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The implications of climate change scenario selection for future streamflow projection in the Upper Colorado River Basin

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Abstract

The impact of projected 21st century climate conditions on streamflow in the Upper Colorado River Basin was estimated using a multi-model ensemble approach wherein the downscaled outputs of 112 future climate scenarios from 16 global climate models (GCMs) were used to drive a macroscale hydrology model. By the middle of the century, the impacts on streamflow range, over the entire ensemble, from a decrease of approximately 30 % to an increase of approximately the same magnitude. Although prior studies and associated media coverage have focused heavily on the likelihood of a drier future for the Colorado River Basin, approximately one-third of the ensemble of runs result in little change or increases in streamflow. The broad range of projected impacts is primarily the result of uncertainty in projections of future precipitation, and a relatively small part of the variability of precipitation across the projections can be attributed to the effect of emissions scenarios. The simulated evolution of future temperature is strongly influenced by emissions, but temperature has a smaller influence than precipitation on flow. Period change statistics (i.e., the change in flow from one 30-yr period to another) vary as much within a model ensemble as between models and emissions scenarios. Even over the course of the current century, the variability across the projections is much greater than the trend in the ensemble mean. The relatively large ensemble analysis described herein provides perspective on earlier studies that have used fewer scenarios, and suggests that impact analyses relying on one or a few scenarios, as is still common in dynamical downscaling assessments, are unacceptably influenced by choice of projections.

1 Introduction

The US Secretary of the Interior, acting through the Bureau of Reclamation (Reclamation), is responsible for the operation of eight major water storage reservoirs on the Colorado River and its upper tributaries, including Glen Canyon Dam and Hoover Dam.

HESSD

9, 847–894, 2012

The Boulder Canyon Project Act of 1928 designated the Secretary as water master, responsible for distributing all Colorado River water below Hoover Dam in conformance with federal law, water delivery contracts and the international agreement with Mexico. Through operation of federal facilities and administration of water deliveries, Reclamation contributes to the management of water supplies for more than 30 million people and nearly 4 million acres of agricultural land. Reclamation is continuously conducting long- and short-term water resources analyses to support planning and operations in the Colorado River Basin. In January 2010, Reclamation initiated the Colorado River Basin Water Supply and Demand Study (Reclamation, 2011a), which is being conducted with water management agencies representing the seven Colorado River Basin States (Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming.) The work described in this paper was conducted in support of the study.

Hydrology and climate change in the Colorado River Basin

An extensive record of streamflows and reconstructed natural flows exists in the Colorado River Basin, but the value of that record as the sole basis for estimating future conditions has come into question because of the prospect that anthropogenic climate change will change the mean and variability of stream flows and evapotranspiration (Milly et al., 2008). Global climate model (GCM) projections of future climate over a multi-decadal time frame indicate that the Colorado River Basin will become warmer. Projections of future precipitation are more complex, with the multi-model average of projections showing little change in annual precipitation in the water-producing regions of the basin, but generally showing a seasonal shift in the temporal pattern of precipitation. Changes in temperature and precipitation will influence hydrologic processes on the land surface, which in turn will cause changes in streamflows (Hayhoe et al., 2004; Barnett et al., 2005; Maurer, 2007) but the magnitude and the sign of these changes is uncertain.

The setting of the Colorado River Basin complicates understanding its hydrology and hydrologic response to projected changes in climate. The latitude of the water-producing regions in the basin lies at the northern boundary of the area in the American southwest where projected declines in runoff are strongly indicated (Milly et al., 2005; Seager et al., 2007; Seager and Vecchi, 2010). To the north of this boundary, in contrast, studies have tended to predict increases in rainfall and runoff. If the future boundary instead falls south of the Colorado River Basin headwaters (water producing regions), streamflows in the Upper Colorado River Basin will be reduced less than projected, or may increase. Given the large uncertainty over future climate evolution at the scale of this transition zone, advances in climate science (perhaps including higher-resolution earth system models) will be required before these consequences can be projected with much confidence (Seager and Vecchi, 2010). The topography of the basin also influences the interaction between climate and hydrology – the majority of precipitation in the basin falls in a very small fraction of its area (Reclamation, 2011b), mostly in the form of snow that is stored over seasonal time scales. Snow accumulation and ablation are the most significant processes affecting the timing of streamflow in the basin, and the dynamics of snow will be significantly impacted by rising temperatures regardless of changes in precipitation. The dynamics of snow ablation is further complicated by the recent understanding that the hydrology of the basin has been affected by sporadic deposition of dust on the surface of the snowpack, which accelerates snowmelt and affects basin efficiency (Painter et al., 2007, 2010). The diversity of topography in the basin is another complicating factor. Outside of the cold, high-elevation areas, evapotranspiration is the dominant process affecting the water budget. Basin efficiencies (outflows divided by precipitation) range from about 0.3 for sub-basins at higher average elevations to virtually zero in lower-elevation sub-basins (Reclamation, 2011b). The average runoff efficiency of the basin is approximately 15 %. All of these factors contribute to the difficulty of rationalizing and simulating the hydrology and hydrologic sensitivity of the basin to climate forcings.

Studies of the impact of climate change on the hydrology of the basin began about thirty years ago. Early, scenario-based assessments of the regional impact of climate change indicated that a warming climate would likely lead to a reduction of 30 % or

HESSD
9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

more in stream flow in the Colorado River Basin (Stockton and Boggess, 1979; Revelle and Waggoner, 1983). Recent regional-scale analyses based on the GCM outputs also promoted an unequivocal consensus that the Southwestern United States would become drier. Milly et al. (2005) evaluated projected change in runoff simulated by GCMs. Seager et al. (2007) and Seager and Vecchi (2010) inferred changes in runoff from changes in atmospheric transport of moisture simulated by GCMs. Seager and Vecchi (2010) analyze precipitation minus evaporation (P-E) as a proxy for runoff in Southwestern North America, which extends from the high plains to the Pacific Ocean and from the latitude of the Oregon-California border to Southern Mexico. They suggest that the region will dry in the coming century, largely driven by a decline in winter precipitation, caused by a pole-ward shift of the winter Pacific storm track. In contrast, the Reclamation Study found that the ensemble mean of downscaled climate projections show consistent increases in wintertime precipitation for basins that contain mountainous areas (Reclamation, 2011b).

Studies that utilized hydrologic models to translate projections of temperature and precipitation from climate models into stream flows show more equivocal results than the large-scale studies based on GCM atmospheric output fields. Nash and Gleick (1991) used a conceptual hydrologic model to evaluate the effect on Colorado River flow at Lees Ferry, AZ (a major stream gage just above the bottom of the Upper Colorado River Basin; see Fig. 1) of changes in precipitation and temperature in several constructed scenarios and as projected by four GCMs. Three of the four GCM projections led to decreases in streamflow (as much as 24 %) while the impact from the fourth projection was to leave stream flow virtually unchanged. When evaluating impact on smaller basins within the Upper Colorado River Basin using a second hydrologic model, Nash and Gleick found that higher-elevation basins might be more likely to respond to some projections of future climate with an increase in flow. As in many studies of climate change impacts in the Western US, all of the scenarios and projections indicated that peak runoff would occur earlier in the year.

HESSD
9, 847–894, 2012

Christensen et al. (2004; hereafter C04) used an ensemble of three projections of future climate from a single GCM based on the "business as usual" emission scenario. These projections were statistically downscaled into 1/8th degree, daily forcings using the bias corrected and spatial-disaggregation (BCSD) method outlined in Wood et al. (2002, 2004) (hereafter W02-04) and were subsequently translated into stream flows using the Variable Infiltration and Capacity (VIC) hydrology model (Liang et al., 1994, 1996). Projected climate, which in that study exhibited reductions in precipitation and increases in temperature, led to reductions in annual runoff at Imperial Dam, near the bottom of the Colorado River Basin, of 17 % over the period 2070–2099. The more detailed spatial and process representation of CO4 indicated that the sensitivity of the Colorado River Basin to changes in precipitation was roughly twice what had been indicated by Nash and Gleick, but confirmed the earlier conclusion that peak runoff would occur earlier in the year.

Using the same technique as C04 but expanding the range of climate projections to the ensemble used in Maurer (2007), and updating the hydrology model calibration to that used in Wood and Lettenmaier (2006), Christensen and Lettenmaier (2007; hereafter CL07) used 22 climate projections from 11 GCMs and two emission scenarios (A2 and B1; Nakicenovic et al., 2000) to assess climate impacts on hydrology and water resources in the Colorado River Basin. With a larger number of projections came a larger range of projected changes in flow at Imperial Dam ranging from an increase (five projections) of as much as 23 % to a decrease (seventeen projections) of as much as 36 % for both emission scenarios for the period 2070–2099.

From these prior studies, it is clear that the range of uncertainty in the future flow projections has increased with increasing numbers of projections evaluated. This observation is the primary motivation for this paper. Using a larger ensemble of projections than those featured in prior studies, we explore the relative contributions of uncertainty between different emissions scenarios, ensemble members and climate models, across several periods of the 21st century. This effort does not describe in great detail the findings of the overall climate change impact assessment study, as they have been

HESSD
9, 847–894, 2012

reported in Reclamation (2011b). Instead, we focus on results for the Colorado River at Lees Ferry, AZ, and contrast the full-ensemble results with those of earlier studies. Our intent is to provide insight to the community on the consequences of model, ensemble and scenario choice for impact assessments of this nature.

2 Methods

The impact assessment approach used in Reclamation (2011b) generally followed that of C04, CL07 and other recent GCM-based, multi-model hydrology studies of the last decade. In brief, an ensemble of downscaled and bias corrected climate projections was used to force a distributed, macro-scale hydrology model which generated estimates of runoff and other hydrology variables consistent with projected future climate. The projections of future climate were produced by 16 GCMs forced by IPCC Special Report on Emissions Scenarios (Nakicenovic et al., 2000) emission scenarios B1, A1B and A2. Simulated runoff was routed to 20 streamflow locations within the Upper Colorado River Basin, including the Lees Ferry location. The Reclamation (2011b) work differed from CL07 primarily by using a much larger ensemble of projections (112 versus 22; including 21 of the CL07 projections). Other differences included using a slightly longer baseline period of natural flows and historical weather (56 years versus 50 years), using a slightly different method to disaggregate monthly projections to a daily time step, encompassing a smaller geographic scope (the Upper Colorado River Basin versus the entire Colorado River Basin), and omitting analysis of consequent water resources impacts in the basin. This section describes the flow and meteorological datasets involved (Sect. 2.1) and the hydrology model and its calibration (Sect. 2.2).

HESSD
9, 847–894, 2012

2.1 Data

2.1.1 Historical natural flows

Monthly incremental natural flows at 20 locations in the Upper Colorado River Basin (UCRB) were obtained from Reclamation (2009). Natural flow represents flow that would have occurred at the location had historical depletions and reservoir regulation not been present; development of these natural flows is described in Prairie and Callejo (1995). The locations at which natural flows have been developed by Reclamation are those required by the Colorado River Simulation System (CRSS), a water resources management model used by Reclamation for long-term planning studies in the Colorado River Basin. In its current configuration, CRSS requires natural flow inputs at 29 locations throughout the Basin. CRSS does not physically route flows, so the 20 incremental flows above Lees Ferry are summed to obtain the total natural flow at that location.

2.1.2 Historical daily meteorology

A daily meteorological climatology that includes precipitation, maximum temperature, minimum temperature and wind speed for the period from 1949 through 2005, developed as described in Maurer et al. (2002), formed the historical climatology and forcing dataset used in this study. The data are aligned spatially to match the NOAA/NASA Land Data Assimilation System (LDAS; Mitchell et al., 2004) grid, which has a spatial resolution of 1/8th degree latitude by longitude and covers a domain from 25° N to 53° N and 67° W to 125° W, which includes the continental United States as well as part of Canada and Mexico.

2.1.3 Simulated historical and projected climate

Simulated monthly average precipitation and monthly average temperature scenarios spanning the period 1950 through 2099 were obtained from the Bias Corrected and

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

Downscaled WCRP CMIP3 Climate Projections website (WCRP, 2009; http://gdo-dcp.ucllnl.org/). At the time of this study, the archive contained 112 projections of monthly temperature and precipitation, aligned spatially with the LDAS grid, with each projection consisting of an overlap period of 1950 through 1999 and a projection period of 2000 through 2099. These projections come from 16 GCMs and three SRES scenarios as shown in Table 1. The emission scenario columns indicate the number of realizations that were available for each GCM.

The monthly climate datasets were produced using the statistical bias-correction and spatial disaggregation (BCSD) method described in W02-04. The method was first implemented for downscaling general circulation model seasonal climate predictions to support hydrologic forecasting (W02; Wood et al., 2005; Wood and Lettenmaier, 2006) and adapted for downscaling future climate scenario model output (W04; also C04; Van Rheenen et al., 2004; Payne et al., 2004). The BCSD method has since been employed in a number of more recent climate change impact analyses, in regions such as the Western US (CL07; Barnett et al., 2008; Maurer, 2007), the Continental US (Maurer et al., 2002; Maurer and Hidalgo, 2008), and central America (Maurer et al., 2009) among other locations.

In brief, BCSD approach involve three steps: (1) bias-correction effects a quantile-mapping adjustment of monthly climate-model-scale precipitation and temperature outputs, a step which aligns the monthly climatologies of the climate model variables during a historical period (e.g., 1950–1999) with an observed climatology for the same period and spatial scale; (2) spatial-disaggregation from the climate model scale to the fine scale is accomplished by applying the interpolated bias-corrected variable anomalies from the coarse scale to a fine scale climatology, using multiplicative anomalies for precipitation and additive anomalies for temperature; and (3) temporal disaggregation from monthly to a finer time step (e.g., daily) via a resampling and adjustment of historical weather patterns from the hydrology model forcing climatology. This development of the monthly scale scenarios is detailed in Maurer et al. (2007b). The final disaggregation step differed in some regards from the original W02-04 studies, instead following

HESSD
9, 847–894, 2012

the Maurer (2007b) implementation. A more detailed discussion of the resampling and disaggregation is provided in Appendix A.

2.1.4 BCSD downscaling considerations

The BCSD downscaling approach has been found in prior studies (such as those referenced above) to be generally successful in translating monthly scale signals from the GCM output to the fine resolution at the monthly scale. W02 showed that using BCSD to downscale retrospective climate-model-scale monthly observed precipitation and temperature fields reproduced the monthly mean and variance of hydrologic simulations (for the Ohio River Basin). BCSD expands upon earlier "Delta method" or "Perturbation method" approaches (as in Lettenmaier and Gan, 1990; Lettenmaier et al., 1999, and many other studies), which adjust monthly precipitation and temperature by the relative changes from a interpolated climate model control climate run to a future climate run. The BCSD approach accounts for different sensitivities in different parts of each climate variable's distributions, and for climate model sequencing (i.e., transient simulation behavior) rather than only future mean time slice changes. Climate model sequences may not be realistic, however, which offers a challenge to BCSD and other approaches that do not attempt to modify this climate characteristic.

For water resources oriented studies which involve monthly and coarser time scale analyses of hydrologic changes resulting from warming and moisture changes, BCSD has provided many useful insights. The BCSD approach is not adequate for every type of climate change study, however. The approach is not suitable for studies in which changes in sub-monthly (e.g., daily) meteorological quantities are important (e.g., assessing changes in extreme precipitation, or changes in minimum temperatures where information beyond GCM average monthly temperature is available). Also, the BCSD approach is likely to be weakest (as are all downscaling approaches) where meteorological climatologies are highly skewed or exhibit threshold behavior. For example, in the US Southwest, the intermittency and resulting skewness of precipitation challenges resampling and distributions-based approaches alike. Adaptations such as sample

HESSD
9, 847–894, 2012

substitution described in W02-04 were developed precisely to ameliorate these difficulties, but they are not a comprehensive solution. Other approaches such as constructed analogues (compared with BCSD in Maurer and Hidalgo, 2008) may be more appropriate in such hydroclimatic regimes.

Reclamation (2011c) reports that BCSD downscaled future projections from the WCRP archive exhibit a "relative wettening" (of up to 5 percent) in precipitation changes from current climate, relative to those from the underlying (raw) CMIP3 GCM output from which they are derived. The difference may be an artifact of the quantile-mapping approach used in the BCSD method or it may be a realistic result of mapping the GCM distributions of precipitation to observed precipitation distributions (generally a transform from a more normal distribution to a more skewed distribution). More analysis is required on this question, but lies beyond the scope of this paper.

2.2 Hydrology model

2.2.1 Description

The daily disaggregated projections were used to force a hydrology model of the Upper Colorado River Basin implemented using the Variable Infiltration Capacity (VIC) Model (Liang et al., 1994, 1996). The VIC model is a distributed (gridded) macro-scale (regional-scale) physical hydrology model that simulates the water balance around each grid cell. VIC produces a time series of runoff, baseflow, evapotranspiration, soil moisture and snow water equivalent for each grid cell. Following completion of simulation of the full forcing period, runoff from all the grid cells in the model are routed to points of interest (Lohmann, 1998a). Distinguishing characteristics of the VIC model are described at length elsewhere (e.g., Wood et al., 1992; Nijssen et al., 2001).

VIC has several applications to climate change studies in numerous basins around the world (Wood et al., 1992; Liang et al., 1994, 1996; Lohmann et al., 1998a,b). The VIC model has been used to support assessments of the impact of climate change in many river basins in the Western United States, including California's Central Valley

HESSD
9, 847–894, 2012

(Van Rheenan et al., 2004; Maurer, 2007b; Anderson et al., 2008; Reclamation, 2008), the Colorado River Basin (C04, CL07) and the Columbia-Snake Basin (Payne et al., 2004). VIC is considered well adapted to application to the UCRB because it allows for a relatively detailed representation of the land surface, considering both the grid scale and sub-grid variability, and because it has physically-based models of snow dynamics and evapotranspiration. These capabilities address the complexities of the basin hydrology described above.

2.2.2 Model calibration

A VIC model is specified by a set of global parameters, options and variables and by reference to a set of gridded parameters and a set of gridded forcings. The most important of the global parameters and options determine the number of soil layers, the time step and the duration of the simulation, and controls the simulation approach. For this application, the model was configured to represent three soil layers using a daily time step at the 1/8th degree resolution matching the forcings and routing model. Each VIC grid cell is characterized with parameters describing vegetation and soil. A calibrated set of model parameters for the Colorado River Basin used by C04, updated by Wood and Lettenmaier (2006) and then used in CL07 was applied for this study. These parameters differed from the Maurer et al. (2002) specifications only as a result of calibration, and by the inclusion of average July air temperatures required to implement a condition removing canopy vegetation above tree line elevations. Documentation regarding the VIC parameters and the tree line adjustment is given at the VIC model website (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/).

This model provided a good fit between simulated and historical natural flows for gage locations covering large basin areas such as the Colorado River at the Lees Ferry gage. The duration of the simulation (i.e., 1950–2099) and the initial value of soil moisture in the simulation were the only modifications to the prior parameter sets. Initial soil moisture conditions can substantially influence simulated runoff and baseflow in the first few years of simulation. Initial simulations of streamflow using the existing soil parameters exhibited considerable low bias in the first year. This bias was reduced when soil moisture values were initialized using the average simulated values for 1970 through 1999.

The calibrated VIC model reproduced annual average flow volumes at Lees Ferry with a bias of approximately 4 %, a coefficient of determination of 0.92 and a Nash-Sutcliffe efficiency of 0.91. The model, on average, tended to simulate slightly earlier runoff and slightly lower peak monthly flows compared to historical natural flows. Figure 2a shows that the model bias appears to be concentrated in a few relatively wet years following dry years. Figure 2b shows that the model exhibits a wet bias prior to June and a dry bias in July, August and September. Figure 2c, showing the empirical cumulative distribution function (ECDF) of the streamflows, shows that the model is relatively unbiased between about the 40th percentile and the 75th percentile of flows, and generally shows a positive bias outside that range. Figure 2c also indicates that the model over-simulates the lowest value and under-simulates the highest values.

The simulation results illustrated in Fig. 2 differ from those reported in the earlier studies. Possible reasons for the difference include: (a) the modeling reported herein used version 4.0.7 of the VIC model, whereas prior studies used versions 4.0.3 and 4.0.4; and (b) the calibration and validation periods varied, with this work evaluating statistics over the period 1950–2005, versus prior studies using generally shorter periods.

3 Results and discussion

In this section, we present results from the climate change impact assessment for the Colorado River at the Lees Ferry, AZ gage, and refer the reader to a wider range of results and analyses in Reclamation (2011b). The single-gage results also serve to illustrate characteristics of the uncertainty in the analysis.

3.1 Downscaled climate, past and future

As noted earlier, the model forcings derived from 112 climate projections are bias corrected so that their monthly climatologies are consistent with historical forcing climatologies. This property is assessed in Reclamation (2011b), and we evaluate (Fig. 3) the consistency of the resulting distributions (ECDFs) of annual total precipitation and annual average temperature for the 112 simulations of historical climate (GCM output over the overlap period, 1950 through 1999), relative to the historical forcing distribution to which they were downscaled. Although the downscaled and historical annual climatologies are indeed similar, residual bias remains in the projected annual values. This result is due to the bias correction having been done on a monthly basis, without further adjustments to correct annual biases that would result from different persistence behavior in historical and GCM anomalies.

Corroborating prior studies, the general consensus from the large ensemble of GCM projections is that temperatures are increasing and will continue to do so, but future precipitation projections contain large uncertainty. Figure 4 shows the evolution of projected temperature and precipitation for the 112 downscaled projections, averaged spatially over the drainage area of the Colorado River at Lees Ferry, AZ, and temporally over 30-year periods (for this reason the analysis starts in 1979). The mean of all 112 projections and the historical values (from the forcing climatology) during the overlap period from 1979 through 1999 are also shown. The color separation of projection trajectories by emissions scenario indicate that the A2 emissions pathways have a weak tendency toward being drier and warmer late in the 21st century than those from the other pathways.

3.2 Downscaled streamflow, past and future

Ideally, the simulated flow climatology driven by the downscaled GCM-based forcings during the historical period is consistent with the historical flow climatology driven by

HESSD
9, 847–894, 2012

historical forcings. Figure 5 compares the ECDFs of annual streamflows at Lees Ferry Arizona for the historical 1950–1999 period, from all 112 GCM-based simulations to the observation-based natural flows and the model-simulated historical flows. The mean of the GCM-based simulations is also included.

The GCM-based ensemble simulations of flow for the historical period show a dry bias above the 40th percentile relative to the observation-based natural flows and a larger dry bias relative to the simulated historical flows. Neither the GCM-based annual precipitation nor temperature exhibited biases in directions consistent with this flow bias (i.e., drier and/or warmer), thus the lower GCM-based flows result from some other aspect of the projections. The most likely source of the bias is either the seasonal pattern or the inter-annual sequence of precipitation and temperature, or some combination of both. Relatively high flow values in the Colorado River Basin follow from the sequencing of multiple months of anomalous climate, having either high precipitation or cold temperatures, often in combination, and such multi-variate, temporal (and possibly spatial) structure may be poorly represented in a GCM's climate system. Re-arranging the baseline climate data in a sequence similar to that simulated by a GCM has been shown to introduce a dry bias (Dr. Joe Barsugli, personal communication, 2010).

The hydrologic consequences of the climate projections are illustrated in Fig. 6, in which part (a) depicts the projected evolution of 30-yr mean streamflow at Lees Ferry Arizona, for all 112 projections. The mean of all projections and the observed natural flows are also shown. For clarity, the flows simulated using the hydrology model forced by the historical climate from Maurer et al. (2002) are omitted, as the difference between the 30-yr mean values of the two sets of flows are slight. The streamflow projection average shows a slight downward trend (reaching −7 % by the end of the century) that is enveloped by broad uncertainty. Consistent with the forcing projections, the largest declines are associated with the A2 emissions pathway, though this ensemble feature is not prominent until the final decades of the century. The signature of warming effects on Western US flow that has appeared in nearly all prior climate change and hydrology studies is manifested in this study as well. The mean monthly

HESSD
9, 847–894, 2012

hydrograph in Fig. 6b shows a mean shift in peak runoff toward earlier in the year and a small decrease in annual volume that progresses during the 21st century.

Using the entire ensemble of projections, an analysis of cross-correlations between the projected changes in average streamflow, precipitation and temperature for each of future 30-yr periods indicates that streamflow changes are almost entirely determined by precipitation, with positive correlations on the order of 0.94 (Table 3). Streamflow is increasingly and negatively correlated with temperature, reaching a correlation of −0.59 by the end of the century; however, temperature exhibits similar, though slightly weaker, correlations with precipitation. The partial correlations of streamflow with temperature after accounting for precipitation influences on flow (i.e., using the residuals from regressing streamflow on precipitation) are negligible, explaining only a few percent of the variance in future streamflow changes. The strengthening relationship between projected temperature and precipitation is a curious finding, but researching the cause lies beyond the scope of this paper.

3.3 Uncertainty in projections of climate impacts

The large ensemble assessed in this study offers an opportunity to evaluate the wide variation (hence uncertainty) in results shown in Fig. 6a across the spectrum of the available projections. Of particular interest are the relative changes derived from the different projections. Here, relative change is calculated for each projection separately, and reported as a percent difference in the mean flow of the future 30-yr period relative to the projection's historical 30-yr period mean flow (for 1970–1999). Note that the baseline is not the observed or simulated historical flow (i.e., forced with observations), but the downscaled simulated historical flow for the projection; this choice avoids including biases or statistical artifacts of the downscaling in the relative change calculation.

Figure 7a shows the ECDF of these changes for the 30-yr periods ending in 2039, 2069 and 2099, and Table 2 highlights values for different percentiles and the maxima and minima of the distributions shown. The range between the end members of

HESSD
9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

projected changes within any period (±30 %) is considerably larger than the difference in changes between the period (±5 % or less, for any probability level). Thus the uncertainty in projections of flow for any given period is substantially larger than the trends in projected flow from one period to the next. Figure 7b shows the empirical distributions of projected changes separately for each SRES emission scenario. Below the 40th percentile, the difference in results between scenarios is larger than the differences across future periods (Fig. 7a) – i.e., about ±10 % – but still much smaller than the range of the ensemble for each emissions pathway, which represents the disagreement among the GCMs. The A2 projections do produce the largest decreases and smallest increases of the three emissions pathways, as illustrated in Fig. 6a. Figure 7 also shows that approximately one third of the scenarios suggest a wetter future for Colorado River flow.

The contrasting influences of GCM choice, emissions scenario and future period on projected changes is illustrated further in Fig. 8, which shows the time evolution of 30-yr average flows for all runs of the 16 GCMs separately. There is substantial variation in flow trends between models, thus the signal of the relative change from present to future depends strongly on the model or set of models selected as a basis for analysis. For instance, the IPSL CM4 model produces slight upward trends in flow until the middle of the of the 21st century and downward trends thereafter, whereas the MIUB ECHO G model produces progressively decreasing flows for nearly all ensemble members. The separation of these results further by emissions scenario indicates that the sensitivity of the models to the emissions scenario varies widely between models as well. Figures 9 and 10 show the time evolution of 30-yr average total precipitation and temperature, respectively, for all runs of the 16 GCMs. The by-now-conventional notion that the A2 scenarios will produce a stronger change for any given period than the more benign B1 scenarios is evident for streamflow and precipitation for only a few models, e.g., the MIUB ECHO G model. While this notion describes future temperature scenarios, it cannot be extended to precipitation or streamflow projections.

HESSD
9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

A significant source of the large uncertainty in projected relative changes in the total ensemble for a given future period is the variation in period and phase of simulated low-frequency (i.e., decadal) variability among GCMs. This finding is highlighted for the NCAR_PCM1 model in the bottom right panel of Figs. 8, 9 and 10, which illustrates low-frequency phase differences for two runs of the A1B emissions pathway. If used to characterize trends for streamflow for the second half of the 21st century, these two runs would represent the end members of the distribution of trends during that period for all projections shown in Fig. 8, despite being generated from the same model when forced with the same emissions trajectory. Similarly, the four A2 scenario runs for the MRI_CGCM2_3_2A model span a range from −30 % to +30 % at the mid-century. All of the model runs exhibit this phase variation to varying degrees, which confounds interpretation of the climate change impacts for any particular future period, particularly when a small subset of projections forms the basis of the analysis.

3.4 Comparison with previous work

The large ensemble used in this study provides perspective on prior published climate change impact assessments. For instance, CL07 estimated future runoff using a similar approach to this study – i.e., BCSD downscaling of GCM outputs and VIC model hydrologic simulation – but only 22 climate projections, which were taken from 11 GCMs forced with the B1 and A2 emissions scenarios. The correlation of projected change results for individual GCMs in CL07 and this study is high, approximately 96 %, due to the similarity of methods, even though CL07 reported impacts on streamflow at a different location (Imperial Dam versus Lees Ferry). The projection ensemble used in Maurer (2007b) and later CL07 presented a large range of future flow uncertainty relative to other studies at the time, but that ensemble is now a sample from the larger set of GCM runs that were available for this study.

In Fig. 11, we illustrate the difference in projected change for Lees Ferry streamflow between the CL07 "subset" and the larger ensemble by highlighting the results from this study for the GCM runs that were also included in CL07. For the 30-yr periods

HESSD
9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

ending in 2069 and 2099, the difference is minimal: the CL07 subset represents the range and central tendency of the larger distribution, although different portions of the distribution are weighted non-uniformly. For the 30-yr period ending in 2039, however, the CL07 projections produce a wetter estimate of the mean and the inter-quartile range of projected impacts. While the selected projections reproduce the ensemble mean for 2069 and 2099, their distribution is uneven, e.g., the projections selected for 2099 are heavily weighted in the inter-quartile range, and this streamflow bias can propagate bias into sectoral impact studies, e.g., water management modeling. And though not shown, reference to Fig. 8 illustrates that projected changes based only on one GCM (such as the NCAR PCM1 of C04) could produce greater differences in findings from the full 112-projection ensemble.

In another study, Milly et al. (2005) reported that 96 % of model runs indicated a reduction in runoff in the Upper Colorado River Basin with an ensemble median runoff decrease of between 10 % and 25 % as shown in Fig. 12 (Backlund et al., 2008; Milly, et al., 2005). Seager et al. (2007) and Seager and Vecchi (2010) also suggest that there is a broad consensus among climate models that changes in atmospheric circulation will cause additional drying in a region of the American southwest that includes the Colorado River Basin, with consequent impacts on water resources. In contrast, our study suggests less certainty about the water resources consequences, in that about one-third of the available climate projections lead to no change or to an *increase* in streamflow at Lees Ferry (just above the outlet of the Upper Colorado River Basin.) CL07 also show a higher likelihood of wetter conditions than were suggested by any of the three large-scale studies that were based directly on analysis of GCM outputs. The different findings likely stem less from the BCSD wettening effects noted earlier because that effect is not large (Reclamation 2011b), and more from the different scale and runoff process representations between the large-scale studies versus the current study and others such as C04 and CL07. The statistical downscaling and hydrologic modeling study includes a far more explicit treatment of the spatial and seasonal heterogeneity in runoff generation in this study (Backlund et al., 2008; CL07), which leads

HESSD
9, 847–894, 2012

to a stronger and more realistic weighting of climate changes in the mountainous runoff generation areas to the basins' northern and eastern boundaries, and during winter, when runoff-producing snowpack accumulates. This view supports the finding of Wilby and Harris (2006) that in climate change impact analyses, the downscaling process and hydrology model structure and scale are the second and third largest sources of uncertainty, respectively.

4 Discussion and conclusions

This study evaluated the impact of projected climate change on streamflows in the Upper Colorado River Basin by applying high-resolution hydrology modeling to the broadest range of climate projections used for any hydrology or water resources impact study published for the region to date. Because of the range of climate projections used in this study, its results help water resources managers understand the substantial uncertainty inherent in impact studies in mountainous areas of the American southwest.

Our findings generally agree with the earlier work that used similar methods with smaller GCM ensembles (e.g., CL07 and C04). For example, we find that a largely temperature-driven shift to earlier runoff is robust in this snowmelt system. Such a timing shift will reduce water availability for agriculture and other economic uses of water where those uses do not have access to sufficient reservoir regulation, and will also affect ecological conditions. This assessment of future Colorado River runoff changes, however, is more equivocal than earlier large-scale studies (based on analysis of runoff or moisture transport in GCM outputs), or the often-cited central tendency of CL07 – approximately one-third of climate projections lead to estimates of future conditions where average annual flows in the UCRB are unchanged or increase. The contrasting finding arises from this study's more comprehensive accounting of the spatial and temperature variability in key hydrologic processes that are driven by downscaled climate changes.

HESSD
9, 847–894, 2012

This study's large ensemble of projections enabled assessment of the contribution to streamflow uncertainty by different components of the analysis. For instance, in comparison to other sources of uncertainty, the effect of different emissions scenarios (i.e., B1 or A2) on projected streamflow was small relative to the effect of disagreement between the GCMs, even by the end of the 21st century. Also, precipitation uncertainty overwhelms temperature uncertainty in determining streamflow uncertainty.

In general, we confirm the assertion of Wilby and Harris (2006) that the uncertainties in the simulation of future climate have a substantially larger effect on streamflow projection than emission uncertainty. This future climate uncertainty has a spatial component that is particularly relevant in the Colorado River Basin because most of the flow in the basin originates in small regions of high, mountainous terrain that are on the northern border of the region (Reclamation, 2011b; Seager and Vecchi, 2010; C04). Depending on the climate projection, these regions may lie beneath an intensifying future winter Pacific storm track, or they may not – which translates directly into future streamflow uncertainty that varies not only in magnitude but also in direction (e.g., including a range of streamflow outcomes from increases to decreases of 30 percent by mid-century). Reducing the spatial component of climate change uncertainty may require higher resolution climate models that better represent the mountainous terrain within the basin, but the simulation of other fundamental climate system phenomena must also advance. For example, climate teleconnections influence the transport of moisture to those high-runoff regions, yet the climate of the tropical Pacific that drives those teleconnections is not well simulated by the current generation of climate models (Seager and Vecchi, 2010).

Future precipitation (hence streamflow uncertainty) also has a temporal component. GCMs differ substantially as to streamflow trend amplitude, direction and particularly the phasing of low-frequency (decadal) variability. Inspection of projected trajectories of streamflow shows that this unforced variability can be the largest source of uncertainty at certain future time periods. The low frequency temporal variability also means that for any given projection, the estimated change in streamflow between one period

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

(say, “the present”) and another (e.g., 2040–2070) is dominated by a random or chaotic component. This variability may reflect imperfections in our state of knowledge about climate system sensitivity and/or the chaotic behavior of the weather and climate system. Regardless of the cause, it means that sampling error is a real danger when interpreting change signals taken from a small numbers of projection analyses. For the Colorado River Basin and likely similar river systems, selecting a priori a subset of projections without a very strong rationale can introduce considerable bias in an impact assessment and lead to a false sense of certainty.

Projection uncertainty yields considerable disagreement about how to apply climate projections to impact assessment. Some work suggests that the range of impact estimates based on a large ensemble of projections is a minimum bound and is practically irreducible, at least in the foreseeable future (Stainforth et al., 2007; Wilby, 2010). This suggests that impact assessments must evaluate what some have termed an “ensemble of opportunity” – i.e., a comprehensive ensemble of all available scenarios. Other work suggests that it may be possible to develop probabilistic estimates of impacts from the comprehensive ensemble (e.g., Tebaldi and Knutti, 2007). Gleckler et al. (2008) suggest that the ensemble mean may be considered skillful. Yet all of these approaches require evaluation of the full ensemble. Statistical approaches offer a path for downscaling a large ensemble cheaply, but impact assessments based on statistical downscaling may assess a small projection ensemble for other reasons of expediency – for instance, to avoid costly follow-on modeling efforts, such as to determine hydrological, ecological, or water resources impacts.

The same is true of small-scale climate simulation using meso- or finer scale regional climate models (RCMs), which often are forced by only one or a few GCM simulations. In light of the projection-associated uncertainty, one cannot help but regard with great concern the use of small projection samples to inform (at least ostensibly) stakeholder planning needs. Stakeholders in application sectors such as agriculture, wine-making, skiing, and ecological assessment that are attracted to one attribute of dynamical downscaling studies – high spatial-resolution – are likely to incur sampling

HESSD
9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

errors that invalidate their findings. Mesoscale models have undeniable value both in applications (such as numerical weather prediction) and research (such as climate and weather system diagnosis). Because their fine-scale results reflect large-scale forcing variability that is projection-dependent, however, a different paradigm is needed for their use in stakeholder-focused climate change impact assessments. One solution, perhaps, is for dynamical downscaling's added value – mesoscale climate sensitivities and dynamics – to be distilled (probably in statistical form, to avoid computational limitations) and combined with boundary forcings from a comprehensive ensemble of GCM projections, the better to account for the GCM-related uncertainties in an impact assessment.

What are individual planning groups to do when the cost of evaluating a comprehensive ensemble exceeds available resources? Though a number of approaches might be suggested, we describe two possibilities. The first is for an external, better-funded group – perhaps a national laboratory or agency – to do it for them via an efficient continental-scale project: that is, to develop downscaled datasets based on a comprehensive ensemble of available projections, running sufficient process models to produce meteorological, hydrological, ecological and other variables of interest for planning purposes at appropriate time and space scales. Planners could evaluate this super-ensemble to define specific impact scenarios or use the full ensemble to characterize probabilistic risk. Examples of this type of centralized effort exist: e.g., Reclamation recently published the hydrologic outputs from their regional water supply assessment (Reclamation, 2011c), leveraging the data platform of Maurer et al. (2007a) at http://gdo-dcp.ucllnl.org/. The cost of developing such a database would be substantial, but less than that of many independent evaluations for particular locales, and far less than the cost of poorly-informed planning decisions.

A second approach is to develop methods to mimic the information in the comprehensive ensemble using a smaller ensemble for detailed process study, while taking care that the smaller ensemble represents the signal and uncertainty of the full ensemble. An obvious challenge here is the need to represent signals and uncertainty that

HESSD
9, 847–894, 2012

vary from one time period or variable or region to the next. Reclamation recently applied a method based on quantile mapping to reduce the 112 projections in the CMIP3 archive to 5 representative scenarios for a specific future period (Reclamation, 2010). In principle, it may be reasonable to reduce the members of the comprehensive ensemble by culling projections from GCMs that have unrealistic climate simulations in the region of interest. It is reasonable to ask whether models such as INMCM3_0 and MIUB_ECHO_G have different quality in the region of interest, given their far different results for streamflow impacts. Culling, model selection and/or weighting has been explored (e.g., Tebaldi et al., 2004; Pierce et al., 2009; Santer et al., 2009; Brekke et al., 2008) but without yielding a consensus that culling is appropriate or necessary. Note that due to the uncertainty such as low-frequency variability and the difficulty of measuring model quality, culling or weighting may not reduce the range of projected precipitation. Further research in this area is needed.

There is no single planning decision that can address the comprehensive ensemble's range of hydrologic outcomes without regrets, thus water planning studies have repeatedly identified reducing future streamflow uncertainty as a critical need (e.g., Barsugli et al., 2009). Until this uncertainty can be reduced, long-term planning decisions will rely heavily on the subjective perceptions and risk appetites of water resources managers, and their stakeholders, investors and financers.

Appendix A

Creating historical and projected meteorological forcings

This section gives additional detail on the creation of the downscaled climate forcings used as hydrological model inputs. The 112 monthly time-step scenarios were disaggregated to a daily time-step by a resampling approach similar to that used in the original W02-04 studies, but differing in some regards, following the Maurer (2007b) implementation. The steps and the differences are as follows.

HESSD
9, 847–894, 2012

1. Daily time step patterns for precipitation and temperature are selected by month from past historical months, using the same selection for both precipitation and temperature to preserve to some extent a pattern association between the two (e.g., rainy days should have a smaller temperature range than dry days).

2. The daily patterns of precipitation and temperature minima and maxima (T_{min} and T_{max}, respectively) are then scaled (in the case of precipitation) or shifted (in the case of temperature) so that their monthly values equate to the bias-corrected, downscaled 1/8th degree monthly values from the earlier steps of BCSD. Note that for temperature, the monthly sample contains daily $T_{\text{min}}$and T_{max}, and their combined average for the month is the variable shifted. The daily temperature range does not change in this shift, i.e., the minima and maxima will shift together. The rationale for this approach is explained in more detail in W02.

3. The month selection is conditioned using a "4-square approach" that randomly selects a historical month from one of four climate-type bins – dry-cool, dry-warm, wet-cool, wet-warm – depending on the bin into which the climate model variable anomalies fell. For example, daily patterns applied to monthly wet-warm climate model anomalies were selected from month-year combinations (e.g., January 1982) which were wet and warm in the observed climatology. The observed climatology is defined for the years 1950–1999, based on Maurer et al. (2002) forcings. In the original W02-04 approach, only two climate-type bins (wet and dry) were used, each having approximately half the years from the climatology period.

4. In keeping with the original approach, the same month-year daily pattern selection was applied to all fine resolution grid cells in a hydrologic domain (in this case, a river basin such as the Colorado River Basin) to preserve the spatial coherence of the daily patterns across domains that when used for hydrologic analysis, would require a realistic degree of spatial synchronization.

HESSD
9, 847–894, 2012

5. In climatologically dry locations and times of year, however, this resampling approach can result in "pathological" pattern selections, even accounting for monthly scale climate characteristics (e.g., wet/warm). It is possible to select a daily pattern that does not include a single day of precipitation, or contains only one or two, that cannot be scaled to produce the target monthly values from the corrected, downscaled climate simulation, without generating unrealistically high values of daily precipitation. In these cases, which occur for a single grid cell and a single month, a replacement month-year selection is made that does not give a pathological result. The drawback of the substitution is that it undermines the spatial pattern preservation at the daily scale and can desynchronize hydrologic responses that are routed downslope in a catchment to produce streamflow. For example, the substitute month may have rainfall at the end of the month versus rainfall earlier in the month for the original selection, across a part of the domain. Viewed from a continental, hydrologic perspective, such substitutions occur most frequently in dry locations and in dry seasons, which have less hydrologic significance than wetter situations because they do not generate significant runoff.

6. The rules for the sample substitution differ between the original W02-04 implementation and the adaptation used for this dataset. The original implementation applied a minimum monthly total precipitation limit (e.g., 4 mm), and if the selection produced a scalar above a threshold (e.g., 2, meaning the sample precipitation would be doubled), the sample had to have no fewer than a specified number of wet days (e.g., 6). Different values were applied for the three settings for different river basins, based on an objective of limiting substitution frequencies to approximately 5 % or lower. This new implementation did not evaluate wet days per month, but limited sample selection to months having greater than 2 mm of precipitation and producing scaling factors of less than 35.

HESSD
9, 847–894, 2012

HESSD

9, 847–894, 2012

Data and code availability

The W02-04 version of the BCSD code (including disaggregation) is available from ftp://ftp.hydro.washington.edu/pub/aww/misc/climate_run_BCSD.tar.gz. The time-series datasets are currently housed at the DOE National Energy Research Computing Center (NERSC), and are stored in a binary format used for input by the VIC model. The datasets and the disaggregation code used for this research (from Maurer et al., 2007b) can be obtained by contacting Dr. Andy Wood (Andy.Wood@noaa.gov). They can be requested by *scenario* (a combination of one of 16 GCMs, one of three emissions scenarios (A1, B2 and A1B) and one of up to 7 ensemble members per GCM-emissions pairing. The forcings have been archived by river basin, as depicted in Fig. 1.

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HESSD
9, 847–894, 2012

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B. L. Harding et al.

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HESSD

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Table 1. Downscaled WCRP CMIP3 GCMS and emission scenarios.

	Modeling Group, Country	IPCC Model I.D.	Emission scenario A2	A1b	B1
1.	Bjerknes Centre for Climate Research	BCCR-BCM2.0	1	1	1
2.	Canadian Centre for Climate Modeling and Analysis	CGCM3.1 (T47)	5	5	5
3.	Météo-France/Centre National de Recherches Météorologiques, France	CNRM-CM3	1	1	1
4.	CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0	1	1	1
5.	US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	1	1	1
6.	US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	1	1	1
7.	NASA/Goddard Institute for Space Studies, USA	GISS-ER	1	2	1
8.	Institute for Numerical Mathematics, Russia	INM-CM3.0	1	1	1
9.	Institut Pierre Simon Laplace, France	IPSL-CM4	1	1	1
10.	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	MIROC3.2 (medres)	3	3	3
11.	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA	ECHO-G	3	3	3
12.	Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM	3	3	3
13.	Meteorological Research Institute, Japan	MRI-CGCM2.3.2	5	5	5
14.	National Center for Atmospheric Research, USA	PCM	4	6	7
15.	National Center for Atmospheric Research, USA	CCSM3	4	4	2
16.	Hadley Centre for Climate Prediction and Research/Met Office	UK UKMO-HadCM3	1	1	1

HESSD
9, 847–894, 2012

Table 2. Cross-correlations of average projected changes in streamflow, precipitation and temperature for three future 30-yr periods.

Cross-correlation between	Projection period 2010–2039	2030–2069	2060–2099
1. Streamflow and precipitation	0.95	0.95	0.94
2. Streamflow and temperature	−0.41	−0.46	−0.58
3. Precipitation and temperature	−0.27	−0.36	−0.49
4. Streamflow and temperature after removal of precipitation dependence	0.10	0.13	0.07

HESSD
9, 847–894, 2012

Table 3. Average projected percent change in streamflow for 30-yr periods ending in 2039, 2069 and 2099, calculated for different percentiles and the extremes of the ensemble distribution. Positive values are flow increases, in percent.

	Projection period		
	2010–2039	2030–2069	2060–2099
Maximum	19	27	34
90 %	10	12	14
75 %	4	1	1
50 %	−4	−8	−6
25 %	−14	−15	−19
10 %	−20	−25	−29
Minimum	−34	−34	−41

HESSD

9, 847–894, 2012

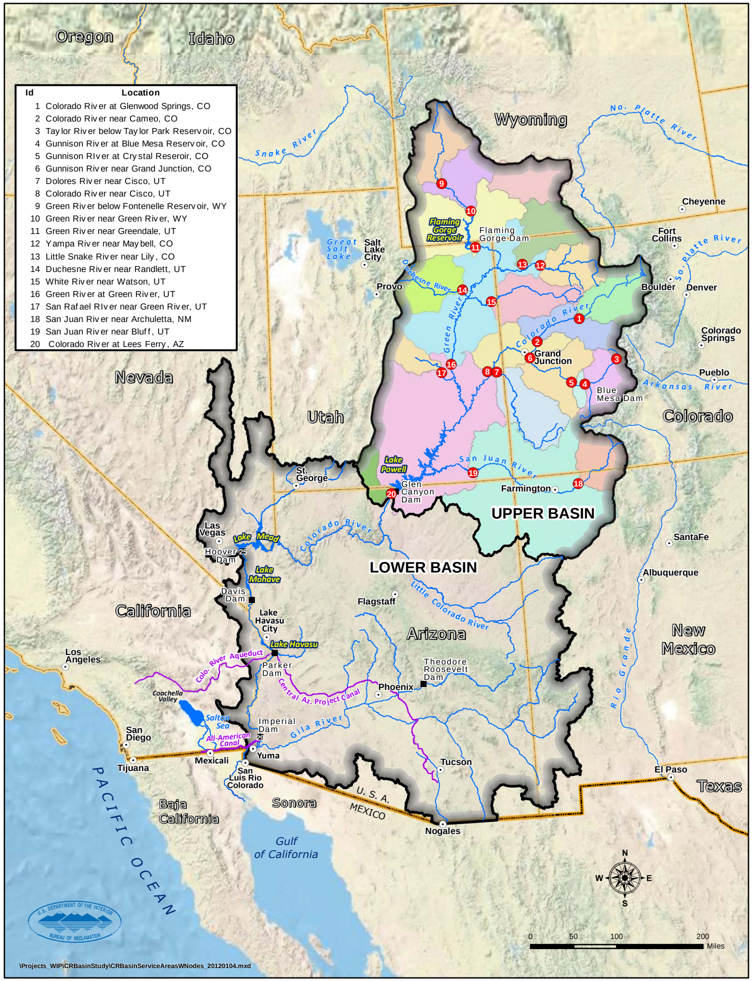

Fig. 1. Colorado River Basin and CRSS inflow points above Lees Ferry, Arizona.

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9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

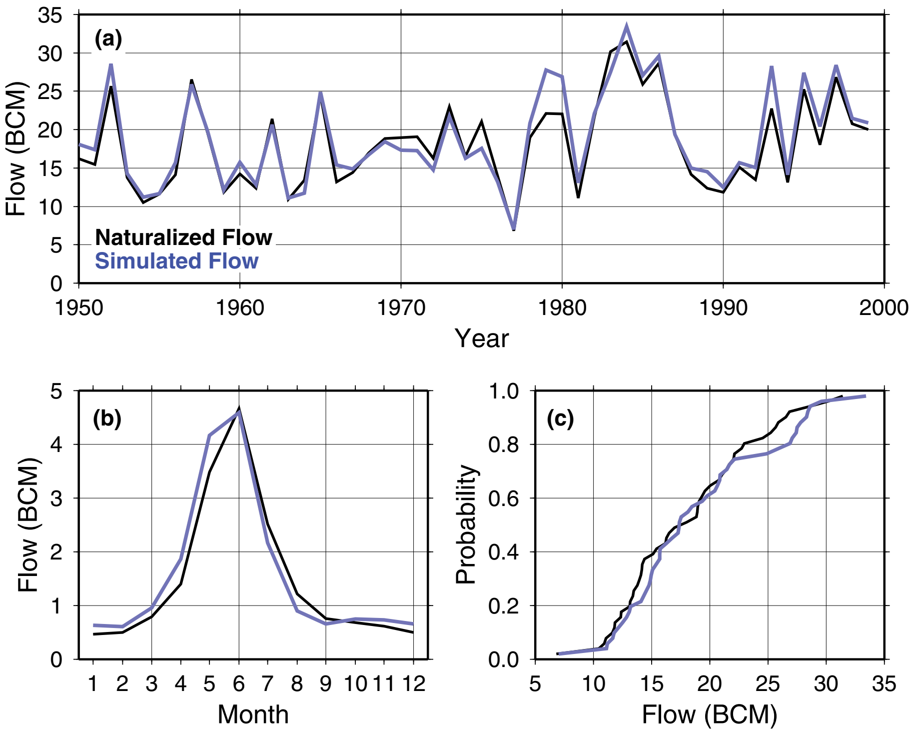

Fig. 2. Comparison of simulated and observed annual streamflow for the Colorado River at Lees Ferry, AZ. **(a)** Time-series, **(b)** monthly hydrographs, and **(c)** ECDFs.

HESSD
9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

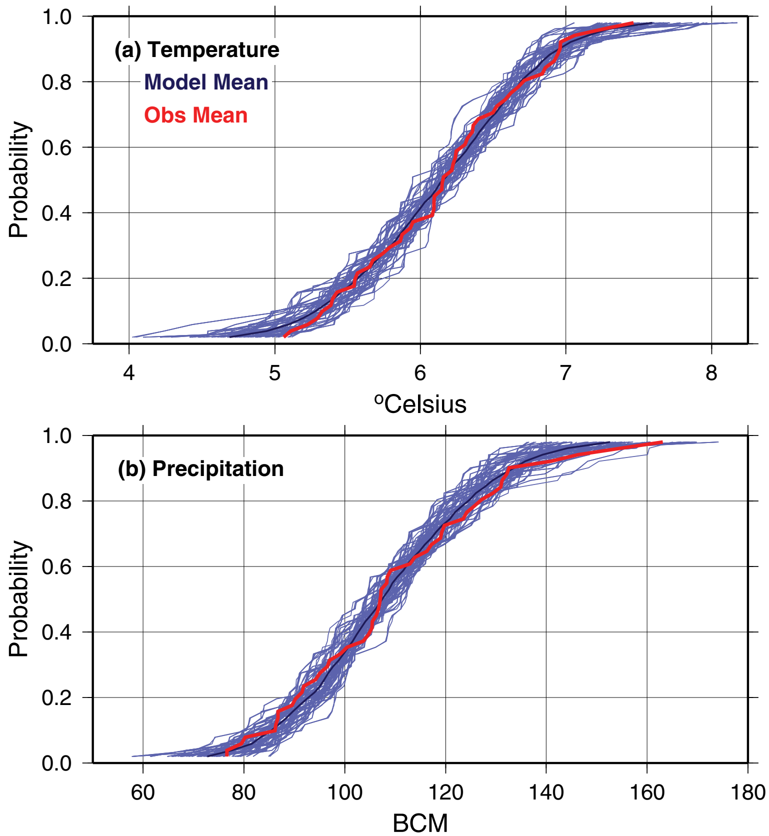

Fig. 3. ECDFs of annual average temperature and total precipitation averaged over the Upper Colorado River Basin above Lees Ferry, Arizona for the period 1950–1999. The downscaled forcing ensemble from 112 GCM projections (light blue), and their mean, is compared with observed **(a)** temperature and **(b)** precipitation calculated from the Maurer et al. (2002) dataset.

HESSD
9, 847–894, 2012

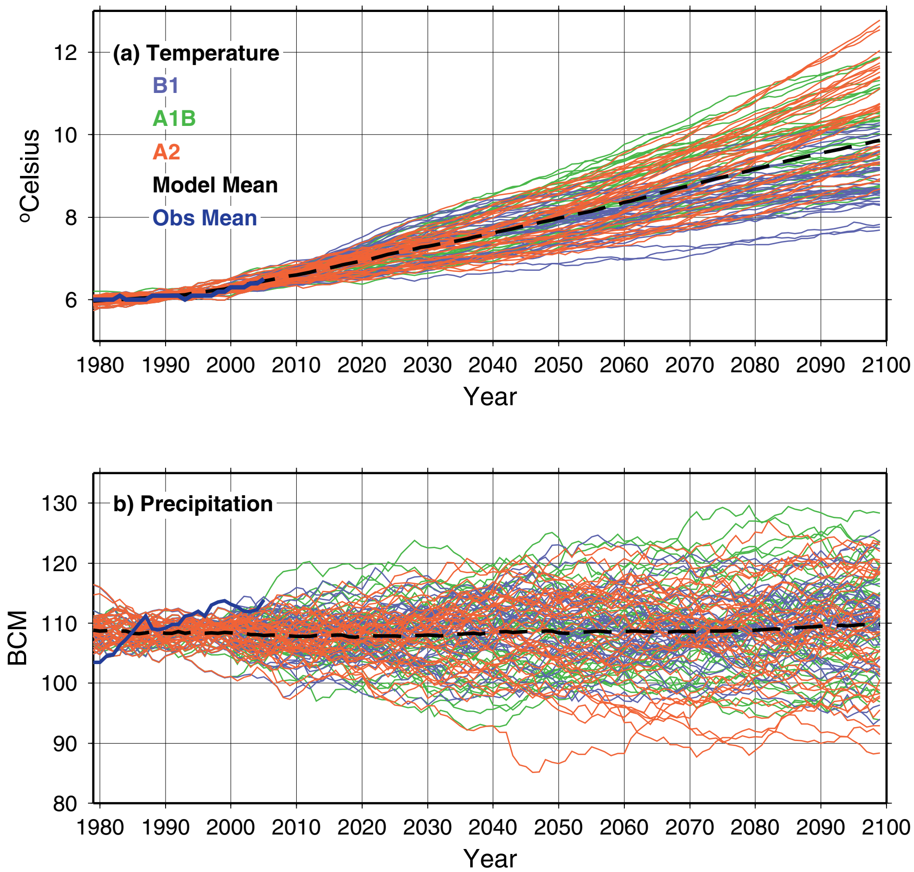

Fig. 4. Projected evolution of climate in the Upper Colorado River Basin above Lees Ferry, Arizona. Shown are 30-yr averages of climate for **(a)** temperature and **(b)** precipitation.

HESSD
9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

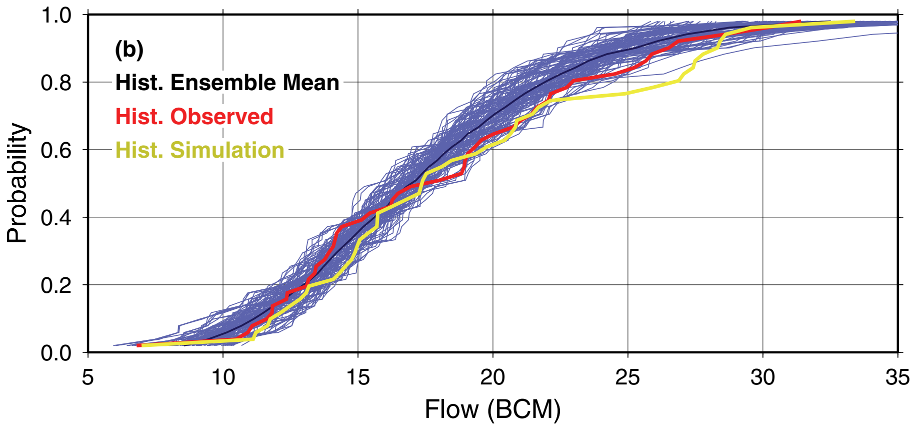

Fig. 5. ECDFs of downscaled simulated flows on the Colorado River at Lees Ferry AZ, 1950 through 1999, compared with observed and historical simulated flows.

HESSD
9, 847–894, 2012

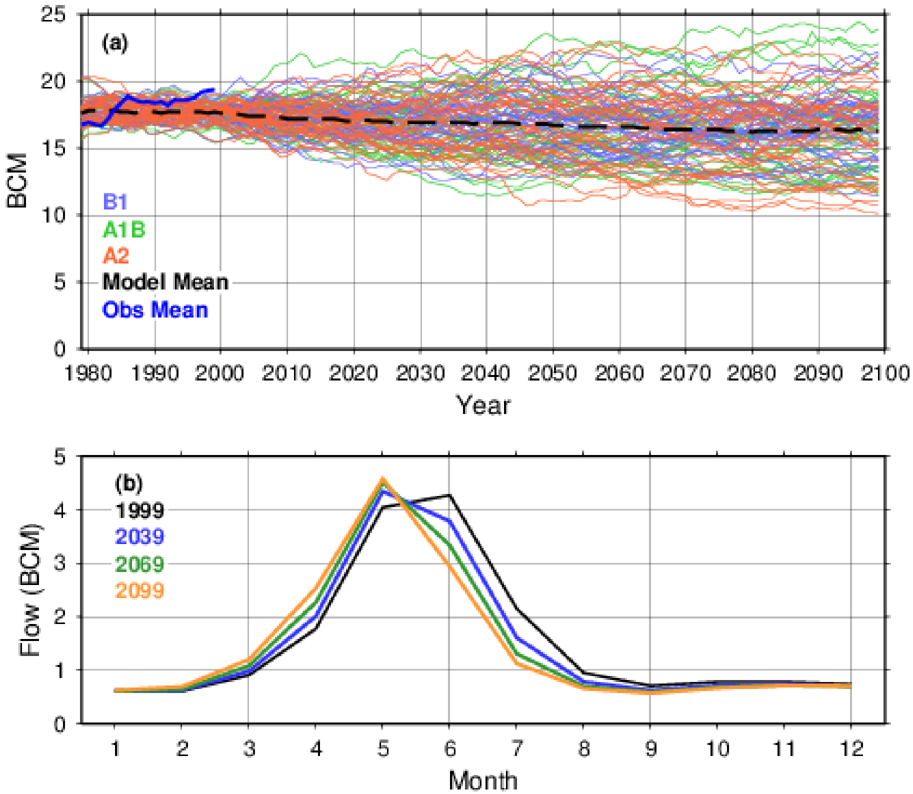

Fig. 6. (a) Simulated 30-yr average streamflows of the Colorado River at Lees Ferry AZ, 1979 through 2099. **(b)** The mean monthly average streamflows for the three future projection periods, compared with the historical 30-yr period flow ending in 1999.

HESSD
9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

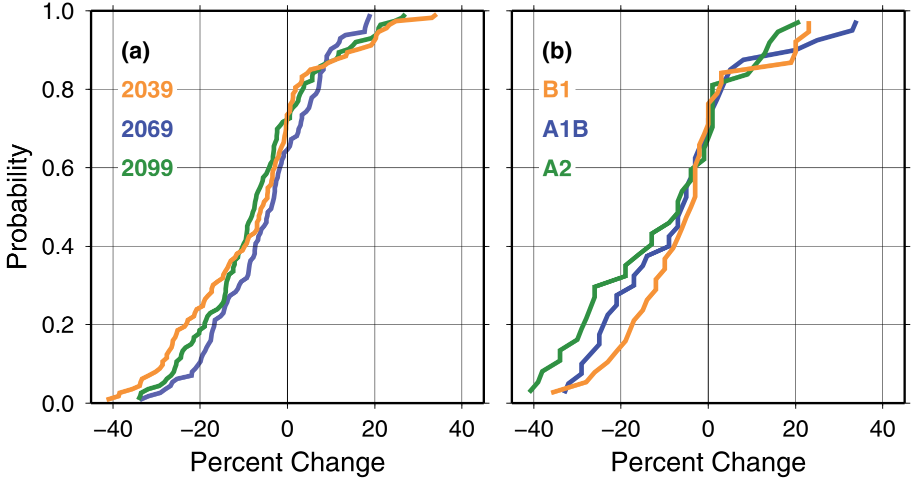

Fig. 7. (a) Distribution of 30-yr projected change in streamflow for 30-yr periods ending in 2039, 2069 and 2099, relative to simulated historical flows from each downscaled projection. Positive values are flow increases. **(b)** Distribution of projected relative flow changes for 2070–2099 for each SRES emission scenario.

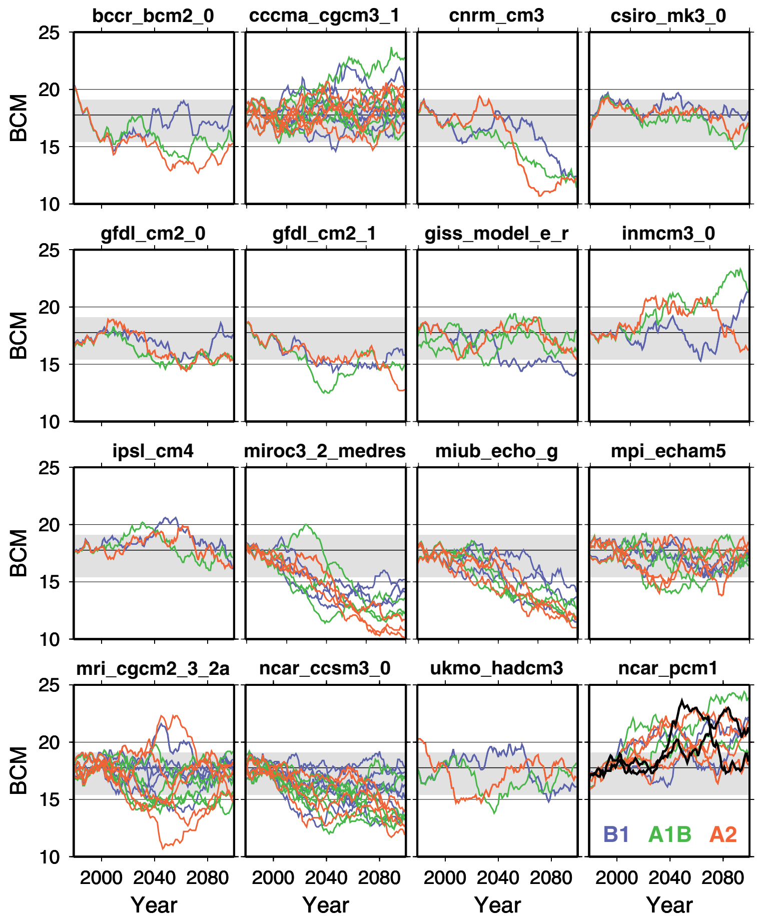

Fig. 8. Time evolution of projected Colorado River streamflow 30-yr averages at Lees Ferry, AZ, from 1979–2099. Projections are color-coded by emissions scenario (see bottom right panel), with the exception of two runs that are highlighted for the NCAR PCM1 model (see text).

HESSD
9, 847–894, 2012

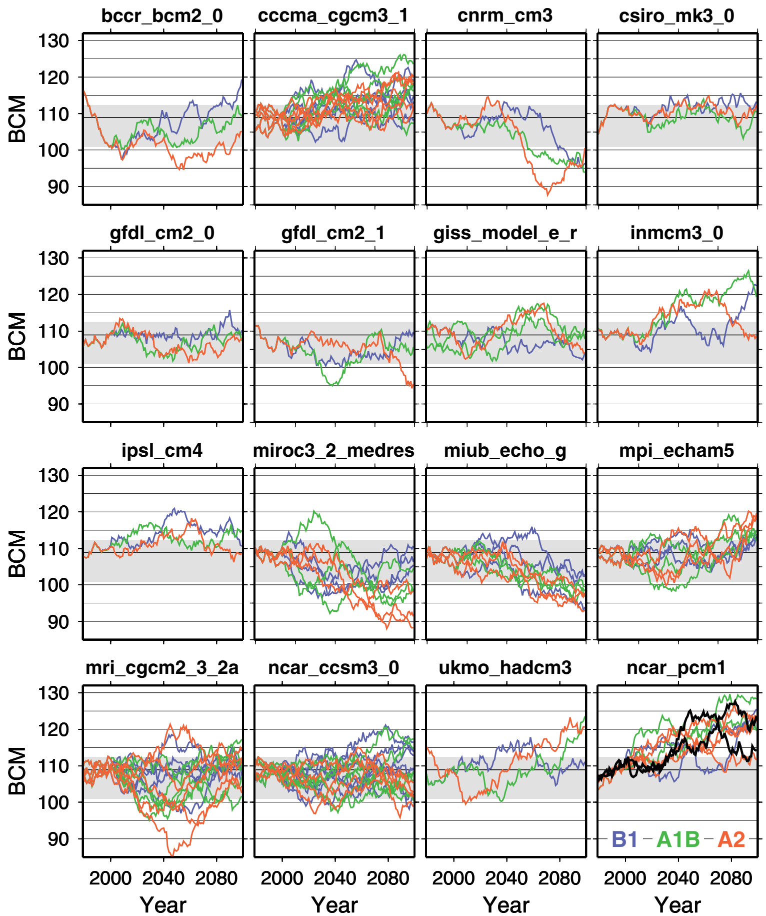

Fig. 9. Time evolution of projected total precipitation upstream of Lees Ferry, AZ, 30-yr averages from 1979–2099. Projections are color-coded by emissions scenario (see bottom right panel), with the exception of two runs that are highlighted for the NCAR PCM1 model (see text).

HESSD
9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

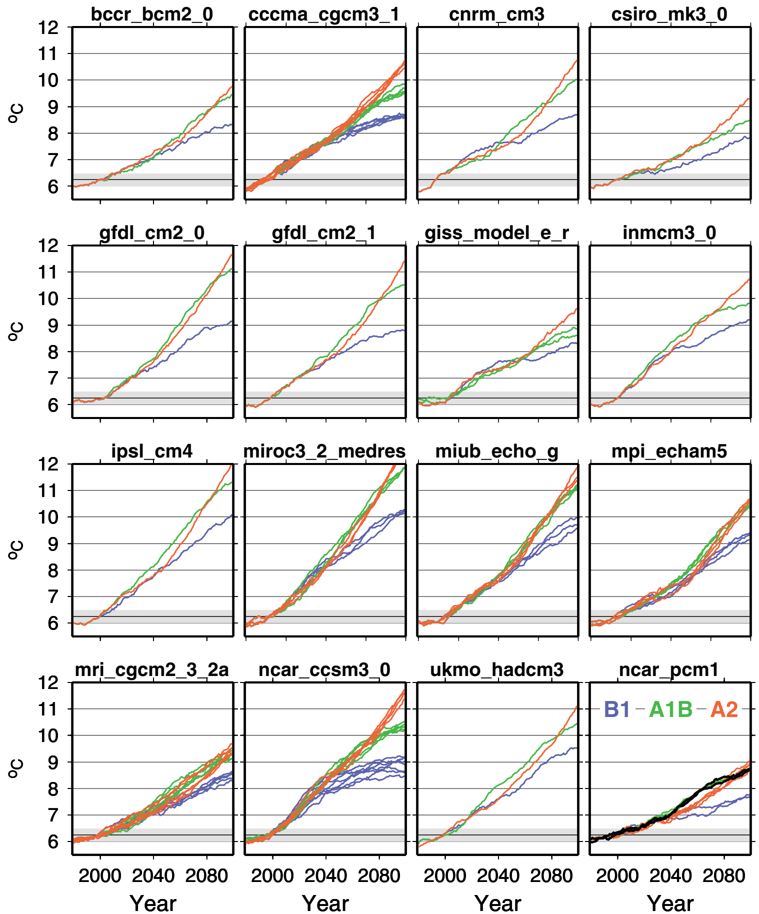

Fig. 10. Time evolution of projected average temperature upstream of Lees Ferry, AZ, 30-yr averages from 1979–2099. Projections are color-coded by emissions scenario (see bottom right panel), with the exception of two runs that are highlighted for the NCAR PCM1 model (see text).

HESSD
9, 847–894, 2012

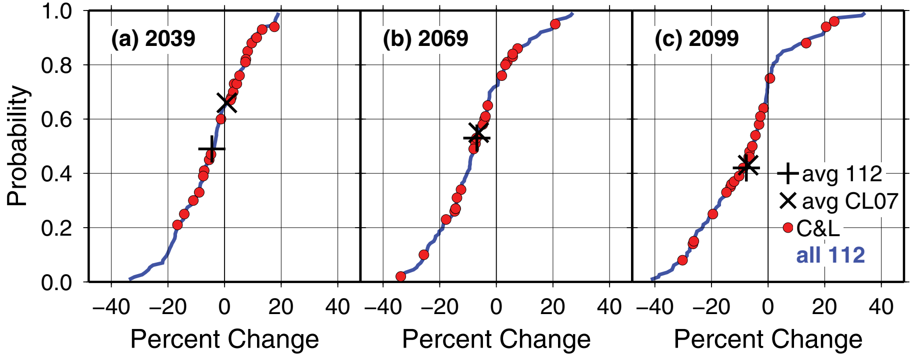

Fig. 11. Distributions of projected changes in 30-yr mean streamflow from GCMs included in CL07, compared to the distribution for all CMIP3 projections in the LLNL archive (present study).

HESSD
9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.

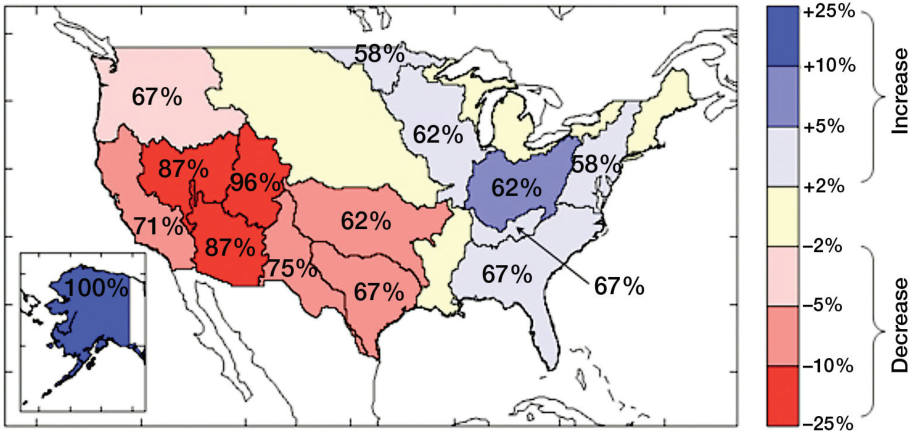

Fig. 12. Median changes in runoff interpolated to USGS water resources regions from Milly et al. (2005) from 24 pairs of GCM simulations for 2041–2060 relative to 1901–1970. Percentages are fraction of 24 runs for which differences had same sign as the 24-run median. Results re-plotted from Milly et al. (2005) by Dr. P. C. D. Milly, USGS. From Backlund et al. (2008).

HESSD
9, 847–894, 2012

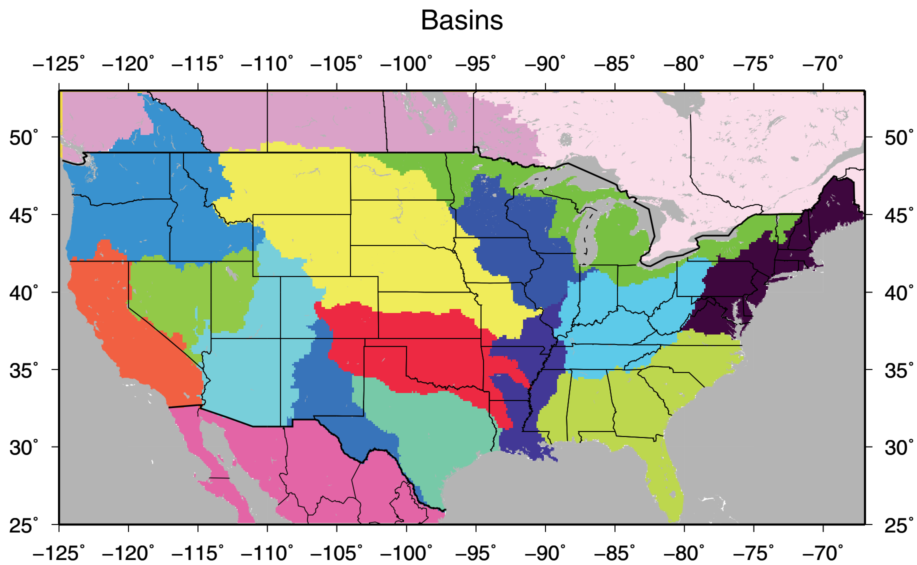

Figure A 1. River basin delineations used in archiving the forcing datasets. Regions include: 1 – Northwest and Columbia; 2 – California; 3 – Great Basin; 4 – Colorado River; 5 – Rio Grande; 6 – Missouri River; 7 – Arkansas-Red; 8 – South Central (Gulf); 9 – Great Lakes Drainage; 10 – Upper Mississippi; 11 – Lower Mississippi; 12 – Ohio; 13 – North East; 14 – South East; 15 – Eastern Canada; 16 – Western Canada; 17 – Mexico.

HESSD
9, 847–894, 2012

Future streamflow projection in the Upper Colorado River Basin

B. L. Harding et al.