Understanding the past to interpret the future: comparison of simulated groundwater recharge in the upper Colorado River basin using observed and GCM historical climate data

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Abstract In evaluating potential impacts of climate change on water resources, water managers seek to understand how future conditions may differ from the recent past. Studies of climate impacts on groundwater recharge often compare simulated recharge from future and historical time periods on an average monthly or overall average annual basis, or compare average recharge from future decades to that from a single recent decade. Baseline historical recharge estimates, which are compared with future conditions, are often from simulations using observed historical climate data. Comparison of average monthly results, average annual results, or even averaging over selected historical decades, may mask the true variability in historical results and lead to misinterpretation of future conditions. Comparison of future recharge results simulated using general circulation model (GCM) climate data to recharge results simulated using actual historical climate data may also result in an incomplete understanding of the likelihood of future changes from past conditions. In this study, groundwater recharge is estimated in the upper Colorado River basin using the distributed-parameter Soil-Water Balance groundwater recharge model for the 1951–2010 time period. Recharge simulations are performed using precipitation, maximum temperature, and minimum temperature data from observed climate data and from 97 CMIP5 model projections. Results indicate average monthly and average annual simulated recharge are similar using observed and GCM climate data. However, 10-year moving average recharge results show substantial differences between observed and simulated climate data, particularly during the 1970–2000 time period, with much greater variability seen for results using observed climate data.

Keywords: Colorado River, groundwater recharge, climate change, groundwater management

1. Introduction

In order to prepare for possible changes in water resources in response to a changing climate, water managers must understand how future hydrologic conditions may differ from conditions in the recent past. Recently, simulations of future hydrologic conditions using downscaled climate data from one or more general circulation models (GCM) and multiple emission scenarios have become a common tool for understanding potential change in hydrologic systems (Holman et al. 2012). These published studies are often of surface-water systems (for example, see Barnett et al. 2007; Christensen et al. 2004; Kopytkovskiy et al. 2015; Miller et al. 2012; Vano et al., 2014). Impacts to groundwater also are expected in future climates (Green et al. 2011) and investigations of potential impacts to groundwater systems, especially changes to groundwater recharge in response to changing climate, also have used this approach. Studies comparing simulated groundwater recharge in future climates projected by GCMs to historical recharge have been reported for basins in Germany (Eckhardt and Ulbrich, 2003), British Columbia (Allen et al., 2010; Scibeck and Allen, 2006; Toews and Allen, 2009), Australia (Crosbie et al., 2010; Crosbie et al., 2011; Crosbie et al., 2013; McCallum et al., 2010), southern Canada (Jyrkama and Sykes, 2007), eastern Canada (Kurylyk and MacQuarrie, 2013), Africa (Mileham et al., 2009; Nyenje and Batelaan, 2009), England (Holman et al., 2009), the western United States (Meixner et al., 2016), and the upper Colorado River basin (Tillman et al., 2016). These studies typically simulate groundwater recharge averaged annually or monthly over future time periods using GCM-output climate data and compare these results to baseline simulated recharge over historical time periods using observed climate data, stochastic-weather-generator climate data, or GCM-simulated climate data. The time periods of comparison, both future and past, as well as the source of historical climate data, both actual observed and generated or simulated, vary among the studies. Although similar recharge-simulation results are expected using observed climate data and GCM-output climate data that are downscaled using the same observed data, understanding any differences in these historical results may be important when comparing with projected future recharge.

In this study, groundwater recharge is estimated in the upper Colorado River basin using the distributed-parameter Soil-Water Balance groundwater recharge model for the 1951–2010 historical time period. Recharge simulations are performed using precipitation, maximum temperature, and minimum temperature data from actual climate observations and from 97 downscaled Coupled Model Intercomparison Project phase 5 (CMIP5) model results over the historical time period. Simulated historical recharge results are compared for the observed and modeled climate input datasets on an average monthly, average annual, and moving ten-year average basis. All SWB groundwater recharge modeling results for the UCRB described in this manuscript are available at the USGS ScienceBase web site (Tillman, 2016).

2. Study area

More than 3 million people in Mexico and 35 million people in the United States depend on the Colorado River to supply their domestic and industrial water needs (Bureau of Reclamation 2011; Colorado River Basin Salinity Control Forum 2013). The Colorado River also supplies irrigation water for over 1.8 million hectares of land in the United States and Mexico and hydroelectric power along the river and its tributaries generates about 12 billion kilowatt hours annually (Colorado River Basin Salinity Control Forum 2011). Miller et al. (2014) estimated that annual discharge of groundwater to rivers and streams (base flow) in the upper Colorado River basin (UCRB) can range from 21 to 58 percent of streamflow, with higher percentages during low-flow conditions. Recently, a study by Castle et al. (2014) using remotely sensed gravity observations from the NASA Gravity Recovery and Climate Experiment (GRACE) mission found that UCRB groundwater was depleted by more than 50 km^3 from December 2004 to November 2013. Understanding groundwater-budget components, including groundwater recharge, is important to sustainably manage both groundwater and surface-water supplies in the Colorado River Basin. From headwaters in the Rocky Mountains through seven states and Mexico, the Colorado River traverses more than 2200 km to discharge into the Gulf of California (fig. 1A). The Colorado River Basin drains parts of Wyoming, Utah, Colorado, New Mexico, Arizona, Nevada, California, and Mexico, and is divided into upper and lower basins at the compact point of Lee Ferry, Arizona, a location 1.6 km downstream of the mouth of the Paria River (fig. 1A; Anderson 2004). The UCRB is defined for this study as the 293,721 km^2 drainage area of the Colorado River basin above the Lee Ferry compact point and the Great Divide closed basin, as delineated by the Region 14 hydrologic unit code (HUC; see http://water.usgs.gov/GIS/huc.html). Major tributaries to the Colorado River in the upper basin include the Dolores, Green, Gunnison, San Juan, White, and Yampa Rivers (fig. 1B). Average annual precipitation ranges from less than 250 mm in low-elevation areas to more than 1000 mm in high elevation areas in the Southern Rocky Mountains (fig. 1C, PRISM Climate Group 2012). The UCRB varies in elevation from about 944 m near the Lees Ferry streamgage to more than 4260 m in peaks in the Southern Rocky Mountains in the eastern part of the

UCRB (Liebermann et al. 1989). UCRB land cover is predominately shrub/scrub and evergreen forest (Fry et al. 2011), with few high-density population centers (fig. 1D).

Fig. 1 Location of the upper Colorado River basin study area within the southwestern United States (A), major tributaries to the Colorado River (B), average annual precipitation (C; PRISM Climate Group 2012), and major land-cover classifications (D; Fry et al. 2011).

Areas with the potential for recharge of groundwater supplies through infiltration of excess precipitation are present across most of the UCRB. Regional aquifers in the UCRB are composed of permeable, moderately to well-consolidated sedimentary rocks ranging in age from Permian to Tertiary (Robson and Banta 1995), although groundwater in shallow alluvial deposits may be locally important in some locations in the Southern Rocky Mountains (Apodaca and Bails 2000). At least three groups of regional, productive water-yielding geologic units have been identified in the UCRB (Robson and Banta 1995; Geldon 2003a,b; Freethey and Cordy 1991). Tertiary aquifers of limited extent in the northern and southeastern parts of the basin overlie Mesozoic aquifers that also are present throughout most of the study area. Deeper Paleozoic aquifers are present throughout much of the UCRB and may outcrop at land surface in uplifted areas. Major aquifers are each partially separated by confining units, and groundwater flows between the aquifers in areas where confining units are missing. Interconnection of the aquifers creates a regional groundwater-flow system (Geldon 2003a,b; Freethey and Cordy 1991). In his investigation of the hydrologic and groundwater-flow systems in the UCRB, Geldon (2003b) estimates about 8.14 km^3 of recharge to all groundwater systems in the area, excluding the upper San Juan basin which was not part of the study.

3. Methods and data

The Soil-Water Balance groundwater recharge model was used to simulate groundwater recharge in the UCRB for the water-year 1951–2010 time period at a daily time step. Recharge simulations were performed using both observed historical climate data and simulated historical climate data from CMIP5 GCM output.

3.1 Soil-water balance recharge model

The Soil-Water-Balance (SWB) computer code (Westenbroek et al. 2010) estimates spatial and temporal variations in groundwater recharge by calculating water balance components at daily time steps. SWB has been used in several completed and ongoing regional groundwater studies in the U.S. including the High Plains Aquifer (Stanton et al. 2011), the Lake Michigan Basin (Feinstein et al. 2010), basins in Wisconsin (Dripps and Bradbury 2009) and Minnesota (Smith and Westenbroek 2015), the Northern Atlantic Coastal Plain Aquifer System (Masterson et al. 2013), the Ozark Plateau Groundwater Availability Study (see http://ar.water.usgs.gov/ozarks/waterbud.html), and the Appalachian Plateaus Groundwater Availability Study (see http://va.water.usgs.gov/appalachianplateaus/waterbud.html). SWB follows a modified Thornthwaite-Mather soil-water-balance accounting approach (Thornthwaite 1948; Thornthwaite and Mather 1957) and recharge is estimated separately for each grid cell within the model domain. Sources and sinks of water within each grid cell are estimated based on climate data and landscape characteristics, and recharge is then estimated as the difference between the change in soil moisture and these sources and sinks:

$$\overbrace{(\text{rainfall} + \text{snowmelt} + \text{inflow})}^{\textit{water sources}} - \overbrace{(\text{interception} + \text{outflow} + \text{AET})}^{\textit{water sinks}} - \Delta\,\text{soil moisture} = \text{RECHARGE} \tag{1}$$

Spatially gridded datasets required for SWB simulations include land cover, overland flow direction, hydrologic soil group, available soil-water capacity, daily precipitation, daily maximum temperature, and daily minimum temperature. Tabular information required by SWB include runoff curve numbers, vegetation rooting depths, interception values, and maximum daily recharge values for each combination of hydrologic soil group and land-cover type. Inflow to a cell is surface flow from adjacent cells, calculated using the National Resources Conservation Service curve number rainfall-runoff relation. The direction of runoff from cell to cell is determined using a flow-direction grid derived from a digital-elevation model (DEM). Interception is a user-specified amount of precipitation that is trapped and used by vegetation. Outflow from a cell is calculated in the same manner as inflow to the cell. There are several methods available for estimating potential evapotranspiration (PET) in the SWB model, from which actual evapotranspiration (AET) is calculated. For the UCRB simulations, the Hargreaves-Samani (1985) method is used as it produces spatially variable estimates of potential ET (PET) from spatially varying minimum and maximum air temperature data for each daily time step:

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

where PET is potential ET, 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 as a function of the day of year and latitude following the method of Allen et al. (2006). The computation of soil moisture in equation 1 requires several intermediary values. First, PET is subtracted from precipitation (P) for all grid cells. If P – PET is negative (i.e., if P < PET), then there is a potential deficiency of water. Accumulated Potential Water Loss (APWL) is computed as 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 soil moisture and APWL. Actual ET (AET) is then equal to only the amount of water that can be extracted from the soil. If P – PET is positive (i.e., if P > PET), a potential surplus of water exists and AET is equal to PET. 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 (calculated 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 capped at the maximum water-holding capacity, excess soil-moisture becomes recharge, and AWPL is set to zero.

All spatially gridded input datasets were resampled to the same cell size and geographic coordinate system as the 1/8th degree climate data described below. For a detailed description of the source, manipulation, and resampling of SWB model inputs for UCRB recharge simulations, and a sensitivity analysis of model results, see Tillman (2015). See Westenbroek et al. (2010) for detailed explanations of SWB processes. Annual recharge simulated during the 1951-2010 historical time period by the SWB model over the same UCRB area as the Geldon (2003b) study is 9.1 km^3 and 8.6 km^3 (mean and median annual values), representing 11% and 6% percent differences, respectively, with the Geldon (2003b) estimate.

Climate changes are expressed in SWB simulated recharge results (equation 1) through the computation of AET (mean temperature) and through precipitation input. The SWB model does not include changes in land use over time or simulate changes in stomatal conductance or leaf area in a CO_2 enriched atmosphere (Eckhardt and Ulbrich 2003; Holman et al. 2012). Only direct impacts of climate change are evaluated in SWB recharge results.

3.2 Climate data

Groundwater recharge was simulated for the 1951–2010 time period on a daily time step using both observed and simulated precipitation and temperature climate data. Daily 1/8th degree gridded observed climate data were processed for the UCRB study area as described in Maurer et al. (2002) and obtained from http://www.engr.scu.edu/~emaurer/gridded_obs/index_gridded_obs.html. Simulated daily precipitation and temperature data for the UCRB study area were obtained from the downscaled climate and hydrology projections archive (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html) as downscaled 1/8th degree bias-corrected spatially disaggregated (BCSD) climate projection datasets (Bureau of Reclamation 2013). For UCRB groundwater recharge simulations, simulated climate datasets were available for 97 climate projections from the Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model archive (supplemental Table S1). Each of the 97 ensemble members were derived from a General Circulation Model (GCM) run using a given future-emission scenario, known as a Representative Concentration Pathway (RCP), with a unique initial condition. The four RCPs, developed at the request of the Intergovernmental Panel on Climate Change (IPCC), are for radiative forcing levels of 8.5, 6, 4.5, and 2.6 W/m^2 by the end of the century (Van Vuuren 2011). The four RCPs include one very high baseline (no climate policy) emission scenario (RCP8.5), two medium stabilization scenarios (RCP4.5 and RCP6), and one very low forcing level (RCP2.6; Van Vuuren 2011). Since GCMs are typically run at coarse spatial resolutions (e.g., ~100-200 km on a grid side) and at time scales of 100-years or longer, there is a need to post-process GCM-derived variables such as precipitation and temperature to finer spatial scales in order to conduct climate impact assessments. This post-processing step is commonly referred to as downscaling, and there is a continuum of downscaling methods ranging from statistical approaches to physically-based modeling. The 97 projections used in this study were developed using a statistical downscaling method referred to as BCSD (Bias-Correction and Spatial Disaggregation; Wood et al. 2004). The BCSD method was used to develop monthly precipitation and temperature fields at 1/8° × 1/8° (latitude × longitude) spatial resolution from the GCM native-scales. The monthly precipitation and temperature fields were subsequently disaggregated to daily values using a historical resampling and scaling technique (Wood et al. 2002). These daily precipitation and temperature data for the UCRB study area were obtained from the downscaled climate and hydrology projections archive (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html; Bureau of Reclamation 2013).

4. Results and discussion

Daily simulated groundwater recharge for the UCRB for water years 1951–2010 was aggregated into monthly time periods for further analysis. Recharge results are presented as boxplots indicating 90th, 75th, 50th (median), 25th, and 10th percentiles, as well as mean values, over the time period of analysis. Simulated recharge results using observed climate data and GCM-simulated climate data are presented separately. Although simulated recharge differences between GCM-climate data from different RCPs are not expected, GCM-climate results are presented by combining results from all RCPs and by presenting results for each RCP separately. In discussing results, differences presented in terms of percent (%) refer to percentage difference, which is the absolute value of the difference between two values divided by their mean.

Simulated UCRB monthly groundwater recharge (fig. 2) indicates substantial recharge in the March through June time frame, during snowmelt and spring precipitation, with little recharge during other months of the year. Mean recharge values for March–June account for over 88% of the mean annual recharge for the UCRB for simulations using both observed and GCM climate datasets. Importantly, differences between monthly recharge results simulated using the different climate datasets are not large during these months. During the high-recharge months of March through June, simulated mean recharge from the GCM climate data, whether results were grouped together or separated by RCP, differed from the Maurer et al. (2002) observed climate data by a maximum of 26%. The highest recharge months of April and May, accounting for over 64% of annual recharge, differed by 4% or less. Similar results are noted comparing median recharge values, with 32% or less difference between observed and GCM climate data results in March through June, and April and May results differing by 5% or less. This similarity in groundwater recharge results using the different climate datasets is consistent whether the GCM-climate data simulations are grouped together (fig. 2b), with 5820 results per month (60 years × 97 ensembles), or separated by RCP (fig. 2c-f), with 960–1860 results per month (fig. 2). Substantial differences of 66–72% between mean recharge results simulated with observed and GCM climate data are seen for July, but this month accounts for only 1% of the mean annual recharge for the basin. Differences in median recharge results are greater than 100% in

August, but this month also contributes very little to total annual recharge (less than 1%). Variability of within-monthly results also are similar whether observed or GCM climate data were used in the recharge simulations. Differences in recharge results from observed or GCM climate data between the 75th percentile and median values and between 25th percentile and median values are ≤25% for the high recharge months of March through June, with the exception of June differences between 75th percentile and median values (36–45%). For the months contributing the majority of recharge, comparisons of mean or median simulated monthly recharge results from future climate scenarios to historical results using either observed or GCM climate data, either with all results grouped together or separated by RCP, would produce similar conclusions about changes to the UCRB groundwater system.

Fig. 2 Statistics for monthly groundwater recharge in the upper Colorado River basin for water-years 1951–2010 simulated with the Soil-Water Balance model using (a) observed climate data (Maurer et al., 2002) and CMIP5 GCM climate data (b-f).

By most measures, annual groundwater recharge results for the UCRB also are similar for simulations using the different climate datasets (fig. 3). Mean annual recharge results differ between simulations using observed climate data and GCM climate data by 5% or less, while median values differ by 2% or less. The spread of recharge results between 25th percentile and median values are likewise similar for simulations using the different climate datasets, with differences of 22% or less. Variability between 75th and median values, however, is substantially greater for recharge results simulated with observed climate data compared with results simulated with GCM climate data (fig. 3). While separate-RCP results differ from all-RCP results by 5% or less, recharge results using observed climate data differ by 42–43% from GCM results, depending on whether GCM results are grouped by RCP or not (fig. 3). This greater spread in higher-than-median recharge values may be important if comparing mean or median recharge results spanning time periods shorter than the full 60 years of historical simulations. Comparisons of climate change impacts on the central tendency (mean or median) of groundwater recharge to historical results averaged over the 60-year record, however, would result in similar conclusions whether observed or GCM climate data were used in historical simulations.

Fig. 3 Annual groundwater recharge in the upper Colorado River basin for water-years 1951–2010 simulated with the Soil-Water Balance model using observed climate data (Maurer et al., 2002; left boxplot) and CMIP5 GCM climate data (all other boxplots).

Simulated annual groundwater recharge during ten-year periods, moving every 5 years, also was analyzed for water years 1951–2010 (fig. 4). The ten-year moving period balances the need to smooth out variability in recharge from individual years, whose effects are integrated over time in groundwater systems (Green et al. 2011), with a desire to provide useful information to water managers over a reasonably short time frame in order to allow for mitigating action. Moving the ten-year period through time by five years eliminates the subjectivity of picking decade start and stop years that may encompass anomalously wet or dry periods. Comparing future and past recharge results over ten-year moving periods addresses the question “how might conditions in future decades differ from conditions experienced in decades since 1951?”

Annual simulated recharge results over moving ten-year periods are similar among results using GCM climate data (fig. 4). The mean of annual separate-RCP results are within 3% of combined RCP results, with median values within 4%. Comparison of simulated recharge results between simulations using observed and GCM climate data, however, reveals substantial differences in mean annual values during some decades (fig. 4). During the 1976–1985 ten-year period, mean annual recharge simulated with GCM climate data differ from simulations with observed climate data by 23–25%, depending on whether results are separated by RCP or are grouped together. Differences of 18–20% are observed in the 1991–2000 time period. Differences between recharge simulations using GCM climate data and observed climate data are even more pronounced when medians are used as an indication of central tendency during the ten-year period. Median annual recharge values differ by more than 41% during the 1976–1985 decade, with differences of 16–20% in both the 1981–1990 and 1991–2000 decades (fig. 4). The distribution of annual values is also noticeably different for recharge simulations using observed climate data versus GCM climate data. Differences between the 75^{th} percentile minus median values of annual recharge are greater than 50% in over one-third of the decadal comparisons between results using simulated climate data and results using observed climate data. Difference in 25^{th} percentile minus median values are 50% or greater in almost half of the decadal comparisons. The differences in distribution of simulated groundwater recharge using observed climate data and

GCM climate data are not as strongly observed in PET results (supplemental fig. S1) where temperature changes are expressed, but are evident in precipitation for the basin (supplemental fig. S2). The difference in variability in simulated groundwater recharge is related to the smaller sample size (n=10) for the observed data decadal analyses (compared with n =160–970 for the GCM analyses), but also is a result of variability in observed precipitation that is not captured by GCM simulated historical climate data. While an annual simulated recharge time period is too short for meaningful comparisons with future changes, the inability of recharge simulations using GCM climate data to capture much of the annual variability of recharge using observed climate data (fig. 5) may affect the interpretation of changes in future versus past conditions over even longer averaging periods. Conclusions about comparisons of future changes in simulated annual groundwater recharge in 10-year moving periods to historical results may depend upon whether the historical results were simulated using observed or GCM climate data. For example, simulated mean annual recharge in future decades appears to increase relative to historical recharge modeled using simulated climate data (fig. 6a). The same projected average annual recharge, however, appears to decline somewhat relative to historical recharge simulated with observed climate data (fig. 6b).

Fig. 4 Annual groundwater recharge in the upper Colorado River basin over 10-year periods, moving every 5 years between water-years 1951 and 2010, simulated with the Soil-Water Balance model using (a) observed climate data (Maurer et al., 2002) and CMIP5 GCM climate data (b-f).

Fig. 5 Percentage change of annual recharge (observed historical climate data) or mean annual recharge (for CMIP5 simulated climate data) from 1951–2010 mean annual values in the upper Colorado River basin.

Fig. 6 Comparison of ten-year averages, moving every five years, of simulated annual groundwater recharge in the upper Colorado River basin using projected climate data to modeled recharge using (a) simulated historical climate data and (b) observed historical climate data. Results presented as changes in recharge relative to historical average of ten-year means from 1951–2010.

5. Summary and Conclusions

Groundwater recharge in the upper Colorado River basin was simulated using the Soil Water Balance model with a daily time step for the water year 1951–2010 time period. Historical SWB recharge simulations were performed using both observed climate data and GCM-output climate data from 97 CMIP5 projections. Mean and median results for monthly and average annual time periods were similar for recharge simulations using observed or GCM climate data, with an increase in variability noted in observed annual results. Substantial differences in mean and median annual averages between simulated recharge using observed versus GCM climate data were seen in several moving ten-year time periods. Investigating potential changes in future groundwater recharge requires an understanding of the historical conditions with which they are compared. The likelihood of future UCRB groundwater recharge differing from that of the last 60 years is dependent upon changes in future climate, as well as potentially the choice of historical climate dataset used in recharge simulations and the time period of comparison.

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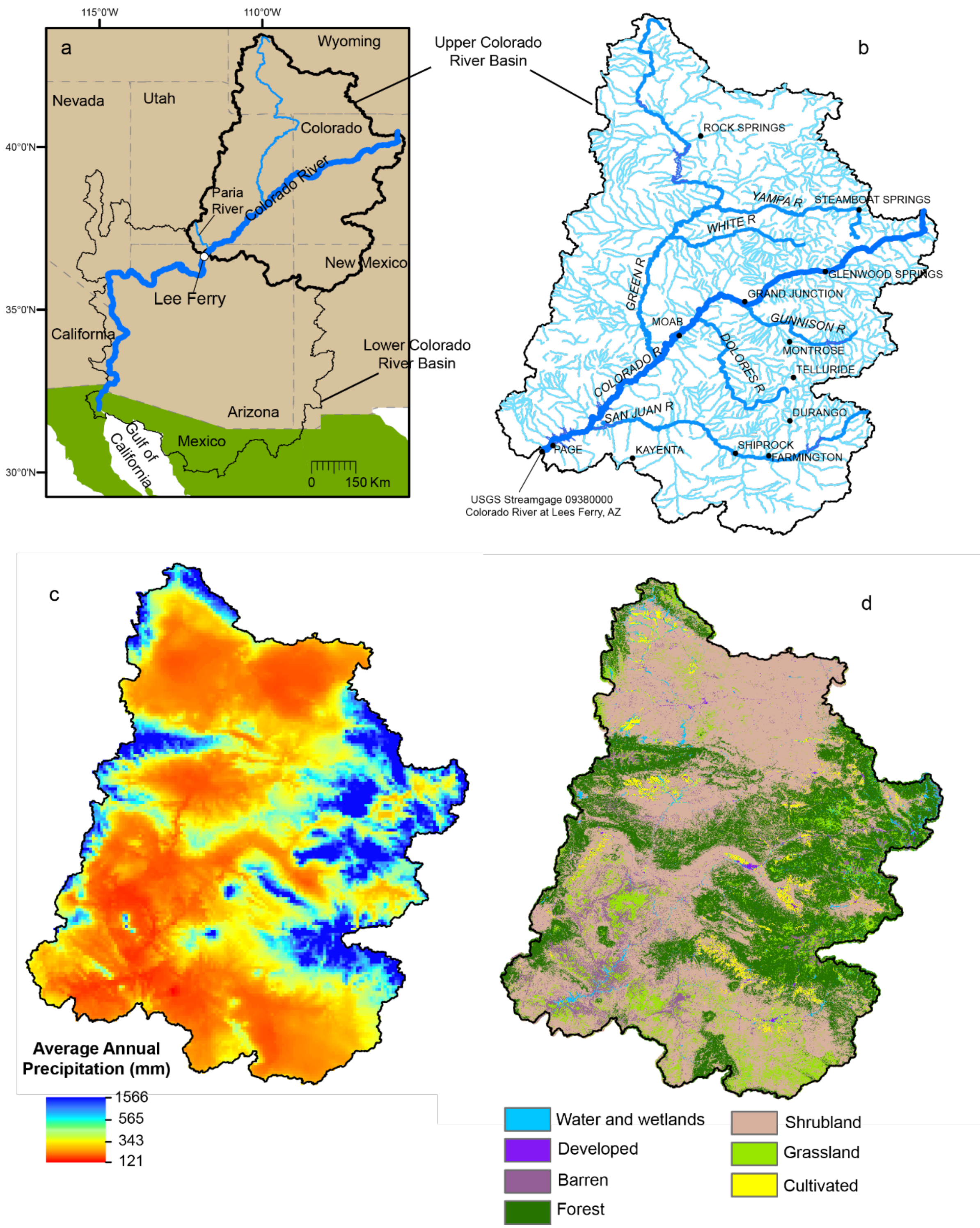

Fig. 1 Location of the upper Colorado River basin study area within the southwestern United States (a), major tributaries to the Colorado River (b), average annual precipitation (c; PRISM Climate Group 2012), and major land-cover classifications (d; Fry et al. 2011).

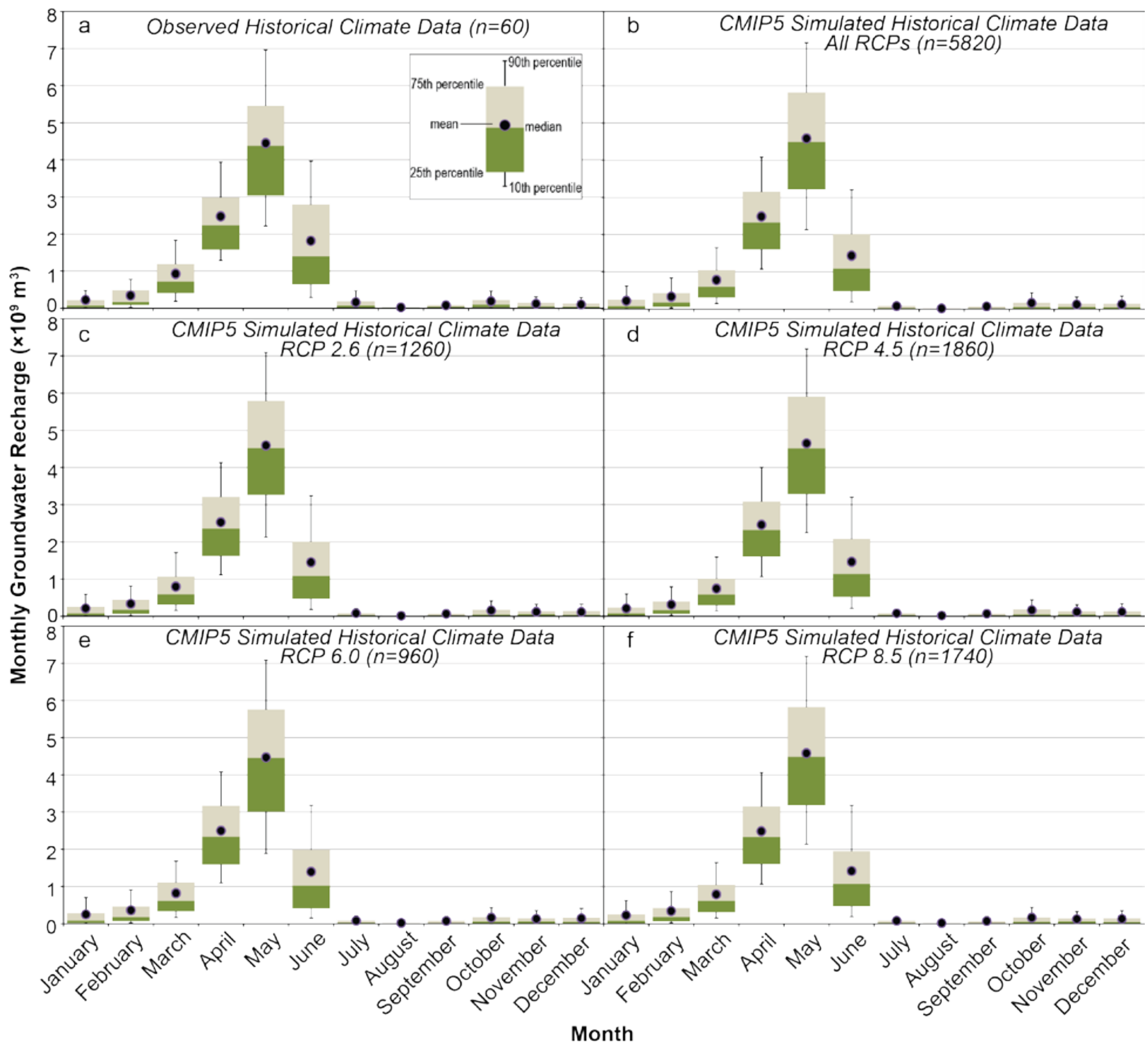

Fig. 2 Statistics for monthly groundwater recharge in the upper Colorado River basin for water-years 1951–2010 simulated with the Soil-Water Balance model using (a) observed climate data (Maurer et al., 2002) and CMIP5 GCM climate data (b-f).

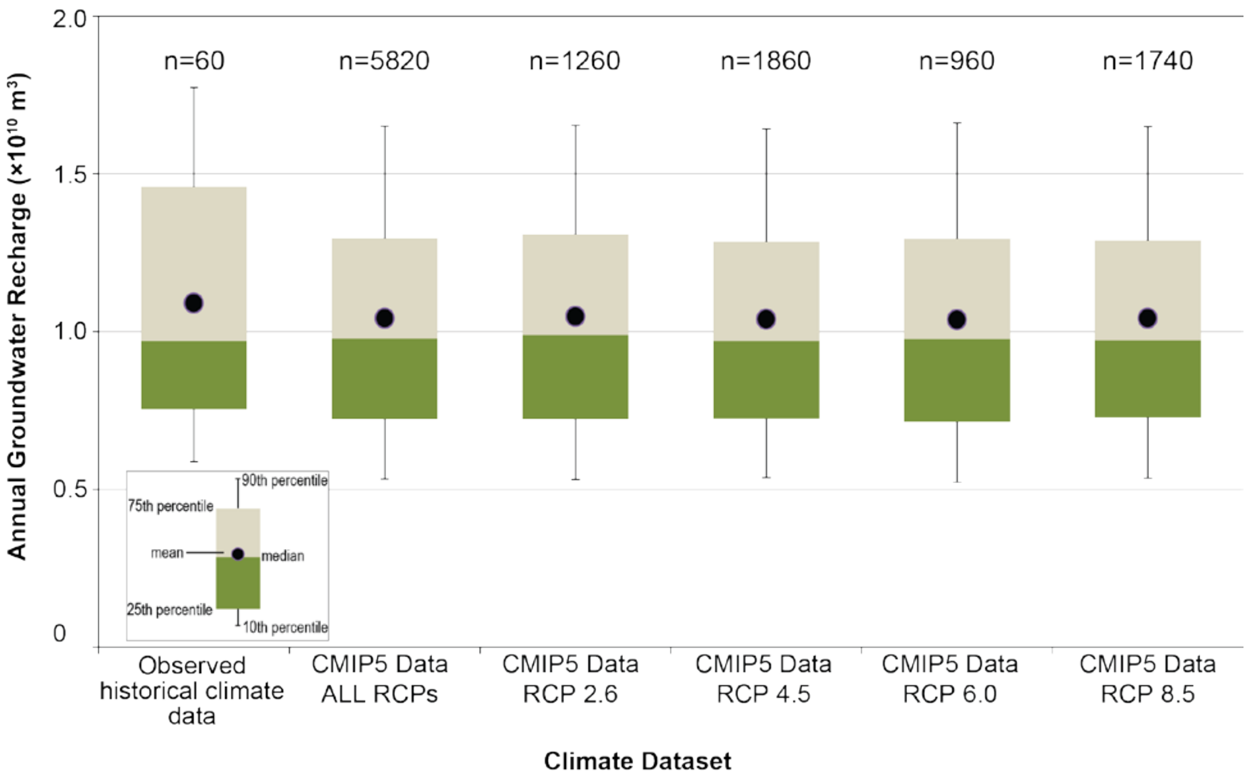

Fig. 3 Annual groundwater recharge in the upper Colorado River basin for water-years 1951–2010 simulated with the Soil-Water Balance model using observed climate data (Maurer et al., 2002; left boxplot) and CMIP5 GCM climate data (all other boxplots).

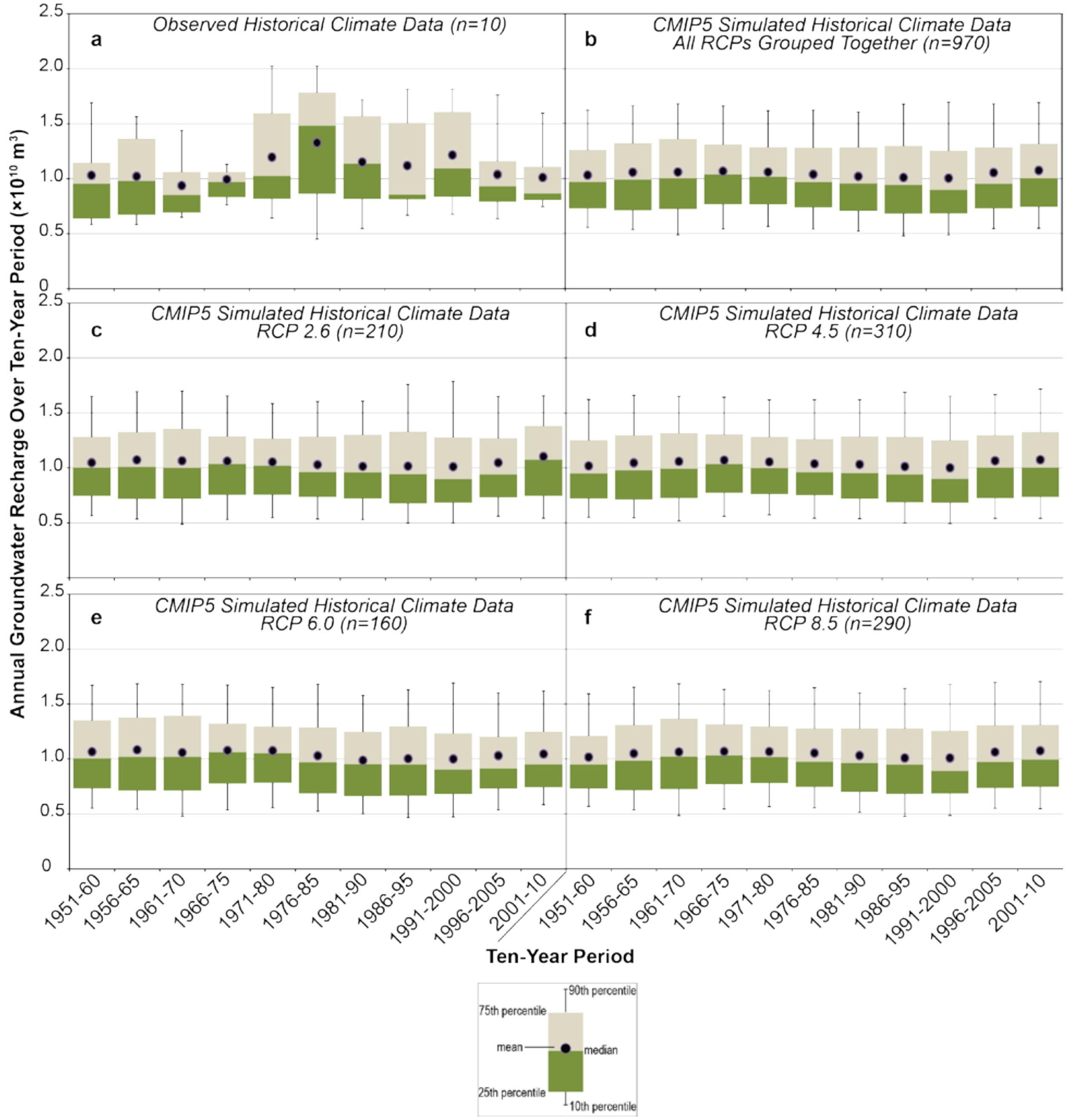

Fig. 4 Annual groundwater recharge in the upper Colorado River basin over 10-year periods, moving every 5 years between water-years 1951 and 2010, simulated with the Soil-Water Balance model using (a) observed climate data (Maurer et al., 2002) and CMIP5 GCM climate data (b-f).

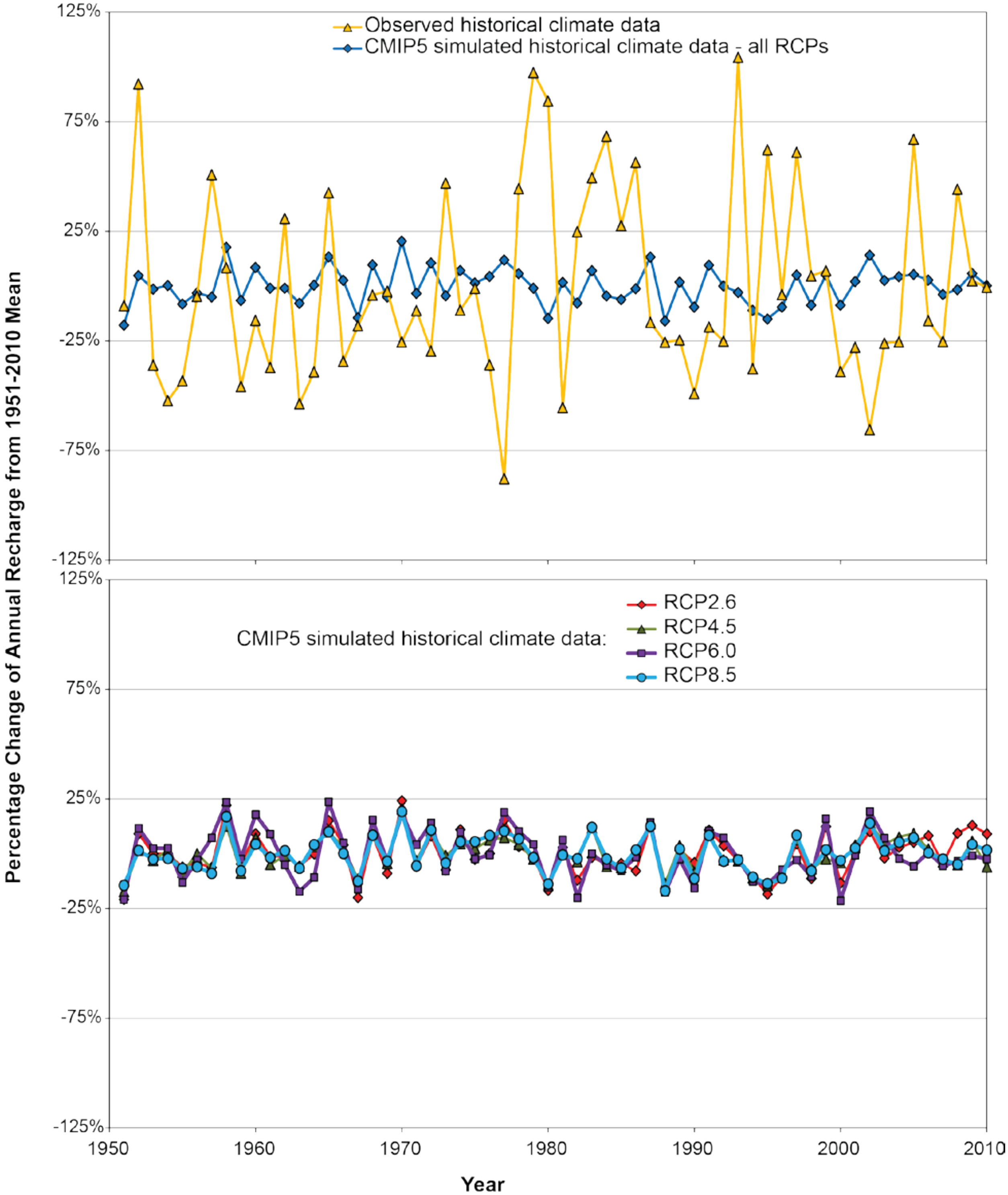

Fig. 5 Percentage change from 1951–2010 mean annual values of simulated annual recharge using observed historical climate data and mean simulated annual recharge using CMIP5 climate data in the upper Colorado River basin.

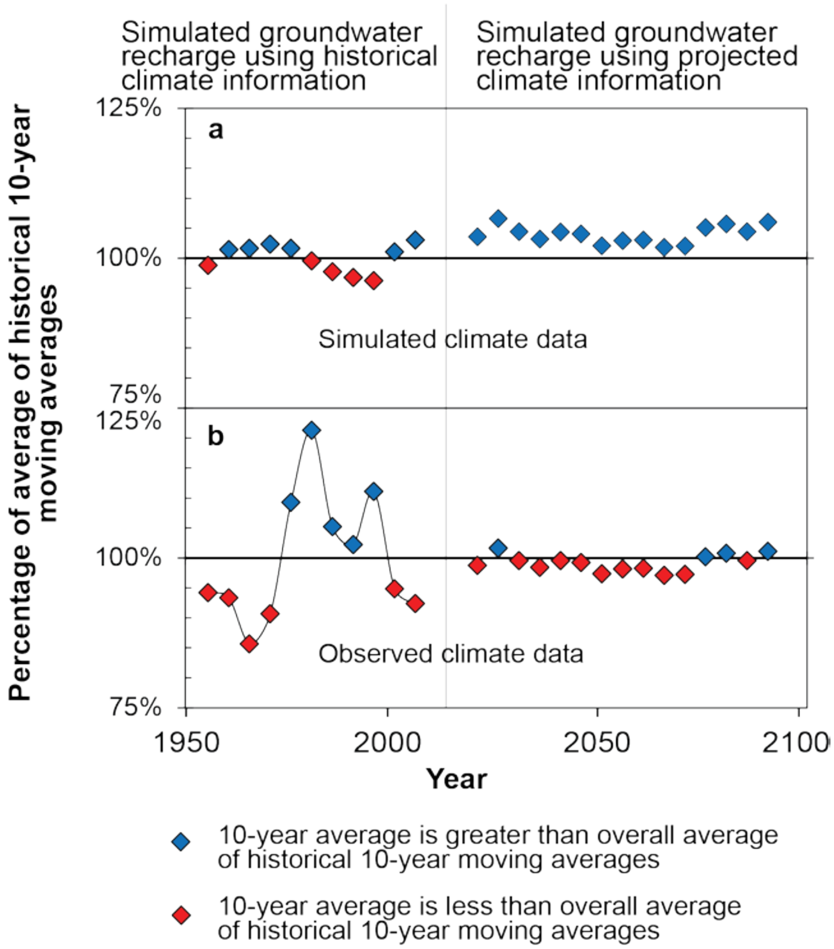

Fig. 6 Comparison of ten-year averages, moving every five years, of simulated annual groundwater recharge in the upper Colorado River basin using projected climate data to modeled recharge using (a) simulated historical climate data and (b) observed historical climate data. Results presented as changes in recharge relative to historical average of ten-year means from 1951–2010.