)	% (mm) change (NF)	Degree of Agreeme-nt	% (mm) change (FF)	Degree of Agreement
W	457	103	11.7	23	−1.2 ± 9.1	5.0 ± 11.1	1.4 ± 0.3	2.9 ± 0.7	−5.8 ± 14.3 (−6.0 ± 14.7)	High	−0.2 ± 16.1 (−0.2 ± 16.6)	Low
SW	372	27	10.6	8	−0.1 ± 3.6	1.1 ± 9.4	1.5 ± 0.4	3.2 ± 0.8	−4.0 ± 6.7 (−1.1 ± 1.8)	High	−4.4 ± 13.0 (−1.2 ± 3.5)	Medium
S	732	61	16.7	8	0.3 ± 4.2	−0.3 ± 7.7	1.4 ± 0.4	3.0 ± 0.8	−1.5 ± 16.5 (−0.9 ± 10.1)	Low	−9.5 ± 24.3 (−5.8 ± 14.8)	High
NW	881	256	6.4	29	2.1 ± 4.3	7.2 ± 4.5	1.4 ± 0.4	3.1 ± 0.9	−1.8 ± 6.5 (−4.6 ± 16.6)	Low	−0.7 ± 16.4 (−1.8 ± 42.0)	Low
NR	481	43	6	9	5.3 ± 4.3	10.4 ± 7.1	1.5 ± 0.4	3.4 ± 0.9	5.3 ± 9.2 (2.3 ± 4.0)	High	11.8 ± 12.3 (5.1 ± 5.3)	High

Note. W: West, SW: Southwest, S: South, NW: Northwest, NR: Northern Rockies and plains, NF: near future, and FF: far future.

3.2.2. Variability in Projected Climate Change (*P* and *T*) Across GCMs

While all models (11 GCMs) projected increased mean annual *T* throughout the regions, there was inconsistency in mean annual *P* projections with some showing increased *P* and some showing decreased *P* (Figure 2). The majority of the GCMs projected increased *P* for the Northern Rockies and Plains for both the near (8 GCMs) and far (10 GCMs) future (Figure 2). While a majority of the models (9 GCMs) projected increase *P* in the Northwest region for the near future, all (11 GCMs) projected increased *P* for the far future (Figure 2). More GCMs (seven GCMs) projected a decrease in *P* in the near future and increase in *P* for the far future for the West and Southwest regions (Figure 2). Although *P* was highly variable among models, *T* was less variable. Projected *P* was most variable in the West region for both near (−12.9% to +14.5%) and far future (−17.8% to +21.7%). *T* increase varied between 0.7°C and 2.2°C for near future and between 1.6°C and 4.4°C among the models across the defined regions.

3.3. Projected Change in Mean Annual Recharge

3.3.1. Ensemble Mean Recharge Change

The relative increase in recharge may be as high as 94% and the decrease will be as much as 50% for the near future (Figure 3) at a grid scale. For the far future the change will be more substantial (−90% to >100%) depending on location (Figure 3).

For the near future, the model ensemble estimated average recharge decrease by 5.8 ± 14.3%, 4.0 ± 6.7%, 1.5 ± 16.5%, and 1.8 ± 6.5% in the West (high agreement), Southwest (high agreement), South (low agreement), and Northwest (low agreement), respectively (Table 1). Similarly for the far future, the model ensemble average estimated average recharge to decrease by 4.4 ± 13.0% in the Southwest (medium agreement) and 9.5 ± 24.3% in the South (high agreement) regions (Table 1). The ensemble models, however, estimated an increased recharge (high agreement) in the Northern Rockies and Plains for both near (+5.3 ± 9.2%) and far future (+11.8 ± 12.3%). The average recharge is predicted to remain fairly constant in the West region in the near future (0.2 ± 16.1%; low agreement) and in the Northwest region in the far future (−0.7 ± 16.4%; low agreement, Table 1). As with the case with *P*, SD > mean in most of the changes is recharge is due to large variability in the projected recharge changes among the models. The average annual change in depth of recharge varied from −6.0 mm to 2.3 mm in near future, and from −5.8 mm to 5.1 mm in far future (Table 1).

Although the change in *P* is minimal (Figure 2 and Table 1) in the far future in the South and Southwest regions, a large increase in *T* (Figure 1 and Table 1) in these regions will cause ET to increase considerably and reduce soil moisture making the soil profile much drier, thereby reducing recharge (Figure 4 and Table 1). The projected increase in recharge

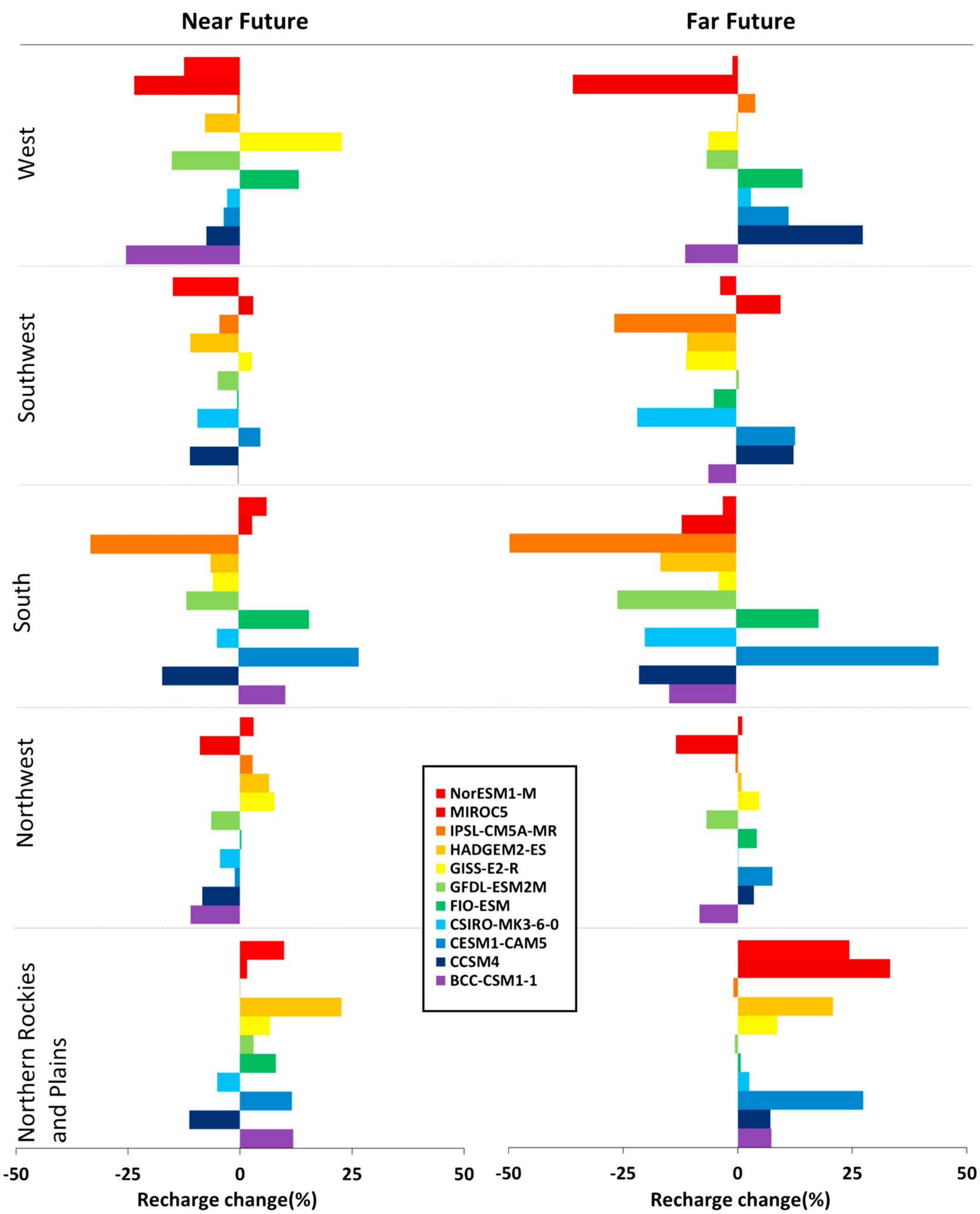

Figure 4. Variability in the relative changes in recharge due to GCMs for five climatic regions in the western U.S. in (left column) near and (right column) far future. Each color coded bar represents the relative change in recharge based on the GCMs.

(Figure 3 and Table 1) is similar to the projected increase in *P* (Figure 1) in the future for the Northern Rockies and Plains, where (particularly in the Northern Rockies) recharge is more controlled by aquifer properties than the climate, limiting recharge due to relatively impermeable rock formations. Although, there will be a slight decrease in recharge in the West in near future (Figure 3 and Table 1), there will be limited change in recharge in the far future (Figure 3 and Table 1). While a slight decrease in *P* and slight increase in *T* resulted in decreased recharge in the near future, the moderate increase in *P* in the far future was offset by a higher increase in *T*. A limited change in recharge is expected for the Northwest region (Figure 3 and Table 1) because some increase in precipitation for this region is offset by increased ET due to increased *T* in the future.

3.3.2. Variability in Projected Annual Recharge Across GCMs

A majority of the VIC simulations projected increased recharge in the Northern Rockies and Plains (nine GCMs) and decreased recharge in the West (GCMs) and Southwest (GCMs) regions (Figure 4) in the near future although the amount of change vary based on GCMs (Figure 4). More models (six GCMs) projected decreased recharge in the South and Northwest regions (Figure 4). The change in recharge is projected to be greatest and highly variable among GCMs for the West (−25.5% to +22.7%) and South (−33.1% to +26.8%) regions in the near future (Figure 4).

A majority of the models projected increases in recharge in the Northern Rockies and Plains (nine GCMs) and decreases in recharge for the South (nine GCMs) in the far future (Figure 4). More models projected decreased recharge in the Southwest (seven GCMs) and West (six GCMs), and increased recharge in the Northwest (seven GCMs) regions. The change in recharge is projected to be greatest and highly variable for the South (−49.4% to +44.1%) and West (−36% to +27.3%) regions in the far future (Figure 4).

Although more models projected increases in precipitation over the region (Figure 2), more models projected decreases in recharge (Figure 4). This result was primarily due to the offset effect of consistent increased temperature (Figure 2) which caused the decrease in recharge through greater increases in evapotranspiration even though there was an increase in precipitation. The properties of land surface (viz., soil properties) also have a role in the decreased recharge. Due to high evaporation loss from soil, the land surface becomes drier and needs more water to saturate the soil before draining from the bottom layer to become recharge. The recharge is primarily related to hydraulic conductivity of the bottom layer, which is a nonlinear function of soil moisture content.

3.4. Comparing the Findings of This Study With the Existing Literature

Recent studies have demonstrated the varied impact of climate change in groundwater recharge in western U.S. Döll and Fiedler (2008) projected an increase in potential recharge of more than 30% in the western U.S., acknowledging that this higher change could be the results of very low baseline recharge rates in many regions and also indicated that recharge is unlikely to decrease by more than 10% until the 2050s (Döll, 2009) in most of the region. Our findings are also consistent with these studies in terms of estimates of projected change in recharge (within 30%) at the regional scale. In addition, our results also indicated that although the changes could be higher at local scale, the changes would be mild at the regional scale. In a study of the High Plains Aquifer, Crosbie et al. (2013) projected increases in recharge in the northern high plains (+8%), and decreases in the central (−3%) and southern High Plains (−8%). Our study also shows a significant decrease in recharge in the southern portion of the High Plains. Based on a synthesis study of aquifers in western U.S., Meixner et al. (2016) estimated average declines of 10–20% in total recharge across the southern aquifers of the western U.S., but with a wide range of uncertainty, and also predicted that the northern aquifers will likely incur little change to slight increases in total recharge. Our study supported and verified the findings of this study with more detailed modeling across the western U.S. and provides more quantitative information. Overall, these findings across the western U.S. suggest that recharge will increase or decrease depending upon the location and projected changes in climate consistent with the findings from our study.

3.5. Uncertainty in Projections

It should be noted that there is uncertainty associated with the recharge projections made in this paper in response to the uncertainties in P and T estimates from different models as well as other factors that are not considered in these models. When a PLSR was conducted on the spatial mean values of percent difference in R using percent changes in P and T as explanatory variables, we find that overall 71% and 72% variations in changes in R were explained by the percent changes in P and T in the near and far future, respectively. We note that percent change in P only explained about 70% and 72% (near far and far future, respectively) variations in percent changes in R with a significant positive correlation, while change in percent change in T explained less than 1% of variations in R. This explains the importance of climate (particularly P) projections in improving recharge projections in future. Hence, about 28%–29% variations in changes in R is not explained by P and T, which could be attributed to other factors that are not controlled in these models. For example, the timing of precipitation and the form of precipitation in the majority of high recharge areas in the snow-dominated West are not well captured in the VIC model that uses global climate projections for climate inputs. In addition, the change in land cover types and its impact on evapotranspiration is not considered, as static vegetative conditions are assumed in these models. Over the study area, the degree of model agreement was medium to high in the direction of projected recharge changes in 60% and 72% of the region for near future and far future, respectively.

Studies (Castro et al., 2012; Dominguez et al., 2012) have suggested that while these models can provide a rough estimate of climate at a coarse spatial resolution, there are more uncertainties at the local and regional scales, than the ones found in our study (Castro et al., 2012; Dominguez et al., 2012), and thus, the use of dynamical downscaling techniques to increase the spatial resolution and reduce potential uncertainties is recommended. The statistically downscaled data which were used in this study, however, have limitations capturing seasonal and interannual variability across the region compared to dynamically downscaled projections, which are just becoming available but are cost intensive (Castro et al., 2012; Hanson et al., 2012). In addition, it has been recognized that it is difficult to capture the monsoon with current GCMs even with appropriate downscaling, and thus, there is a large uncertainty in projections especially during the summer (Dominguez et al., 2012).

3.6. Limitations of the Study

Recharge is a complex process that is affected by the properties of land, vegetation, soil, climate, and human activities. In this study, we focused on the effects of climate (viz., *P* and *T*) exclusively on recharge. Change in climate (viz., *P* and *T*) can bring changes in all these other aspects of the environments that can influence the recharge rate and process individually and synergistically, which are not included in this study. For example, the use of static vegetation cannot consider the consequence of climate-induced change on vegetation structure and dynamics (Cramer et al., 2001), which can eventually affect evapotranspiration and recharge. Similarly, the possible offsetting effect of reduced plant transpiration due to higher CO_2 concentrations in the atmosphere (Cramer et al., 2001; Morison, 1987) is an important issue to be considered. Effects on recharge due to change in vegetation response (as discussed above) from projected climate change was beyond the scope of this study but could be an interesting and important aspect to be considered in future studies. Human activities such as irrigation and pumping can have a significant effect on recharge but are complex to incorporate (Meixner et al., 2016; Steward et al., 2013) in large-scale models. Other processes like water temperature change from increasing temperature and changes in the soil characteristics like hydraulic conductivity over time, which can affect infiltration and thus recharge, is also not considered in this study.

4. Conclusions

The southern portion of the western U.S. can expect reduced recharge, while the northern portion can expect increased recharge in the future compared to baseline conditions. While the northern part of the western U.S. has fewer water resources challenges and thus have lesser concern about the change, the study reveals that the southern portion of the western U.S. which is already dry and stretched for water resources will get less recharge in the future and thus have significant challenges for managing water resources. Climate (viz., *P* and *T*) change will interact with land surface properties (viz., soil and vegetation) to affect the amount of recharge that occurs in the future; thus, the magnitude and/or direction of recharge cannot be predicted based solely on changes in precipitation. Land surface models like the Variable Infiltration Capacity (VIC) model can improve estimates of future recharge by simulating the interactions of climate with land surfaces processes that influence recharge. Effects on recharge due to change in vegetation response from projected changes in climate and CO_2 concentration, though important, are not considered in this study, and thus an interesting and vital aspect to be considered in future studies. While the Northern Rockies region is expected to get more recharge in the future, recharge is expected to decrease in the future in the South and Southwest regions. Despite the large variability in projected recharge across the GCMs, recharge projections from this study provide vital information required by water managers for long term water management planning.

Acknowledgments
We acknowledge the World Climate Research Programme's Working Group on Coupled Modeling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table S1 of this paper) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. We also acknowledge Bureau of Reclamation for archiving and distributing the BSCD CMIP5 hydrology projections (ftp://gdo-dcp.ucllnl.org/pub/dcp/archive/cmip5/hydro/). And we acknowledge USGS John Wesley Powell Center and NSF EAR (EAR-1328505) for funding this research.

References

Aguilera, H., & Murillo, J. M. (2009). The effect of possible climate change on natural groundwater recharge based on a simple model: A study of four karstic aquifers in SE Spain. *Environmental Geology*, *57*(5), 963–974. https://doi.org/10.1007/s00254-008-1381-2

Ajami, H., Meixner, T., Dominguez, F., Hogan, J., & Maddock, T. (2012). Seasonalizing Mountain system recharge in semi-arid basins-climate change impacts. *Groundwater*, *50*(4), 585–597. https://doi.org/10.1111/j.1745-6584.2011.00881.x

Anderson, M. T., & Woosley, L. H. (2005). Water availability for the western United States—Key scientific challenges. *U.S. Geological Survey Circular*, *1261*, 85.

Anderson, T. W., Freethey, G. W., & Tucci, P. (1992). Geohydrology and water resources of alluvial basins in South Central Arizona and parts of adjacent states, *U.S. Geological Survey Professional Paper, 1406-B*, Washington, DC: United States Government Printing Office.

Bates, B. C., Kundzewicz, Z. W., Wu, S., & Palutikof, J. P. (Eds.) (2008). *Climate change and water technical paper of the Intergovernmental Panel on Climate Change* (p. 210). Geneva: IPCC Secretariat.

Beyene, T., Lettenmaier, D. P., & Kabat, P. (2009). Hydrologic impacts of climate change on the Nile River basin: Implications of the 2007 IPCC climate scenarios. *Climatic Change*, *100*(3-4), 433–461. https://doi.org/10.1007/s10584-009-9693-0

Castle, S. L., Thomas, B. F., Reager, J. T., Rodell, M., Swenson, S. C., & Famiglietti, J. S. (2014). Groundwater depletion during drought threatens future water security of the Colorado River basin. *Geophysical Research Letters*, *41*, 5904–5911. https://doi.org/10.1002/2014GL061055

Castro, C. L., Chang, H., Dominguez, F., Carrillo, C., Kyung-Schemm, J., & Juang, H. H.-M. (2012). Can a regional climate model improve warm season forecasts in North America? *Journal of Climate*, *25*(23), 8212–8237. https://doi.org/10.1175/JCLI-D-11-00441.1

Cook, B. I., & Seager, R. (2013). The response of the north American monsoon to increased greenhouse gas forcing. *Journal of Geophysical Research: Atmospheres*, *118*, 1690–1699. https://doi.org/10.1002/jgrd.50111

Cramer, W., Bondeau, A., Woodward, F. I., Prentice, I. C., Betts, R. A., Brovkin, V., … Young-Molling, C. (2001). Global response of terrestrial ecosystem structure and function to CO_2 and climate change: Results from six dynamic global vegetation models. *Global Change Biology*, *7*(4), 357–373. https://doi.org/10.1046/j.1365-2486.2001.00383.x

Crosbie, R. S., Dawes, W. R., Charles, S. P., Mpelasoka, F. S., Aryal, S., Barron, O., & Summerell, G. K. (2011). Differences in future recharge estimates due to GCMs, downscaling methods and hydrological models. *Geophysical Research Letters*, *38*, L11406. https://doi.org/10.1029/2011GL047657

Crosbie, R., Pickett, T., Mpelasoka, F. S., Hodgson, G., Charles, S. P., & Barron, O. V. (2012). An assessment of climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs. *Climatic Change*, *117*(1-2), 41–53. https://doi.org/10.1007/s10584-012-0558-6

Crosbie, R. S., Scanlon, B. R., Mpelasoka, F. S., Reedy, R. C., Gates, J. B., & Zhang, L. (2013). Potential climate change effects on groundwater recharge in the High Plains aquifer, USA. *Water Resources Research*, *49*, 3936–3951. https://doi.org/10.1002/wrcr.20292

Cuo, L., Lettenmaier, D. P., Alberti, M., & Richey, J. E. (2009). Effects of a century of land cover and climate change on the hydrology of Puget sound basin. *Hydrological Processes*, *23*(6), 907–933. https://doi.org/10.1002/hyp.7228

Dettinger, M. D., & Earman, S. (2007). Western groundwater and climate change—Pivotal to supply sustainability or vulnerable in its own right? *Association of Ground Water Scientists and Engineers Newsletter*, *4*(1), 4–5. Westerville, OH.

Döll, P. (2009). Vulnerability to the impact of climate change on renewable groundwater resources: A global-scale assessment. *Environmental Research Letters*, *4*(3), 035006. https://doi.org/10.1088/1748-9326/4/3/035006

Döll, P., & Fiedler, K. (2008). Global-scale modeling of groundwater recharge. *Hydrology and Earth System Sciences*, *12*, 863–885.

Dominguez, F., Rivera, E., Lettenmaier, D. P., & Castro, C. L. (2012). Changes in winter precipitation extremes for the western United States under a warmer climate as simulated by regional climate models. *Geophysical Research Letters*, *39*, L05803. https://doi.org/10.1029/2011GL050762

Faunt, C. C. (2009). Groundwater availability of the Central Valley aquifer, California, *U.S. Geological Survey Professional Paper, 1766*, 225.

Flint, L. E., & Flint, A. L. (2014). California basin characterization model: A dataset of historical and future hydrologic response to climate change, U.S. Geological Survey. https://doi.org/10.5066/F7BV7DNG

Gao, H., Tang, Q., Shi, X., Zhu, C., Bohn, T. J., Su, F., … Wood, E. F. (2010). Water budget record from variable infiltration capacity (VIC) model. In *Algorithm theoretical basis document version 1.2*. Computational Hydrology Group, Seattle, University of Washington.

Gorelick, S. M., & Zheng, C. (2015). Global change and the groundwater management challenge. *Water Resources Research*, *51*, 3031–3051. https://doi.org/10.1002/2014WR016825

Green, T. R., Taniguchi, M., Kooi, H., Gurdak, J. J., Allen, D. M., Hiscock, K. M., … Aureli, A. (2011). Beneath the surface of global change: Impacts of climate change on groundwater. *Journal of Hydrology*, *405*(3-4), 532–560. https://doi.org/10.1016/j.jhydrol.2011.05.002

Gurdak, J. J., & Roe, C. D. (2010). Review: Recharge rates and chemistry beneath playas of the High Plains aquifer, USA. *Hydrogeology Journal*, *18*(8), 1747–1772. https://doi.org/10.1007/s10040-010-0672-3

Hamlet, A. F., & Lettenmaier, D. P. (1999). Effects of climate change on hydrology and water resources in the Columbia river basin. *Journal of the American Water Resources Association*, *35*(6), 1597–1623.

Hansen, M. C., DeFries, R. S., Townshend, J. R. G., & Sohlberg, R. (2000). Global land cover classification at 1 km spatial resolution using a classification tree approach. *International Journal of Remote Sensing*, *21*(6-7), 1331–1364. https://doi.org/10.1080/014311600210209

Hanson, R. T., Flint, L. E., Flint, A. L., Dettinger, M. D., Faunt, C. C., Cayan, D., & Schmid, W. (2012). A method for physically based model analysis of conjunctive use in response to potential climate changes. *Water Resources Research*, *48*, W00L08. https://doi.org/ 10.1029/2011WR010774

Herrera-Pantoja, M., & Hiscock, K. (2008). The effects of climate change on potential groundwater recharge in great Britain. *Hydrological Processes*, *22*(1), 73–86.

Intergovernmental Panel on Climate Change (IPCC) (2014). Summary for policymakers. In C. B. Field, et al. (Eds.), *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1–32). Cambridge, UK and New York: Cambridge University Press.

Jyrkama, M. I., & Sykes, J. F. (2007). The impact of climate change on spatially varying groundwater recharge in the Grand River watershed (Ontario). *Journal of Hydrology*, *338*(3-4), 237–250. https://doi.org/10.1016/j.jhydrol.2007.02.036

Konikow, L. F. (2013). Groundwater depletion in the United States (1900–2008), *U.S. Geological Survey Scientific Investigations Report 2013-5079*, 63.

Kundzewicz, Z. W., Mata, L. J., Arnell, N., Döll, P., Kabat, P., Jiménez, B., … Shiklomanov, I. (2007). Freshwater resources and their management. In M. L. Parry, et al. (Eds.), *Climate change 2007: Impacts, adaptation and vulnerability, contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 173–210). UK: Cambridge University Press.

Lee, S.-Y., Ryan, M. E., Hamlet, A. F., Palen, W. J., Lawler, J. J., & Halabisky, M. (2015). Projecting the hydrologic impacts of climate change on montane wetlands. *PLoS One*, *10*(9), e0136385. https://doi.org/10.1371/journal.pone.0136385

Leng, G., Tang, Q., Huang, S., Zhang, X., & Cao, J. (2015). Assessments of joint hydrological extreme risks in a warming climate in China. *International Journal of Climatology*, *36*(4), 1632–1642. https://doi.org/10.1002/joc.4447

Li, B., Rodell, M., & Famiglietti, J. S. (2015). Groundwater variability across temporal and spatial scales in the central and northeastern U.S. *Journal of Hydrology*, *525*, 769–780. https://doi.org/10.1016/j.jhydrol.2015.04.033

Liang, X., Lettenmaier, D. P., Wood, E. F., & Burges, S. J. (1994). A simple hydrologically based model of land surface water and energy fluxes for GSMs. *Journal of Geophysical Research*, *99*, 14,415–14,428. https://doi.org/10.1029/94JD00483

Liang, X., Xie, Z., & Huang, M. (2003). A new parameterization for surface and groundwater interactions and its impact on water budgets with the variable infiltration capacity (VIC) land surface model. *Journal of Geophysical Research*, *108*(D16), 8613. https://doi.org/10.1029/2002JD003090

Maupin, C. R., Partin, J. W., Shen, C.-C., Quinn, T. M., Lin, K., Taylor, F. W., … Sinclair, D. J. (2014). Persistent decadal-scale rainfall variability in the tropical South Pacific convergence zone through the past six centuries. *Climate of the Past*, *10*(4), 1319–1332. https://doi.org/10.5194/cp-10-1319-2014

Maurer, E. P., O'Donnell, G. M., Lettenmaier, D. P., & Roads, J. O. (2001). Evaluation of the land surface water budget in NCEP/NCAR and NCEP/DOE reanalyses using an off-line hydrologic model. *Journal of Geophysical Research*, *106*, 17,841–17,862.

Maurer, E. P., Wood, A. W., Adam, J. C., Lettenmaier, D. P., & Nijssen, B. (2002). A long-term Hydrologically-based data set of land surface fluxes and states for the conterminous United States. *Journal of Climate*, *15*(22), 3237–3251. https://doi.org/10.1175/1520-0442(2002)015%3C3237:ALTHBD%3E2.0.CO;2

McMahon, P. B., Dennehy, K. F., Bruce, B. W., Böhlke, J. K., Michel, R. L., Gurdak, J. J., & Hurlbut, D. B. (2006). Storage and transit time of chemicals in thick unsaturated zones under rangeland and irrigated cropland, High Plains, United States. *Water Resources Research*, *42*, W03413. https://doi.org/10.1029/2005WR004417

Meixner, T., Manning, A. H., Stonestrom, D. A., Allen, D. M., Ajami, H., Blasch, K. W., … Walvoord, M. A. (2016). Implications of projected climate change for groundwater recharge in the western United States. *Journal of Hydrology*, *534*(2016), 124–138. https://doi.org/10.1016/j.jhydrol.2015.12.027

Miller, D. A., & White, R. A. (1998). A conterminous United States multilayer soil characteristics dataset for regional climate and hydrology modeling. *Earth Interactions*, *2*(2), 1–26. https://doi.org/10.1175/1087-3562(1998)002%3C0001:ACUSMS%3E2.3.CO;2

Mitchell, K., Houser, P., Wood, E., Schaake, J., Tarpley, D., Lettenmaier, D., … Vinnikov, K. (1999). The GCIP land data assimilation (LDAS) project—Now underway. *GEWEX News*, *9*(4), 3–6.

Morison, J. I. L. (1987). Intercellular CO_2 concentration and stomatal response to CO_2. In E. Zeiger, G. D. Farquhar, & I. R. Cowan (Eds.), *Stomatal Function* (pp. 229–252). Stanford, CA: Stanford University.

Munoz-Arriola, F., Avissar, R., Zhu, C., & Lettenmaier, D. P. (2009). Sensitivity of the water resources of Rio Yaqui Basin, Mexico to agriculture extensification under multi-scale climate conditions. *Water Resources Research*, *45*, W00A20. https://doi.org/10.1029/2007WR006783

Nijssen, B., Lettenmaier, D. P., Liang, X., Wetzel, S. W., & Wood, E. F. (1997). Streamflow simulation for continental-Scale River basins. *Water Resources Research*, *33*(4), 711–724. https://doi.org/10.1029/96WR03517

Nijssen, B., O'Donnell, G. M., Hamlet, A. F., & Lettenmaier, D. P. (2001). Hydrologic vulnerability of global rivers to climate change. *Climatic Change*, *50*(1/2), 143–175. https://doi.org/10.1023/A:1010616428763

Niraula, R., Meixner, T., Ajami, H., Rodell, M., Gochis, D., & Castro, C. (2016). Comparing potential recharge estimates from three land surface models across the western US. *Journal of Hydrology*, *545*, 410–423.

Overpeck, J., & Udall, B. (2010). Dry times ahead. *Science*, *328*(5986), 1642–1643. https://doi.org/10.1126/science.1186591

Parr, D., Wang, G., & Ahmed, K. F. (2015). Hydrological changes in the U.S. northeast using the Connecticut River basin as a case study: Part 2. Projections of the future. *Global and Planetary Change*, *133*, 167–175. https://doi.org/10.1016/j.gloplacha.2015.08.011

Rasmussen, R., Ikeda, K., Liu, C., Gochis, D., Clark, M., Dai, A., Gutmann, E., … Zhang, G. (2014). Climate change impacts on the water balance of the Colorado headwaters: High-resolution regional climate model simulations. *Journal of Hydrometeorology*, *15*, 1091–1116. https://doi.org/10.1175/JHM-D-13-0118.1

Rasmussen, R., Liu, C., Ikeda, K., Gochis, D., Yates, D., Chen, F., … Gutmann, E. (2011). High-resolution coupled climate runoff simulations of seasonal snowfall over Colorado: A process study of current and warmer climate. *Journal of Climate*, *24*, 3015–3048. https://doi.org/10.1175/2010JCLI3985.1

Reclamation (2013). Downscaled CMIP3 and CMIP5 climate projection: Release of downscaled CMIP5 climate projections, Comparison with preceding information, and summary of user needs, U.S. Department of the Interior, Bureau of Reclamation, 104 p. Retrieved from http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/ techmemo/downscaled_climate.pdf

Reclamation (2014). Downscaled CMIP3 and CMIP5 hydrology projections—Release of hydrology projections, comparison with preceding information and summary of user needs, U.S. Department of the Interior, Bureau of Reclamation, 110 p. Retrieved from http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/ BCSD5HydrologyMemo.pdf

Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L., & McMahon, P. B. (2012). Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(24), 9320–9325. https://doi.org/10.1073/pnas.1200311109

Scanlon, B. R., Reedy, R. C., Stonestrom, D. A., Prudic, D. E., & Dennehy, K. F. (2005). Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology*, *11*, 1577–1593. https://doi.org/10.1111/j.1365-2486.2005.01026.x

Seager, R., Ting, M., Li, C., Naik, N., Cook, B., Nakamura, J., & Liu, H. (2013). Projections of declining surface-water availability for the southwestern United States. *Nature Climate Change*, *3*(5), 482–486.

Serrat-Capdevila, A., Valdés, J. B., Pérez, J. G., Baird, K., Mata, L. J., & Maddock, T. III (2007). Modeling climate change impacts—and uncertainty—on the hydrology of a riparian system: The San Pedro Basin (Arizona/Sonora). *Journal of Hydrology*, *347*(1-2), 48–66. https://doi.org/10.1016/j.jhydrol.2007.08.028

Sleeter, B. M., Wilson, T. S., & Acevedo, W. (2012). Status and trends of land change in the Western United States—1973 to 2000, *U.S. Geological Survey Professional Paper, 1794–A*, 324. Retrieved from http://pubs.usgs.gov/pp/1794/a/

Steward, D. R., Bruss, P. J., Yang, X., Staggenborg, S. A., Welch, S. M., & Apley, M. D. (2013). Tapping unsustainable groundwater stores for agricultural production in the High Plains aquifer of Kansas, projections to 2110. *Proceedings of the National Academy of Sciences*, *110*(37), E3477–E3486. https://doi.org/10.1073/pnas.1220351110

Stonestrom, D. A., Constantz, J., Ferré, T. P. A., & Leake, S. A. (2007). Groundwater recharge in the arid and semiarid southwestern United States, *U.S. Geological Survey Professional Paper, 1703*, 414 pp., Reston, VA.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., … Holman, I. (2013). Groundwater and climate change. *Nature Climate Change*, *3*(4), 322–329.

Vaccaro, J. J. (1992). Sensitivity of groundwater recharge estimates to climate variability and change, Columbia plateau, Washington. *Journal of Geophysical Research*, *97*(D3), 2821–2833. https://doi.org/10.1029/91JD01788

Vano, J. A., Udall, B., Cayan, D. R., Overpeck, J. T., Brekke, L. D., Das, T., … Lettenmaier, D. P. (2014). Understanding uncertainties in future Colorado River Streamflow. *Bulletin of the American Meteorological Society*, *95*(1), 59–78. https://doi.org/10.1175/BAMS-D-12-00228.1

Widmann, M., & Bretherton, C. S. (2000). Validation of mesoscale precipitation in the NCEP reanalysis using a new gridcell dataset for the northwestern United States. *Journal of Climate*, *13*(11), 1936–1950. https://doi.org/10.1175/1520-0442(2000)013%3C1936:VOMPIT%3E2.0.CO;2

Wood, A. W., Maurer, E. P., Kumar, A., & Lettenmaier, D. P. (2002). Long range experimental hydrologic forecasting for the eastern U.S. *Journal of Geophysical Research*, *107*(D20), 4429.