Technical Memorandum | FINAL

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Subject: **CRWAS Phase II Climate, Task 1, Literature Review**
Date: **September 8, 2015**

This Technical Memorandum is developed as part of Task 1 of the Colorado River Water Availability Study, Phase II, Updating Climate Impacted Hydrology (CRWAS-II or Study).

The objective of Task 1 is to develop an approach for creating future climate scenarios and model forcings. A principal deliverable for Task 1 is this technical memorandum describing a literature review covering the CMIP5 ensemble and recent work in methods for developing climate scenarios (subsets) and model forcing data, and recommending one or more potential methods for developing climate scenarios. In addition, this technical memorandum is to describe efforts by the Bureau of Reclamation (Reclamation) to analyze and rationalize an observed "wettening" difference in the CMIP5 projections. This analysis is ongoing, so the description in this memorandum is simply a status report.

Introduction

The Colorado Water Conservation Board (CWCB) provides policy direction, data, analysis and analytical tools in support of water resources management in Colorado. As part of this mission, and implementing direction from the Colorado General Assembly, CWCB conducted Phase I of the Colorado River Water Availability Study, beginning in 2008 (CRWAS-I, CWCB, 2012). This study was completed with the issuance of a Final Report in March, 2012. Among other things, CRWAS-I provided data to support evaluation of water resources planning in the face of projected climate change. This work extends the CRWAS-I climate change assessment to incorporate newly released climate and hydrology projections and to develop new and refined climate scenarios.

Planning requires estimates of future conditions. There is now broad recognition that the future climate will be different than the past and that this will affect hydrology and water supplies: 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, 2007a, Ray, *et al.,* 2008, Lukas, *et al.,* 2014). However, all projections of future climate are uncertain, and this uncertainty is manifested in part by the disagreement among those projections. The future will not be identical to any single projection, though some projections will prove to be closer to the true future than others, but at this time there is no scientific basis for determining which projections will prove to be the best representations of future conditions. Thus, planners must evaluate a range of future conditions that they assume contains the true future conditions. In practice, this requires evaluating an *ensemble* of climate projections created by climate models (known as general circulation models, or GCMs). Science cannot now even say with certainty that all of the currently available GCM outputs encompass the range of future conditions, and there is currently no research to quantify the probability that the true future conditions may fall outside any given range of estimated conditions (Stainforth, *et al.,* 2007). As discussed below, the ideal approach to conducting a modern assessment of the impact of projected climate change is to evaluate impacts for every available projection, and thus construct an empirical distribution of those impacts. In many cases, including CRWAS, this is not practical (Salath´e, *et al.*, 2007), yet great care should be taken when inferring the distribution of future conditions from a small number of analyses.

One objective of CRWAS-II work is to develop a tractable number of climate scenarios that take information from the full available ensemble of projections and represent a substantial portion of the range of projected conditions with respect to impacts on water resources systems. Creating such scenarios could be accomplished by selecting a small subset of model runs, but though this was once a common approach, it presented difficulties in CRWAS-I and has no support in the current literature. An alternative approach has been identified, where sub-ensembles of available model runs are identified in “pools” and are aggregated by averaging change fields. That approach is summarized in this memorandum; the details of the selected approach and how it is implemented are described in CRWAS Phase II Technical Memorandum Task 1 – *Approach for constructing climate scenarios*.

Climate and Hydrology Projections

Projections of future climate conditions are created by climate models (called general circulation models or sometimes global climate models and abbreviated as GCMs), which simulate the trajectory of climate over a century or more, based on a number of assumptions, including assumptions about the amount of greenhouse gases in the future atmosphere.

The first, and still primary motivation for developing climate models is diagnosis—learning more about how the climate works, and how increasing concentrations of greenhouse gases will affect climate. GCM outputs were initially archived and analyzed by the modeling groups that developed and maintained the models. Exchange of model output was by request and agreement, transfers were ad hoc in nature and evaluations were generally not formalized (Meehl, *et al.*, 2007). GCM outputs have been used by researchers for impact assessment (as opposed to diagnosis) for almost as long as the models themselves have existed, but the use of GCM outputs to inform adaptation planning in practice is a much more recent development.

Climate scientists saw the advantage of a widespread evaluation of model outputs, both to improve understanding of climate dynamics, but also to improve the models themselves. The Coupled Model Intercomparison Project (CMIP) was conceived in 1994 and initiated in 1995 (Meehl *et al.*, 2000) to provide a mechanism for such an evaluation. Motivation for the CMIP came from less formal intercomparisons that were useful in identifying model problems (Gates, *et al.*, 1996). The CMIP began with two experiments, CMIP1, which focused on simulations of historical climate, and CMIP2 which compared model simulations of future conditions forced by a one-percent-per-year increase in CO_2 concentrations. The CMIP2 experiment was supplemented by transient runs of models forced by time-evolving emissions from the IS92a emissions scenarios

(CMIP2+), and evaluations of these runs, called projections, was included in the IPCC Second Assessment Report (AR2, Houghton, *et al.*, 1995). However, the motivation of this work was not to support adaptation, and data and network infrastructure were not available to disseminate projections from the CMIP2+ project.

Prior to the Third Assessment Report (AR3, issued in 2001, Houghton, *et al.*, 2001), a set of scenarios of future greenhouse gas emissions were developed; these became known as the SRES scenarios, after the name of the report in which they were transmitted, the Special Report on Emission Scenarios (Nakicenovic *et al.*, 2000). Climate modeling groups were asked to perform model experiments with the SRES scenarios in support of the AR3, but logistical limitations and the short amount of time available to inform the AR3, limited the number of model runs that were completed (Meehl, *et al.*, 2007). These runs, encompassing just a few models and runs, were the first that became available to the climate impact community from a central repository, the IPCC Data Distribution Centre in Hamburg, Germany.

The outcomes from CMIP1, CMIP2 and CMIP2+, and the limitations of the AR3 archive, due to its development on short notice, motivated the climate modeling community to develop a more formalized evaluation and archiving process, and to do this with more lead time before the Fourth Assessment Report (AR4) (Meehl, *et al.*, 2007). Thus, in 2003 the World Climate Research Programme (WCRP)/Climate Variability and Predictability (CLIVAR) Working Group on Coupled Models (WGCM) began the work that led to the development of the third CMIP experiment, CMIP3. A central part of this effort was to archive and organize model outputs so that they could be accessed by the climate science community. The Program for Climate Model Diagnosis and Intercomparison (PCMDI) took on the task of archiving and providing access to model outputs (Meehl, *et al.*, 2007). To highlight the challenges of such an endeavor, the volumes of model output data were so large that then-conventional on-line methods for data transfer were not practical, so many model groups shipped hard disks containing model outputs to PCMDI. (These practical limitations had also limited the effectiveness of earlier archiving and evaluation efforts.)

The CMIP3 archive of 21st-Century projections contains 112 projections from 16 GCMs forced with three SRES emissions pathways. Each projection consists of a 20th-century simulation running through 1999 and a 21st-century projection running from 2000 through 2099.

The IPCC assessment reports contain information on impacts, and the CMIP3 archive informed those assessments and all of the other model-based assessments in the in the AR4. But even by that time, use of the CMIP3 archive for impacts assessments outside the IPCC process was apparently not widely contemplated in the climate science community. In that era, as the CMIP3 archive increased the availability of model outputs, climate scientists expressed a range of opinions about whether or how it was appropriate to use climate model output for decision making (Schmidt, *et al.*, 2008). However, by the time the AR4 was published in 2007, climate impact researchers had already made the CMIP3 archive available, downscaled to a 1/8° grid and bias corrected, for the contiguous United States (CMIP3 BCSD archive, Maurer, *et al.*, 2007; Brekke, *et al.*, 2013). The availability of this archive facilitated the use of GCM output for quantitative evaluation of the impact of future climate on water resources and other systems. CRWAS-I, the Joint Front Range Climate Change Vulnerability Study

(JFRCCVS, Woodbury, *et al.*, 2012), and a number of other impact assessments, relied on this archive.

In 2011, the Bureau of Reclamation, Santa Clara College and Lawrence Livermore National Laboratory used the CMIP3 BCSD archive to force a hydrology model (the Variable Infiltration Capacity, VIC, model) covering the western U.S. These hydrology projections were archived and made accessible at the same site that housed the climate projections (Gangopadhyay, *et al.*, 2011; Brekke, *et al.*, 2014).

During 2012-2013, WCRP released global climate projections from CMIP Phase 5 (CMIP5). The CMIP5 archive was intended to support the IPCC Fifth Assessment Report (AR5). Recognizing the evolution of the objectives of the CMIP to include support of IPCC assessment reports, the phase number of the CMIP experiment was advanced to correspond to the assessment report number, therefore there is no 4th phase to the CMIP. CMIP5 projections were based on a new set of assumptions about future greenhouse gas emissions, referred to as Representative Concentration Pathways (RCPs, van Vuuren, *et al.*, 2011).

The CMIP5 consists of a number of model experiments involving more than 20 modeling groups and more than 50 models (Taylor, *et al.*, 2012). Among those CMIP5 experiments are long-term simulations, extending to the end of the 21st century, forced with the RCPs. The long-term experiments provide projections of the forced response of climate to greenhouse gas concentrations and are used in CRWAS-II.

Each long-term simulation consists of a historical run (sometimes referred to as a “twentieth century” simulation), which usually runs from the mid-nineteenth century to near the present, and a simulation of future climate that runs from the end of the historical run through the end of this century (sometimes referred to as a 21st-century run), which are forced by one of four RCPs. The CMIP5 long-term projection ensemble consists of 234 runs of 37 climate models.

Although the CMIP5 projections are more recent, and presumably GCMs and data have been improved since the CMIP3 archive was developed, there is not yet any scientific evidence to indicate that one or the other archive is to be preferred (Rupp, *et al.*, 2013).

The Bureau of Reclamation, again in cooperation with Santa Clara College and the Lawrence Livermore National Laboratory (LLNL), downscaled and bias-corrected 97 runs from the CMIP5 archive and developed hydrology projections based on these projections for the contiguous United States (Brekke, *et al.* 2014).

Uncertainty in Climate Projections

Because climate models represent an unprecedented future condition, they cannot be verified, or even validated; at best they can be evaluated to try to “…demonstrate the degree of correspondence between the model and the material world it seeks to represent and to delineate the limits of that correspondence…” (Oreskes *et al.*, 1994). In addition, the principal anthropogenic forcing of the GCMs, the pathway of future emissions (emissions scenarios or representative concentration pathways) are models themselves, are also unprecedented, are dependent on many assumptions, and are similarly impossible to verify or validate. Accordingly, projections of future climate must be viewed as highly uncertain—any individual projection will not come true, and the information contained in the available set of projections may not accurately characterize future conditions (Schmidt, *et al.*, 2008; Stainforth, *et al.*, 2007).

Uncertainty in climate projections can be broken down into three categories (Meehl *et al.* 2007): 1) natural variability of climate, 2) uncertainties in the responses to climate forcing factors (these include atmospheric concentrations of greenhouse gases and sulfate aerosols), and 3) uncertainties about future emissions of greenhouse gases and aerosols (a direct influence on their atmospheric concentrations), and about other factors that could affect climate.

Model disagreement is especially great in the study domain of the CRWAS, which encompasses the State of Colorado and the Upper Colorado River Basin (Harding, *et al.*, 2012). In the CRWAS study domain, almost all model runs show a continuous increase in temperature over this century, but models don't even agree on whether future precipitation will increase or decrease. In the full ensemble of CMIP3 model runs, approximately half of those runs project an increase in average annual precipitation along the Continental Divide at the headwaters of the Colorado River (Harding, *et al.*, 2012; Bureau of Reclamation, 2012).

The model simulation of natural variability, referred to also as unforced or internal variability, is an important component of model uncertainty (Deser *et al.*, 2012; Harding, *et al.*, 2012). A single GCM (i.e., holding factor 2 constant) when forced by a single assumption regarding greenhouse gas emissions (i.e., holding factor 3 constant) will generate different results at any given point in time and space due to the stochastic nature of simulated natural variability (factor 1).

One way to conceptualize unforced variability is to imagine a perfect model (factor 2), forced by a perfect emission scenario (factor 3), but initialized randomly (factor 1). This model would generate one possible future each time it was run, but each run would have a different year-to-year sequence of conditions. When these runs are smoothed with a multi-decadal running average (e.g. over a 30-year period) large deviations from mean conditions will be evident in the runs, but these will be simulated at different times in the future (i.e. they are “out of phase”). We can't know which of these simulations might be closest to the true future sequence. Looking backwards, at paleo reconstructions in the Colorado River Basin, the variability of 30-year mean natural flows are similar to simulations from many GCMs; the 30-year mean flow can deviate from the long-term average by ten percent or more.

This disagreement is large enough to be important for planning; in the Upper Colorado River Basin, unforced variability in streamflow is larger than the change in the ensemble mean at any point during this century (Harding *et al.*, 2012). Thus, any planning study that uses one or a few model runs to estimate conditions at a particular point in time is almost certain to attribute at least a portion of the effect of unforced variability to forced climate change. The resulting biases can be either positive or negative.

Motivation for Scenario Development

Careful planning must admit to this considerable uncertainty, and incorporate a sufficient range of future possibilities in the evaluations of system reliability that are central to a climate impact assessment. There is considerable disagreement about how to address projection uncertainty in impact assessments.

Broadly speaking, researchers have suggested three different approaches to addressing the uncertainty in climate projections. Some research suggests that the range of impact estimates based on a large ensemble of projections places a minimum bound on future conditions. (Stainforth *et al.*, 2007; Wilby, 2010). More information may be available in the ensemble of projections; it may be possible to develop probabilistic estimates of impacts (Tebaldi and Knutti, 2007) and a skillful ensemble mean (Gleckler *et al.*, 2008, Pierce, *et al.,* 2009). All of these methods depend on evaluation of a large ensemble (Salath´e, *et al.*, 2007), the largest being all available projections, what some have termed “ensemble of opportunity” (EOO).

Assessment of impacts on a specific sector or sectors requires an “end-to-end” evaluation of the selected ensemble. An end-to-end evaluation is one that starts with projections of climate and results in sector-specific impacts, and is the evaluation method used in CRWAS. Such an evaluation often involves uncoupled, distributed hydrology modeling, followed by simulation of sector-specific system performance. In CRWAS, these steps involve distributed hydrology modeling using the VIC model, development of irrigation water requirements using StateCU, and simulation of the yields of water rights and systems, and of instream conditions, using StateMod. In addition, planning involves the iterative evaluation of multiple, often many, combinations of responses (e.g. combinations of infrastructure and operational rules) across a range of future conditions, which increases the required computational effort geometrically.

These computational costs usually preclude an end-to-end evaluation of every ensemble member (Salath´e, *et al.*, 2007). This is the motivation for the development of climate scenarios. In some cases, impact assessments have been conducted using one or a few individual climate projections, selected based on model attributes; though this was once conventional, it is no longer advisable (Harding *et al.*, 2012). Nevertheless, practical considerations require that the end-to-end evaluations be relatively few, in which case a reliable, or at least a scientifically rationalized method of developing climate scenarios should be used. CRWAS-I used two methods of selecting a subset of projections for use as scenarios, but both methods have limitations (CWCB, 2012). The method adopted for CRWAS-II is intended to overcome, or at least mitigate those limitations.

Overview of Climate Scenarios

“A climate scenario is a plausible representation of future climate that has been constructed for explicit use in investigating the potential impacts of anthropogenic climate change” (Mearns, *et al.*, 2001). Climate scenarios provide information about future climate conditions (e.g. precipitation and temperature), which are used to inform adaptation planning. Climate scenarios should be distinguished from “emission scenarios,” a term used for about a decade to refer to representations of how future emissions of greenhouse gas emissions may unfold (Nakicenovic, *et al.*, 2000*).* Emission scenarios are used to force GCM runs that simulate future climate, and it is the outputs from those runs that are used in CRWAS to construct climate scenarios for adaptation planning. Thus, in the discussions below, when the word *scenario* is used it refers to a climate scenario, except when specifically addressing an emissions scenario in order to characterize one or more runs of a GCM. (The term “emission scenario” is being used less frequently because in current climate modeling the SRES emission scenarios have been replaced by “representative concentration pathways” (van Vuuren, *et al.*, 2011))

A climate scenario can consist of the output of a single GCM (though this is not advisable) and can even be estimates of future conditions that are based on subjective judgment. With the current state of climate modeling technology and data availability, and current planning practices, climate scenarios often consist of the output of several GCMs, and in some cases of hundreds of GCMs. The key questions that will be addressed here is how to construct scenarios that incorporate enough information from the available GCM runs to, at a minimum, represent reliably the uncertainty of future conditions as expressed by the current EOO.

The overarching proposition, often implicit, in the selection or definition of a climate scenarios is that it will encompass the true future condition. In fact, even the full range of all available GCM projections may not contain the true future condition (Stainforth, *et al.*, 2007). Because of this uncertainty, a principal objective of a set of climate scenarios must be a sufficient representation of the range of projected conditions, but this sufficiency cannot itself be evaluated with respect to the true future condition (Stainforth, et al, 2007; Oreskes, *et al.*, 1994). Given the scientific limitations inherent in climate projections, even the best set of scenarios, including the best approach of a comprehensive evaluation of all projections, should be interpreted with caution and humility.

Characteristics of Climate Scenarios

Table 1 summarizes some important characteristics of climate scenarios. These are discussed in the following sections.

Table 1. Important characteristic of climate scenarios

Source of change signals	Synthetic or GCM
Source of variability	Historical/paleo or GCM
Dynamic perspective	Quasi-steady-state or transient
Sampling	Culled/selected or pooled

Source of change signals

The very first assessments of the impact of climate change on water resources were done with synthetic scenarios (Stockton and Boggess, 1979). A synthetic scenario is built on subjective values of change, usually for only precipitation and temperature (Feenstra, *et al.*, 1998). The prescribed values of change are usually informed by climate modeling. The changes are usually applied to the historical weather record by the use of change factors for precipitation and change offsets for temperature. In the earliest studies these changes were applied on an annual basis (i.e. all months of the year were adjusted by the same amount) but later uses of the approach used seasonal patterns of change (Feenstra, *et al.*, 1998).

The principal advantage of synthetic scenarios is their ease of development and ease of explanation. They also can be used either for impact assessment or sensitivity analyses. Their principal disadvantage is that they are not tied together in space and time in a consistent and physically based way.

The use of synthetic scenarios was originally a matter of necessity, because GCM output was not generally available, and when they were, the insufficiency of then-current data transmission, data processing and modeling tools made it difficult to use them in modeling studies. As GCM output became available researchers began to use those data to study the impacts of projected changes (see, e.g., Lettenmaier, *et al.*, 1999; Christensen, *et al.*, 2004, Christensen and Lettenmaier, 2007). With the availability of the CMIP3 archive, practical impact studies began to quantify change from GCM output, and this approach is almost universal today. CRWAS-I relied on GCM output from CMIP3 archive, as did the JFRCCVS, Woodbury, et al,, 2012), which also evaluated synthetic scenarios.

Source of variability

Four principal types of variability influence the relationship between atmospheric processes and hydrologic processes, Annual variability, seasonal variability, short-term variability and spatial variability. All types of variability change as the earth's average temperature changes (Milly, *et al.*, 2008), but the effect of anthropogenic warming on variability is not yet well understood and probably not well simulated by GCMs. Water resources systems supporting water supply are sensitive to annual and seasonal variability. GCMs are suspect with respect to simulate the inter-annual sequencing of precipitation and the seasonal distribution of precipitation. But, because of the high degree of certainty that temperatures will increase, studies consistently show that in snowmelt-driven systems such as Colorado runoff will increase in early winter and spring (Nash and Gleick, 1991; Nash and Gleick, 1993; Barnet, *et al.*, 2005; CWCB, 2012, Harding, *et al.*, 2012; Reclamation, 2012)

There are at least two perspectives on how to simulate future variability of climate in impact studies. One is to take climate variability from the historical record, recognizing that this will certainly not be the true future condition (Wood, *et al.*, 2004, Mearns, *et al.,* 2001), while the alternative is to accept the variability represented by the GCMs (which is also understood not to be true, but which might represent changes in the mode of variability). 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, Schmidt, *et al.*, 2008) and are not reliable for predicting changes in variability (Schmidt, *et al.*, 2008), so less faith is placed in simulations by GCMs of changes in variability than in changes in mean conditions (Mearns, *et al.*, 2001). A middle ground is to take the annual and short-term (weather) variability from the historical record and to take the change in seasonal variability from the GCMs. Annual variability can also be informed from proxy paleo records. Seasonal variability of streamflow will be simulated in a hydrology model as the net effect of precipitation and temperature changes.

In current analyses, spatial variability can come solely from the GCM, or the spatial pattern of change can be mapped onto the historical spatial pattern of conditions. In early synthetic change analyses, a single change field might be used across a large region, or even at a continental scale (Stockton & Boggess, 1979; Nash & Gleick, 1991), in which case spatial variability originated completely from observations. Typical downscaling methods now map spatially variable change fields derived from GCM output onto observed spatial variability. Hydrology modeling may further modulate spatial variability due to non-linear responses and the interaction of topography with the GCM-informed change fields. This is a secondary process, but it very important factor in formulating climate scenarios for the assessment of impacts on water resources systems.

CRWAS-I used the delta-change approach, which mapped GCM-derived changes in monthly mean precipitation and temperature onto annual and daily variability of those variables from the historical record. The delta-change approach maps the spatial variability of the GCM-derived changes in precipitation and temperature onto the observed spatial variability.

Dynamic perspective

The representation of future climate conditions can be either transient or quasi-steady state. Transient analyses represent the time-evolution of climate, and hence hydrologic conditions. This is the approach used by the Bureau of Reclamation in the Colorado River Basin Water Supply and Demand Study (Bureau of Reclamation, 2012). Quasi-steady-state analyses represent variability at a period of time where a future climate condition is assumed to be fully developed and at equilibrium (i.e. the long-term mean and variability are stationary) (Salath´e, *et al.*, 2007). This is the approach used in CRWAS-I and JFRCCVS. Quasi-steady-state analyses are based on an observed record onto which statistics of future climate variability are mapped, using either a delta approach (Hamlet and Lettenmaier, 1999; Miller, *et al.*, 2003) or a quantile-mapping approach (Salath´e, *et al.*, 2007). Transient analyses use GCM output directly, downscaled as necessary to force hydrologic and impact models, and thus obtain variability from the GCM (Payne, *et al.*, 2004; though methods of mapping transient change in mean and seasonal patterns onto historical records can be conceived.) Quasi-steady-state analyses take a baseline variability from the observed record (or perhaps a record reconstructed by proxy methods, e.g. tree rings) and map changes in variability from GCMs. Issues related to the source of variability have been discussed above.

Sampling

For the purposes of CRWAS, climate scenarios are used to reduce the number of model runs required for an impact assessment, while still representing a substantial portion of the range of conditions across the EOO. Reducing the EOO to a small number of climate scenarios can be done either by selecting individual projections or by pooling and aggregating model runs.

Climate projections cannot be verified, but model performance can be evaluated by comparison to historical conditions. The rationale for climate model selection is that models that perform better in simulating historical conditions can be inferred to perform better in making projections. Culling is the inverse of selection, where poorly performing models are excluded from an analysis. Comparisons of historical simulations with historical conditions indicate that models differ substantially in their ability to reproduce important climate metrics in a particular region (Pierce *et al.*, 2009) and their performance will vary from one point to another at any particular point in time or at any location at various points in time (Deser, *et al.*, 2012). Culling, model selection and/or weighting have been explored (e.g., Tebaldi *et al.*, 2004; Pierce *et al.*, 2009; Santer *et al.*, 2009; Brekke *et al.*, 2008) but with little effect on the projection range for variables such as precipitation. Though it is probably worthwhile to eliminate models with serious methodological or data flaws, this is not something that an impact assessor, who is not also a climate modeler, can be expected to do.

Selection of models with incomplete information can introduce bias into the impact assessment. This was evident in the original selection of projections for CRWAS-I, which is reviewed in detail in CRWAS Phase I Technical Memorandum – *Projection Selection (refinement to CRWAS Phase I Tasks 7.1, 7.2 and 7.5).* See also, CWCB (2012).

Pooling models is another approach to reducing the dimensionality of an impact assessment. The most aggressive pooling approach is to use a multi-model ensemble mean of the largest possible ensemble, i.e. the ensemble mean of the EOO. At least in the western U.S., the multi-model ensemble mean performs better than any individual model, and this is true for simulation of both the mean and the seasonal pattern of conditions (Pierce, *et al.*, 2009). A shortcoming of using multi-model ensemble mean of the EOO is that doing so conceals model disagreement. Though the ensemble mean may be the best predictor, it is not the truth, and it is important to understand something about the range of future possibilities.

An approach that exploits the skill of the ensemble mean but also provides information about the range of possibilities is to pool subsets of models across the distribution of the EOO and take the mean of those pools. Reclamation used this approach for an analysis in Oklahoma (Brekke, *et al.*, 2010). Reclamation used the same temperature/precipitation (T/P) anomaly space for selection of pools as CRWAS-I did for selection of individual projections. However, Reclamation identified five regions of the T/P anomaly space and pooled projections across those regions. Four regions represented quadrants centered on the median values of temperature and precipitation changes, and one represented a rectangle centered on the medians and covering the interquartile range of both temperature and precipitation. The multiple model runs in each region were aggregated using a quantile mapping approach. This method was also used by the Oklahoma Water Resources Board to construct climate scenarios .for a statewide assessment of the impacts of future climate (AMEC, 2011)

One concern with pooling is that the range of future conditions with respect to changes in the seasonal pattern of precipitation in any given pool will be suppressed and represented by a single, mean pattern. If the projected changes in the seasonal pattern of precipitation are not correlated with the variables used to define pools then little variety in that seasonal pattern will be evaluated. However, climate models have difficulty simulating seasonal pattern (when compared to historical conditions, Pierce, *et al.*, 2009), so model-to-model differences in simulating changes in seasonal variability may be artificial. If this proves to be the case, model pooling would not reduce the variability of seasonal patterns, but this remains an open question at this time.

It is probably inappropriate to use a pooling approach with a direct, transient analysis, because since the "phasing" of inter-annual variability in model simulations is random, pooled model outputs would contain reduced inter-annual variability, which in turn would introduce substantial bias into analyses of impacts on water resources and natural systems where the sequencing of wet and dry years is second only to mean conditions in importance.

Recommended Approach for CRWAS-II Scenario Development

The approach identified for developing scenarios for CRWAS-II is summarized here. Additional detail about the CRWAS-II approach is provided in CRWAS Phase II Technical Memorandum Task 1 – *Approach for constructing climate scenarios*.

The approach to development of climate scenarios described here uses a priori assumptions about the relationship between proxy variables and important system-performance metrics. The proxy variables used to develop the scenarios used in CRWAS-II, runoff and crop growing season consumptive irrigation requirement (CIR), were selected because they are the primary determinants of the water balance on a water resources system in the study domain. Currently, we are not aware of literature that has examined the reliability of proxy scenario development, and even if such analyses were available they would probably not be generally indicative of performance with respect to all systems. Accordingly, it cannot be known, *a priori*, that climate scenarios developed using proxy variables will reliably characterize the uncertainty in climate model results with respect to impacts on systems in the CRWAS domain. Thus, among other frustrations, climate impact assessments must accept uncertainty about uncertainty itself.

Objectives for development of climate scenarios for CRWAS-II are:

1. Incorporate projections from the CMIP5 archive;
2. Reduce or eliminate the problems arising from the use of the T/P anomaly space in CRWAS-I;
3. Reduce or eliminate the problems arising from selecting individual projections in CRWAS-I.
4. Provide a sufficient representation of the range of projected *system impacts* across the combined CMIP5 and CMIP3 archive;
5. Maintain comparability with CRWAS-I results; and
6. Continue to represent future conditions relative to the historical natural flow records;

Objective 1 will be met if all projections from the CMIP3 and CMIP5 archives are combined into an ensemble from which scenarios are developed for CRWAS-II. Objective 5 will be met if a set of scenarios are developed using the CRWAS-II methodology and the CMIP3 archive.

Objectives 2, 3 and 4 suggest the use of a pooling approach, but with pools defined by variables other than temperature and precipitation and selected to cover a broad range of future conditions. Recognizing the difficulties encountered in the CRWAS-I scenario selection work, a new approach was developed for CRWAS-II. The first step in developing a new approach was to clarify the objective of scenario development. In CRWAS-I the objective was to represent the range of projected future runoff or streamflow anomalies. But, the true need for planning is an understanding of the future performance of *water resources systems*. The objective for scenario development in CRWAS-II was therefore refined to be full representation of the range of future *water resources system performance*.

Streamflow, only represents the supply side of a water resources system; the success of the system in meeting demand for diversions from streams and reservoirs represents the primary performance metric for systems. On a basin scale, the balance between runoff and beneficial consumptive use is the primary metric of water supply stress.

Accordingly, the approach developed for CRWAS-II uses as proxy variables runoff and consumptive irrigation requirement (CIR, also referred to as irrigation water requirement, IWR). Estimates of future runoff and CIR are available from the hydrology modeling done across the continental United States by the Bureau of Reclamation.

To address Objective 2, the approach adopted for CRWAS-II uses a nearest neighbor approach to identify clusters of projections in a specified region of the runoff/CIR anomaly space, and aggregates the projected seasonal changes for the projections in the cluster.

To address Objective 4, regions for which clusters are developed are identified across the full range of the runoff/CIR anomaly space. Because when averaged over sufficient time and space the water balance of a water resources system is a linear relationship between supply and use, the relationship between *system* impacts and location on the runoff/CIR anomaly space is also expected to be linear, with the result that scenarios should, at a minimum, retain an ordering of severity across the space. This should reduce or eliminate the unexpected relationships between impacts and the predictor variables seen in CRWAS-I. Those unexpected results were due to the complex and non-linear relationship of changes in flow to changes in temperature, precipitation and the seasonal pattern of precipitation.

Objectives 5 and 6 dictate that CRWAS-II use the delta approach applied to the historical climate record and the historical natural flow record, as was done in CRWAS-I.

In summary, the approach selected for CRWAS-II has the following characteristics:

- Develops scenarios from the combined CMIP3/CMIP5 archive and, separately, from the CMIP3 archive;
- Uses a clustering approach in the runoff/CIR anomaly space to identify projections with similar characteristics in terms of projected change in runoff and CIR.
- Specifies the regions in which clusters are developed to cover the full range of severity of combinations of changes in runoff and CIR. For example, the most severe situation is the combination of the largest projected reduction in runoff with the largest projected increase in CIR. The projection closest to the point in the runoff/CIR anomaly space is the most severe projection in the ensemble.

- Aggregates change factors across each cluster by averaging monthly change factors (precipitation) and change offsets (temperature). Aggregated change factors are used to adjust historical weather forcings in the same manner as in CRWAS-II.

"Wettening" of CMIP3 and CMIP5 Projections

Reclamation determined that the bias correction process used in the BCSD (Wood, *et al.*, 2004) offset projected changes in precipitation positively over areas of California and the Upper Colorado River Basin (Brekke, *et al.,* 2013). CMIP5 projections of precipitation show an additional positive offset of projected changes relative to the CMIP3 projections (Barsugli, *et al.,* 2013; Brekke, *et al.,* 2014). These differences do not necessarily represent an artificial bias; no evaluation of the sources of the differences has yet been conducted. The Bureau of Reclamation is currently funding research to examine these effects, but when this analysis will be completed and available is uncertain (Personal communication, Jim Prairie, June, 2015).

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