U.10 Summary of Analysis Options and Future Needs

The information presented in this report highlight several important areas where Reclamation may use past and future climate information in the planning of water resources for the Colorado River basin.

U.10.1 Summary Points

- Climate models project that temperatures will increase globally by 1 to 2ºC in the next 20-60 years. The projections are fairly consistent for the next 20 years with a 1ºC increase, with larger uncertainty in the 40-year projections. The downscaling of global temperature increase to Colorado River Basin (CRB) climate change is less certain; however, it is expected that regional temperatures will also increase. Regional precipitation response is even less certain with comparable evidence suggesting wetter or drier conditions.

- The potential impacts of climate change on the CRB's water resources have been a subject of research for several decades. Initial studies related assumed regional climate change to region runoff response. Recent studies have been refined in several ways, including (a) how assumed climate changes are derived from global climate projections produced by various GCM simulations that reflect a range of global

climate forcing scenarios, (b) how GCM output is bias-corrected and downscaled, and (c) how this output translated into region runoff response. Various analytical design options are represented by the survey of studies referenced in Section W.5 (Table U-3). Although an aggregate message from these studies may be that the *typical runoff response averaged across climate projections* spanning wetter to drier and less-warming to more-warming conditions is generally a mean annual decrease, the *range of runoff response across these same scenarios* is considerably broader and varies from increase to decrease. Note that due to advances in knowledge, technical abilities, and other factors, not all past studies retain the same significance today.

- Studies highlighted in Section W.5 show that system storage is very sensitive to changes in mean inflows as well as sequences of dry and wet years. This highlights the importance of properly investigating changes in both mean and variability in analyses of future system operations.

- Studies considered in Table U-3 feature varied treatment of projected climate *variability*, ranging from earlier studies where variability change was essentially not considered to more recent studies where GCM transient climatic conditions, bias-corrected or not, are used as input to the runoff response analysis. The significance of projected "change in climate variability" and its interaction with "change in climate norms" remains a question for research and affects ability to evaluate projected runoff uncertainty in the CRB.

- Paleoclimatic information suggests that long term average of natural flows from the upper CRB is 13.0 to 14.7 maf, compared to the gage record average of 15.2 maf. The paleoclimatic information may not necessarily represent future climate scenarios, but could be useful in framing assumed variability in future planning hydrologic sequences, with or without the joint consideration of future climate change. In particular, paleoclimate information offers evidence on drought spell potential beyond what has been experienced during the instrumental record, indicating a broader range of drought possibilities for the future.

- Interannual/interdecadal oscillation phenomena such as ENSO, PDO and/or AMO are *very significant* in the context of water resources planning within a 10- to 20-year horizon because such oscillations can persist in a given phase for a decade or longer. Evaluating the state of these oscillations and understanding their forcing mechanisms may be more important than evaluating impacts of projected climate change within a 10- to 20-year horizon.

U.10.2 Recommendations for Planning Studies

U.10.2.1 Shorter Look-Ahead Studies

For studies and management decisions involving shorter look-ahead horizons (e.g., less than 20 years), an appropriate level of analysis might involve a qualitative discussion of climate change and how interannual to decadal variability during the study's look-ahead horizon could be a more significant uncertainty than that associated with near-term

projected climate change. This decision would be based on the limited projected change in climate trends over the near term and general inability to predict phase shifts in the interdecadal oscillations (e.g., AMO, PDO, etc.) that might overwhelm the trend signal during the same period. (See Figure U-29). Alternatively, if the role of shorter-term climate is critical to the study, the proposed qualitative discussion might be accompanied by a quantitative sensitivity analysis, where a range and distribution of 10- to 20-year hydrologic conditions are estimated based on instrumental record and paleoclimate evidence (in terms of mean, variance, and sequence; perhaps conditioned by understood relations with climate oscillations) and subsequently related to operations during the same look-ahead horizon.

U.10.2.2 Longer Look-Ahead Studies completed during the Near-Term

For studies and decisions concerned with greater than 20-year look-aheads and being evaluated on the near-term, it is suggested that a quantitative sensitivity analysis be conducted on operations response to projected climate change. By comparing system performance using projected climate change hydrology to historical hydrology, useful knowledge about system sensitivity should be ascertained. Given Reclamation's current limited ability to easily simulate runoff response to climate change in the CRB, which are highlighted in Section W.9.3, near-term studies should be framed using existing projections of climate and related runoff response. For such studies addressed during the near-term, scoping of sensitivity analysis should begin with a focused consideration of available literature. Rather than try to frame the analysis on all climate change and runoff impacts studies that have been conducted for the CRB (e.g., representing all studies listed in Table U-3), it is recommended that the criteria listed in Section W.6.5 be considered when reviewing available information.

U.10.2.3 Longer Look-Ahead Studies initiated beyond the Near-Term

Recommendations from section W.9.2.1 and Section W.6.5 are still relevant for studies that may be scoped beyond the near-term. However, we recommend that research and development be pursued as described in section W.9.3 to improve Reclamation's ability to consider and incorporate climate change information in future CRB studies. Some of the research and development can be pursued in-house, but much will need the broader assistance of scientists and engineers from the research and consulting communities.

U.10.3 Recommendations for Research and Development

- **Improved Availability and Temporal Resolution of Regional Climate Projection Datasets.** Currently, there is limited access to bias-corrected and downscaled climate projection datasets over the Colorado River basin. For example, there are more than 140 archived IPCC AR4, SRES A2, A1b, and B1 projections archived at LLNL PCMDI, compared to the 22 SRES A2 and B1 projections considered in Christensen and Lettenmaier (2006). Bias-correction and spatial downscaling procedures should be applied to the raw GCM outputs before they can be used to support regional to local

hydrologic and water management impacts studies (see criteria in Section W.6.5)[9]. An archive of such data should be made available to researchers and the public. In addition, as dynamically downscaled datasets become available, these datasets should be added to the archive. Reclamation should encourage PCMDI and others to make daily and potentially sub-daily data available rather than the current monthly data which requires an additional and unnecessary temporal downscaling step for many hydrologic models.

- **Improved Ability to Model Runoff Under Climate Change.** Currently there are only a few runoff models available to generate CRB natural flow given climate inputs and Reclamation does not have easy access to these models. Reclamation needs to build internal staff expertise with available runoff model applications in the basin, and build coalitions with external groups that use such applications (e.g., working with groups familiar with UW's VIC hydrologic model, or NWSRFS). Ideally, such runoff applications would also report other hydrologic processes' response to climate change (e.g., soil moisture, evapotranspiration, groundwater interactions with surface water), which might involve development of applications that involve coupling of rainfall-runoff (e.g., NWSRFS) or land-surface model applications (e.g., VIC) with groundwater models (e.g., ModFlow). Several analytical designs (Section W.6.4) involve statistical methods that do not require runoff simulation. These methods should also be investigated by Reclamation.

- **Investigate Paradigm for Colorado River basin Precipitation Response.** While there is an evolving paradigm for how the American Southwest and other existing dry subtropical areas of the globe should respond to climate change, it is not clear how nearby relatively wet mountainous areas such as the Rockies should respond. In addition, the ability of GCMs to simulate future precipitation conditions at this spatial scale is questionable. Both the lack of a paradigm and current modeling capabilities constrain assumptions about future precipitation over the basin, and necessitate probabilistic or scenario-based approaches that explicitly recognize these uncertainties, to the extent that they might be quantified.

- **Diagnose and Improve Existing Climate Models Before Adding Additional Features.** Given known GCM limitations in simulating regional precipitation, climate research groups should focus a portion of their efforts on diagnosing and correcting biases in the current collection of IPCC AR4 AOGCMs, even though such efforts would compete for human and computational resources currently reserved for the development of new "Earth System Models" (i.e. ESMs, or AOGCMs modified to include interactive

[9] As of Summer 2007, Reclamation has begun working with research collaborators at Lawrence Livermore National Laboratory and Santa Clara University to produce an archive of bias-corrected and downscaled IPCC AR4 climate projections. The objective is to produce archived datasets featuring monthly 20th to 21st century time-series of surface air temperature and precipitation at eighth degree spatial resolution, and with geographic coverage spanning the contiguous United States (i.e. encompassing all of Reclamation's service areas). Bias-correction and downscaling procedures are being implemented using methods featured in Maurer (2007) and Christensen and Lettenmaier (2006). This effort may partially fulfill this need, but it is uncertain.

carbon cycle, chemistry, computed aerosols, and dynamic vegetation.)[10]. There is evidence that systematic errors in AR4 AOGCMs would still be present after coupling with additional ESM components and hence waiting for ESM models to solve existing problems is unlikely to be entirely satisfactory.

- **Investigate Changes in Modeled Climate Variability at Multiple Time Scales.** It is well appreciated that the Colorado River is sensitive to changes in mean flow. However, variability as represented by drought spells, wet refill periods, and extended decadal and longer periods of above and below average flow are also critical for determining system yield. Therefore, investigation of such variability in modeled sequences of precipitation, runoff and other climatic variables is critical. While future variability may not be similar to past variability, the variability in models should be characterized and explained both in the context of the historical record and the paleo record. In addition, the ability of the current generation of GCMs and the hydrology models to reproduce the historical variability of the CRB has not been studied.

- **Improve Understanding of Surface water, Groundwater and Land cover Interaction.** Because rivers and groundwater are intimately connected, understanding the entire recharge process and its response to climate change is critical. Hence, research is required on groundwater recharge and movement at scales relevant to regional runoff analysis, and this in turn requires understanding the aggregate process of mountain block recharge and the role of riparian and root zone vegetation. The latter leads to additional research questions on how basin land cover and natural evapotranspirative demand will respond to global climate change (Section W.6.3).

- **Improve Prediction of Interdecadal Oscillations.** The predictability of interdecadal climate oscillation phases (e.g., AMO, PDO) and their associated hydrologic impacts on the Colorado River basin are not well understood. Shorter-term planning may be more influenced by phase persistence and transition among these oscillations than by projected changes in climate means. Reclamation should actively support, either materially or otherwise (i.e., through partnerships and inter- or extra-agency interactions), efforts in the science and the applications community to advance knowledge in this area (i.e., 2- to 10-year climate prediction research).

- **Investigate use of Paleo Record to Inform Modeled Streamflow Variability.** Reclamation has funded some paleo-climate research on how to use information from the paleoclimate record in modeling studies. While the past will not repeat, the paleo record contains a wealth of information on natural variability that should not be ignored. For example, there may be valuable ways of combining paleo data with modeled and or historical data to modify the variability in these sequences in useful ways.

[10] (Jerry Meehl, 16 February 2007, presentation comments at WGNE/PCMDI Systematic Errors Workshop, 12-16 February 2007, San Francisco, CA; P. Chris Milly, 31 May 2007, personal communication)

- **Interact with Federal Climate Change Science Program and other Climate Change Research Initiatives.** Although Reclamation can pursue and fund some of the Research and Development work described above, many of these problems will require the assistance of the larger scientific and engineering community. The Department of the Interior is one of thirteen agency members of the approximately $2 billion per year federal Climate Change Science Program, the umbrella under which all federal climate change activity is pursued. In order to raise the profile of these issues and obtain resources to help solve them, Reclamation should engage the CCSP. In addition, Reclamation should collaborate with NOAA, the National Center for Atmospheric Research, and the University research community.