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Authors

Niraula, R
Meixner, T
Dominguez, F
et al.

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

R Niraula[1,*], **T Meixner**[1], **F Dominguez**[2], **M Rodell**[3], **H Ajami**[4], **D Gochis**[5], and **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]Hydrological Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland
[4]Environmental Sciences, University of California, Riverside, California [5]NCAR HR Regional Modelling, Boulder, Colorado

Abstract

Although groundwater is a major resource of water 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. Recharge is expected to decrease slightly (highly certain) in the West (−1.6%) and Southwest (−2.9%) regions in the near future and decrease considerably (highly certain) in the South region (−10.6%) in the far future. The Northern Rockies region is expected to get more recharge (highly certain) in both the near (+5.0%) and far (+9.0%) future. In general, southern portions of the western US are expected to get less recharge in the future and northern portions will get more. This study also shows that climate change interacts with land surface properties to affect the amount of recharge that occurs in the future.

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 predicted reduced recharge (e.g. Herrera-Pantoja and Hiscock, 2008). However, the effects

[*]*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. rewatin@email.arizona.edu.

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 replenishing the groundwater discharge through natural processes. 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 recharge under projected climate change are needed throughout the western US. Since groundwater recharge projections are closely related to highly uncertain projected changes in precipitation and temperature [Bates et al., 2008; Crosbie et al., 2012, 2013, Cook and Seager, 2013; Taylor et al., 2014; IPCC, 2014], it is important to analyze more than a few GCMs when projecting recharge associated with climate change before drawing conclusions.

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 future 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).

This study aims to provide consistent recharge projections based on 11 Bias-Correction and Spatial Disaggregation (BCSD) Coupled Model Inter-comparison Project Phase 5 (CMIP5) climate projections (Table 1) using the Variable Infiltration Capacity (VIC; Liang et al., 1994) model over the whole western US and addresses the following questions:

1. What is the effect of projected climate change on groundwater recharge (mean annual and seasonality) 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 1a)?

2. METHODS

2.1. 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. BCSD5 hydrology projections

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, section 2.4] model which have been archived by the Bureau of Reclamation. VIC was found to make reasonable estimates for recharge in the western US [Niraula, 2015; Niraula et al., 2016] and Northeastern US [Li et al., 2015]. 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., 2002,2004; Reclamation, 2013]. These downscaled climate projections were then translated into hydrologic projections over the contiguous US using the VIC model which was run at 1 hour temporal resolution. These projections are available from the Downscaled Climate and Hydrology Projections (DCHP) website [Reclamation, 2013]. 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).

2.3. Representative Concentration Pathways (RCP) 6 – Intermediate emissions

Outputs from RCP 6.0 emission scenario-based predictions were selected for this study since this is the scenario which is consistent with the application of a current range of technologies and strategies for reducing greenhouse gas emissions (IPCC, 2014). This RCP was developed by the National Institute for Environmental Studies in Japan. In this scenario, radiative forcing is stabilized shortly after year 2100, which is consistent with the application of a range of technologies and strategies for reducing greenhouse gas emissions [IPCC, 2014]. Outputs from 11 GCMs (Table 1) for this emission scenario were selected based on availability of data and were analyzed to incorporate the uncertainty associated with the climate as well as recharge projections.

2.4. VIC

The VIC model [Liang et al., 1994; Liang et al., 1996; Nijssen et al., 1997] is a spatially distributed hydrologic model that solves the water and energy balance at each model grid cell. The VIC model contains a subgrid-scale parameterization of the infiltration process (based on the Nanjing model), which impacts the vertical distribution of soil moisture in, typically, a three-layer model grid cell (Liang et al., 1994). Potential evapotranspiration is calculated using a Penman Monteith approach. Evapotranspiration from each vegetation type is characterized by potential evapotranspiration together with canopy resistance and aerodynamic resistance to the transfer of water. VIC uses a spatial probability distribution to represent subgrid heterogeneity in soil moisture and treats subsurface runoff/recharge as a nonlinear recession curve which is a function of soil moisture in the bottom layer. 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 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, VIC was found to make reasonable estimates for recharge in the western US [Niraula, 2015; Niraula et al., 2016] and Northeastern US [Li et al., 2015].

2.5. Relative change and uncertainty analysis:

Using historical (1971-2000) recharge from VIC as the base scenario (Fig. 1), estimates of relative changes in recharge were made at each grid over the western US for the near (2021-2050) and far (2071-2100) future. The uncertainty analysis on directions of those relative changes depending on model ensemble average is then analyzed for each grid based on the number of models that agree on the direction of change. In this study, we considered the direction of change (increase or decrease) to be “highly certain” if > 80% of the models agree (>8 out of 11 models in this study), “moderately certain” if 60% - 80% of the models agree (7 - 8 out of 11) and “uncertain” if <60% of the models agree (<7 out of 11) on the direction of change.

3. RESULTS AND DISCUSSIONS

3.1. Baseline (1971-2000) recharge estimates

Over the whole domain, the average annual recharge (R, Fig. 1) is estimated to be 83 mm/yr (15% of Precipitation (P), Table 2) 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 2). Relatively higher evapotranspiration (ET) in the South, Southwest and the Northern Rockies resulted in lower recharge ratios (R/P) (<9%) in these regions (Table 2). Rock formations of the Rocky Mountains are minimally permeable and thus resulted in minimal recharge.

3.2. Projected change in climate

3.2.1 Ensemble mean climate change—The average P is expected to increase in some locations and decrease in others, with a slight increase when averaged over the domain

(+1.43% and +4.75% 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. 2). 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 (Fig. 2) which is minimal (< 2.1%) for all the regions except for the Northern Rockies and Plains (+5.3%) (Table 2). The change in P is expected to be minimal for the South (−0.3%) and Southwest (+1.1%), a moderate increase for the West (+4.9%) and higher increases for the Northwest (+7.2%) and Northern Rockies and Plains (+10.4%) for the far future based on the ensemble of models (Table 2). It is highly certain P will increase in the Northern Rockies and Plains for both the near and far future (Fig. 2). P is also expected to increase in the Northwest region for the near future (moderately certain) and far future (highly certain). It is moderately certain P will decrease in near future and increase in far future (Fig. 2) for the West and Southwest regions.

The average T is expected to increase (highly certain) in both the near (1.43 °C) and far future (3.15 °C) throughout the western US (Table 2) but varies spatially. The increase in T is lower towards the Pacific and Gulf coast and higher towards the Interior Plains and higher in the far future compared to the near future. While slightly higher increases in T are projected for the Northern Rockies, slightly lower T increases are projected for the West region (Table 2).

3.2.2 Variability in projected climate change across GCMs—

While all models (11 GCMs) projected increased T throughout the regions, there was inconsistency in P projections with some showing increased P and some showing decreased P (Fig. 3). 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. 3). 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. 3). More GCMs (7 GCMs) projected decrease in P in the near future and increase in P for the far future for the West and Southwest regions (Fig. 3). High variability in projected T and P across GCMs was seen throughout the region (Fig. 3).

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. 4) at a grid scale. For the far future the change will be more substantial (−90% to >100%) depending on location (Fig. 4).

For the near future, the model ensemble estimated average recharge decrease by 1.6%, 2.9% and 3% in the West (highly certain), Southwest (highly certain), and South (uncertain) respectively (Table 2). Similarly for the far future, the model ensemble average estimated average recharge to decrease by 4.4% in the Southwest (moderately certain) and 10.6% in the South (highly certain) regions (Table 2). The ensemble models however estimated an increased recharge (highly certain) in the Northern Rockies and Plains for both near (+5%) and far future (+9%). The average recharge is predicted to remain fairly constant in the West

(uncertain) region in far future and in the Northwest region (uncertain) in both the near and far future (Table 2).

Although the change in P is minimal (Fig. 2, Table 2) in the far future in the South and Southwest region, a large increase in T (Table 2) 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 2). The projected increase in recharge (Fig. 4, Table 2) is similar to the projected increase in P (Fig. 2) 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. 4, Table 2), there with be limited change in recharge in the far future (Fig. 4, Table 2). 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. 4, Table 2) 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 recharge across GCMs—A majority of the models of the VIC simulations projected increased recharge in the Northern Rockies and Plains (9 out of 11) and decreased recharge in the West (9 out of 11) and Southwest (8 out of 11) regions (Fig. 5) in the near future although the amount of change vary based on GCMs (Fig 5). More models (6 out of 11) projected decreased recharge in the South and Northwest regions (Fig. 5). 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. 5).

A majority of the models projected increases in recharge in the Northern Rockies and Plains (9 out of 11) and decreases in recharge for the South (9 out of 11) (Fig. 5). Increases in recharge were as high as 33.3% for the Northwest region (Fig. 5). It should however be noted that of the two models that projected increased recharge in the South, one showed a substantial increase in recharge (+44.1 %; Fig. 5). More models projected decreased recharge in the Southwest (7 out of 11) and West (6 out of 11), and increased recharge in the Northwest (7 out of 11) regions (Fig. 5). 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. 5).

Although more models projected increases in precipitation over the region (Fig. 3), more models projected decreases in recharge (Fig. 5). This result was primarily due to the offset effect of consistent increased temperature (Fig. 3) 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.

3.3 Projected change in recharge seasonality

Although no significant change in mean recharge was projected for some regions, a significant change in the seasonality of the recharge is projected to occur across the entire region (Table 3). Analyses at the seasonal time scale will help better explain the sensitivity of climate change to recharge in the western US as it is easy to detect the change at a seasonal than at an annual time scale- similar decreases in one season and increases in another could result in no change in recharge at an annual time scale. The model ensemble average projected a decrease in recharge during summer (−4.5% - −25.3%) for all regions, with the largest decrease in the West and the smallest in the South for the near future (Table 3). For the far future, the same results holds for the summer however there is a much larger decrease (−11.5%- −37.3%) in recharge (Table 3). The higher decreases in recharge are mostly related to decreases in P and increases in T during the summer when most of the ET occurs. A significantly higher decrease in the far future compared to the near future is related to significantly higher increases in T in the far compared to the near future. A decrease in recharge is projected to occur throughout the year in the South region for far future (Table 3) which will see a decrease in P and significantly higher increase in T during that period.

An increase in recharge during winter (+2.4% to +7%) is projected for most of the regions for the near future (Table 3) with the smallest increase for the West and highest for the Northern Rockies and Plains, where more increases are projected during spring (+24.9%). A significant increase is also expected to occur in winter for the Northern Rockies and Plains (+13%), West (+22.5%) and Northwest (+18%) regions for the far future (Table 3). Increases in recharge in the winter months are related to P increases high enough to offset the effect of increased T during the winter season. A significant increase is also expected to occur in spring for the Northern Rockies and Plains (+59%), Southwest (+13.6%) and Northwest (+12.7%) regions (Table 3) which is related to higher P in winter and spring months in the form of snow and higher melting during the spring from increased T.

3.4. Comparing the findings of this study with the existing literature

In addition to supporting the findings from the current existing literature regarding the effect of climate change on groundwater recharge, this study further provided the finer scale information, region wide assessment at better resolution than Doll et al (2012), and broader analysis than the studies by Crosbie et al., 2013 and Meixner et al. 2016 for the western US. However our study also indicated uncertainty in the recharge projections in agreement with existing studies.

Other existing studies have demonstrated varied impact of climate change in groundwater recharge. In a study of recharge in Europe, substantial reductions in potential groundwater recharge were projected in southern Europe whereas increases were consistently projected in northern Europe [Taylor et al., 2009]. Application of an ensemble of 13 GCMs resulted in projected changes in groundwater recharge for the 2080s of between −26% and +31% [Jackson & Prudhomme, 2011] in England. Similarly, in southern British Columbia, recharge projections for the 2080s range from −10% to +23% relative to historical recharge [Allen et al., 2010]. Regional simulations using 16 GCMs in Australia project potential

recharge decreases in the west, central and south, and increases in the north based on the ensemble median [Crosbie et al., 2012]. These findings across the world suggested that recharge will increase or decrease depending upon the location and projected changes in climate. The findings are also consistent with these studies in terms of estimates of projected change in recharge (within 30%) at the regional scale.

Doll and Fiedler (2008) used two GCMs to investigate changes in groundwater recharge on global scale. They concluded a decrease in potential groundwater recharge of more than 70% by the 2050s in northeast Brazil, and southwest Africa and an increase in potential recharge of more than 30% in the Sahel, Middle East, northern China, Siberia and the western United States, acknowledging that this higher change could be the results of very low baseline recharge rates in many of these areas. However, for most of the areas, model results indicated that groundwater recharge is unlikely to decrease by more than 10% until the 2050s [Döll, 2009]. Our results also indicated that although the changes could be higher at local scale, at the regional scale, the changes will be mild. In a study of the American 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%) amplifying the current spatial trend in recharge from north to south. Our study also shows a significant decrease in recharge in the southern portion of the High Plains.

Based on synthesis study of aquifers in western US, Miexner et al. (2016) estimated an average declines of 10-20% in total recharge across the southern aquifers of the western US, but with a wide range of uncertainty that includes no change, and also predicted that the northern set of 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 also provides more quantitative information.

3.5. Uncertainty in projections

It should be noted that there is a large uncertainty associated with the recharge projections made in this paper (Figs. 4, and 5) in response to the uncertainties in P & T (Figs. 2 and 3). The climate estimates used as input to run VIC are based on global climate projections. While these models can provide a rough estimate of climate at a coarse spatial resolution, there is more uncertainty at the local and regional scales [Dominguez et al., 2012; Castro et al., 2012]. Using these models at the local and regional scale thus requires the use of statistical or dynamical downscaling techniques to increase the spatial resolution. Statistically downscaled data, which was used in this study, 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; Dominguez et al., 2012; Castro et al., 2012]. Also, 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]. The major source of uncertainty in the future projections of recharge is linked to the GCMs projections of the future climate (Crosbie et al., 2011; Crosbie et al 2013), followed by the downscaling of the future climate from the GCMs [Holman et al., 2009; Mileham et al., 2009]. The choice of hydrological model was found to be the source of the least

uncertainty in previous studies of ground water recharge [Crosbie et al., 2011] and should not have affected recharge projections significantly in this study with the selection of the VIC model.

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/recent past (1971-2000). While the northern part of the western US has fewer water resources challenges and thus have lesser concern about the change, the study reveal 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 pose 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.

A majority of the VIC simulations projected increased recharge in the Northern Rockies and Plains for both the near and far future. A majority of the simulations agreed on reduced recharge in the West and Southwest region for the near future. For the far future, a majority of the simulations agreed on decreased recharge in the South and Southwest regions. There is large variability in the projected recharge change based on GCMs across the regions.

At grid scale ($1/8^{th}$ degree), the relative increase in recharge will be as high as 94% and the relative decrease will be as high as 50% for the near future. For the far future the change will be more substantial (−90% to >100%) depending on the location of interest and scale. When analyzed at a regional scale, the Northern Rockies region is expected to get more recharge in the future. However, 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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References:

Aguilera H, and Murillo JM (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 57:963–974

Ajami H, Meixner T, Dominguez F, Hogan J, and Maddock T (2012), Seasonalizing Mountain System Recharge in Semi-Arid Basins-Climate Change Impacts, Groundwater, 50, 585–597. doi: 10.1111/j.1745-6584.2011.00881.x

Allen DM et al. 2010 Variability in simulated recharge using different GCMs. Wat. Resour. Res46, W00F03

Anderson MT and Woosley LH (2005), Water availability for the Western United States—Key scientific challenges, U.S. Geological Survey Circular 1261, 85 p.

Anderson TW, Freethey GW, and 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, United States Government Printing Office, Washington.

Bates BC, Kundzewicz ZW, Wu S, and Palutikof JP (2008), Climate Change and Water Technical Paper of the Intergovernmental Panel on Climate Change VI (IPCC, 2008).

Beyene T, Lettenmaier DP, and Rabat P (2009), Hydrologic impacts of climate change on the Nile River basin: Implications of the 2007 IPCC climate scenarios, Climatic Change, online first, doi: 10.1007/s10584-009-9693-0.

Castle SL, Thomas BF, Reager JT, Rodell M, Swenson SC, and Famiglietti JS (2014), Groundwater depletion during drought threatens future water security of the Colorado River Basin, Geophys. Res. Lett, 41, doi:10.1002/2014GL061055.

Castro CL, Chang H, Dominguez F, Carrillo C, Kyung-Schemm J, and Juang HH-M, (2012), Can a regional climate model improve warm season forecasts in North America?, J. Clim, 25 (2012), pp. 8212–8237 10.1175/JCLI-D-11-00441.1

Cook BI, and Seager R (2013), The response of the North American monsoon to increased greenhouse gas forcing, J. Geophys. Res. Atmospheres, 118 (4), 1690–1699, doi: 10.1002/jgrd.50111

Crosbie RS, Dawes WR, Charles SP, Mpelasoka FS, Aryal S, Barron O, and Summerell GK (2011), Differences in future recharge estimates due to GCMs, downscaling methods and hydrological models, Geophys. Res. Lett, 38, L11406, doi: 10.1029/2011GL047657.

Crosbie R et al. 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 10.1007/s10584-012-0558-6.

Crosbie RS, Scanlon BR, Mpelasoka FS, Reedy RC, Gates JB, and Zhang L (2013), Potential climate change effects on groundwater recharge in the High Plains Aquifer, USA, Water Resour. Res, 49, doi: 10.1002/wrcr.20292.

Cuo L, Lettenmaier DP, Alberti M, and Richey JE (2009), Effects of a century of land cover and climate change on the hydrology of Puget Sound basin, Hydrological Processes, 23, 907–933.

Dettinger MD, and 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, 6 2007, 4–5.

Döoll P and Fiedler K (2008), Global-scale modeling of groundwater recharge, Hydrol. Earth Syst. Sci. 12, 863–885 (2008).

Döoll P Vulnerability to the impact of climate change on renewable groundwater resources: A global-scale assessment. Environ. Res. Lett. 4, 035006 (2009).)

Döoll P, Hoffmann-Dobrev H, Portmanna FT, Siebert S, Eicker A, Rodell M, Strassberg G, Scanlon BR (2012), Impact of water withdrawals from groundwater and surface water on continental water storage variations, J. Geodyn 59–60, 143–156.

Dominguez F, Rivera E, Lettenmaier DP, and Castro CL (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: 5, p. L05803, doi: 10.1029/2011GL050762.

Faunt CC (2009), Groundwater availability of the Central Valley Aquifer, California, U.S. Geol. Surv. Prof. Pap, 1766, 225 pp.

Flint LE, and Flint AL (2014), California Basin Characterization Model: A dataset of Historical and Future Hydrologic Response to Climate Change, U.S. Geological Survey, DOI: doi:10.5066/F7BV7DNG

Gorelick Steven M., and Zheng Chunmiao (2015), Global change and the groundwater management challenge, Water Resources Research, 51 (5), 3031–3051.

Green TR et al. (2011), Beneath the surface of global change: Impacts of climate change on groundwater. J. Hydrol. 405, 532–560.

Gurdak JJ, and Roe CD (2010), Review: Recharge rates and chemistry beneath playas of the High Plains aquifer, USA, Hydrogeology Journal, v. 18, 1747–1772, doi:10.1007/sl0040-010-0672-3.

Hamlet AF, and Lettenmaier DP (1999), Effects of climate change on hydrology and water resources in the Columbia river basin, J. AWRA, 35 (6), 1597–1623

Hanson RT, Flint LE, Flint AL, Dettinger MD, Faunt CC, Cayan D, and Schmid W (2012), A method for physically based model analysis of conjunctive use in response to potential climate changes, Water Resources Research, 48(6),W00L08.

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

Holman I, Allen D, Cuthbert M, and Godemiaux P (2012), Towards best practice for assessing the impacts of climate change on groundwater, Hydrogeol. J, 20(1), 1–4, doi: 10.1007/s10040-011-0805-3.

IPCC (2014), Summary for Policymakers, In: 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 [Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatteijee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, and White LL (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–32.

Jackson CR, Meister R & Prudhomme C 2011, Modelling the effects of climate change and its uncertainty on UK Chalk groundwater resources from an ensemble of global climate model projections. J. Hydrol 399, 12–28.

Jasechko S, Birks SJ, Gleeson T, Wada Y, Fawcett PJ, Sharp ZD, McDonnell JJ, and Welker JM (2014), The pronounced seasonality of global groundwater recharge, Water Resour. Res, 50, 8845–8867, doi:10.1002/2014WR015809.

Jyrkama ML, and Sykes JF (2007), The impact of climate change on spatially varying groundwater recharge in the Grand River watershed (Ontario), J. of Hydro, 338, 237–250.

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

Kundzewicz ZW, Mata LJ, Arnell N, Döoll P, Rabat P, Jiménez B, Miller K, Oki T, Şen Z, and Shiklomanov I (2007), Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (ed. by Parry ML, Canziani OF, Palutikof JP, van der Linden PJ & Hanson CE), 173–210. Cambridge University Press, UK.

Lee S-Y, Ryan ME, Hamlet AF, Palen WJ, Lawler JJ, and Halabisky M (2015), Projecting the Hydrologic Impacts of Climate Change on Montane Wetlands, PLoS ONE 10(9): e0136385. doi: 10.1371/journal.pone.0136385 [PubMed: 26331850]

Leng G, Tang Q, Huang S, Zhang X, and Cao J (2015), Assessments of joint hydrological extreme risks in a warming climate in China, Int. J. Climatol. doi: 10.1002/joc.4447

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

Liang X, Lettenmaier DP, Wood EF, and Burges SJ (1994), A Simple hydrologically Based Model of Land Surface Water and Energy Fluxes for GSMs, J. Geophys. Res, 99(D7), 14,415–14,428.

Liang X, Xie Z, and 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, J. Geophys. Res, 108, 8613, doi:10.1029/2002JD003090.

Maupin CR, Partin JW, Shen C-C, Quinn TM, Lin K, Taylor FW, Banner JL, Thirumalai K, and Sinclair DJ (2014), Persistent decadal-scale rainfall variability in the tropical South Pacific Convergence Zone through the past six centuries, Clim. Past 10, 1319e1332 10.5194/cp-10-1319-2014

McMahon PB, Dennehy KF, Bruce BW, Böhlke JK, Michel RL, Gurdak JJ, and Hurlbut DB (2006), Storage and transit time of chemicals in thick unsaturated zones under rangeland and irrigated

cropland, High Plains, United States, Water Resources Research, v. 42, 18 p., doi: 10.1029/2005WR004417.

Meixner Thomas, et al. (2016), Implications of projected climate change for groundwater recharge in the western United States, Journal of Hydrology 534 (2016): 124–138. 10.1016/j.jhydrol.2015.12.027

Mileham L, Taylor RG, Todd M, Tindimugaya C, and Thompson J (2009), The impact of climate change on groundwater recharge and runoff in a humid, equatorial catchment: Sensitivity of projections to rainfall intensity, Hydrol. Sci. J, 54(4), 727–738.

Munoz-Arriola F, Avissar R, Zhu C, and Lettenmaier DP (2009), Sensitivity of the Water resources of Rio Yaqui Basin, Mexico to agriculture extensification under multi-scale climate conditions, Water Resour. Res 45, W00A20, doi:10.1029/2007WR006783.

Nijssen B, Lettenmaier DP, Liang X, Wetzel SW, and Wood EF (1997), Streamflow Simulation for Continental-Scale River Basins, Water Resour. Res, 33, 711–724.

Nijssen B, O'Donnell GM, Hamlet AF, and Lettenmaier DP (2001), Hydrologic vulnerability of global rivers to climate change, Clim. Change, 50, 143–175.

Niraula R (2015). Understanding the hydrologic response of changed environmental boundary conditions in semi-arid regions: Role of model choice and model calibration. A PhD dissertation submitted to University of Arizona for the partial fulfillment of PhD degree in Hydrology.

Niraula R, Meixner T, Ajami H, Rodell M, Gochis D, and Castro C (2016). Comparing potential recharge estimates from three Land Surface Models across the Western US. Journal of Hydrology (in review)

Overpeck J, and Udall B (2010), Dry times ahead, Science, 328.5986: 1642–1643. [PubMed: 20576877]

Parr D, Wang G, and Ahmed KF (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 Volume 133, 10 2015, Pages 167–175

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., available at: 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., available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf.

Scanlon BR, et al. (2012), Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley, *Proc. Nat. Acad. Sci.* USA 109, 9320–9325. [PubMed: 22645352]

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

Serrat-Capdevila A, Valdées JB, Pérez JG, Baird K, Mata LJ, and 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.

Sleeter BM, Wilson TS, and 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 p. (Available at http://pubs.usgs.gov/pp/1794/a/.)

Stonestrom DA, Constantz J, Ferré TPA, and Leake SA (2007), Groundwater recharge in the arid and semiarid southwestern United States, U.S. Geological Survey Professional Paper 1703, Reston, VA, 414 p

Taylor RG, Koussis A & Tindimugaya C Groundwater and climate in Africa: A review. Hydrol. Sci. J. 54, 655–664 (2009).

Taylor RG, et al. (2013), Groundwater and climate change, Nature Climate Change, 3(4), 322–329.

Vaccaro JJ (1992), Sensitivity of groundwater recharge estimates to climate variability and change, Columbia Plateau, Washington, Journal of Geophysical Research: Atmospheres, v. 97, no. D3, p. 2821–2833, doi:10.1029/91JD01788.

Vano JA, et al. (2014), Understanding Uncertainties in Future Colorado River Streamflow. Bulletin of the American Meteorological Society, 95(1), 59–78.

Wood AW, Maurer EP, Kumar A, and Lettenmaier DP (2002), Long Range Experimental Hydrologic Forecasting for the Eastern U.S., J. Geophys. Res, 107(D20), pp. ACL 6-1–ACL 6-15, 27.

Wood AW, Leung LR, Sridhar V, and Lettenmaier DP (2004), Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs, Climatic Change, 15(62):189–216.

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.

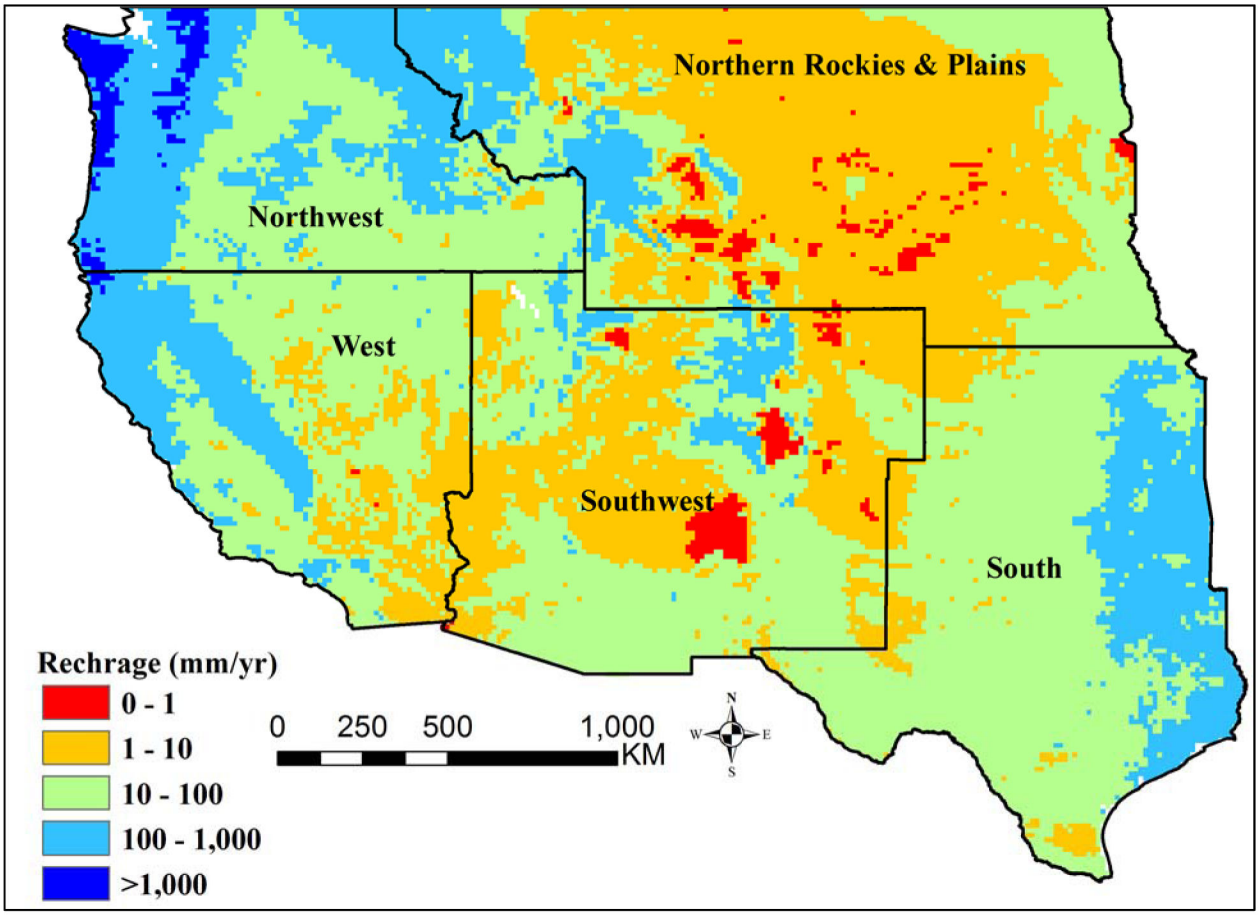

Fig 1:

Historical (averaged over 1981-2000) recharge estimates across the western US from the VIC model.

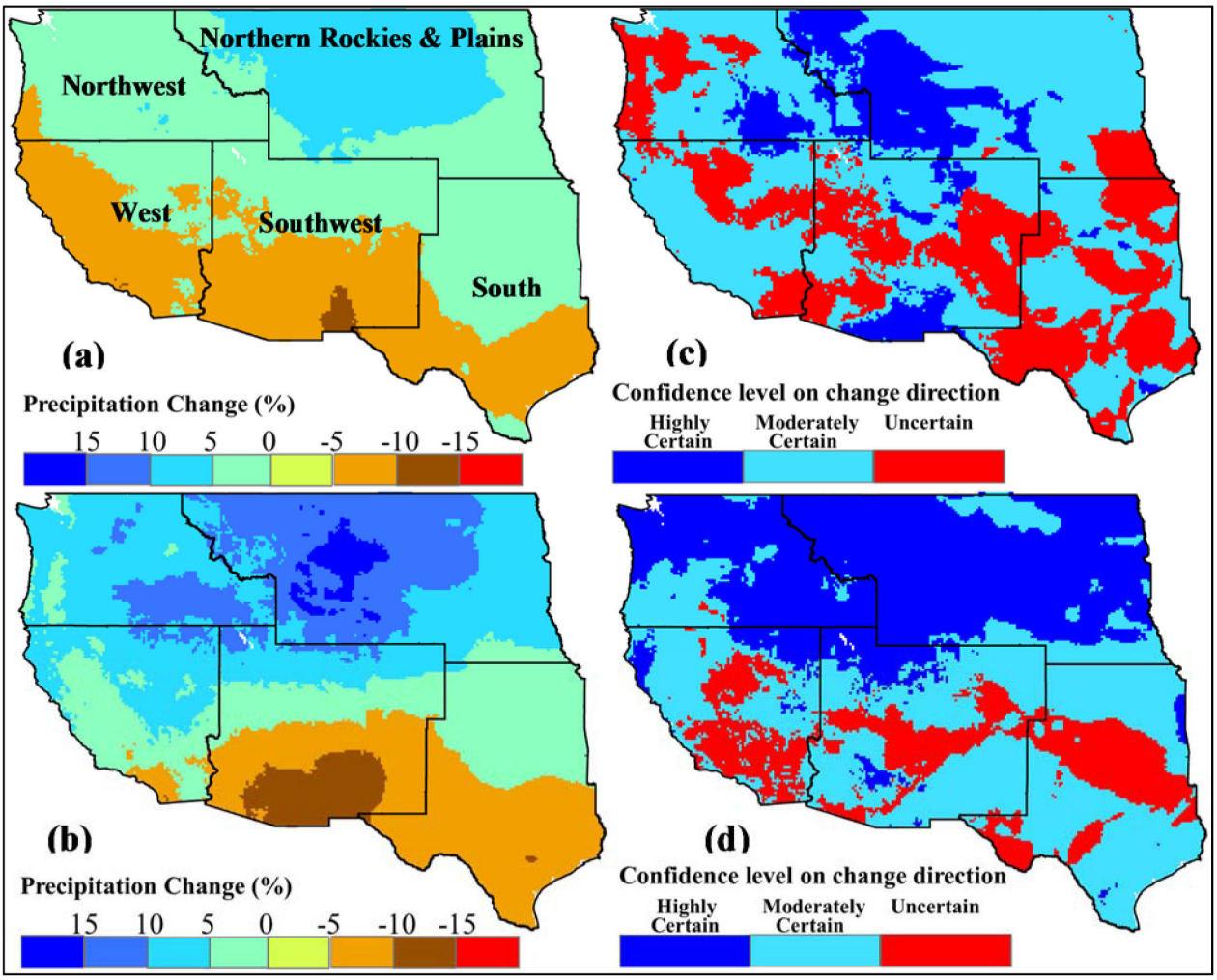

Fig 2:

Ensemble average relative change in precipitation for the (a) near and (b) far future compared to historic period along with the level of confidence in the direction of those changes for the near (c) and far (d) future.

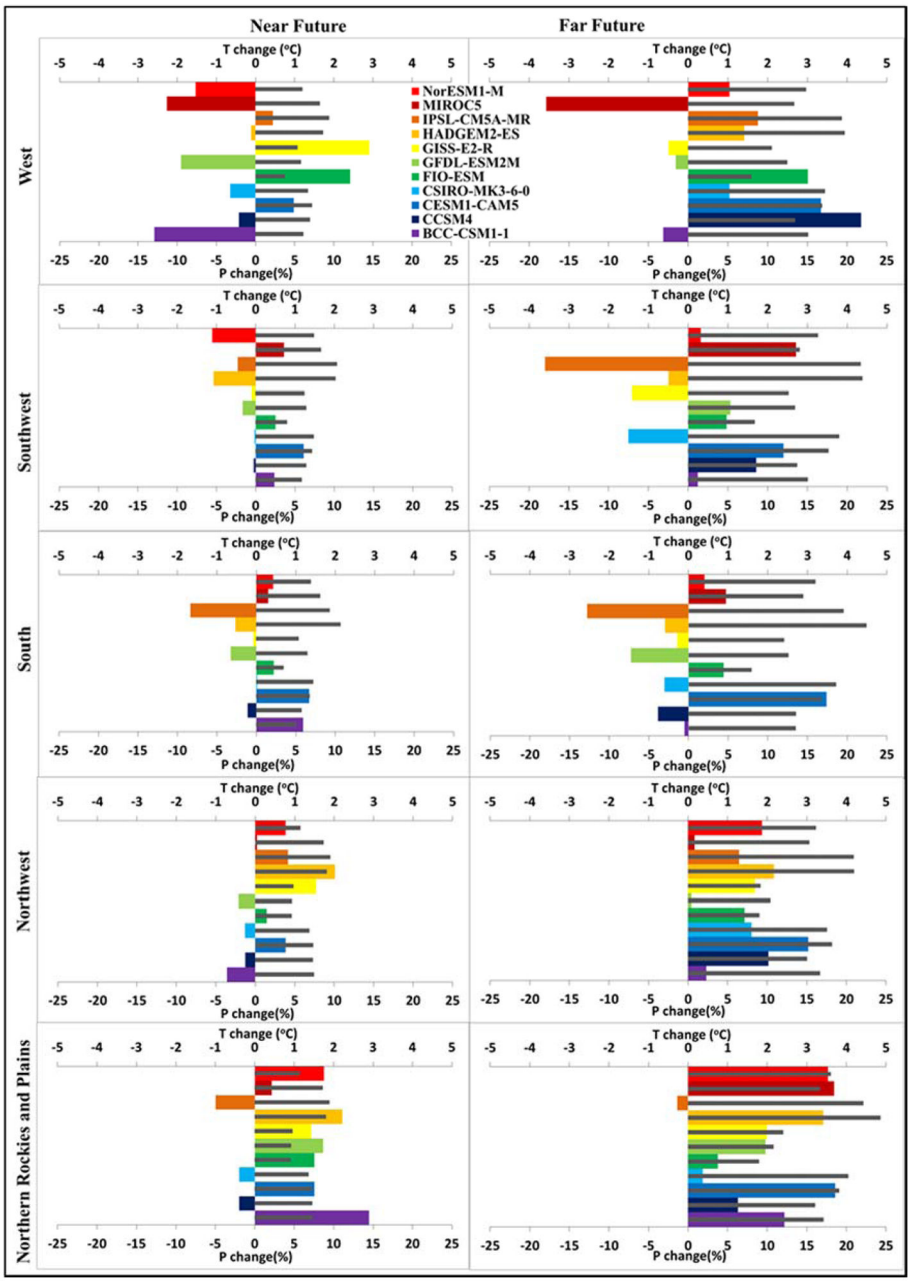

Fig 3:

Variability in the relative changes in climate (P and T) due to GCMs tor 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.

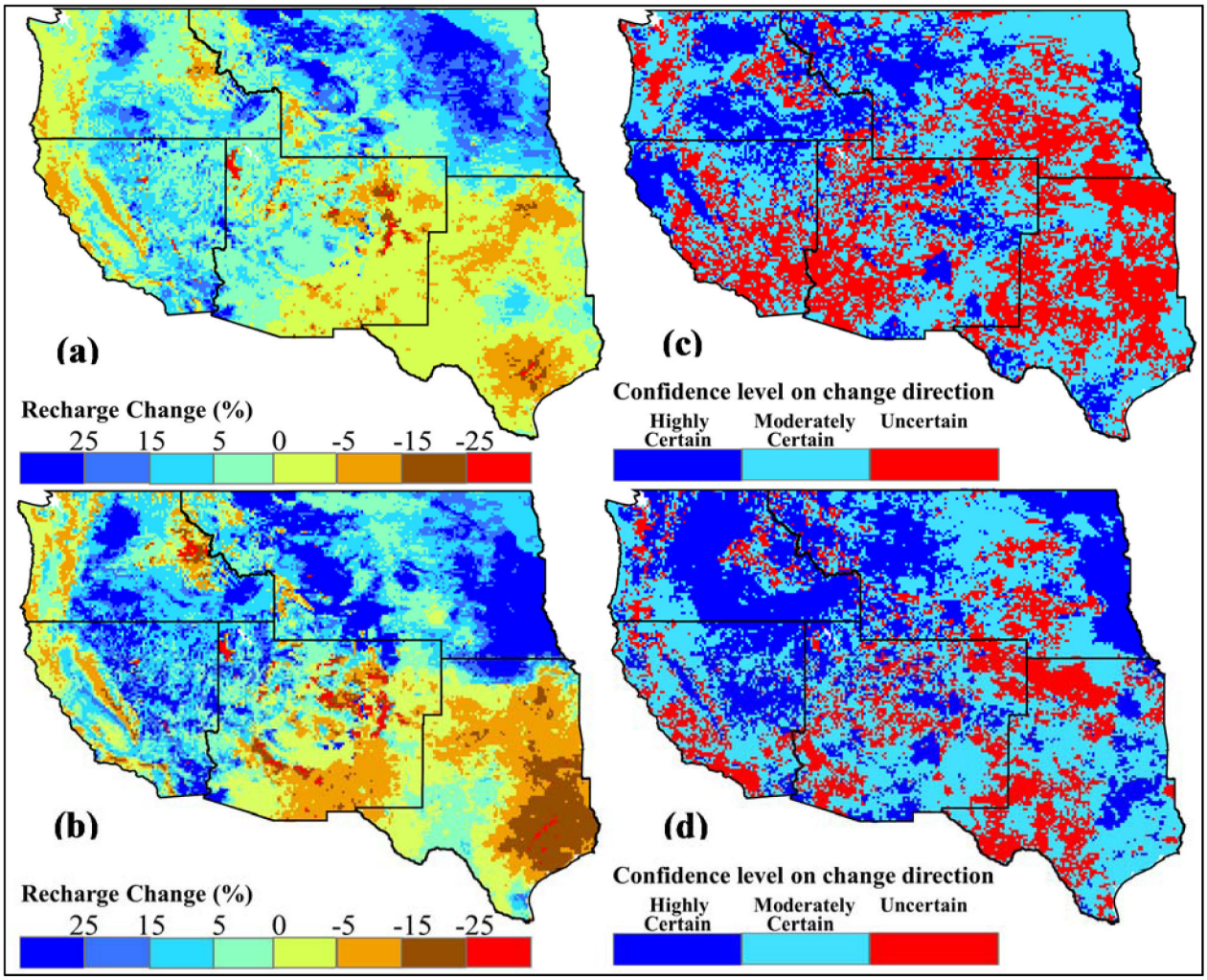

Fig 4:

Ensemble average relative change in recharge for the (a) near and (b) far future compared to historic period along with the level of confidence in the direction of those changes for the near (c) and far (d) future.

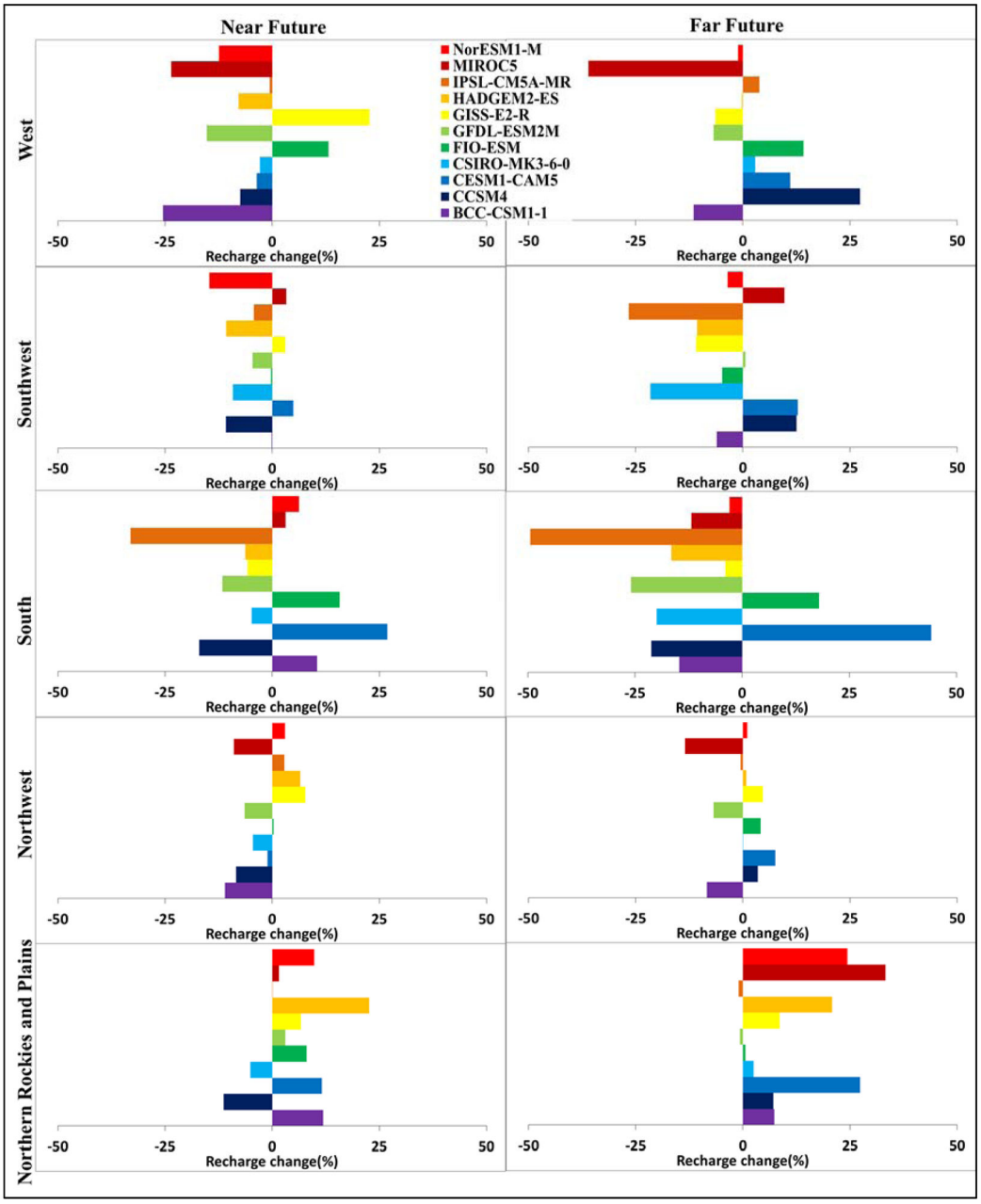

Fig 5:

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.

Table 1:

BCSD CMIP 5 (BCSD5) VIC Hydrology Projection Ensemble available for RCP 6.0 emission scenario

WCRP CMIP5 Climate Modeling Group	CMIP5 Climate model ID	Emission
Beijing Climate Center, China Meteorological Administration	BCC-CSM1-1	RCP 6.0
National Center for Atmospheric Research	CCSM4	RCP 6.0
Community Earth System Model Contributors	CESM1-CAM5	RCP 6.0
Commonwealth Scientific and industrial Research organization, Queensland Climate change center of excellence	CSIRO-MK3-6-0	RCP 6.0
The First Institute of Oceanography, State Oceanic Administration, China	FIO-ESM	RCP 6.0
NOAA Geophysical Fluid Dynamics Laboratory	GFDL-ESM2M	RCP 6.0
NASA Goddard Institute for Space studies	GISS-E2-R	RCP 6.0
Met Office Hadley Center	HADGEM2-ES	RCP 6.0
Institut Pierre-Simon Laplace	IPSL-CM5A-MR	RCP 6.0
Japan Agency for Marine-Earth Science and Technology, atmosphere and Earth research institute, The university of Tokyo	MIROC5	RCP 6.0
Norwegian Climate Center	NorESM1-M	RCP 6.0

Table 2:

Current conditions of climate and recharge and projected climate in the western US

	Current Conditions				Projected Climate Change				Projected Recharge Change			
Region	**Mean P (mm)**	**Recharge (mm)**	**Mean T (°C)**	**Recharge ratio (%)**	**%P change (NF)**	**%P change (FF)**	**T change (°C) (NF)**	**T change (°C) (FF)**	**% change (NF)**	**Confidence Level**	**% change (FF)**	**Confidence Level**
W	457	103	11.7	23	−1.3	4.9	1.35	2.93	−1.6	Highly Certain	−0.5	Uncertain
SW	372	27	10.6	8	−0.1	1.1	1.45	3.16	−2.9	Highly Certain	−4.4	Moderately Certain
S	732	61	16.7	8	0.3	−0.3	1.37	3.05	−3	Uncertain	−10.6	Highly Certain
NW	881	256	6.4	29	2.1	7.2	1.38	3.08	−0.4	Uncertain	−0.7	Uncertain
NR	481	43	6	9	5.3	10.4	1.54	3.37	5	Highly Certain	9	Highly Certain

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

Table 3:

Projected change in seasonality of recharge due to climate change

Region	Near Future (%)				Far Future (%)			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
West	2.4	−14.0	−25.3	−1.4	22.5	−5.1	−37.3	2.2
Southwest	−1.4	3.9	−15.3	−5.5	0.2	13.6	−30.5	−10.2
South	2.6	0.2	−4.5	−4.5	−16.0	−15.0	−11.2	−3.0
Northwest	6.1	−0.4	−17.1	−3.1	18.0	12.7	−30.8	−7.7
Northern Rockies	7.0	24.9	−6.4	1.3	13.0	59.0	−17.7	−6.3