Southwest Climate Science Center – FINAL TECHNICAL REPORT

1. **USGS GRANT/COOP AGREEMENT G13AC00327**

2. **PROJECT TITLE: Colorado River Basin streamflow projection under IPCC scenarios: from the global to basin scale using an integrated dynamic modeling approach**

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6. **PROJECT START DATE** (MM/YYYY): 09/2013

7. **EXPECTED COMPLETION DATE** (MM/YYYY): 12/2016

8. **PURPOSE AND OBJECTIVES:**
Describe the project goals and objectives, with particular emphasis on any changes made to the objectives as stated in the original proposal. If the objectives have been added to, eliminated, or modified, please explain why these changes have been made.

This project aims to better characterize how the changing climate of the Southwest is affecting cool and warm season precipitation in the Colorado River basin, and the corresponding response of streamflow in select individual sub-basins. The principal research objective is to assess whether the level of complexity of downscaling, applied to the official global climate change projection models used by the Intergovernmental Panel on Climate Change (IPCC), substantially affects resultant future streamflow projections used for operational planning purposes. The current methodological standard used for future streamflow projection by the US Bureau of Reclamation (BOR) applies the Bias Correction and Spatial Disaggregation (BCSD) technique to IPCC global climate change projection models to generate surface temperature and precipitation, which is then used as input to a pre-calibrated hydrologic model in a given river basin or sub-basin. Within this work select IPCC global climate models (GCMs) are dynamically downscaled with regional climate models (RCMs), to generate alternative temperature and precipitation inputs to hydrologic models. The differences in resultant modeled streamflow then inform as to the sensitivity of the downscaling approach in generating projected streamflow in the Colorado River basin, and therefore robustness of the current BCSD-based BOR streamflow projections. The other research objective is to assess how regional climate models can improve upon the representation of natural climate variability in the western United States during the cool and warm season, by dynamically downscaling select IPCC global climate change projection models and a historical 20th century atmospheric reanalysis. The investigation of historical climate variability in the context of a dynamically downscaled 20th century reanalysis is a new aspect to the project not included in the original proposal, and informed by the stakeholder interaction during the course of the project. There was a strong desire from the participating water resource providers to have more reliable historical climate information for the early twentieth century. This particular period is of interest for several reasons related to water resource planning: 1) it is when most of present-day water resource delivery infrastructure in the southwestern United States was constructed (i.e. major dams and reservoirs), 2) it corresponds to the period when the Colorado River Compact was enacted, which governs Colorado River water allocation among the states 2) where significant long-term wet and dry periods occurred, that are used as a basis for present-day operational planning purposes.

9. ORGANIZATION AND APPROACH:

Explain how each research task is being conducted. Briefly list which research methods are being used to achieve results, including any new methods that were not described in the original proposal. Please also discuss any problems or delays encountered in conducting the research during the reporting period.

1) Regional climate modeling

Within the scope of the project, various sources of regional climate model data have been utilized, that have been generated within the Department of Hydrology and Atmospheric Sciences at the University of Arizona (UA-HAS) as part of the project activities or from the North American Regional Climate Change Assessment Program (NARCCAP). These regional climate model datasets are described as follows:

(a) UA-HAS regional climate model simulations

Regional climate model simulations have been generated within UA-HAS using the Weather Research and Forecasting (WRF) model used as a regional climate model. The model physical parameterizations are approximately consistent with the existing WRF NWP system within the University of Arizona Department of Hydrology and Atmospheric Sciences (UA-HAS) that produces quasi-operational forecasts for the state of Arizona and surrounding states in the Southwest U.S. Spectral nudging is utilized in WRF RCM simulations to maintain the variability of synoptic-scale circulation features (i.e. upper-air ridges and troughs) and still allow the RCM to add value on the mesoscale.

Boundary forcing data for WRF-RCM simulations are from the following sources noted in bullet points below. Note that for downscaled CMIP data, either the A2 greenhouse gas emission scenario or Radiative Concentration Pathway (RCP 8.5) is utilized. In practical terms this is the “business as usual” greenhouse gas emission scenario that assumes no major global economic shifts will occur to substantially reduce emissions, and this best corresponds to the currently observed trajectory of greenhouse gases in the atmosphere. Simulations for dynamically downscaled CMIP5 data utilize the North American domain of the Coordinated Ensemble Downscaling Experiment (CORDEX)[1]. As of the date of this report, they are being transferred to a data repository at the National Center for Atmospheric Research (NCAR) for permanent archival and anticipated availability through the Earth System Grid (ESG)[2] sometime shortly after the conclusion of this project. Additional support for generation of the North American CORDEX simulations has been provided by the National Center for Atmospheric Research during the course of the project. The complete list of regional atmospheric model simulations within the scope of the project includes:

- NCEP-NCAR global atmospheric reanalysis: Completed simulation period 1948-2012 for a U.S.-Mexico domain at 35 km grid spacing.
- United Kingdom Meteorological Office-Hadley Center Coupled Model Version 3 (UKMO-HadCM3) from CMIP3: Completed simulation period 1967-2081 for a U.S.-Mexico domain at 35 km grid spacing.
- Max Planck Institute-European Center Hamburg Model, Version 5 (MPI-ECHAM5) from CMIP3: Completed simulation period 1950-2100 for a U.S.-Mexico domain at 35 km grid spacing
- UKMO-Hadley Center Global Environmental Model, Version 2 (HadGEM2) from CMIP5: Completed simulation period for 1950-2100 for a North American CORDEX domain at 50 km and 25 km grid spacing.
- MPI-ECHAM6 from CMIP5: Completed simulation period for 1950-2100 for a North American CORDEX at 50 km and 25 km grid spacing.
- 20th Century reanalysis*: Completed simulation for a contiguous U.S-Mexico domain at 35 km grid spacing for the period 1871-2010.

  *Note that though the dynamical downscaling of the 20th century reanalysis was not included in the original proposal, consideration of retrospective hydrologic projections during this period is very important from the perspective of local water resource providers, for the reasons already mentioned in the previous section. The 20CR is a coordinated, international effort to produce a retrospective atmospheric reanalysis from 1871-present, the longest period to date of an atmospheric reanalysis.

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[1] http://wcrp-cordex.ipsl.jussieu.fr/

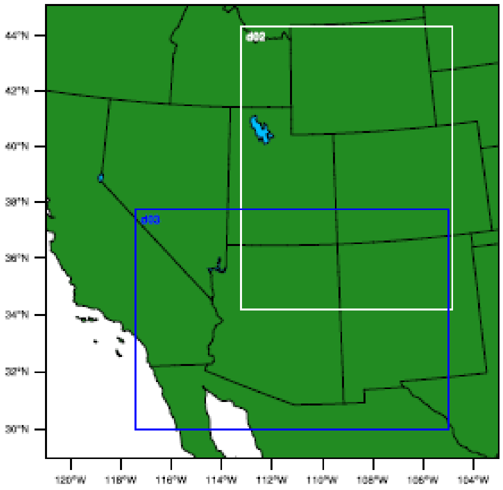
[2] http://www.earthsystemgrid.org

(b) NARCCAP models

The North American Regional Climate Change Assessment Program (NARCCAP, http://www.narccap.ucar.edu) employs multiple regional climate models to dynamically downscale a matrix of select CMIP3 models for the A2 emission scenario at 50 km grid spacing, for a historical period (1971-2000) and a climate change projection period (2041-2070). Most, but not all, of the NARCCAP models are used within the scope of the executed research in this project. The particular NARCCAP models that are excluded tended to have a much poorer climatological representation of precipitation within the Colorado River Basin, relative to precipitation observations.

(c) Convection-permitting 10-year regional climate simulations

The dynamically downscaled WRF-CMIP5 regional climate simulations, as summarized in (a), provides climate projections account for long-term changes in heat and moisture associated with increases in greenhouse gases. However, we recognize RCM model configurations with grid spacing in the range of 25-50 km are not sufficient to explicitly resolve localized convection and orographic-forced snowfall in complex terrain, crucial precipitation mechanisms for the western United States. Convection-permitting simulations are executed using long-term WRF RCM outputs from (a) as forcing, with two nested domains at 12km and 3km model grid spacing for the period of 2000 to 2010. *Fig. 1* shows the outer domain (12km grid spacing) that covers Southwest U.S., with two separate inner domains centered over upper (d02) and lower (d03) Colorado River Basins at 3km grid spacing. These convective-permitting (< 4km) RCM simulations aims to more explicitly represent precipitation extremes associated with monsoon thunderstorms and large winter storms.



<u>Figure 1</u>: Domain configuration for convection-permitting 10-year simulations. Outer domain (12km grid spacing) covers Southwest U.S.; two inner domains (3km grid spacing) covers upper (d02) and lower (d03) Colorado River Basins.

2) Observed surface data

Various sources of surface meteorological data are used to compare and validate results from global and regional climate models, as direct input to a hydrologic model, and to bias correct atmospheric model generated surface meteorological data prior to input into a hydrologic model. These data include:

- P-NOAA data: Observed precipitation data from a new 0.5 gridded National Oceanic and Atmospheric Administration produce (P-NOAA) produced by Drs. Russ Vose and Richard Heim. P-NOAA covers a US-Mexico domain and incorporates a terrain correction interpolation function, similar to the Parameter-elevation Regressions on Independent Slopes Model (PRISM).
- Maurer surface meteorological data: A comprehensive surface meteorological dataset at 1/8° that provides daily observed values of precipitation, maximum, and minimum temperature and wind speed, considered for the period 1950-2010.

Both of these observed datasets incorporate long-term station precipitation from the cooperative observing network.

3) Variable Infiltration Capacity (VIC) model

Hydrologic modeling is performed using the Variable Infiltration Capacity (VIC) model (Liang et al., 1994). VIC is a semi-distributed, macro-scale model that solves the water balance at each grid cell, which represents surface and subsurface hydrologic processes on spatially distributed grid cells. Distinguishing characteristics of the model include the representation of subgrid scale variability in vegetation coverage, topography, precipitation, and soil moisture storage capacity. The subsurface is represented by three soil layers. Evapotranspiration can occur from soil moisture in the three layers, while slow response runoff or baseflow is only generated from the third layer. To represent the sub-grid spatial variability in soil moisture storage, the model assumes that the infiltration capacity is a non-linear function of the soil moisture storage within the grid cell. Simulations in this project are performed at a daily time step with a 12.5 km resolution (1/8 degree).

VIC model parameters must be calibrated for an accurate representation of a given watershed basin. The following five VIC parameters are calibrated: 1) the maximum baseflow that can occur from the lowest soil layer, dependent on the hydraulic conductivity (Ds_{max}), 2) the fraction of Ds_{max} where non-linear (rapidly increasing) baseflow begins (Ds), 3) fraction of the maximum soil moisture of the lowest soil layer where non-linear baseflow occurs (Ws), 4) shape of the Variable Infiltration Capacity curve (b_{inf}) and 5) the soil depth of each layer (mm). The set of VIC model parameters that are used in this study for all modeled basins are obtained from the Bureau of

Reclamation (BOR). BOR used the aforementioned Maurer et al. (2002) observed dataset at 1/8° resolution to calibrate the five VIC model parameters for the western U.S. with multiple USGS gauge stations at various major locations for the period 1950-1999 (Reclamation, 2011).

4) Precipitation and temperature bias correction: CMIP GCMs

Bias Correction and Spatial Disaggregation (BCSD) (Wood et al. 2002; Wood et al. 2004; Maurer 2007) is technically a statistical downscaling method coupled with a non-parametric quantile mapping bias correction technique (NP-QM) (Gudmundsson et al., 2012). BOR has previously used BCSD to bias correct and statistically downscale 16 CMIP3 GCMs of varying runs to create 36 SRES A2 fine-scale models for the continuous period of 1950-2099 at 1/8° resolution. In the BOR methodology, BCSD involves three steps: (1) bias correction for the historic and future GCM monthly precipitation and daily temperature data using NP-QM method at 2° resolution, (2) spatial disaggregation (SD) of the bias corrected GCMs from 2° to 1/8° resolution, and (3) temporal disaggregation to generate daily VIC forcing files from the downscaled monthly GCM data. The bias correction in step (1) is done against aggregated (1/8° to 2°) Maurer data.

Bias correcting precipitation on a monthly scale reduces the complexity associated with replicating the intensity and number of no rain days in the raw GCM (Wood et al., 2002), but this step results in loss of information that quantifies the increase or decrease in the precipitation intensity during the future. The spatial disaggregation in step (2) involves adding (or multiplying) the spatial anomalies for each month, that was obtained between 2° and 1/8° observed climatology, to the 2° GCM temperature (or precipitation) respectively. This step assumes that the anomalies that are generated also holds valid for a future period (assumption of temporal invariance), since the large scale future data is also downscaled to fine-scale. Step (3) samples the daily sequence in a given month at random and scales the monthly value according to it. This sequencing may be critical to the representation of extremes in the streamflow projections, especially in the smaller basins. This step also creates an assumption of future intra-monthly variability to have the same pattern as the past.

5) Precipitation and temperature bias correction: RCMs

Four variables (precipitation, maximum and minimum temperature and wind speed) for each regional climate modes are temporally aggregated to daily values and further spatially downscaled to 1/8° resolution using aa ordinary kriging method (Ly et al., 2010), with the grid locations being consistent with the observed dataset. The lowest denomination period among the two sets of models (NARCCAP and UA-HAS), 1971-2000 and 2041-2070 are thereby chosen to be our historic and future scenario periods. The systematic biases present in each grid cell of each raw regional climate data (wind speed included, Haddeland et al., 2012) are corrected against observations in two ways.

First, a modified version of BCSD is applied, but in a manner that preserves the daily sequencing of precipitation events. Second, a new bias correction technique of scaled distribution mapping (Switanek et al., 2017). As described in the original proposal, SDM not only corrects for the biases in seasonal and daily precipitation present in the historical and future period of climate models, but it also preserves the relative change or trend from the original climate model. However, in applying both BCSD and SDM bias correction methods to regional climate model-generated surface meteorological data, the resultant streamflow generated by the hydrologic model was not substantially different between the two bias correction methods. Therefore, the modeled streamflow as presented in this final project report and for all project-related publications uses SDM technique only.

6) Generation of historical (1971-2000)and projected (2041-2070) streamflow using VIC model

Three sub-basins within the larger Colorado River basin are considered in this project for generation of modeled streamflow with the VIC model:

- Upper Colorado River Basin (Lees Ferry Gauge)
- Verde River Basin
- Salt River Basin

These three basins are chosen because they account for the majority of Colorado River water supply in both the upper and lower portions of the basin. Per the needs of water resource planning for water resource stakeholder participants in the project, the Upper Colorado is of relatively greater interest to BOR and the Central Arizona Project, and the Verde and Salt River basins are more of interest to the Salt River Project.

To generate VIC modeled streamflow projections, the model requires daily values of precipitation, maximum and minimum temperature and wind speed. These variables are provided on a common grid for all sources of input data (observed and bias-corrected models) at 1/8° spatial resolution, with appropriate spatial disaggregation applied for all sources of global and regional climate model information. All modeled streamflow (and changes between past and future periods) is shown for the gauging point that defines the lowest (exit) point for streamflow in the basin.

7) Statistical techniques for analysis of atmospheric model data, comparison with observations

Within the project, various statistical analysis techniques commonly used in geophysical data analysis have been employed to analyze atmospheric model results and observations. These have included:

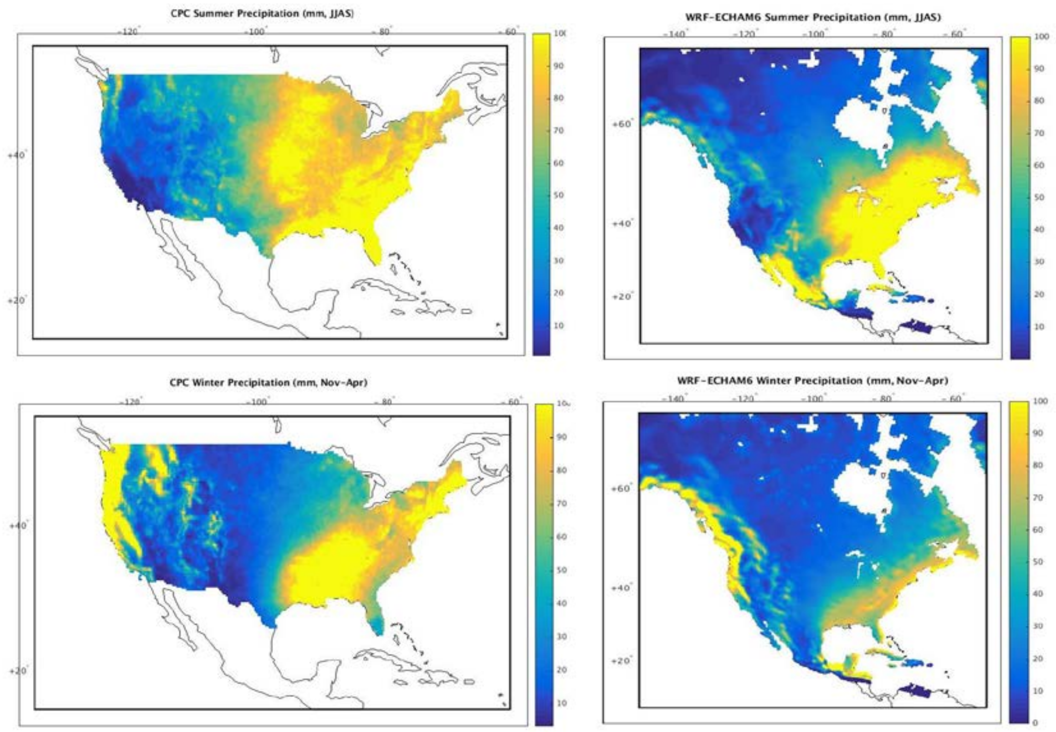
- Standardized precipitation index (SPI): Used to specify cool and warm season precipitation anomalies. Computed using a gamma-normalization procedure applied to total precipitation at various timescales, typically ranging from a month to multiple years (McKee et al. 1993). It is typically used as a measure to monitor short and long-term drought in operational practice (e.g. Heim et al. 2002).
- Principal components analysis (PCA): Identifies the dominant patterns (or modes) of variability in a time sequence of mapped data of a given geophysical field, with percent explained variance of each pattern.
- Multi-Taper-Method Singular Value Decomposition (Mann and Park 1994, 1996; Mann and Lees 1996; Rajagoplan et al. 1998): used to determine dominant patterns of spatiotemporal variability. The resultant analysis produces a local fractional variance spectrum, reconstructed spatial patterns, and reconstructed time series. MTM-SVD essentially shows the spatial patterns associated with significant temporal variability.

10. **RESULTS:** *Present your preliminary project results if possible. Both quantitative and qualitative results (descriptions of how well or poorly something worked) are useful. Of particular interest are major discoveries, innovative approaches and solutions, and accomplishments made by the project team to date.*

1) Regional climate model seasonal climatology and variability

It is first necessary to evaluate the dynamically downscaled IPCC GCMs in their simulation of the historical climatology. WRF-ECHAM6 is shown here as an example. The seasonal precipitation comparison with the Climate Prediction Center data shows WRF-ECHAM6 has good representation of both summer and winter precipitation (*Fig. 2*). There is a clear signal North American monsoon summer precipitation over Mexico and Southwest U.S. Orographically-forced winter precipitation in the Northwest is also present. The precipitation bias over eastern U.S. is a commonly observed in RCMs, and is likely due to land surface feedback.

Statistical analysis using Principal Component (PC) is performed on cool and warm season precipitation to analyze the dynamics of atmosphere and sea surface temperature variability that drives the dominant patterns of seasonal precipitation variability. WRF-ECHAM6 simulations are shown as an illustrative result in *Fig. 3*. The dominant mode of standardized precipitation index (SPI) during the warm season (JJAS, top of figure) is an anti-phase relationship in precipitation variability between the Southwest U.S. and central U.S. This mode has a relationship to a warm season atmospheric teleconnection emanating from the western tropical Pacific (Castro et al. 2007). A similar dominant warm season precipitation pattern has found in the downscaled WRF-ECHAM5 simulation and observations (Chang et al. 2015). A corresponding cool season (November – April, bottom of figure) dominant precipitation mode from WRF-ECHAM6 also has a clear connection to Pacific SST variability during the cool season, which is a crucial indicator for water resource projection in the western United States. Winter ENSO influences are related split-flow of jet stream over the western U.S., affecting winter precipitation in opposite ways between the northern and southern part of the Colorado River basin.



<u>Figure 2:</u> Seasonal precipitation climatology (mm) for summer (JJAS) and winter (Nov-Apr). Observation (From Climate Prediction Center, left) and a dynamically downscaled CMIP5 model (WRF-ECHAM6, right), 1950-1969.

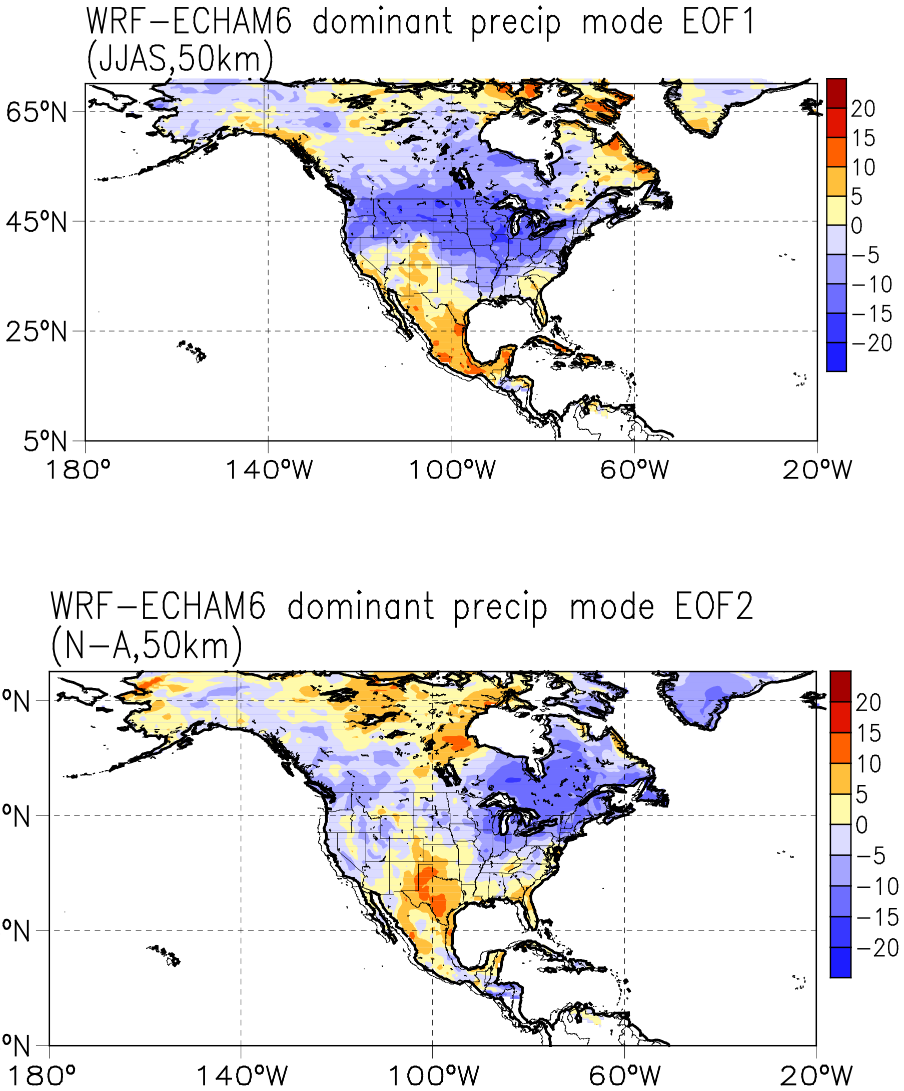


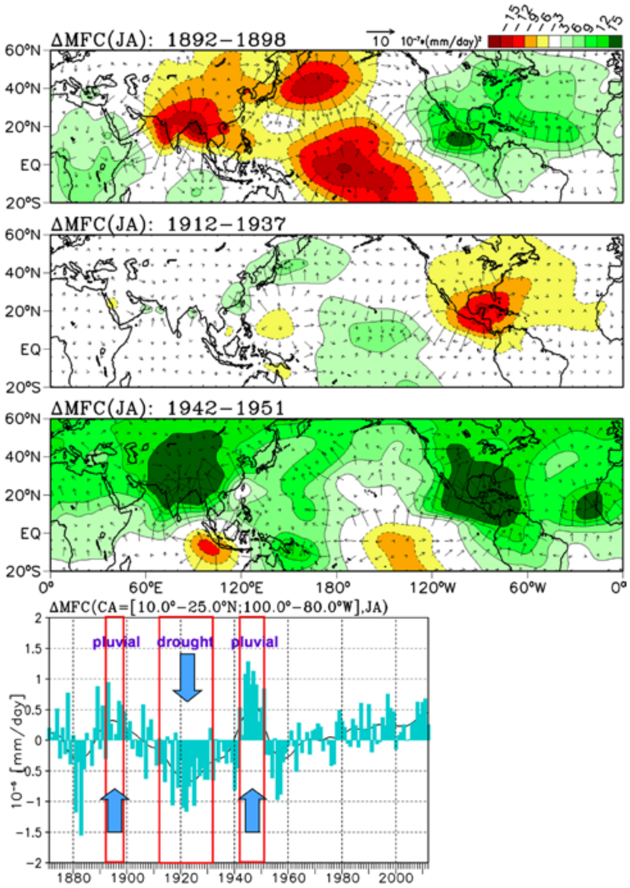
Figure 3: Historic WRF-ECHAM6 dominant modes of precipitation for summer (June-September, top) and winter (November – April, bottom) related to Pacific SST variability.

2) Dynamical downscaling of the 20th century reanalysis (summary of Carrillo et al. 2017):

Historic long-term drought has a significant impact on hydroclimate and vegetation change. Under anthropogenically influenced climate change, prolonged drought is expected intensify, especially in Southwest U.S. (Ault et al. 2014). Therefore, understanding the physical mechanism underlying historic drought events is crucial. A long-term historic regional climate simulation is produced using WRF regional model, forced with NCEP-NCAR twentieth century reanalysis version 2 project dataset (20CR, Compo et al. 2011).

Dominant low-frequency climate variability in Central America and the Southwest U.S.

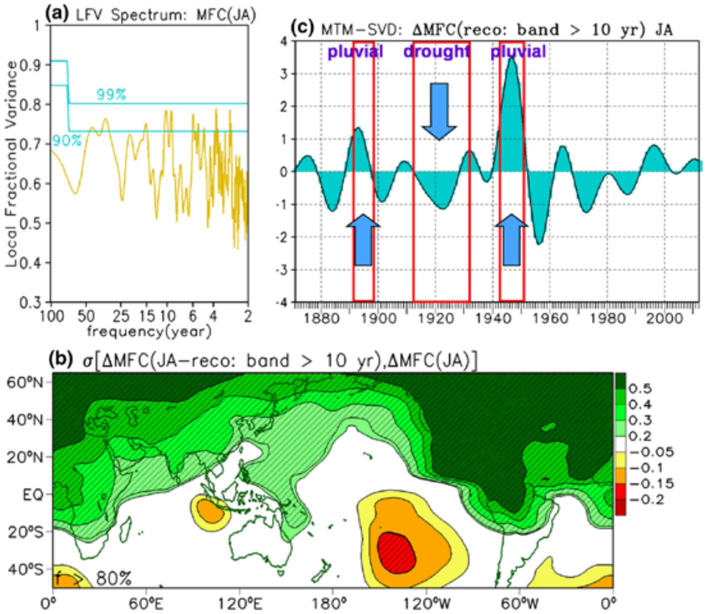
Persistent long-term droughts in the Southwest and northern Mexico are inversely related to anomalously wet conditions in Central America (Méndez and Magaña 2010; Cook et al. 2004). If the low-frequency variability of precipitation in these two geographic regions is related, then it must be due to coherent variability in atmospheric circulation patterns at continental to global scales. Low-frequency climate variability in the 20CR is evaluated by exploring global to continental-scale spatiotemporal variability in moisture flux convergence (MFC) to the occurrence of multiyear droughts and pluvials in Central America (CA). The 10-year running mean filtered and the original time series of JA and NA MFC spatially averaged over CA are shown in *Fig. 4* (bottom). The 10-year running mean reveals low-frequency climate variability. Periods with a sustained positive (negative) sign of MFC are associated with pluvials (droughts) in CA. The summer MFC time series identify three distinct pluvial and drought-related periods related to low-frequency climate variability: the 1892–1899 pluvial, the 1912–1937 drought, and the 1942–1951 pluvial. These periods are defined by the range of consecutive year exceeding ±75% of the standard deviation of the 10-year running mean time series (*Fig. 4*; bottom). Selected periods for the summer season only and their ranges are used for the winter composite, for comparison purposes. The spatial pattern for these three periods for summer MFC are shown as a composite in *Fig. 4* (top). Positive (negative) values represent convergence (divergence), which are emphasized with vectors. The spatial and temporal patterns of these results suggest an in-phase relationship between the winter and summer composite at least for Central America (winter figure not shown, see Carrillo et al. 2017, their Figure 3).



<u>Figure 4</u>: JA Moisture Flux Convergence (MFC) composite anomaly for the periods: 1892–1898, 1912–1937, and 1942–1951 (upper). These periods are defined using the positive and negative anomalies in the JA MFC anomaly time series (bottom), as highlighted by the red boxes. Vectors in the map show the convergence/ divergence of the flux. The JA MFC time series is calculated over the Central America (CA) region (10–25°N; 100°–80°W). Big arrows highlight the intensity of these peaks associated with pluvial and drought regimes. The vertical bars are the interannual variation and the solid line is the 10-year running mean

<u>Assessment of statistically significant low-frequency variability in 20CR MFC</u>

The composite analyses of MFC in Central America during major droughts and pluvials in this region suggest an existing coherent pattern of low-frequency climate variability. Is this spatiotemporal variability in MFC statistically significant at the decadal timescale and longer? To address this question, the MTM-SVD was applied to the JA MFC field for the entire record of the 20CR. Three main results are shown in *Fig. 5*: the Local Fractional Variance (LFV) spectrum, the reconstructed time series for low-frequencies (decadal and longer), and the pattern correlation map of the reconstructed time series with MFC. The LFV is an alternative form of a power spectrum where the temporal and spatial variation is accounted for simultaneously. Statistically significant spectral peaks in the LFV spectrum are identified by statistical significance intervals determined by bootstrap re-sampling (Rajagopalan et al. 1998). The MTM-SVD reference point is selected at the center of the NAME2 region. The LFV spectrum reveals a statistically significant low-frequency band, in the range of 25–50 years. The reconstructed MFC time-series of this low-frequency (25–50 years) reveals a similar spatial pattern as shown with the 10-year running mean time series. The spatial correlation map in also shows a similar anti-phase relationship in MFC between Central America and the central tropical Pacific, but the negative center of action is located more in the southern hemisphere, maximized at 30°S. Therefore we conclude that low-frequency climate variability exists and it is a statistically significant dominant feature in the 20CR dataset that drives the droughts and pluvials in Central America, similar to Méndez and Magaña (2010).



*<u>Figure 5</u>: Local Fractional Variance (LFV) spectrum of the leading Multi Taper Method-Singular Value composition (MTM-SVD) mode for the Moisture Flux Convergence anomaly (ΔMFC) (**a**), for the warm (July–August; JA) season of the Twenty-Century Reanalysis (20CR). Spatial correlation pattern of MFC anomaly obtained between the JA 20CR ΔMFC and its reconstructed MTM-SVD temporal pattern for frequencies greater than 10 years (**b**). Local significance is shown with oblique lines and field significance in percentage. The reconstructed temporal pattern of JA 20CR ΔMFC for frequencies greater than 10 years (**c**).*

<u>Low-frequency precipitation variability in the dynamically downscaled regional climate data</u>

The out-of-phase spatial relationship in precipitation between Central America and the Southwest is explicitly resolved by identical analyses for warm and cool seasons of the dynamically downscaled 20CR (*Figs. 6, 7*). The reconstructed low-frequency time series closely matches the known sequencing of droughts and pluvials in southwestern US from the tree-ring record (Carrillo et al. 2016). Moreover, it was found that the DD-20CR precipitation yielded a result for low-frequency precipitation variability in North America that has better correspondence with the tree-ring record and global MFC, in comparison to the P-NOAA product (not shown). The dynamically downscaled precipitation is a result of consistent large-scale dynamical forcing mechanisms (i.e. atmospheric teleconnections) as input boundary forcing to the RCM. Statistically significant low-frequency spatiotemporal variability in cool season precipitation is in phase with that of the warm season, with the peaks of the 1890s drought, 1912–1937 pluvial and 1942–1951 drought present. Important to note is that cool and warm season precipitation anomalies are in-phase, which is consistent with the idea of dual-season drought.

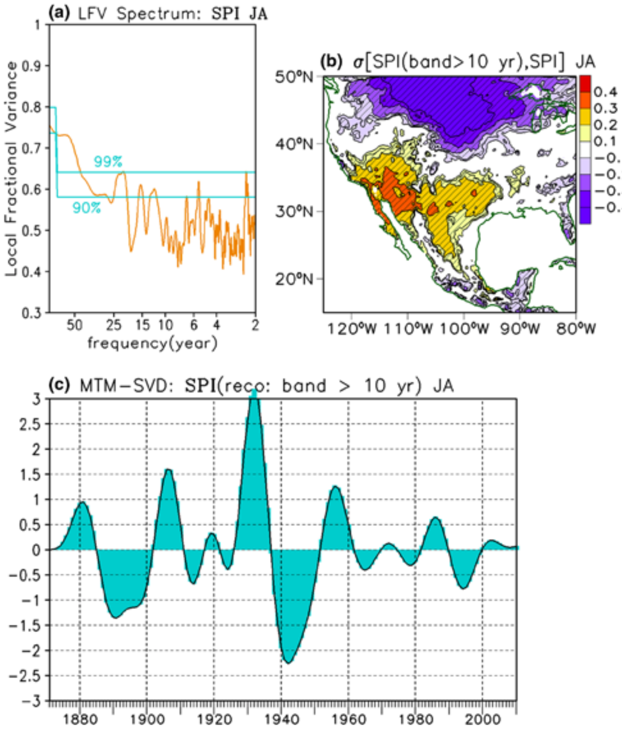


Figure 6: Local Fractional Variance (LFV) spectrum of the leading Multi Taper Method-Singular Value Decomposition (MTM-SVD) mode for the Standardized Precipitation Index (SPI) from the dynamically- downscaled Twenty-Century Reanalysis (DD-20CR) (a), for the warm (July–August; JA) season. The spatial correlation pattern of SPI obtained between the JA DD-20CR SPI and its reconstructed temporal pattern for frequencies greater than 10 years (b). Local significance is shown with oblique lines. The reconstructed temporal pattern of JA DD-20CR SPI for frequencies greater than 10 years (c)

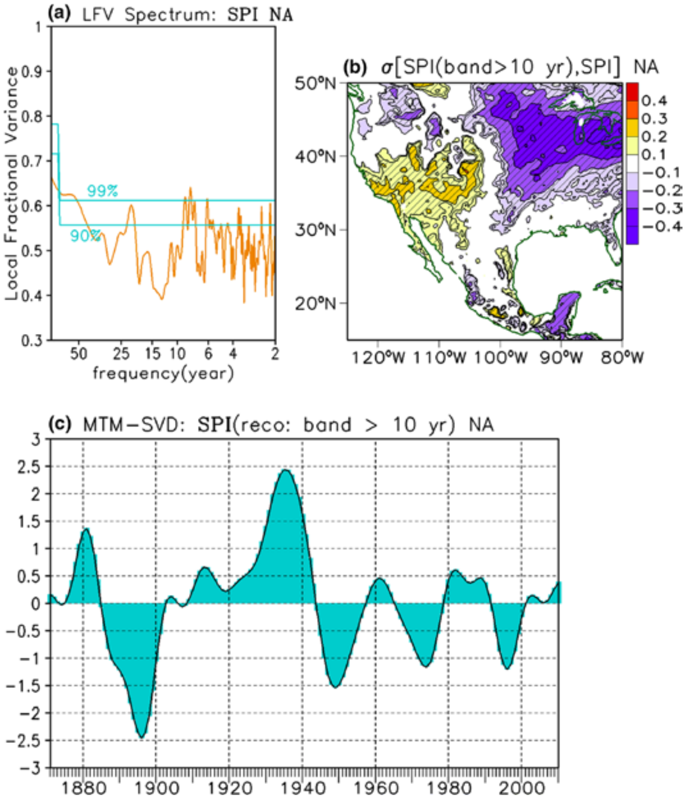


Figure 7: Similar to Fig. 8 but for the cold season, November through April (NA)

Pertinent project-related conclusions from Carillo et al. (2017)

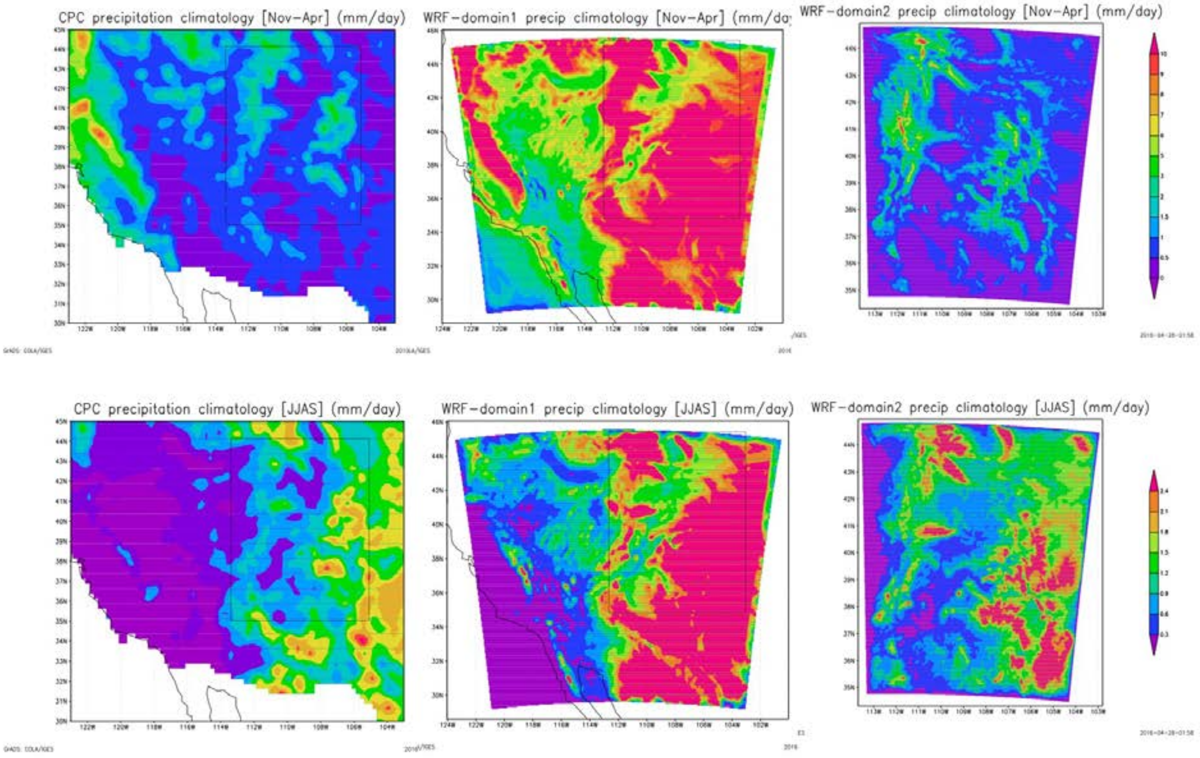
- Tree-ring data used for data validation and the 20CR reanalysis data are only able to effectively statistically characterize climate variability at the multi-year to multi-decadal timescale. The even lower temporal frequencies at the centennial timescale, however, still cannot be resolved. A global climate model (GCM) integrated for period longer than several hundred years would be necessary to capture this type of variability (Coats et al. 2015).
- A long-term GCM integration could presumably be used to provide boundary forcing to a RCM to resolve precipitation patterns tied to centennial-scale climate variability, provided that the GCM can reasonably represent this type of variability as best as available paleoclimate data can inform.
- As the dynamically downscaled 20CR is able to reasonably capture low-frequency climate variability in a quite similar manner to tree ring chronologies, it could be potentially used to investigate Southwest by employing a pseudo global warming modeling framework (Kawase et al. 2009) using boundary condition for long-term global climate change projection models. A pseudo-global warming experiment with DD-20CR may actually be quite socially valuable from the standpoint of assessing the impact of climate change with known climate variability in the early twentieth century because it would not subject to the vagaries of the widely different representations of natural climate variability that exists within the CMIP climate change projection models (Sheffield et al. 2013).
- The period of 1871 to 1950 is very important for water resource risk assessment, as it corresponds to the construction of major infrastructure (e.g. dams along the Colorado River) and the establishment of the Colorado River compact. Water resource management agencies that participated in this project already account for the major droughts of this period in their operational planning.

3) Convection-permitting 10-year regional climate simulations for Upper Colorado Basin:

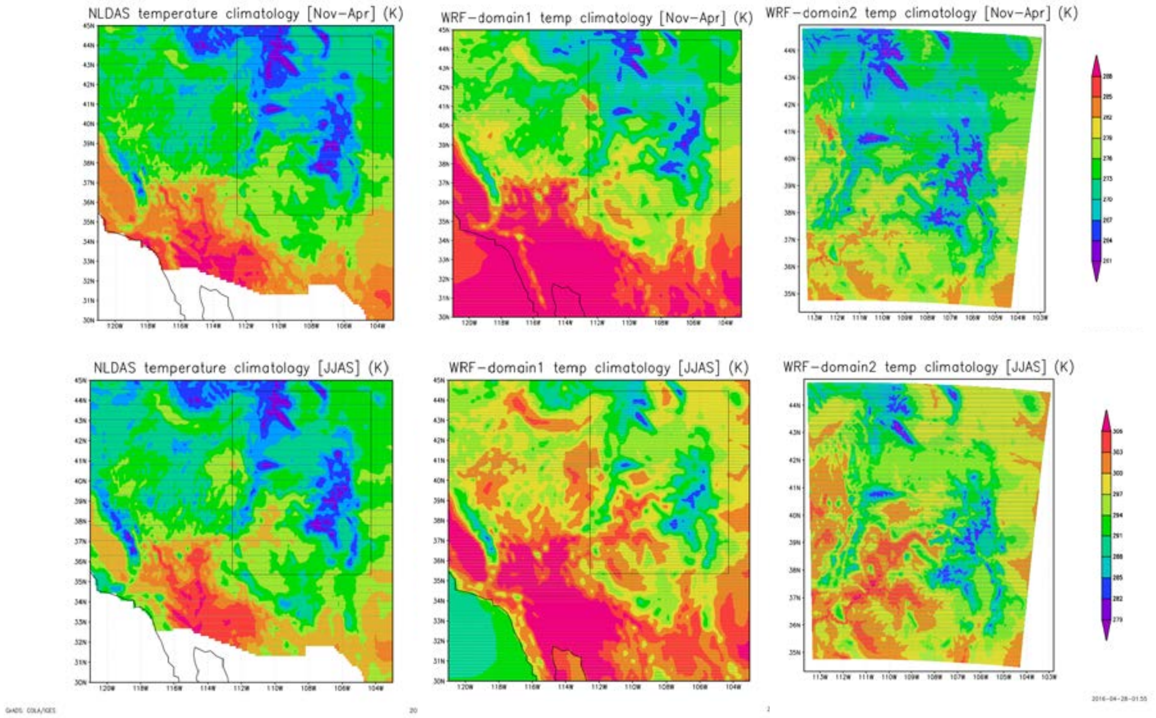
As mentioned, a model grid spacing in the range of 25-50 km, as used for dynamical downscaling of reanalyses and CMIP data, is not sufficient to capture terrain-forced convection in the warm season or cool season orgraphically-forced precipitation. This section shows results from additional 10-year RCM simulation (2000 to 2010) at 12km and 3km (convective-permitting) grid spacing for the Southwest and Upper Colorado River Basin.

A seasonal precipitation comparison demonstrates the value added using model grid spacing at convection permitting scale. For the cool season (November to April), the 10-year climatology over Upper Colorado Basin is at least 4-times wetter from 12 km RCM output (*Fig. 8* upper panel, center) than CPC observation record (*Fig. 8* upper panel, left). The extreme wet bias over complex terrain is greatly reduced in the convective-permitting RCM output (3km, *Fig. 8* upper panel, right). The pattern of precipitation is also better captured, as Upper Colorado Basin receives more mountain snow during the cool season.

Similarly, the 12 km RCM simulation also generates a large area of wet bias for both Upper and Lower Colorado Basins in the warm season (*Fig. 8,* lower panel, center). The convection dominant summer precipitation is much better simulated by the convective-permitting RCM simulation (*Fig. 8,* lower panel, right). The value added using convection-permitting scale RCM simulations for precipitation is quite pronounced, while both the 12 km and 3km simulations reasonably captured cool and warm season temperature climatology with relative little difference in the overall spatial pattern (*Fig. 9*). These experiments show the potential value of using convective-permitting modeling for purposes of climate and water resource projection, though this was not explicitly done within the scope of this project.



<u>Figure 8</u>: Seasonal precipitation climatology for both cool (upper panel) and warm (lower panel) seasons. Comparison between gridded observation (CPC, left panel) and WRF convection-permitting RCM simulations from the outer domain (center panel, 12km grid spacing) and inner domain at Upper Colorado River Basin (right panel, 3km grid spacing)



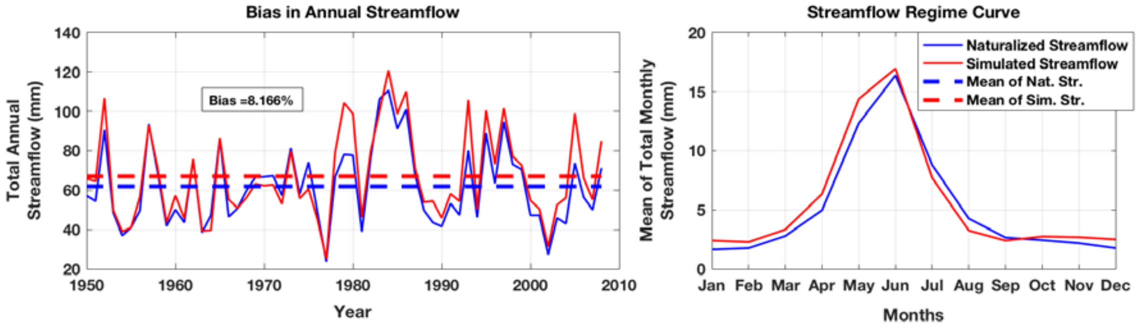
<u>Figure 9:</u> Seasonal temperature climatology for both cool (upper panel) and warm (lower panel) seasons. Comparison between gridded observation (Maurer data, left panel) and WRF convection-permitting RCM simulations from the outer domain (center panel, 12km grid spacing) and inner domain at Upper Colorado River Basin (right panel, 3km grid spacing).

4) VIC-modeled streamflow: performance during historical period and climate projections (summary of MS thesis of R. Mukherjee corresponding manuscript in preparation)

This section shows the results for VIC-generated streamflow historical simulations and future climate projections, demonstrating the complete methodological approach for the Lees Ferry Upper Colorado River basin (UCRB) gauge point, using the CMIP3 models as input forcing. After some baseline conclusions are established in the framework of the CMIP 3 models, then similar behavior is demonstrated for CMIP 5 models. Some of the corresponding results for the Salt and Verde River basins within the Lower Colorado basin are then finally shown. Note that in the figures, the dynamically downscaled models are referred to as DD and the statistically downscaled models are referred to as BCSD.

Historic VIC model performance using observed meteorological forcing

First, the performance of the VIC model is evaluated using the observed surface meteorological forcing from the Maurer et al. (2002) gridded dataset. The simulated streamflow at Lees Ferry (*Fig. 10*, left, red line) for the period of 1951 to 2008 exhibits very similar year-to-year variability as compared to the observed, naturalized streamflow (*Fig. 10*, left, blue line), with a positive 8.17% bias. The monthly streamflow regime curve for both model and observations (*Fig. 10*, right) demonstrates the ability of the VIC model to well capture the mean annual cycle of streamflow curve at Lees Ferry, with a maximum in simulated streamflow correctly occurring during the month of June. Thus, the VIC hydrologic model demonstrates a reasonable ability to simulate streamflow at Lees Ferry when forced with "perfect" gridded meteorological observed data.



<u>Figure 10</u>: Comparison of VIC 4.1.2 simulated streamflow against naturalized reconstructed monthly flow at Lees Ferry for the period 1951-2008; (a) annual and (b) monthly regime

VIC-generated streamflow during historical period (1971-2000)

VIC-generated streamflow during a historical period (1971-2000) is produced by using dynamically downscaled (DD) meteorological inputs from the regional climate models versus the equivalent inputs from standard BOR-based BCSD statistical downscaling (SD), utilizing the same CMIP 3 driving models. *Fig. 11* shows the VIC model performance in replicating the observed hydroclimatic regimes and streamflow quantiles for the Upper Colorado basin. Although both DD and SD approaches capture the pattern of evolution of the basin aggregated mean monthly precipitation over the course of the annual cycle, SD tends to underestimate the precipitation the mean precipitation during the winter to spring months (Jan-May) and exhibits a relatively larger spread of solutions, as compared to dynamical downscaled simulations. In fact, the spread of the DD models is essentially negligible in all months except during the late summer, probably due to the variation in the representation of North American monsoon precipitation within the NARCCAP models (Bukovsky et al., 2013). The amount of winter (DJFM) precipitation falling over the upper basin, especially at the highest elevations, is important in resolving the winter snowpack.

Viewing the precipitation bias across all grid cells as a function of elevation, the DD simulations show a much more faithful representation of observed precipitation as compared to SD simulations at all elevations. DD simulations and SD simulations both underestimate the observed monthly streamflow regime during the period in late spring to the maximum in June when the hydrograph is rising, but with smaller bias for DD. The greater underestimation of streamflow with SD and could be attributed to its greater underestimation of precipitation in the winter months. The error can be viewed as a function of streamflow probability of exceedance in *Fig. 11*, with highest flows to left and lowest flows to the right. The spread and mean of SD simulations shows a negative bias (~10% for the mean that is independent of the level of streamflow. In comparison, the mean of the DD simulations performs comparatively much better in simulating high to low streamflow, within a 5% bias. Overall, DD yields the superior representation of modeled precipitation and streamflow for the Upper Colorado basin, by these objective measures.

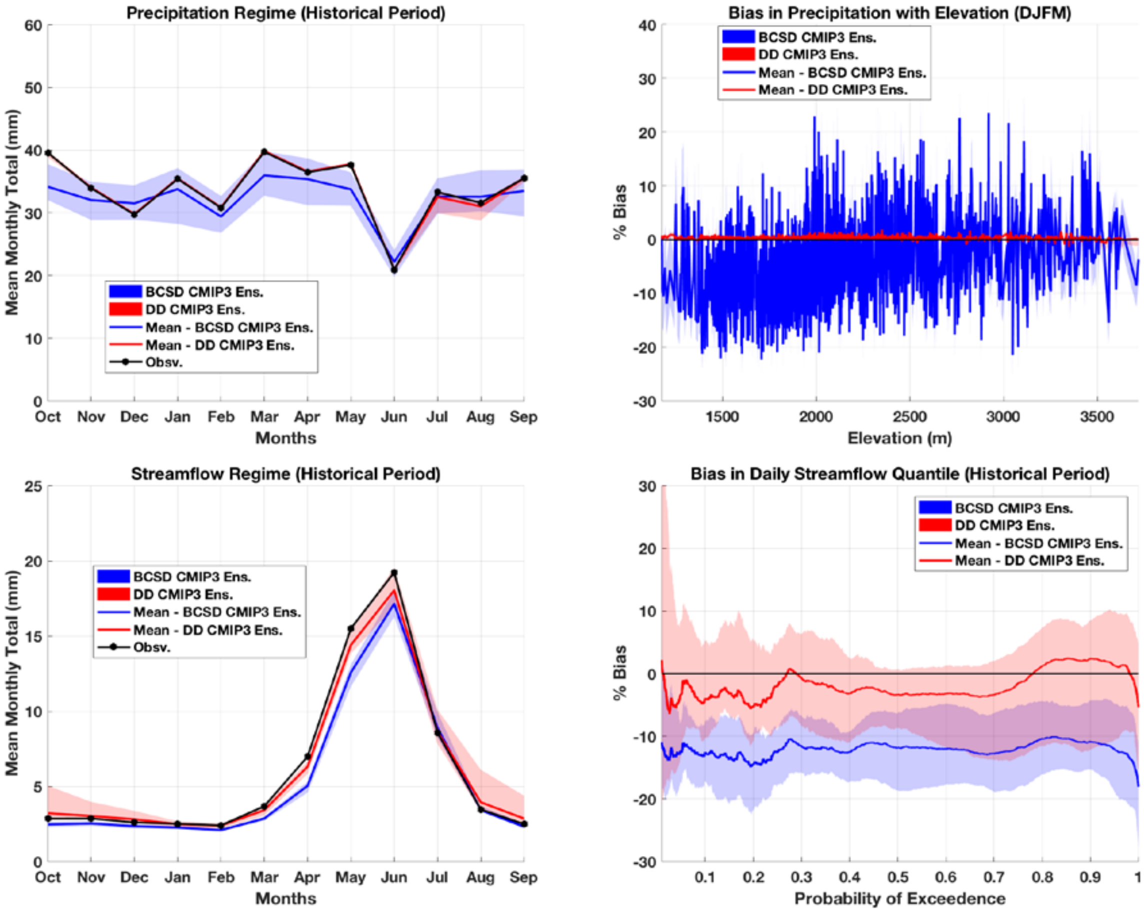
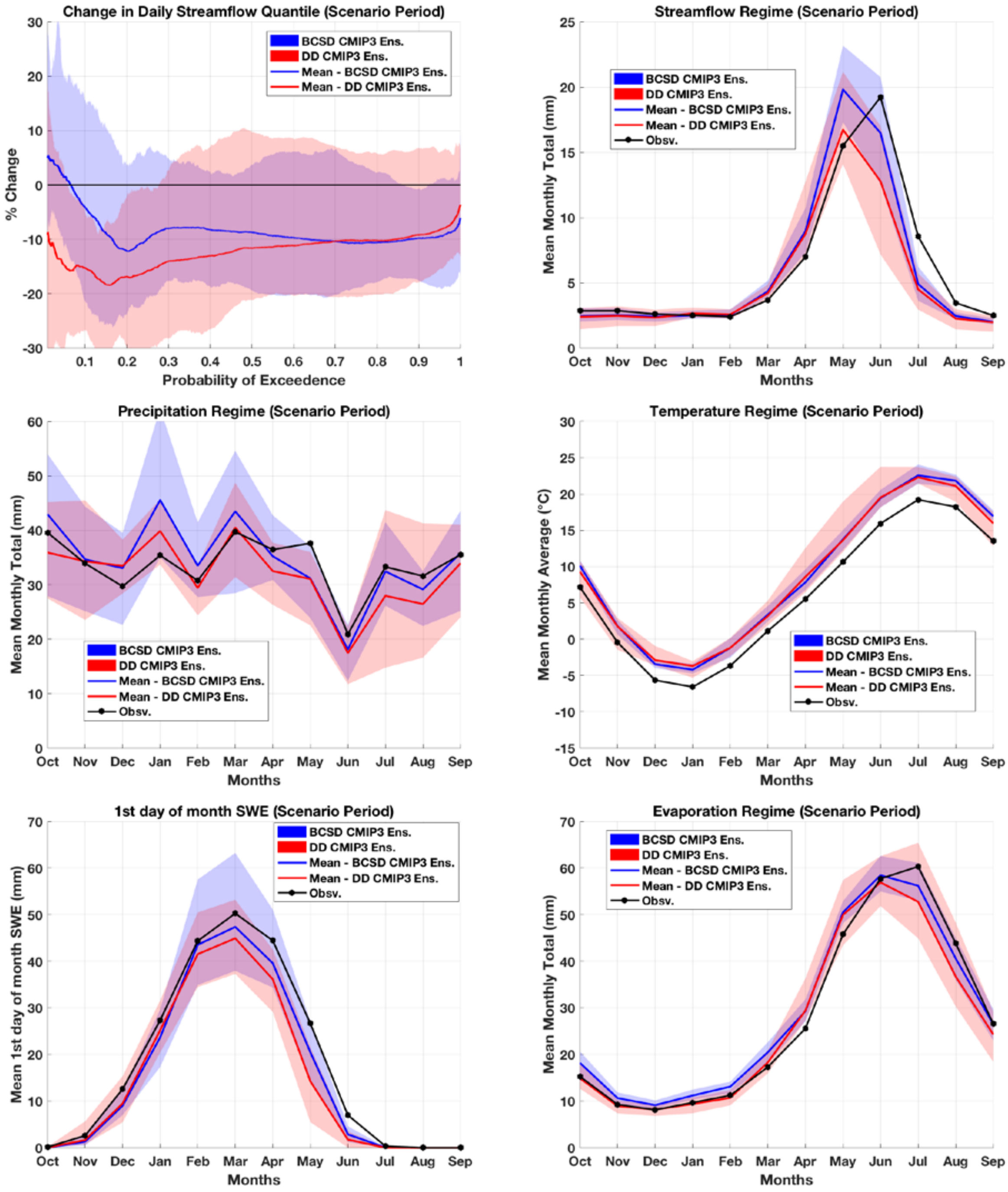


Figure 11: Performance of DD models against SD (BCSD) models in the historical period (1971-2000); (a) basin averaged precipitation regime (b) % bias in winter (DJFM) precipitation for each 1/8° model grid cell sorted by elevation (c) streamflow regime (d) % bias in daily streamflow quantiles on annual timespan.

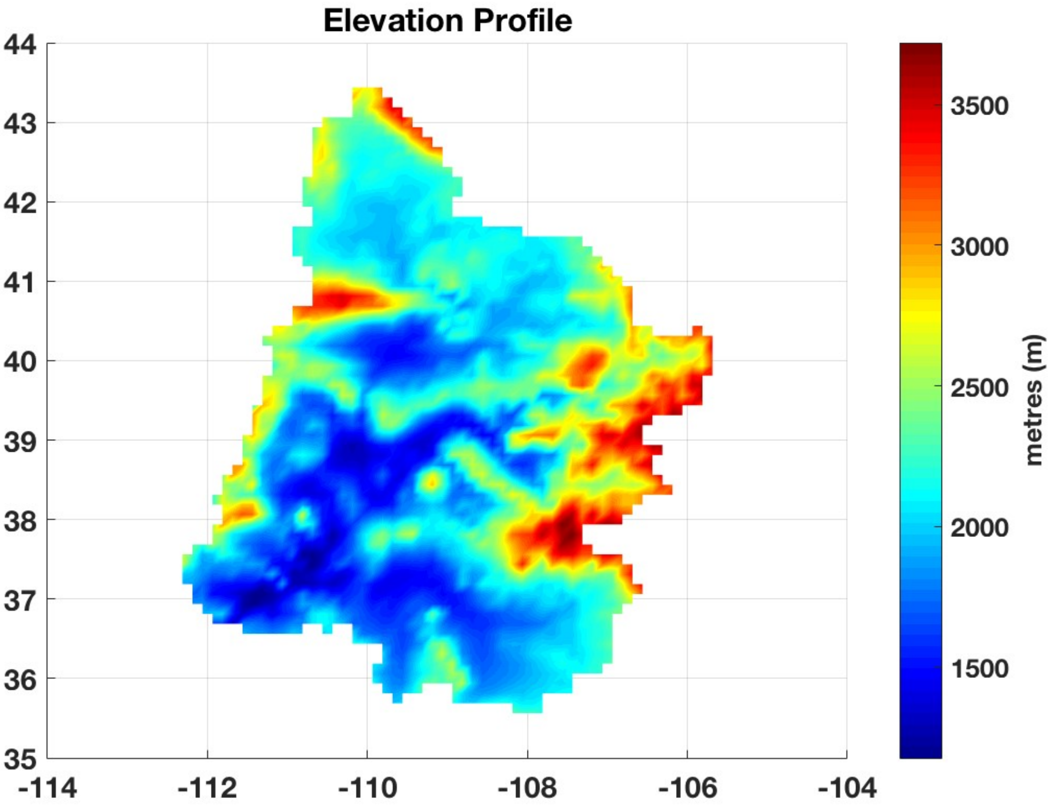
VIC-projected streamflow changes during the mid-21st century (2041-2070) with CMIP3 models

The annual and seasonal projected changes (2041-2070 compared to 1971-2000) in UCRB streamflow and basin aggregated precipitation, evaporation and temperature are computed for SD and DD simulations, using the equivalent CMIP 3 driving models. The mean of the DD simulations projects a decrease of 14.23% in annual streamflow, as compared to a 4.74% decrease by the SD simulations. *Fig. 12* shows the changes in projected streamflow as a function of probability of exceedance, with highest streamflows to the right and lowest streamflows to the left. Viewed as a function of probability of exceedance, the reduction in streamflow in the DD simulations versus the SD simulations is most substantial during high flow regimes (probability of exceedance less than 0.4). For the highest flows, DD simulations project approximately an additional 10% decrease in streamflow over the SD-projected streamflow change in the UCRB. The difference becomes negligible for low flows that would occur during dry conditions (probability of exceedance greater than 0.6). Though the variability in streamflow projections obtained from both DD and simulations are similar, it is important to note that for the high flow regimes, the range of potential decreases simulated by the DD simulations is outside of the bounds of SD simulations. So the "worst case" scenario for decreases in high streamflow in the SD simulations is on the order of 20%, while in the DD simulations it is on the order of 30%. Observing the changes in the streamflow regime curve, both SD and DD simulations shift in the hydrograph peak from June to May, due to an increase in winter temperature (of 2.4°C) and resultant earlier snowmelt, and this is quite consistent with previous documented studies of projected changes in Colorado river streamflow. Though both SD and DD simulations project the shift to earlier timing of maximum streamflow, the DD simulations project a reduction in peak streamflow while SD simulations maintain streamflow at approximately its presently observed level. The latter portions of *Fig. 12* show the SD and DD monthly simulated changes in precipitation, temperature, snow water equivalent (SWE) and evaporation. Averaged across the basin, the most appreciable difference between the SD and DD simulations occurs for the variable of precipitation during winter and summer. Though both SD and DD simulations project increases in winter precipitation, this increase is less in the DD simulations (+5.6% as compared to +14%). There is also a comparatively wider spread in summer precipitation solutions in the DD simulations, due to uncertainties in the regional model representation of monsoon precipitation. The projected winter temperature change for DD simulations is also 0.2°C higher than SD simulations. Comparing DD to SD simulations, the DD simulations produce comparatively lesser amount of precipitation received within the winter months and have a greater increase in temperature. Therefore, in the DD simulations there are greater decreases in SWE and resultant peak streamflow.

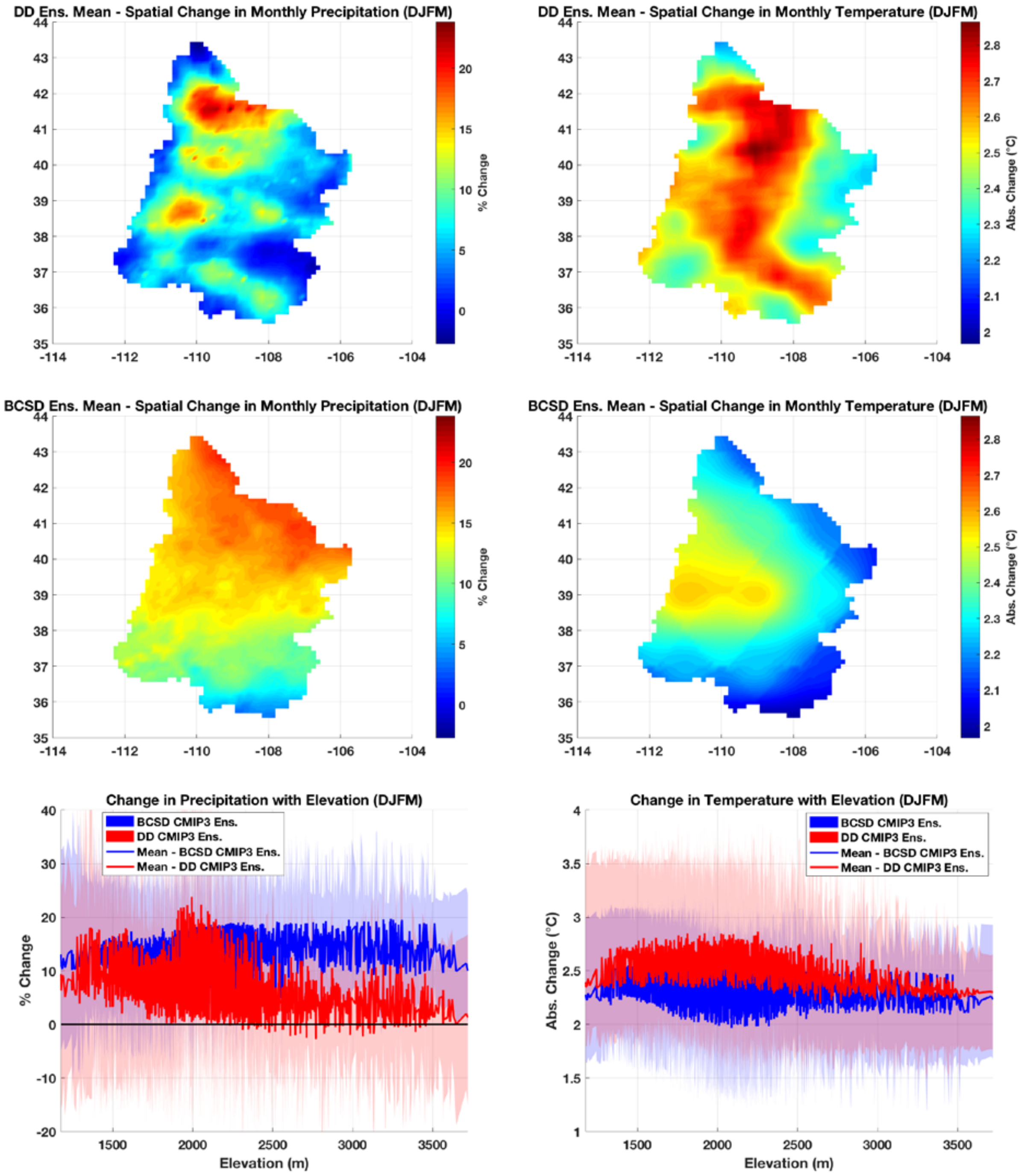
The magnitude of the peak streamflow depends on the amount of snowpack accumulated in the headwaters of the basin, which depends on the winter precipitation that falls as snow over the region. For reference, *Fig. 13* shows the spatial distribution of elevation in the UCRB. *Fig. 14* (top two rows) shows the spatial change in the winter precipitation and temperature for the UCRB and *Fig. 14* (bottom row) shows these same changes as a function of elevation within the basin. The DD simulations exhibit a greater spatial heterogeneity for the changes in temperature and precipitation as compared to SD simulations, due to the better representation of the topographic influences on temperature and precipitation at finer resolution. The DD simulations project a precipitation increase of lower magnitude (by about 10%) in the higher elevations the SD simulations, especially above 2500 m. The relatively lower increases in precipitation at higher elevations in the DD simulations lead to lower values of snowpack, confirmed by metric of snow water equivalent (SWE) as previously discussed. So accounting for elevation shows that it is more the high elevation precipitation differences that are important in accounting for the decrease in streamflow within the DD simulations.



<u>Figure 12:</u> Projections of streamflow and basin averaged hydroclimatological regimes in the scenario period (2041-2070); (a) % change in daily streamflow quantiles on annual timespan (b) streamflow regime (c) precipitation regime (d) temperature regime (e) 1st day of month SWE (f) evaporation regime.



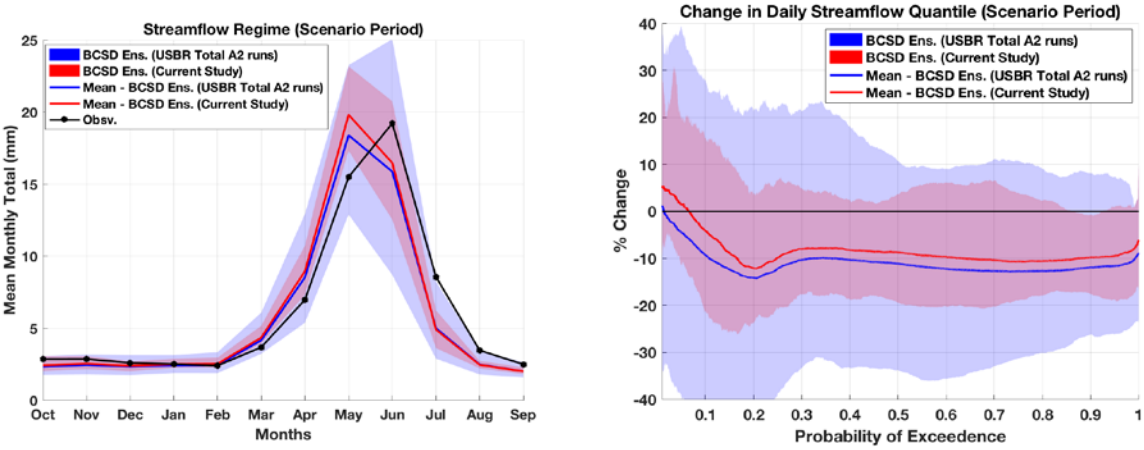
<u>Figure 13:</u> Elevation profile (m) within the UCRB.



<u>Figure 14</u>: Percentage change in winter (DJFM) precipitation (top) and absolute change in winter (DJFM) temperature (middle) in the scenario period (2041-2070); top two rows correspond to spatial change and the last row accounts for each 1/8° model grid cell sorted by elevation

Representativeness of selected CMIP 3 models in VIC hydrologic projections

A disadvantage in this project is that the number of CMIP models that can be realistically included within a DD modeling framework is limited, because of the relatively high computational expense of generating dynamically downscaled regional climate model simulations. Even a large community effort like the NARCCAP experiment was only able to dynamically downscale four of the nearly 20 CMIP3 global climate models with its various participating regional climate models. To address this issue, *Fig. 15* shows the comparison of BSCD-generated streamflow projections (2040-2071 period) with the limited number of driving CMIP 3 models used in this project as compared to the entire suite of CMIP 3 models available from BOR projections, for the streamflow regime curve and the probability of exceedance. The more limited CMIP3 model subset of simulation used in this project is representative of the entire lot of 20 CMIP3 models, falling well within the range of variability and projecting nearly identical mean changes.

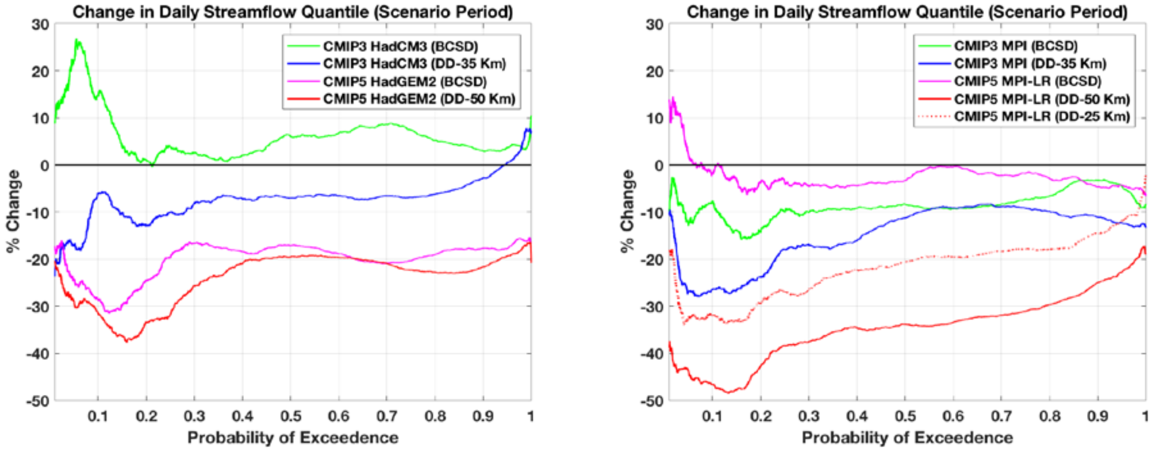


<u>Figure 15:</u> Comparison of streamflow projections in the scenario period (2041-2070) obtained from the ensemble of 14 BCSD CMIP3 models used in our current study against the entire ensemble of 36 BCSD CMIP3 models compiled by BOR; (left) % change in daily streamflow quantiles on annual timespan (right) streamflow regime

Changes in projected UCRB streamflow within the context of CMIP 5 models

The ensemble DD CMIP 3 models projects a decrease in streamflow across the UCRB, as compared to equivalent SD models that use the BCSD technique. It is desirable to evaluate if these results would be strongly dependent on the particular CMIP 3 models and would potentially change using the next generation of CMIP 5 global climate change projection models. Therefore, the same downscaling and bias correction procedures are applied to two CMIP 5 models, and the resultant surface meteorological forcing data is then used in exactly the same way as boundary forcing to the VIC model. The particular CMIP 5 models selected are HadGEM2 and MPI-ECHAM6, as they can be directly compared with the equivalent models generated at the same institutions within CMIP 3 (HadCM3 and MPI-ECHAM5) that were part of the previous CMIP 3 analysis. The regional model simulations generated with WRF are available at 50 km grid spacing for both models, with an additional simulation at 25 km grid spacing available for MPI-ECHAM6.

Fig. 16 shows the streamflow projections for each quantile obtained from the CMIP 3 and CMIP 5 Hadley models (left) and MPI models (right), using SD and DD. The results show that dynamically downscaling both the CMIP3 models reduces the flows as compared to using the BCSD methods, with the reduction being greater for HadCM3 than MPI. In light of the previous analysis of UCRB streamflow changes presented for CMIP 3 models, the basic conclusions do not substantially change with the use of CMIP 5 models. That is, DD simulations produce a relatively larger decrease in projected streamflow, and this decrease is largest during the high flow regimes. What is different, at least in the context of the two CMIP 5 models used in this project, is that both DD CMIP 5 models project even larger streamflow decreases than the equivalent DD CMIP 3 models. For example, for a probability of streamflow exceedance less than 0.4, the DD MPI-ECHAM5 projects streamflow decreases on the order of 20% or more. In this same portion of the distribution, the equivalent DD MPI-ECHAM6 simulation projects decreases on the order of 30% or more. However, these results are dependent on grid spacing of the regional model, with the finer resolution 25 km producing the lesser decrease in streamflow.



<u>Figure 16:</u> Comparison of daily streamflow probability of exceedance for CMIP3 and CMIP5 downscaled models as labeled from the Hadley Centre (Had, left) and Max Plank Institute (MPI, right).

Changes in projected streamflow in the Salt and Verde basins

The same modeling and analysis procedures were also applied to the Salt and Verde basins within the lower Colorado River Basin. For brevity in this technical report, only the final results for differences in projected streamflow during the future scenario period (2041-2070) are shown in the context of the CMIP 3 models. The DD simulations generated a better representation of observed precipitation and streamflow in these basins in the cool season months (November - April) during the historical period (1970-2000), very similar to the UCRB. *Fig. 17* shows the projected changes in monthly precipitation, monthly streamflow, and changes in streamflow as a function of the probability of exceedance. Streamflow in these basins is driven mostly by cool season precipitation. The basic messages in these projection results for the Salt and Verde are qualitatively similar to the UCRB, though there are some subtle differences. DD simulations project a larger decrease in cool season precipitation relative to SD. Though timing of the peak streamflow in March does not change from the historical period, the DD simulations project a lower peak streamflow at this time. These greater decreases are largest for the highest flow regimes, resulting in an additional 10% decrease in projected streamflow in the DD simulations, as compared to SD simulations. The range of “worst case scenario” decreases in high streamflow also expands by an additional 10-20% in the DD simulations in both basins.

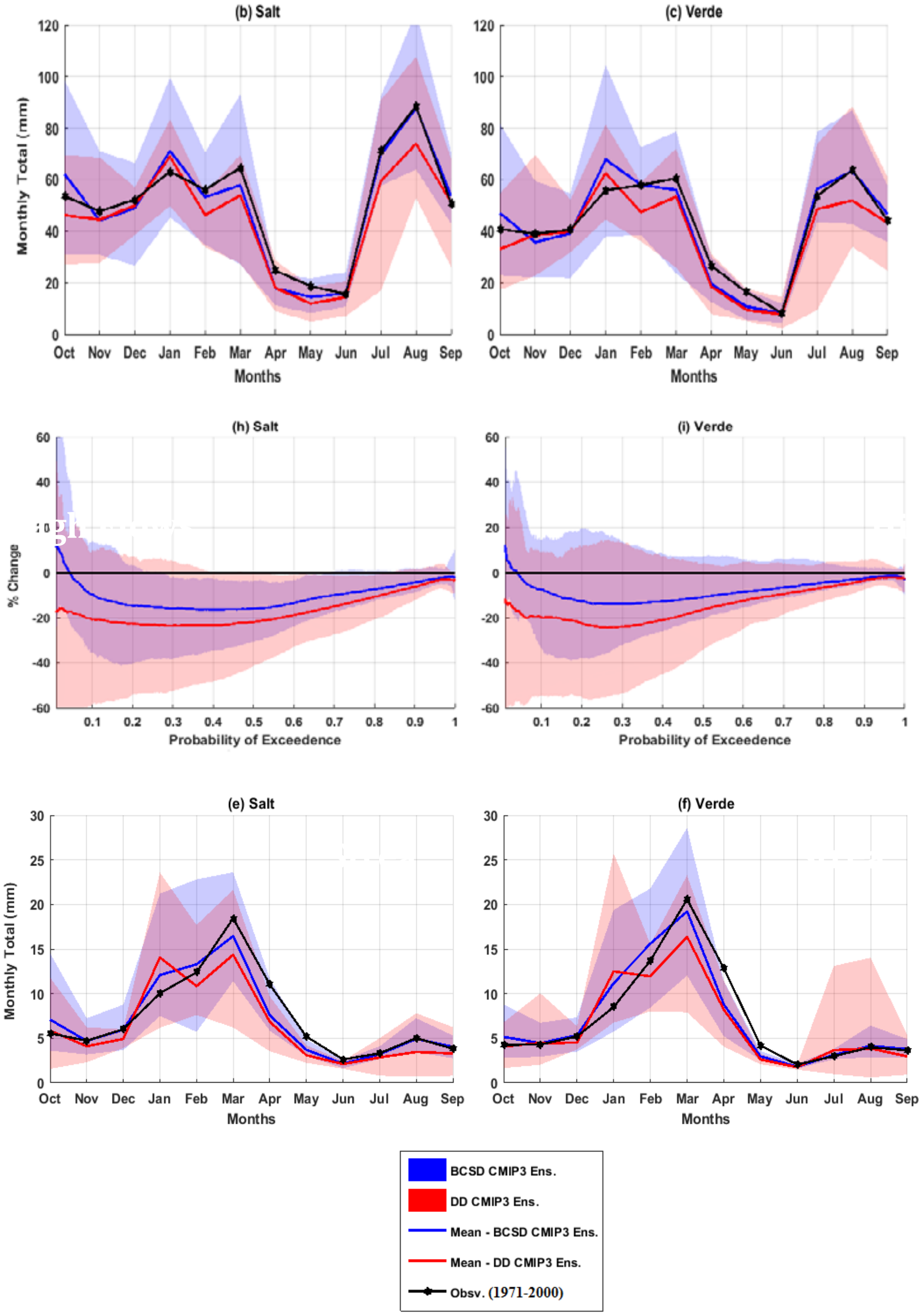


Figure 17: Projected changes for the Salt and Verde River basins: monthly precipitation (top), probability of exceedance of streamflow (middle), and monthly streamflow (bottom).

Conclusions of Mukherjee et al. (in preparation)

The essential concluding points of the study that evaluates the effect of methodological approach on the projection of streamflow in the Colorado River basin most pertinent to project objectives are as follows:

- The choice of downscaling technique that is used to generate input meteorological data to a hydrologic model can make a substantial difference in the resultant projected streamflow within the Colorado River basin.
- Dynamical downscaling of global climate models produces surface meteorological are more consistent with observed meteorological data during a historical period (1971-2000). Therefore, the statistical properties of the simulated streamflow better captured than with comparable statistical downscaling.
- Current BOR operational projections that utilize a BCSD-based statistical downscaling approach to generate future projected streamflow are likely underestimating projected decreases in streamflow within the Colorado River basin. The equivalent dynamically downscaled streamflow projections show comparatively larger projected decreases in streamflow, especially during periods of relatively high streamflow. In both statistically downscaled and dynamically downscaled simulations, there is an earlier occurrence of peak streamflow, consistent with prior investigations of changes in Colorado streamflow.
- In the Upper Colorado River Basin, relative to statistical downscaling, dynamical downscaling projects less of a precipitation increase at the highest elevations where snow would accumulate and a relatively larger increase in temperature in the future projection period. These factors appear to explain why dynamical downscaling produces a relatively larger decrease in streamflow.
- In the Verde and Salt River basins, dynamical downscaling also produces larger decreases in projected streamflow as compared to statistical downscaling, although the timing of peak streamflow in March does not change.
- Resultant larger projected decreases in streamflow with the use of dynamical downscaling in the Colorado River basin do not appear to be dependent on the particular driving global climate models, as very similar results were obtained using CMIP 5 models. In fact, the CMIP 5 models actually projected even steeper declines in Upper Colorado basin streamflow as compared to the previous CMIP 3 models generated from the same research institutions (Hadley Center and Max Planck Institute).

11. **NEXT STEPS:** *State and describe the next steps in the research, including an updated project timeline and anticipated completion date.*

The only major pending item in the documentation of the executed work per what was originally proposed is the submission of the article that documents the change in Colorado

River streamflow projection results (thesis of R. Mukherjee). This document is currently in preparation to submit to Water Resources Research (WRR).

There are several fruitful possible future lines of research inquiry, as informed partly by stakeholder interaction through the course of the project:

1. Inclusion of more CMIP 5 models from North American CORDEX to generate Colorado Streamflow projections, similar to the multimodel ensemble with NARCCAP data that was generated as part of the project. The UA-HAS team has obtained additional North American CORDEX RCM simulations (i.e. WRF-ERA Interim, WRF-GFDL) at equivalent model grid spacing and ready for bias correction and basin-scale hydrologic streamflow simulation.

2. Hydrologic projections in Colorado River basin based on convective-permitting model simulations. This has already been done in the context of psuedo-global warming experiments by Research Applications Laboratory at National Center for Atmospheric Research (2015 RAL annual report, https://nar.ucar.edu/2015/ral/high-resolution-modeling-current-and-future-climate-over-north-america). One of the CMIP5 models (MPI-ECHAM6) is currently been dynamically downscaled convective-permitting scale for Lower Colorado Basin and is expected to complete by Mid-April. Convective-permitting multi-model ensembles downscaled from multiple RCM CMIP5 CORDEX ensembles for basin-scale hydrologic study is likely crucial for water management resource planning.

3. Psuedo-global warming experiment using the dynamically downscaled 20th Century reanalysis, to project climate changes of known reference periods of wet and dry conditions during the early 20th century under an anthropogenically-influenced warming climate. This was explicitly stated as a suggestion in the project-related publication of Carrillo et al. (2017).

4. Expand the present study to dynamically downscaled subseasonal to seasonal forecasts, to inform operational streamflow projection. BOR has been in discussion with project team to possibly submit a proposal along these lines. Retrospective reforecast data from the North American multimodel ensemble is available at a sufficient space and time resolution necessary to dynamically downscale with a regional climate model, similar to what has been done with CMIP5 data in the scope of the present project.

5. Apply and evaluate the Intermediate Complexity Atmospheric Research (ICAR) model (developed at the National Center for Atmospheric Research, Research Applications Laboratory) to generate convective-permitting simulations of future climate at much less computational expense. This would allow the possibility of retaining the advantage of dynamical downscaling but with being able to consider a much larger multi-model ensemble.

12. **OUTPUTS: (Please carefully READ (Attached) Updated USGS Reporting and Publishing Guidance (10-11-16) .**

   a. *Please list any* ***peer-reviewed publications*** *that have resulted from this project (full citations). Please include articles in preparation, in review, accepted, or published*

Chang, H., C. Castro, C. Carrillo, and F. Dominguez, 2015: The more extreme nature of U.S. warm season climate in the recent observational record and two "well performing" dynamically downscaled CMIP3 models. *J. Geophys, Res*, **120**, 8244–8263, doi:10.1002/2015JD023333.

Carrillo, C. M., C. Castro, H. Chang, T. M. Luong, 2017: Multi-year climate variability in the Southwestern United States within a context of a dynamically downscaled twentieth century reanalysis. *Clim. Dyn*. Doi:10.1007/s00382-017-3569-1

Mukherjee, R., H. Chang, C. Castro, P. A. Troch, Regional climate models project a drier future for the Upper Colorado river basin: Implications of using dynamical over statistical downscaling methods for streamflow projection, in preparation.

   b. ***Non-peer-reviewed publications*** *(full citations).*

Rajarshi Mukherjee, 2016: Implications of statistical and dynamical downscaling methods on streamflow projections for the Colorado River Basin. M.S. Thesis, Department of Hydrology and Atmospheric Sciences, University of Arizona

   c. *Please list any* ***conference talks*** *you have given based on this project (conference title, date, and location).*

Chang, H., C. L. Castro, P. Troch, R. Mukherjee, S. Megdal, E. Tapia, 2017: Toward improved seasonal forecasting of water resources and North American monsoon precipitation in the Southwestern United States. 31st Conference on Hydrology, Seattle, WA, January, 2017.

Chang, H., C. L. Castro, P. Troch, R. Mukherjee, 2014: Regional climate and streamflow projections in North America under IPCC CMIP5 scenarios. *3rd Lund Regional-scale Climate Modeling Workshop*, Lund, Sweden, June 14-19.

Chang, H., C. L. Castro, P. Troch, R. Mukherjee, 2014: Regional climate and streamflow projections in North America under IPCC CMIP5 scenarios. American Geophysical Union Fall Meeting, San Francisco, CA, December 2014.

d. *Please list any* ***data outputs, maps, decision-support or other informational tools*** *developed as part of this project and provide: 1) a very brief description of the product 2) Internet links if applicable.*

Data outputs of regional climate and hydrologic streamflow projections are made available in the following blog and data portal:

(1) Blog: https://swclimatehydro.wordpress.com/
The blog "Colorado River Basin streamflow projection under IPCC CMIP5 scenarios: from the global to basin scale using an integrated dynamic modeling approach" has documented the research activities during the project period. Users can find research outline, experimental design, progress reports, conference presentations, publications, workshop proceedings and photos from the blog. Detailed description for both regional climate modeling, new method of bias correction, and streamflow projection analysis provides a comprehensive introduction to this hydroclimate research project. Most importantly, the basin-scale streamflow historic and future projection data for Salt, Verde and Upper Colorado Basins are all made available via the following link:
https://swclimatehydro.wordpress.com/project-data/streamflow-projection-data/

(2) Data portal for regional climate datasets:
The dynamically downscaled regional climate datasets contains more than 100 Terabytes of continuous historic to future climate for the entire United States. Our research blog does not have the capacity to store such large dataset, and conventional web browser is not the ideal data transfer method. Therefore, the UA-HAS team has utilized the CyVerse cyberinfrastructure (www.cyverse.org). CyVerse Data Portal (http://www.cyverse.org/) is a cloud infrastructure to use remote servers for computation, analysis, and storage. Funded by NSF for Biological Sciences and lead by the University of Arizona and other partners, CyVerse is designed to be an interactive analytical platform that provides data storage, bioinformatics tools, image analyses, cloud services, and also support computational algorithms to run on large, high-speed computers.

CyVerse has proven to be a powerful and easy-to-use data sharing portal. Data Commons Repository (DCR) from CyVerse allows users to access a suite of large-scale computational analysis resources, so that users can seamlessly analyze, manage, and publish new results. Project PIs and related personnel have various privilege to upload/edit/download the data directories. The archive can also be accessed externally via a login system and request to the data management staff. To date, the UA research group has used the Cyverser portal to exchange past research outcomes with more than a dozen users within U.S. and international collaborators in Europe, Central and South America.

13. **OUTREACH AND ENGAGEMENT:** Describe all project-related outreach opportunities to date.

e. *Please list any* ***presentations, seminars, webinars, or workshops*** *made to stakeholders, the public at large, or any other group outside the research community.*

The following workshops were conducted during the active period of the project:

Workshop #1: initial stakeholder engagement, March 28th, 2014 (University of Arizona campus)

Workshop #2: mid-term project update, stakeholder feedback on research design, May 28th, 2015 (University of Arizona campus)

Workshop #3: final project workshop, present research outcome and project deliverables, May 20th, 2016 (University of Arizona campus)

Summaries of all workshops are included in the website blog link as described in the previous section.

f. ***Communications with decision-makers****, including their name and agency and the date(s) and frequency of your communications. Information on whether the decision-makers were involved in the design of the project plan or if the research has been tailored to address a specifically stated management need is also helpful.*

During the course of the project, the PIs were in regular communication (emails and phone calls at least quarterly) with designated representatives of the water resource agencies that provided matching financial support for the project. These representatives were:

- Jim Prairie, Bureau of Reclamation
- Jon Skindlov, Salt River Project
- Mohammed Mahmoud, Central Arizona Project

g. *Are you aware of any* ***resource management decisions*** *that have come out of this project? If so, please provide a brief description.*

The form of the project data provided via the website contains streamflow information that is directly usable by the water resource agencies listed above in their management planning tools, and this was the agreed upon deliverable from the research team to these agencies.

The project research results have motivated Bureau of Reclamation to continue to work with the project team to use data in other projects, for example assessment of climate change in the Lower Santa Cruz River basin, a project lead by Ms. Eve Halper.

14. **OTHER** *project impacts, outcomes, or communications not discussed above.*

Nothing to report in this category.

15. **BUDGET:** Briefly describe the budget, with particular emphasis on changes to the budget that was submitted in the original proposal. Please discuss reasons for substantial budget modifications or why funds have not been spent as expected.

The funds provided on this project total $172,894. These funds have been spent as follows, in reference to the original proposal budget (to nearest dollar amount).

Spending category	**Original proposed budget**	**Actual funds spent**	**Explanatory notes**
Personnel services	$108,045	$109,752	Salaries and employee related expenses for principal investigators and graduate student supported by the project
General expenses	$7,700	$5,542	Publication expenses, data storage and processing, laptop computer
Travel	$3,800	$3,382	Domestic and international professional conferences
Indirect costs	$53,349	$54,216	
TOTAL	**$172,894**	**$172,894**	

There were no substantial modifications to proposed spending plan as outlined in the original proposal, as the difference between original versus actual funds spent does not deviate by more than $2000 in any of the spending categories.

Submitted by:

Christopher L. Castro		**3/31/2017**
Hsin-I Chang		**3/31/2017**

Reviewed by:

Jonathan T. Overpeck, Award PI University of Arizona	____________________________	__/_/_/
Stephen T. Jackson, SWCSC Director, USGS	____________________________	__/_/_/