Niraula Rewati (Orcid ID: 0000-0003-4102-3666)
Meixner Thomas (Orcid ID: 0000-0002-8567-9635)
Dominguez Francina (Orcid ID: 0000-0003-2674-3382)
Bhattarai Nishan (Orcid ID: 0000-0003-2749-3549)
Rodell Matthew (Orcid ID: 0000-0003-0106-7437)
Ajami Hoori (Orcid ID: 0000-0001-6883-7630)
Gochis David, J (Orcid ID: 0000-0001-8668-4850)

How might recharge change under projected climate change in the western US?

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

[1*]*Department of Hydrology and Atmospheric Sciences, University of Arizona, Tucson, Arizona*

[2]*Department of Atmospheric Sciences, University of Illinois, Urbana-Campaign, Illinois*

[3]*School for Environment and Sustainability, University of Michigan, Ann Arbor, Michigan*

[4]*Hydrological Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland*

[5]*Environmental Sciences, University of California, Riverside, California*[6]

[6]*NCAR HR Regional Modelling, Boulder, Colorado*

Corresponding author address: Rewati Niraula, Department of Hydrology and Atmospheric Sciences, University of Arizona, 1133 E James E Rogers Way, JW Harshbarger Bldg. Rm 202, Tucson, AZ 85719, USA. E-mail: rewatin@email.arizona.edu

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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 US 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.

ABSTRACT

Although groundwater is a major water resource in the western US, 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 US. VIC model was run with RCP 6.0 forcing from 11 GCMs and ‘subsurface runoff’ output was considered as recharge. Recharge is expected to decrease in the West (-5.8±14.8 %) 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±6.3%) and far (+11.8±8.3%) future. Overall, southern portions of the western US 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 [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 [Stonestorm, 2007; Green et al., 2011] and indirectly through changes in groundwater use with changes in water demands. Climate change and variability have numerous effects on recharge rates and mechanisms [Vaccaro, 1992; Green et al., 2011; Kundzewicz et al., 2007; Aguilera and Murillo, 2009]. Many climate change studies have predicted reduced recharge [e.g. Herrera-Pantoja and Hiscock, 2008]. However, the effects of climate change on recharge may not necessarily be negative or decrease in all regions over the world [Jyrkama and Sykes, 2007; Döll, 2009; Gurdak and Roe, 2010]. 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 semi-arid zones [Doll and Fiedler, 2008].

Groundwater withdrawals represent 25% of total fresh water withdrawals in the US [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 US [Anderson and Woosley, 2005]. Reduced reliability of surface water supplies in the western US with projected increases in evaporative demand and uncertain changes in annual precipitation [Rasmussen et al., 2011, 2014] may increase groundwater use [Scanlon, 2005]. Many areas of the western US are already experiencing groundwater depletion caused by sustained groundwater pumping [Faunt, 2009; Konikow, 2013; Castle et al., 2014]. 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 and Udall 2010; Seager et al., 2013; Vano et al., 2014] with limited studies on groundwater recharge projections [Meixner et al. 2016].

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

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; Fig 1)?

2. METHODS

2.1. Background on the Western US

The western US (Fig. 1), which covers more than half of the land area of the contiguous US, is geographically and climatically diverse. Parts of the region receive high amounts of precipitation (~5000 mm) and other parts are true deserts and receive little precipitation (~58 mm/yr). With high topographic variability (elevation varies between -86 m to 4402 m), the western US is composed of grassland or shrubland (59%), forest (28.1%), agriculture (6.3%), developed (1.5%), and barren (1.9%) lands [Sleeter at 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] model which have been archived by the Bureau of Reclamation [Reclamation, 2013]. 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 degree, ~12 kilometers on a side) across the contiguous US using the Bias-Correction and Spatial Disaggregation (BCSD) technique [Wood et al., 2002] and then translated into hydrologic projections over the contiguous US 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 [Hamlet and Lattenmier, 1999, Nijssen et al., 2001, Beyene et al., 2007, Cuo et al., 2009, Munoz-Arriola et al., 2009, Lee et al., 2015, Parr et al., 2015, Leng et al., 2015]. Previously, the VIC was found to make reasonable estimates of recharge in the western US [Niraula, 2015; Niraula et al., 2016] and Northeastern US [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, 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 degree 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 (Fig. 2a), estimates of relative changes in recharge (mean ±standard deviation, SD) were made at each grid location over the western US 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 square 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 (Fig. 2a) 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 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 (Fig. 1). The winter jet stream and storm track are expected to move northward, resulting in more precipitation north of approximately 40^{o} 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 (Fig. 1) which is minimal (<2.1±4.3 %) for all the regions except for the Northern Rockies and Plains

(+5.3±2.9 %) (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±5.1%) 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, Figs. 1, 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 (Fig. 1) for the West and Southwest regions (medium agreement).

The average T is expected to increase (high agreement) in both the near (1.4±0.36^{o}C) and far future (3.2±0.79 ^{o}C) throughout the western US (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).

3.2.2 Variability in projected climate change (P & 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 (Fig. 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 (Fig. 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 (Fig. 2). More GCMs (7 GCMs) projected a decrease in P in the near future and increase in P for the far future for the West and Southwest regions (Fig. 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 +21.74%). T increase varied between 0.7 ^{o}C to 2.2 ^{o}C for near future and between 1.6 ^{o}C and 4.4 ^{o}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 (Fig. 3) at a grid scale. For the far future the change will be more substantial (-90% to >100%) depending on location (Fig. 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±.4.0% 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±6.3 %) and far future (+11.8±1.8 %). 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±6.4%; 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 to 5.1 mm in far future (Table 1)

Although the change in P is minimal (Fig. 2, Table 1) in the far future in the South and Southwest region, a large increase in T (Table 1) in these regions will cause ET to increase considerably and reduce soil moisture making the soil profile much drier, thereby reducing recharge (Fig. 4, Table 1). The projected increase in recharge (Fig. 3, Table 1) is similar to the projected increase in P (Fig. 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 (Fig. 3, Table 1), there will be limited change in recharge in the far future (Fig. 3, 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 (Fig. 3, 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 (9 GCMs) and decreased recharge in the West (GCMs) and Southwest (GCMs) regions (Fig. 5) in the near future although the amount of change vary based on GCMs (Fig 4). More models (6 GCMs) projected decreased recharge in the South and Northwest regions (Fig. 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%) region in the near future (Fig. 4).

A majority of the models projected increases in recharge in the Northern Rockies and Plains (9 GCMs) and decreases in recharge for the South (9 GCMs) in the far future (Fig. 4). More models projected decreased recharge in the Southwest (7 GCMs) and West (6 GCMs), and increased recharge in the Northwest (7 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 (Fig. 4).

Although more models projected increases in precipitation over the region (Fig. 2), more models projected decreases in recharge (Fig. 4). This result was primarily due to the offset effect of consistent increased temperature (Fig. 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 US. Doll and Fiedler [2008] projected an increase in potential recharge of more than 30% in the western US, 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 US, Meixner et al. [2016] estimated average declines of 10–20% in total recharge across the southern aquifers of the western US, 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 modelling across the western US, and provides more quantitative information. Overall, these findings across the western US 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 & 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 [Dominguez et al., 2012; Castro 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 [Dominguez et al., 2012; Castro 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 was used in this study, however, have limitations capturing seasonal and inter-annual variability across the region compared to dynamically downscaled projections, which are just becoming available but are cost-intensive [Hanson et al., 2012; Castro 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 [Morison, 1987; Cramer et al 2001] 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 [Steward et al 2013; Meixner et al 2016] in large-scale models. Other processes like water temperature change from increasing temperature and changes in the soil characteristics like hydraulic conductivity over time, that can affect infiltration and thus recharge, is also not considered in this study.

4. CONCLUSIONS

The southern portion of the western US 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 US has fewer water resources challenges and thus have lesser concern about the change, the study reveals that the southern portion of the western US 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.

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Table 1: Current conditions of climate and recharge, and projected change in climate and recharge in the western US

	Current Conditions				***Projected Climate Change (Mean±SD)***				***Projected Recharge Change(Mean±SD)***			
Region	P (mm)	Recharge (mm)	T (^{o}C)	Recharge ratio (%)	% P change (NF)	% P change (FF)	T change (^{o}C) (NF)	T change (^{o}C) (FF)	% (mm) change (NF)	Degree of Agreement	% (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±1.0)	High

* W: West, SW: Southwest, S: South, NW: Northwest, NR: Northern Rockies and Plains, NF: Near Future, FF: Far Future

List of Figures:

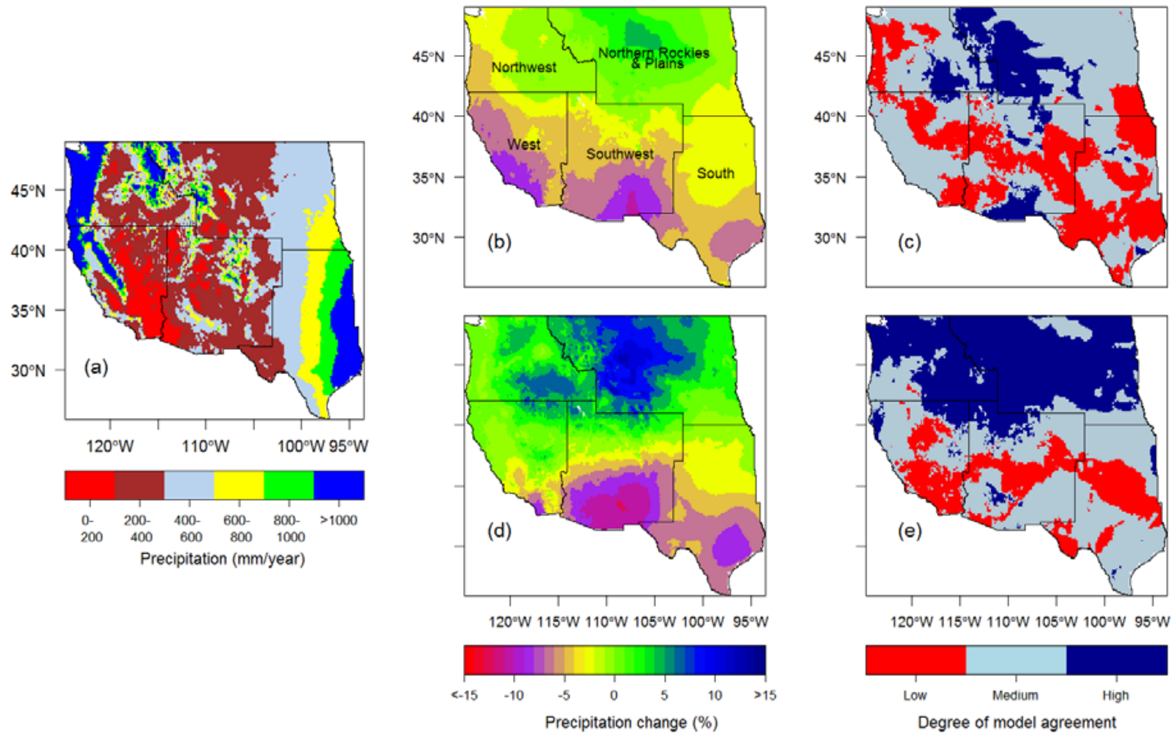

Fig 1: Historic precipitation (a) and relative change in precipitation for the near (b) and far (c) future compared to historic period along with the degree of agreement in the direction of those changes for the near (d) and far (e) future.

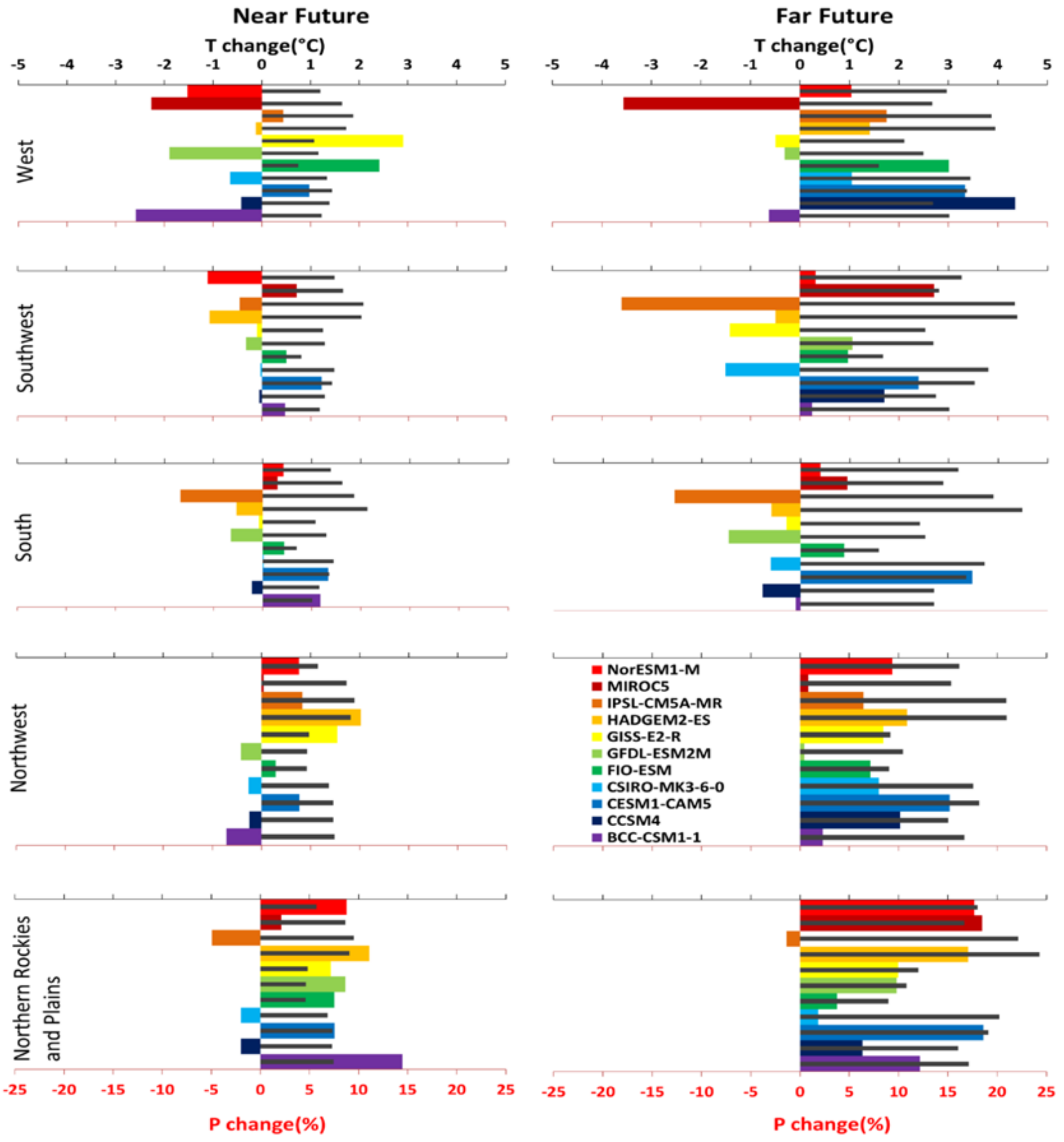

Fig 2: Variability in the relative changes in climate (P and T) due to GCMs for 5 climatic regions in the western US in near (1st column) and far future (2nd column). Each color coded bar represents the relative change in precipitation based on the GCMs and the overlying gray bars represent the change in temperature associated with the particular GCMs.

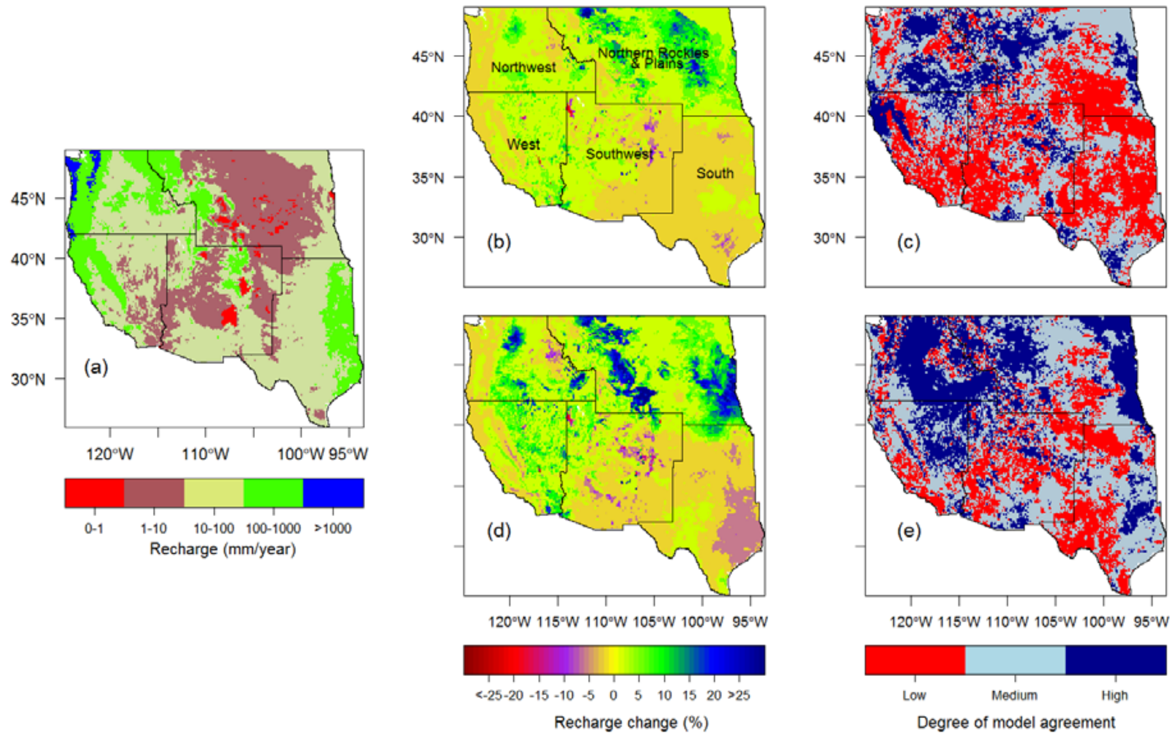

Fig 3: Historical recharge (a) , ensemble average relative change in recharge for the near (b) and far (c) future compared to historic period along with the degree of agreement in the direction of those changes for the near (d) and far (e) future.

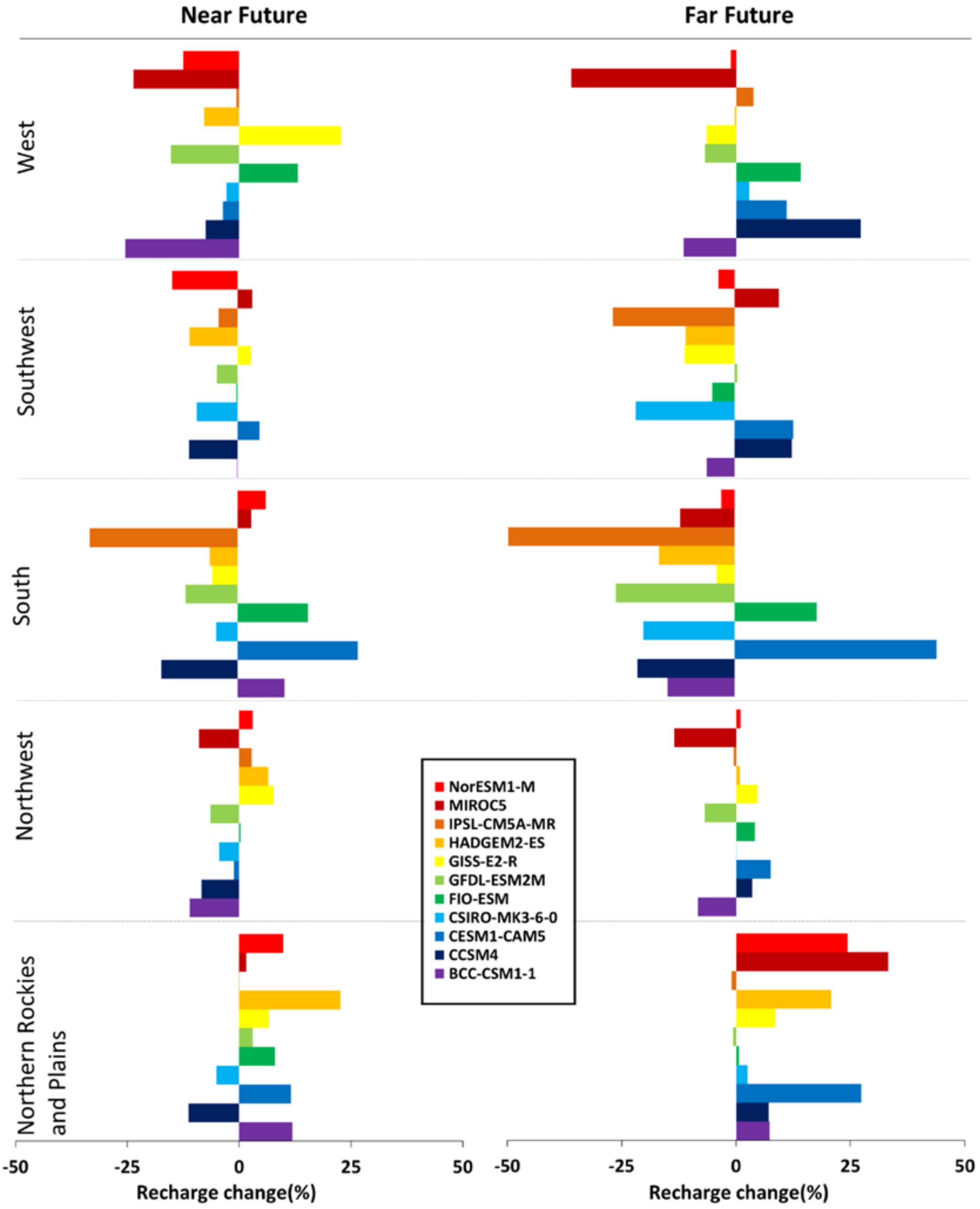
Near Future
Far Future
West
Southwest
South
Northwest
Northern Rockies and Plains
NorESM1-M
MIROC5
IPSL-CM5A-MR
HADGEM2-ES
GISS-E2-R
GFDL-ESM2M
FIO-ESM
CSIRO-MK3-6-0
CESM1-CAM5
CCSM4
BCC-CSM1-1
-50
-25
0
25
50
Recharge change(%)
-50
-25
0
25
50
Recharge change(%)

Fig 4: Variability in the relative changes in recharge due to GCMs for 5 climatic regions in the western US in near (1st column) and far future (2nd column). Each color coded bar represents the relative change in recharge based on the GCMs