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Technical Memorandum | Final

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Subject:	**CRWAS Phase I | Task 7.2 | Climate Change Literature Review and Methods Evaluation**
Date:	**~~April 20, 2009~~ January 2012 updates in red**

CRWAS Phase I included a public comment period on the draft CRWAS Phase I Report and public outreach workshops to solicit feedback from stakeholders on the Study. CWCB and the CRWAS technical team used these forms of feedback to refine Study deliverables, such as this technical memorandum, which may include content that has been updated.

Introduction

This Technical Memorandum summarizes information developed as part of Task 7 of the Colorado River Water Availability Study (CRWAS or Study).

The objective of Task 7 is to:

Provide agency coordination, literature review, diagnostic analysis, data preparation, and model testing to generate projections for temperature, precipitation, weighted and scaled alternate hydrology, and water use relative to potential changes in forest and climate scenarios.

This memo is associated with CRWAS Subtask 7.2 (Climate Change Literature Review and Methods Evaluation) and responds to the requirements of the Subtask to "…address the available science related to the regional response to climate change, methods of translating climate projections into hydrologic conditions, and understanding and quantifying the uncertainty in those projections." Subsequent sections of this technical memorandum discuss: 1) the requirements of CRWAS; 2) a summary of the overall analytical framework; 3) analysis type and time frames; 4) emission scenarios, Global Climate Models, and downscaling; 5) hydrology modeling; 6) representation of year-to-year variability; 7) water resources planning modeling; 8) analysis uncertainty; 9) references; and an appendix that contains a detailed review of important publications, a bibliographic list of other relevant sources, and a glossary. Sections 3 through 8 each include a description of available approaches / methods, an evaluation of alternative approaches in the context of CRWAS requirements, and a recommended approach for CRWAS.

1) Requirements of CRWAS

The principal objective of Task 7 of CRWAS is to develop an alternate hydrology of climate change. Although not specifically stated as a requirement, a reliable alternative hydrology would reflect both the mean and variability of streamflow.

Phase I of the CRWAS will conduct water availability analyses at one level of development, which is described in the State's Scope of Work as "…historical levels of use from existing absolute water rights." Phase II of CRWAS will include water demands.

The work under Task 7 of CRWAS is to be coordinated with the Front Range Vulnerability Study (FRVS), which is a cooperative study among several front-range water providers that involves simulating climate change impacts in the Upper Colorado River Basin, Upper South Platte River Basin and Upper Arkansas River Basin. The Boyle team has begun coordinating with FRVS and has determined that coordination with FRVS will be consistent with the policy and technical objectives of CRWAS. In particular, as discussed in more detail below, we recommend that CRWAS use the same time frames for projection of climate change impacts and the same selection of *climate projections* as will be used by FRVS. In addition, we recommend that CRWAS use an approach similar to FRVS to develop future climate inputs for hydrologic modeling. This coordination will facilitate comparison between the results of CRWAS and FRVS where they directly overlap (in the Upper Colorado River Basin) and will make the results of the two studies compatible for other evaluations.

The approach to be used by FRVS and which we recommend for use by CRWAS for developing climate change impacts can be described as using a steady-state perturbation, which involves perturbing the observed climate conditions to reflect the *mean* change in projected climate relative to the observed climate. This approach, which is discussed further below, is compatible with the objectives of both projects.

From a practical perspective, there are several constraints on CRWAS that influence some aspects of the analysis, the most significant of which is the choice of the water resources planning models to be used to make calculations of water availability and system conditions. To facilitate public acceptance of CRWAS results and to limit the overall level of effort, we recommend that CRWAS use the existing Colorado River Simulation System (CRSS) from the Bureau of Reclamation and the existing Colorado Decision Support System (CDSS) from the Colorado Water Conservation Board.

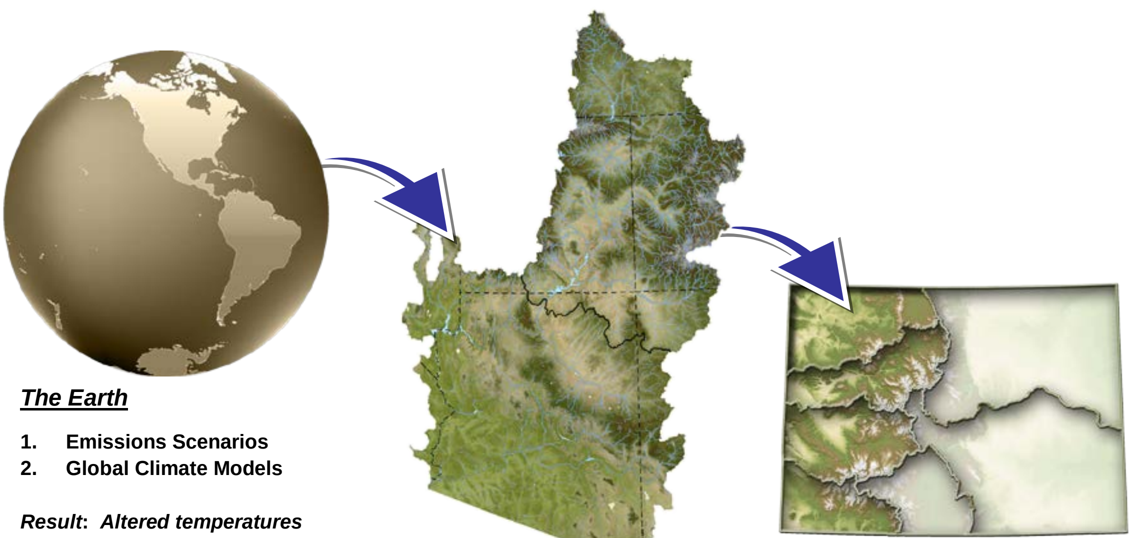
2) Summary of Analytical Framework

Global Climate Model (GCM) projections of future climate over a multi-decadal time frame indicate that the Colorado River basin will become warmer. Temperatures in Colorado are projected to increase by 2.5º F by 2025 and 4º F by 2050. (Ray et al., 2008) Projections of future precipitation are more complex, with the multi-model average of projections showing little change in annual precipitation, but generally showing a seasonal shift in the temporal pattern of precipitation. The objective of CRWAS is to provide quantitative estimates of the impact of projected change in climate on streamflows, water use and water availability to Colorado water rights. 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). Even if precipitation remains unchanged, projected increases in temperature alone will cause a shift in the seasonal distribution of streamflow (due to changes in snow accumulation and ablation) and these changes in the timing of streamflow will affect water availability for consumptive and non-consumptive uses.

Designing the approach to be used to make quantitative estimates of these effects requires selecting several modeling methods as well as the underlying data to be used in the analysis, and determining a number of fundamental assumptions that will guide the analysis. The following paragraphs outline the elements of a climate change impact analysis, and the subsequent sections evaluate and recommend methods and assumptions that we believe are appropriate for CRWAS.

Figure 1 depicts the analysis process required to make quantitative estimates of impacts to water resources from projected changes in climate.

Figure 1.
Climate Change Modeling Approach



The process begins with the development of scenarios of future emissions of *greenhouse gases* (Step 1 in Figure 1) [1]. These *emission scenarios* are used to drive a *global climate model* (GCM)[2] that simulates future conditions in the Earth's atmosphere and on its surface (Step 2). GCMs estimate atmospheric and surface conditions in a three-dimensional grid with a resolution of hundreds of kilometers per side. The problems with

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[1] Carbon dioxide is the best-known greenhouse gas, but methane and nitrous oxide also contribute to the greenhouse effect.
[2] Global climate models were originally called *generalized circulation models*, but this terminology, though still in use, has recently become less common.

this coarse resolution are that it does not represent very well the mountainous terrain in Colorado, and the scale of the grid cells is very large compared to the scale of the watersheds that supply water within Colorado. Therefore, a *downscaling* step is required to translate the outputs from GCMs to a scale that is useful for hydrologic modeling in Colorado (Step 3). The downscaled GCM output (usually projections of temperature and precipitation) are then used to drive a hydrologic model to estimate the impact of climate change on streamflows (Step 4). Information about long-term drought that is determined from paleohydrology is blended with the information about climate change impacts to streamflows to generate sequences of flows at many points in the study area (Step 5) and these in turn are used to drive water resources planning models to determine water availability (Step 6).

Sections 3 through 8 address the major elements of an analysis of water availability by first describing the approaches or methods that are available for the element, evaluation the options in the context of the requirements of CRWAS, and finally recommending an approach for CRWAS.

Section 3 addresses approaches to a high-level decision about a climate change analysis, which is the choice of analysis type and the time frame(s) of the analysis.

Section 4 addresses approaches to another fundamental basis for a climate change analysis: the selection of which climate projections to use.

The downscaled output from GCMs contains only estimates of future temperature and precipitation. Hydrologic modeling is required to simulate future streamflow based on those projections. **Section 5** addresses approaches to hydrology modeling.

Section 6 addresses approaches that are available to represent year-to-year variability of stream flow, an important factor influencing the availability of water supplies, particularly in systems that have little storage, such as is the case for many diversions under direct flow water rights in Colorado.

Section 7 addresses approaches to the final step in making estimates of water availability such as is required by CRWAS: use of water resources planning models to translate the streamflows produced by the hydrology model into yields from water rights and water supply systems.

Section 8 addresses approaches to address the inherent uncertainty in projection of future conditions.

3) Analysis Type and Time Frames

Two types of analysis can be used, a *transient* analysis, which examines the expected impacts as they develop from year to year, or an *equilibrium* analysis, where the mean impact of the expected change in climate is evaluated under the assumption that the climate has reached equilibrium at some specified time or times in the future. An equilibrium analysis is consistent with the concept of a “build-out” analysis in water resources planning, whereas a transient analysis provides information that may be useful in planning the *timing* of adaptation measures. If an equilibrium analysis is chosen, it will also be necessary to determine the future time frame(s) for which impact estimates will be made.

The decision regarding the type of analysis (transient or equilibrium) and the time frames for the analysis for development of the CRWAS alternate hydrology of climate change should be based on the objectives of the analysis. The objective of CRWAS is to evaluate the availability of water to meet Colorado's *long-term* future needs. CRWAS is not intended to provide detailed information to help determine how water supply projects should be staged to meet increasing water demand in the face of a changing climate.

Evaluation of Alternative Approaches

While a number of previous studies have applied a transient climate scenario to force hydrologic models, for the purposes of CRWAS an analysis using an equilibrium climate scenario is consistent with the project objectives and has the following technical advantages over a transient approach:

- A transient representation of climate change would confound estimation of the frequency of future conditions (e.g. drought) because of the positive trend in growth of greenhouse gases, which will be reflected in future climate conditions and thus in future streamflows.

- A transient representation of climate change would involve an assumption that the variability and year-to-year sequence of climate conditions generated by GCMs is reliable. Some evidence indicates that, at least for precipitation, this may not be true. (Lau et al., 1996, Wood, et al., 2004, Tebaldi, et al., 2008)

- Using a consistent year-to-year sequencing for both current and projected water availability analyses (which would not be possible with a transient analysis) isolates the impact of changes in mean climate from the impact of sequencing.

If an equilibrium approach is used, estimates of future impacts can be made at one or more point in time. For CRWAS, representing long-term future water availability would be accomplished by selecting a time frame toward the end of the 21st century, which is as far as the readily available climate projections extend. An estimate at an intermediate point in time would be useful to better understand the urgency of adaptations to changes in future water availability.

We are not aware of any work that establishes a scientific basis for selection of analysis time frames. One exception to that is the common observation that the differences in GHG concentrations among the SRES scenarios do not appear to diverge until after about 2010 and the differences among scenarios do not appear to become significant until around the middle of this century. However, another objective of CRWAS is to coordinate its methods with the FRVS where such coordination allows CRWAS to meet its technical objectives, and FRVS has determined that it will use two time frames, 2040 and 2070.

Recommended Approach

An equilibrium analysis is consistent with the objectives of CRWAS and avoids technical difficulties that would arise from the use of a transient approach. It is also consistent with the approach adopted by the FRVS, which will allow for more comparability between CRWAS and FRVS. Therefore, we recommend that the analysis framework be based on an **equilibrium analysis** at the two time frames. Because warming temperatures and changes in the seasonal pattern of precipitation are expected to change the seasonal distribution of flows, we recommend that **changes in climate conditions be expressed on a monthly basis**, that is changes in climate conditions (i.e. changes in precipitation and temperature) should be calculated as the average change for each of the twelve months of the year, e.g. the average for January, the average for February, and so on.

The time frames selected by the FRVS are consistent with the objectives of the CRWAS, and using the same time frames will allow for more comparability between CRWAS and FRVS, therefore we recommend that the time frames to be used for analysis by CRWAS be **2040** and **2070**.

4) Emission Scenarios, Global Climate Models and Downscaling

Projections of future changes in climate attributed to human activity rely on projections of future concentrations of greenhouse gases, which in turn depend on current concentrations and future rates of greenhouse gas (GHG) emissions. GHG emissions depend, in complex ways, on socio-economic development, technology, demographics and politics. The Intergovernmental Panel on Climate Change (IPCC) has developed a number of "storylines" of future global conditions, which are used as the basis for estimates of future GHG emissions. These storylines are documented in the Special Report on Emissions Scenarios (SRES) and are often referred to as *SRES scenarios.* IPCC did not assign a likelihood to the SRES scenarios—all are considered equally probable "alternative images of how the future might unfold" (Nakicenovic et al., 2000, Technical Summary). From the four SRES scenario "families" (A1, A2, B1, B2), only the B1, A1B (a member of the A1 family) and A2 scenarios have been used as the basis for projections on many GCMs. These have come to be known, respectively, as the "low", "medium" and "high" scenarios, based on their impact on climate conditions in the year 2100[3].

Emissions scenarios are used as input to GCMs, which are computer simulation models of the Earth's atmosphere and its interaction with the Earth's surface. GCMs provide estimates of future conditions that reflect the levels of greenhouse gas emissions in the SRES scenarios. GCMs differ in their simulation approach and their degree of sophistication, and each run of a particular GCM using the same SRES scenario will differ in how it is initialized. A particular run of a GCM using a particular SRES scenario is referred to as a *projection.* No two projections will be the same, and there can be substantial differences among multiple projections from the same GCM and based on the same SRES scenario. Selection of which projections to use is another fundamental basis for a climate change analysis.

GCM output is available in grid scales that range from about 100 to about 200 miles square, a substantial fraction of the area of western Colorado. While one GCM grid cell covers from 10,000 to 40,000 square miles, a substantial mountain watershed might cover several hundred to a thousand square miles, and many tributaries drain considerably smaller areas. Before GCM output can be used for analysis of local conditions, or for local hydrologic modeling, it must go through a process called *downscaling*, which relates the large scale GCM data to detailed terrain and observed climate conditions. GCM projections contain *bias*, which is exhibited as systematic error in replicating observed conditions, and these biases are usually removed during downscaling in a process called

[3] The impacts of different GHG emissions scenarios do not begin to diverge substantially until roughly the middle of this century.

bias correction. There are a number of methods available for downscaling and bias correction. Fowler et al. (2007) provides an overview of several methods.

There are two primary approaches to downscaling, *statistical downscaling* and *dynamic downscaling*. Dynamic downscaling uses a model similar to a GCM, but based on a finer grid resolution, called a *Regional Climate Model* (RCM). Statistical downscaling develops the statistical relationship between temperature and precipitation in the GCM grid to temperature and precipitation observed within that grid cell and uses that statistical relationship to estimate local conditions that are consistent with the GCM output. Statistical downscaling often also incorporates a spatial disaggregation step to convert local point observations to a gridded data set.

The reader is referred to Ray, et al. (2008) for a discussion of GCMs and their characteristics that are relevant to Colorado. From a practical standpoint, outputs from 16 GCMs are included in the most accessible archive of downscaled GCM outputs. Similarly, the three common emissions scenarios, B1, A1B and A2 (i.e. low, medium and high emissions, respectively), are the ones that are included in that archive[4].

Evaluation of Alternative Approaches

Formulation of emission scenarios and operation of GCMs are outside the control of CRWAS, although CRWAS will rely on the SRES scenarios and several GCM runs. While it would be possible for downscaling to be conducted as part of CRWAS, downscaled data are readily available, these data are being used in climate change studies, and the methods used to develop them have been published and peer reviewed. It would not be an efficient use of CRWAS resources to undertake a new downscaling effort, and to do so would make the results of CRWAS less comparable to other studies.

The availability of dynamically downscaled data is very limited, and usually are available for only one or a few GCMs. This would limit the ability of CRWAS to represent the uncertainty among climate projections. Statistically downscaled data have been developed jointly by the Bureau of Reclamation, Santa Clara College and the Lawrence Livermore National Laboratory (USBR/SCC/LLNL) (WCRP CMIP3, 2008). These data have been placed in a readily-available archive of statistically downscaled GCM output that contains output for 112 projections of future climate based on 16 GCMs and the B1, A1B and A2 emission scenarios. The USBR/SCC/LLNL has been developed using peer reviewed methods (Maurer et al., 2002) and is currently being used by the Bureau of Reclamation for climate change impact analyses. Use of the USBR/SCC/LLNL is feasible and it will provide the most reliable and most comparable results based on current science.

Recommended Approach

Please refer to the July 25, 2011 Technical Memorandum, " CRWAS Phase I – Projection Selection (refinement to CRWAS Phase I Tasks 7.1, 7.2 and 7.5)", posted at http://cwcb.state.co.us, for updated information associated with this section of this technical memorandum.

[4] A fourth scenario, A1F1, the “business as usual” scenario may also be available in a downscaled form in time for possible use in CRWAS.

To retain consistency with the FRVS and based on technical factors and cost effectiveness, we recommend that CRWAS use the **USBR/SCC/LLNL archive** of statistically downscaled GCM outputs.

For consistency between the two projects, we recommend that CRWAS use the same projections as FRVS. By doing so, the results developed by the FRVS for those parts of the Upper Colorado River above Cameo can be compared directly to those developed by CRWAS. After consultation between the FRVS and CRWAS technical teams, FRVS adopted an approach for selection of projections that is described here. Up to ten projections will be selected with the following method.

Five qualitative future climate scenarios have been defined as follows:

- **Hot and Dry**
- **Hot and Wet**
- **Warm and Dry**
- **Warm and Wet**
- **Median**

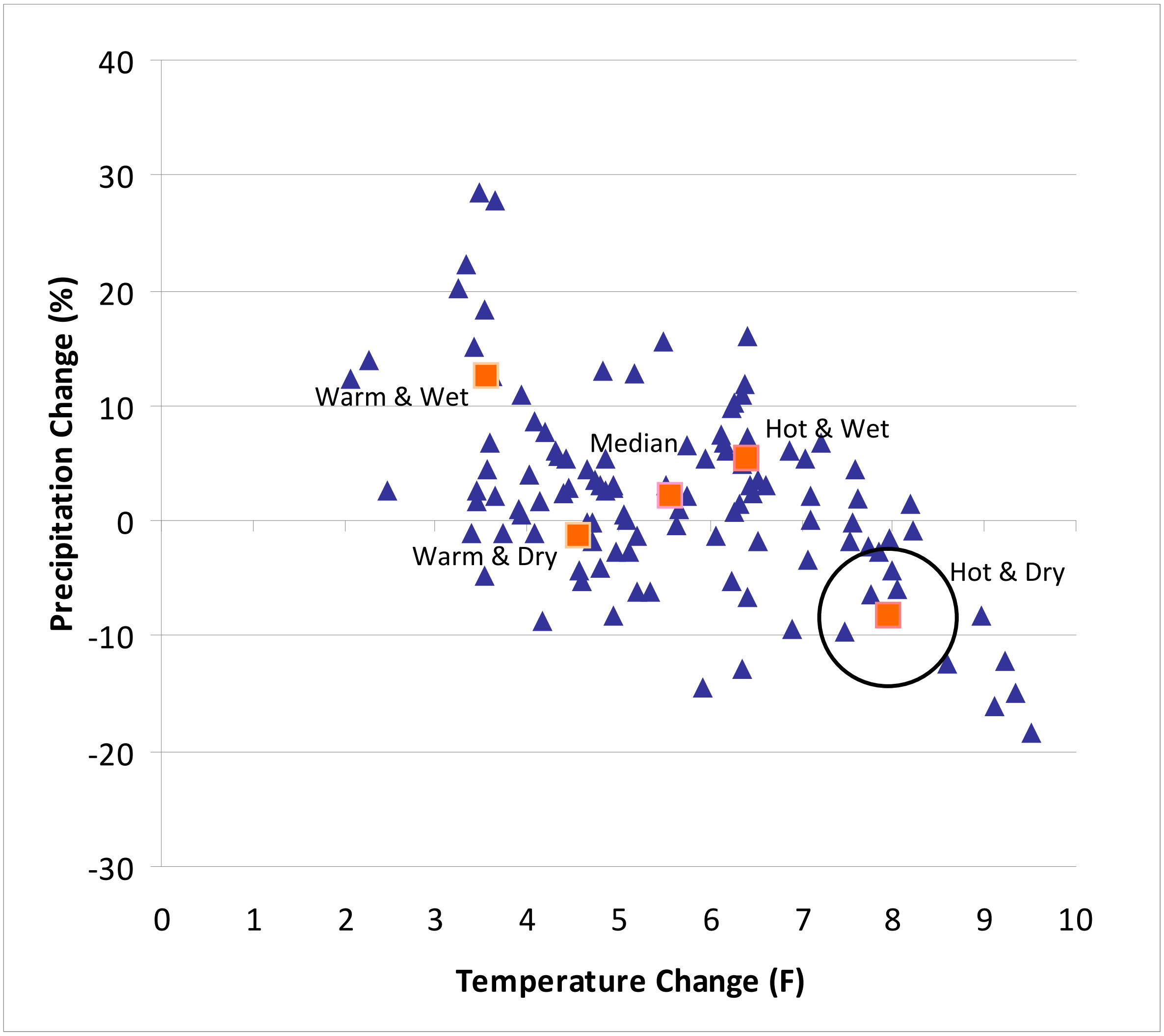
For each time frame, a projection will be selected for each of the five qualitative scenarios, so if two time frames are analyzed up to ten projections may be used in the analysis (it is possible that the same projection will be selected for both time frames for a given qualitative scenario).

For each of the five qualitative scenarios, a characteristic value will be determined for the projected change in temperature and precipitation. Change in temperature will be expressed as an absolute projected increase while change in precipitation will be expressed as a percent projected increase or decrease. The characteristic values will be determined as follows and are illustrated on Figure 2.

Qualitative Scenario	Characteristic Temperature	Characteristic Precipitation
Hot and Dry	90th Percentile	10th Percentile
Hot and Wet	70th Percentile	70th Percentile
Warm and Dry	30th Percentile	30th Percentile
Warm and Wet	10th Percentile	90th Percentile
Median	50th Percentile	50th Percentile

Figure 2 illustrates the characteristic conditions for the qualitative scenarios. The figure shows 112 projections of future temperature and precipitation plotted by the percent change in precipitation and the absolute change in temperature. The four larger squares represent the characteristic conditions for the five scenarios. The temperature for the hot and dry scenario is the 90^{th} percentile of all 112 temperatures (only about 11 projections have a hotter temperature). The precipitation for the hot and dry scenario is the 10^{th} percentile precipitation (only about 11 projections have a lower precipitation).

Figure 2.
Characteristic Conditions for Selecting Projections for 2070

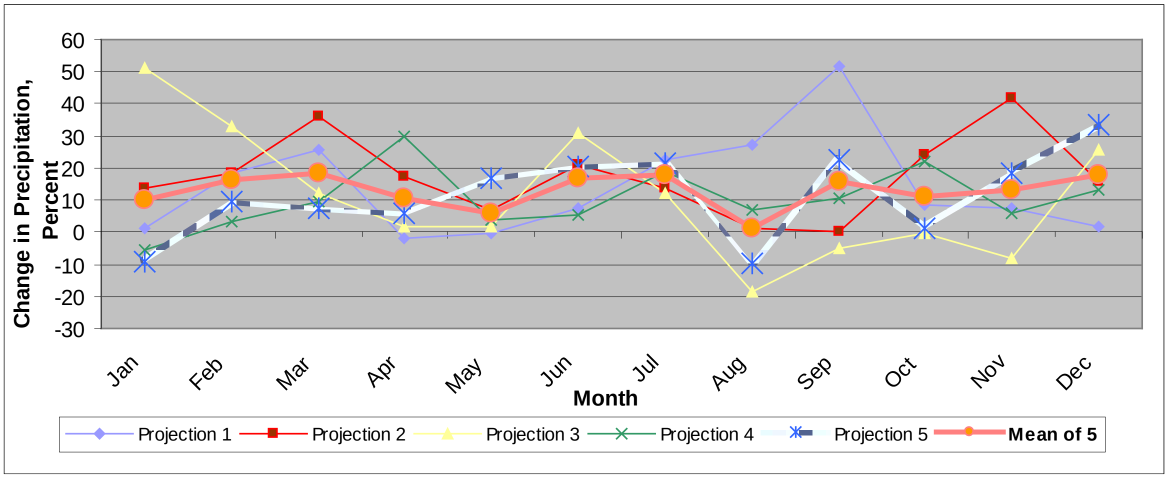


Projections will be selected based on their proximity (in terms of Euclidean distance in the T and P dimension space) to the characteristic values for the five scenario points. The five nearest projections will be selected as candidate projections at each scenario point—an illustration of this is shown for the Hot and Dry scenario. One of these candidate projections will be selected based on the following criteria:

- **Proximity to the characteristic point**
- **Having a representative monthly pattern**

For the five scenarios selected on the basis of proximity, the average monthly pattern of normalized precipitation (normalized against the annual mean value) will be averaged to obtain a mean normalized pattern for precipitation. The relationship among precipitation traces and the mean trace is illustrated in Figure 3.

Figure 3.
Monthly Precipitation Changes, Warm & Wet Qualitative Scenario



The individual pattern with the lowest root mean square error to the mean pattern will be selected to represent that qualitative scenario.

5) Hydrology Modeling

Two principal categories of hydrology modeling (statistical models and process models) have been applied to climate change research, and among these two primary modeling categories there are a large number of individual models. The suitability of hydrology models for application to climate change impact studies varies based on both practical and scientific considerations. In addition, there are different choices of how hydrology modeling is used to represent the impacts of climate change.

Statistical hydrology models are based on deriving a functional relationship between streamflow and the climate variables – precipitation, temperature, etc—several of which are typically developed for selected seasons (i.e., monthly or for a set of months, e.g., Dec-Jan-Feb, etc.) In climate change studies, like CRWAS, use of statistical models requires the assumption that the relationships on which the model is based will hold under the climate change scenarios. However, under climate change seasonal shift is expected in the annual streamflow hydrographs with, for example, warmer temperatures bringing earlier spring runoff (Hayhoe et al., 2004; Barnett et al., 2005; Maurer, 2007). Thus, statistical models are expected to have only a limited application in analyzing streamflows under climate change. For the CRWAS, we propose to use a physical process-based hydrology model. Specifically, the Variable Infiltration Capacity (VIC) macro-scale hydrology model is proposed to be used to develop alternate streamflow hydrology under the selected climate change scenarios.

Where to find more detailed information:

Details on the choice of the VIC model are provided in the CRWAS Technical Memorandum *Task 7.5 Climate Change Approach, Hydrology Model Selection*.

In addition to the choice of a hydrology model, there is an additional choice in how changes in streamflow are represented, whether a *direct simulation* approach or a *differencing* approach is used. In a direct simulation approach, the future streamflows used as input to water resources planning models are taken directly from output of the hydrologic model, and the outputs from the water resources planning models are compared to results developed using the observed streamflows. This approach places tremendous reliance on the quality of the calibration of the hydrology model, since any residual bias in streamflows will directly impact the results of the water resources planning modeling.

The bias in hydrology modeling can be reduced by adopting the differencing approach, which can be completed through at least two methods:

- *Modeled baseline.* Use the calibrated streamflow output of the hydrology model (forced by observed climate conditions) as the basis for estimating the current (baseline) water availability and compare the baseline water availability to estimates of projected water availability made based on streamflow output from the hydrologic model forced by projected climate conditions.

- *Perturbed baseline.* Use the accepted naturalized observed streamflow data to define the current (baseline) water availability. Perturb (adjust) the naturalized observed streamflow by the ratio between flows that result when the hydrology model is forced first with the observed climate and then with the projected climate. Use the perturbed flows to make estimates of projected water availability using the water resources planning model.

The two approaches will not produce the same result because the relationship between streamflow and water availability in prior appropriation water allocation systems is very non-linear, and often has step-function responses at threshold values (e.g. when a water right comes into priority). Thus, a relatively small difference in flow can cause a more significant difference in water availability for particular water rights, especially junior rights. The modeled baseline approach reduces bias from the hydrologic simulation between the baseline and projected condition, but leaves a residual difference between the water availability based on the accepted observed flows and the water availability defined as the baseline condition. The perturbed baseline approach assumes that the residual bias in the hydrology model is relatively constant across the ranges of projected climate and therefore does not introduce significant bias into the estimate of the ratio between current and projected flows (see discussion below).

Evaluation of Alternative Approaches

Hydrology Models

A range of hydrology models that are potentially applicable to CRWAS have been evaluated, and the recommendation has been made for the use of the Variable Infiltration Capacity Model (VIC).

Where to find more detailed information:

Details on the choice of the VIC model are provided in the CRWAS Technical Memorandum *Task 7.5 Climate Change Approach, Hydrology Model Selection*.

Hydrology Analysis Framework

The direct simulation approach has the following disadvantages relative to a differencing approach for use in CRWAS:

- In any hydrologic model, perfect agreement between modeled flows and observed flows cannot be achieved because the data used to force the model (temperature and precipitation) are imperfect, because the simulation of natural processes is imperfect, and because processes that are distributed continuously over time and space are represented by discrete simulations at a finite resolution[5]. Therefore, no matter how well the hydrology model is calibrated, the resulting streamflows will not exactly match the current accepted flow data sets for CRSS or CDSS. Any bias in streamflows (for example, a small difference in the mean flow or in the timing of runoff) could lead to more significant differences in water availability. When the direct simulation approach is employed, the baseline case is represented by modeled flows and by water availability based on those modeled flows, so stakeholders will be required to evaluate a new baseline condition.

- The use of a direct simulation technique requires the use, verbatim, of GCM sequences when simulating future conditions. The statistics of these sequences will be different from the historical and paleo-reconstructed sequences. This may influence acceptance from stakeholders. Further, there is some evidence that GCM skill in replicating year-to-year variability of precipitation is low (Lau et al., 1996, Wood, et al., 2004, Tebaldi, et al., 2008).

Because the CRWAS will not be evaluating the dynamics of the onset of climate change, there are no apparent compelling advantages to the use of a direct simulation approach.

Differencing approaches have the following attributes relevant to the CRWAS:

- A differencing approach does not rely on perfect agreement between modeled and observed flows (a perfect calibration) but instead on a realistic representation of the physical processes that produce streamflows.

- When the perturbed baseline approach is used, the baseline case is represented by accepted natural flow data and accepted water availability results. This should lead to more ready acceptance of results by stakeholders.

- The perturbed baseline approach assumes that the residual bias in the hydrologic model is substantially constant across the range of projected climate. The degree to which this is true will be case specific and is unknown, but in our judgment, any bias in response introduced by use of the perturbed baseline approach will be significantly smaller than the uncertainties in projections of future climate.

[5] An analogy to the effect of discretization and model resolution can be made to the changes apparent in a digital photograph at levels of magnification that begin to reveal the individual pixels that make up the image.

Recommended Approach

Hydrology Models

A range of potentially applicable hydrology models have been evaluated, and recommendation has been made for the use of the **Variable Infiltration Capacity Model (VIC)**.

Hydrology Analysis Framework

Based on the evaluation of the different approaches for applying hydrologic modeling to climate change analyses, we recommend the use of a **differencing approach** which will reduce the impact of model bias. We also recommend the use of the **perturbed baseline method** because it allows the streamflows used in CRWAS to be anchored to the CRSS and CDSS natural flows. Though these flow data may be the object of contention among stakeholders, they are the data most widely accepted by the stakeholders.

6) Representation of Year-to-year Variability

The nature of wet or dry (drought) periods in a stream system has an enormous impact on the reliability of water supply from that system. Accordingly, the representation of the year-to-year sequences of flow is an important factor in the water availability analyses required for CRWAS. A great deal is known about the patterns of flows in the historical record and, through paleo-reconstructions, about the patterns of flows in prehistory. However, it is not yet clear how projected changes in climate will affect the patterns of streamflow.

Future, climate-impacted streamflows can be obtained by direct simulation, where a calibrated hydrologic model is forced with the output from a GCM. However, there is some evidence that GCMs may not have significant skill predicting year-to-year variability of precipitation outside the tropics (Lau et al., 1996, Wood, et al., 2004, Tebaldi, et al., 2008) and are not reliable for predicting changes in variability (Tebaldi, et al., 2008).

An alternate approach is to represent the change in mean future climate conditions using GCM output while representing year-to-year sequencing and variability based on the observed record, on paleo-reconstructions, or on some combination of both.

Evaluation of Alternative Approaches

The use of year-to-year sequences generated by GCMs is not well suited to meet the objectives of CRWAS for the following reasons:

- We are not aware of any published evidence to indicate that GCM year-to-year sequences are reliable, and there is some evidence that their skill in representing year-to-year variability in precipitation is low (Lau et al., 1996, Wood, et al., 2004, Tebaldi, et al., 2008).

- Direct use of GCM sequences will require the use of a dynamic analysis which will have the disadvantage of introducing a trend in the climate projections.

- The year-to-year sequences will change from projection to projection, which will make it difficult to separate impacts on water availability caused by sequencing from the impacts caused by changes in mean climate conditions.

The use of sequences generated from observed or paleo-reconstructed flows has the following advantages:

- These sequences are relatively familiar to policy makers and stakeholders who use or review the output of model analyses.

- A consistent set of sequences can be used across all analyses, which will allow for a better understanding of the impact of projected mean changes in future climate.

- They can be used as the basis for the equilibrium climate change analysis that has been recommended above and adopted by FRVS.

Recommended Approach

Based on the evaluation of different approaches for representing year-to-year variability as well as other considerations, we recommend that CRWAS use **paleo-hydrology** to develop the year-to-year sequences used to extend the observed streamflows.

Where to find more detailed information:

Additional discussion about this part of the methodology, along with an evaluation of applicable approaches and a recommendation for an approach to the use of paleo information is provided in CRWAS Technical Memorandum *Task 6.1 / 6.2 / 6.3 Literature Review and Method Evaluation / Analyses of Tree-Ring Data / Recommendation for Extending Historical Hydrology*.

7) Water Resources Planning Modeling

From a practical perspective the choice of the water resources planning models to be used to make calculations of water availability and system conditions is limited. Only the CDSS models developed and maintained by the CWCB provide a comprehensive and consistent simulation of water use, water rights and system operations in the Colorado River Basin in Colorado. There are several models of the entire Colorado River System, but the Colorado River Simulation System (CRSS) from the Bureau of Reclamation is the model that is most accepted by stakeholders in the Basin, and is the only model of which we are aware that fully represents the latest changes in the operating rules for the federal facilities on the Colorado River. The CDSS and CRSS models include associated streamflow and water use data sets that are maintained on an ongoing basis. While certain aspects of these models and data sets are the subject of ongoing contention among stakeholders, they are nevertheless the most widely accepted means for evaluating and comparing policies.

Evaluation of Alternative Approaches and Recommended Approach

In CRWAS, the choice of water resources planning models is determined by the requirements of the project, so we recommend that the **CRSS** model developed by the Bureau of Reclamation and the **CDSS** models developed by the Colorado Water Conservation Board be used for CRWAS.

8) Uncertainty

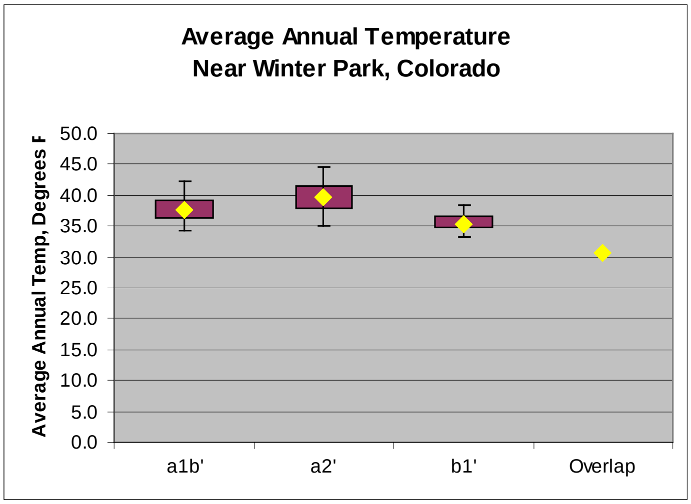
In projecting future climate conditions, uncertainty is introduced in every element of the analysis: developing the emissions scenarios, simulating future climate conditions, and downscaling the GCM outputs. In estimating water availability, additional uncertainty is introduced in hydrology modeling and water resources planning modeling. The uncertainty in climate projections is reflected in the variability of estimates of future climate conditions across the population of available downscaled projections, but the range and distribution of projected conditions does not necessarily fully define the uncertainty of these projections (Tebaldi, et al., 2008). This is because the available projections cannot be thought of as an unbiased sample from a population of values. The models are not independent—many share simulation algorithms and even codes as well as parameters. However, at this time the available projections are the only quantitative indication of the uncertainty inherent in climate projection. This uncertainty can be reflected, though imperfectly, by selecting a range of projections for the analysis of water availability.

Some insight into the uncertainty inherent in hydrology modeling and water resources planning modeling can be gained by comparing results from different models when forced with identical or very similar input data. In 2007, NOAA funded a research effort to reconcile differing estimates of impact of climate change on Colorado River flows (Reconciling Projections of Future Colorado River Streamflow, 2009). This project is intended, among other things, to provide some insight into the source of differences among approaches to hydrology modeling for climate change impact analyses. The results of this work may help understand the uncertainty attributable to hydrology modeling, but they will not be available prior to the completion of Phase I of CRWAS.

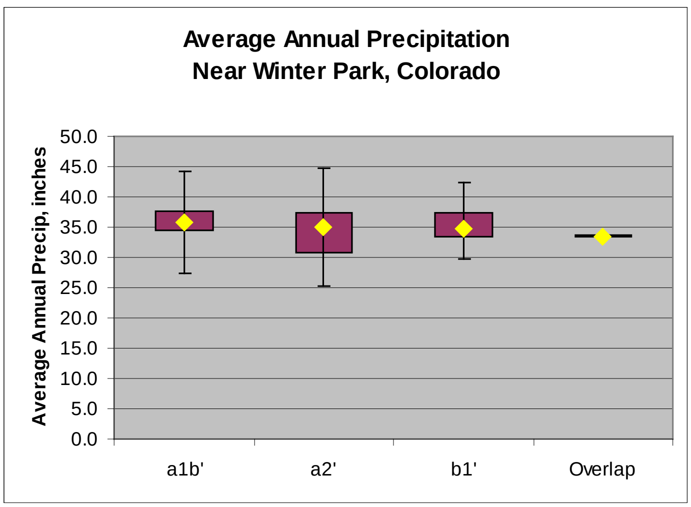
Uncertainty presents the largest challenge for planning based on projections of the impact of climate change. The principal source of uncertainty in CRWAS is the future estimates of temperature and precipitation but additional uncertainty will also be introduced in the hydrology models, water use models and water resources planning models. Feasible and technically defensible computational approaches are available for every required element of a climate change impact analysis, but the uncertainty in the results has been so large as to have led to public confusion about the validity of climate change (Tebaldi, et al., 2008). The extent of uncertainty of climate and hydrology projections for a location relevant to CRWAS is reflected in Figure 4.

The values represented in Figure 4 were calculated by AMEC based on projected climate data taken from the USBR/SCC/LLNL archive. Figure 4.a shows the distribution of projected average temperature over a 10-year period from 2090 through 2099 for a 1/8th degree grid cell near Winter Park Colorado. Winter Park was used in this example because it is located near one of the most hydrologically productive regions of the upper Colorado Basin. The box plots represent the median value as the central diamond, the inter-quartile range (from the 25th percentile to the 75th percentile) as the box, and the 5th and 95th percentiles as the end of the “whiskers”. The projected results for 112 projections are broken down according to the three emission scenarios, A1B, A2 and B1. The value for the overlap period, 1950 through 1999, the period for which both model results and observed results are available, is also shown. The results for temperature indicate that all models show an increase, with even the 5th percentile value for all scenarios being significantly higher than the observed value.

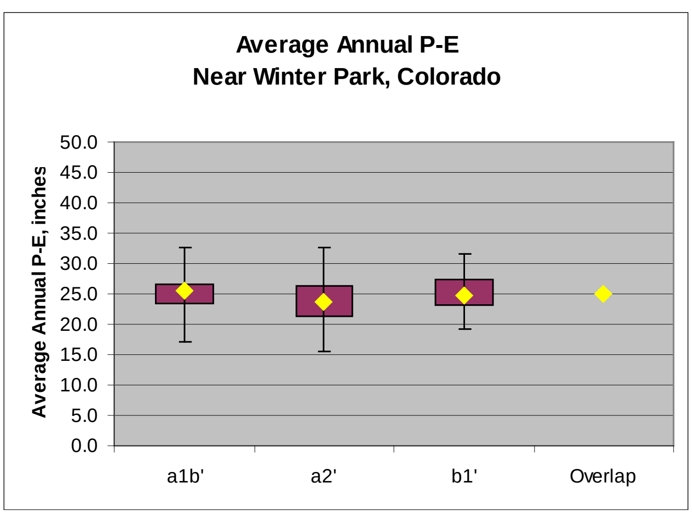
Figure 4.
Projected Climate and Hydrology near Winter Park, Colorado, 2095



a



b



c

Figure 4.b shows results for projections of precipitation. The median value of projected precipitation for all three scenarios is similar to the observed value, and roughly half of the projections are above and half below the observed value.

Figure 4.c shows the net of precipitation less evaporation (P-E) calculated using the Thornthwaite equation. P-E is an index of hydrology that combines the effect of changes in temperature and precipitation. The results show a slight tendency toward drying in the A2 scenario, but in all cases the range of the distribution of values is very large relative to the expected value of impact as represented by the median value. The projected impact of climate change on P-E ranges from a reduction of about 30% to an increase of about 35%, with the results roughly equally distributed above and below the observed value.

These analyses only represent one location in the Colorado River Basin, but this location is in one of the most productive watersheds in the Basin. If these results should be representative of the effect on broader areas of the snow-dominated areas of the Basin, we can see that the uncertainty in model estimates of the impact of climate change on water supply in the Colorado River Basin could be very large.

However, the differences shown in Figure 4 may overstate the differences between models, or even between different runs of the same model, because the presence of low-frequency variability may contribute to the apparent run-to-run differences. The issue can be illustrated by imagining that you calculate average flows for a small number of short periods from the roughly 1000 year record of reconstructed streamflows at Lees Ferry. It is likely that some of the samples will be from wet periods and some from dry periods, so that there will be a large range across the average flows. Because we know we are sampling from the same population, we interpret the differences between the samples as variability.

Climate models represent low-frequency variability (changes that occur over multi-decadal periods), but individual model runs don't always start at the same phase (point in the cycle). Thus, a model run that starts in the wet part of a cycle will, over the length of a 100-year run, show a numerically larger trend toward drying than a model that starts in a dry phase. When projected conditions are sampled from near the end of the run, as is the case for most impact analyses and was the case for the analyses on which Figure 4 is based, the effect of phase differences in low-frequency cycles is to increase the apparent model-to-model or run-to-run differences and, hence, the apparent uncertainty. We are not aware of work that has quantified the impact of this effect.

Evaluation of Alternative Approaches

We have considered three approaches to addressing uncertainty in climate projections:

- Use of average value
- Weighting projections
- Selection of a subset of projections

Use of average value—It is commonly said of weather forecast models that the average of all the models is usually better than any single forecast. This statement is repeated often, but we are not yet aware of published research that supports it. Regardless, use of the average value will give a false sense of certainty to the results.

Weighting projections—Projections may be weighted to reflect their performance (Tebaldi et al., 2004, Tebaldi et al., 2005, Wigley, 2008) or subjectively to reflect their credibility (Vick, 2002). Wigley (2008) found that when all models were included the weighting scheme that was used had little influence on the average pattern of climate conditions. He did not examine the result of weighting on the range or distribution of projected impacts.

Selection of a subset of projections—Wigley (2008) found that selection of a small subset (five out of a total of 20 models) did result in a significant difference in the average pattern of climate conditions. Wigley selected his subset based on model performance, selecting the five “best” models. He did not examine the result of selection on the range or distribution of projected impacts.

Some important caveats should be kept in mind when considering uncertainty in climate projections. First, the available climate projections may not fully represent the actual uncertainty. Additionally, the projections should not be taken to represent the probability of future conditions. The model results cannot be viewed as a representative sample of future conditions in the same way that we use traces extracted from reconstructed pre-historic flows. That is because the models are different, but they are not independent in the statistical sense (Tebaldi et al., 2008). The models are developed by approximately twenty different research groups, and each group has made some independent decisions about how to represent physical processes. However, the models share similar computational limits, similar limits in terms of the state of scientific knowledge and similar limits to observed data, and often share methods and even code—they are developed in the same “modeling tradition” (Tebaldi, et al., 2008).

Recommended Approach

The approach to addressing uncertainty is a policy decision. There is no unequivocal scientific basis for selecting one approach over another.

We recommend that uncertainty be addressed in CRWAS through the **selection of projections**, which is being coordinated with the FRVS. Selection of the method for presenting CRWAS analysis results will be determined in Subtask 9.3.

9) References

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Appendix

A. Literature Review

Principal Publications

Allan, R. P., and B. J. Soden. "Atmospheric Warming and the Amplification of Precipitation Extremes." Science, 12 Sept. 2008: 1481-1484.

Investigating trends in extreme precipitation events resulting from an anthropogenically warmed climate. Used satellite observations and model simulations to examine response of tropical precipitation events to changes in surface temperature and atmospheric moisture. Found that heavy rain events increase during warm periods and decrease during cold periods and that the observed amplification is larger than that predicted by models.

Allen, M. R., P. A. Stott, J. F. B. Mitchell, R. Schnur, and T. L Delworth. "Quantifying the Uncertainty in Forecasts of Anthropogenic Climate Change." Nature, 5 Oct. 2000: 617-620.

Assessed the range of warming rates over the coming 50 years that are consistent with the observed near-surface temperature record as well as with the overall patterns of response predicted by several general circulation models. Determined that the global mean temperatures in the decade from 2036-46 will be 1-1.25 K warmer than in pre-industrial times given a 'business as usual' emission scenario.

AWWA. "Drinking Water Research, Climate Change and Drinking Water." AWWA Research Foundation. 2008. 1-32.

Big picture summaries of the possible impacts on water quantity and quality as a result of climate change as well as possible modes of adaptation. Also contains lists of resources for water utilities and things to consider.

Barnett, T. P., D. W. Pierce. "When will Lake Mead go dry?" Accepted by Journal of Water Resources Research, 23 Jan. 2008. 1-45.

Determined using a water budget analysis that there is a 10% chance storage in Lakes Mead and Powell will be gone by 2013 and a 50% chance it will be gone by 2021 if there are no changes in water allocation for the Colorado River System. These calculations are based on previous research findings that flow in the Colorado River is likely to decline 10-30% over the next 30-50 years. Errors were found in the water budget described in this publication.

Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger. "Human-induced changes in the Hydrology of the Western United States. Science. 22 Feb. 2008. 1080-1083.

Used a high resolution hydrologic model forced by global climate models in a climate change detection and attribution study to determine if the hydrologic shift in this area in the last 50 years is a result of normal oscillations or anthropogenic forcings. Found that human effects modeled from the Parallel Climate Model (PCM) account for 60% of the observed 1950-1999 trend in signal strength.

Bureau of Reclamation. "Appendix U: Climate Technical Work Group Report." Final Environmental Impact Statement: Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead. October 2007.

Part of a program by the Bureau of Reclamation's Lower Colorado Region to investigate climate change in the region and design a more responsive decision support framework. The climate technical working group investigated potential climate change impacts in the Colorado River Basin and how these changes can be related to reservoir operation. They determined what should be involved in shorter term and longer term studies and the directions that future research and development should go in.

Christensen, N. S., A. W. Wood, N. Voisin, D. P. Lettenmaier, and R. N. Palmer. "The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin." Climate Change. 2004: 337-363.

Using simulated hydrologic and water resources scenarios driven by downscaled climate simulations compared to scenarios driven by observed historical climate to determine the potential effects of climate change on the hydrology and water resources of the Colorado River Basin. Three 105 year Parallel Climate Model scenarios were run based on business-as-usual greenhouse gas emissions and static 1995 greenhouse gas emissions data from these runs were used in the Variable Infiltration Capacity (VIC) model to simulate streamflow sequences. Results showed on average; an increase in temperature of 3.1 ºF, a decrease in precipitation of 6% and a decrease in runoff of 18% by 2040-2069.

Christensen, N. and D.P. Lettenmaier. "A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River Basin." Hydrology and Earth System Sciences Discussion. 9 July 2007: 1417-1434.

Downscaled and bias corrected output from 11 General Circulation Models (GCMs) was used to drive macroscale hydrology and water resources planning models. Downscaled climate scenarios were used as forcings to the Variable Infiltration Capacity (VIC) macroscale hydrology model, which in turn forced the Colorado River Reservoir Model (CRMM). Ensembles of downscaled precipitation and temperature, and derived streamflows and reservoir system performance were assessed through comparison with current climate simulations for the 1950-1999 historical period. Results showed on average an increase in temperature of 4.5 ºF, a decrease in precipitation of 1% and a decrease in runoff of 6% by 2040-2069.

Cunderlik, J. M. "Hydrologic Model Selection for the CFCAS Project: Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions." University of Western Ontario, Project Report I. October 2003: 1-38(40).

Comparison of existing hydrologic models that are potentially suitable for the Canadian Foundation for Climatic and Atmospheric Sciences (CFCAS) funded project, "Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions." Contains a summary of 18 models they considered.

Dessai, S., and M. Hulme. "Does Climate Adaptation Policy Need Probabilities?" Climate Policy, 21 July 2004: 1-22.

Analyzing the questions: (1) why we do need probabilities of climate change? (2) What are the problems in estimating probabilities? (3) How are researchers estimating probabilities? Conclude that it is still up for debate whether probabilities are useful for climate adaptation policy as probability assessment is always subjective, conditional and provisional.

Dessai, S., X. Lu, and M. Hulme. "Limited Sensitivity Analysis of Regional Climate Change Probabilities for the 21st Century. Journal of Geophysical. Research. 8 Oct. 2005: 1-17.

Examining the sensitivity of regional climate change probabilities to various uncertainties using a simple probabilistic energy balance model and General Circulation Models (GDMs). Regional skill scores were devised for each GCM, season and climate variable in 22 regions based on model performance and model convergence. Sensitivity analysis showed that for temperature change probabilities emission scenarios uncertainty tends to dominate the 95th percentile whereas climate sensitivity uncertainty plays a more important role at the 5th percentile.

Diffenbaugh, N. S., J. S. Pal, R. J. Trapp, and F. Giorgi. "Fine-scale Processes Regulate the Response of Extreme Events to Global Climate Change." PNAS. 1 Nov. 2005: 15774-15778.

Investigating the response of extreme temperature and precipitation events to fine-scale processes. Found that important climate-system modifiers operate at fine scales and can substantially influence local changes. For example, albedo effects influence response of hot and cold events and extreme precipitation is enhanced on the lee side of rain shadows and over coastal areas dominated by convective precipitation. Projections of substantial, spatially heterogeneous increases in both hot and wet events over the contiguous United States in the next hundred years, suggest a need for the consideration of fine-scale processes for the accurate assessment of local and regional scale vulnerability to climate change.

Enfield, D. B., A. M. Mestas-Nunez, and P. J. Trimble. "The Atlantic Multidecadal Oscillation and its Relation to Rainfall and River Flows in the Continental U.S. Geophysical Research Letters. 15 May 2001: 2077-2080.

The Atlantic Multidecadal oscillation (AMO) accounts for a 0.4 ºC temperature range in North Atlantic Sea surface temperatures oscillating on a 65-80 year cycle. During AMO warming most of the US experiences below normal rainfall (1930's and 1950's droughts). Variability is influenced mostly by summer rainfall but there is also a connection between AMO and the winter rainfall patterns associated with ENSO.

Front Range Vulnerability Study (FRVS), Project description.

Study to enable entities that obtain their water supplies from the upper Colorado, South Platte, Arkansas, Cache la Poudre, St. Vrain, Boulder Creek, Big Thompson and other similar river basins to examine the potential effects climate change may have on those supplies. Main objective is to assess changes in the timing and volume of hydrologic runoff that might be expected from selected climate change scenarios for the years 2040 and 2070. Two hydrologic models will be used, the Water Evaluation and Planning (WEAP) Model, and the Sacramento Soil Moisture Model with the Snow-17 Model. Future temperature and precipitation scenarios that will be used to generate streamflow predictions will be based on 16 global climate models (GCMs) driven by three future greenhouse gas emissions scenarios.

Fu, G., S. P. Charles, and F. H. S. Chiew. "A Two-parameter Climate Elasticity of Streamflow Index to Assess Climate Change Effects on Annual Streamflow." Water Resources Research. 24 Nov. 2007: 1-12.

Creates a two parameter streamflow climate elasticity index which is a function of both precipitation and temperature in order to account for the fact that the relationship between streamflow and precipitation varies depending on temperature. Used the Spokane River Basin and the Yellow River Basin as case studies, although magnitudes vary by basin they found that streamflow is positively correlated to precipitation and negatively correlated to temperature. Climate elasticity of streamflow is not fixed for a given basin and varies with temperature and precipitation.

Fu, Q., C. M. Johanson, S. G. Warren, and D. J. Seidel. "Contribution of Stratospheric Cooling to Satellite-inferred Tropospheric Temperature Trends." Nature. 6 May 2004: 55-58.

Temperatures observed globally by the mid tropospheric channel of the satellite-borne Microwave Sounding Unit (MSU channel 2) and the inferred temperatures in the lower troposphere show only small warming trends, significantly less than observed surface temperature trends. It is determined that the MSU channel 2 trends are weak because the instrument partly records stratospheric temperatures whose large cooling trend offsets the tropospheric warming trend. With the cooling trend removed reconstructed tropospheric temperatures are consistent with observed surface temperature trend.

Ghosh, S., and P. P. Mujumdar. "Nonparametric Methods for Modeling GCM and Scenario Uncertainty in Drought Assessment." Water Resources Research. 6 July 2007: 1-19.

A methodology to assess the uncertainties of the hydrologic impacts of GCM simulations on a smaller spatial scale for the purpose of drought impact assessment. Principal component analysis, fuzzy clustering, and statistical regression are used for downscaling the mean sea level pressure (MSLP) output from the GCMs to precipitation at a smaller spatial scale. Samples of a drought indicator are generated with downscaled precipitation and non parametric methods are used to determine the probability distribution function of the drought indicator.

Giorgi, F., and L. O. Mearns. "Probability of Regional Climate Change Calculated using the Reliability Ensemble Averaging (REA) Method." Geophysical Research Letters. 24 June 2004: 31-1 to 31-4.

Using the Reliability Ensemble Averaging, REA, method to calculate the probability of regional climate change exceeding given thresholds based on ensembles of different model simulations. Using 2 IPCC emission scenarios with 9 different atmosphere-ocean General Circulation Models the probabilities of surface air temperature and precipitation change are calculated for 10 regions of sub-continental scale spanning a range of latitudes and climate settings.

Gleick, P. H., and E. L Chalecki. "The Impacts of Climatic Changes for Water Resources of the Colorado and Sacramento-San Joaquin River Basins." Journal of the American Water Resources Association. December 1999: 1429-1441.

Summaries of the differences and similarities in results among regional research on water related impacts of climatic change for the Colorado River Basin and the Sacramento River Basin. Significant and consistent impacts across a wide range of potential climate changes for these basins include the shift in timing of runoff that results from changes in snowfall and snowmelt dynamics. Considerable uncertainty still remains concerning the likely impacts of climatic change on precipitation intensity and patterns.

Hamlet, A. F., and D. P. Lettenmaier. "Production of Temporally Consistent Gridded Precipitation and Temperature for the Continental United States." Journal of Hydrometeorology. 14 Dec. 2004: 330-336.

Method for adjusting gridded daily precipitation and temperature maxima and minima over the continental United States based on U.S. Cooperative Observer station data, in order to produce gridded meteorological datasets that can be used, in conjunction with hydrologic modeling, for long-term trend analysis of simulated hydrologic variables. Data were gridded to 1/8º latitude longitude resolution using the Symap algorithm and four nearest neighbors, then daily data was aggregate to a monthly time step and the Butterworth filter was used for temporal smoothing. Used the Variable Infiltration Capacity (VIC) model to analyze simulated streamflows and SWE, based on the gridded data.

Hayhoe, K., D. Cayan, C. B. Field, P. C. Frumhoff, E. P. Maurer, N. L. Miller, S. C. Moser, S. H. Schneider, K. N. Cahill, E. E. Cleland, L. Dale, R. Drapek, R. M Hanemann, L. S. Kalkstein, J. Lenihan, C. K. Lunch, R. P. Neilson, S. C. Sheridan, and J. H. Verville. "Emissions Pathways, Climate Change and Impacts on California." Proceedings National Acad Sci USA. 101 (34) 24 Aug. 2004: 12422-12427.

Comparing the impacts of the highest and lowest Intergovernmental Panel on Climate Change emissions pathways for climate change on California. Find that annual temperature increases double from the lower to the higher scenarios before 2100, and 75% of scenarios show greater increases in summer temperatures than winter. Also notes the different expected impacts on forest area and snow pack, and heat related mortality. .

Hayhoe, K., C. P. Wake, T. G. Huntington, L. Luo, M. D. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T. J. Troy, and D. Wolfe. "Past and Future Changes in Climate and Hydrological Indicators in the US Northeast." Springer 1 Aug. 2006: 1-27.

Using key climate, hydrological, and biophysical indicators across the US Northeast to assess the influence of global climate change at the regional scale. Considers the extent to which nine atmosphere-ocean general circulation models (AOGCMs) are able to reproduce observed changes in these indicators and the projected future trends in primary climate characteristics and indicators of change. Confident in the direction and potential range of regional trends in temperature and precipitation related indicators, however still some uncertainty still exists in fine scale spatial and temporal distributions.

Hayhoe, K., C. Wake, B. Anderson, X. Liang, E. Maurer, J. Zhu, J. Bradbury, A. DeGaetano, A. M. Stoner, and D. Wuebbles. "Regional Climate Change Projections for the Northeast USA." Springer. 2 July 2007: 1-12.

Using statistical and dynamical methods to downscale outputs from coarse-scale atmosphere-ocean general circulation models in order to improve simulation of spatial and temporal variability in temperature and precipitation across the Northeast US and to develop high resolution projections for future climate change based on IPCC SRES emissions scenarios. Predict increases in temperature that are larger at higher latitudes and inland as well as potential for changing precipitation patterns especially along the coast.

Hereford, R., R. H. Webb, and S. Graham. "Precipitation History of the Colorado Plateau Region." USGS Fact Sheet. 7-17-2002: 1-4.

There are three precipitation regimes in the recorded history of this area: 1905-1941, 1942-1977 and 1978-1998, the first and last were wet and the middle was dry. Precipitation is related to short term climate variations, El Nino and La Nina, and long term variations, PDO. Recent precipitation trends and PDO suggest that the next 2-3 decades could be dry and resemble the drought of 1942-1977.

Hoerling, M., and A. Kumar. "The Perfect Ocean for Drought." Science. 31 Jan. 2003: 691-694.

Attributes the 1998-2002 drought across the US, southern Europe and Southwest Asia to cold sea surface temperatures (SSTs) in the eastern tropical Pacific and warm SSTs in the western tropical Pacific and Indian oceans. Suggests an increased risk for increased mid-latitude drying, if the tropical mean SSTs or their inter-annual variability increase the ocean's west-east contrast over the equatorial Pacific.

Hoerling, M. and J. Eischeid. "Past Peak Water in the Southwest." Southwest Hydrology. .Jan. / Feb. 2007: 18, 19, 35.

A regression based on downscaled monthly PDSI was used to calculate future streamflows at Lees Ferry based on 42 climate simulations spanning 1895 to 2060, using multiple runs of 18 different coupled ocean-atmosphere-land models. The models were forced with known changes in atmospheric constituents and solar variations from 1895 -2000 and a business-as-usual assumption for future carbon emission after 2000. Found an increase in drought severity corresponding to surface warming. Results show on average an increase in temperature of 5 ºF, no decrease in precipitation but a decrease in runoff of 45% by 2035-2060.

Hurd, B. H., J. Coonrod. "Climate Change and its Implications for New Mexico's Water Resources and Economic Opportunities." July 2007: 1-44(47).

Using a hydro-economic model of the Rio Grande watershed to integrate plausible changes in climate, hydrologic responses and water demands within a framework that optimizes water use allocations for the greatest economic benefit. The study uses three climate change scenarios across two future time periods, these scenarios are the basis for the WATBAL hydrologic model used to model runoff and for changes in water demand input to the hydro-economic model. Found that ecosystems are at the greatest risk followed by agricultural users as more water gets diverted for industrial and urban users. Total annual economic losses are estimated at about $300 million and are expected to be much higher under severe climate change scenarios.

IPCC (2007), Summary for policy makers in: climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report for the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY USA

Report describing progress in the understanding of the human and natural drivers of climate change, observed climate change, climate processes and attribution, and estimates of projected future climate change. Scientific progress since the Third Assessment Report is based upon large amounts of new and more comprehensive data, more sophisticated analysis of data, improvements in understanding of processes and their simulation in models and more extensive exploration of uncertainty ranges.

Jones, R. N. "Analyzing the Risk of Climate Change using an Irrigation Demand Model." Climate Research. 20 March 2000: 89-100.

Calculating the risk of threshold exceedance by quantifying user defined thresholds as a function of key climatic variables and creating projections for these variables that take account of a comprehensive range of quantifiable uncertainties. Using an irrigation demand model for perennial pasture, Monte Carlo sampling is employed to scale 100 years of weather-generated data to calculate the probability of the annual farm cap being exceeded across ranges of temperature and rainfall change projected at 10 yr intervals from 2000 to 2100.

Karl, T. R., and W. E. Riebsame. "The Impact of Decadal Fluctuations in Mean Precipitation and Temperature on Runoff: a Sensitivity Study over the United States." Climatic Change. 29 March 1989: 424-447.

Investigating the impacts of decadal fluctuations in average temperature and precipitation during the modern climate record (the last 60 years), on runoff for 82 streams across the United States. Found that the effects of temperature fluctuations on streamflow are minimal but, the impacts of relatively small fluctuations in precipitation (about 10%) are often amplified by a factor of 2 or more. This result shows that climate change predictions must focus on reliable prediction for precipitation change.

Keedy, J. A., J. D. Salas, D. G. Fontane, and D. H. Meritt. "Understanding the Behavior of the Colorado River System under uncertain Streamflows." Colorado Water; Newsletter of the Water Center of Colorado State University. December 2006.

Comparing historical streamflows, tree-ring reconstructed streamflows and synthetically generated streamflows for the Colorado River Basin. Historical flows were obtained from naturalized streamflows at 29 stations throughout the basin, tree ring indices were provided by NOAA, and synthetic streamflows were generated using a stochastic model implemented in the statistical software package SAMS. The RIVERWARE Colorado River Simulation System (CRSS) was used to analyze each streamflow scenario based on Lake Powell release volumes and Lake Mead storage volumes. Found a much wider range of possible occurrences with the paleo-reconstructed and stochastically generated scenarios than with the historical flow scenario.

Knowles, N., M. D. Dettinger, and D. R. Cayan. "Trends in Snowfall versus Rainfall in the Western United States." Journal of Climate. 15 Sept. 2006: 4545-4559.

Looking at the regional trend toward smaller ratios of winter-total snowfall water equivalent (SFE) to winter-total precipitation (P) from 1949-2004. Attribute this trend to warming throughout the west noted by wet-day temperature increases from 0-3ºC over the study period. Reduced SFE/P ratio trends were most pronounced in March throughout the region and in January near the West Coast.

Koutsoyiannis, D., A. Efstratiadis, and K. P. Georgakakos. "Uncertainty Assessment of Future Hydroclimatic Predictions: a Comparison of Probabilistic Scenario-based Approaches." Journal of Hydrometeorology. June 2007: 261-281.

A stochastic framework for future climatic uncertainty based on the following lines: 1) climate is not constant but rather varying in time and expressed by the long-term (e.g., 30 yr) time average of a natural process, defined on a fine scale; 2) the evolution of climate is represented as a stochastic process; 3) the distributional parameters of a process are estimated from an available sample by statistical methods; 4) the climatic uncertainty is the result of at least two factors, the climatic variability and the uncertainty of parameter estimation; 5) a climatic process exhibits a scaling behavior, also known as long-range dependence or the Hurst phenomenon; and 6) because of this dependence, the uncertainty limits of the future are affected by the available observations of the past. This framework is applied to a catchment in Greece and the uncertainty limits are superimposed on deterministic projections up to 2050 obtained for several scenarios and climatic models combined with a hydrologic model. Found a significant increase in temperature in future years but no significant trends in rainfall or runoff outside the uncertainty limits.

Maurer, E.P. "Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios." Climatic Change. 82:309-325 (2007).

Uses a hydrologic model of portions of the Sierra Nevada mountains forced by projections from 11 GCMs and two emission scenarios to investigate whether projected hydrologic changes and the differences between the two emissions scenarios have a high statistical confidence. The analysis shows that there is high confidence in increasing winter streamflow and decreasing late spring and summer flow and confidence in less snow at the end of winter and earlier arrival of the annual flow volume. Some impacts from the two emissions scenarios differ with a high degree of statistical confidence.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen. "A long term Hydrologically-based Data Set of Land Surface Fluxes and States for the Conterminous United States." Journal of Climate. 15 Nov. 2002: 3237-3251.

A model-derived dataset of land surface states and fluxes for the conterminous United States and portions of Canada Mexico spanning from 1950-2000 at a three hour time step with a spatial resolution of 1/8 degree. This data set is distinct from reanalysis products because precipitation is a gridded product derived directly from observations, and both the land surface water and energy budgets balance at every time step. Simulated runoff is shown to match observation quite well over large river basins and it is argued that other terms in the surface water balance (e.g., soil moisture and evapotranspiration) are well represented at least for the purposes of diagnostic studies.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt. "Pacific and Atlantic Ocean Influences on Multidecadal Drought Frequency in the United States." Proceedings of the National Academy of Sciences of the United States of America. 23 March 2004: 4136-4141.

Suggests two possible future drought scenarios should the current positive Atlantic Multidecadal Oscillation (AMO) continue. One resembles the continental scale patterns of the 1930s (positive PDO) and the other resembles the 1950s (negative PDO). Found that more than half of the spatial and temporal variance in multi-decadal drought frequency over the conterminous United States is attributable to the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal oscillation (AMO), an additional 22% of the variance is related to a complex spatial pattern of positive and negative trends in drought occurrence possibly related to increasing Northern Hemisphere temperatures or some other unidirectional climate trend.

McCabe, G. J., and D. M. Wolock. "Warming May Create Substantial Water Supply Shortages in the Colorado River Basin." Geophysical Research Letters. 27 Nov. 2007: 1-5.

Analyzing the potential effects of specific levels of atmospheric warming on water-year streamflow in the Colorado River basin using a water balance model within the context of long term tree ring streamflow reconstructions. Used 0.86 ºC and 2.0 ºC temperature increase scenarios run through the water balance model using 20th century climate data and the driest century of the reconstructed streamflow record. Results indicate that if future warming occurs and is not accompanied by increased precipitation then the basin is likely to experience periods of water supply shortages more severe than those inferred from the tree-ring reconstructed data. They project a decrease in runoff of 17% if this is the case.

McCabe, G. J., and S. L. Markstrom. "A Monthly Water-balance Model Driven by a Graphical User Interface." USGS and US Department of the Interior, Open-File Report 2007-1088. Page 1-6(10).

The Thornthwaite model analyzes the allocation of water among various components of the hydrologic system using a monthly accounting procedure. Inputs to the model are total monthly precipitation, average monthly temperature, the latitude of the location, runoff factor, direct runoff factor, soil-moisture storage capacity, rain temperature threshold, snow temperature threshold, and maximum snow-melt rate of the snow storage. Calculations are described for snow accumulation, direct runoff, snow melt, evapotranspiration, soil moisture and, runoff generation.

Milly, P. C. D., K. A. Dunne, and A. V Vecchia. "Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate." Nature. 17 Nov. 2005: 347-350.

Using an ensemble of 12 climate models to simulate observed regional patterns of twentieth-century multi-decadal changes in streamflow and to predict future streamflows. Predict 10-40% increases in runoff in eastern equatorial Africa, the La Plata Basin and high latitude North America and Eurasia and 10-30% decrease in runoff in southern Africa, southern Europe, the Middle East and mid-latitude western North America by 2050.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. "Stationarity is Dead: Whither Water Management?" Science. 1 Feb. 2008: 573-574.

In general water management systems have been designed around the principal of stationarity. Although planners have long had tools to adjust for known human disturbances, like changes in infrastructure or channel modifications, the magnitude and ubiquity of hydroclimate change now undermines the entire assumption of stationarity. New techniques must be developed which incorporate climate change scenarios into the assessment of risk.

Mote, P. W. "Climate-driven Variability and Trends in Mountain Snow pack in Western North America." 1 Dec. 2006: 6209-6220.

Using multiple linear regression to examine the sensitivity of April 1st SWE to temperature and precipitation for nearly 1000 sites in the western US. Determined that long term variations in SWE are reasonably well explained by seasonal climate of nearby locations however, variations in ENSO and PDO only account for about half of the variability in the Pacific Northwest. At most sites there has been winter and spring warming resulting in decreasing SWE trends in the second half of the twentieth century which are persistent even after known patterns of climate variability are accounted for. In some places like the Southern Sierra Nevada Mountains large increases in precipitation have offset this trend.

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. "Declining Mountain Snow pack in Western North America." Bulletin of the American Meteorological Society. January 2005: 39-49.

Looking for trends in snow data using long term monthly manual observations and more recent (dating back about 20 yr) daily telemetered snow observations and trying to determine to what extent trends can be attributed to site or climatic changes. Analysis of snow data is corroborated using a hydrological model (Variable Infiltration Capacity Model, VIC) driven with observed daily temperature and precipitation data. Analysis indicates that climate factors account for most of the snow pack variability and that the mountains in the Cascades and northern California have the greatest sensitivity to temperature and regional warming. This result also implies serious snow pack implications with respect to climate change scenarios.

Mujumdar, P. P., and S. Ghosh. "Modeling GCM and Scenario Uncertainty using a Possibilistic Approach: Application to the Mahanadi River, India." Water Resources Research. 11 June 2008: 1-15.

Applied a downscaling method based on fuzzy clustering and Relevance Vector Machine (RVM) to project monsoon streamflow from three GCMs with two green house emission scenarios. Possibilities are assigned to all the GCMs with scenarios based on their performance in modeling the streamflow of the recent past (1991-2005), when there are signals of climate forcing. The possibilities associated with different GCMs and scenarios are used as weights in computing the possibilistic mean of the CDFs projected for three standard time slices 2020s, 2050s and 2080s. Found that the value of streamflow at which the CDF reaches 1 decreases with time, which shows a reduction in probability of occurrence of extreme high flow events in the future.

Nash, L. L., and P. H. Gleick. "Sensitivity of Streamflow in the Colorado Basin to Climatic Changes." Journal of Hydrology. 12 Oct. 1990: 221-241.

Using a conceptual hydrologic model, developed and operated by the National Weather Service, to study the sensitivity of surface runoff in several sub-basins of the Colorado River to these changes. Noted changes in runoff as a result of changing temperature and precipitation and determined that runoff in the basin is somewhat more sensitive to changes in precipitation than to changes in temperature. Additionally they noted earlier peak runoff, increased fall and winter flows and decreased spring and summer flows attributed to and increase of the ratio of rain to snow and to a higher snowline.

New, M., and M. Hulme. "Representing Uncertainty in Climate Change Scenarios: A Monte Carlo Approach." Integrated Assessment. 28 April 2000: 203-213.

A hierarchical impact model is developed that addresses uncertainty about future greenhouse gas emissions, climate sensitivity, and limitations and unpredictability in general circulation models. The hierarchical model is used in Bayesian Monte-Carlo simulations to define *posteriori* probability distributions for changes in seasonal-mean temperature and precipitation over the United Kingdom that are conditional on *prior* distributions for the model parameters.

New Mexico First. "Climate Change and Water, Is New Mexico Vulnerable? A Final Report for Public Forums on Water Policy." September 2007: 1-28.

Summary of five regional citizen forums held throughout New Mexico in September 2007 where participants learned about basic climate change science and developed recommendations for managing the states water resources. The forums produced over 200 recommendations that fall into eight basic themes; conservation and reclamation, education, managed growth, water resource planning and research, government collaboration and funding, watershed and forest management, agriculture and private industry. All of the recommendations are listed in this report.

Ozekin, K. "Climate Change and Water Initiatives." APWA Symposium on Climate Change, Tempe, Arizona. April 9-10, 2008: 1-28.

Summary of government initiatives and university programs. Also summarizes research projects being done by AWWA RF

Prairie, J.R., B. Rajagopalan, U. Lall, and T. Fulp. "A Stochastic Nonparametric Technique for Space-time Disaggregating of Streamflows." Water Resources Research. 22 March 2007: 1-10.

Stochastic disaggregation models are used to simulate streamflows at multiple sites preserving their temporal and spatial dependencies. A K-nearest-neighbor approach is used to resample monthly flows conditioned on an annual value in a temporal disaggregation or multiple upstream locations conditioned on a downstream location for a spatial disaggregation. The utility of this methodology is demonstrated by applying it for space-time disaggregation of streamflows in the Upper Colorado River basin. The method appropriately captures the distributional and spatial dependency properties at all the locations.

Ray, A. J., J. J. Barsugli, and K. B. Averyt. "Climate Change in Colorado; A Synthesis to Support Water Resources Management and Adaptation." A report by the Western Water Assessment for the Colorado Water Conservation Board. 2008: 1-58.

Summary of Colorado-specific findings from peer-reviewed regional studies focusing on observed trends, modeling, and projections of temperature, precipitation, snowmelt and runoff. All recent hydrologic projections show a decline in runoff for most of Colorado's River Basins by the mid by the mid-21st century as a result of decreased total water supply combined with temperature increases and related changes in evaporation and soil moisture

Climate models project Colorado will warm by 2.5ºF by 2025 and 4ºF by 2050 with more warming expected in summers than winters. Winter projections show fewer extreme cold months, more extreme warm months and more strings of consecutive warm winters. Individual models projections do not agree whether annual mean precipitation will increase or decrease by 2050. However runoff is projected to shift earlier in the spring and to decline by 6-20% by the mid-to-late 21st century. The range of individual model projections within a single study can include both increasing and decreasing runoff due to the range of climate model output used to drive the hydrology models, reflecting both model-simulated climate variability and differences in model formulation.

Reichler, T., and J. Kim. "How Well Do Coupled Models Simulate Today's Climate?" Bulletin of the American Meteorological Society. September 2007: 1-37.

Testing the realism of coupled climate models used for the 1995, 2001, and 2007 reports of the Intergovernmental panel on Climate Change (IPCC) by validating against observations of present climate. Notes that the coupled models have been steadily improving over time and although the current models are not perfect, they show significant improvements over earlier generations of models. However, these results only relate to climate predictions to the degree that a greater ability to simulate current mean climate translates to increased skill in predicting future climate. Additionally this study did not consider higher moments of climate such as temporal variability.

Reilly, J., P. H. Stone, C. E. Forest, M. D. Webster, H. D. Jacoby, and R. G. Prinn. "Uncertainty and Climate Change Assessments." Science Magazine. 20 July 2001: 430-433.

Highlights the shortcomings of the uncertainty analysis in the Intergovernmental Panel on Climate Change's Third Assessment Report (TAR). For example they give a range for future temperature increases but no probability of exceedance. Also there are no probabilities assigned to the different climate change scenarios. Further procedural documentation is needed along with much clearer and more explicit uncertainty analysis.

Revelle, R. R. and P. E. Waggoner. "Effects of a Carbon Dioxide-induced Climatic Change on Water Supplies in the Western United States." Changing Climate. 1983: 419-432.

Predict that warmer air temperatures and a slight decrease in precipitation would severely reduce both the quantity and quality of water resources in the western United States. Used the Langbein et al. (1949) empirical relationship between mean annual precipitation, temperature and runoff, to show that a 2 ºC rise in average temperature and a 10% reduction in precipitation over the next 100 years would result in an 18% decrease in runoff. Furthermore to counteract the effects of a 2 ºC temperature increase a 28% increase in precipitation would be required.

Rind, D., R. Goldberg, J. Hansen, C. Rosenzweig, and R. Ruedy. "Potential Evapotranspiration and the likelihood of Future Drought." Journal of Geophysical Research. 20 June 1990: 9983-10004.

Considering the likelihood of future drought based on two drought indices, the Palmer drought severity index (PDSI) and a supply-demand drought index (SDDI), calculated from the Goddard Institute for Space Studies general circulation model (GISS GCM) transient and doubled CO_2 climate changes. Both indices show increasing drought for the next century and suggest that severe drought will occur about 50% of the time by 2050s. Results can be explained by the fact that evapotranspiration will increase most where the temperatures are highest, in the mid to low latitudes, while precipitation will increase most where the air is coolest and easiest to saturate by additional moisture, at higher latitudes.

Samuel, J. M., M. Sivapalan, and I. Struthers. "Diagnostic Analysis of Water Balance Variability: A Comparative Modeling Study of Catchments in Perth, Newcastle, and Darwin, Australia." Water Resources Research. 4 June 2008: 1-13.

A comparative study to explore the interactions between climate variability and landscape factors that control water balance variability. Signatures of streamflow, soil moisture variability and systematic sensitivity analysis with respect to parameters representing various landscape characteristics are taken into account using a conceptual model. Found that the biggest contributor to the differences between catchments is the distribution of soil depth and soil's drainage characteristics. Climate is the second largest contributor, as exemplified by the climatic dryness index and the intra-annual variability of rainfall, evaporation and rainfall intensity patterns.

Sankarasubramanian, A., R. M. Vogel, and J. F. Limbrunner. "Climate Elasticity of Streamflow in the United States." Water Resources Research. June 2001: 1771-1781.

Using a Monte Carlo experiment to compare a nonparametric estimator of precipitation elasticity of streamflow, ε_p , with various watershed model-based approaches. Found that the nonparametric estimator has low bias and is as robust or more than the alternate model-based approaches. Gives a contour map of ε_p for the United States which shows that precipitation elasticity tends to be low for basins with significant snow accumulation and for basins whose moisture and energy inputs are seasonally in phase with one another.

Saunders, S., and M. Maxwell. "Less Snow, Less Water: Climate Disruption in the West." A Clear the Air Report. September 2005: 1-36.

The most important climate disruptions in the west are impacts on snow pack and water supply. Predict that climate change will bring: more heat, less snow pack, earlier snowmelt and runoff, more evaporation and dryness, more flood-control releases, less groundwater, more legal restrictions and more droughts. Analyzed historical temperature and snow pack records for upper basins in the west and increases in temperature, spring warming and reduced snow packs are already occurring.

Seager, R. "Abrupt Climate Change and Early Warning Systems: the case of Imminent Drying of the U. S. Southwest. Comments before: The Climate Research Committee of the National Research Council." Washington, DC. National Academies of Sciences. 1 Dec. 2007: 1-17.

Discussing the causes of historic droughts and the climate mechanisms relevant for future droughts. Also covers the improvements in observations that need to be made, current information gaps that need to be filled and future studies that are needed in order to develop an early warning system.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H. Huang, N. Harnik, A. Leetmaa, N. Lau, C. Li, J. Velez, and N. Naik. "Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America." Science. 25 May 2007: 1181-1184.

Examining future subtropical drying by analyzing the time history of precipitation in 19 climate models participating the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Emissions scenario A1B was used in which carbon dioxide emissions increase until about 2050 and decrease modestly thereafter. Results showed a decrease in runoff of 8-25% by 2050.

Spott, M. "A Theory of Possibility Distributions." Fuzzy Set Systems. 1999: 135-155.

A general mathematical framework for possibilistic reasoning based on three axioms and the Principle of Minimal Specificity. It is shown in particular that the max-min composition is an unambiguous mechanism for the aggregation of possibility distributions that are defined on *different* and *freely chosen* subspaces of a given Cartesian product of universes. A special type of possibility distribution (*Possibilistic Relation of Dependence or PROD)* is postulated as a description of dependencies between variables.

State of New Mexico, Agency Technical Working Group (2005), Potential effects of climate change on New Mexico, December 30, 2005.

Summarizes the general range of climate predictions for the 21st century and goes through possible impacts on; water resources, infrastructure, agriculture, natural systems, outdoor recreation and related tourism, environmental quality and health, environmental justice, and native peoples. Most of the main concerns are related to changes in precipitation patterns and severe drought made worse by increased temperatures.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. "Changes toward Earlier Streamflow Timing across Western North America." Journal of Climate. 15 April 2005: 1136-1155.

Investigates changes in the timing of snowmelt derived streamflow from 1948 to 2002 for 302 western North America gauges. Center of mass for flow, spring pulse onset dates and seasonal fraction flows were assessed using trend analysis and PCA. Found widespread trends toward earlier onset of springtime snowmelt and streamflow by 1-4 weeks. These trends are immediately connected to increasing winter and spring temperatures which are partly controlled by Pacific Decadal Oscillation (PDO) but also follow a springtime warming tend which spans the PDO phases.

Tebaldi, C., L. O. Mearns, D. Nychka and R. L. Smith. "Regional Probabilities of Precipitation Change: A Bayesian Analysis of Multimodel Simulations." Geophysical Research Letters. 28 Dec. 2004: 1-5.

A Bayesian approach to determining probability distribution functions (PDFs) of temperature change at regional scales, from the output of a multi-model ensemble, run under the same scenario of future anthropogenic emissions. The Bayesian model is applied to a set of transient experiments under two SRES scenarios and precipitation PDFs are derived for 22 regions of sub-continental scale. Within the Bayesian framework two criteria of model evaluation, bias and convergence are formalized. The results show large inter-regional variability.

Tebaldi, C., R. L. Smith, D. Nychka, and L. O. Mearns. "Quantifying Uncertainty in Projections of Regional Climate Change: a Bayesian approach to the analysis of multi-modal ensembles." Journal of Climate. 15 May 2005: 1524-1540.

A Bayesian statistical model that combines information from a multi-model ensemble of atmosphere-ocean general circulation models (AOGCMs) and observations to determine the probability distributions of future temperature change. This study found large spatial variability among temperature distributions supporting the idea that for some regions the signal of climate change is stronger and less uncertain than for others.

Udall, B., G. Bates (2007), Climatic and hydrologic trends in the western U.S.: a review of recent peer-reviewed research, Intermountain West Climate Summary.

Investigates six studies with respect to findings on; SWE, streamflow amounts and timing, temperature and precipitation trends, and proportion of rain verses snow. Most of the studies confirm: widespread warming in the west, statistically significant declining snow packs and advances in spring runoff timing in the Pacific Northwest and California. Findings for the intermountain west show few statistically significant trends other than a warming trend which is greater than other parts of the West.

USGS (2004), Climate fluctuations, drought and flow in the Colorado River Basin, USGS Fact Sheet, 2004-3062 version 2.

Summary of precipitation, drought and streamflow in the Colorado River Basin. Attributes inter-annual variability to ENSO and longer term fluctuations to PDO. Classifies precipitation for the region as bi-seasonal, having both winter and summer extremes and moisture sources.

Wilby, R. L., and I. Harris. "A Framework for Assessing Uncertainties in Climate Change Impacts: Low-flow Scenarios for the River Thames, UK." Water Resources Research. 28 Feb. 2006: 1-10.

A probabilistic framework for combining information from an ensemble of four general circulation models (GCMs), two greenhouse gas emission scenarios, two statistical downscaling techniques, two hydrological model structures and two sets of hydrological model parameters. After weighting the GCMs, model structures and model parameters a Monte Carlo approach was used to explore components of uncertainty affecting projections for the River Thames by the 2080s. Found that the resulting cumulative distribution functions of low flows were most sensitive to uncertainty in the climate change scenarios and downscaling of different GCMs.

Winstanley, D., W. M. Wendland. "Climate Change and Associated Changes to the Water Budget." Illinois State Water Survey. Chapter 6.

Summary of the large scale implications of climate change and historical climate in Illinois. Uncertainties in water availability for Illinois based on climate change scenarios ranges from annual precipitation increases or decreases of 10 in.

Wood, A. W., L.R. Leung, V. Sridhar, and D.P. Lettenmaier. 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs, Climatic Change. 2004: 189-216.

Evaluating six approaches for downscaling climate model outputs for use in hydrologic simulation with particular emphasis on each method's ability to produce precipitation and other variables used to drive a macroscale hydrology model applied at much higher spatial resolution than the climate model. Comparisons were made on the basis of a twenty year retrospective (1975-1995) climate simulation produced by the NCAR-DOE Parallel Climate Model, and the implications of the comparison for a future (2040-2060) PCM climate scenario were also explored. Found the bias-correction and spatial disaggregation method to be successful in reproducing the main features of the observed hydrometeorology. This was also the only method able to produce hydrologically plausible results for the future climate scenario.

Wurbs, R. A., R. S. Muttiah, and F. Felden. "Incorporation of Climate Change in Water Availability Modeling." Journal of Hydrologic Engineering. Sept./Oct. 2005: 375-385.

Using the Texas water-availability modeling (WAM) system to investigate the best way to incorporate climate change scenarios into the model and the potential effects of climate-change on hydrologic and institutional water availability. Naturalized streamflow data show hidden but significant multiple-year cycles but no long-term trends during the twentieth century. When the model was adjusted to reflect anomalous climate during 2040-2060, generally results showed decreased mean streamflows and greater variability, however there is significant variability in projected water availability by region within the basin and water user.

Yates, D., S. Gangopadhyay, B. Rajagopalan, and K. Strzepek. "A Technique for Generating Regional Climate Scenarios using a Nearest-neighbor Algorithm." Water Resources Research. 1 July 2003: 7-1 to 7-15.

The K-nearest neighbor (K-nn) resampling scheme which is used to produce alternative regional daily weather data sets conditioned upon hypothetical climate scenarios, e.g., warmer-drier springs, warmer-wetter winters, that can be used in integrated assessment and water resource management models for addressing the potential impacts of climate change and climate variability. Uses the Mahalanobis distance as the metric for neighbor selection as opposed to Euclidian distance to avoid having to standardize data. When applied to station data in the Rocky Mountains and the north central United states the model is shown to produce synthetic series that largely preserve important cross correlations and autocorrelations.

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B. Glossary

Baseline/reference--The baseline (or reference) is the state against which change is measured. It might be a 'current baseline', in which case it represents observable, present-day conditions.

Bias-correction--Simulations or forecasts of climate from dynamical models do not always correspond to reality (i.e., observations), thus, resulting in 'bias'. There are statistical methods to correct this and often referred to as 'bias correction' tools.

Climate Model--A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parameterizations are involved. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and inter-annual climate predictions.

Climate Projection--A projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/ radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty.

Downscaling -Downscaling is a method that derives local- to regional-scale (10 to 100 km) information from larger-scale models or data analyses. Two main methods are distinguished: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the downscaled product depends on the quality of the driving model.

Equilibrium and transient climate --An equilibrium climate experiment is an experiment in which future climate is represented as if it is fully adjusted to a change in radiative forcing. Such experiments provide information on the difference between the initial and final states of the model, but not on the time-dependent response. If the forcing is allowed to evolve gradually according to a prescribed emission scenario, the time-dependent response of a climate model may be analyzed. Such an experiment is called a transient climate experiment.

General(ized) Circulation Models (GCMs)--see climate model.

Global Climate Models (GCMs)--see climate model.

Greenhouse gas--Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. This property causes the greenhouse effect. Water vapor (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary greenhouse gases in the Earth's atmosphere. As well as CO2, N2O, and CH4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

IPCC--The Intergovernmental Panel on Climate Change (IPCC) established by World Meteorological Organization (WMO) and United Nations Environmental Program (UNEP) provides an assessment of the state of knowledge on climate change based on peer-reviewed and published scientific/technical literature in regular time intervals.

Paleo-climate, Paleo-hydrology—Climate or hydrology for periods prior to the development of measuring instruments, including historic and geologic time, for which only proxy climate records are available. Streamflow volumes prior to the gage record can be estimated using a statistical model, which captures the relationship between tree growth and the gage record during their period of overlap. Then, this model is applied to the tree-ring data for the period prior to the gage record.

SRES scenarios--SRES scenarios are emission scenarios developed by Nakićenović and Swart (2000) and used, among others, as a basis for climate projections shown. The following terms are relevant for a better understanding of the structure and use of the set of SRES scenarios:

Scenario family--Scenarios that have a similar demographic, societal, economic and technical change storyline. Four scenario families comprise the SRES scenario set: A1, A2, B1 and B2.

Illustrative Scenario--A scenario that is illustrative for each of the six scenario groups reflected in the Summary for Policymakers of Nakićenović and Swart (2000). They include four revised scenario markers for the scenario groups A1B, A2, B1, B2, and two additional scenarios for the A1FI and A1T groups. All scenario groups are equally sound.

Storyline: A narrative description of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces and the dynamics of their evolution.