Appendix B3
Supplemental Analysis of Future Climate Data

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During the development of the hydrologic simulations under historical and projected climate forcings as part of the Water Supply Assessment, biases were observed for the overlapping period of 1950 to 1999 as compared to the natural flow data set. These biases are due to differences between the General Circulation Model (GCM)-simulated historical climate and observed climate data, differences in hydrology model inputs and parameterization, and differences between the Variable Infiltration Capacity (VIC)-simulated hydrologic responses and observed watershed responses implied in the natural flows. This appendix describes analysis that was conducted to determine the effect of bias in climate forcings used to simulate streamflows and whether choice of the daily weather generation (temporal disaggregation) method significantly affects this bias.

Although it was expected that biases would exist due to the hydrology model and historical gridded climate, it was believed that these biases would be similar (same magnitude and direction) when comparing to simulations of GCM-simulated historical climate. However, the biases were found to be substantially different when comparing three representations of the historical period (1950 to 1999) streamflow: 1) natural flows derived from gage measurements; 2) VIC-simulated flows when forced with observed (derived) historical climate; and 3) VIC-simulated flows when forced with GCM-simulated historical climate. For example, the VIC simulation using observed historical climate for 1950 to 1999 suggested an over-estimation of flows in the Colorado River at Lees Ferry, Arizona. However, the same VIC model, when forced with GCM-simulated historical climate, produced an under-estimation of flow. Without a robust streamflow bias correction method, it is possible that the effects of climate change could be overstated.

Several potential causes of streamflow bias were investigated to support the use of the downscaled climate projections on a daily scale and to support the development of a streamflow bias correction method. The biases were investigated through various separate analyses using the historical climate forcings and VIC model simulations for the period of 1950 to 1999. The following areas related to climate forcing bias were investigated:

1. ***Bias due to 2-degree climate forcings***. The projected climate forcings are bias corrected through the bias correction and spatial downscaling (BCSD) process at a common 2-degree scale. The forcings are corrected for each month, but residual bias at seasonal, annual, and multi-year scales are possible.
2. ***Bias due to 1/8th-degree spatial downscaling***. Because the BCSD process corrects for month-specific bias at the 2-degree scale, it is possible that residual bias exists after performing spatial downscaling to the 1/8th-degree scale.
3. ***Bias due to daily weather generation method***. Two data sets were available using slightly different methods to temporally disaggregate monthly climate data into daily weather inputs. It is possible that the choice of method could affect the resulting streamflow bias.

The evaluation of each of the potential causes of bias is discussed further in the following sections. In each of these evaluations, GCM-simulated historical climate was compared to historical observed climate from Maurer et al. (2002) for the period of 1950 to 1999. Although any of the 112 downscaled climate projections could have been used, one particular projection (Trace 44 – sresa2.ccma_cgcm3_1.4) was selected for presentation of results. Biases were found to be relatively consistent across the range of projections.

Analyses were performed for precipitation at representative grid cells at the locations in the Colorado River Basin (Basin) shown in table B3-1. However, results are shown for the grid cell at the Colorado River at the Glenwood Springs, Colorado, location.

TABLE B3-1
Locations where Evaluation of Biases Was Performed (decimal latitude and longitude)

No.	Location	Nearest Grid Cell (Latitude, Longitude)
1	Colorado River at Lees Ferry, Arizona	36.4375, -112.0625
2	Green River at Green River, Utah	38.8125, -111.3125
3	San Juan River near Bluff, Utah	35.5625, -110.6875
4	Colorado River near Cisco, Utah	38.6875, -109.6875
5	Colorado River above Imperial Dam, Arizona	32.9375, -114.8125
6	Colorado River at Glenwood Springs, Colorado	39.3125, -107.5625
7	Colorado River below Fontenelle Reservoir, Wyoming	42.0625, -110.8125
8	San Juan River near Archuleta, New Mexico	36.6875, -107.8125
9	Colorado River below Davis Dam, Arizona-Nevada	35.1875, -115.0625
10	Taylor River below Taylor Park Reservoir, Colorado	38.8125, -106.5625

1.0 Bias Due to 2-degree Climate Forcings

The BCSD method adjusts monthly biases in climate projections at the 2-degree spatial scale. By construction, the method preserves monthly precipitation and temperature statistics to the observed for the overlapping 1950 to 1999 period at the 2-degree spatial scale. However, because hydrologic responses are dependent on seasonal, annual, and sometimes multi-year sequences of precipitation and temperature, the bias was evaluated for longer temporal scales.

Figures B3-1A and B3-1B show the observed, raw GCM, and the bias corrected GCM monthly precipitation for grid cell at the Colorado River at Glenwood Springs location. As can be seen from the figures, the raw GCM results need to be bias corrected to achieve similar statistics to the observed in the overlapping period. The raw GCM biases appear to be largest in the December and January months. However, after bias correction, the monthly statistics are preserved for all months as compared to the observed (bias corrected [BC] line is same as observed line in figures).

FIGURE B3-1A
Comparison of Monthly Precipitation Non-exceedance Probability Using 2-degree Raw GCM (Raw), Bias Corrected GCM (BC), and Observation (Obs) Data, January–June
2-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GCM-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from 2-degree spatially aggregated precipitation from Maurer et al. (2002).

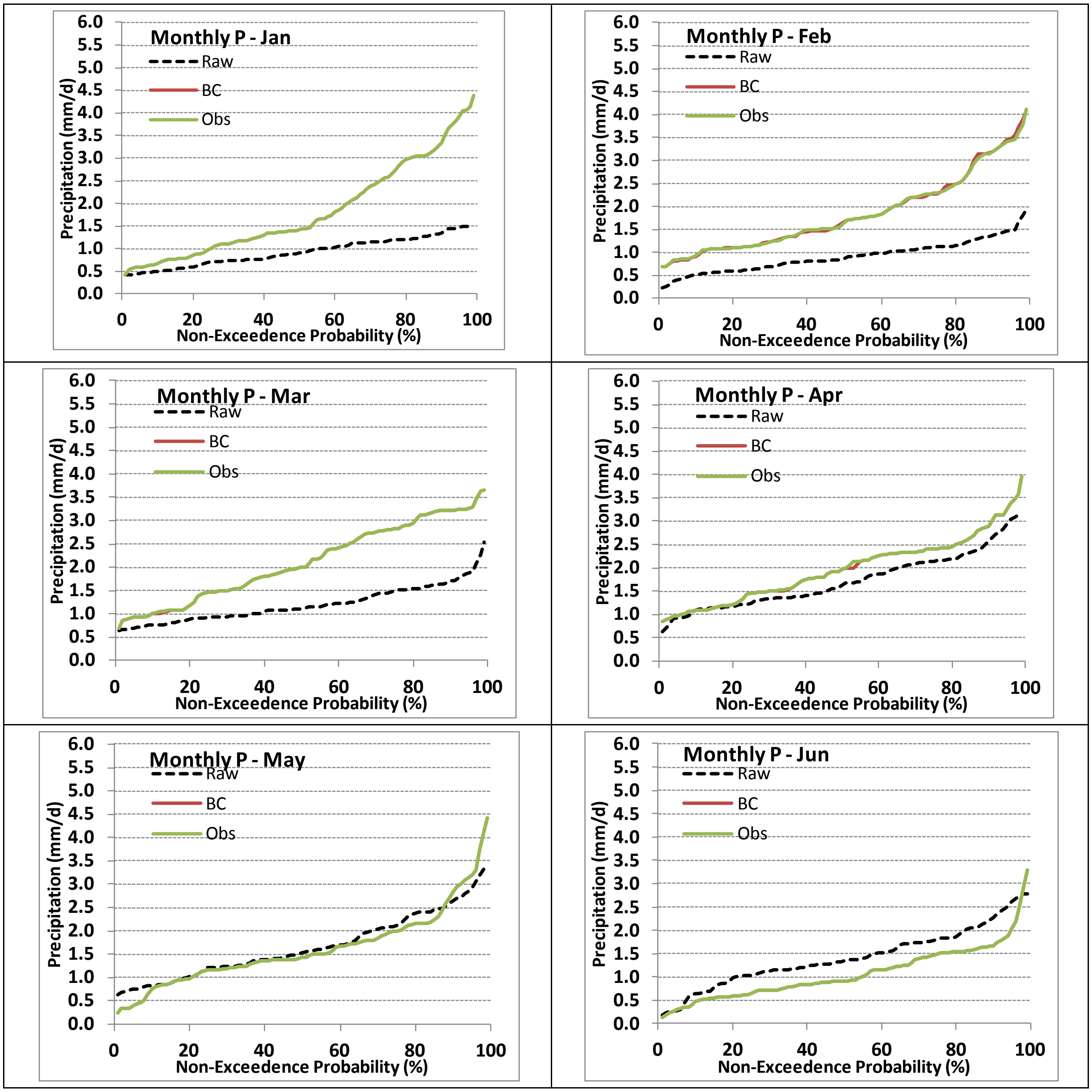


FIGURE B3-1B
Comparison of Monthly Precipitation Non-exceedance Probability Using 2-degree Raw GCM (Raw), Bias Corrected GCM (BC), and Observation (Obs) Data, July–December
2-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GCM-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from 2-degree spatially aggregated precipitation from Maurer et al. (2002).

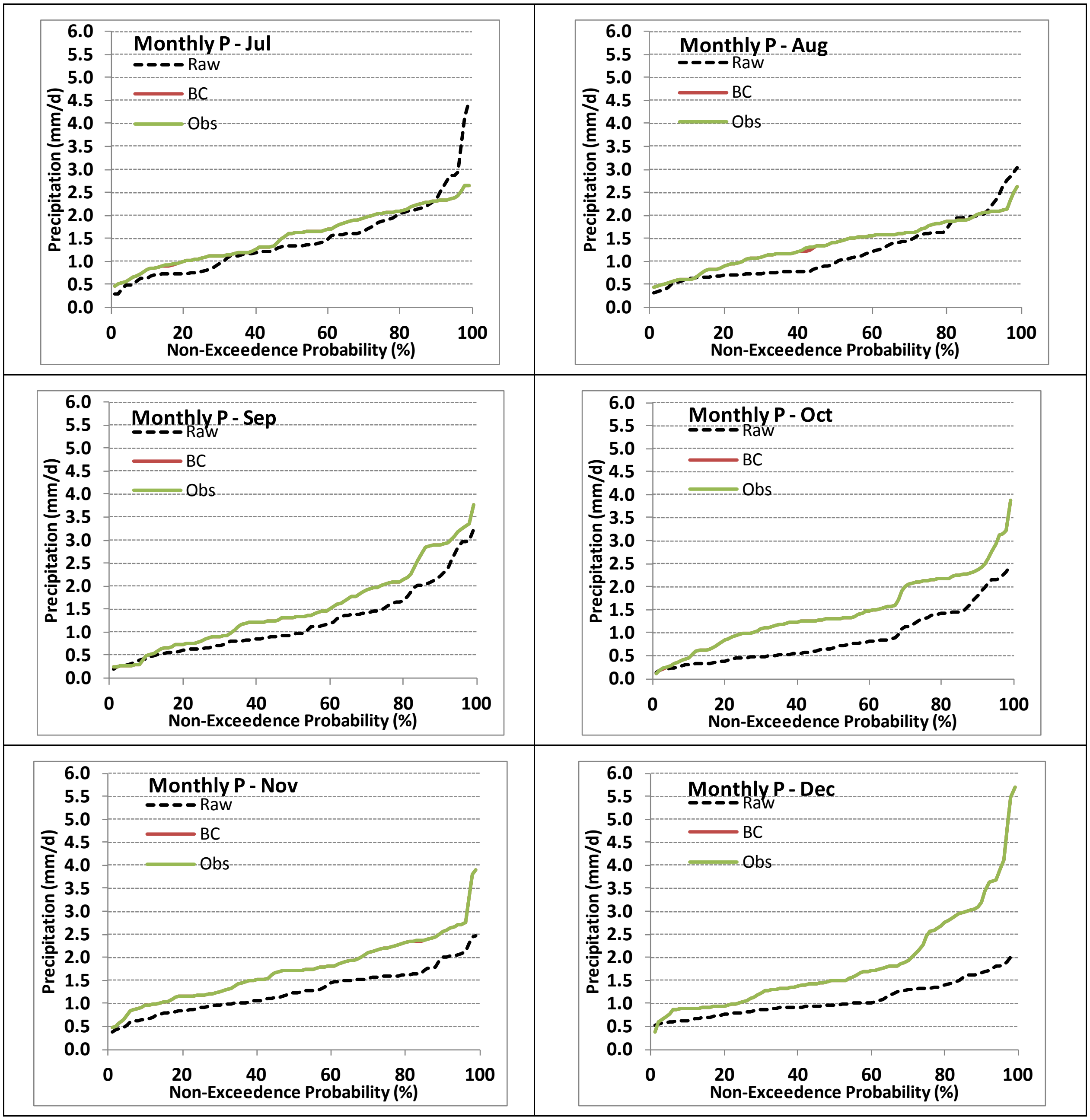


Figure B3-2 shows the same information for the seasonal and annual time scales. As shown in this figure, despite monthly BC, residual bias exists at seasonal and annual scales as compared to the observed. The 2-degree bias corrected GCM precipitation appears to underestimate the periods of high seasonal precipitation. The underestimation of high seasonal precipitation appears to be caused by differences in sequences of wet months within the season between the GCM-simulated historical climate and the observed climate. The seasonal bias is largest during the winter (January, February, and March) and fall (October, November, and December) and relatively small in other seasons. However, small bias continues to persist at annual scales as shown in the bottom panel of the figure. Figure B3-3 also indicates that GCM-simulated historical climate (after bias correction) retains bias at multi-year scales. In almost all multi-year averaging periods, the observed precipitation is larger than the bias corrected GCM precipitation, although the magnitude of this impact has not been isolated.

The temperature biases (not shown) are significantly less than precipitation biases at all time scales and are not believed to represent a significant source of bias to streamflow assessments.

2.0 Bias Due to 1/8th-degree Spatial Downscaling

The BCSD method adjusts for monthly biases in climate projections at 2-degree spatial scale. By construction, the method preserves monthly precipitation and temperature statistics to the observed for the overlapping 1950 to 1999 period at the 2-degree spatial scale. However, to be useful for most watershed assessments, the climate information is needed at finer spatial scales. The spatial downscaling transforms the climate information to the 1/8th-degree scale. The 1/8th-degree spatial scale climate data were used as inputs into the VIC hydrologic model. Analyses were performed to investigate bias after downscaling to this finer spatial scale.

As shown in figures B3-4A and B3-4B, although there is generally agreement between the observed and simulated historical climate statistics at the 1/8th-degree scale, bias exists even at the monthly scale. As with the 2-degree climate information, the biases are largest in winter; particularly December and January. Biases continue to exist at the seasonal, annual, and multi-year scales (figure B3-5 and B3-6). These longer time-scale biases are larger at the 1/8th-degree than at the 2-degree spatial scales.

FIGURE B3-2
Comparison of Seasonal and Annual Precipitation Non-exceedance Probability Using 2-degree Raw GCM (Raw), Bias Corrected GCM (BC), and Observation (Obs) Data
2-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GCM-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from 2-degree spatially aggregated precipitation from Maurer et al. (2002).

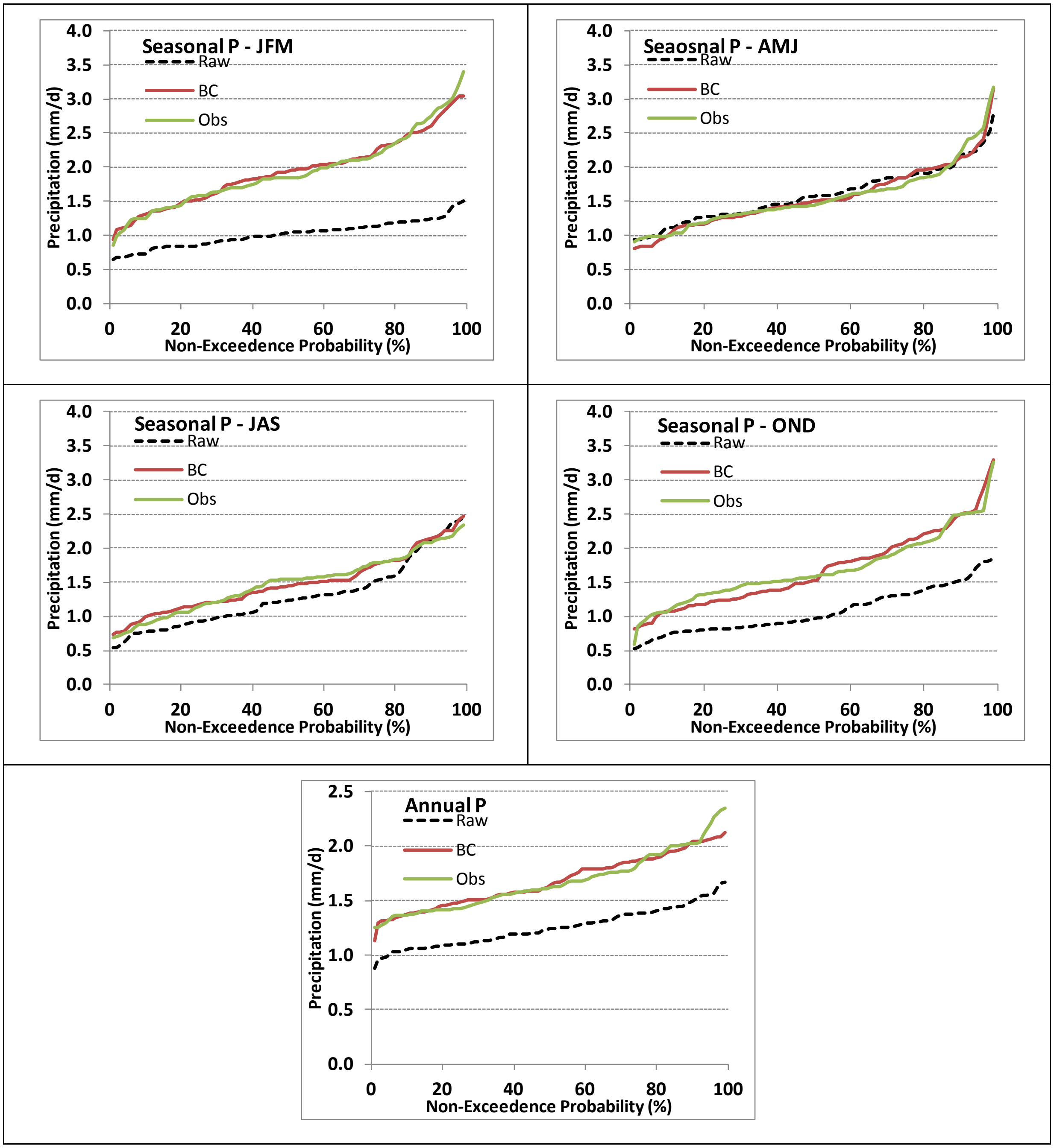


FIGURE B3-3
Comparison of Non-exceedance Probability for Precipitation Averaged over 2-year, 3-year, 5-year, and 10-year Periods, Using 2-degree Raw GCM (Raw), Bias Corrected GCM (BC), and Observation (Obs) Data
2-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GMC-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from 2-degree spatially aggregated precipitation from Maurer et al. (2002).

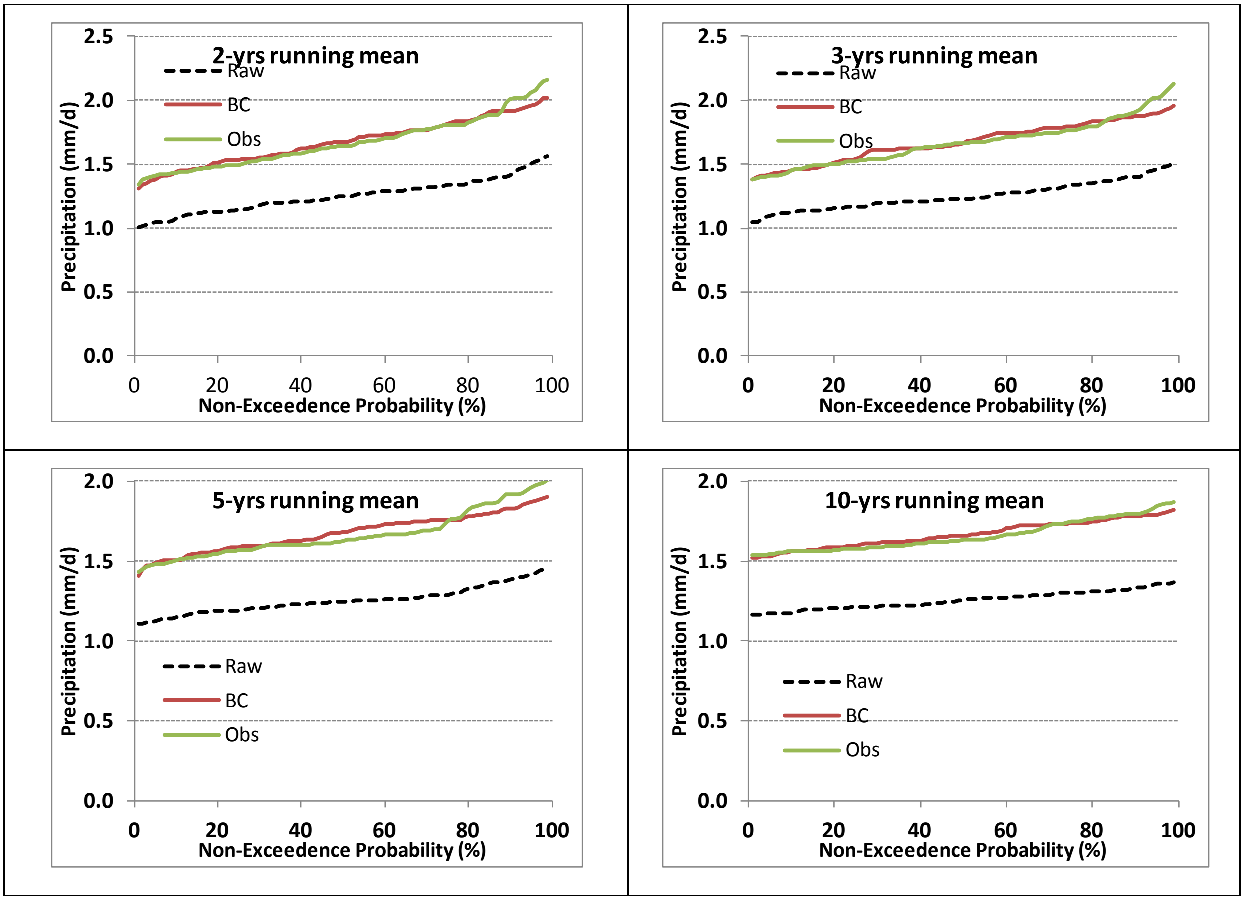


FIGURE B3-4A
Comparison of Monthly Precipitation Non-exceedance Probability Using 1/8th-degree BCSD (sresa2.cccma_cgcm3_1.4) and Observed (Obs) Data, January–June
1/8th-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GMC-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from Maurer et al. (2002).

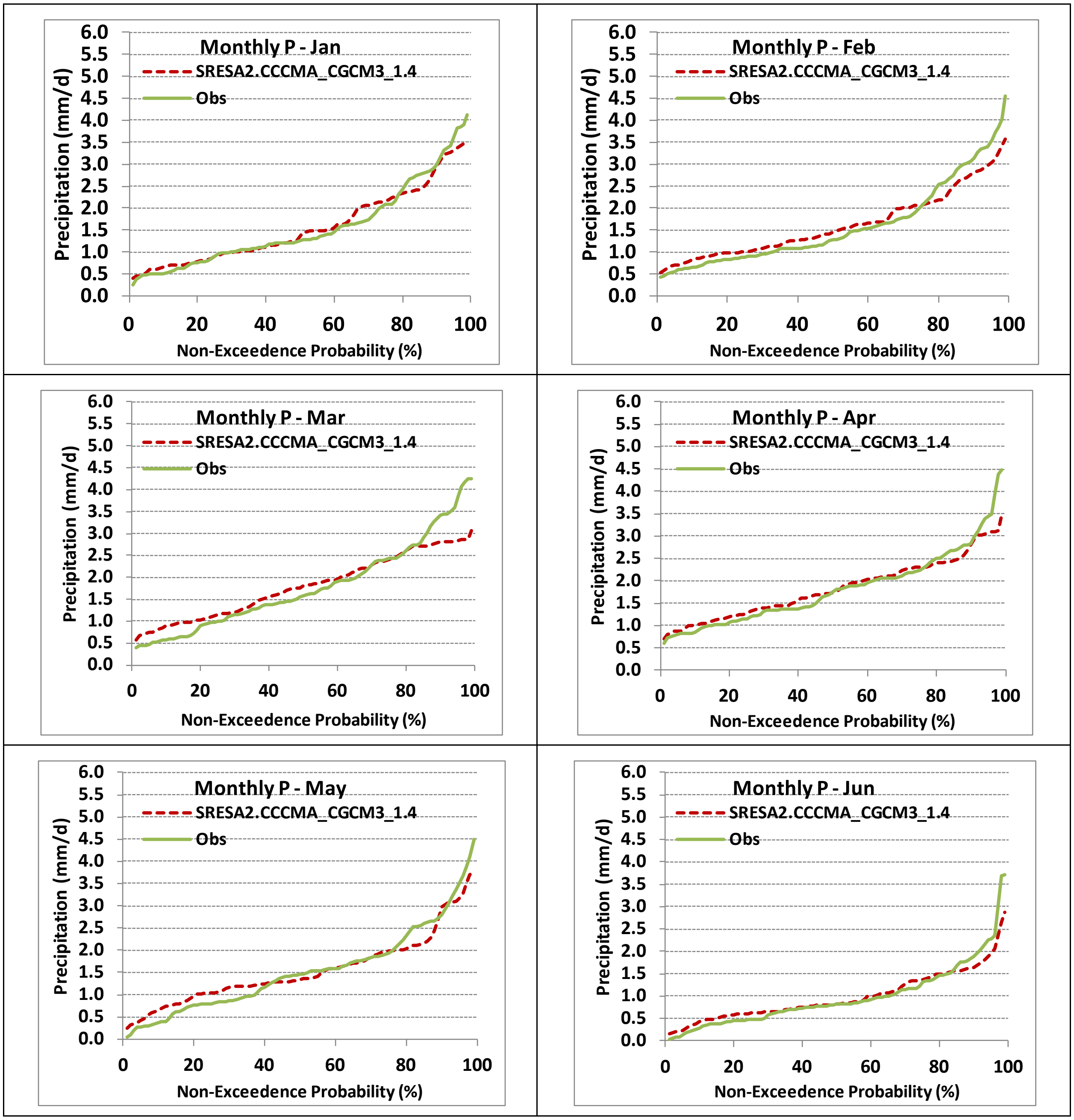


FIGURE B3-4B

Comparison of Monthly Precipitation Non-exceedance Probability Using 1/8th-degree BCSD (sresa2.cccma_cgcm3_1.4) and Observed (Obs) Data, July–December

1/8th-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GMC-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from Maurer et al. (2002).

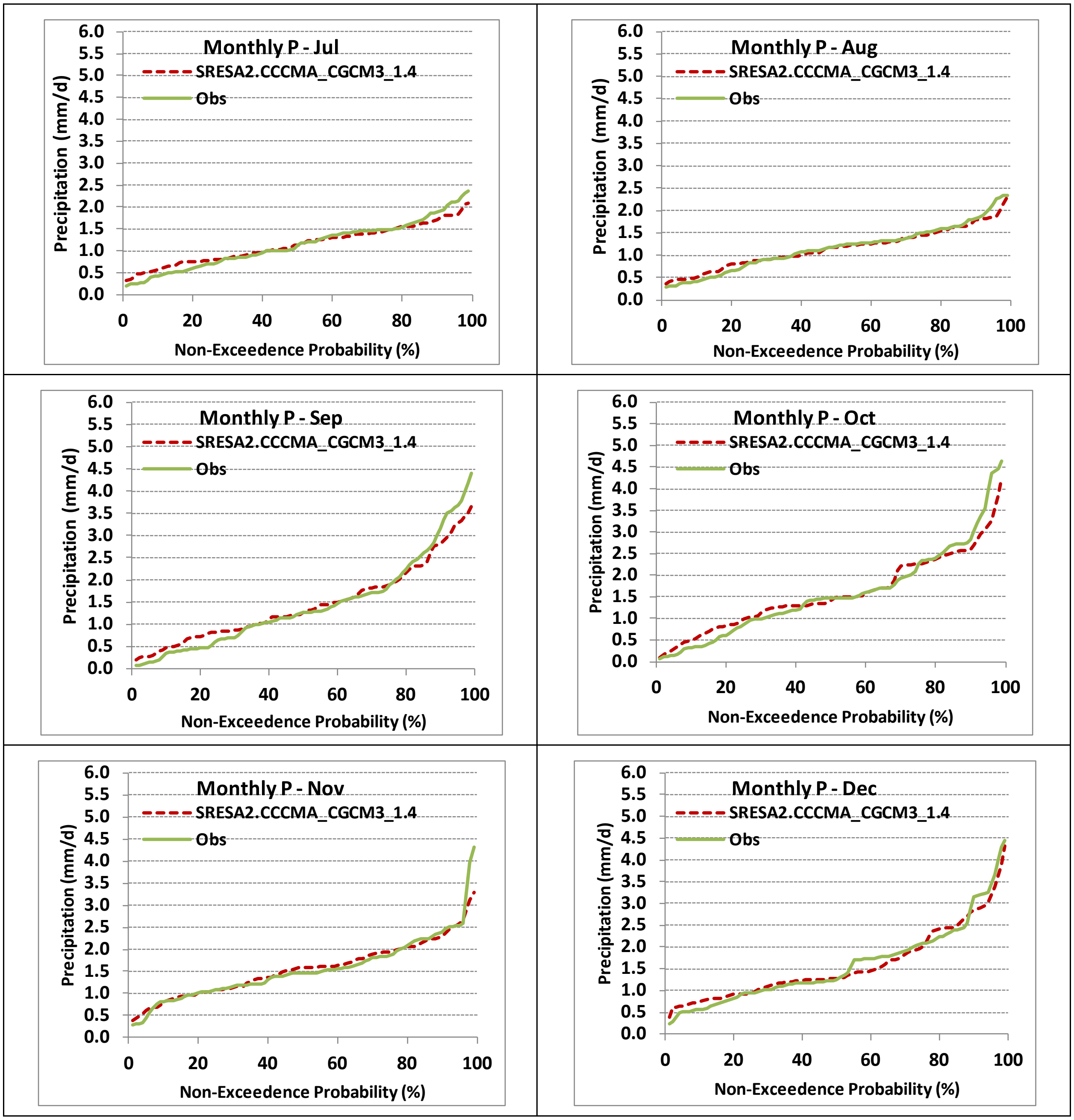


FIGURE B3-5
Comparison of Seasonal Precipitation Non-exceedance Probability Using 1/8th-degree BCSD (sresa2.cccma_cgcm3_1.4) and Observed (Obs) Data
1/8th-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GMC-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from Maurer et al. (2002).

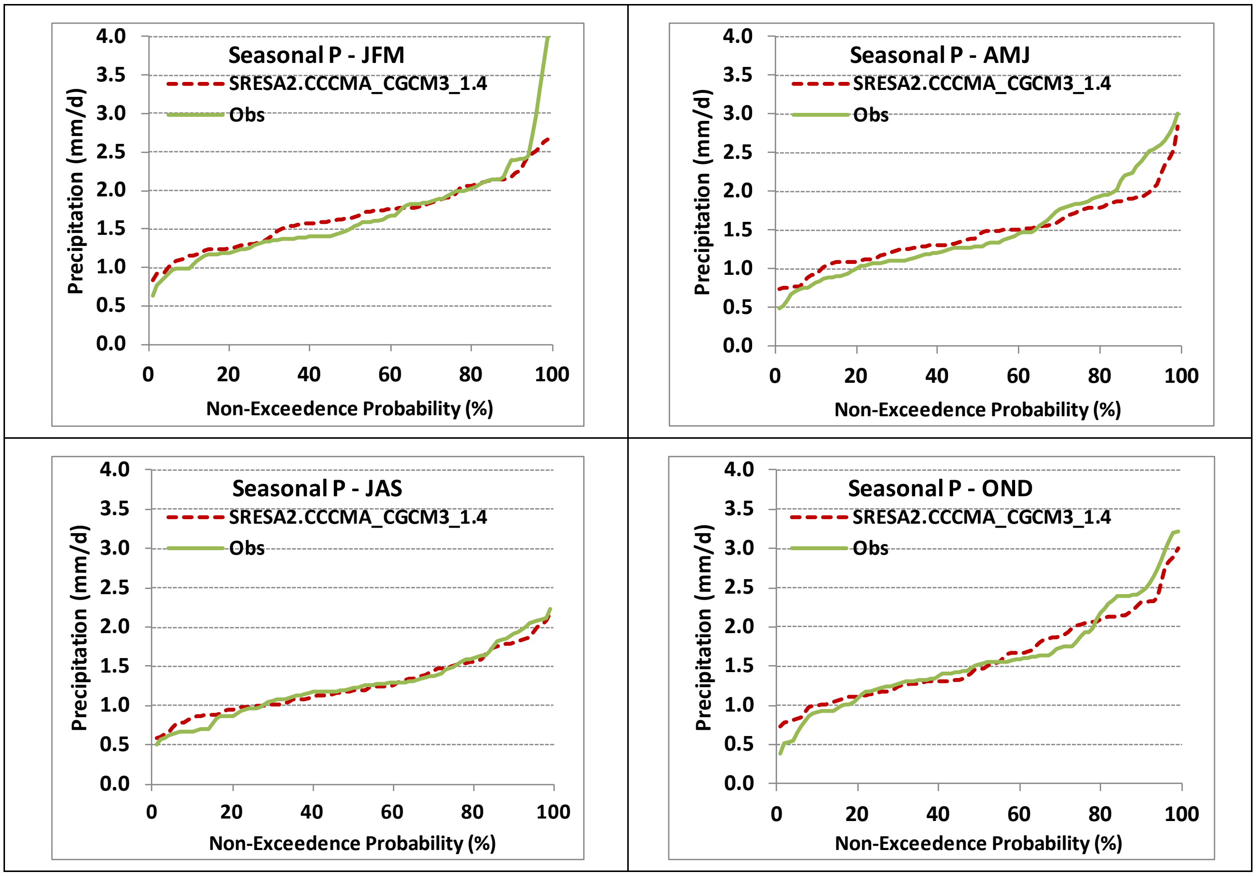


FIGURE B3-6
Comparison of Seasonal and Averaged over 2-year, 3-year, 5-year, and 10-year Periods, Precipitation Non-exceedance Probability Using 1/8th-degree BCSD (sresa2.cccma_cgcm3_1.4) and Observed (Obs) Data
1/8th-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GMC-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from Maurer et al. (2002).

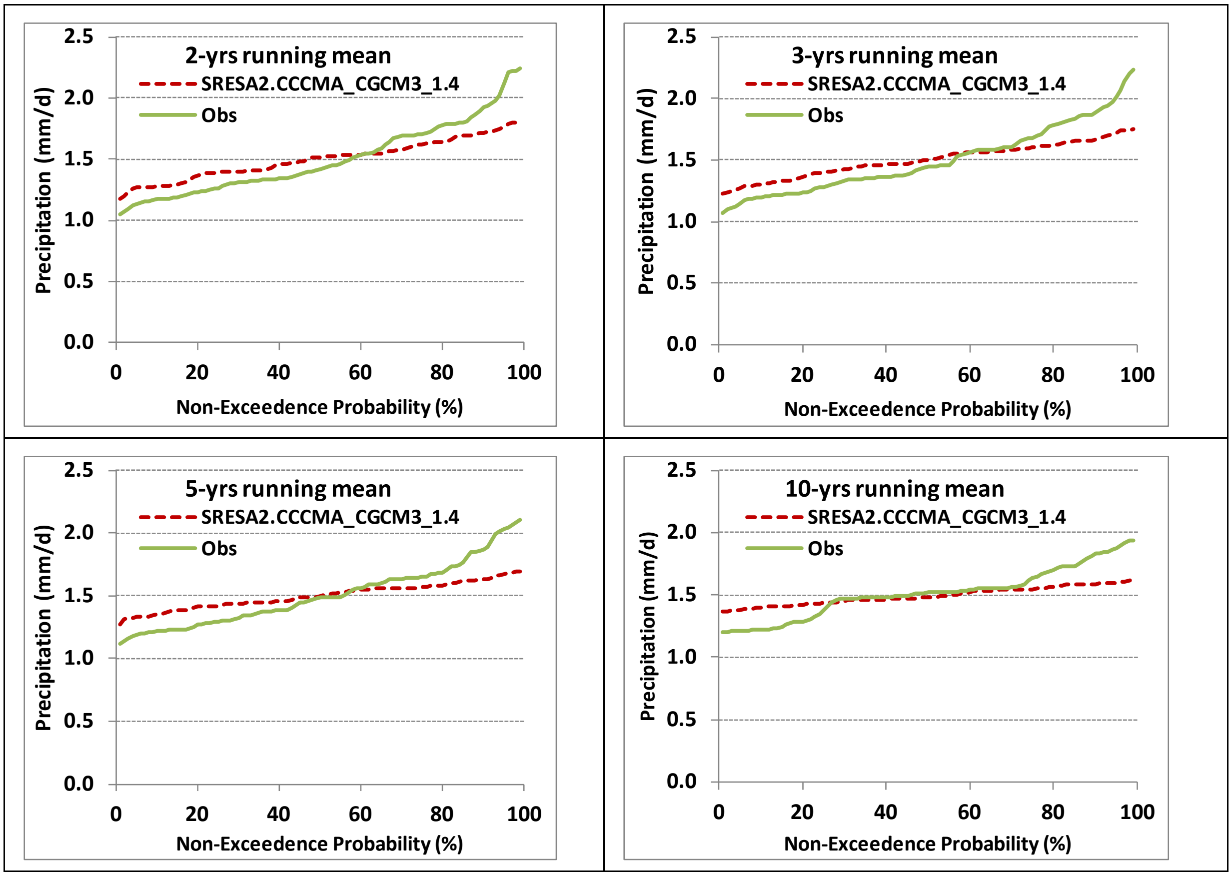
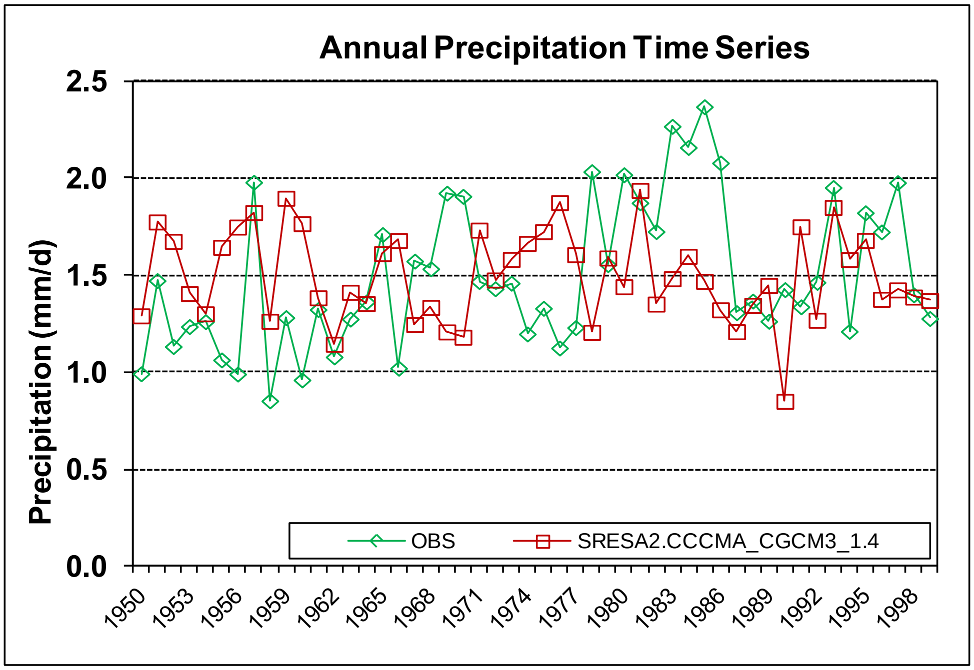


Figure B3-7 shows the annual time history of the observed precipitation and the simulated historical period precipitation for one particular GCM projection for 1950 to 1999. The GCMs are not expected to reproduce the identical sequences of observed precipitation due to differences between actual and simulated initial ocean and climate states, differences between actual and simulated emissions and other radiative forcings, and other model limitations. As shown in the figure, multi-year wet periods such as that observed in 1983 to 1986 are not expected to occur at the same time in the historical simulations, but are expected to be reproduced over some historical period. However, the magnitude of this wet persistence was not reproduced in the simulated climate (see figure B3-7). This under-representation of wet persistence appears to be common across all 112 projections.

FIGURE B3-7
Comparison of Annual Precipitation Non-exceedance Probability Using 1/8th-degree BCSD (sresa2.cccma_cgcm3_1.4) and Observed (Obs) Data, July–December
1/8th-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GMC-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from Maurer et al. (2002).

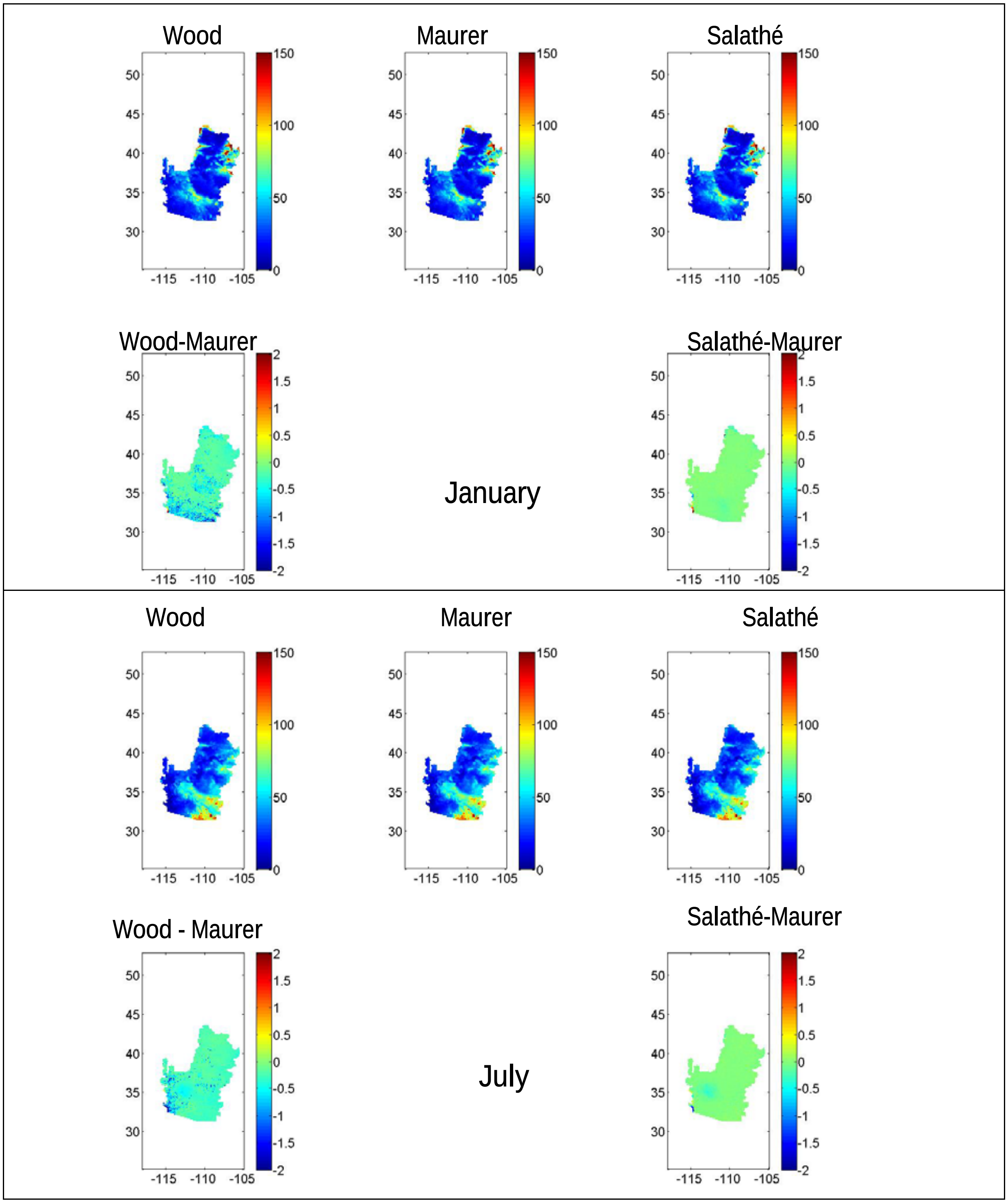


3.0 Comparison of Daily Weather Generation (Temporal Disaggregation) Methods

As part of the assessment of future climate data and their impact on streamflow, two different daily weather datasets were available for the Colorado River Basin Water Supply and Demand Study (Study). The two methods used to develop these datasets are: 1) a method developed by the Climate Impacts Group at the University of Washington (Salathé, 2005) and that used in the Bureau of Reclamation's (Reclamation) West-Wide Climate Risk Assessment (WWCRA) (Reclamation, 2011), and 2) the method developed by Wood et al. (2002) and used in previous Colorado River VIC assessments (Christensen and Lettenmaier, 2007). Both daily weather generation methods preserve monthly total precipitation from the downscaled climate projections and use the historical database to develop realistic daily storm patterns through a temporal disaggregation method. The differences between the two approaches are relatively subtle, but it was found that VIC hydrologic model results were sensitive to the choice of method.

Analysis of the precipitation statistics between the two methods indicates no significant differences at the *monthly* scale. The observational data set was derived from Maurer et al. (2002). Comparisons have been prepared for one downscaled climate projection: Trace 44 – sresa2.cccma_cgcm3_1.4 under the two different daily weather generation methods. Figure B3-8 illustrates a graphical comparison of the monthly precipitation for January and July between the two methods and the observed. The differences between simulated and observed are generally zero, as can be seen from the bottom plots. However, some small differences occur in the extreme southwest of the Basin under the Wood methodology.

FIGURE B3-8
Comparison of Monthly Precipitation between Observational Data (Maurer et al., 2002) and Downscaled Precipitation (Wood et al. 2002; Salathe, 2005), January and July
Only January and July monthly averaged values in millimeters per day [mm/d] are shown. Downscaled climate data for Wood et al. (2002) and Salathé (2005) are from Trace 44 – sresa2.cccma_cgcm3_1.4. Maps are shown with decimal latitude and longitude coordinates.



To better understand the differences in storm patterns generated under each weather generation method, analyses of precipitation events greater than certain thresholds were conducted. Figure B3-9 shows the comparison for 2 mm/d (0.08 inches per day [in/d]) and 20 mm/d (0.8 in/d) precipitation events. Figure B3-10 shows the comparison for 50 mm/d (2 in/d) and 100 mm/d (4 in/d) precipitation events. In general, the method (Salathé, 2005) applied in the WWCRA produces precipitation events more similar to those in the observed record, although differences exist at all precipitation thresholds.

FIGURE B3-9
Comparison of Number of Days (percent) with Precipitation Greater than 2 mm/d (top) and 20 mm/d (bottom) between Maurer et al. (2002) Observed Precipitation and GCM Downscaled Precipitation Using Two Methods (Wood et al., 2002; Salathé, 2005)
GCM downscaled precipitation from Trace 44 – sresa2.cccma_cgcm3_1.4. Maps are shown with decimal latitude and longitude coordinates.

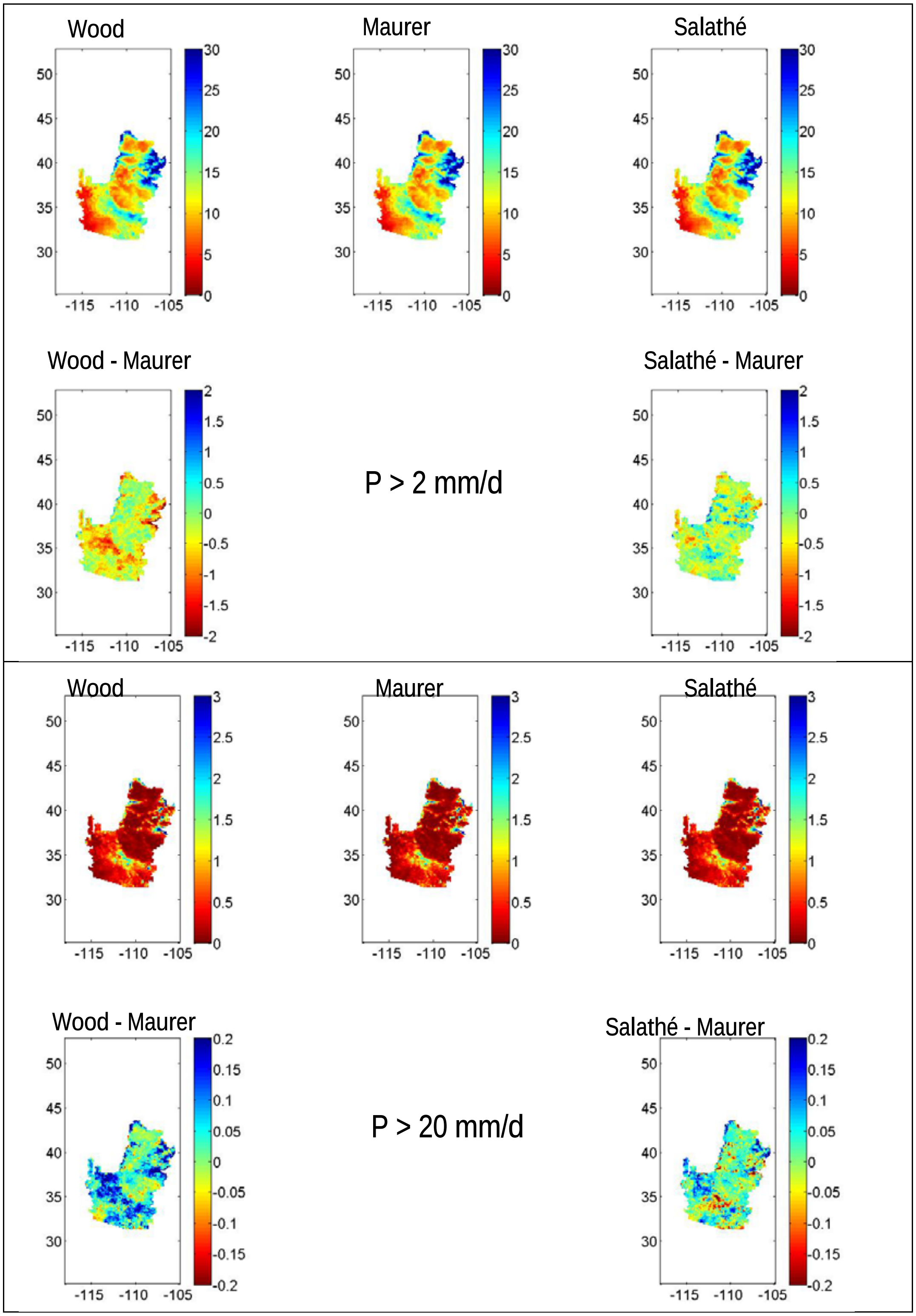
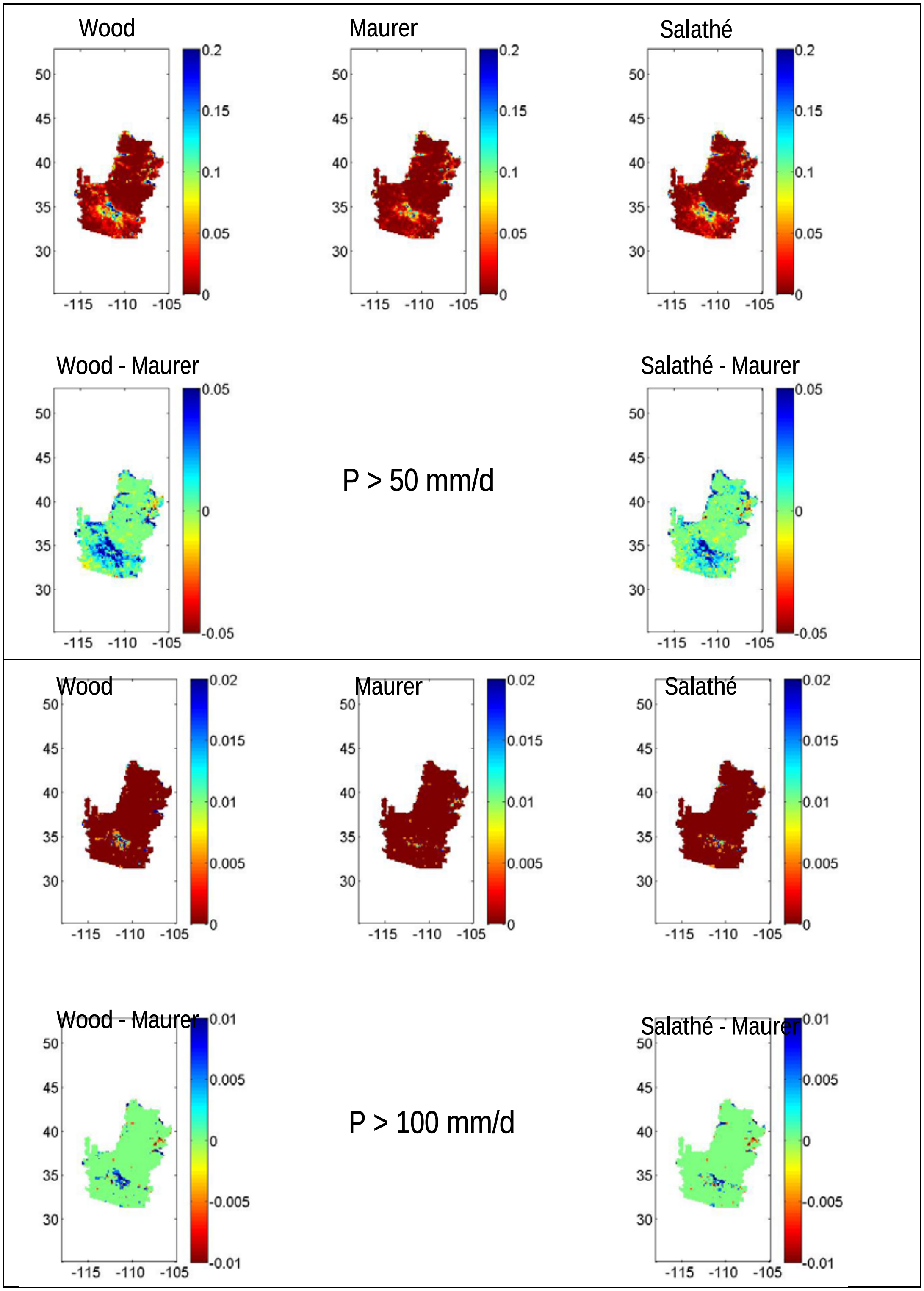
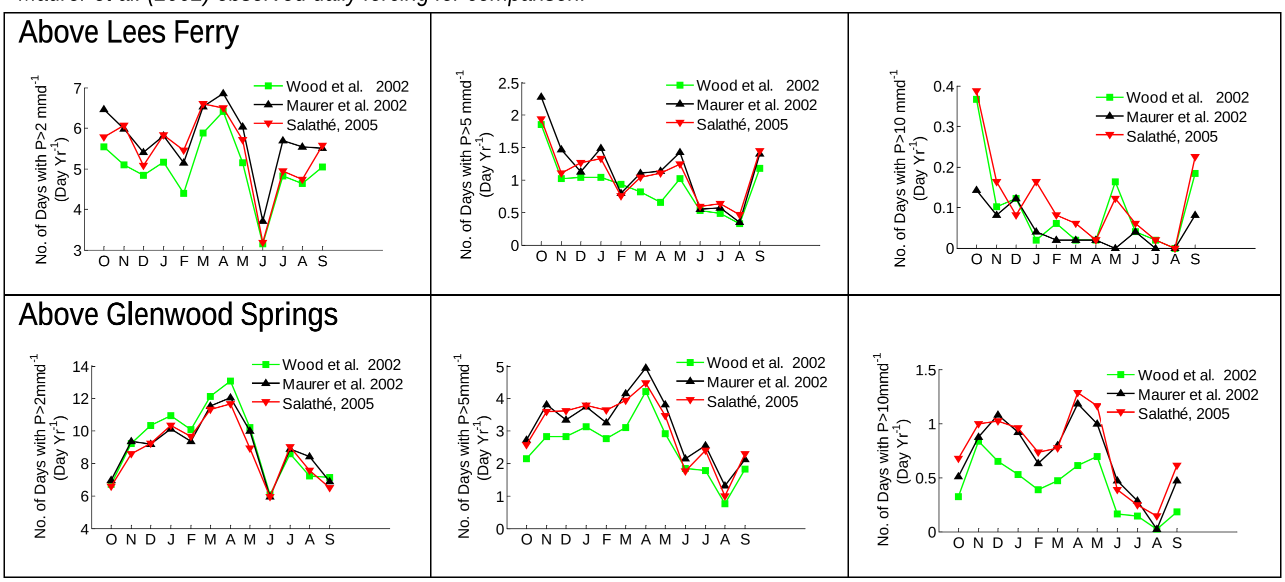


FIGURE B3-10
Comparison of Number of Days (percent) with Precipitation Greater than 50 mm/d (top) and 100 mm/d (bottom) between Maurer et al. (2002) Observed Precipitation and GCM Downscaled Precipitation Using Two Methods (Wood et al., 2002; Salathé, 2005)
GCM downscaled precipitation from Trace 44 – sresa2.cccma_cgcm3_1.4. Maps are shown with decimal latitude and longitude coordinates.



The analysis shown in the spatial figures was performed for each grid cell independently and did not reflect spatial correlation during storm events. In figure B3-11, the spatially averaged precipitation for all grid cells above Lees Ferry was analyzed for thresholds likely to produce runoff (2 mm/d, 5 mm/d, and 10 mm/d). The method employed by Salathé (2005) and incorporated in the WWCRA appeared to more faithfully reflect observed precipitation frequencies for this spatial area. This method produced significantly more representative precipitation frequencies to the observed than that used in the previous VIC simulations, particularly at the 2–mm/d and 5–mm/d thresholds. At the 10–mm/d threshold, both methods overestimated the frequency of occurrence; however, the observed frequency was already low. For the area above Glenwood Springs (figure B3-11), the method applied by Salathé was significantly better at all precipitation frequencies considered.

FIGURE B3-11
Number of Days per Year (averaged over the 1950–1999 period) with Precipitation Larger than Selected Thresholds (2 mm/d, 5 mm/d, and 10 mm/d)
Computed from the daily precipitation over the period 1950–1999 using spatially averaged precipitation for all grid cells above Colorado River at Lees Ferry contributing area (top) and above Colorado River at Glenwood Springs (bottom). Wood et al.(2002) and Salathé (2005) are from downscaled data from Trace 44 – sresa2.cccma_cgcm3_1.4. Values are also shown from Maurer et al. (2002) observed daily forcing for comparison.



Finally, VIC simulations were prepared using the two methods of daily weather generation for the historical period 1950 to 1999 using identical GCM-simulated monthly climate. These simulations were compared to the VIC simulation using historical observed climate; and the natural flow estimates for the Colorado River at Lees Ferry, Arizona. The VIC historical validation (VIC simulation using the historical observed methodology) suggests an overestimation of mean annual flows by about 4 percent. Of the two daily weather generation methods, the VIC simulation using the Salathé method is closest to this historical validation simulation (table B3-2); 2.8 percent compared to 5.8 percent using the Wood et al. (2002) method. Although the differences between methods appear to be relatively small in percentage terms, the difference in mean annual flows is nearly 500,000 acre-feet between methods.

TABLE B3-2
Annual Average Streamflows at Colorado River at Lees Ferry Computed from the Period 1950–1999

Colorado River at Lees Ferry Estimate (1950–1999)	Mean Annual Flow (million acre-feet)	% Difference from Natural Flow Estimate (% Difference from Validation)
Reclamation Natural Flow Estimate	14.673	–
VIC Historical Validation	15.248	3.9%
VIC Historical Simulation (Trace 44; Wood et al., 2002)	14.362	-2.1% (-5.8%)
VIC Historical Simulation (Trace 44; Salathé, 2005)	14.839	1.1% (-2.8%)

4.0 Conclusions

Based on the analysis of climate data, biases, and weather generation methods, several conclusions can be drawn. First, although the bias correction of GCM-simulated climate occurs to preserve monthly statistics, biases for seasonal, annual, and multi-year exist even at the 2-degree spatial resolution. Second, spatial downscaling of climate data to the $1/8^{th}$-degree resolution, required for hydrologic analysis, introduces small biases at the monthly scale that do not exist in the 2-degree data. Finally, even under identical monthly climate forcings, the method for developing daily patterns of precipitation is important and can contribute to substantially different streamflow results. The analysis included in the Study addresses these findings by adopting the Salathé approach of daily weather generation because it produced smaller overall biases as compared to the historical validation simulations. In addition, the analysis indicates that biases in climate data and hydrologic simulation will continue to be present, and that a final adjustment to VIC-simulated streamflows is necessary to use these flows in comparable fashion in systems modeling. For these reasons, a method for bias correction of resulting VIC-simulated flows is incorporated and discussed in appendix B4.

5.0 References

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