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Understanding Uncertainties in Future Colorado River Streamflow

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Abstract

The Colorado River is the primary water source for more than 30 million people in the U.S. and Mexico. Recent studies that project streamflow changes in the Colorado River all project annual declines, but the magnitude of the projected decreases range from less than 10% to 45% by the mid-21st century. To understand these differences, we address the question the management community has raised: "*why is there such a wide range of projections of impacts of future climate change on Colorado River streamflow, and how should this uncertainty be interpreted*?" We identify four major sources of disparities among studies that arise from both methodological and model differences. In order of importance, these are differences in: (1) Global Climate Models (GCMs) and emission scenarios used; (2) ability of land surface and atmospheric models to simulate properly the high elevation runoff source areas; (3) sensitivities of land surface hydrology models to precipitation and temperature changes; and (4) methods used to statistically downscale GCM scenarios. In accounting for these differences, there is substantial evidence across studies that future Colorado River streamflow will be reduced under the current trajectories of anthropogenic greenhouse gas emissions, due to a combination of strong temperature-induced runoff curtailment and reduced annual precipitation. Reconstructions of pre-instrumental streamflows provide additional insights; the greatest risk to Colorado River streamflows is a multi-decadal drought, like those observed in paleo reconstructions, exacerbated by a steady reduction in flows due to climate change. This could result in decades of sustained streamflows much lower than have been observed in the ~100 years of instrumental record.

CAPSULE: A synthesis of studies related to future Colorado River streamflow projections examines methodological and model differences and their implications for water management.

INTRODUCTION

The Colorado River is the primary water source for more than 30 million people in seven rapidly growing, mostly arid U.S. states and Mexico. The Colorado River water supply system, which consists of two large reservoirs (Lakes Mead and Powell) and numerous smaller reservoirs, is already stressed because of growing water demand and an ongoing drought that is outside the historical norm of 20th century climate variability (Fulp 2005; USBR 2011a). Concerns have been voiced that this recent prolonged drought could be a harbinger of a permanent shift to a drier climate (Seager et al. 2007; Barnett and Pierce 2008, 2009; Overpeck and Udall 2010; Cayan et al. 2010; USBR 2011a; among others).

Numerous studies of the Colorado River basin's hydroclimate provide evidence for increased drying, although each study (Fig. 1; Table 1) has its own unique approach and results. Seager et al. (2007) summarize Global Climate Model (GCM) results for the Western U.S., which they state indicate that "this region [southwestern U.S.] will dry in the 21st century and that the transition to a more arid climate should already be under way." These results, when extracted for the Colorado River basin, which we do in comparisons below, show reductions in runoff of ~19% by the mid-21st century, although Seager and Vecchi (2010) subsequently argued the need for higher resolution modeling to better represent the role of complex topography of the Colorado River headwaters in future climate projections. Other studies using off-line simulation methods also indicate drying with magnitudes of runoff decline that vary widely from as little as 6% (Christensen and Lettenmaier 2007) to as much as 45% (Hoerling and Eischeid 2007) by mid-century.

Despite indications of consensus of climate models regarding future drying (e.g., NRC 2011), there is still considerable variability in future climate projections – for instance, one-third of 112 future climate projections from a set of Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR4) CMIP3 GCM projections investigated by the USBR (2011a) show no change or increases in Colorado River streamflow, a number which varies depending on the GCMs and emission scenarios used (Harding et al. 2012). Furthermore, more recent work based on Regional Climate Models (RCMs), rather than GCMs, suggest that the sensitivities of streamflow to climate change may be somewhat less in RCMs than GCMs due to the inability of GCMs to represent the high elevation runoff source areas for the Colorado River. These RCM scenarios also mostly suggest reductions in 21st century Colorado River discharge (2040– 2069 relative to 1970–1999), as do their related GCMs (Gao et al. 2011).

A sensitivity study by Das et al. (2011) suggests that among the major western U.S. river basins, reductions in discharge caused by warming would be largest in the Colorado River basin. This can be explained by the fact that the semi-arid Colorado basin yields a relatively small increment of runoff relative to the precipitation it receives. Any increase in evapotranspiration, from warmer temperatures or shifts in seasonality, produces a larger percentage loss in the amount left for runoff in the Colorado basin compared to more humid river basins. Also unique to the Colorado basin is the size of its reservoirs relative to annual streamflow, with total storage relative to annual inflow ratios of over 4 (vs. ~0.3 in the Columbia River basin, for example). Therefore, for the basin as a whole, water management implications of runoff change are controlled by annual rather than shorter period discharge volumes, which is fundamentally different than other major reservoir systems. Our analysis, therefore, focuses on annual, not seasonal, changes. This large ratio and current water demands also indicate that adding additional reservoirs will likely not improve basin water supply or water management (Burges 1991).

Collectively, the uncertainties among studies have stimulated an interesting scientific debate, but to many practitioners this appears to be a tangle of conflicting predictions. This poses a serious impediment to water managers, who are faced with securing an adequate water supply in the region.

The obvious question to scientists from the water management community is: "*why is there such a wide range of projections of impacts of future climate change on Colorado River streamflow, and how should this uncertainty be interpreted?"*

To understand and reconcile differences in future streamflow projections, we have explored uncertainties in the methodologies and models on which they were based at multiple levels in the climate-hydrology-water resources continuum. We find no single factor can explain the differences, but rather they arise from multiple factors involving differences in methodologies and models. These differences, the nature and implications of which we summarize below, highlight the need for the research community to better identify, effectively communicate, and focus research efforts to reduce climate uncertainties.

Future streamflow projections are also complicated by the Colorado River's large natural variability (Fig. 2). When the Colorado River Compact, which allocated water between the upper and lower basins, was signed in 1922, less than 30 years of streamflow data had been collected, and thus there was little understanding of the system's natural variability at interdecadal time scales. Since then, methods have been developed to extend the instrumental record based on paleoclimate studies (Fig. 2, lower panels), which now date back to B.C. 268 in some locations in the Western U.S. (e.g., Cook et al. 2004; Woodhouse et al. 2006; Meko et al. 2007a; Routson et al. 2011). Although these paleo reconstructions were not included in the future climate studies mentioned above, these long-term records contain droughts more severe than the historical record and have often been considered proxies for future flows (e.g., USBR 2007a; USBR 2011a), which further increases the impression of conflicting research results. Reinforcing this impression, a recent study suggests that even the existing tree-ring based flow reconstructions may underestimate the magnitude of interdecadal to centennial-scale drought variability (Ault et al. 2013).

To address the question posed above, we explore four possible causes for the wide range of future Colorado River projections and follow with discussion of how paleoclimate records relate to future projections. We also discuss the connection of this information to planning and management and conclude by summarizing future research and presenting an interpretation for decision makers. Throughout the paper, we highlight seven "Lessons" that help place individual studies within the broader research context. By providing this context, researchers can reduce uncertainty in the interpretation of results and thus provide information more useful to decision makers.

SOURCES OF UNCERTAINTY IN FUTURE PROJECTIONS

We identify four major sources of disparities in future projections (sections below), ranked from greatest to least importance using information from this and other studies. Two sources of disparities arise from differences in the specific GCM projections used (including both differences in the GCMs and emissions scenarios) and differences in the statistical downscaling methodologies (ranked 1 and 4 respectively). These two sources of disparities among studies can be partially addressed by standardizing methodologies. In contrast, the other two - spatial scale and topographic dependencies of climate change projections (ranked 2) and differences in the sensitivities of land surface hydrology model representations to precipitation and temperature change (ranked 3) - are somewhat more complex, and require further analyses. Together these underscore the imperative of gaining a better understanding of uncertainties inherent in the predictions, and the need to better communicate these uncertainties to the larger water management community.

1. Global Climate Model (GCM) and emission scenario selection

Future climate can be represented in many ways, but most climate change assessments rely on GCM output for multiple greenhouse gas emission scenarios (e.g., IPCC SRES A2 from AR4 and RCP 8.5 from AR5 - see Nakic´enovic´et al. (2000) and Moss et al. (2010) for details). GCM projections vary in their internal model dynamics and thus have wide ranges of precipitation change, as well as in other surface atmospheric variables (e.g., surface air temperature, downward shortwave and longwave radiation). These differences relate to how GCMs represent important physical processes - e.g., stratospheric resolution (Scaife et al. 2011; Karpechko and Manzini 2012) and tropical Pacific sea surface temperature responses to anthropogenic forcing (Seager and Vecchi 2010) – as well as natural variability which can operate on timesteps that are multi-decadal or longer (Deser et al. 2012; Karnauskas et al. 2012). Recent studies have dealt with these differences by using projections from multiple GCMs to characterize future projections more fully. The selection of which GCMs are used (e.g., output from over 20 GCMs was archived by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) that were run for the IPCC AR4 has been based on a range of criteria, but often instead of model performance, the GCMs used have hinged upon model output availability at the time the study was conducted. The choice of models and emission scenarios (Table 1), however, can have substantial implications. Some studies have used only one GCM and one emission scenario and therefore have a single projection of future runoff. This was the case in Christensen et al. (2004) who found declines of 18% in the mean annual discharge of the Colorado River by the mid-21st century with the “business as usual” (BAU) global greenhouse gas emissions scenario for the Parallel Climate Model GCM. Later work (Christensen and Lettenmaier 2007, herein referred to as C&L) using similar methods but applied to 11 GCMs with a roughly equivalent emission scenario (A2) found average declines of 6%, with a range from 40% decline to 17% increase. The USBR study (2011a) also used essentially the same approach as in Christensen et al. (2004) but expanded simulations to include 16 GCMs. The A2 emission scenarios average for the USBR’s study (2011a) had declines of 10% at Lees Ferry (slightly upstream of the location for which flows were reported by C&L) (data from J. Prairie, personal communication), which included multiple runs for certain GCMs for a total of 36 simulations that produced a range in mid-21st century annual runoff change from -40% to +21% (see Harding et al. 2012 for additional comparisons).

In addition to GCM selection, scenarios for future greenhouse gas concentrations must be specified. This affects the magnitude of temperature and precipitation changes – generally higher concentrations translate to larger temperature increases especially in the latter part of the 21st century. In the IPCC AR4 report, these increasing concentrations (e.g., B1, B2, A1B, A2) were determined through emission scenarios as described by Nakic´enovic´et al. (2000). In the AR5 simulations, emissions are represented somewhat differently -- as representative concentration pathways (e.g., RCP4.5, RCP6, RCP8.5) (Moss et al. 2010).

Fig. 3 demonstrates how both GCM and emission scenario selection can influence results by showing differences in precipitation minus evaporation (P-E, equivalent to runoff in the long-term mean, and E includes evapotranspiration) for different GCMs across the same A1B emission scenario (left panel) and different emission scenarios across the same 11 GCMs (right panel). Data were downloaded from http://esg.llnl.gov:8080/home/publicHomePage.do and http://kage.ldeo.columbia.edu:81 for gfdl_cm2_1 model latent heat. We use a single run from every model, thus weighing all the GCMs' natural variabilities equally, and average values for eighteen 2x2° grids that cover the basin, with GCM output regridded to fit a consistent grid. Left panels show P-E anomalies for the A1B scenario from 19 GCMs (top panel) whose output was analyzed by Seager et al. (2007), in comparison with the same P-E anomalies over the same region for the 11 GCMs (middle panel) used by C&L (almost two-thirds of the models used by Seager et al., 2007). P-E anomalies in GCMs included in Seager et al. but not in C&L are lower ("Non Union" GCMs, lower panel on left) indicating that Seager et al.'s study included drier GCMs than did C&L. Changes in mid-21st century P-E, averaged across GCMs for 2040-2069 relative to 1950-1999, also indicate that Seager et al. (2007) models had more negative P-E values (-19.4%) than C&L (-13.4%). Fig. 3 differences are strictly from GCM output and are directly comparable, whereas streamflow comparisons between these two studies involve methodological differences (Seager et al. use GCM output similar to what we report here, whereas C&L employed a higher resolution hydrological model which essentially was used, after downscaling, as a post-processor to GCM output). Nevertheless, comparisons of GCM P-E suggest that model selection may be a major source of differences between the Seager et al. (2007) estimated runoff declines (~19%) and the much smaller projected changes reported by C&L (~6% decline for A2, ~7% decline for B1).

The two studies also differ in the emissions scenarios they report. Seager et al. (2007) used A1B emissions scenarios, whereas C&L used A2 and B1. Fig. 3, right panels show P-E anomalies for the 11 GCMs in C&L for all three scenarios. For A2, this results in mid-21st century declines of 7.8%, which are similar to those reported by C&L (~6%). Similar GCM and emission scenarios are, however, not a guarantee that studies using different methodologies for producing runoff estimates will agree, as demonstrated by B1 scenario changes; C&L, which use a hydrology model to generate runoff, report average runoff declines of ~7% whereas our P-E calculation estimates declines of 15.3%. This figure also illustrates how the time period of analysis matters, a 30-year time slice in the mid-21st century (where B1 declines of 15% are greater than A2 of 8%) does not capture the same trend between emission scenarios as in the late-21st century (where the 2070-2099 average B1 declines of 10% are less than A2 declines of 17%). This change is due to both the strength of the human-induced signal and random natural climate variability in GCMs, which can either hide or amplify radiatively-forced trends making a climate change signal difficult to detect (see Deser et al. (2012) and Harding et al. (2012) for further discussion). Furthermore, some GCMs archived for IPCC contribute an ensemble of multiple simulations for the same emission scenario. Typically differences between ensemble members are less than differences among different GCMs and emission scenarios, however some GCMs have larger ranges (see Figure 2 in Seager et al. 2007 and Figure 8 in Harding et al. 2012 for examples), implying a need to balance intra and inter model variability in multi-model ensemble estimates.

Lesson 1: Differences between studies are attributable in part to differences in the GCMs used. Differences can arise from: (a) how many and which GCMs were used, and (b) the emission scenarios used and time period over which changes are analyzed. In the Colorado basin, most AR4

GCMs project declines in (annual) precipitation (with the headwaters being close to the nodal line of drying to the south and wetting to the north, which implies greater uncertainty and an increased likelihood that results in future studies (e.g., AR5) may differ) and increases in temperature, although the magnitude of change depends strongly on which GCMs and emission scenarios are used. Natural variability can mask climate signals, but on the whole, higher future greenhouse gas emissions translate to a warmer, and in most cases, drier climate, with larger decreases in Colorado River streamflow.

2. Spatial scale and topographic dependence of climate change projections

Runoff production in the Colorado River varies greatly across the complex terrain and climate of the basin, and also changes markedly with season and year. About 85% of the basin's runoff is produced from about 15% of its area – mostly in the high-elevation headwaters region (Christensen and Lettenmaier 2007). Furthermore, although summer and winter precipitation on average are roughly equal basin-wide, winter precipitation is much greater in the headwaters and more efficiently produces runoff than does summer precipitation. Differences in the ability of models to represent the disproportionate contribution to Colorado River discharge of the relatively small high-elevation source areas can have important effects on a model's sensitivities to climate change. Off-line hydrology model simulations, which are often employed to increase spatial resolution to better capture the hydrologic dynamics of the headwaters region (which reflect highly variable topographic, soil, and vegetation characteristics) use techniques such as Penman Monteith, Thornthwaite, or related methods to estimate potential evapotranspiration and are, by construct, not coupled with (and hence constrained by) the climate system. On the other hand, moisture recycling within the Colorado Basin (one indicator of the constraining role the system might play) has been estimated to be quite small -- less than 3% by Trenberth (1998).

i. Simulations of land processes

We used a simple water balance model (McCabe and Markstrom 2007) to demonstrate how sensitive runoff is to the spatial resolution of climate forcing data (Fig. 4) – and hence, the ability of models to resolve high elevation runoff source areas within the Colorado basin. This model, referred to as the Thornwaite water balance model (TWB), was previously used by McCabe and Wolock (2007) to investigate how future warming might impact Colorado basin water supply. They ran the model for each of the 62 U.S. Geological Survey hydrologic cataloging units (HUC8 subbasins) above Lees Ferry, with monthly precipitation and temperature aggregated for each HUC8 from Parameter-elevation Regressions on Independent Slopes Model (PRISM) data (PRISM Climate Group 2004). The model was calibrated by tuning basin-wide parameters that govern snow accumulation, snowmelt, and runoff. We used the model version and parameters from McCabe and Wolock (2011) and the same gridded climate forcing dataset used in Vano et al. (2012), with climate forcings aggregated at four spatial resolutions (1/8°, 1/2°, 1°, and 2° latitude-longitude spatial resolutions). We calculated runoff averaged over the period 1975-2005 and calculated temperature sensitivities at each resolution using a 0.1°C increment change as in Vano et al. (2012).

In our simulations, as the model resolution was increased from 2° to 1/8°, the simulated runoff from the Upper Basin increased from an average of 73 mm/year to 107 mm/year, an increase of 45% (Fig. 4, black line). Similarly, as model resolution increased, the basin's sensitivity to temperature increases became less negative – in other words, higher resolution simulations were less sensitive to temperature change (Fig 4, orange line). We believe that the mechanisms that underlie the sensitivity's dependence on spatial resolution are twofold (keeping in mind that these are offline simulations; i.e., the land surface is forced by, but does not feed back to, the atmosphere): (1) Higher resolution simulations are colder in the headwaters where a majority of the basin's runoff is generated; these colder temperatures accumulate larger snowpacks that more efficiently generate runoff because their larger spring pulses are more likely to be associated with soil saturation, and (2) in coarser resolution simulations the highest elevations are lower, hence temperatures are warmer, which results in higher rates of evaporation and more rain than snow, which increases water availability and subsequently evaporation. The results shown in Fig. 4 are qualitatively similar to those reported in Hoerling et al. (2009) in their re-evaluation of Hoerling and Eischeid's (2007) results, where they used a high spatial resolution model, and found considerably smaller projected future climate runoff declines than in their earlier (coarse resolution) study.

More detailed process-based hydrology models, e.g., the Variable Infiltration Capacity model (VIC), account for the effects of finer-spatial scale topographic variations through the use of elevation bands (i.e., meteorological forcings are adjusted according to a lapse rate and snow processes simulated at multiple elevations within a single grid). Haddeland et al. (2002) found that in the Columbia River basin, which also has snowmelt-dominated hydrology, when elevation bands were not used, VIC runoff simulated at a coarse 2° spatial resolution was 15% lower than simulations at much higher (1/8°) resolution, but when elevation bands (at 200 m elevation intervals) were represented, the difference was reduced to 4%. In other words, whether through finer grid resolution (2° vs. 1/8°) or by use of elevation bands, a hydrologic model's representation of the effects of orography can strongly affect hydrologic predictions at the basin scale in topographically complex river basins.

ii. Simulations of atmospheric processes

Atmospheric models are also affected by complex terrain that can affect how temperature changes translate to changes in runoff. In the Colorado River headwaters in particular, estimates of future flow will benefit from using high-resolution atmosphere models to simulate high-elevation snow (as suggested by Seager and Vecchi 2010). RCMs simulate processes similar to GCMs but at a much finer resolution. For this reason, computational requirements have often constrained the time period and spatial domain for RCM simulations – although this restriction has been relaxed somewhat in recent studies like the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2012). Many studies with RCMs have highlighted the importance of representing the effects of complex terrain in climate simulations, particularly the implications of snow processes (e.g., Rauscher et al. 2008; Rasmussen et al. 2011; Gao et al. 2011, 2012; Dominguez et al. 2012; Wi et al. 2012). For example, Rasmussen et al. (2011) found a spatial resolution coarser than 6 km results in overestimating low-elevation and underestimating high-elevation snowfall in the Colorado River headwaters by 20 to 40%. How an improved regional simulation of snow processes in topographically complex regions translates into more realistic regional climate change sensitivity has yet to be determined. Although this might be done in a regional climate modeling context, a consensus on RCM sensitivities to climate change in the Colorado River Basin does not yet exist (e.g., Rauscher et al. 2008; Gao et al. 2011; Rasmussen et al. 2011; Gao et al. 2012). Furthermore, complications with specification of boundary conditions suggest that it might be better attempted through use of global simulations over a range of spatial resolutions spanning the approximate range in our Fig. 5. Racherla et al. (2012) note, for instance, in a more general analysis of the added value of RCM downscaling "that there is not a strong relationship between skill in capturing climatological means and skill in capturing climate change", and we believe that this is a central unresolved issue in the context of understanding the climatic sensitivity of snow dominated mountainous regions.

<u>Lesson 2:</u> Spatial resolution of both land surface and atmospheric models is critical to realistic representation of the changes in future hydrology of the Colorado basin - both mean conditions and variability. The basin's headwater areas accumulate much of the precipitation that is available for runoff, an effect amplified by reduced evaporation resulting from colder temperatures and snowpack at these elevations. As a result, the water fluxes from models with coarser spatial resolution tend to be more sensitive to change from both warming and precipitation reductions, the details of which warrants further investigation. Runoff changes (not magnitudes) calculated directly from GCM output (~200 km spatial resolution at present) or other methods based on basin-wide area average temperature and precipitation change likely overestimate runoff change sensitivities, and should be interpreted with considerable caution.

3. Land surface representations

In the Colorado River basin, there is a substantial range in the sensitivity of different land surface hydrology models to changes in climatic variables – that is, the fractional change in runoff associated with a given precipitation or temperature change. Vano et al. (2012), for instance, compared the land surface response of five land surface models (LSMs), with two versions of Noah, to changes in precipitation and temperature (Fig. 5). Changes in precipitation are magnified in runoff changes, with lower flows being more sensitive to precipitation changes. This sensitivity can be expressed as an elasticity, defined as percent change in annual model runoff divided by percent change in annual precipitation. Vano et al. (2012) found elasticities ranging from a little over 2 to 6 at Lees Ferry depending on the model and reference condition (the derived value from observations is ~2), and the elasticities among models were reduced to between about 2 to 3 when model biases (mostly underestimates of runoff) were accounted for. Similarly, the sensitivity of modeled runoff to temperature, defined as percent change in annual runoff for an imposed increase in annual temperature, differed among LSMs from about -3% to -10% per °C increase in annual basin-average temperature, with no evident change in the range of sensitivities with model biases.

The temperature sensitivity depends on the model's physical parameterizations. When temperature changes were applied only to the maximum temperature instead of holding the temperature range constant - an experiment that effectively generated larger changes in net radiation and vapor pressure deficit - temperature sensitivities roughly doubled for most models. Although there were substantial spatial variations in temperature sensitivities (and precipitation elasticities), differences among models generally were smaller in the headwater regions that produce most of the runoff. The form of precipitation (rain or snow) was dependent on temperature, but this was consistent across models.

In addition to elasticities and temperature sensitivities reported in Vano et al. (2012), we computed the same metrics for two other hydrological models at Lees Ferry (also in Fig. 5). The National Weather Service Colorado Basin River Forecast Center operational version of the Sacramento Soil Accounting model (SAC; Burnash et al. 1973) is essentially a spatially lumped (for 29 Colorado River sub-basins) version of the SAC distributed version reported by Vano et al. (2012). The operational version had an elasticity of 2.4 (vs. 2.6 for the distributed version) and temperature sensitivity of -4% (vs. -5%) per ºC of annual warming. This is an updated version of the model used by Nash and Gleick (1991). We also calculated sensitivities using the simple Thornwaite water balance (TWB) computation described in section 2. This is a slightly updated version of the model used by McCabe and Wolock (2007) in their study of climate change in the Colorado basin, with key differences being that we applied the model using the same 1/8º grid mesh, climate dataset, and +0.1°C temperature perturbation used by Vano et al. (2012). McCabe and Wolock (2007) found a basin-wide 0.86° C temperature increase resulted in an 8% streamflow reduction (equivalent to -9% per °C), whereas we found a 5% decline per °C using a +0.1°C temperature change. They did not report precipitation elasticity; our result was 2.0. Generally, values reported in Fig. 5 are also similar to values in Figure 3 of Tang and Lettenmaier (2012) for Colorado basin-wide values of elasticity (between 1.8 and 2.2) whereas their temperature sensitivities (between -2% and -4% per °C derived using regression equations from GCM output) are somewhat smaller in absolute value.

To test for robustness, we also calculated hydrologic sensitivities using different historical climate datasets and time periods. Specifically, we calculated precipitation elasticities and temperature sensitivities using the historical gridded datasets of Maurer et al. (2002), Hamlet and Lettenmaier (2005), Wood and Lettenmaier (2006), and the PRISM Climate Group (2004) as described in Daly et al. (1994), averaged across different time periods with varying lengths (e.g., 1975-2005, 1990-1999, 1895-2006). In general, runoff change differences are considerably less sensitive to differences in historical datasets than they are to differences in hydrology models (and how net radiation and vapor pressure forcings were derived).

Lesson 3: Land surface hydrology models exhibit substantial differences in their sensitivities of runoff to temperature increases (approximately -6.5±3.5% per °C at Lees Ferry). Responses to precipitation change, when runoff biases are accounted for, are more consistent across models (between 2 to 3 at Lees Ferry). Differences in precipitation elasticity and temperature sensitivities among models are generally smaller in the headwater regions than elsewhere in the basin, although further research is needed to better understand these differences and how they relate to observations. In general, differences in precipitation elasticity and temperature sensitivity are independent of the datasets and historical periods for which evaluations are conducted.

4. Statistical downscaling methods

To represent hydrologic processes, such as snow accumulation and ablation, spatially distributed hydrologic models need inputs of order 10-20 km spatial and sub-daily temporal resolution. In contrast, current generation GCMs have spatial resolutions of ~200 km. Furthermore, while the computational time step of most GCMs is 1 hour or less, GCMs generally do not produce physically realistic precipitation (e.g., daily drizzle, storm interarrival times), which is the primary driver of the land surface hydrologic system, at time steps << 1 month. Through IPCC AR4, most

GCM output was archived as monthly values; hence temporal disaggregation to daily values is also required. The procedures that produce hydrologic forcings at appropriate spatial and temporal resolutions are usually referred to as statistical downscaling. They are essential for hydrological modeling even if dynamical downscaling (e.g., based on RCMs rather than GCMs) is used (Wood et al. 2004).

Statistical downscaling methods carry with them sources of uncertainty. We contrast here the Bias Correction and Spatial Disaggregation (BCSD) method, used in several studies noted above (including Christensen et al. (2004), Christensen and Lettenmaier (2007), and USBR (2011a)) and the "delta method", described in Hamlet et al. (2010). We recognize that there are an increasing number of statistical downscaling methods (see Future Research Directions section) where each method has strengths and weaknesses that make it more or less appropriate for particular studies. Hamlet et al. (2010) discuss strengths and weaknesses of the BCSD and delta methods.

The BCSD method as described by Wood et al. (2004) is the most common approach in previous studies of the Colorado Basin. The method maps the probability distribution of modeled historical precipitation and temperature to the probability distribution of observations, i.e. if the modeled current climate precipitation in a given month and year is the xth percentile of the climate model's (historical) distribution, this is adjusted to the xth percentile of the historical precipitation distribution for that month. This approach can be subdivided into bias correction techniques and spatial disaggregation methods (as in USBR (2011b)), but for our purposes we consider this as a single downscaling method. In contrast, the delta method applies changes in mean monthly precipitation and temperature between current and future climate simulations, and applies those differences (typically as means ratios for precipitation and means differences for temperature) to a record of historical observations.

We contrast the BCSD approach as used in Christensen and Lettenmaier (2007) with the delta method based on 30-year average monthly changes in temperature and percent changes in precipitation for 2040-2069 compared with 1950-1999 across the basin, applied to gridded historical (monthly) observations for 1950-1999 generated by Maurer et al. (2002). These monthly delta changes are then applied to every day in the historical record to create a future simulation (a 50-year time series of 2040-2069 climate change). Fig. 6 compares the percent difference in flows at Lees Ferry for individual GCM simulations using these two methods to generate input for the VIC hydrologic model, as used in Christensen and Lettenmaier (2007). The delta method tends to generate larger declines in future flows (by a factor of almost two on an annual average basis) than the BCSD method. The 11-model average decline is 7% at Lees Ferry with the BCSD method compared to 13% for the delta method for the A2 scenario. For B1 scenario results (not shown), BCSD had average declines of 8% while the delta method had declines of 11%. The differences between downscaling methods (which is at most 15% for either scenario, orange bars on Fig. 6) are, however, considerably less than the differences of mid-21st century downscaled GCM responses relative to historical streamflows, which have a BCSD range of -42% to +18% (with an interquartile range of -17% to +4%) for A2 and -26% to +16% (interquartile range -16% to 0%) for B1. The important aspect of an appropriate downscaling approach is that it reproduces space-time attributes of GCM changes. In this example, in the Colorado the spatial distribution and broad temporal characteristics (seasonal) matter. The BCSD method and related approaches, see Future Research Direction section, captures this in a more sophisticated way than the delta method and therefore arguably is more desirable.

<u>Lesson 4:</u> The choice of downscaling method can affect the magnitude of the derived climate signal, leading to differences in measures such as long-term projected runoff changes that for some individual ensemble members can be comparable to differences among individual GCMs, although, on average, these differences are smaller. Differences in downscaling methods also translate to important differences in seasonal changes and extreme events. Downscaling methods should therefore be carefully evaluated and selected. Unlike GCMs selection where multiple models delineate the range of future projections, the most appropriate downscaling technique depends on what questions a study intends to address.

PAST RECORDS PROVIDE CONTEXT FOR FUTURE PROJECTIONS

When planning for the future, process-based models reflect our best scientific understanding of future impacts. It is, however, also helpful to look to the past, particularly given emerging evidence that GCMs may underestimate the risk of decadal and multi-decadal drought (Ault et al. 2012). Records of past flows and droughts, including paleoclimatic records, are being used increasingly in the Colorado River basin to help managers plan for similar events in the future (e.g., Woodhouse and Lukas 2006; USBR 2007a). Droughts in the 1930s and 1950s are commonly used in planning, but provide only a limited perspective of what could occur in the future. Paleoclimate reconstruction methods extend the record backwards in time well prior to the beginning of the instrumental record. These studies provide more understanding of the range of drought variability, for instance, than is possible solely through examination of the instrumental record (e.g., Woodhouse and Lukas 2006). Stockton and Jacoby (1976) were the first to reconstruct streamflows at Lees Ferry with a tree-ring analysis that extended back to 1512. The reconstructed annual hydrographs caused concern -- as their abstract cautioned, "[w]hen the results of our analysis are viewed in the context of future demand for water usage in the Upper Colorado River Basin, it is apparent that projected demand could soon outstrip the natural annual supply of surface water." This study has been followed by many others, which refined reconstruction methods and extend the record further (Hidalgo et al. 2000; Woodhouse et al. 2006; and others). Meko et al. (2007a) produced a 1200-year dataset for the entire Upper Colorado basin, and recently, Routson et al. (2011) generated a 2200-year tree ring reconstruction for the nearby Rio Grande headwaters region in Colorado. Although methods and datasets used in reconstruction studies differ, they all indicate that the period used in the

1922 Colorado Compact to determine water allocations was exceptionally wet (Woodhouse et al. 2006) and that the basin has a history of multi-decadal dry periods, referred to as 'megadroughts' (Fig. 2).

Paleoclimate records are key to assessing future projections by providing a longer record for context, helping to understand underlying climate mechanisms, and providing a framework for evaluating how well models simulate the full range of past observed change. For example, the leading hypotheses for megadroughts has been shifts in tropical sea surface temperatures (Graham et al. 2007, 2010; Seager et al. 2007, 2008; Conroy et al. 2009; Oglesby et al. 2012) caused either by natural variability or a response to solar irradiance and volcanism variations (Emile-Geay et al. 2008). Independent of climate change considerations, paleo-data prove it is realistic to expect conditions outside the range of recorded streamflow measurements – simply stated, there is reason to believe megadroughts will occur again (Woodhouse et al. 2010), although new work suggests that existing tree-ring reconstructions (including of past streamflow) likely underestimate the full magnitude of interdecadal to centennial-scale drought variability (Ault et al. 2013). Information on the length, duration, and extent of drought can also help identify global weather patterns that result in longer dry periods (e.g., variations in sea surface temperatures) (Hidalgo 2004; Woodhouse and Overpeck 1998). Advances in techniques, multiple indicators, and more paleoclimate data, has improved the ability to understand the nature of seasonal changes in hydrologic conditions and land surface conditions such as snowpack (Pederson et al. 2011).

As with future GCM-based projections, paleo reconstructions using tree rings also have uncertainties and limitations. For instance, relationships between radial growth and streamflow generally do not account for some climate factors such as temperature through growing season length and snowpack storage of available moisture (Meko et al. 2007a). Variations in reconstruction methods are reflected in reconstructed streamflows, especially in extreme years (Woodhouse and Brown 2001). Future and current drivers of hydro-climatic variability may also be novel with respect to the paleo record (Woodhouse et al. 2010); examples include anthropogenic influences on climate, as well as land cover changes such as irrigated agriculture, grazing, dust on snow, urbanization, changing fire regimes through fire suppression, bark beetle infestations, and human ignition. Past droughts are also unlikely to be identical to current and future droughts (Woodhouse et al. 2010). There is evidence of this already in that past megadroughts seem to be driven primarily by precipitation anomalies – whereas in the current drought, temperature appears to be playing a more important role (Cook et al. 2010; Woodhouse et al. 2010). This underscores the need for further attention to the role of temperature, such as in investigations by Cook et al. (2011) of the early 20th Century pluvial.

Interpretation of megadroughts in a future context is somewhat complicated by the fact that the relative role of anomalously low precipitation (detected in most paleo droughts) is in contrast with the role of increasing temperature (a key element in the ongoing Colorado River drought, and implicated in future projections). Nonetheless, the superposition of megadroughts, as seen in paleo projections, and a steady reduction in flows due to climate change should be considered in future planning.

Lesson 5: To understand future streamflow and subsequent uncertainties, a comprehensive approach should be taken, including analyses of paleoclimate reconstructions as well as future projections. Together these two lines of discovery can be used to explore the basin's response to megadrought-like reductions in precipitation compounded by anthropogenic climate change, the real 'worst-case' scenario.

PLANNING AND MANAGEMENT IMPLICATIONS

Planning in the face of uncertainty, across multiple spatial and temporal scales, is not a new problem for water managers. However, most water resources planning protocols are based on a fundamental assumption of stationarity, which implies that time-invariant statistical characteristics adequately represent expectations for the future (Salas 1993). Climate change and new paleoclimatological records belie the appropriateness of this stationarity assumption (Hartmann 2005; Milly et al. 2008), and while model-based studies offer the best prospect for uncovering likely future conditions not contained in the historical record, they do not provide definitive answers for decision makers.

Climate change science advances by using different approaches that are often not easily reconciled, while planners prefer clear, explicit characterizations of uncertainties that can be directly incorporated into risk-based calculations. Reconciliation of this dichotomy is a challenge that requires effort from both the science and management community (see supplementary text for specific examples from our work). It calls for more “actionable science” that is “sufficiently predictive, accepted, and understandable to support decision-making, including capital investment decision-making” (Behar 2009; Kerr 2011). It also implies exploring adaptation strategies that can proceed from a focus on the certainties presented by multiple studies, rather than uncertainties (in our effort we provide such messages for decision makers, see Interpretations for Decision Makers section). Capital investment decisions, particularly for projects that cannot be implemented incrementally and that have irreversible or multi-decadal consequences, present a more intractable challenge for actionable science. These decisions need to require approaches that accommodate high uncertainty, complex systems, and ambiguity of model evidence, such as strategic scenario planning (Mahmoud et al. 2009) and the need for discussion about tradeoffs between stranded costs, the costs of inaction, and the timeframe under which investments are evaluated for meeting criteria, e.g., effectiveness and economic feasibility. Additionally, decision makers may not lack options, but rather need support from their constituencies for implementation of options that differ from past practice, in which case well-communicated science can be useful in building support.

It is also important to recognize that implications of climate uncertainties are not fully assessed by understanding hydrologic impacts. Considerations of different management strategies or planning options require hydrology model outputs be run through water management models that include physical processes (e.g., streamflow, solute transport), infrastructure (e.g., reservoirs, diversions), and policies (e.g., minimum instream flow requirements). Although uncertainties may be too great to satisfy design studies, management models (e.g., Colorado Rivers Simulation System (USBR, 2007b)) can identify unanticipated sensitivities and thresholds in these complex systems, and can be used to evaluate tradeoffs among options. Recent work by Brown and Wilby (2012) has proposed a "bottom up" approach that, rather than being based solely on GCM information, uses distributional mapping to perturb historical probability distributions of streamflow. This may be a practical approach to identifying system vulnerabilities to climate risk that complements the information gained from a scenario-led strategy.

Lesson 6: The water/climate research and water management communities need to work more closely to generate the actionable science needed for planning and other decision making. Collaboration is particularly important under non-stationary conditions in order to develop and update information that allow management tools to represent the various sources of uncertainty. It is crucial that the management community seek decision approaches that accommodate uncertainty, complex systems, and ambiguity of model evidence, such as strategic scenario planning.

FUTURE RESEARCH DIRECTIONS

Fig. 1 conceptualizes how the climate change studies mentioned above relate to each other and where future research might progress within the land-atmosphere continuum. For each study it is important to consider: (1) what emission scenarios, (2) what spatial scale and time period, (3) how many and which models (GCMs, RCMs, and hydrology), and (4) which methods of statistical downscaling and regression equations were used (Table 1). Ongoing and future research will offer additional insights into these various elements and help better understand how future streamflow projections can be used by water managers. We present seven key areas where research is evolving, which are intended to provide an overview of ongoing work, not a ranking of research priorities.

i. New climate change projections: PCMDI is now making available climate change simulations produced for the IPCC Fifth Assessment Report (AR5). The archive includes daily and monthly model output for most models (in contrast to AR4, for which the norm was monthly output) with longer multi-century control simulations, which are forced by known and estimated changes such as irradiance and volcanism, that can be used to compare GCMs to paleoclimate data. These new simulations will provide a basis for improving upon the AR4 simulations used in most studies cited above. For example, Seager et al. (2012) evaluate precipitation, evaporation, runoff, and soil moisture from AR5 GCM output. These AR5-based scenarios should provide better estimates of how human emissions of greenhouse gases (e.g., via burning of fossil fuel) translate to changes in Colorado River discharge and should improve on the state of climate science represented in earlier scenarios. Furthermore, they should better represent stratosphere-troposphere coupling processes of relevance to the mid-latitude storm track, as well as tropical Pacific sea surface temperature variability and change, and have improved spatial resolution relative to AR4. Nonetheless, there will remain inherent uncertainty in GCMs as in earlier assessments (e.g., Seager and Vecchi 2010; Ault et al. 2012) and natural variability will continue to complicate identification of trends (Deser et al. 2012; Knutti and Sedláˇcek 2012). Thus, ensemble approaches will continue to be needed to delineate the range of future projections (see e.g., Mote et al. 2010).

ii. Increased spatial resolution of climate models: Many GCMs have increased spatial resolution for the new the CMIP5 simulations (Seager et al. 2012). Additionally, RCMs with higher spatial and temporal resolution have been run over the Colorado River basin (e.g., Rasmussen et al. 2011), and generally provide more realistic representations of climate features (such as storm tracks and jet stream patterns) that are strongly topographically dependent. These higher resolution simulations have important implications for the associated hydrologic impacts of climate change. Examples include the NARCCAP archive (Mearns et al. 2012) as well as recent work by Dominguez et al. (2012) and Wi et al. (2012).

iii. New statistical downscaling techniques: BCSD has been the standard approach in many of the key studies we have reviewed. There are, however, alternative approaches such as Constructed Analogs (Hidalgo et al. 2008; Maurer et al. 2010), Multivariate Adapted Constructed Analogs (MACA; Abatzoglou and Brown 2012), and Hybrid-Delta (Hamlet et al. 2010) that are becoming more widely used and may constitute an additional source of uncertainty in future studies. PCMDI's archive of daily GCM output will make alternative downscaling methods more viable, but will also require more evaluation of the appropriate applications of alternative approaches and how they relate to each other.

iv. Improved land surface simulations: LSMs continue to evolve and better represent land surface processes (e.g., Niu et al. 2011; Livneh et al. 2011). For example, the Unified Land Model (ULM) combines the atmospheric exchange process of the Noah LSM with the surface water budget components of the SAC hydrology model (Livneh et al. 2011). Additionally, the coupling of atmospheric models with dynamic vegetation models will help better understand potential land cover feedbacks (Diffenbaugh 2005).

v. New paleoclimate reconstructions and model evaluation: New records and new techniques continue to reveal better understandings of the climate of the past 2000 years, which can feed into more rigorous model evaluation efforts (e.g., Ault et al. 2012); and be used to understand how well state of the art GCMs capture the realistic risk of multi-decadal megadrought. For example, it is essential to test the new results of Ault et al. (2013) that indicate that current models (e.g., CMIP5) do not capture the full range of possible interdecadal to intercentennial drought risk.

vi. Improved observational records: Observations are crucial to improving our understanding of how future streamflow will respond to a changing climate. Of particular importance is extending the length and continuity of observational time series especially in areas that are not well represented by the existing stream gauge network, observations in critical zones, and new observations to better understand snowpack, precipitation, evaporation, transpiration, sublimation and how these processes are affected by land cover change (e.g., dust on snow, changing vegetation) and topography. The impacts of these changes are becoming better understood (e.g., Painter et al. 2010) and could be incorporated to help improve future simulations and adaptation planning.

vii. Strengthened connection with the management community: Our efforts as well as past studies (e.g., Waggoner 1990; AWWA 1997; Kirchhoff 2010; NRC 2010; and others) highlight the importance of sustained networks for connecting active research efforts and water resources practitioners (see supplementary text). Ongoing efforts allow scientists to engage with decision makers and gather feedback that can provide guidance for future priorities as science and adaptation progress. Better understanding how this can efficiently and effectively occur is an important line of research.

Lesson 7: As climate science evolves, our understanding of future uncertainties will continue to improve. However, the evidence indicates there is no single magic bullet that will “reduce uncertainties”, nor will uncertainty ever be reduced to zero. Therefore, it is critical that both researchers and water managers redouble efforts and research to incorporate uncertainty and reconcile differences in future projections when possible. This will require continued communication and collaboration between the management and science communities, and will require scientists to more clearly articulate how their studies fit into existing knowledge, and explain how and *why* their studies do or do not agree with past work.

INTERPRETATIONS FOR DECISION MAKERS

While many studies over the last few years have projected future declines in Colorado River streamflows, the magnitude of the projected changes varies greatly. In response to our call for scientists to communicate more clearly with decision makers, we identify statements in which we have confidence, instead of just statements of uncertainty. These statements include implications for water resources planning and management based on multiple studies, which provide a path toward actionable science for decision makers. From our evaluation of past studies, we can say with high likelihood that:

- Temperatures will rise in the Colorado River basin over the coming decades, as indicated by all AR4 GCMs, for all emission scenarios.
- As indicated by most AR4 GCM projections for the Colorado River basin (more so than for most of the conterminous United States), precipitation will decline on an annual basis. Because the Basin is at the nodal line of drying to the south and wetting to the north, there is a wide range in the projected magnitude of reductions (and a minority of GCMs that project increases) and results in future studies (e.g., AR5) may differ.
- The magnitude of temperature and precipitation response depends on the intensity of future human greenhouse gas emissions, with larger emissions resulting in larger increases in temperature and a greater likelihood of precipitation declines. AR4 estimates project temperature increases of 2.5±1°C with -4%±12% changes in precipitation for high emissions scenarios and temperature increases of 2±1°C with -2.5%±6% changes in precipitation for low emission scenarios by the mid-21st century (Cayan et al. 2013).
- Warmer temperatures alone (ignoring possible changes in precipitation) will reduce annual runoff production in the Colorado River basin. For example, our evaluation of multiple

hydrological models estimates streamflow declines of 6.5%±3.5% per °C at Lees Ferry. If we apply this to estimates of mid-21st century warming of +2.5±1°C, we estimate a future streamflow change that ranges approximately from -5% to -35%.

- The ratio of annual runoff change to annual precipitation change (precipitation elasticity) at Lees Ferry is between about 2 to 3, based on our evaluation of multiple hydrological models and observations. This means that a 5% decline in precipitation will likely result in a 10% to 15% decline in streamflow, in addition to the temperature driven declines.
- The coarse spatial resolutions of current state-of-the-art GCMs and even RCMs do not resolve the scales of high elevation hydrologic processes that dominate runoff production in the Colorado River Basin. This necessitates downscaling and investigation of future climate implications using off-line hydrological model simulations.
- Natural variability in paleoclimate reconstructions clearly indicate that the modern climate can produce prolonged multi-decadal dry periods (megadroughts). This type of drought, exacerbated by a steady reduction in flows due to ongoing climate change, would result in decades of sustained streamflows much lower than have been observed in ~100 years of instrumental record.

CONCLUSIONS

We have identified four major reasons for discrepancies in past projections of changes in Colorado River streamflow. In order of importance, these are differences in:

1) the GCMs and emission scenarios on which the climate scenarios are based;

2) the ability of the land surface and atmospheric models used to simulate properly the disproportionate contribution to Colorado River discharge of the relatively small high elevation runoff source areas;

3) the sensitivities of the land surface hydrology models to precipitation and temperature changes; and

4) the methods used to statistically downscale (both spatially and temporally) the GCM scenarios.

Projections of future climate change impacts on Colorado River streamflow will always be uncertain, despite future research that will offer new insights, and may reduce uncertainty somewhat. It is thus important that water management decision making consider approaches that accommodate uncertainty and ambiguity of model evidence. It is also important that scientists more clearly articulate how their studies fit into the existing body of knowledge, explaining how and *why* their studies do or do not agree with past work. Scientists also need to reframe discussions when engaging decision makers to focus on certainties characterized by multiple studies and their implications for water resources planning and management.

Overall, the IPCC AR4 global simulations suggest substantial reductions in future Colorado River streamflow by the end of the 21st century, due to a combination of strong temperature-induced runoff curtailment and a probable reduction in annual precipitation. An increasing number of IPCC AR5 climate model results are now available (e.g., Seager et al. 2012) and will shed additional light on the nature of future Colorado River streamflow changes; the methods outlined herein provide a template for evaluation of the AR5 model implications, and should help to reduce uncertainty in their interpretation. In addition to this, paleoclimate reconstructions clearly indicate that there have been prolonged multi-decadal dry periods that created megadroughts not seen in ~100 years of instrumental record. The superposition of such megadroughts on a continued trend of warming, and possible precipitation declines, should be viewed as the most realistic 'worst case' scenarios for future planning.

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FIGURE CAPTIONS

Fig. 1. Approaches to generating future projections. Dotted lines indicate possible future studies. Land surface models (LSMs) are often incorporated in GCMs and RCMs, or they can be run (usually after downscaling) off-line, in which case they use output from climate models (e.g., precipitation, temperature, wind speed) and essentially serve as macroscale hydrology models. Paleoclimate data can also be used to evaluate and improve how GCMs simulate historical climate.

Fig. 2. Colorado River Flows at Lees Ferry and paleoclimate reconstructions that provide evidence of drought occurrence and persistence over the past 2000 years. (a) Naturalized streamflow values from the USBR (2012) from 1906-2008. (b) Streamflow reconstruction 762-2005 at Lees Ferry from the Upper Colorado River Flow Reconstruction dataset (Meko et al. 2007b), as described in Meko et al. (2007a), confidence intervals were generated using RMSE values. (c) Soil moisture reconstruction (black line) from Cook et al. (2008) using an average of six PDSI points representing the Four Corners region from 0-2006, as reported by Routson et al. (2011). Reconstructed flow values (red line) are provided as reference and are the same as in the panel above. The reality of the 2nd century mega drought has been recently confirmed by Routson et al. (2011) with strong indications that the longest multi-decadal megadrought observed in the last 2000 years lasted close to 50 years.

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Fig. 6. Comparison of BCSD downscaling from Christensen and Lettenmaier (2007) with a delta method downscaling approach for Lees Ferry in the 2040-2069 future period for A2 emission scenarios. On average, the BCSD approach has a decline in streamflow of 7% (average values of 93%) whereas with the delta method, declines are 13% (average values of 87%). The differences are the BCSD minus the delta method approach.

TABLES

Table 1. Details of studies used in evaluating future Colorado streamflow

	# of GCMs	# of RCMs	emission scenarios	total projections[A]	spatial resolution	type downscaling	land surface representation
Seager et al. 2007	19	-	SRES A1B	49	~2^{0} lat-lon (~200 km)	-	GCM P-E
Seager et al. 2012	16[B]	-	CMIP5 RCP8.5	43	~2^{0} lat-lon (~200 km)[C]	-	GCM P-E & runoff
Milly et al. 2005	12	-	SRES A1B	24	~2^{0} lat-lon (~200 km)	-	GCM runoff
Christensen et al. 2004	1	-	ACPI BAU	3	1/8^{O} lat-lon (~12 km)	BCSD	VIC hydrologic model
Christensen and Lettenmaier 2007	11	-	SRES A2 & B1	22	1/8^{O} lat-lon (~12 km)	BCSD	VIC hydrologic model
Cayan et al. 2010	2[D]	-	SRES A2 & B1	4	1/8^{O} lat-lon (~12 km)	constructed analogs	VIC hydrologic model
USBR 2011a (approach 3[E])	16	-	SRES A2, A1B, & B1	112	1/8^{O} lat-lon (~12 km)	BCSD	VIC hydrologic model
Gao et al. 2011	3	3	SRES A2	3	50 km grids	dynamical	RCM runoff
Rasmussen et al. 2011	1	1	SRES A2	1	2, 6, 18, & 36 km grids	psuedo global warming approach	RCM runoff
Gao et al. 2012	4	4	SRES A2 & A1B	4	50 & ~35 km grids	dynamical	RCM P-E
Hoerling and Eischeid 2007	18	-	SRES A1B	42	climate divisions (~150 km)	downscaling regression	PDSI Index with regession
Cook et al. 2004	-	-	-	1	2.5^{O} lat-lon	-	PDSI reconstruction
Woodhouse et al. 2006	-	-	-	1	62 tree ring chronologies	-	proxy reconstructions
Meko et al. 2007	-	-	-	1	11 chronologies, Upper basin	-	proxy reconstructions
McCabe and Wolock 2007	estimate 2^{O}C[F]	-	-	2	62 HUC8s	-	% adjust based on TWB model & proxy reconst.
USBR 2011a (approach 8[E])	-	-	-	1244 & 1000 traces[G]	11 chronologies, Upper basin	-	proxy reconstructions

*Abbreviations not identified in text: SRES=Special Report on Emissions Scenarios; CMIP=Coupled Model Intercomparison Project; RCP=Representative Concentration Pathways; Accelerated Climate Prediction Initiative=ACPI; BAU= Business As Usual

[A]total projections include multiple runs for the same GCM and emission scenarios

[B]as more GCMs become available, results are updated at: http://www.ldeo.columbia.edu/~cli/NCC_paper.html

[C]spatial resolution for GCMs in CMIP5 are, on average, smaller than those in earlier assessments (Seager et al. 2012)

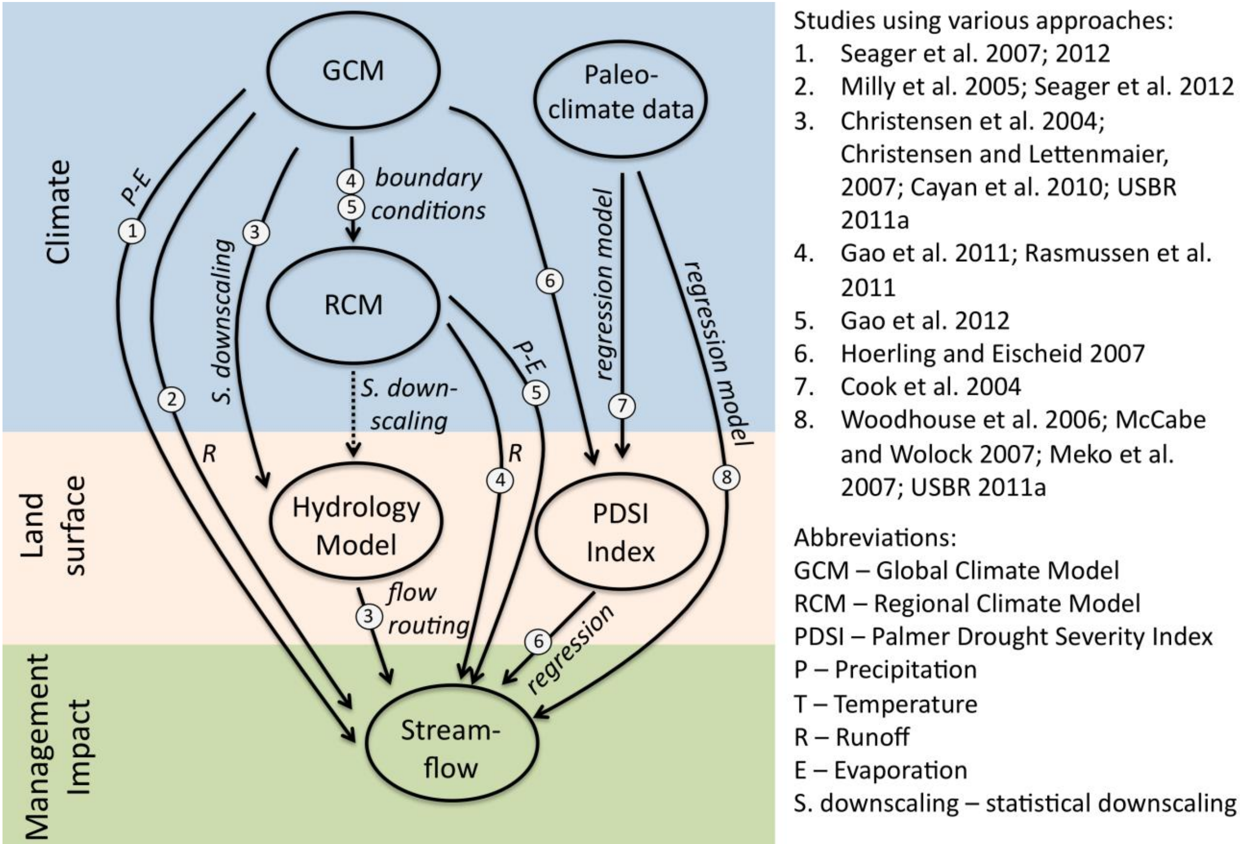
[D]twelve GCMs were used in total, but only two were downscaled for more detailed analysis of droughts

[E]as specified in Fig. 1

[F]two warming scenarios, 0.86 and 2^{O}C increases. 0.86^{O}C was based on measured trend in Upper basin annual temperature during the 20th century and 2^{O}C warmer scenario based on GCM scenarios

[G]resampled using Paleo Resampled (1244) and Paleo Conditioned (1000) methods to generate 50-year periods

FIGURES



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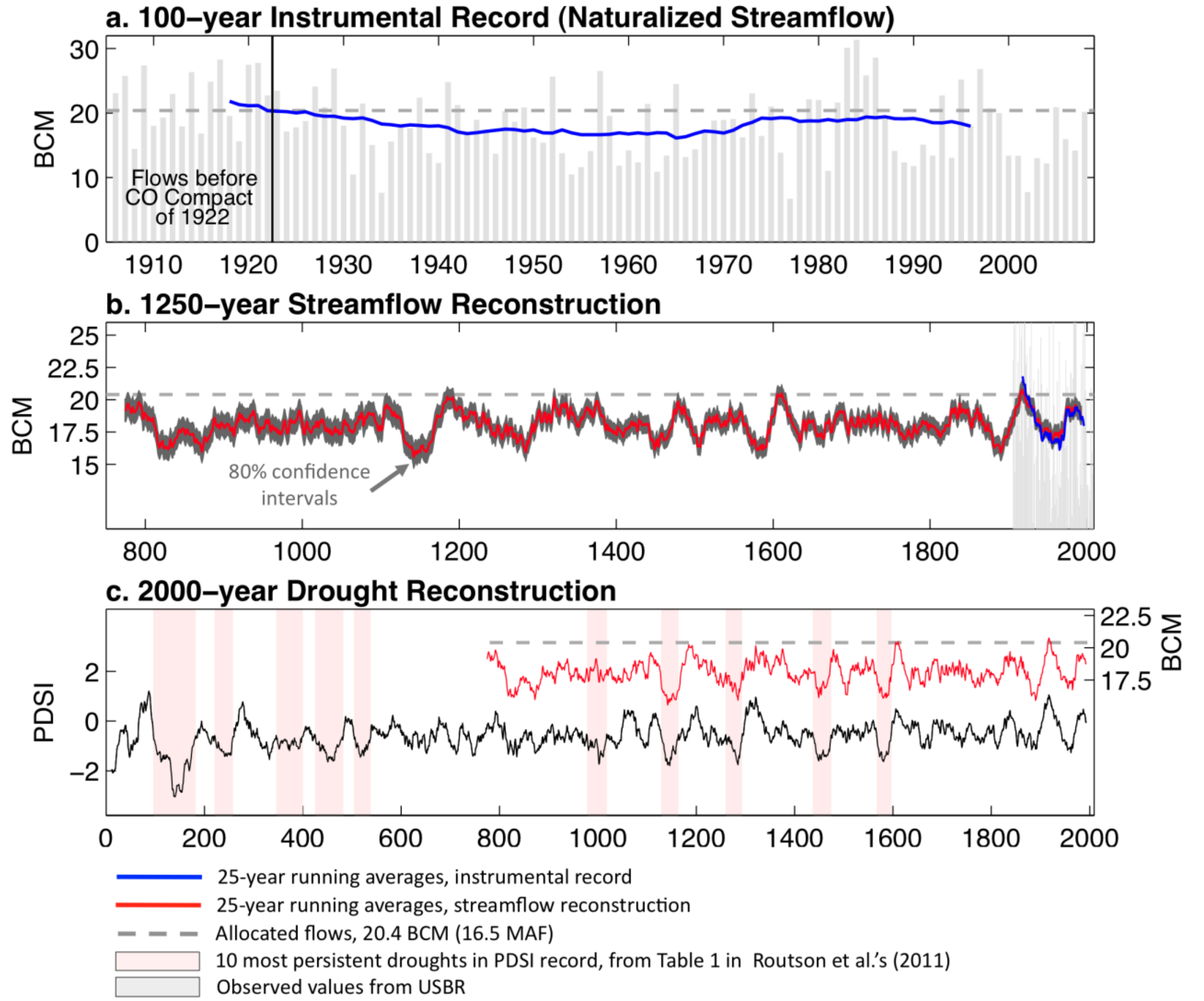

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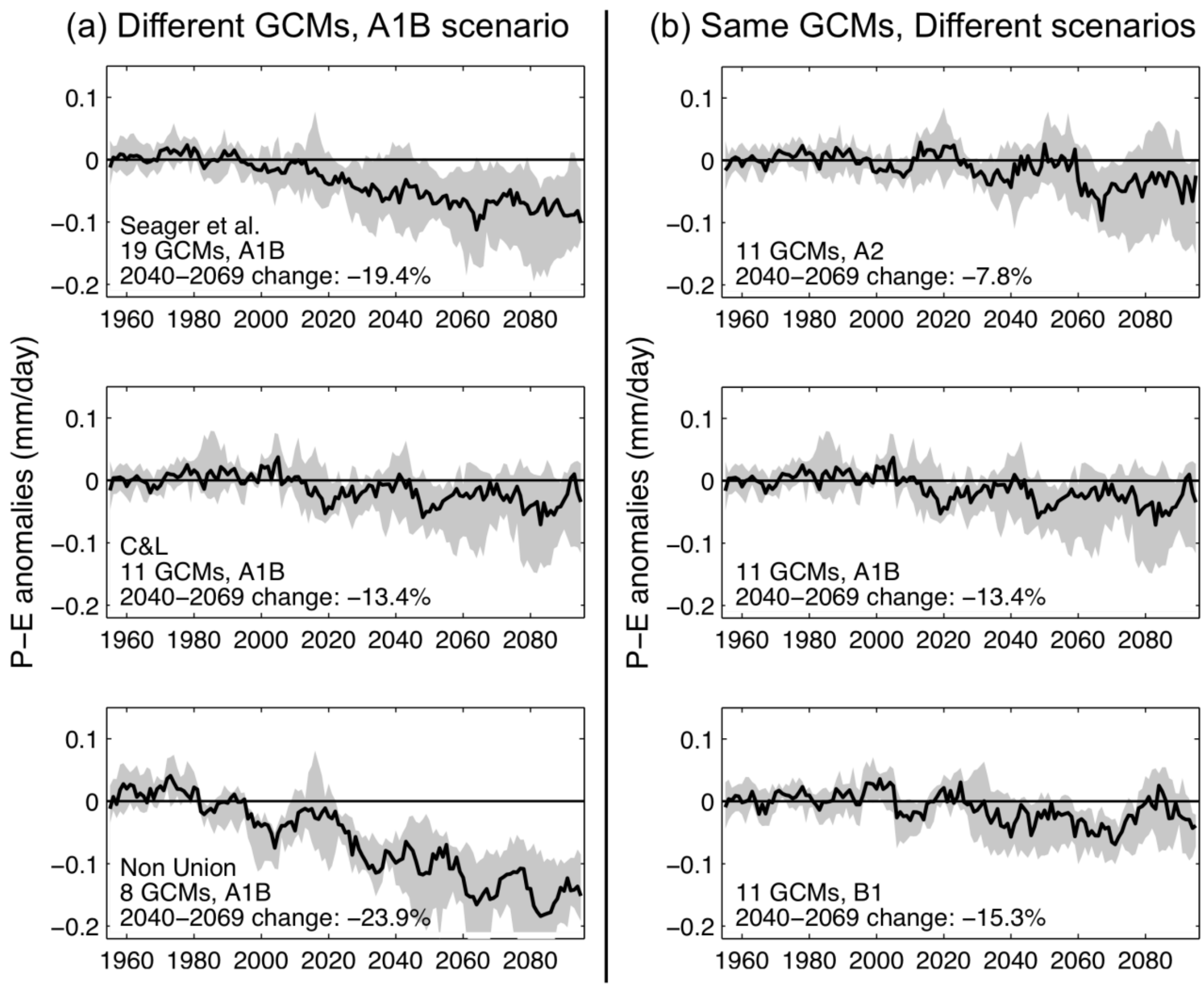

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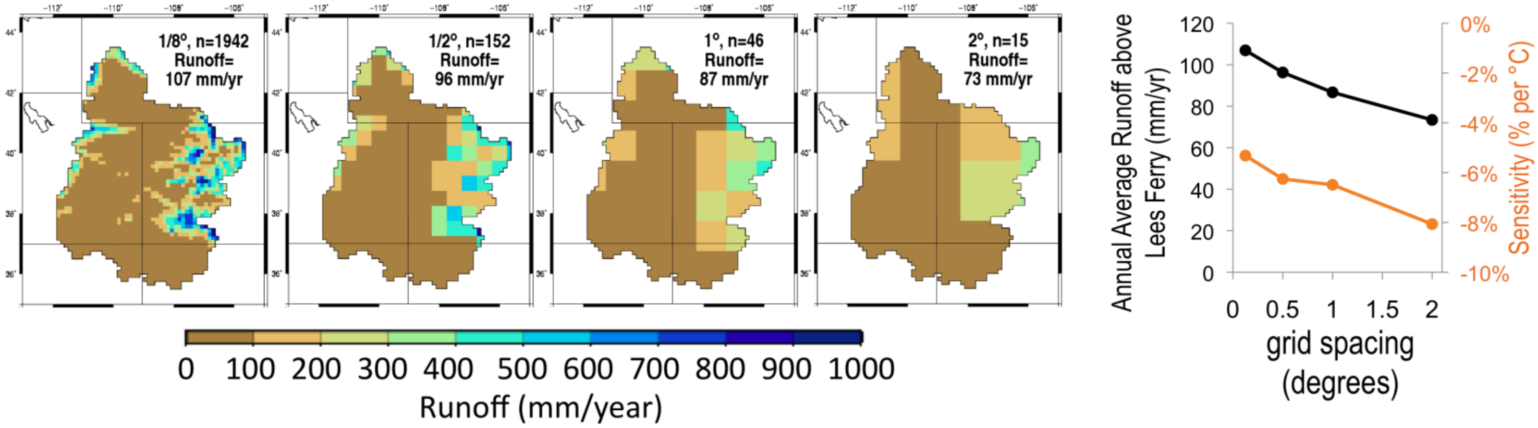

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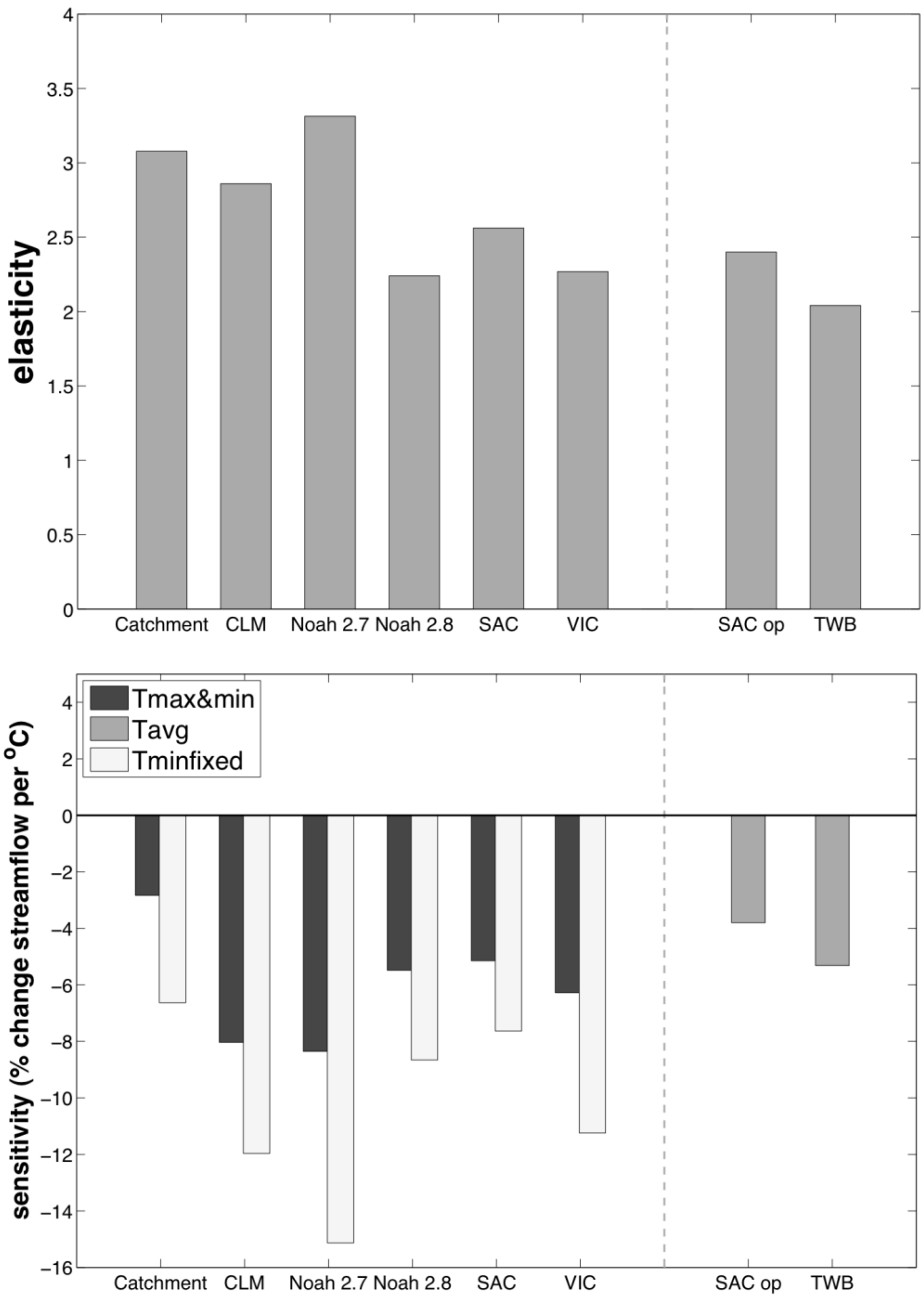

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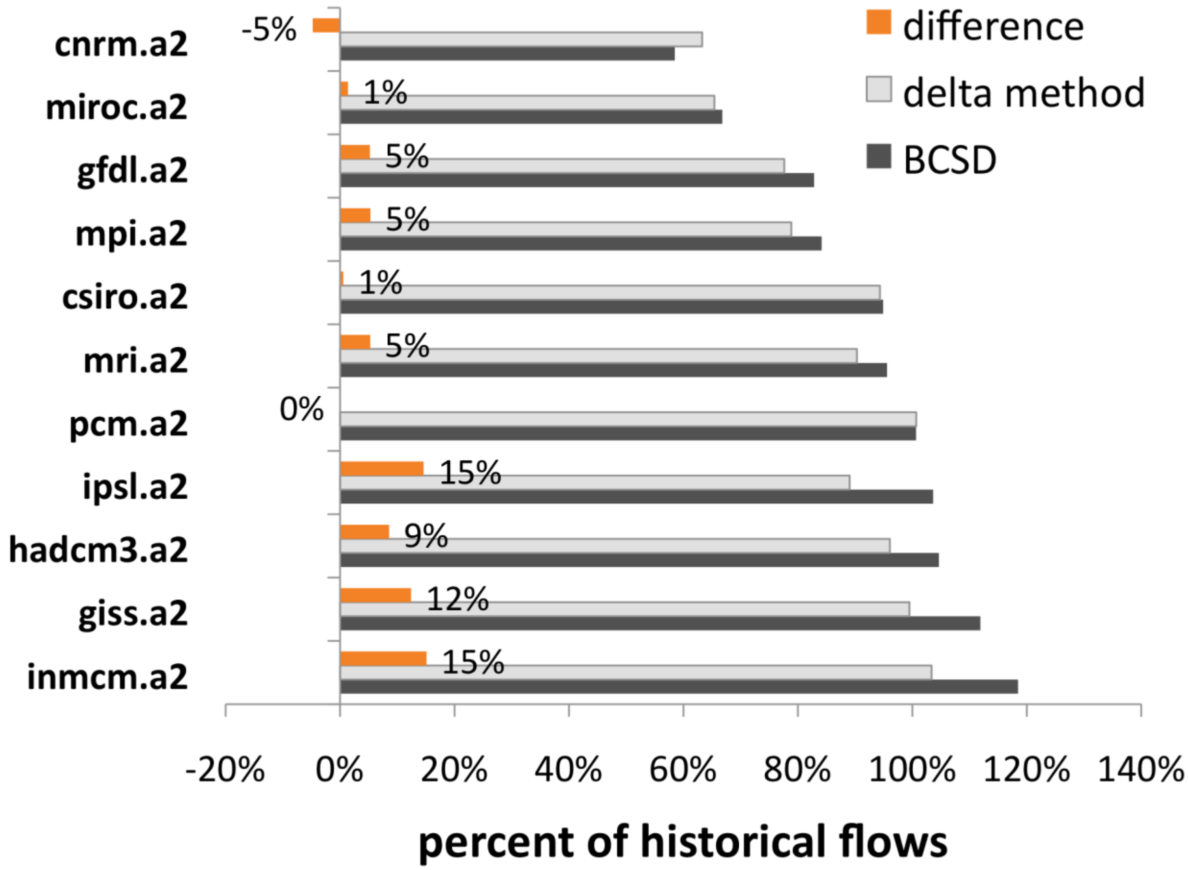

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