RECLAMATION

Managing Water in the West

Effect of spatial and temporal scale on simulated groundwater recharge in the upper Colorado River basin (USA)

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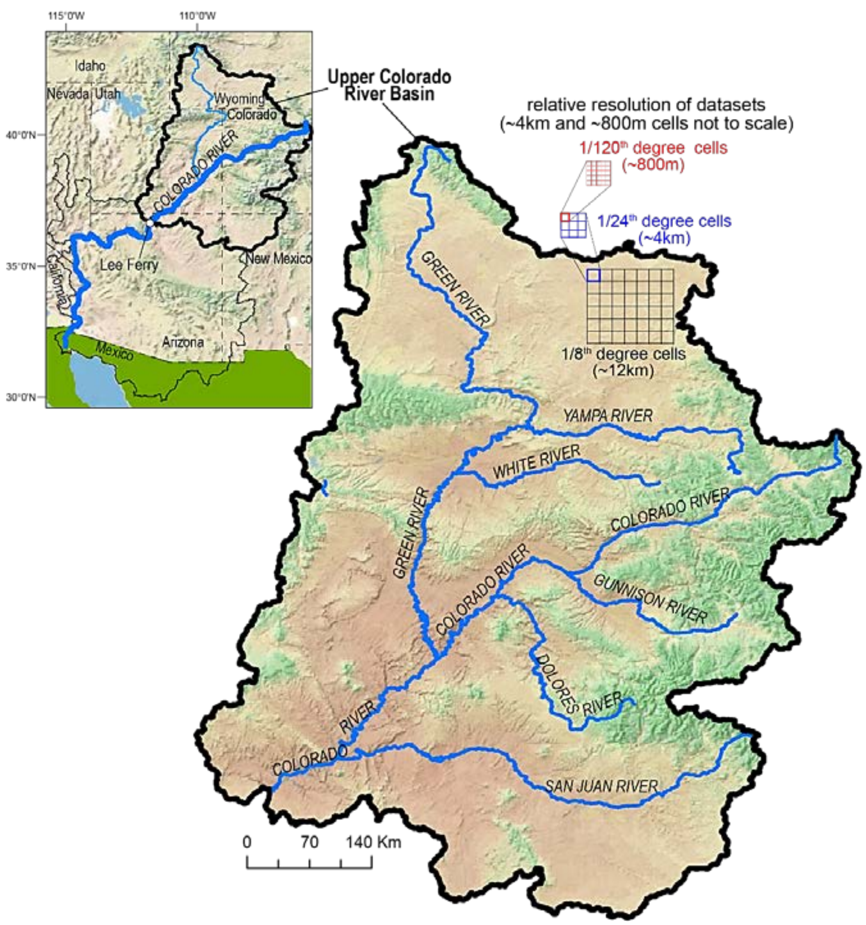

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Mission Statements

Protecting America's Great Outdoors and Powering Our Future

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

Cover image: Location of the upper Colorado River basin study area within the southwestern United States

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Smaller spatial and temporal scale input data allow groundwater recharge models to simulate more physically realistic processes and presumably result in more accurate estimates of groundwater recharge. Projected climate data are, therefore, often downscaled to smaller spatial and temporal scales for use in hydrologic models. It is unknown, however, if increasingly smaller-scale climate data produce substantially different simulated recharge results, either in magnitude or trend. Historical climate datasets at the three spatial and two temporal scales were used in Soil Water Balance model groundwater recharge simulations for the upper Colorado River basin over the water-year 1982–2014 time period. The magnitude of annual and moving ten-year annual average recharge results for daily climate data were within 5% and 7% of ~4km results for ~800m and ~12km climate data, respectively, with deviations from 1982–2014 means within 1% and 3% (median), respectively. Comparison of simulated recharge results using the coarsest spatial and temporal climate data with results from the finest scale data indicated similar small differences over ten-year moving annual averages, over water years, and during high recharge months. While differences in simulated groundwater recharge magnitude, which may be important for groundwater-flow simulations, were substantial during some seasonal comparisons, trends in recharge were almost identical across scales, leading to similar conclusions about change from "normal". Considering the uncertainty inherent in projected climate data, coarser spatial and longer temporal scale climate data may be sufficient for simulating changes in groundwater recharge, particularly for understanding trends in recharge over water year or longer time scales.

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Acronyms and Abbreviations

BCSD	Bias Correction and Spatial Disaggregation
DJF	December, January, and February
ESM	electronic supplementary material
GCM	general circulation models
JJA	June, July, and August
MAM	March, April, and May
NCAR	National Center for Atmospheric Research
POR	period-of-record
PET	potential evapotranspiration
SON	September, October, and November
SWB	soil-water balance
U.S.	United States
UCRB	upper Colorado River basin

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Executive Summary

Problem definition

Investigation of impacts from projected climate change on groundwater systems often involve the use of hydrologic model simulations with climate data from one or more general circulation models (GCM). Climate output from GCMs is typically provided at coarse spatial resolutions of ~100–200km on a cell side, which are then downscaled to ~12km (1/8th degree) daily datasets. For groundwater recharge simulations, finer spatial-scale models permit incorporation of more realistic variations in geologic, land use, and topographic information. Likewise, recharge in many areas of the southwestern United States occurs on a daily (or sub-daily) time scale. Considerable time and effort is therefore expended in downscaling GCM output to smaller spatial and temporal scales for use in hydrologic models. While smaller scales allow more realistic hydrologic processes to be simulated, it is unknown whether meaningfully different groundwater recharge simulations, either in magnitude or trend, result from using smaller versus larger scale climate data.

Research activities and solutions

This paper presents results from an investigation of simulated groundwater recharge in the upper Colorado River basin (UCRB) using historical climate data at the ~12km (1/8th degree), ~4km (1/24th degree), and ~800m (1/120th degree) scales on both daily and monthly time steps. These scale choices correspond to available contemporary climate data from archives such as the Downscaled Climate and Hydrology Projections and PRISM that are routinely used in a range of water resources planning studies. Simulated basin-scale groundwater recharge results for the different spatial and temporal scale data were compared on seasonal, annual, and moving ten-year average bases. Results of the magnitude of simulated groundwater recharge were compared as well as deviations from the period-of-record mean, which may be of more interest to water managers to whom changes from 'normal' are important.

UCRB groundwater recharge was simulated with the distributed-parameter soil-water balance (SWB) model for this study. Groundwater recharge is estimated by the SWB model by calculating water-balance parameters at daily time steps. SWB uses a modified Thornthwaite-Mather soil-water-balance accounting approach and groundwater recharge is estimated within each cell of the model domain. SWB estimates sources and sinks of water within each model cell from climate data and landscape characteristics, and then computes groundwater recharge as the difference between the change in soil moisture and these water sources and sinks. Daily climate data for the 1981–2014 time period at a 1/24th degree (~4km) spatial scale covering the UCRB study area were obtained from the PRISM Climate Group at Oregon State University. The daily ~4km PRISM climate data were aggregated to 1/8th degree (~12km) spatial scale and disaggregated to 1/120th (~800m) spatial scale climate data. Disaggregation from coarse to finer scale data (~4km to ~800m) was performed using the bilinear interpolation method. Fine grid to a coarse grid (~4km to ~12km) aggregation was performed using local area averaging to interpolate from a high resolution rectilinear grid to a low resolution rectilinear grid. Daily precipitation and temperature data at the three spatial scales also were aggregated into monthly stress periods for SWB simulations. Daily precipitation data were summed over each month and then the daily average for a month assigned to each day in that month. Daily minimum and maximum temperatures were each averaged over each month with the daily average for a month then assigned to each day in that month. In this way, the SWB model, which runs on a daily time step, could be used to simulate groundwater recharge as if only monthly climate data were available.

Application and results

Groundwater recharge in the UCRB was simulated over the water-year 1982–2014 time period using ~12km, ~4km, and ~800m climate data at both daily and monthly time steps. For both daily and monthly temporal scale simulations, similar recharge magnitude and trend (deviation from period-of-record mean) were seen across all spatial scales for ten-year annual average and water-year comparisons. Seasonal comparisons of results revealed similarities in magnitude and trend of recharge during the spring season of March, April, and May when ~70% of UCRB recharge occurs. Substantial differences were seen in simulated recharge magnitudes in other seasons between different spatial scales, with median differences of as much as 36% from ~4km results. Comparison of simulated recharge results using the coarsest spatial and temporal climate data, ~12km monthly scale, with results from the finest scale data, ~800m daily data, indicated similar small differences in results from the different scales over ten-year moving annual averages, over water years, and during the high recharge months of March, April, and May.

While differences in simulated groundwater recharge magnitude, which may be important for groundwater-flow simulations, across spatial and temporal scale simulations are substantial during some seasonal comparisons, trends in recharge are almost identical across scales, leading to similar conclusions about change from “normal”. Especially considering the uncertainty inherent in projected climate data, coarser spatial and longer temporal scale climate data may be sufficient for simulating changes in groundwater recharge, particularly for understanding trends in recharge over water year or longer time scales.

Future plans

An additional question regarding the impact of projected climate change on groundwater recharge is, how might future changes in land use coupled with projected climate change affect groundwater recharge? Increases in certain land use types and decreases in others will change both the magnitude and distribution of simulated groundwater recharge. Are these changes important relative to the large variance in simulated groundwater recharge from projected climate data alone?

Effect of spatial and temporal scale on simulated groundwater recharge in the upper Colorado River basin (USA)

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Abstract Smaller spatial and temporal scale input data allow groundwater recharge models to simulate more physically realistic processes and presumably result in more accurate estimates of groundwater recharge. Projected climate data are, therefore, often downscaled to smaller spatial and temporal scales for use in hydrologic models. It is unknown, however, if increasingly smaller-scale climate data produce substantially different simulated recharge results, either in magnitude or trend. Historical climate datasets at the three spatial and two temporal scales were used in Soil Water Balance model groundwater recharge simulations for the upper Colorado River basin over the water-year 1982–2014 time period. The magnitude of annual and moving ten-year annual average recharge results for daily climate data were within 5% and 7% of ~4km results for ~800m and ~12km climate data, respectively, with deviations from 1982–2014 means within 1% and 3% (median), respectively. Comparison of simulated recharge results using the coarsest spatial and temporal climate data with results from the finest scale data indicated similar small differences over ten-year moving annual averages, over water years, and during high recharge months. While differences in simulated groundwater recharge magnitude, which may be important for groundwater-flow simulations, were substantial during some seasonal comparisons, trends in recharge were almost identical across scales, leading to similar conclusions about change from “normal”. Considering the uncertainty inherent in projected climate data, coarser spatial and longer temporal scale climate data may be sufficient for simulating changes in groundwater recharge, particularly for understanding trends in recharge over water year or longer time scales.

Keywords upper Colorado River basin, groundwater recharge, climate change

1. Introduction

Investigation of impacts from projected climate change on groundwater systems often involve the use of hydrologic model simulations with climate data from one or more general circulation models (GCM) (for example, see Tillman et al. 2016; Allen et al. 2010; Crosbie et al. 2010; Kopytkovskiy et al. 2015). Climate output from GCMs is typically provided at coarse spatial resolutions of ~100–200km on a cell side, which are then downscaled to ~12km (1/8th degree) daily datasets (Brekke et al. 2013). For groundwater recharge simulations, finer spatial-scale models permit incorporation of more realistic variations in geologic, land use, and topographic information. Likewise, recharge in many areas of the southwestern United States occurs on a daily (or sub-daily) time scale (Stonestrom et al. 2007). Considerable time and effort is therefore expended in downscaling GCM output to smaller spatial and temporal scales for use in hydrologic models. While smaller scales allow more realistic hydrologic processes to be simulated, it is unknown whether meaningfully different groundwater recharge simulations, either in magnitude or trend, result from using smaller versus larger scale climate data. This paper presents results from an investigation of simulated groundwater recharge in the upper Colorado River basin using historical climate data at the ~12km (1/8th degree), ~4km (1/24th degree), and ~800m (1/120th degree) scales on both daily and monthly time steps. These scale choices correspond to available contemporary climate data from archives such as the Downscaled Climate and Hydrology Projections (Maurer et al. 2007) and PRISM (PRISM Climate Group 2016) that are routinely used in a range of water resources planning studies (e.g., Tillman et al. 2017a; Tillman et al. 2017b; see Bureau of Reclamation 2017 for others). Simulated basin-scale groundwater recharge results for the different spatial and temporal scale data are compared on seasonal, annual, and moving ten-year average bases. Results of the magnitude of simulated groundwater recharge are compared as well as deviations from the period-of-record mean, which may be of more interest to water managers to whom changes from 'normal' are important.

This study investigates the effect of spatial and temporal scale on simulated groundwater recharge in the upper Colorado River basin (UCRB; Fig. 1). The Colorado River is an important source of water in the southwestern United States (U.S.), supplying the domestic and industrial water needs of more than 38 million people in the U.S. and Mexico (Bureau of Reclamation 2011; Colorado River Basin Salinity Control Forum 2013). At Lake Mead in Arizona, downstream of which nearly all of the Colorado River water is used, the UCRB contributes almost 90% of the flow in the River (U.S. Geological Survey 2016). The UCRB stream system receives an estimated 30-50% of its flow from groundwater discharge (Miller et al. 2014; Rumsey et al. 2015). For this study, the UCRB is defined as the drainage area of the Colorado River upstream of the Lee Ferry, Arizona compact point, plus the Great Divide closed basin, as delineated by the U.S. Geological Survey region 14 hydrologic unit code (Fig. 1; see http://water.usgs.gov/GIS/huc.html).

2. Methods and Data

UCRB groundwater recharge was simulated with the distributed-parameter soil-water balance (SWB) model for this study (Westenbroek et al. 2010). Groundwater recharge is estimated by the SWB model by calculating water-balance parameters at daily time steps. SWB uses a modified Thornthwaite-Mather (Thornthwaite 1948; Thornthwaite and Mather 1957) soil-water-balance accounting approach and groundwater recharge is estimated within each cell of the model domain. SWB estimates sources and sinks of water within each model cell from climate data and landscape characteristics, and then computes groundwater recharge as the difference between the change in soil moisture and these water sources and sinks. SWB model simulations require spatially gridded datasets including daily precipitation, daily maximum temperature, daily minimum temperature, hydrologic soil group, land cover, available soil-water capacity, and overland flow direction. SWB simulations also require input datasets in a tabular format including vegetation rooting depths, runoff curve numbers, interception values, and maximum daily recharge values for each combination of land-cover type and hydrologic soil group. A detailed discussion of input datasets, computational details, and limitations of the SWB model are presented in the Supplemental Material.

Daily climate data for the 1981–2014 time period at a 1/24th degree (~4km) spatial scale covering the UCRB study area were obtained from the PRISM Climate Group at Oregon State University (PRISM Climate Group 2016). The daily ~4km PRISM climate data were aggregated to 1/8th degree (~12km) spatial scale and disaggregated to 1/120th (~800m) spatial scale climate data (Fig. 1). Disaggregation from coarse to finer scale data (~4km to ~800m) was performed using the bilinear interpolation method, specifically the 'linint2' function from the National Center for Atmospheric Research (NCAR) Command Language (NCL; NCAR 2017). This method has been used by Reclamation and Reclamation collaborators to downscale relatively coarse (~100-200km) climate projections to finer spatial scales (1/8th degree) using the Bias Correction and Spatial Disaggregation (BCSD) statistical downscaling algorithm. Fine grid to a coarse grid (~4km to ~12km) aggregation was performed using the 'area_hi2lores' NCL function (NCAR 2017). This function uses local area averaging to interpolate from a high resolution rectilinear grid to a low resolution rectilinear grid. Though NCL provides a number of re-gridding functions, the 'linint2' and 'area_hi2lores' for disaggregation and aggregation respectively, were used in this study because they have been used previously in developing and studying contemporary climate datasets from GCM projections (e.g., Maurer et al. 2007; Gutmann et al. 2014).

Daily precipitation and temperature data at the three spatial scales also were aggregated into monthly stress periods for SWB simulations. Daily precipitation data were summed over each month and then the daily average for a month assigned to each day in that month. Daily minimum and maximum temperatures were each averaged over each month with the daily average for a month then assigned to each day in that month. In this way, the SWB model, which runs on a daily time step, could be used to simulate groundwater recharge as if only monthly climate data were available.

3. Results and Discussion

UCRB groundwater recharge was simulated with the SWB model at three spatial and two temporal scales. Results from simulations using ~12km and ~800m daily climate data are compared with simulation results using the original ~4km daily PRISM climate data. Similarly, simulation results using ~12km and ~800m climate data on monthly time steps are compared with simulation results using ~4km monthly climate data. For both daily and monthly climate data, results are summarized and compared over ten-year average annual periods, over water years, and over three-month seasons. To summarize and compare temperature data, potential evapotranspiration (PET) values are used. PET values are a convenient measure of the effect of basin-wide temperature differences and are based on maximum and minimum daily temperatures (see electronic supplementary material (ESM) for description). All SWB groundwater recharge modeling results for the UCRB are available at the U.S. Geological Survey ScienceBase web site (Tillman 2016).

3.1 Daily climate data results

Annual simulated groundwater recharge averaged over ten-year periods, moving every year, for the original ~4km daily PRISM climate data ranged from a high of 10.4 billion (B) m^3 over the 1982–1991 time period to a low of 7.8B m^3 over the 1998–2007 time period (Fig. 2a). Recharge results using ~12km and ~800m climate data follow the same temporal pattern as the ~4km results (Fig. 2a), but are systematically less than the ~4km results (Fig. 2b). The amount of reduced recharge, however, is relatively small, with a median percentage change from the ~4km results (difference divided by the ~4km result) of 4.6% for the ~800m results and 5.8% for the ~12km results (Fig. 2b, Table 1). The temporal trend in simulated recharge, defined here as deviation from the 1982–2014 period-of-record (POR) average for each spatial scale, ranged from 114% to 86% of the POR mean for the ~4km results (Fig. 2c). Recharge trends for the ~12km and ~800m results are even more similar to the ~4km trends than the recharge magnitude results, with median percentage change from the ~4km ten-year average annual recharge trends of less than 1% for both the ~800m and ~12km results (Fig. 2d, Table 1). Over ten-year moving annual averages, recharge simulations using daily climate data at the smallest spatial scale investigated do not differ substantially from simulations at the larger scales, either in absolute magnitude or in trend.

UCRB simulated recharge over water years from 1982 through 2014 using the original ~4km daily PRISM climate data ranged from a high of 16.6B m^3 during water year 1993 to a low of 2.9B m^3 during water year 2002 (Fig. 3a). Similar to the ten-year moving annual average results, water-year recharge results using ~12km and ~800m climate data follow the same temporal pattern as the ~4km results (Fig. 3a), also are systematically less than the ~4km results (Fig. 3b), and only by a similarly small amount (median percentage change from the ~4km results of 4.7% for the ~800m results and 6.3% for the ~12km results; Fig. 3b; Table 1). Simulated recharge in a few low-recharge years, however, is substantially less for the ~12km climate data than for the ~4km climate data, including a 13.6% decrease in 1992, a 13.1% decrease in 2012, and a 12.1% decrease in 2002 (Fig. 3). Differences in simulated recharge in these years are in contrast to the very small differences in precipitation of <0.18% and potential evapotranspiration (PET) of <0.03% (Fig. S2 and S3 of the ESM). Deviation from the POR average is predictably greater for the water-year results compared with the smoothed ten-year moving annual average results (Fig. 3c). Water-year recharge results using the ~4km climate data are as much as 76% greater and 70% less than the 1982–2014 average (Fig. 3c). Recharge trends for the ~12km and ~800m results also are similar to the ~4km trends, with median percentage change from the ~4km water-year recharge trends of less than 3% for both the ~800m and ~12km results (Fig. 3d, Table 1). Unlike the ten-year moving annual average results, water-year deviations from POR means are less for ~4km results than for the other spatial resolutions in several years, particularly the ~12km results (Fig. 3d). With the exception of a few years, water-year simulation results for the 1982–2014 time period for all spatial resolutions are similar in both magnitude and trend of recharge.

Simulated recharge results from daily climate data also were summarized in water-years 1982 to 2014 over seasonal time periods including the winter months of December, January, and February (DJF), spring months of March, April, and May (MAM), summer months of June, July, and August (JJA), and fall months of September, October, and November (SON). Winter and spring seasonal recharge, which account for 8% and 71% of simulated annual recharge in the UCRB, respectively, showed similar small differences in both magnitude and trend between simulations using the different spatial resolution datasets as were seen with the water-year and ten-year moving annual average results (Figs. S4 and S5 of the ESM). Median differences in DJF recharge magnitude from ~4km results were 4% and 7% for ~800m and ~12km climate data, respectively, and median MAM differences in recharge magnitude from ~4km results were 4% for both ~800m and ~12km climate data (Figs. S4 and S5 of the ESM; Table 1). Simulated recharge in the JJA summer months, which account for 16% of simulated annual UCRB recharge, resulted in substantial differences in recharge magnitude between the ~4km climate data and the ~800m (median difference of 21%) and ~12km (median difference of 36%) climate data (Fig. 4a, b; Table 1). The somewhat higher simulated JJA recharge using ~4km climate data than simulations using ~800m or ~12km data cannot be explained by differences in either precipitation (Fig. S6 of the ESM) or PET (Fig. S7 of the ESM), both of which differ by less than 0.2% from ~4km data for both resolutions. Simulated snowmelt in JJA, however, differs from ~4km results by a similar amount to differences in recharge results, with a 15% median difference in snowmelt for the ~800m climate data and a 35% median difference for the ~12km data (Fig. 5). Differences in temperature between the different spatial datasets, particularly when temperatures are near freezing, in relatively limited high-altitude areas of the UCRB can result in differences in the amount of snow cover and subsequent differences in the amount of snowmelt during warmer months. These potentially small temperature differences in limited areas would not show up in the UCRB-wide summary of temperature in the PET comparisons (Fig. S7 of the ESM). Trends in JJA recharge from simulations using the different spatial resolutions, however, were more similar than magnitude results, with a median difference of 5% for the ~800m results and a median difference of 12% for the ~12km results, compared with results from the ~4km climate data (Fig. 4c,d; Table 1). Recharge magnitude during fall months of September, October, and November differs between simulations using the different spatial resolutions somewhat less than during JJA, with median percentage change of 18% and 16% for ~800m results and ~12km results compared with results from the ~4km climate data (Fig. S8 of the ESM; Table 1). Differences in trends in SON recharge are similar to those from JJA, with median differences of 7% and 9% for ~800m results and ~12km results compared with results from the ~4km climate data (Fig. S8 of the ESM; Table 1). Simulated recharge in SON, however, is only about 5% of the total annual amount for the UCRB.

3.2 Monthly climate data results

Daily precipitation and temperature data at the three spatial scales were aggregated into monthly stress periods for SWB simulations as described previously. Annual simulated groundwater recharge averaged over ten-year periods, moving every year, using the ~4km monthly climate data ranged from a high of 9.5 billion (B) m^3 over the 1982–1991 time period to a low of 6.8B m^3 over the 1998–2007 time period (Fig. 6a). Recharge results using ~4km monthly climate data were 6.3–12.5% less than results using ~4km daily data over comparable time periods (Fig. 6a). As with the daily climate data results, recharge results using ~12km and ~800m monthly climate data follow the same temporal pattern as the monthly ~4km results (Fig. 6a), but are systematically less than the ~4km results (Fig. 6b). The amount of reduced recharge from monthly data is similar to comparative reductions from daily climate results, with a median percentage change from the ~4km results of 3.6% for the ~800m results and 5.9% for the ~12km results (Fig. 6b; Table 2). The temporal trend in simulated recharge ranged from 116% to 83% of the POR mean for the monthly ~4km results, with nearly identical deviations from POR mean as results from daily ~4km climate data (Fig. 6c). Recharge trends for the monthly ~12km and ~800m results also are nearly identical to the ~4km trends (Fig. 6d; Table 2).

UCRB water-year simulated recharge over the 1982–2014 time period using monthly ~4km climate data ranged from a high of 15.7B m^3 during water year 1993 to a low of 2.6B m^3 during water year 2002 (Fig. 7a). Recharge results using ~4km monthly climate data were from 2.8% more in 2004 to 22.8% less in 2007 than results using ~4km daily data over comparable time periods, with most water-year values about 10% less (Fig. 7a). Similar to water-year results using daily climate data, water-year recharge results using ~12km and ~800m monthly climate data follow the same temporal pattern as the ~4km monthly data results (Fig. 7a), and also are systematically less than the ~4km monthly results by a small amount (Fig. 7b). The median percentage change of ~800m and ~12km monthly data results from ~4km monthly data results is 3.5% and 6.9%, respectively (Fig. 7b; Table 2). Simulated recharge in a few low-recharge years also is substantially less for the ~12km monthly climate data than for the ~4km monthly climate data, including a 14.3% decrease in 1992 and a 12.7% decrease in 2012. In a similar manner to daily climate data results, differences in monthly climate data simulated recharge in these years are in contrast to the very small differences in precipitation of <0.17% and potential evapotranspiration (PET) of <0.03% (Fig. S9 and S10 of the ESM). Deviation of water-year results from the 1982–2014 average are similar between results from all spatial resolution data on a monthly time step and between the monthly and daily ~4km climate data results (Fig. 7c, d). Median percentage change from the monthly ~4km recharge trends is less than 2.5% for both the monthly ~800m and ~12km results (Fig. 7d; Table 2). Median percentage change of monthly ~4km climate data results from daily ~4km climate data results is 4.8%. For the most part, water-year simulation results for the 1982–2014 time period using monthly climate data are similar among all spatial resolutions and between ~4km daily and all monthly resolutions, particularly when comparing deviation of recharge from POR means.

As seen with simulated recharge results using daily climate data over seasonal time spans, the magnitude of recharge results from simulations using monthly climate data were more variable among the different spatial datasets for the summer (JJA; Fig. 8) and fall (SON; Fig. S11 of the ESM) months than for winter (DJF; Fig. S12 of the ESM) or spring (MAM; Fig. S13 of the ESM). The magnitude of simulated recharge in the summer months of JJA, which account for 27% of the annual simulated recharge using monthly climate data, were less than ~4km results by median values of 19% and 32% for ~800m and ~12km results, respectively. The magnitude of recharge results from the fall months of SON differ from ~4km results by 25% and 30% for ~800m and ~12km results, respectively, but make up only 2% of the annual simulated UCRB recharge using monthly climate data (Fig. S11 of the ESM). Recharge trends are more similar among the different spatial scales during all seasons, with the highest median difference of 19% between ~12km and ~4km results in SON (Fig. S11 of the ESM). For the two seasons of MAM (Fig. S13 of the ESM) and JJA (Fig. 8) comprising almost 95% of the annual UCRB recharge, median differences between monthly ~4km results and other spatial data results was 12% or less (Table 2). In a similar manner to the daily climate data results, differences in simulated recharge in JJA using monthly climate data appears to be related to differences in snowmelt during this time period (Fig. 9).

3.3 Comparison of ~800m daily and ~12km monthly results

UCRB recharge from simulations using ~800m daily and ~12km monthly data were compared in order to explore the effect of the maximum range in both spatial and temporal data on recharge results. The magnitude of annual simulated groundwater recharge averaged over ten-year periods, moving every year, was greater for the ~800m daily climate data than for the ~12km monthly climate data, by about 10% over the 1982–2014 time period (Fig. 10a, b). Comparison of results from each climate dataset to their respective POR mean, however, indicate almost identical simulated groundwater recharge trends, with a median difference in results between the two climate datasets of less than 2% (Fig. 10c, d).

The magnitude of UCRB simulated recharge over water years from 1982 through 2014 using ~800m daily climate data also were somewhat greater than results using ~12km monthly data, by a median difference of 11% (Fig. 11a, b). Simulated recharge trends between the two climate datasets were similar, with deviation from the POR mean sometimes greater for the ~800m daily climate data but sometimes less (Fig. 11c, d), with an overall median difference between the two datasets of 5.9%.

As with results within the daily and monthly time scale comparisons, smaller differences in seasonal results between simulations using ~800m daily climate data and ~12km monthly data are seen in the season with largest percentage of UCRB yearly recharge (Fig. 12). The spring months of March, April, and May account for about 73% of the yearly UCRB recharge for both the ~800m daily and ~12km monthly simulations, with median differences in simulated recharge magnitude of about 9% and median differences in trends of about 6% (Fig. 12). Recharge in summer (JJA) is less, but still accounts for a substantial 14-21% of simulated annual UCRB recharge. JJA simulated recharge differs between the ~800m daily and ~12km monthly simulations by a median of 55% for magnitude comparisons and by 21% for trend comparisons (Fig. 13). Fall and winter seasons together account for about 10% of annual UCRB recharge, and differ between simulations from the two climate datasets by a median 80% or more in magnitude and 34% or more in trend (Figs. S14 and S15 of the ESM).

4. Conclusions

While smaller spatial and temporal scale input data allow hydrologic models to simulate more physically realistic processes, it is not clear that increasingly smaller scale data produce substantially different results. This study investigated the effect of spatial and temporal scale on simulated groundwater recharge in the upper Colorado River basin using the Soil Water Balance model over the water-year 1982–2014 time period. Groundwater recharge was simulated using ~12km, ~4km, and ~800m climate data at both daily and monthly time steps. For both daily and monthly temporal scale simulations, similar recharge magnitude and trend (deviation from period-of-record mean) were seen across all spatial scales for ten-year annual average and water-year comparisons. Seasonal comparisons of results revealed similarities in magnitude and trend of recharge during the spring season of March, April, and May when ~70% of UCRB recharge occurs. Substantial differences were seen in simulated recharge magnitudes in other seasons between different spatial scales, with median differences of as much as 36% from ~4km results. Comparison of simulated recharge results using the coarsest spatial and temporal climate data, ~12km monthly scale, with results from the finest scale data, ~800m daily data, indicated similar small differences in results from the different scales over ten-year moving annual averages, over water years, and during the high recharge months of March, April, and May.

While differences in simulated groundwater recharge magnitude, which may be important for groundwater-flow simulations, across spatial and temporal scale simulations are substantial during some seasonal comparisons, trends in recharge are almost identical across scales, leading to similar conclusions about change from “normal”. Especially considering the uncertainty inherent in projected climate data, coarser spatial and longer temporal scale climate data may be sufficient for simulating changes in groundwater recharge, particularly for understanding trends in recharge over water year or longer time scales.

Acknowledgments

Investigation of the impact of spatial and temporal scale of climate data on simulated groundwater recharge in the upper Colorado River basin was supported by the Bureau of Reclamation Science and Technology Program and the USGS Groundwater Resources Program. All SWB groundwater recharge modeling results for the UCRB discussed in this manuscript are available at the U.S. Geological Survey ScienceBase web site (Tillman, 2017).

Electronic supplementary material The online version of this article contains supplementary material, which is available to authorized users.

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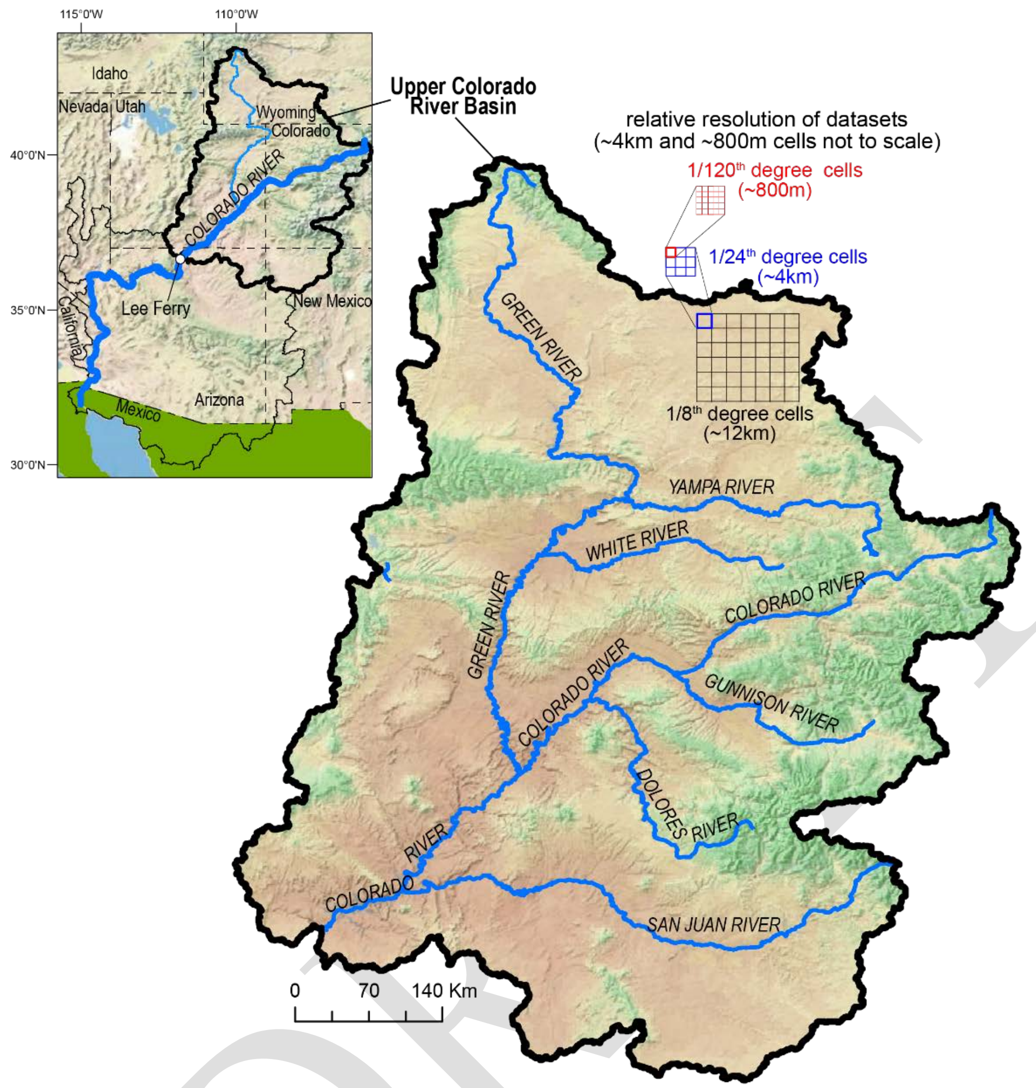

Fig 1 Location of the upper Colorado River basin study area within the southwestern United States

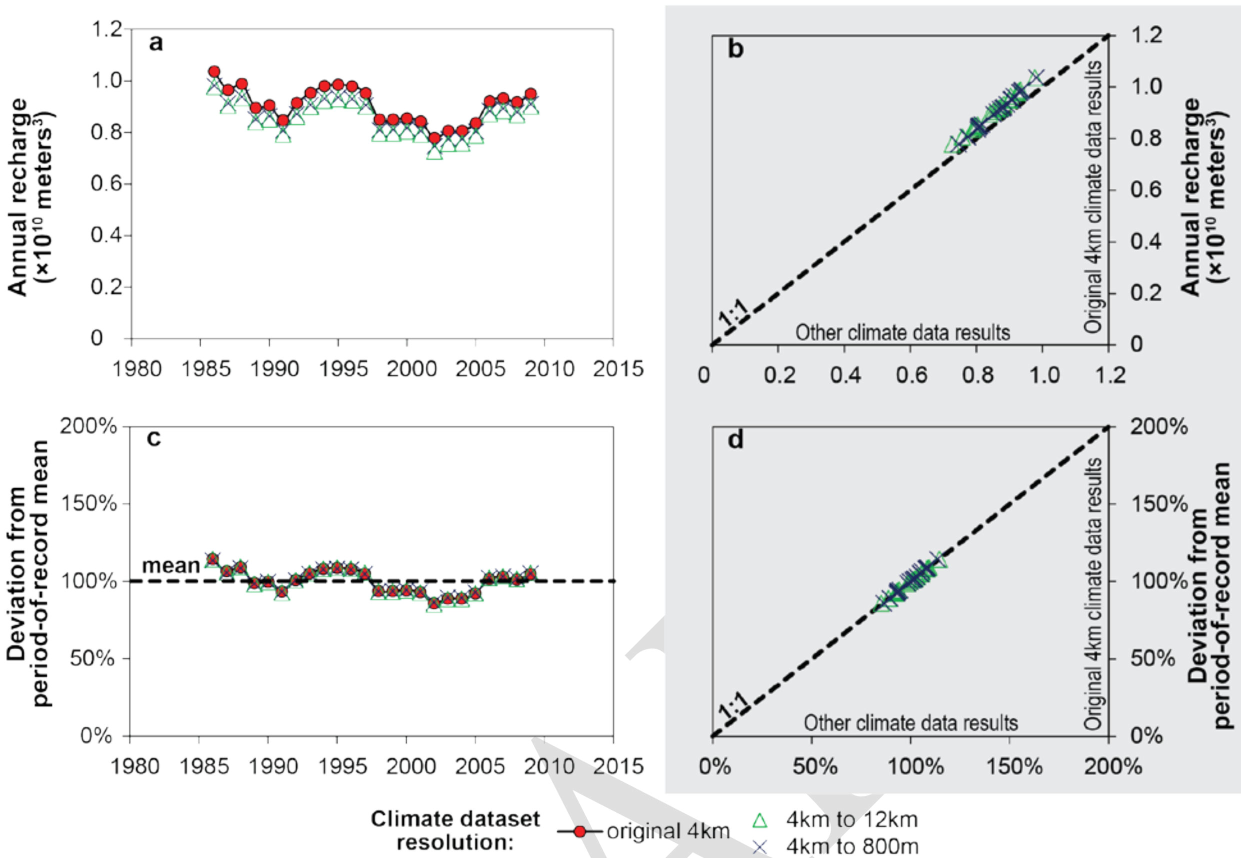

Fig 2 Annual simulated groundwater recharge in the upper Colorado River basin averaged over ten-year periods, moving every year, for water years 1982–2014 using ~800m, ~4km, and ~12km daily climate data. Results presented as (a) magnitude of average annual recharge through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of average annual recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data. Symbols on time series charts are placed in the middle of the ten-year averaging period

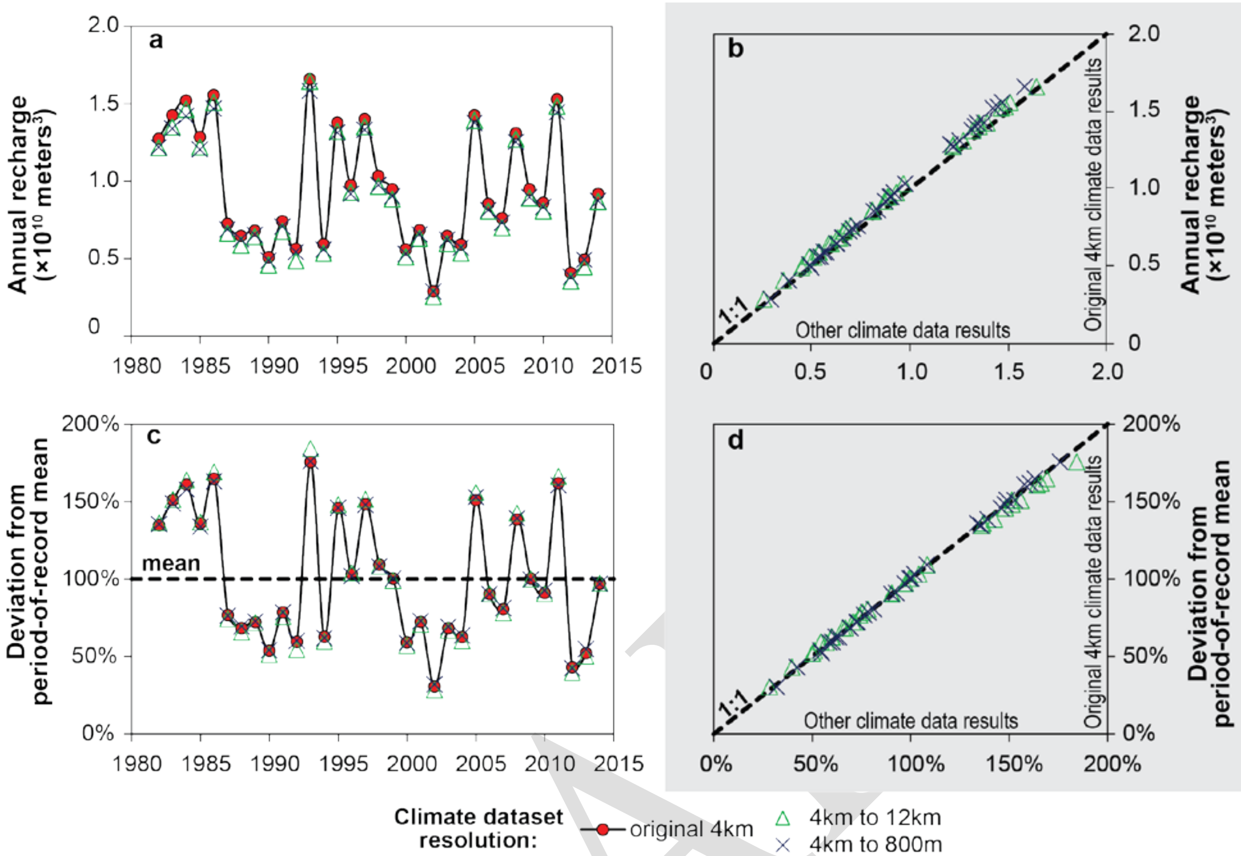

Fig 3 Annual simulated groundwater recharge in the upper Colorado River basin for water years 1982–2014 using ~800m, ~4km, and ~12km daily climate data. Results presented as (a) magnitude of annual recharge through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of annual recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data

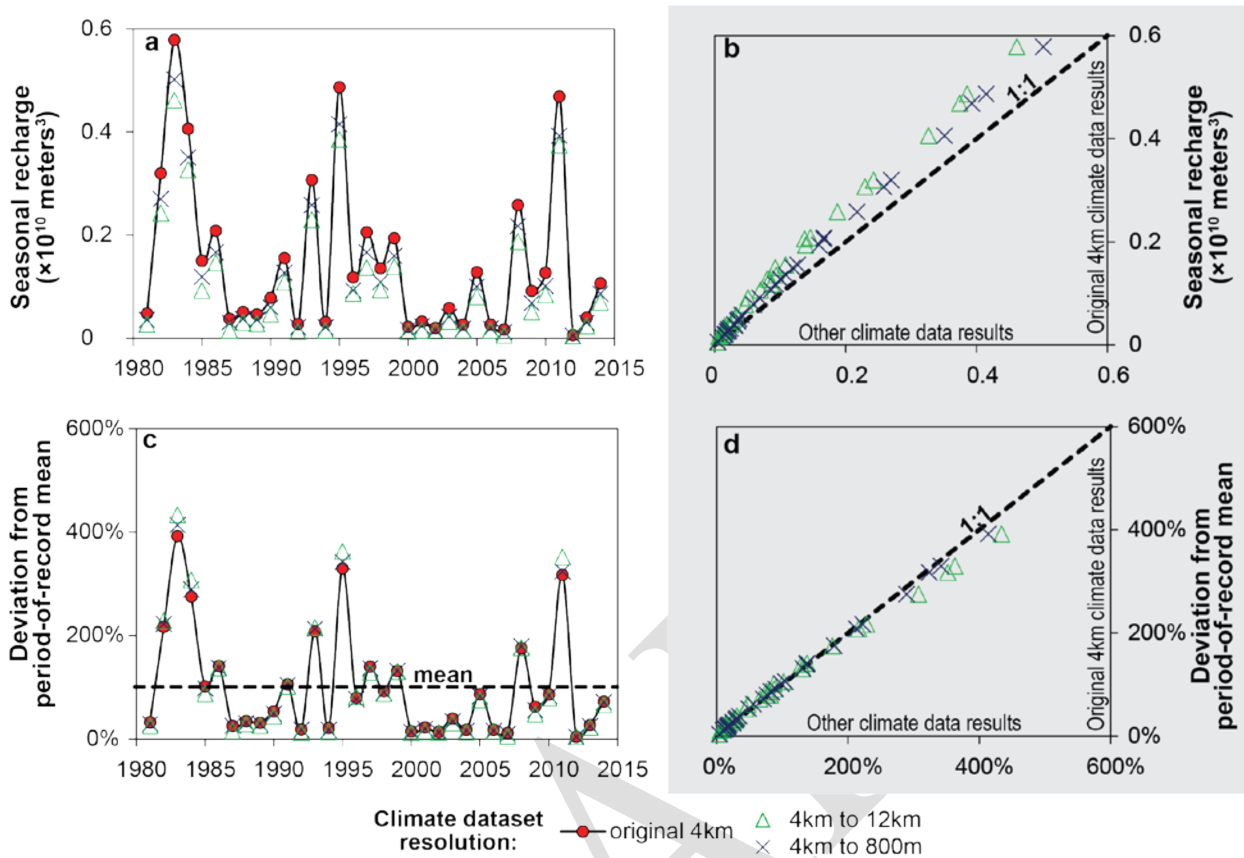

Fig 4 Simulated groundwater recharge in the upper Colorado River basin in June, July, and August of water years 1982–2014 using ~800m, ~4km, and ~12km daily climate data. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data

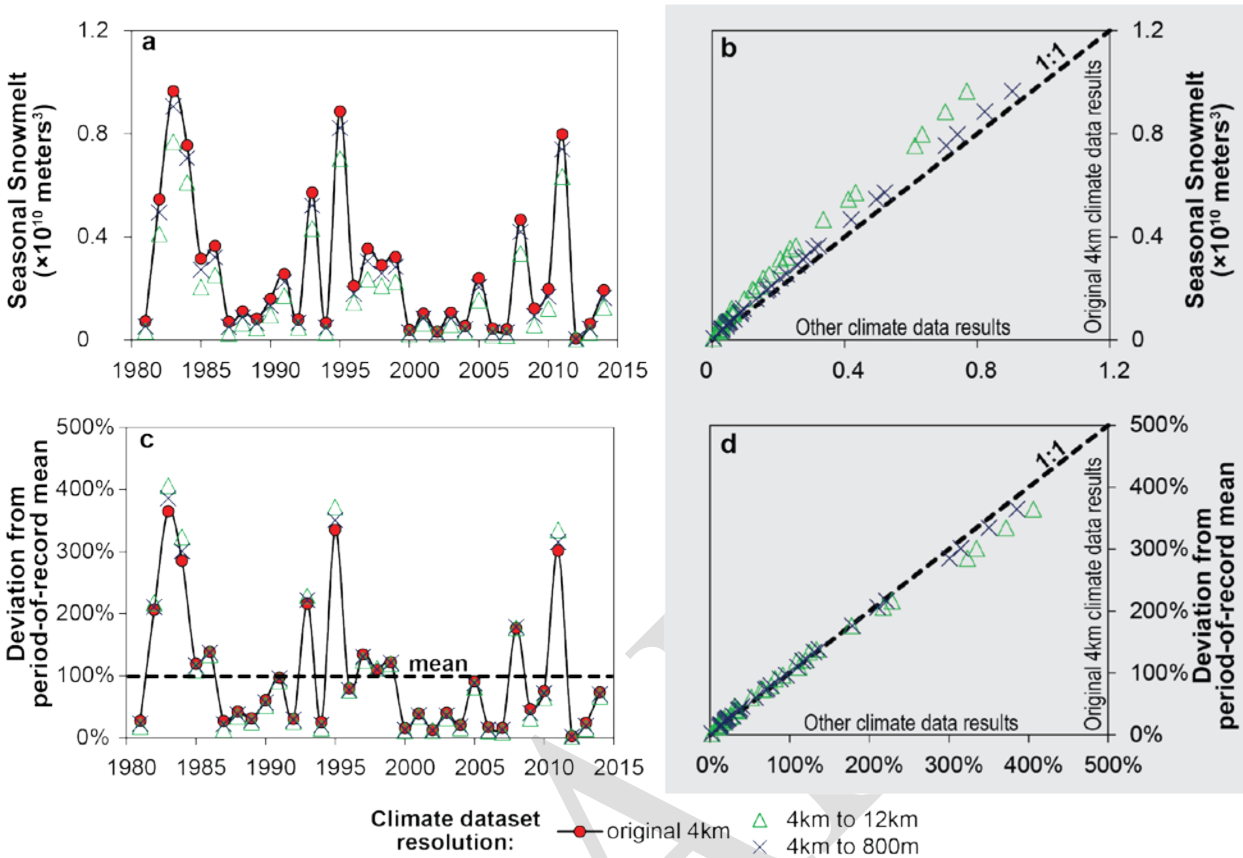

Fig 5 Simulated snowmelt in the upper Colorado River basin in June, July, and August of water years 1982–2014 using ~800m, ~4km, and ~12km daily climate data. Results presented as (a) magnitude of seasonal snowmelt through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of seasonal snowmelt from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data

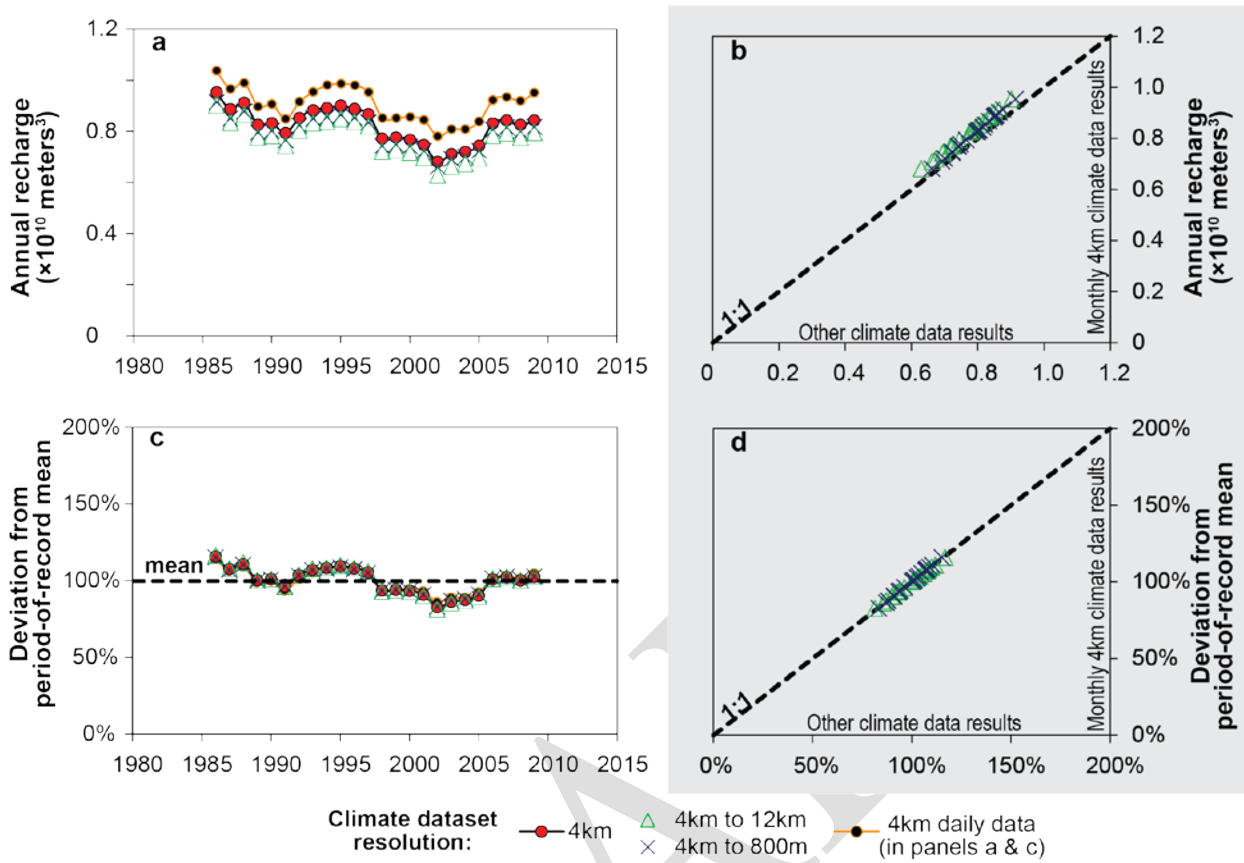

Fig 6 Annual simulated groundwater recharge in the upper Colorado River basin averaged over ten-year periods, moving every year, for water years 1982–2014 using ~800m, ~4km, and ~12km monthly climate data. Simulation results from daily ~4km climate data provided for reference. Results presented as (a) magnitude of average annual recharge through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of average annual recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data. Symbols on time series charts are placed in the middle of the ten-year averaging period

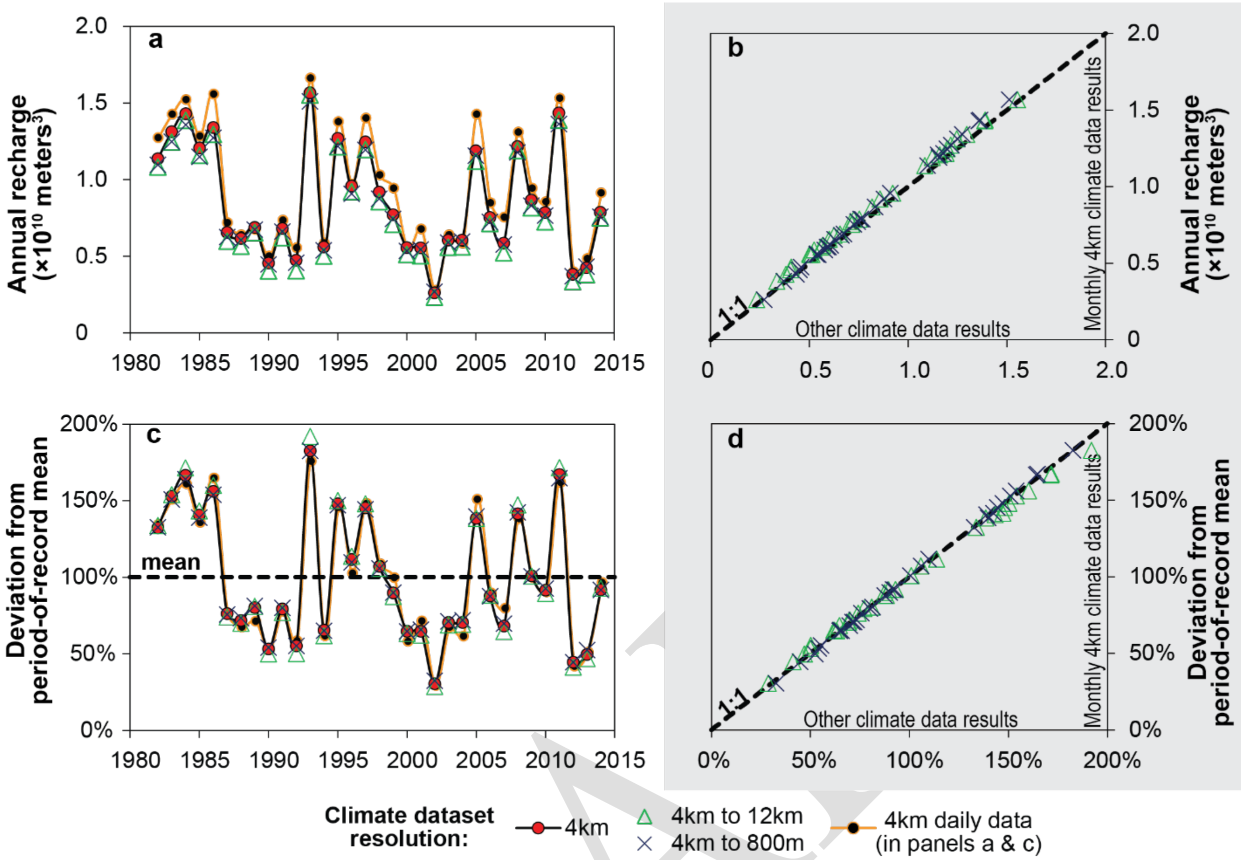

Fig 7 Annual simulated groundwater recharge in the upper Colorado River basin for water years 1982–2014 using ~800m, ~4km, and ~12km monthly climate data. Simulation results from daily ~4km climate data provided for reference. Results presented as (a) magnitude of annual recharge through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of annual recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data

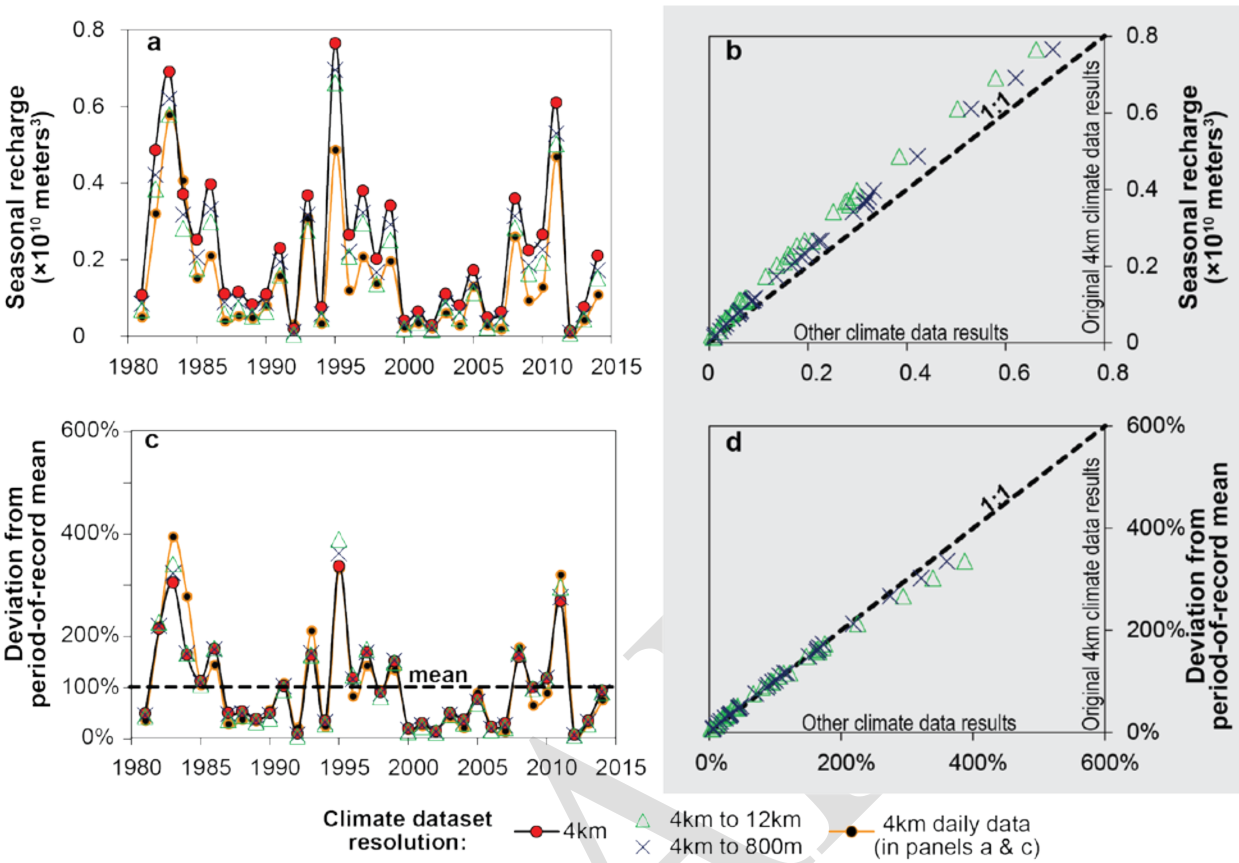

Fig 8 Simulated groundwater recharge in the upper Colorado River basin in June, July, and August of water years 1982–2014 using ~800m, ~4km, and ~12km monthly climate data. Simulation results from daily ~4km climate data provided for reference. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data

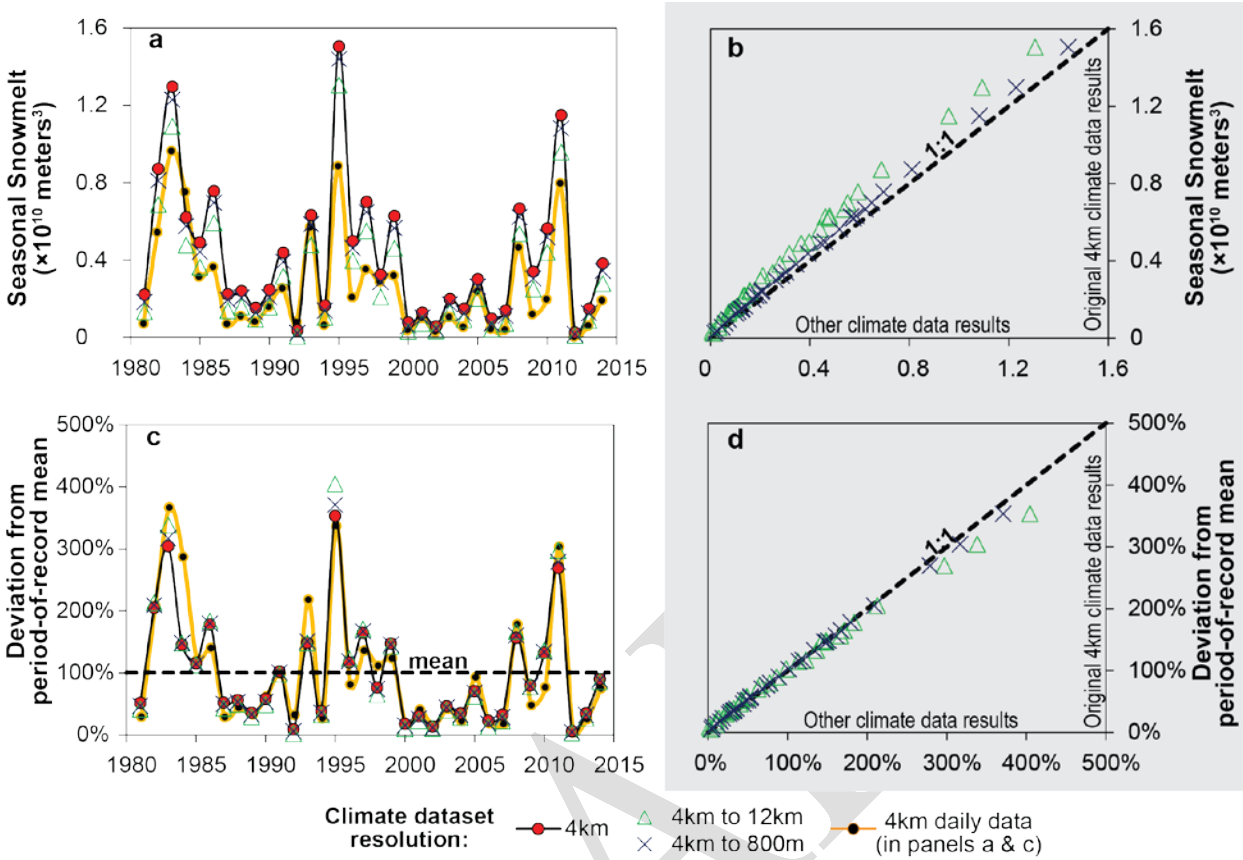

Fig 9 Simulated snowmelt in the upper Colorado River basin in June, July, and August of water years 1982–2014 using ~800m, ~4km, and ~12km monthly climate data. Results presented as (a) magnitude of seasonal snowmelt through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of seasonal snowmelt from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data

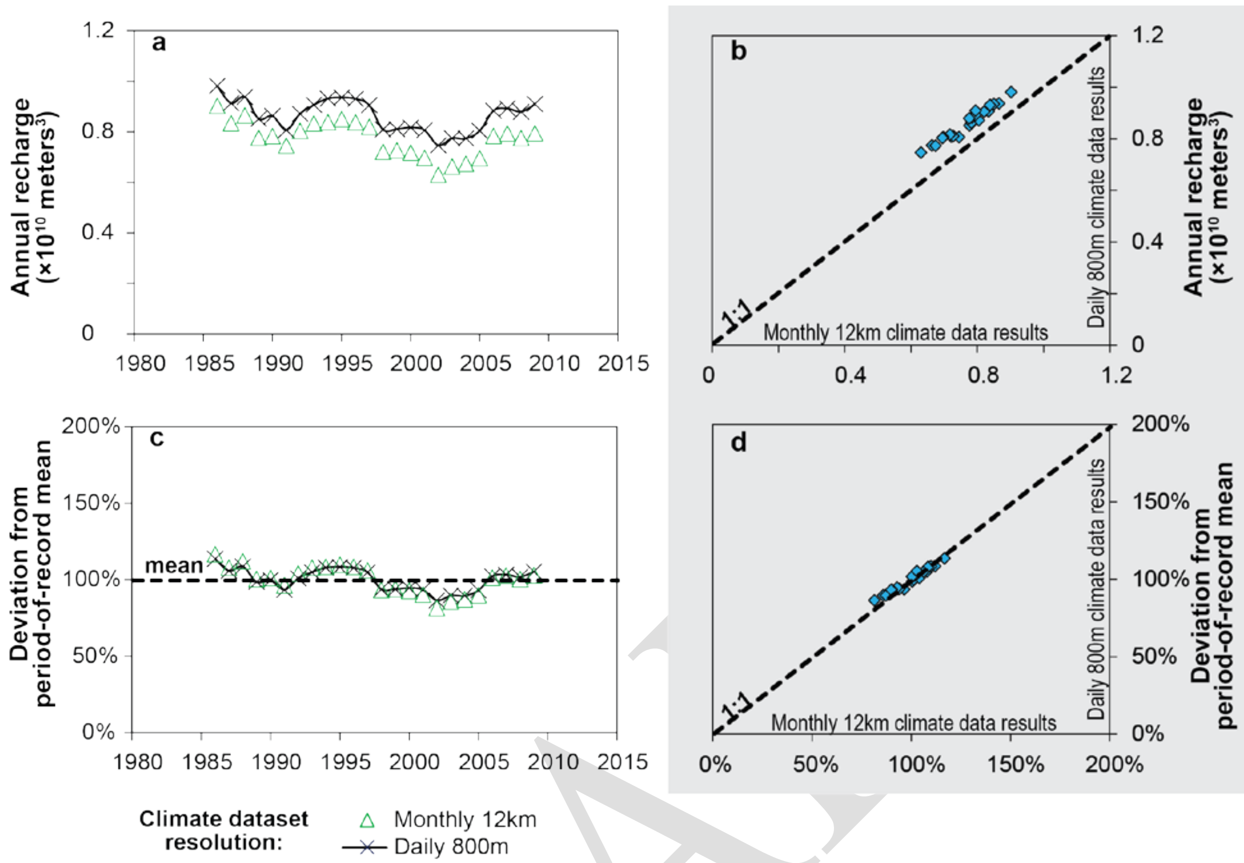

Fig 10 Annual simulated groundwater recharge in the upper Colorado River basin averaged over ten-year periods, moving every year, for water years 1982–2014 using ~800m daily and ~12km monthly climate data. Results presented as (a) magnitude of average annual recharge through time, (b) comparison of magnitudes of results from the two climate datasets, (c) change of average annual recharge from period of record mean through time, and (d) comparison of changes from period of record mean for the two climate datasets. Symbols on time series charts are placed in the middle of the ten-year averaging period

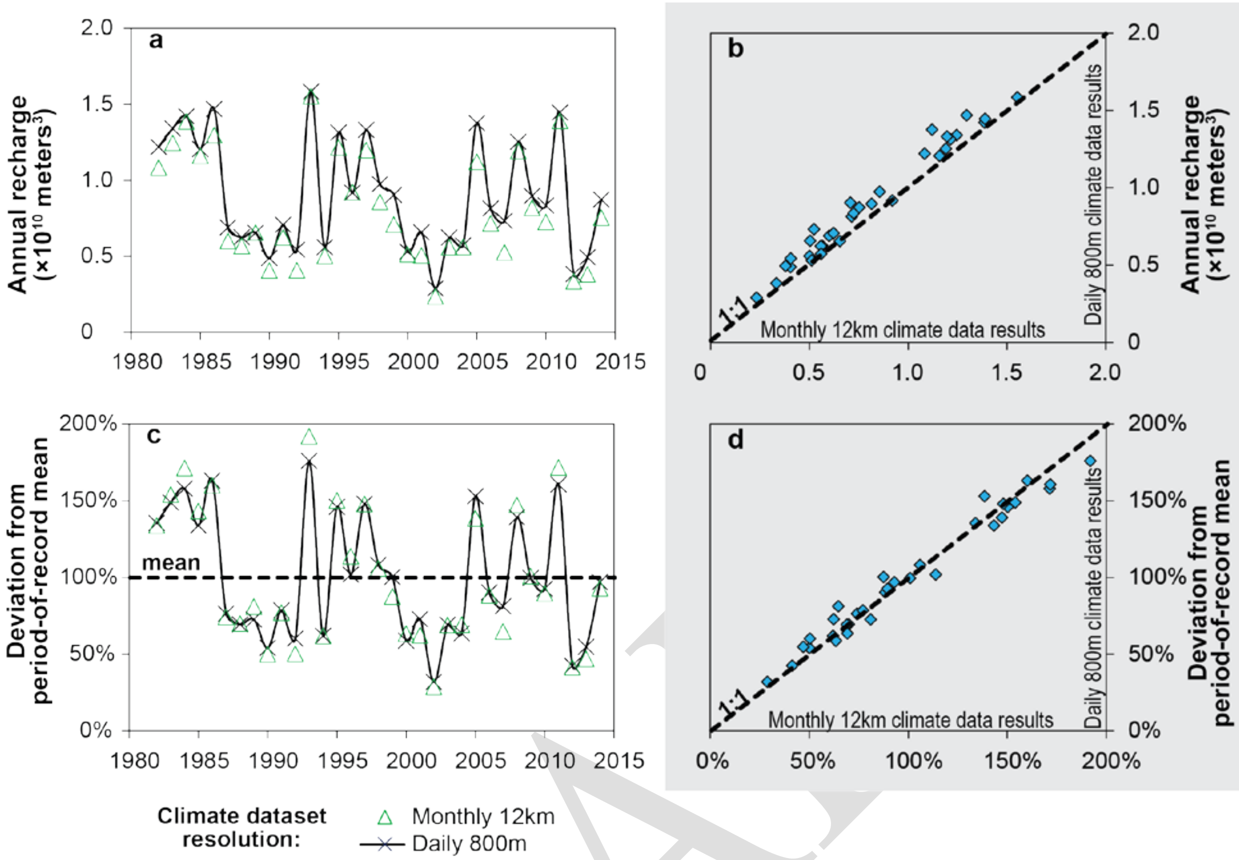

Fig 11 Annual simulated groundwater recharge in the upper Colorado River basin for water years 1982–2014 using ~800m daily and ~12km monthly climate data. Results presented as (a) magnitude of annual recharge through time, (b) comparison of magnitudes of results from the two climate datasets, (c) change of annual recharge from period of record mean through time, and (d) comparison of changes from period of record mean for the two climate datasets

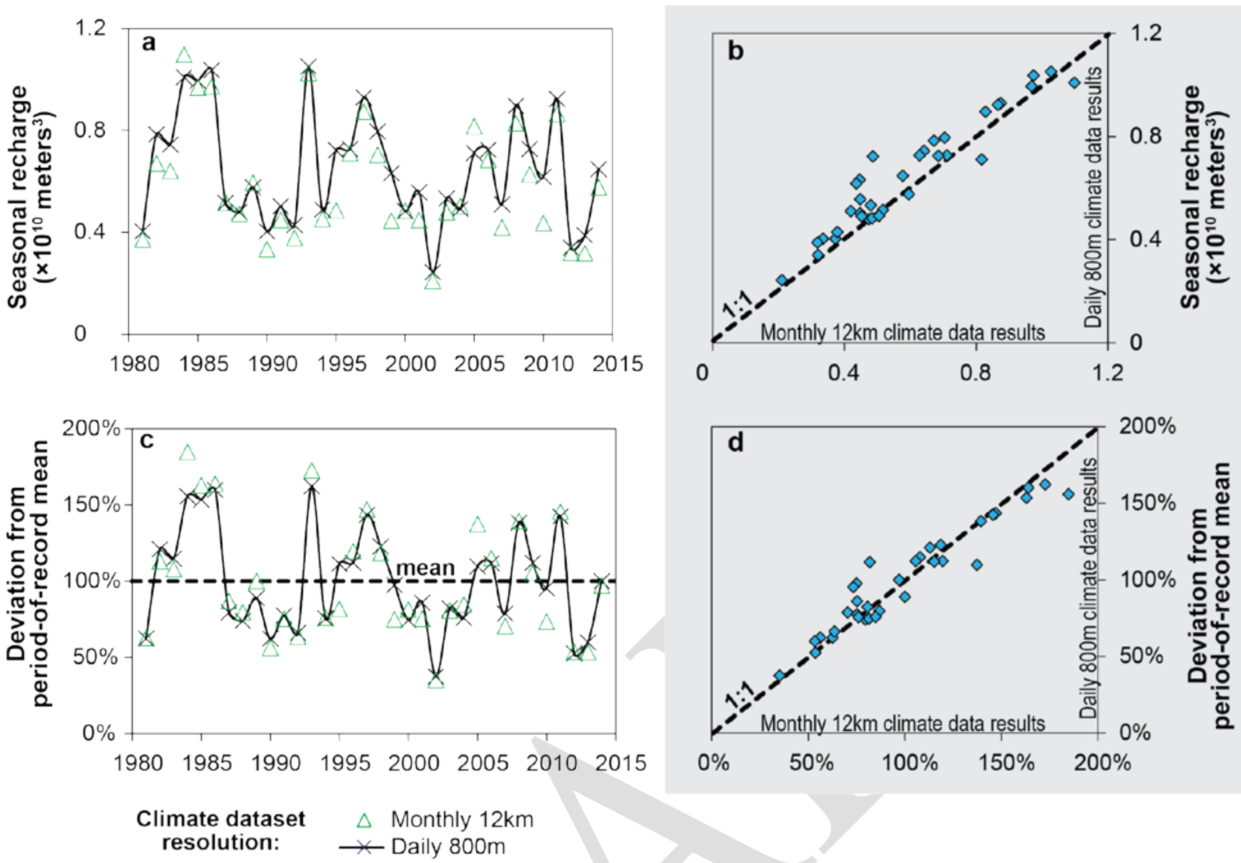

Fig 12 Simulated groundwater recharge in the upper Colorado River basin in March, April, and May of water years 1982–2014 using ~800m daily and ~12km monthly climate data. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from the two climate datasets, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean for the two climate datasets

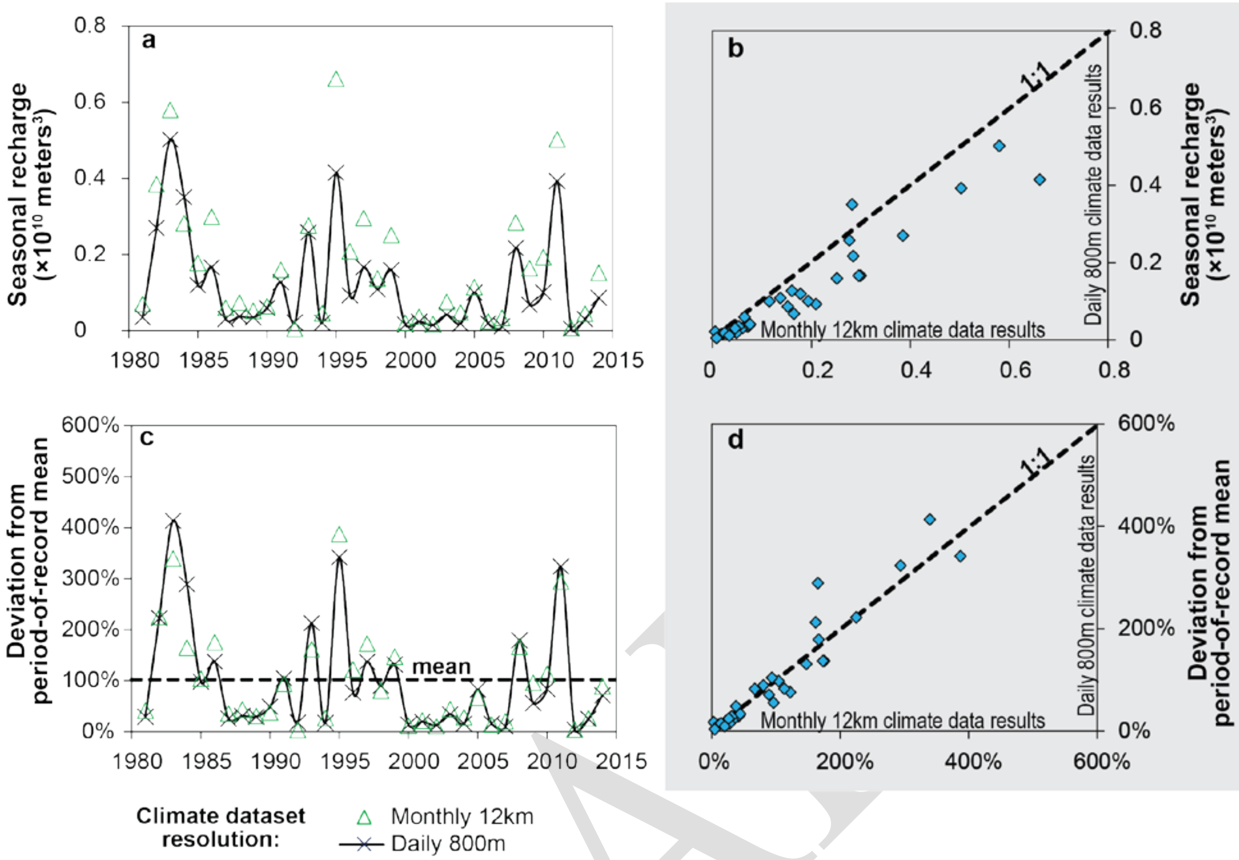

Fig 13 Simulated groundwater recharge in the upper Colorado River basin in June, July, and August of water years 1982–2014 using ~800m daily and ~12km monthly climate data. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from the two climate datasets, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean for the two climate datasets

Table 1. Summary of percentage change comparison of simulated groundwater recharge in the upper Colorado River basin between simulations using daily ~4km climate data and simulations using ~800m and ~12km daily climate data over ten-year moving annual average, water-year, and seasonal time periods.

		|Percentage change from ~4km recharge results[a]|			
		Magnitude of recharge		Deviation from period-of-record mean	
Time period of comparison	**Spatial resolution**	**Median**	**25th-75th percentile**	**Median**	**25th-75th percentile**
Ten-year moving average	~800m	4.6	4.2-4.9	0.3	0.2-0.5
	~12km	5.8	5.5-6.1	0.3	0.2-0.5
Water year	~800m	4.7	3.8-5.5	0.9	0.4-1.3
	~12km	6.3	4.6-9.1	2.7	0.9-3.7
December, January, February (8% of annual recharge)	~800m	4.1	1.1-7.1	3.4	1.3-7.4
	~12km	6.9	3.7-9.4	6.6	3.4-9.0
March, April, May (71% of annual recharge)	~800m	4.0	2.4-5.0	1.4	0.8-2.1
	~12km	4.4	2.2-7.1	4.5	1.8-6.6
June, July, August (16% of annual recharge)	~800m	20.5	17.9-25.8	4.7	2.4-9.8
	~12km	35.8	27.7-43.1	12.3	5.8-21.1
September, October, November (5% of annual recharge)	~800m	18.5	10.3-22.9	6.7	3.8-9.7
	~12km	15.7	9.8-25.2	9.2	4.1-17.9

[a]Absolute value of difference from ~4km results divided by ~4km results, in percent.

Table 2. Summary of percentage change comparison of simulated groundwater recharge in the upper Colorado River basin between simulations using monthly ~4km climate data and simulations using ~800m and ~12km monthly climate data over ten-year moving annual average, water-year, and seasonal time periods.

		|Percentage change from ~4km recharge results[a]|			
		Magnitude of recharge		Deviation from period-of-record mean	
Time period of comparison	**Spatial resolution**	**Median**	**25th-75th percentile**	**Median**	**25th-75th percentile**
Ten-year moving average	~800m	3.6	3.1-3.8	0.4	0.2-0.5
	~12km	5.9	5.7-6.5	0.3	0.1-0.6
Water year	~800m	3.5	2.8-4.2	0.9	0.4-1.5
	~12km	6.9	4.4-8.5	2.5	1.5-4.0
December, January, February (3% of annual recharge)	~800m	16.2	10.7-28.9	10.4	5.2-22.5
	~12km	14.6	7.8-31.3	14.5	7.7-31.3
March, April, May (68% of annual recharge)	~800m	1.4	0.8-2.8	1.5	0.7-2.9
	~12km	4.7	2.1-7.1	4.4	2.5-6.8
June, July, August (27% of annual recharge)	~800m	19.1	14.9-23.2	6.3	2.3-9.2
	~12km	32.1	24.7-40.9	11.9	5.2-21.0
September, October, November (2% of annual recharge)	~800m	25.4	13.2-30.9	8.4	4.8-18.8
	~12km	29.8	16.7-40.1	18.9	10.5-34.5

[a]Absolute value of difference from ~4km results divided by ~4km results, in percent.

APPENDIX A

Electronic supplementary material

Electronic supplementary material

Effect of spatial and temporal scale on simulated groundwater recharge in the upper Colorado River basin (USA)

Fred D Tillman[1*], Tom Pruitt[2], Subhrendu Gangopadhyay[2]

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S1. Introduction

This electronic supplementary material includes a discussion of details and limitations of the Soil-Water Balance (SWB) groundwater recharge model used in this study and a description of additional spatially gridded input datasets required by the SWB model other than climate data. SWB simulation results, in addition to results included in the main manuscript, are provided in Figs. S2 through S15.

S2. Soil-Water Balance Model Details and Limitations

Spatial and temporal variations in groundwater recharge are estimated by the Soil-Water-Balance (SWB) computer code (Westenbroek et al. 2010) by calculating water balance parameters at daily time steps. SWB uses a modified Thornthwaite-Mather soil-water-balance accounting approach (Thornthwaite 1948; Thornthwaite and Mather 1957) and groundwater recharge is estimated within each cell of the model domain. SWB estimates sources and sinks of water within each model cell from climate data and landscape characteristics, and then computes groundwater recharge as the difference between the change in soil moisture and these sources and sinks:

$$\underbrace{(\text{rainfall} + \text{snowmelt} + \text{inflow})}_{\text{water sources}} - \underbrace{(\text{interception} + \text{outflow} + \text{AET})}_{\text{water sinks}} - \Delta\,\text{soil moisture} = \text{RECHARGE} \qquad (1)$$

The SWB groundwater recharge model requires spatially gridded input datasets including available soil-water capacity, overland flow direction, land cover, hydrologic soil group, daily precipitation, daily maximum temperature, and daily minimum temperature. SWB also requires input datasets in a tabular format including vegetation rooting depths, runoff curve numbers, interception values, and maximum daily recharge values for each combination of land-cover type and hydrologic soil group. In equation 1, model cell inflow is surface water flow from adjacent model cells, estimated using the National Resources Conservation Service (NRCS) curve number rainfall-runoff relation and a flow-direction grid derived from a digital-elevation model (DEM). Interception in equation 1 is a user-specified amount of precipitation that is trapped and used by vegetation. Outflow from a model cell is estimated in the same manner as inflow to the cell. For the UCRB simulations, the Hargreaves-Samani (Hargreaves and Samani 1985) method was used to estimate potential evapotranspiration (PET), from which actual evapotranspiration (AET) is calculated:

$$\text{PET} = 0.0135 \times \text{RS} \times (\text{T}+17.8) \qquad \text{with RS} = \text{KRS} \times \text{RA} \times \text{TD}^{0.5} \qquad (2)$$

Where RS is incoming solar radiation, T is mean air temperature in °C, KRS is a calibration coefficient, RA is extraterrestrial radiation, and TD is the measured air temperature range (Hargreaves and Samani 1985). Extraterrestrial radiation is estimated from latitude and the day of year (Allen et al. 1998). The estimation of soil moisture in equation 1 is performed in several steps. First, PET is subtracted from precipitation (P) for all model cells. If P – PET is negative (P < PET), then there is a potential deficiency of water. Accumulated Potential Water Loss (APWL) is the running sum of daily P – PET values during times when P < PET. Soil moisture is estimated using the current AWPL value in the Thornthwaite-Mather relation that describes the nonlinear relation between APWL and soil moisture. Actual ET (AET) is then equal to only the amount of water that can be extracted from the soil on a given day. If P – PET is positive (P > PET), a potential surplus of water exists and AET is equal to PET. In this case, soil moisture is calculated by adding P – PET directly to the previous day's soil-moisture value. If the new soil moisture value is less than the maximum water-holding capacity of the soil (estimated as the product of the available soil water capacity and the root-zone depth), then the Thornthwaite-Mather relation is used to back-calculate a reduced APWL. If the new soil moisture value is greater than the maximum water-holding capacity of the soil, then soil moisture is limited to the maximum water-holding capacity, any excess soil-moisture becomes recharge, and AWPL is set to zero.

The SWB model has been used to estimate groundwater recharge in several completed and ongoing regional groundwater studies including basins in Wisconsin (Dripps and Bradbury 2009) and Minnesota (Smith and Westenbroek 2015), the High Plains Aquifer (Stanton et al. 2011), the Lake Michigan Basin (Feinstein et al. 2010), the Northern Atlantic Coastal Plain Aquifer System (Masterson et al. 2013), the Ozark Plateau Groundwater Availability Study (USGS 2016a), and the Appalachian Plateaus Groundwater Availability Study (USGS 2016b). While the SWB recharge model has been shown to provide reasonable basin-scale estimates of groundwater recharge, SWB assumptions and limitations should be considered when evaluating recharge results (Westenbroek et al. 2010). SWB's daily time step permits short-term water surpluses to become groundwater recharge, but also requires that routed runoff either infiltrate downslope cells or be routed out of the model domain on the same day in which it originated. Although there may be significant time required for water to travel through the unsaturated zone, the SWB model does not consider the depth to the top of the aquifer surface. The SWB models estimates runoff using the NRCS curve number method which may introduce limitations including that the method was not designed to simulate daily flows of ordinary magnitude and that some studies indicate that curve numbers may not constant but may vary from event to event (Westenbroek et al. 2010). Finally, there are numerous methods for estimating evapotranspiration, each with its own benefits, uncertainties, limitations, and data requirements. This study uses the Hargreaves-Samani (Hargreaves and Samani 1985) method for estimating PET, in which climatic changes are reflected only in the daily air temperature range. More complex ET relations require additional data including wind speed, percentage of actual to possible daily sunshine hours, and relative humidity among others (Westenbroek et al. 2010).

S3. Non-climate Spatially Gridded SWB Datasets

Other spatially gridded datasets required for SWB simulations in addition to climate input data include land cover, overland flow direction, hydrologic soil group, and available soil-water capacity. Information on the original source and processing of each of these datasets is described in detail in Tillman (2015). Each of these spatially gridded datasets were aggregated from their original spatial resolutions to match the ~800m, ~4km, and ~12km climate data resolutions for SWB simulations. For categorical datasets of land cover, overland flow direction, and hydrologic soil group, a majority resampling technique was used to assign cell values. For the continuous available soil-water capacity dataset, a bilinear resampling technique was used. While comparison of overland flow direction at different spatial scales is not meaningful, UCRB basin-scale distributions for hydrologic soil group, available soil-water capacity, and land cover values at the 3 spatial scales in this study are all similar to distributions from the original datasets (Fig. S1).

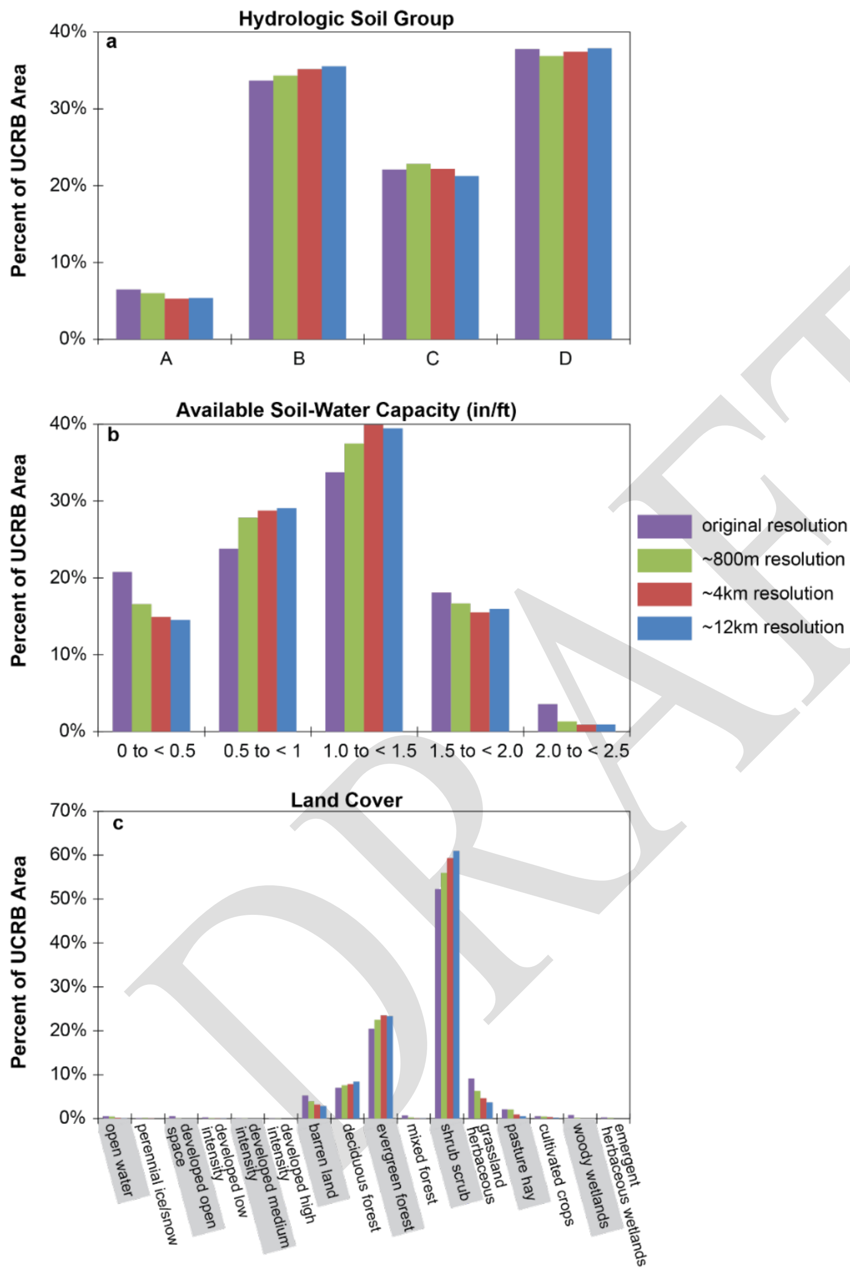

Fig S1 Comparison of distribution of spatial SWB input datasets other than climate data at different spatial resolutions used in this study including a) hydrologic soil group, b) available soil-water capacity, and c) land cover

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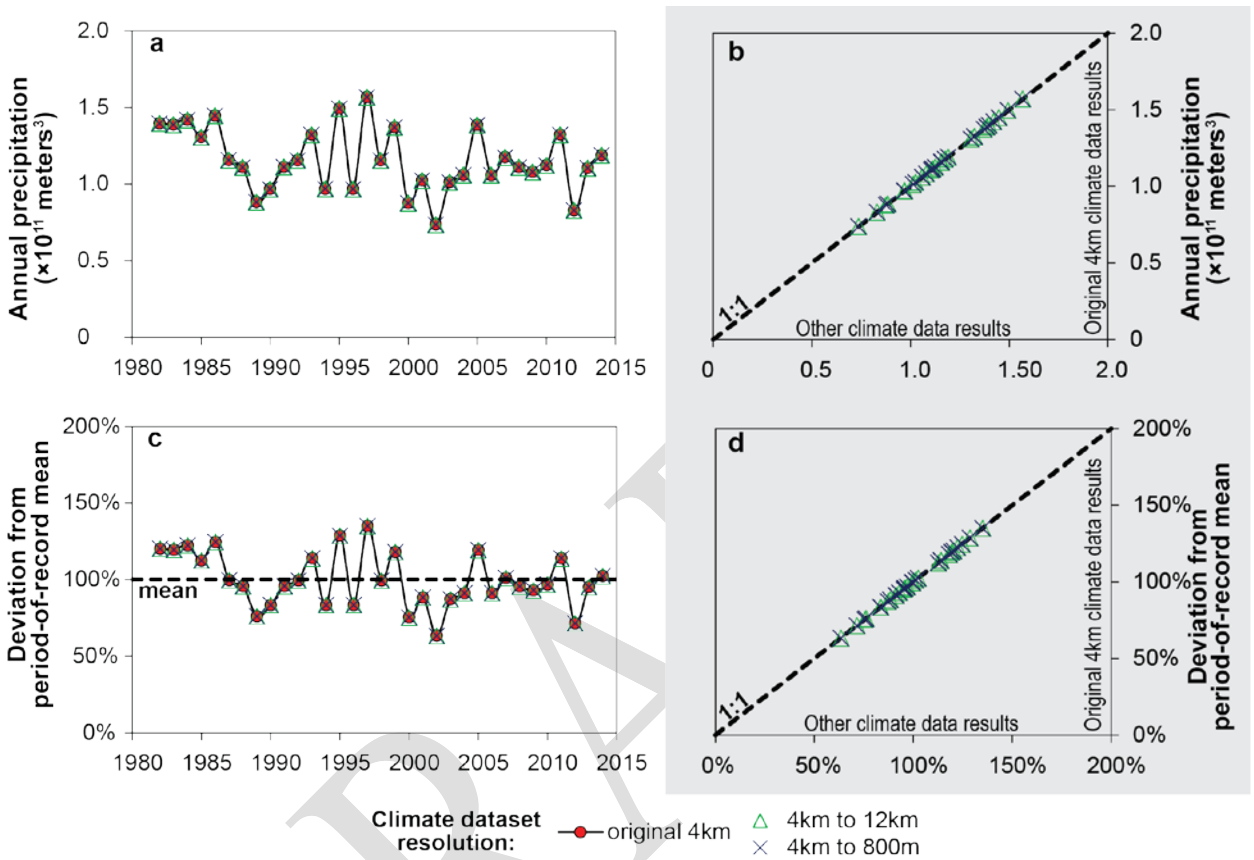

Fig S2 Annual precipitation in the upper Colorado River basin for water years 1982–2014 from ~800m, ~4km, and ~12km daily climate data. Results presented as (a) magnitude of annual precipitation through time, (b) comparison of magnitudes from ~4km climate data with ~12km and ~800m climate data, (c) change of annual precipitation from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data with ~12km and ~800m climate data

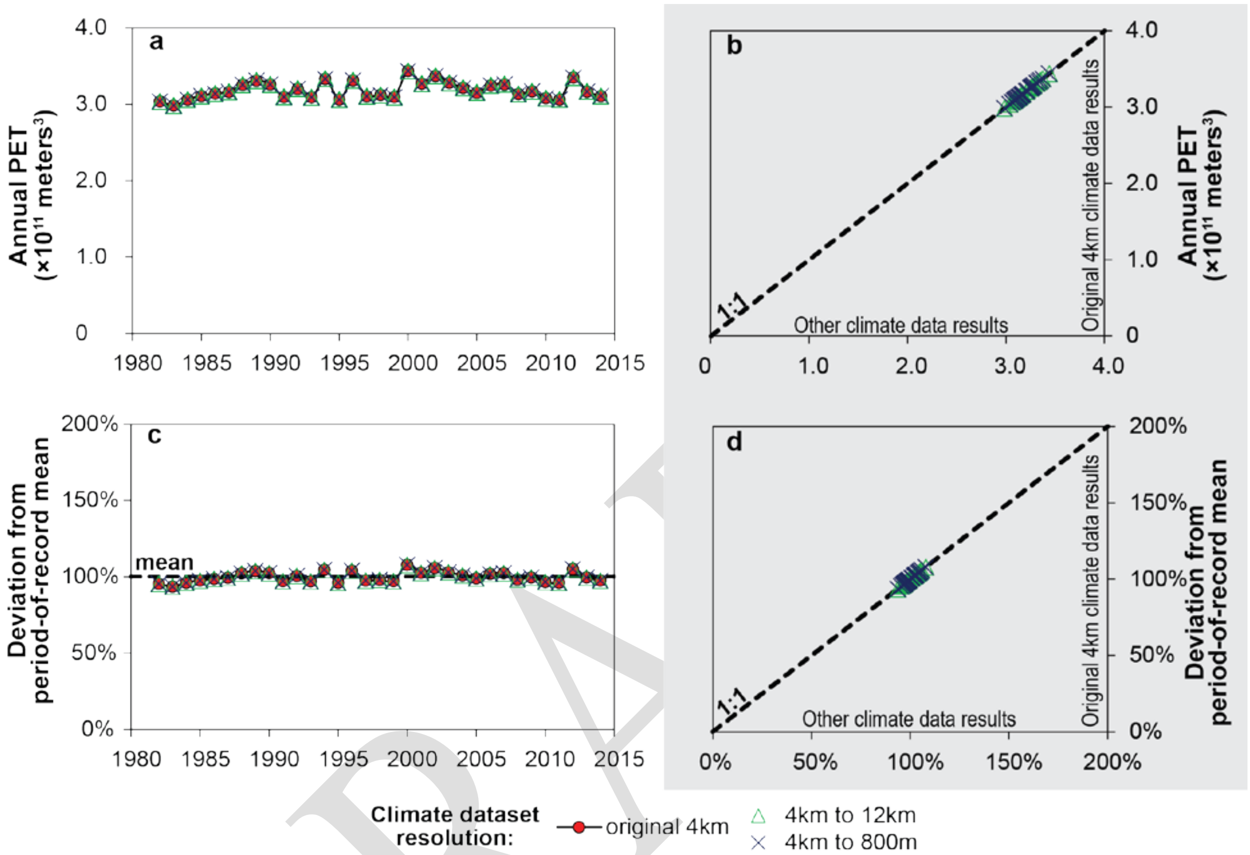

Fig S3 Annual potential evapotranspiration (PET) in the upper Colorado River basin for water years 1982–2014 from ~800m, ~4km, and ~12km daily climate data. Results presented as (a) magnitude of annual PET through time, (b) comparison of magnitudes from ~4km climate data with ~12km and ~800m climate data, (c) change of annual PET from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data with ~12km and ~800m climate data

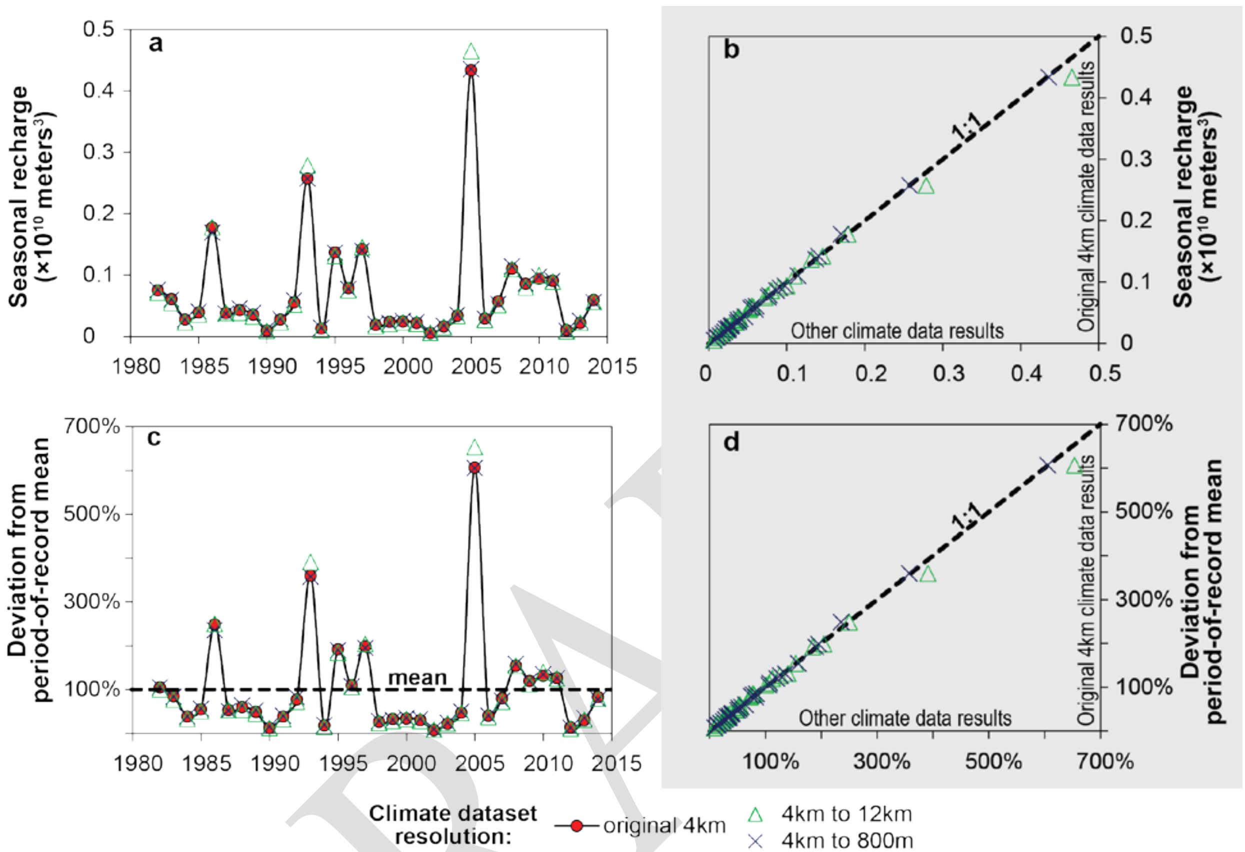

Fig S4 Simulated groundwater recharge in the upper Colorado River basin in December, January, and February of water years 1982–2014 using ~800m, ~4km, and ~12km daily climate data. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data

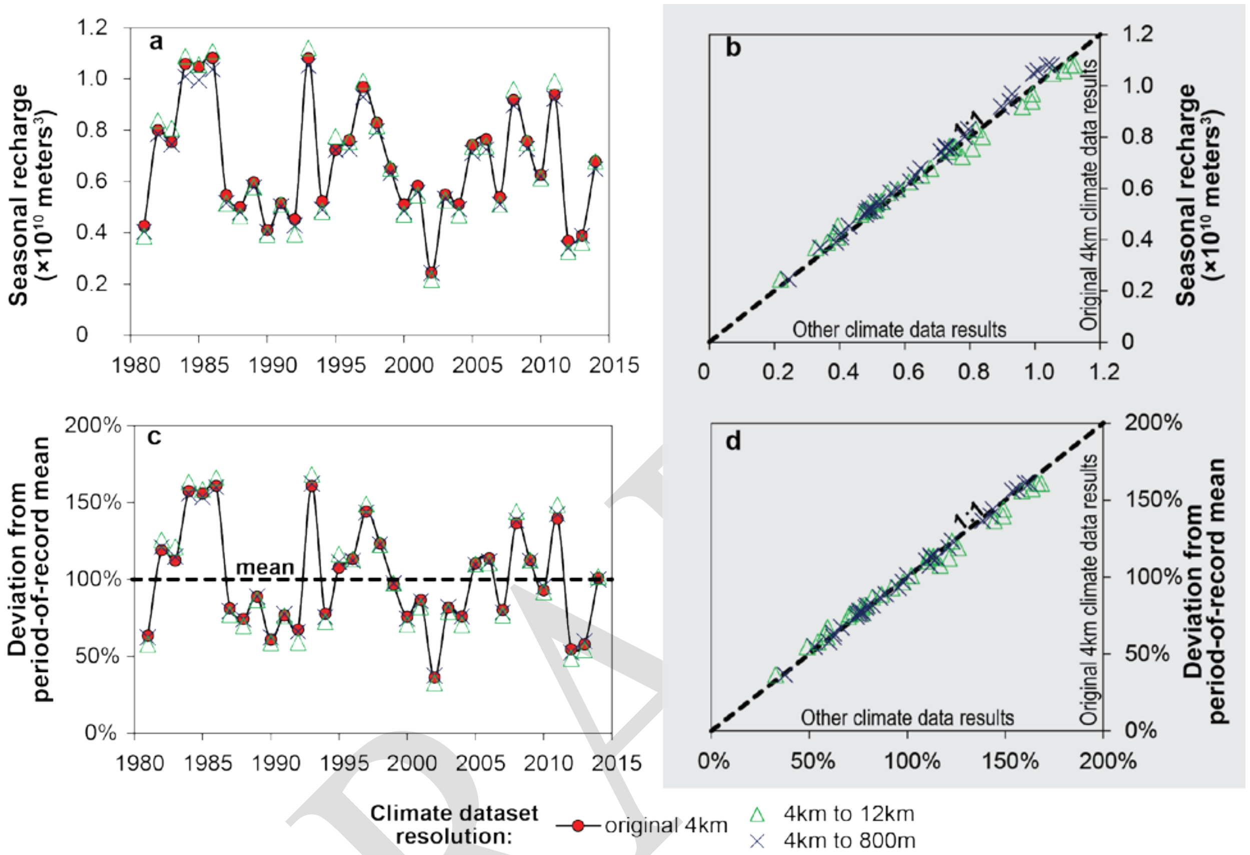

Fig S5 Simulated groundwater recharge in the upper Colorado River basin in March, April, and May of water years 1982–2014 using ~800m, ~4km, and ~12km daily climate data. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data

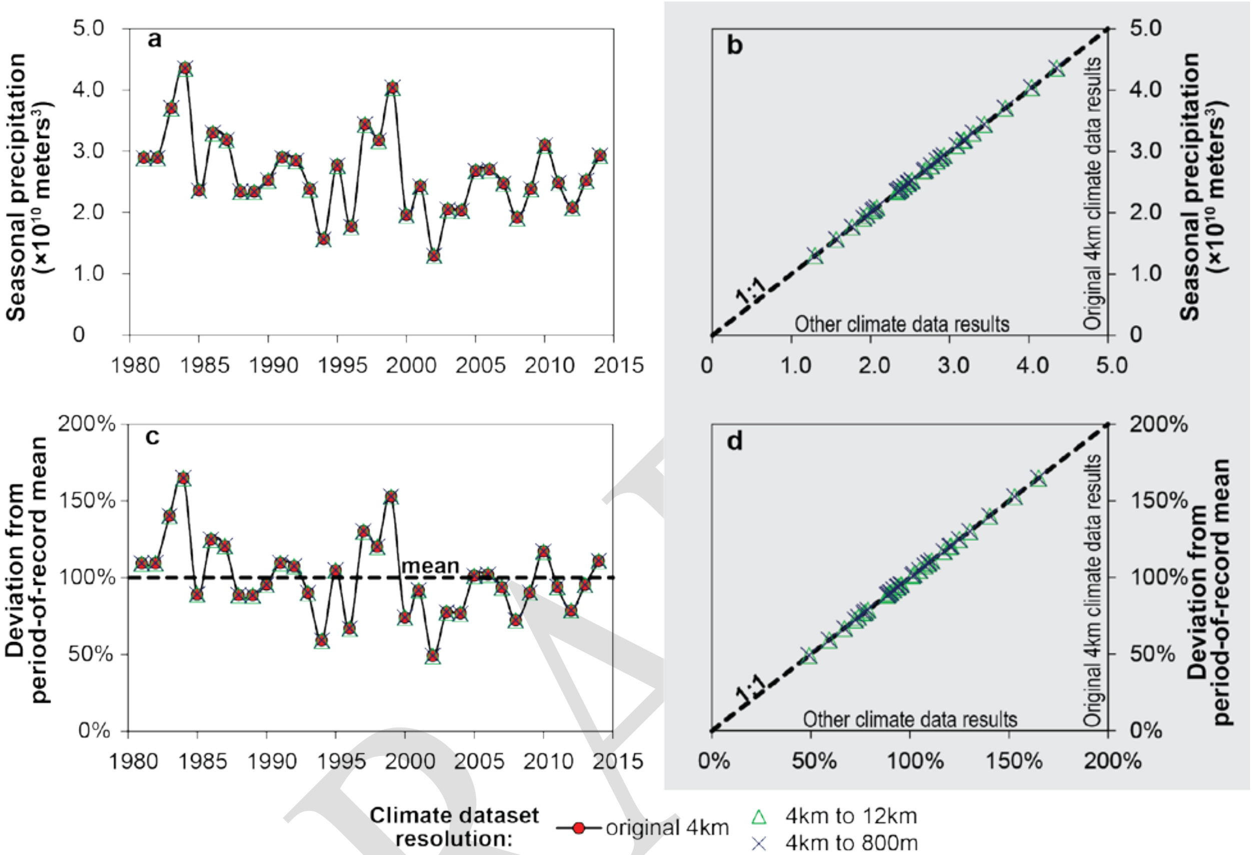

Fig S6 Precipitation in the upper Colorado River basin in June, July, and August of water years 1982–2014 from ~800m, ~4km, and ~12km daily climate data. Results presented as (a) magnitude of seasonal precipitation through time, (b) comparison of magnitudes from ~4km climate data with ~12km and ~800m climate data, (c) change of seasonal precipitation from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data with ~12km and ~800m climate data

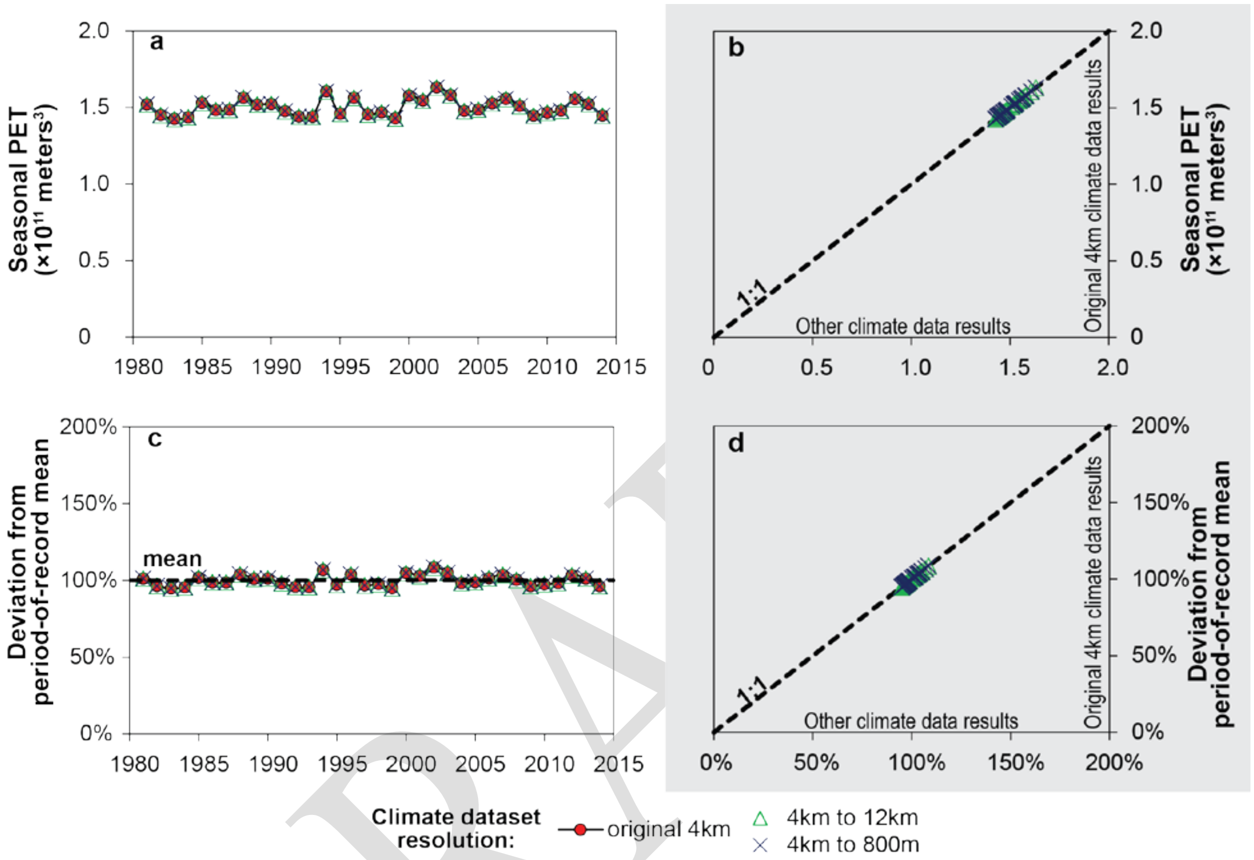

Fig S7 Potential evapotranspiration (PET) in the upper Colorado River basin in June, July, and August of water years 1982–2014 from ~800m, ~4km, and ~12km daily climate data. Results presented as (a) magnitude of seasonal PET through time, (b) comparison of magnitudes from ~4km climate data with ~12km and ~800m climate data, (c) change of seasonal PET from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data with ~12km and ~800m climate data

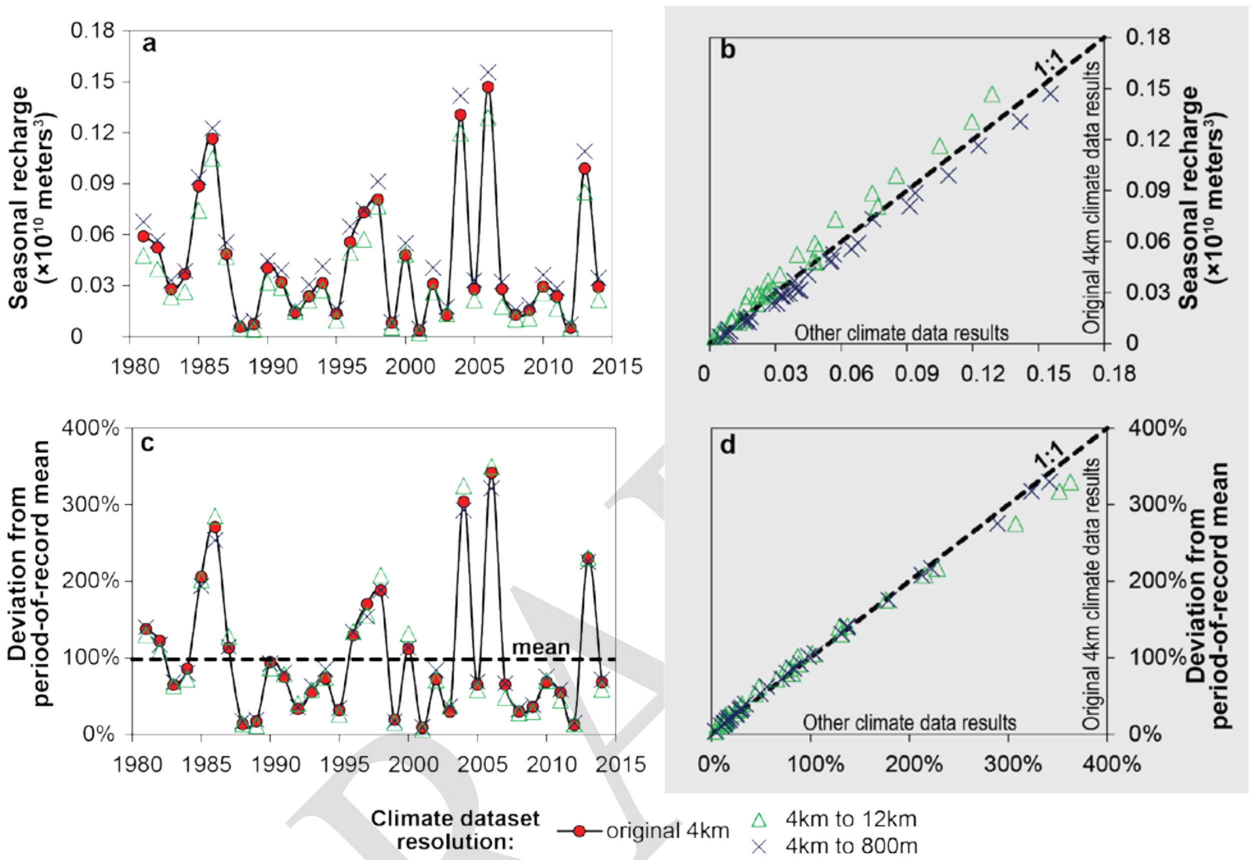

Fig S8 Simulated groundwater recharge in the upper Colorado River basin in September, October, and November of water years 1982–2014 using ~800m, ~4km, and ~12km daily climate data. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data

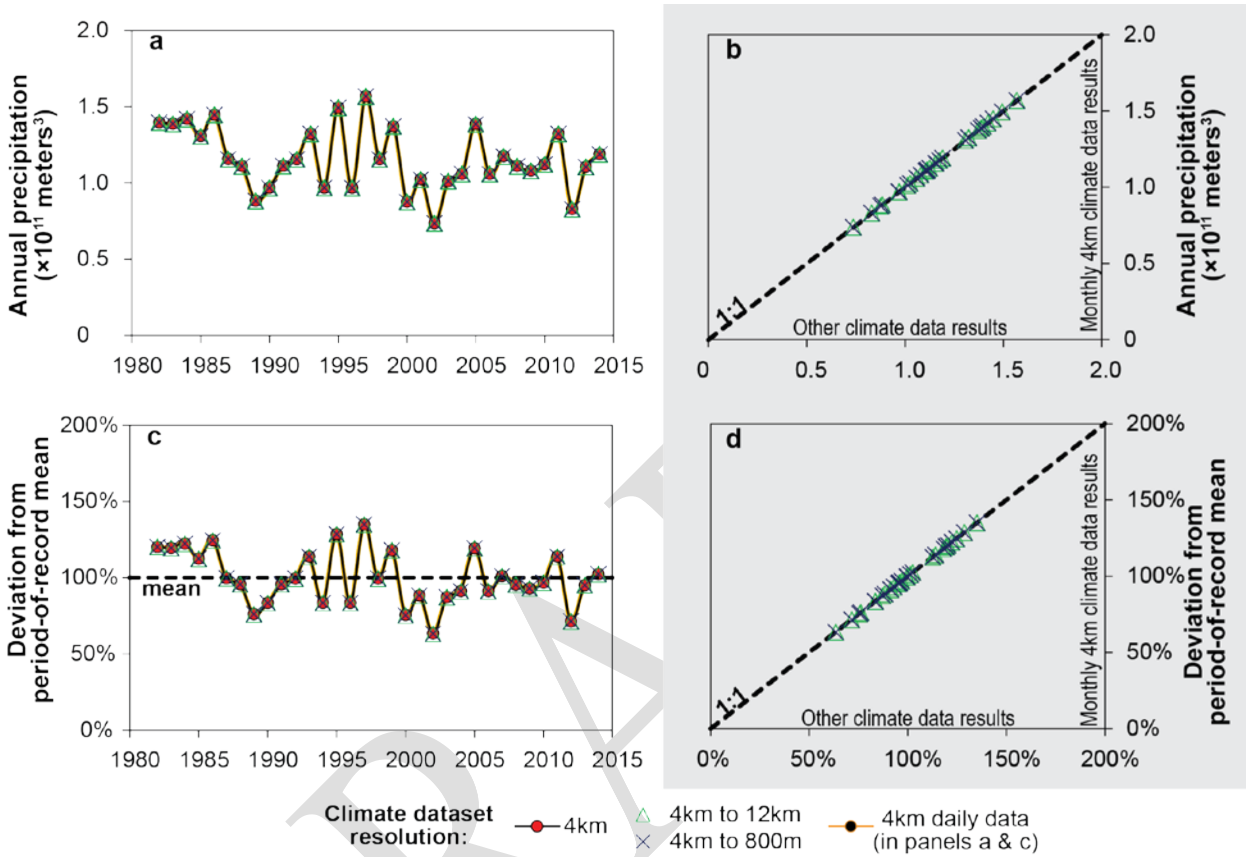

Fig S9 Annual precipitation in the upper Colorado River basin for water years 1982–2014 using ~800m, ~4km, and ~12km monthly climate data. Precipitation from daily ~4km climate data provided for reference. Results presented as (a) magnitude of annual precipitation through time, (b) comparison of magnitudes from ~4km climate data with ~12km and ~800m climate data, (c) change of annual precipitation from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data with ~12km and ~800m climate data

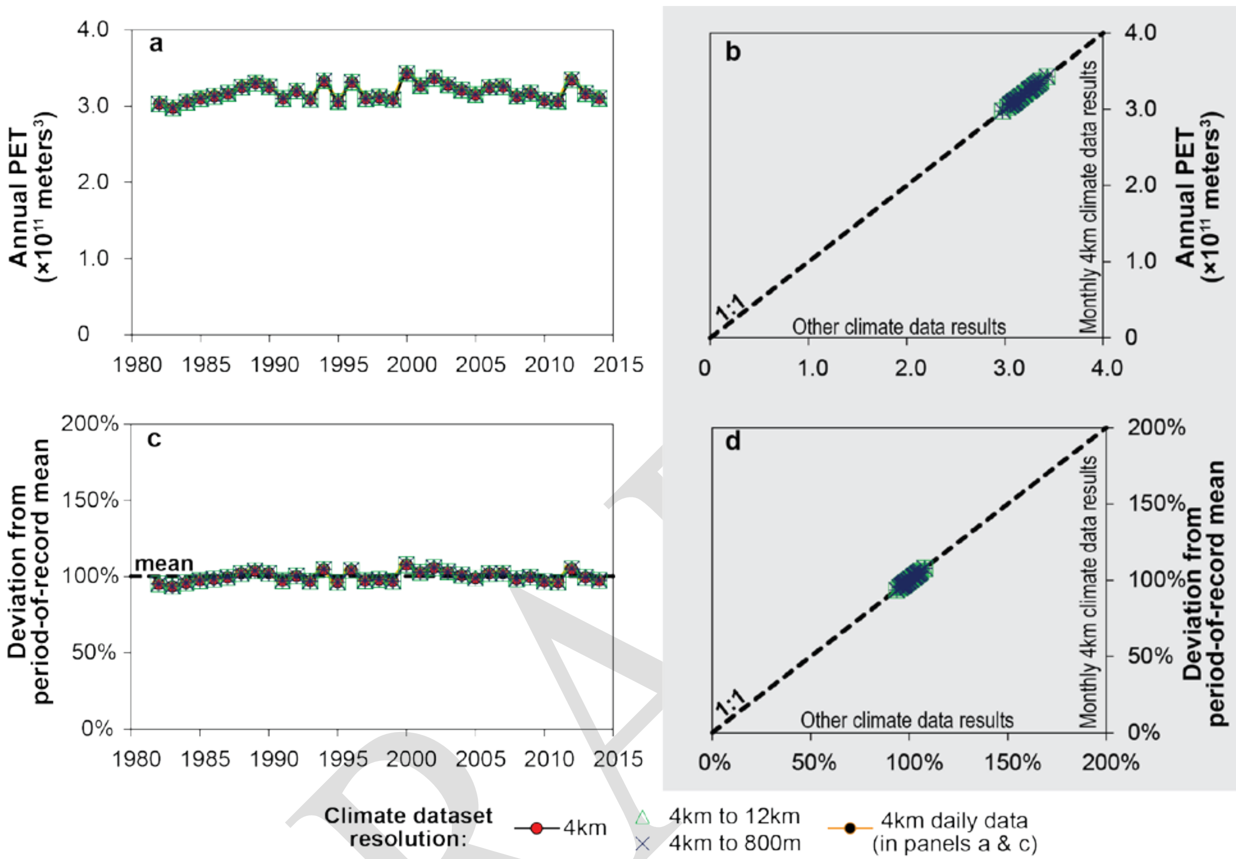

Fig S10 Annual potential evapotranspiration (PET) in the upper Colorado River basin for water years 1982–2014 from ~800m, ~4km, and ~12km monthly climate data. PET from daily ~4km climate data provided for reference. Results presented as (a) magnitude of annual PET through time, (b) comparison of magnitudes from ~4km climate data with ~12km and ~800m climate data, (c) change of annual PET from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data with ~12km and ~800m climate data

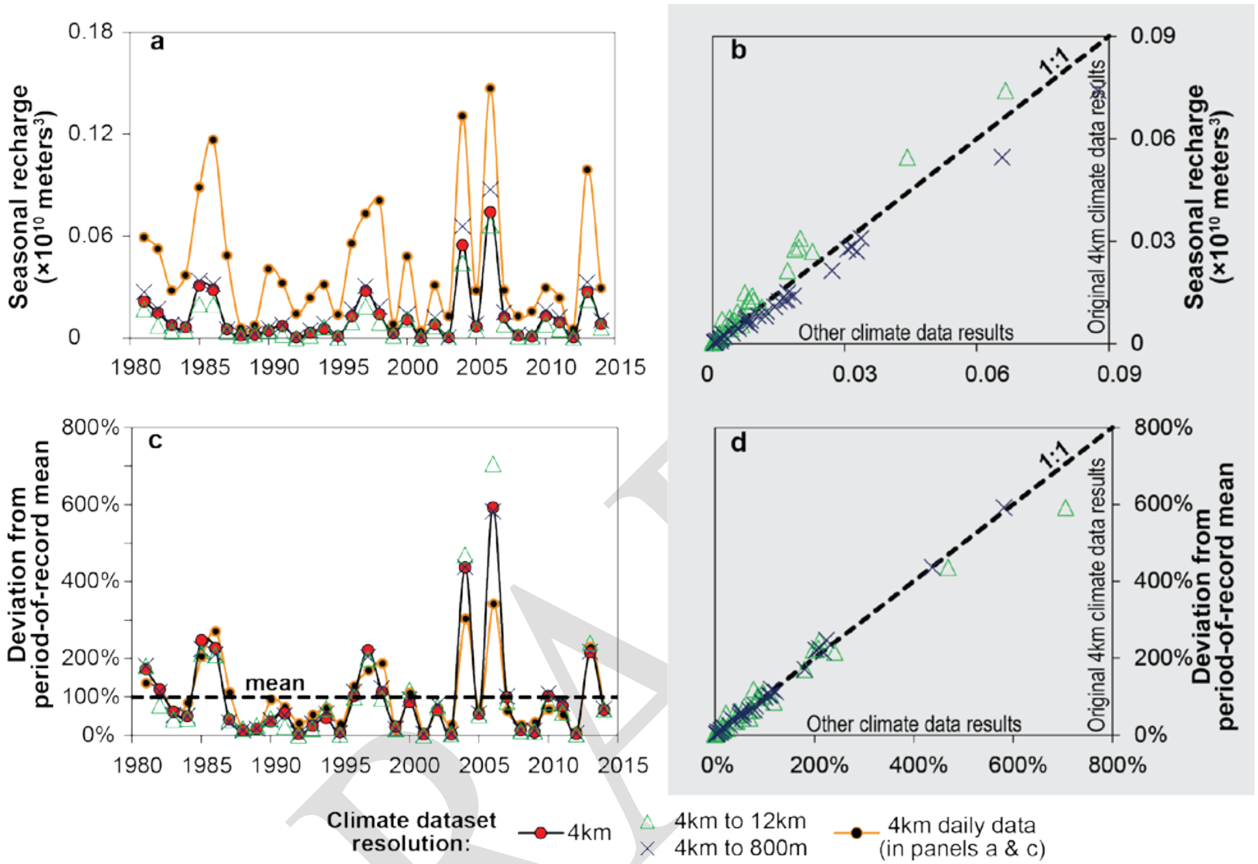

Fig S11 Simulated groundwater recharge in the upper Colorado River basin in September, October, and November of water years 1982–2014 using ~800m, ~4km, and ~12km monthly climate data. Simulation results from daily ~4km climate data provided for reference. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data

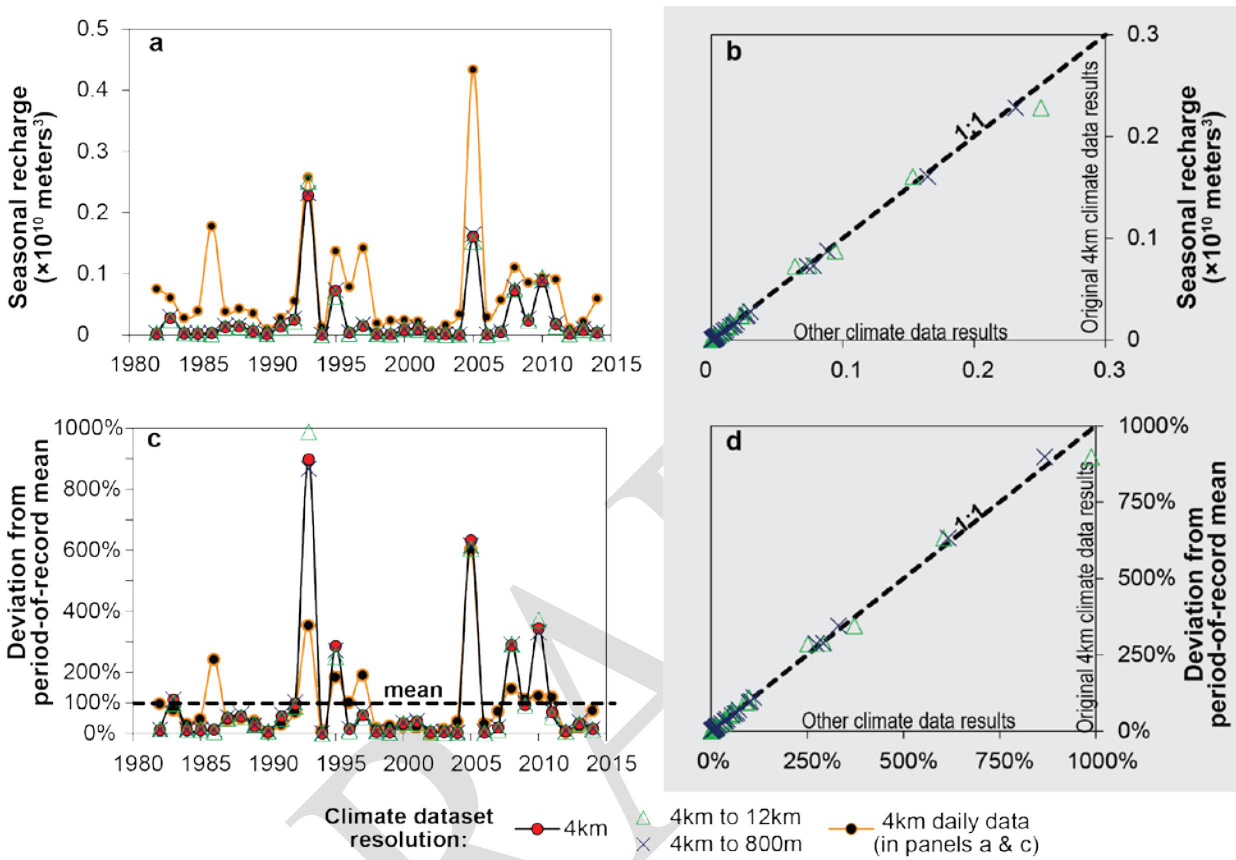

Fig S12 Simulated groundwater recharge in the upper Colorado River basin in December, January, and February of water years 1982–2014 using ~800m, ~4km, and ~12km monthly climate data. Simulation results from daily ~4km climate data provided for reference. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data

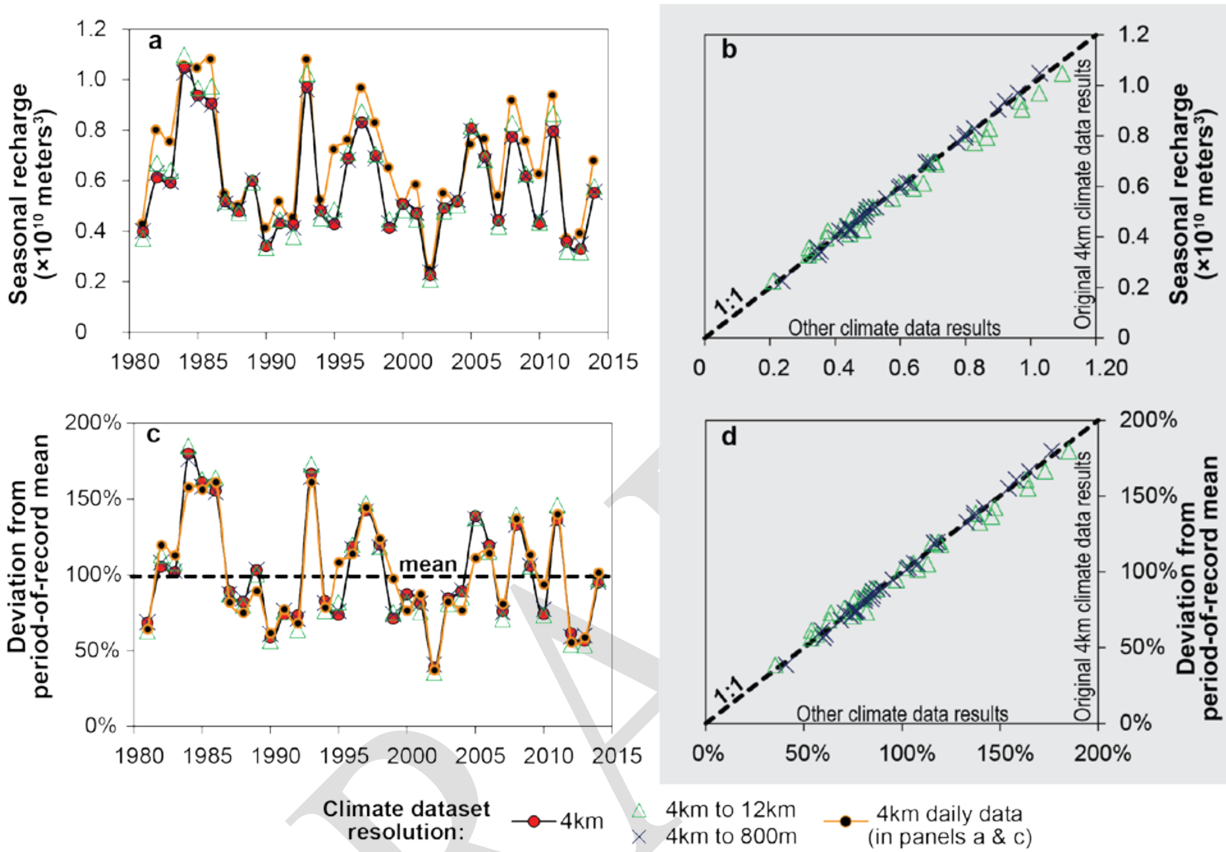

Fig S13 Simulated groundwater recharge in the upper Colorado River basin in March, April, and May of water years 1982–2014 using ~800m, ~4km, and ~12km monthly climate data. Simulation results from daily ~4km climate data provided for reference. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from ~4km climate data with results from ~12km and ~800m climate data, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean from ~4km climate data results with results from ~12km and ~800m climate data

Effect of spatial and temporal scale on simulated groundwater recharge in the upper Colorado River basin (USA)

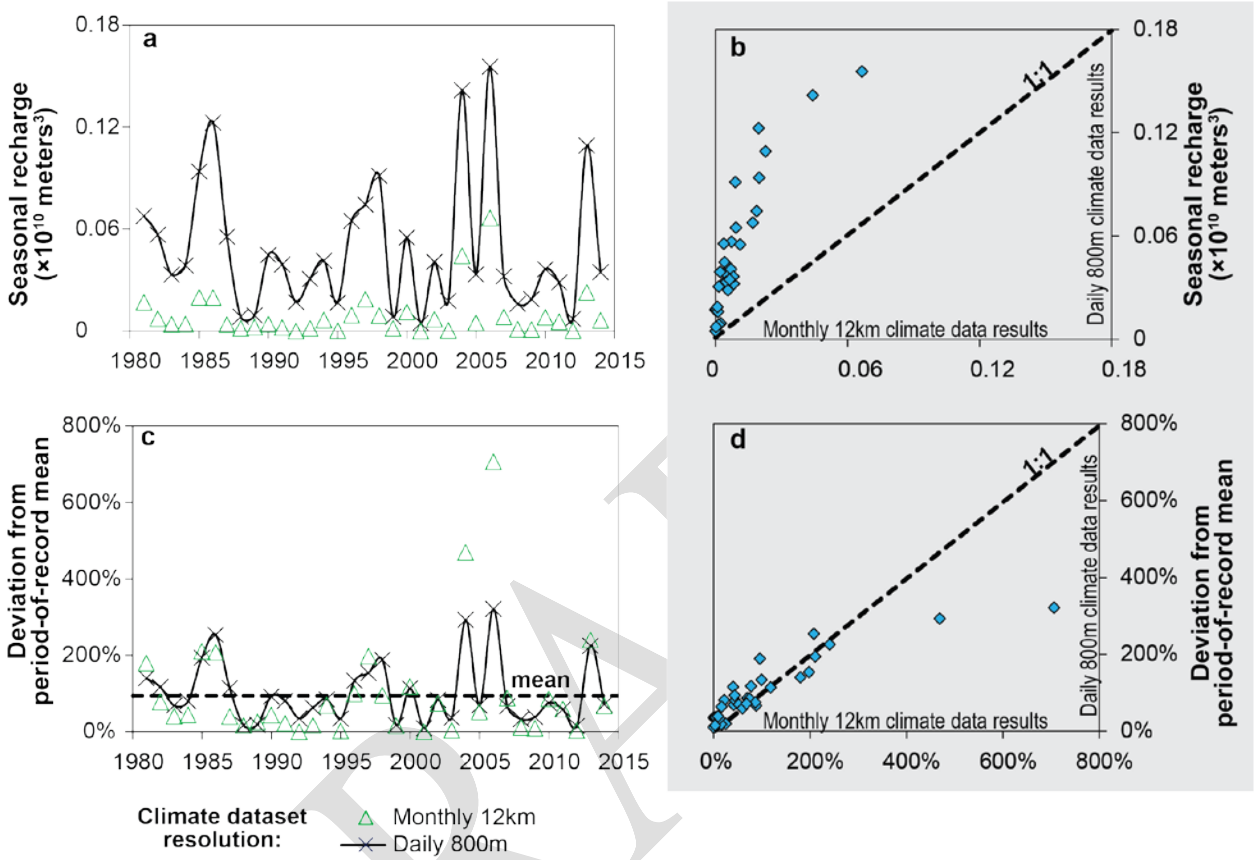

Fig S14 Simulated groundwater recharge in the upper Colorado River basin in September, October, and November of water years 1982–2014 using ~800m daily and ~12km monthly climate data. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from the two climate datasets, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean for the two climate datasets

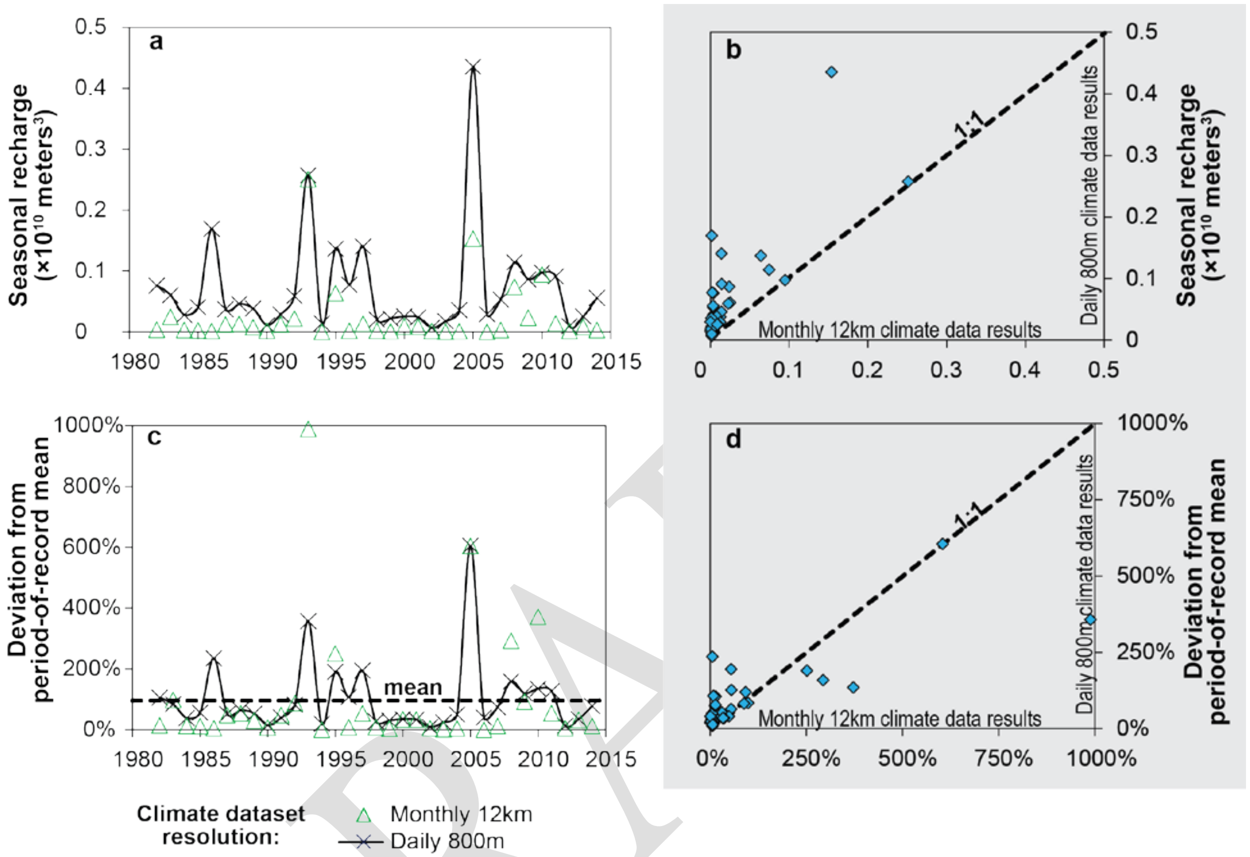

Fig S15 Simulated groundwater recharge in the upper Colorado River basin in December, January, and February of water years 1982–2014 using ~800m daily and ~12km monthly climate data. Results presented as (a) magnitude of seasonal recharge through time, (b) comparison of magnitudes of results from the two climate datasets, (c) change of seasonal recharge from period of record mean through time, and (d) comparison of changes from period of record mean for the two climate datasets