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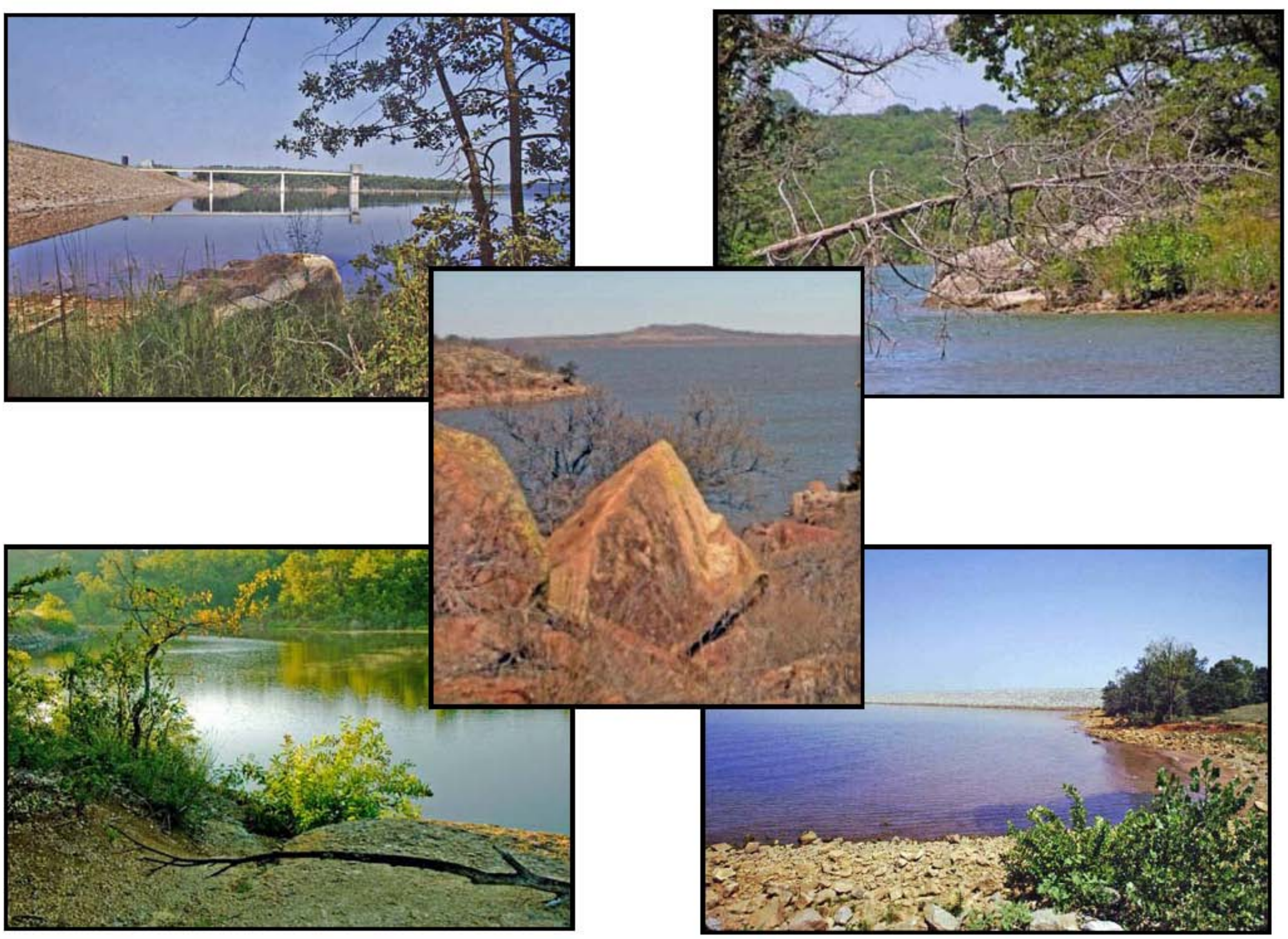
Technical Memorandum 86-68210-2010-01

Climate Change and Hydrology Scenarios for Oklahoma Yield Studies



U.S. Department of the Interior
Bureau of Reclamation

April 2010

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Climate Change and Hydrology Scenarios for Oklahoma Yield Studies

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U.S. Department of the Interior
Bureau of Reclamation

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Executive Summary

The Reclamation Oklahoma-Texas Area Office (OTAO) is re-evaluating the firm yield of seven Reclamation reservoirs in Oklahoma. The yield determination approach is similar to the method used in the original Bureau of Reclamation (Reclamation) planning studies. The study is based on hydrologic and weather variability observed from 1926–2008. These observations have been translated into 1926–2008 assumed monthly time series for reservoir inflow (had the reservoir existed for the entire historical period), reservoir evaporation, and reservoir precipitation. This historical hydroclimate then is used as an assumption for the future hydroclimate when assessing water availability from each reservoir during the next 50 years. The updated yield results are meant to serve future water planning in the State, especially in cases where the updated yield has changed significantly.

One question facing the yield assessment is how sensitive the results are to assumptions about future climate over Oklahoma and Texas. A change in the regional precipitation aspects of climate would affect water supply through changes in reservoir inflow and reservoir precipitation. Likewise, a change in the regional temperature aspects of climate would affect water supply through changes in reservoir evaporation and watershed evapotranspiration.

Given that the yield assessment already considers reservoir sedimentation projections through 2060, it was decided to develop yield assessment assumptions for a range of future climates also through 2060, where the future climate definitions are based on current climate change science. The merit of doing this analysis is that a sense of yield uncertainty and, thus, a more robust characterization of yield would be conveyed to subsequent water planning efforts. The objectives of this study were to (1) define climate change scenarios (i.e., changes in monthly climate from an historical period to a future period), (2) assess changes in reservoir inflow, precipitation, and evaporation associated with each scenario, and then (3) use those changes to generate "alternative historical" data series for reservoir inflow, precipitation, and evaporation for use in conducting alternative yield assessments (i.e., one for each climate change scenario). One theme within these objectives is that priority was placed on retaining our sense of the region's historical hydroclimate variability observed from 1926–2008 (e.g., envelope of monthly and annual possibilities, interarrival of drought and surplus periods) but shifted to represent a scenario change in monthly hydroclimate.

Definition of future climate change scenarios, in part, is motivated by awareness of recent climate observations but ultimately rooted in contemporary climate projection (or climate simulation) information. Recent observations suggest that the global climate system has been warming and is likely to continue warming during the 21st century, partly due to human activities translating into greenhouse gas emissions. Evidence also suggests that warming has been experienced over much of the United States during the 20th century. Climate simulation models have been developed and applied to reproduce global to continental temperature trends during the 20th century. Successes in these efforts have built confidence in use of these models to project future climate conditions under scenarios of future greenhouse gas emission rates. This study bases climate change definitions on the results of these global climate simulations, spatially downscaled over the Oklahoma/Texas region.

Review of current downscaled climate projections over the study region suggests a consensus message that the southern Great Plains are likely to be warmer in the future. However, the rate of warming varies among climate projections. Review of these same projections suggests that regional precipitation change may vary from drier to wetter over the southern Great Plains. On the whole, in order to relate this yield assessment to the breadth of current climate projection information, it was decided to focus on projected climate change over the region measured from climate during 1950–1999 to climate during 2030–2059. It was then decided to define five climate change scenarios based on review of downscaled projections discussed above: four scenarios to represent the range of projected changes from less to more warming, paired with drier to wetter conditions, and a fifth scenario to represent the central tendency of projected changes. So in summary, the analytical outline features three steps mapping to the three objectives mentioned above:

1. Define five climate change scenarios that reflect current climate projections and reflect climate projection uncertainty and central tendency over Oklahoma and North Texas.

2. Assess hydrologic response under each climate change scenario in each watershed using comparative hydrologic simulations: one with historical observed weather and one with weather adjusted for change in monthly temperature and precipitation.

3. Assess reservoir precipitation and evaporation response under each climate change scenario, where evaporation response is related to temperature change.

Stepping down into the details of defining climate change scenarios and assessing hydrologic conditions, there were several candidate methodologies that could be borrowed from peer-reviewed literature. In this study, the preferred technique was steered by three scoping decisions, including the first decision reflected in Step 1 above, involving the definition of five representative climate change scenarios. The second and third decisions are:

- Portray change in monthly climate variability rather than monthly climate mean.

- Emphasize consensus change information from a collective of projections.

Available peer-reviewed techniques have been demonstrated to address the first two scoping decisions, but not necessarily the third. The priority to emphasize consensus climate change information from climate projections motivated the decision to modify an available peer-reviewed technique to be informed by a collective, or "ensemble," of climate projections rather than a single climate projection. Given that a new technique is being introduced for supporting the yield assessment, it was decided to show the merits of the new technique through comparative application with two predecessor peer-reviewed techniques, including the one that was modified for purposes here. The three techniques are similar in that they each focus on period-change in monthly climate (i.e., temperature and precipitation). Their applications differ in terms of (1) what monthly climate aspects are reflected in the climate change definitions and (2) how many climate projections inform the climate change definitions. The techniques are labeled here as:

- ***Delta*****:** where the analysis reflects change in period monthly mean temperature and precipitation over the study region, sampled from a single climate projection

- ***Hybrid-Delta (HD)*****:** where the analysis reflects change in period monthly distributions of temperature and precipitation over the study region, sampled from a single climate projection

- ***Ensemble Hybrid-Delta (HDe)*****:** **(*****chosen technique*****)** where the analysis reflects change in period monthly distributions of temperature and precipitation over the study region, sampled from an ensemble of climate projections.

Delta might be thought of as reflecting change in "climate norms." *HD* and *HDe* might be thought of as reflecting change in "the envelope of climate variability." *Delta* and *HD* both involve defining a climate change scenario based on information from a single climate projection. *HDe* involves defining a climate change scenario based on pooled information from a collection of climate projections. The reason for doing the latter is to address an interpretation question about a computed period change within a single climate projection: is the computed change actually "climate change" or misunderstood multidecadal climate variability within the projection? The interpretation issues stem from the facts that contemporary climate projections are produced by a collective of global climate models (GCM) that express multidecadal variability to variable degree and that the projections do not all originate from a common initial climate system condition (e.g., state of the oceans in 1900 or 2000). *HDe* addresses this interpretation concern by defining climate change scenarios that emphasize consensus monthly changes from a collection of climate projections. This would seem to mute the significance of GCM differences in simulating multidecadal variability and effects of inconsistent initial conditions among the projections.

For each technique (*Delta*, *HD*, and *HDe*), five climate change scenarios were defined and carried forward to the response analyses: four scenarios to "bracket" the projected climate changes from 1950–1999 to 2030–2059 and a fifth to reflect the central tendency of projected changes. For each climate change scenario, associated weather inputs were generated to drive both hydrologic modeling and the analyses on change in reservoir precipitation and evaporation. Hydrologic modeling was performed using an application of the Variable Infiltration Capacity model in each of the seven reservoir basins in this study. Change in reservoir evaporation was based on the empirical relationship between historical evaporation and temperature at each reservoir.

Results show that all three techniques lead to a generally consistent portrayal of annual changes in reservoir hydroclimate. However, for the portrayal of monthly changes in reservoir hydroclimate (i.e., inflow, precipitation, and evaporation), the *HDe* stands out relative to *Delta* or *HD* techniques by portraying more consistent, and perhaps more realistic, month-to-month changes. This attribute stems from emphasizing consensus change information from a collective of projections and is viewed as a desirable trait of hydroclimate scenarios for framing the yield sensitivity analysis.

Deliverables from this analysis are five *HDe*-based scenarios of changes in mean-monthly runoff at each of the seven reservoir basins in this study and also change in mean-annual reservoir inflow. These changes then are used to adjust the default 1926–2008 historical time series for monthly inflow. Deliverables also include five HDe-based scenarios of changes in watershed mean-monthly precipitation and temperature, which are then used to adjust the default 1926–2008 historical time series of reservoir precipitation and evaporation, respectively.

This analysis is designed to provide some quantitative illustration of how runoff in Reclamation's Oklahoma reservoir watersheds would respond to range of future climate possibilities. The study was designed to take advantage of best available datasets and modeling tools and to follow methodologies documented in peer-reviewed literature where possible. However, there are a number of analytical uncertainties that are not reflected in study results, including uncertainties associated with future global climate forcings, global climate simulation, climate projection bias-correction, climate projection spatial downscaling, generating weather sequences consistent with climate projections, and how to best simulate natural runoff response to changes in climate.

Contents

Figures

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Acronyms

°C	degrees Celsius
°F	degrees Fahrenheit
%	percent
ALTUS	Lugert-Altus Reservoir on the North Fork of the Red River, W.C. Austin Project above Lake Altus
ARBUC	Lake of the Arbuckles on Rock Creek tributary of the Washita River, Arbuckle Project
BCSD	Bias Correction Spatial Disaggregation
CMIP	Coupled Model Intercomparison Project (CMIP1, CMIP2, and CMIP3 are CMIP phases 1, 2, and 3, respectively)
COBB	Fort Cobb Reservoir on Pond (Cobb) Creek tributary of the Washita River, Washita Project
COOP I.D.	identification number for station in NWS Cooperative Observer Program
DCP	Downscaled Climate Projections
Delta	Delta method for assessing hydrologic impacts, where “climate change” weather reflects change in period monthly mean temperature and precipitation sampled from a single projection
ET	evapotranspiration
FOSS	Foss Reservoir on the Washita River, Washita Project
GCM	General Circulation Model, or Global Climate Model
GHG	greenhouse gas
GP	Great Plains
HD	Hybrid-Delta method for assessing hydrologic impacts, where “climate change” weather reflects change in period monthly distributions of temperature and precipitation sampled from a single projection
HDe	Ensemble Hybrid-Delta method for assessing hydrologic impacts, where “climate change” weather reflects change in period monthly distributions of temperature and precipitation sampled from a pooled ensemble of projections
IPCC	Intergovernmental Panel on Climate Change
km	kilometer

LCRA/SAWS	Lower Colorado River Authority (TX)/San Antonio Water System (TX)
MCGEE	McGee Creek Reservoir on McGee Creek, McGee Creek Project
MTNPA	Tom Steed Reservoir on West Otter Creek, Mountain Park Project
NARCCAP	North American Regional Climate Change Assessment Program
NORMA	Lake Thunderbird on Hog Creek and Little River, Norman Project
NWS	National Weather Service
OK	Oklahoma
OTAO	Oklahoma-Texas Area Office
RCM	Regional Climate Model
SWE	snow water equivalent
TX	Texas
USGCRP	U.S. Global Change Research Program
VIC	Variable Infiltration Capacity hydrologic model
WCRP	World Climate Research Programme

1. Introduction

The Reclamation Oklahoma-Texas Area Office (OTAO) is re-evaluating the firm yield of seven Bureau of Reclamation (Reclamation) reservoirs in Oklahoma:

- ALTUS: Lugert-Altus Reservoir on the North Fork of the Red River above Lake Altus Dam
- ARBUC: Lake of the Arbuckles on Rock Creek, tributary of the Washita River above Lake of the Arbuckles Dam
- FOSS: Foss Reservoir on the Washita River above Foss Dam
- COBB: Fort Cobb Reservoir on Pond (Cobb) Creek tributary of the Washita River above Fort Cobb Dam
- MCGEE: McGee Creek Reservoir on McGee Creek above McGee Creek Dam
- MTNPA: Tom Steed Reservoir on West Otter Creek supplemented by Elk Creek via the Bretch Diversion Canal above Mountain Park Dam
- NORMA: Lake Thunderbird on Hog Creek and Little River above Norman Dam

The yield determination approach is similar to the method used in the original Reclamation planning studies. The study is based on hydrologic and weather variability observed from 1926–2008. These observations have been translated into 1926–2008 assumed monthly time series for reservoir inflow (had the reservoir existed for the entire historical period), reservoir evaporation, and reservoir precipitation. This historical hydroclimate then is used as an assumption for the future hydroclimate when assessing water availability from each reservoir during the next 50 years. The updated yield results are meant to serve future water planning in the State, especially in cases where the updated yield has changed significantly.

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For each technique (*Delta*, *HD*, and *HDe*), five climate change scenarios were defined and carried forward to response analyses: four scenarios to "bracket" the projected climate changes from 1950–1999 to 2030–2059 and a fifth to reflect the central tendency of projected changes. For each climate change scenario, associated weather inputs were generated to drive both hydrologic modeling and the analyses on change in reservoir precipitation and evaporation. Hydrologic modeling was performed using an application of the Variable Infiltration Capacity

(VIC) model in each of the seven reservoir basins in this study. Change in reservoir evaporation was based on the empirical relationship between historical evaporation and temperature at each reservoir.

2. Defining Climate Change Scenarios

The first task in the analytical outline involves assessing climate changes within contemporary climate projections and then selecting, or "defining," climate changes to serve as scenarios of monthly change for use in subsequent tasks. The focus is on changes in monthly temperature and precipitation over the study region. Thus, defining climate change scenarios involves:

- Surveying available climate projection information over the study region.
- Deciding whether to eliminate some of the projections from consideration.
- Defining climate change scenarios from the remaining climate projections under consideration.

The third step was conducted in two ways, as mentioned in the "Introduction." Each way is tailored for the weather generation method to be featured in the hydrologic response assessment of Task 2. The first way involves use of single climate projections to define climate change scenarios and supports the *Delta* and *HD* methods of weather generation. The second way is ensemble-informed and supports the *HDe* method of weather generation.

2.1 Survey of Available Climate Projections

During the past decade, global climate projections have been made available through the efforts of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP), which has advanced in three phases (CMIP1 [Meehl et al. 2000], CMIP2 [Covey et al. 2003], and CMIP3 [Meehl et al. 2007]). The WCRP CMIP3 efforts were fundamental to completing the *IPCC Fourth Assessment Report* (IPCC 2007). The CMIP3 dataset was produced using climate models that include coupled atmosphere and ocean general circulation models, each applied to simulate global climate response to various future greenhouse gas (GHG) emissions paths (IPCC 2000) from various end-of-20th century climate conditions ("runs"). The emissions paths vary from lower to higher emissions rates, depending on global technological and economic developments during the 21st century.

One issue with the CMIP3 dataset and climate models projections, in general, is that the spatial scale of climate model output is too coarse for regional studies on water resources response (Maurer et al. 2007). Spatial downscaling of GCM outputs typically is conducted to address this issue. By definition, spatial downscaling is the process of taking GCM output on simulated climate and translating that to a finer spatial scale that is more meaningful for analyzing local and regional climate conditions. Many downscaling methods have been developed, all of which have strengths and weaknesses. Several reports offer discussion on the various methodologies, notably the *Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment* (IPCC 2007 (Chapter 11, Regional Climate Projections), Wigley, 2004, Brekke et al. 2009 (Appendix B)). The various methodologies might be classified into two classes: dynamical, where a fine scale regional climate model (RCM) with a better representation of local terrain simulates climate processes over the region of interest; and statistical, where large-scale climate features are statistically related to fine scale climate for the region.

To date, there has not been a demonstration of dynamical downscaling to produce an archive that comprehensively reflects the 100+ CMIP3 climate projections available, particularly to characterize climate projection uncertainty throughout the 21st century. While there are new efforts to downscale multiple climate projections using multiple RCMs, such as the North American Regional Climate Change Assessment Program (NARCCAP, http://www.narccap.ucar.edu/), the computational requirements of RCM implementation for more than a few years of simulation have limited the feasibility of using dynamical downscaling for the purpose above. Among the various statistical methods that might be considered for the given purpose, certain characteristics are desirable:

- Well tested and documented, especially in applications in the United States.
- Automated and efficient enough to feasibly permit the downscaling of many 21st century climate projections, thereby permitting more comprehensive assessments of regional to local climate projection uncertainty.
- Able to produce output that statistically matches historical observations.
- Capable of producing spatially continuous, fine-scale gridded output of precipitation and temperature suitable for water resources and other watershed-scale impacts analysis.

One technique that satisfies these criteria is the Bias-Correction and Spatial Disaggregation (BCSD) approach of Wood et al. (2002). This technique was used to generate downscaled translations of 112 CMIP3 projections, which are available online at the "Bias-Corrected and Downscaled WCRP CMIP3 Climate Projections" archive[1] (Downscaled Climate Projections [DCP] archive). These projections were produced collectively by 16 different CMIP3 models simulating 3 different emissions paths (e.g., B1 (low), A1b (middle), A2 (high)) from different end-of-20th century climate conditions. Compared to dynamical

[1] http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/.

downscaling approaches, the BCSD method has been shown to provide downscaling capabilities comparable to other statistical and dynamical methods in the context of hydrologic impacts (Wood et al. 2004). However, dynamical downscaling also has been shown to identify some local climate effects and land-surface feedbacks that BCSD cannot readily identify (Salathé et al. 2007). Another potential limitation of BCSD, like any statistical downscaling method, is the assumption of some statistical stationarity in the relationship between GCM-scale precipitation and temperature and finer-scale precipitation and temperature.

The DCP archive data were used as the initial set of climate projections considered for defining climate change scenarios in this study. The decision follows approached used in recent Reclamation studies (Reclamation 2008, Reclamation 2009). Each climate projection is specified on a monthly time step from 1950 to 2099 and at roughly a 12-kilometer (km) (1/8 degree [º]) spatial resolution over the contiguous United States. DCP data were surveyed for this study within a region that encapsulates the seven reservoir watersheds considered in the yield assessment (Figure 1). Note that this large-region view is only used in Task 1 to select projections or projection-ensembles to inform climate change scenarios. Moving on to Task 2, the spatially distributed information from these DCP data are related to the hydrologic response analysis.

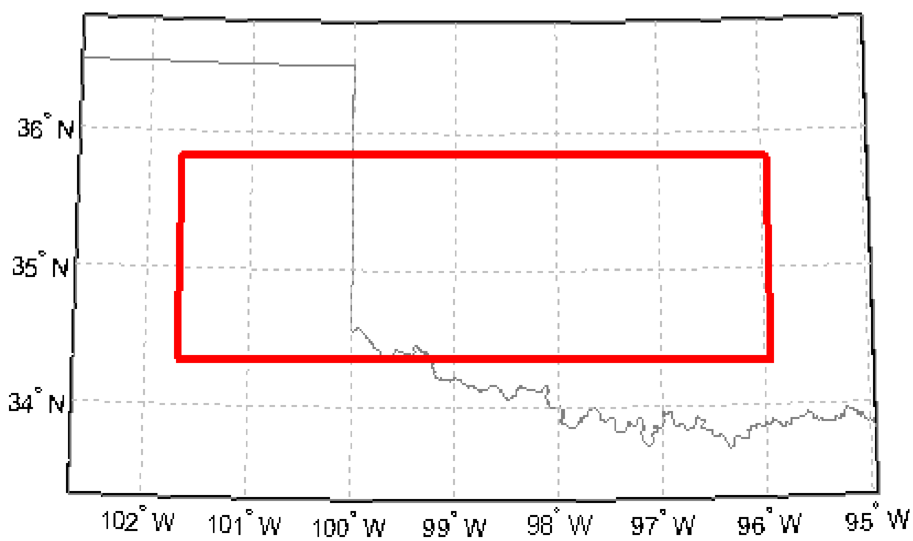

Figure 1. Study Region of Climate Projections Survey and Climate Change Scenario Definition.

2.2 Considering Elimination of Climate Projections Based on Credibility

The next step involves defining climate change scenarios from the surveyed projections. Before defining such scenarios, deliberations were made on whether to first eliminate some of the climate projections from consideration. For example, one might rationalize exclusion of projections viewed to be less credible than others, perhaps based on an unequal regard for the different future climate forcings, represented in the collection of projections, or based on a view that some GCMs used to generate projections are more credible than others based on their relative skill in simulating the past. Ultimately, a rationale was adopted, following similar rationale stated in earlier Reclamation studies (Reclamation 2008,[2] Reclamation 2009), whereby it was judged that there is unclear basis for excluding climate projections based on relative emissions likelihoods or relative GCM simulation skill. Thus, all surveyed projections were kept in consideration during the definition of climate change scenarios.

2.3 Defining Climate Change Scenarios – Projection-specific Approach

As stated at the beginning of this chapter, the final step involves defining climate change scenarios from the climate projections under consideration. As will be shown in this section, contemporary climate projections over Oklahoma and north Texas all suggest a warmer future to lesser or greater degrees. For precipitation, they suggest a future ranging from drier to wetter. To represent these possibilities, this task involves defining climate change scenarios that bracket uncertainty, namely that they vary from less to more warming and drier to wetter conditions and also a climate change scenario that represents the middle tendency of this information.

This scenario definition task was conducted two ways. The first way supports weather generation for hydrologic modeling using the *Delta* and *HD* techniques. In this approach, individual climate projections are identified to provide climate change scenarios (i.e., changes in period monthly temperature and precipitation conditions). The approach for identifying these individual projections was introduced in Reclamation (2008) and later applied in Reclamation (2009). It features a four-factor rationale that leads to selection of: (a) four climate projections that express change in period-climate that "bracket" changes from all projections and (b) a fifth climate projection that expresses change in period-climate that is among the center of changes from all projections. The four factors are:

[2] Reclamation 2008, Appendix R, section 2.2.1, available at: http://www.usbr.gov/mp/cvo/ocap_page.html.

- #1: Climate Change Location
  - Choice: Region-mean condition over the Oklahoma (OK)/Texas (TX) region (Figure 1)[3]
- #2: Simulated Climate Periods Within Climate Projections
  - Choice: historical = 1950–1999, future = 2030–2059
- #3: Climate Change Metrics for Assessing Spread of Projected Changes
  - Choice: Change in period mean-annual temperature and precipitation, region-average
- #4: Climate Change Range of Interest
  - Choice: Following Reclamation (2008), define the change range of interest as the intersection of 10- to 90-percentile changes in temperature and 10- to 90-percentile changes in precipitation. Also following Reclamation (2009), define the intersection of median change in temperature and median change in precipitation as the central tendency of interest.

Given these considerations, five projections were identified for how they expressed paired changes in mean-annual precipitation and temperature that come closest to the 5-percentile intersects of interest:

- drier, less warming (10 percent [%] P change, 10% T change)
- drier, more warming (10% P change, 90% T change)
- wetter, more warming (90% P change, 90% T change)
- wetter, less warming (90% P change, 90% T change)
- central tendency, or middle (50% P change, 50% T change)

Figure 2 and Figure 3 illustrate implementation of the four-factor rationale. Following Factor #1, monthly temperature and precipitation projections were first

[3] Factor #1 may seem to be at odds with the objectives of the hydrologic response assessment that follows in Task 2. Specifically, it may be questioned that this assessment of the spread of projected climate changes is based on changes in region-average climate, which contrasts with the changes in spatially distributed climate featured in the hydrologic response assessment (Task 2). A reason for the region-average focus in Task 1 is that the hydrologic response assessment that follows should have consistent projections underlying the analysis at each watershed; and, thus, projections-based definition of climate change scenarios should be regionally consistent. Factor #3 also may seem at odds, given that we're focused in Task 1 on change in period mean-annual climate and that the hydrologic assessment is focused on change in period mean-monthly climate. A reason for the period-mean annual focus in Task 1 is that, while many climate metrics may be used to judge climate projections spread, such as change in monthly or seasonal conditions, it is assumed that change in annual conditions affects a broad set of monthly to annual hydrologic conditions and, therefore, serves as a reasonable basis for judging spread of projected changes.

obtained for the study region (Figure 1). These monthly data were regionally averaged and aggregated to annual series, as shown on Figure 2. Viewing the envelope of projected conditions as it evolves through time (i.e., light red on top panel and light blue on bottom panel), it would appear that the region is projected to become warmer during the 21st century, with perhaps growing uncertainty on the annual temperature condition during any given year. Likewise, it would appear that the region's expected annual precipitation might remain steady but with possibly growing uncertainty on the annual precipitation condition during any given year.

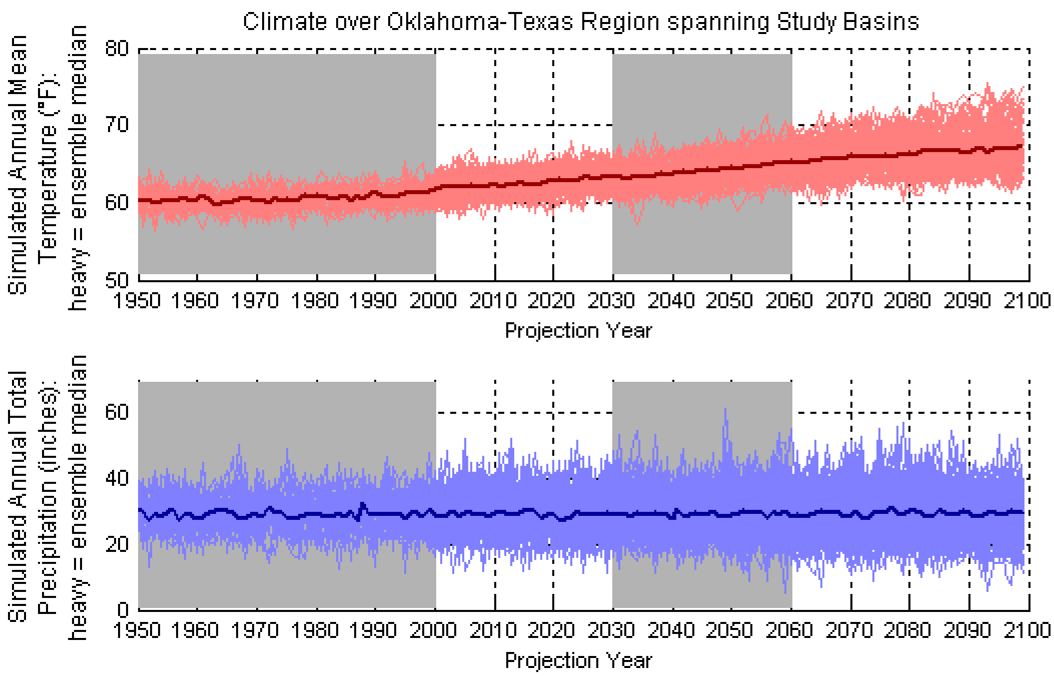

Figure 2. Annual Climate Projections Spatially Averaged in Study Region.

Switching to a projection-specific period change view, different impressions emerge on climate projection uncertainty relative to those from the time-series ensemble view. The projection-specific period change view underlies definition of climate change scenarios in this approach. Figure 2 highlights the climate change assessment periods (Factor #2) as gray boxes: historical (1950–1999) and future (2030–2059).[4] Following Factor #3, period-mean annual conditions

[4] Notice that the climate projections occupy a common envelope of variability during the historical period of 1950–1999. This is by design of the bias-correction procedure applied to the raw GCM outputs before spatial downscaling (http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/#About). In this procedure, each raw GCM projection is adjusted to reflect the same monthly 1950–1999 period distribution (i.e., period statistics) as an observed historical reference dataset (Maurer et al. 2002). This procedure does not force projections to have common sequencing characteristics, which vary due to differences in the originating climate model and in the assumed climate-system state (e.g., distributed ocean heat)

were computed for each projection (112), period (historical 50-year and future 30-year), and variable (temperature and precipitation). Figure 3 shows the rank distribution of projected period-mean temperature changes (upper left panel), period-mean precipitation changes (lower right panel) and paired changes (upper right panel). The 10-, 50-, and 90-percentile changes (Factor #4) are highlighted for both temperature and precipitation changes (black diamonds on upper left and lower right panels). The 10- and 90-percentile changes in temperature and precipitation intersect to produce the change range of interest shown on Figure 3 upper right panel (gray region). The 50-percentile changes in both variables intersect to produce central change of interest. Five projections are then indentified for how they express paired change in temperature and precipitation that most closely match the T/P percentile intersects mentioned above. The paired changes of these projections are shown on Figure 3 as black filled circles.

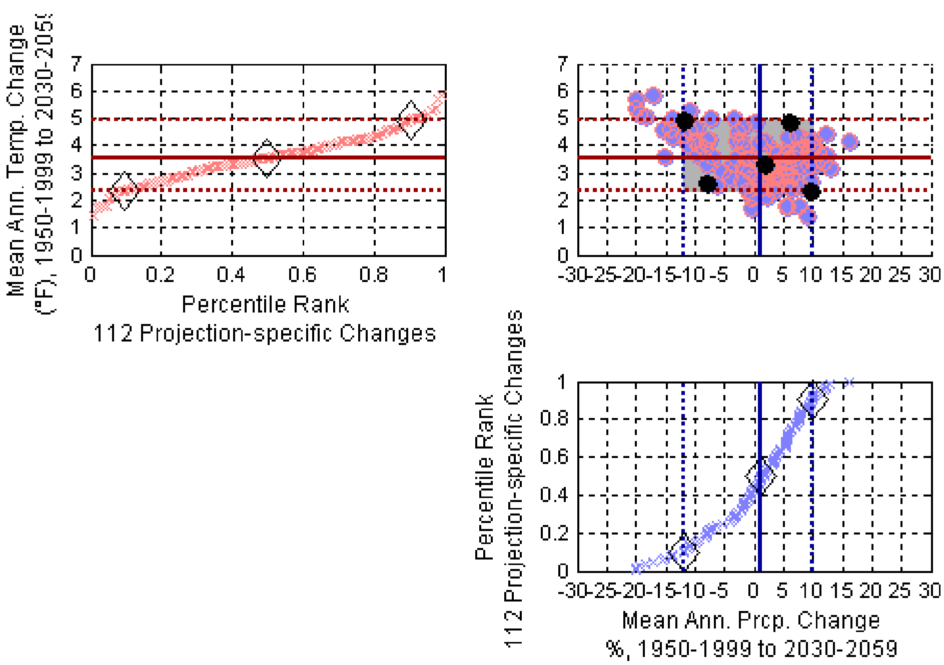

Figure 3. Selecting Individual Projections to Underlie Climate Change Scenarios.

In summary, this first way of defining climate change scenarios, focusing on information from single climate projections, led to selection of five climate projections for use in the *Delta* and *HD* weather generation techniques of Task 2. The projections are:

- (drier, less warming) mri_cgcm2_3_2a, run 3, emissions A2
- (drier, more warming) inmcm3_0, run 1, emissions A2

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at the start of 20th century climate simulations. After year 2000, climate projections reflect scenario greenhouse gas forcings and not actual emissions.

- (wetter, more warming) ncar_ccsm3_0, run 1, emissions A1b
- (wetter, less warming) csiro_mk3_0, run 1, emissions A2
- (middle) cccma_cgcm3_1, run 4, emissions B1

2.4 Defining Climate Change Scenarios – Ensemble-informed Approach

The second way of defining climate change scenarios supports weather generation for hydrologic modeling using the *HDe* technique. Although the projection-specific approach is easy to implement, the matter of interpreting computed changes in period-mean climate is more challenging. As with any period change approach for defining climate scenarios, the goal is to be able to interpret such changes as "climate change possibilities" and not a blend of some climate change and some misunderstood multi-decadal, or low frequency, variability. The matter of low frequency variability is relevant when interpreting period-mean changes in projected precipitation (Giorgi 2005). It is understood that historical regional precipitation has varied on multidecadal time scales and other lower frequencies. It also is understood that GCMs express different degrees of low-frequency climate variability on global to regional scales. Thinking ahead to Task 2, where climate changes are identified from Task 1 projections and then superimposed on historical climate variability to generate weather inputs for hydrologic models, the concern is that there may be a "double counting" of climate variability, where projected changes in climate are misinterpreted as climate change (rather than sampled cycles of natural variability) and mistakenly superimposed on the historical envelope of hydroclimate variability used in the yield assessment. The consequence of doing this is to potentially feature an amplified sense of climate change possibility in the yield sensitivity analysis, contributing to an amplified sense of uncertainty.

To reduce the concern of double counting climate variability, an alternative approach (*HDe*) is introduced where climate change scenarios are defined so that they emphasize consensus change information from a collective of projections rather than information from individual projections. Doing so also reduces the matter of sampling change information from projections that address lesser or greater degrees of low frequency climate variability. The merits of this approach will be revealed and discussed in the context of hydrologic modeling results of Task 2. For this discussion, the intent is to describe how climate projection ensembles are defined to generate climate change scenarios that are qualitatively similar to scenarios developed using the projection-specific approach (drier, less warming; drier, more warming, etc.).

Initially, the definition of climate change scenarios for *HDe* is similar to that for *Delta* and *HD* and follows the same first three factors discussed in section 2.3.

The difference is Factor #4, which is modified to focus on threshold period-temperature and period-precipitation changes to define projection ensembles. Specifically, the 50th percentile temperature and precipitation changes are used to partition the space into four nonoverlapping quadrants, representing the four ensembles that will define "bracketing" climate change scenarios. Next, the 25th to 75th percentile temperature and precipitation changes are used to define an interquartile change quadrant, defining an ensemble to inform the "middle" climate change scenario. Figure 4illustrates implementation of this procedure. The figure shows the same 112 projection-specific pairings of changes in mean-annual temperature and precipitation as shown in the upper right panel of Figure 3. Projection-specific paired changes are highlighted to denote ensemble membership

- (drier, less warming) gold asterisks
- (drier, more warming) red triangles
- (wetter, more warming) green "x"
- (wetter, less warming) blue crosses
- (middle) orange circles

Note that the ensemble membership of the interquartile quadrant (middle) overlaps with membership in the four other quadrants. The sum of membership in the four perimeter quadrants is 112, but membership is not equal between these four quadrants, as shown.

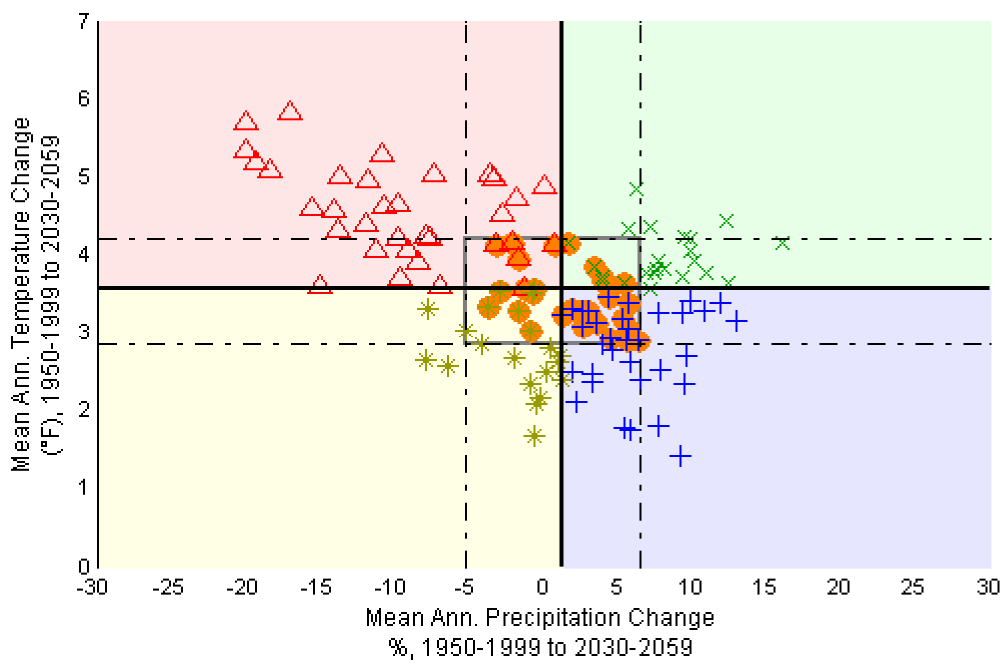

Figure 4. Selecting Projection Ensembles to Underlie Climate Change Scenarios.

3. Hydrologic Response Assessment

Given the five climate change scenarios defined for a given technique (Delta, HD, and HDe), the next task in the analytical outline involves assessing surface water hydrologic response to changes in monthly temperature and precipitation associated with each scenario. The task involves:

- Selecting a hydrologic model to simulate surface water conditions under different climates.
- Developing input weather data satisfying model input requirements and being consistent with the monthly climate change scenarios of Task 1.
- Conducting simulations and reporting results.

3.1 Hydrologic Model Description

Hydrologic simulation was conducted using an Arkansas-Red River Basin application of the Variable Infiltration Capacity hydrologic model (Liang et al. 1994).[5] The VIC model has been used to support hydrologic impacts assessments in many Western United States river basins, including California's Central Valley (Van Rheenan et al. 2004, Maurer 2007, Anderson et al. 2008, Reclamation 2008), the Colorado River Basin (Christensen et al. 2004, Christensen and Lettenmaier 2007), the Columbia-Snake Basin (Payne et al. 2004), and the southern Great Plains (LCRA/SAWS 2008).

The Arkansas-Red VIC application was developed at the University of Washington and has been used to support experimental hydrologic forecasting activities.[6] The application is gridded at a spatial resolution of 1/8º, meaning that surface water balance is simulated through time for grid cells that are roughly 12 x 12 km square (see Figure 5, gray grid of squares). The application simulates surface water balance on a daily time-step, forced by input gridded daily time series of precipitation, minimum temperature, maximum temperature, and wind speed. At the end of simulation, gridded runoff results are routed to runoff locations of interest.

In approaching this study, it was recognized that this VIC application could benefit from calibration refinement. Biases between observed and VIC-simulated

[5] http://www.hydro.washington.edu/Lettenmaier/Models/VIC/.

[6] Personal communication, Dr. Andrew Wood, National Weather Service (NWS) Colorado Basin River Forecast Center, who maintained the Arkansas-Red VIC application while at The University of Washington and shared the application for uses here.

hydrologic conditions may be apparent when reviewing results presented later in this chapter. However, the significance of these biases is somewhat muted based on how the VIC simulation results are being used to inform the yield sensitivity analysis. Specifically, the VIC-simulated results are assessed for percentage changes in mean-monthly runoff, which then is used to scale historical observed reservoir inflow variability in the yield sensitivity analysis. Thus, the focus is on how the VIC model portrays runoff response to climate change, which is revealed by conducting comparative VIC simulations under two different climates (i.e., historical observed and a future climate reflecting one of the climate change scenarios tiering from historical observed) rather than how it simulates magnitude runoff under any individual climate.

For this study, focus was placed on the hydrologic response within seven reservoir watersheds (Figure 5). Hydrologic modeling was conducted only for these watersheds after stenciling out the grid cells from the Arkansas-Red VIC application overlying these watersheds. Each VIC application grid cell may be thought of as containing a water balance model that is independent of other grid cell conditions. This is because VIC is a surface water simulation model that assumes no lateral subsurface flow. This aspect of VIC is convenient in that it permits grid cells of interest to be isolated and simulated, as opposed to having to simulate the entire Arkansas-Red domain.

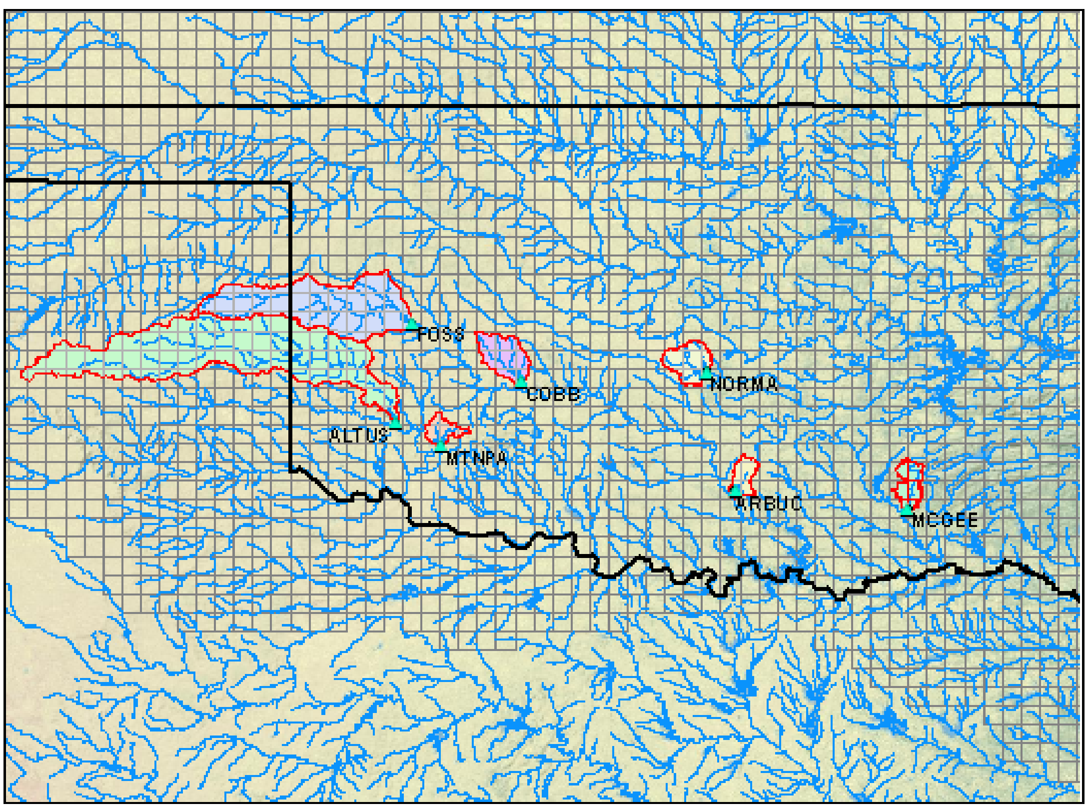

Figure 5. Study Basins.

3.2 Development of Weather Inputs

The Arkansas-Red VIC application is packaged with a "Base" set of historical, gridded daily weather inputs reflecting weather station observations during 1950–1999 (Maurer et al. 2002).[7] For Task 2, this Base 50-year weather sequence is used as the base climate condition, and simulated runoff using these weather data are used as a Base 50-year hydrologic sequence. For each climate change scenario in Task 1, a 50-year gridded daily weather sequence was generated to reflect the given scenario's future monthly climate, as changed from the Base historical climate. This means that 15 "Future Climate" weather sequences were generated, corresponding to 5 climate change scenarios associated with each of 3 climate change assessment techniques (*Delta*, *HD*, and *HDe*).

The following sections highlight differences between the mechanics of generating weather sequences corresponding to each technique. The implications for generated weather then are illustrated using the example of 1950–1999 May precipitation at a VIC grid cell over Lake Altus. Before proceeding with technique descriptions, the following list outlines aspects of Future Climate weather generation common to each technique:

- Weather sequences are generated on a 1/8º grid-cell specific basis, reflecting changes in monthly climate over that grid cell.

- Resultant daily gridded weather sequences are generated for four variables, as required by VIC: precipitation, minimum temperature, maximum temperature, and wind speed. However, only daily precipitation, minimum temperature, and maximum temperature are adjusted to reflect changes in monthly climate relative to Base weather. Wind speed sequences are kept the same as Base.

- Precipitation adjustments reflect percentage changes in a given month's condition. Temperature adjustments reflect incremental changes in monthly condition, with the same incremental change applied to both minimum and maximum temperature variables.

- Monthly Future Climate weather sequences are first generated. Monthly sequences are then temporally disaggregated to daily sequences. The disaggregation preserves the daily pattern of weather within a specific month of the Base period (e.g., Base January 1961 and Future Climate January 1961 will have perfectly correlated daily sequence), but with the pattern shifted (temperature) or scaled (precipitation) to reflect change in that month's climate. Put another way, each daily Future Climate weather sequence reflects the same sequencing aspects as the Base weather,

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[7] This is the same gridded historical observations dataset that guided the bias-correction and spatial downscaling of GCM data, producing the downscaled climate projections used in Task 1.

including interarrival of droughts, storms, etc., but adjusted to reflect change in monthly temperature and precipitation conditions.

3.2.1 Technique #1 – *Delta*

The *Delta* technique involves identifying a vector of 12-month-specific adjustment factors for precipitation and 12-month-specific adjustment factors for temperature. For a given month and variable, the adjustment factor is applied uniformly to a calendar month's 50 values in the Base weather sequence to produce corresponding values for the Future Climate weather sequence (e.g., 50 May precipitation totals from Maurer et al. 2002 are all adjusted by a common May precipitation-adjustment factor from a given *Delta* climate change scenario). The adjustment factors are computed as change in period monthly mean using the same periods used in Task 1 (i.e., change in a given climate projection's 1950–1999 mean to its 2030–2059 mean). The vector of 12-month-specific adjustment factors is computed for each grid cell, variable (temperature and precipitation), and climate change scenario (five from Task 1, Approach 1).

3.2.2 Technique #2 – Hybrid-Delta (*HD*)

The *HD* technique involves identifying a vector of adjustment factors reflecting a unique period-change in monthly condition at each rank-percentile of a given month's climate condition. Thus, the adjustment differs for relatively drier to wetter precipitation conditions and for relatively cooler to warmer temperature conditions. Like the *Delta* technique, climate change is defined in this *HD* application using a single climate projection and using periods from Task 1: 1950–1999 to 2030–2059. Also like the *Delta* method, the *HD* technique is applied on a projection-, month-, variable-, and grid cell-specific basis. The key difference between *Delta* and *HD* is that the *HD* requires adjustment factors that vary by climate "year-type." This is done by identifying three rank-distributions for a given set of variable, month, grid cell location, and climate change scenario. The rank-distributions are respectively fit to:

(a) Observed Historical: 50 values from the 1950–1999 Base weather sequence discussed above (Maurer et al. 2002),

(b) Simulated Historical: 50 values from the given projection's simulated historical 1950–1999, and

(c) Simulated Future: 30 values from the given projection's simulated future 2030–2059.

The *HD* technique proceeds where percentile-specific changes are computed by comparing distributions Simulated Historical and Simulated Future. To ease the calculation, the values of distribution Simulated Future are first interpolated from 30-percentile positions to the same 50-percentile positions as distribution Simulated Historical (i.e., 1/51 to 50/51, on a 1/51 increment). As with *Delta* technique and period-mean change, the *HD* technique and percentile-specific change is computed as percentage change for precipitation and incremental change for temperature (at every percentile). These computed changes constitute the percentile-vector of adjustment factors that vary with climate year-type and vary according to the given month, grid cell, and underlying climate projection. Percentile-specific changes then are imposed on the values from distribution Observed Historical (i.e., comprised of Base monthly weather values) corresponding to the same percentiles of adjustment, generating a distribution of Future Climate monthly weather values for the given month. These monthly data then are arranged in time consistent with the Base weather sequence, followed by daily disaggregation.

3.2.3 Technique #3 – Ensemble Hybrid-Delta (*HDe*)

The *HDe* technique is identical to the *HD* technique except that, rather than construct distributions Simulated Historical and Simulated Future using data from a single climate projection, these distributions are constructed using pooled data from an ensemble of climate projections. The projection ensembles were defined in Task 1. Thus, the amount of fitting data for distribution Simulated Historical is 50 period values for the given month (1950–1999) x N projections in the given projection ensemble, and the amount of fitting data for distribution Simulated Future is 30 period values for the given month (2030–2059) x N projections. For example, the “drier, more warming” projection ensemble has 34 projections. Thus, distribution Simulated Historical was fit to 50 x 34 values for a given month (or 1,700 values) and distribution Simulated Future was fit to 30 x 34 values for the same month (or 1,020 values). To ease calculations, distributions Simulated Historical and Simulated Future are first interpolated to a common set of percentile positions (0.001 to 0.999 on a 0.001 increment). The percentile-vector of adjustment factors is then computed only at the percentile positions of distribution Observed Historical (1/51 to 50/51 on a 1/51 increment).

3.2.4 Example Application of Techniques #1 through #3

The application of each technique is illustrated on Figure 6 through Figure 11. The example involves generating Future Climate monthly May precipitation totals at a VIC grid cell overlying Lake Altus (Figure 6). Figure 7 shows the Base weather series (or, Observed Historical weather series) of monthly (blue line) and May-only precipitation (black circles). For each climate change scenario and each technique (*Delta*, *HD*, and *HDe*), a unique series of monthly May precipitation is generated, for a total of 15 series. Switching from the series view to the distribution view, Figure 8 shows three panels corresponding to the three adjustment techniques. Each panel shows the Observed Historical distribution of 50 May precipitation values (black circles) and five Simulated Historical distributions. In the first two panels (*Delta* and *HD*), the Simulated Historical distributions come from a common set of five climate projections (Task 1, Approach 1).

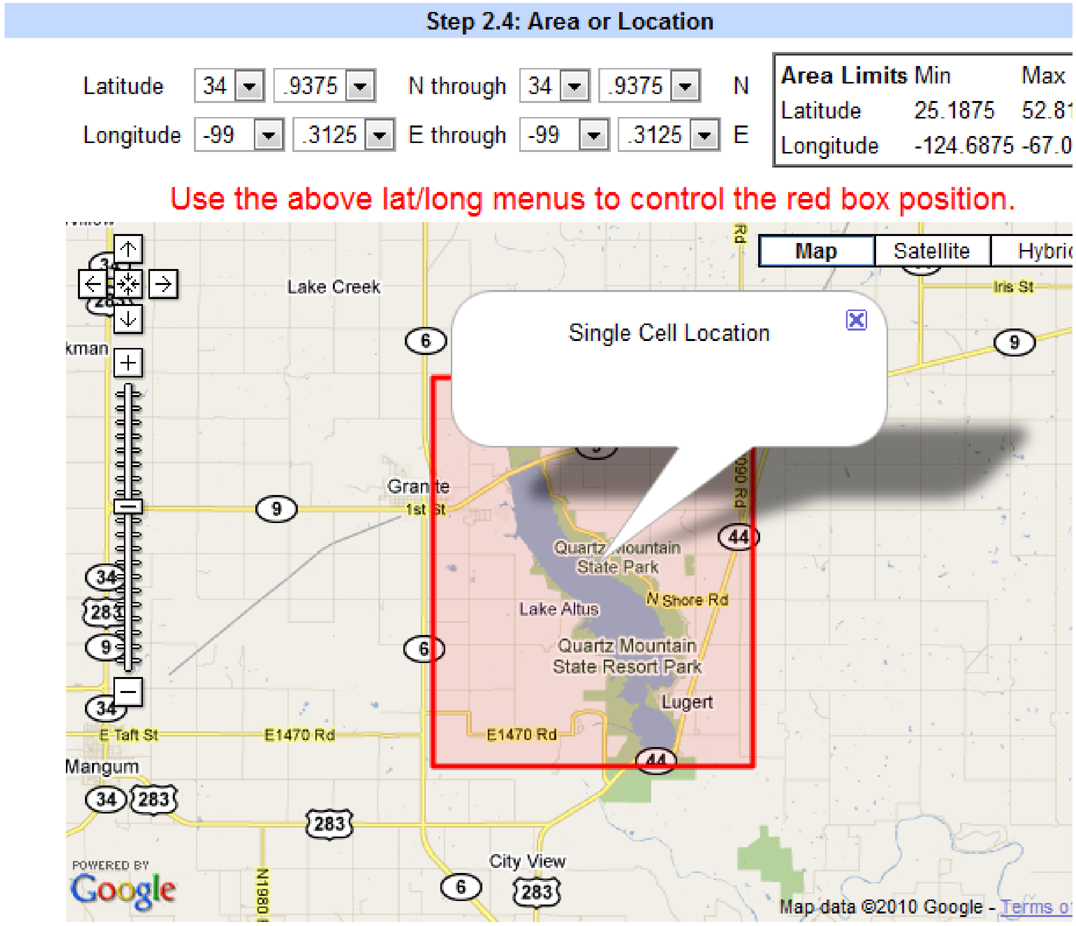

Figure 6. Example Weather Generation – Grid-Cell Location over Lake Altus.

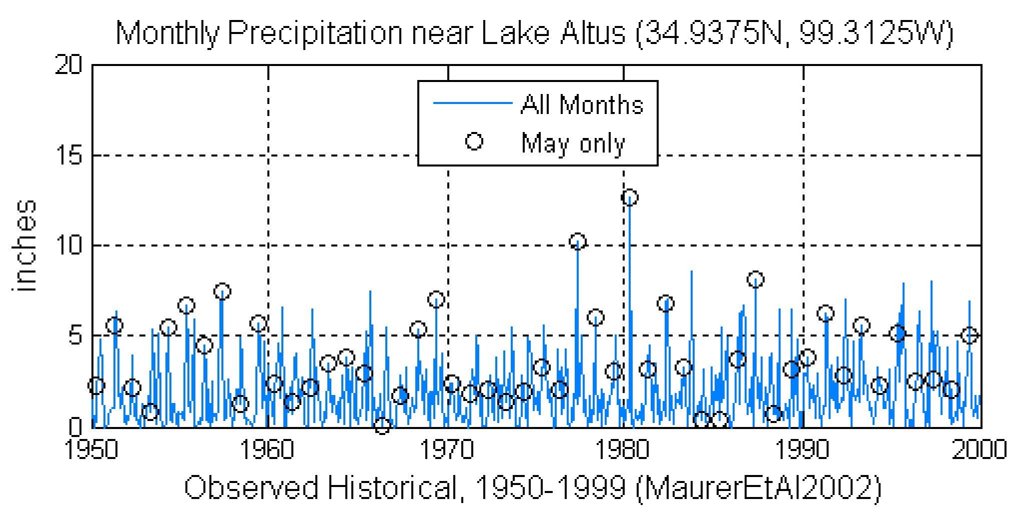

Figure 7. Example Weather Generation – Observed Historical Monthly Precipitation 1950–1999, Highlighting May Values.

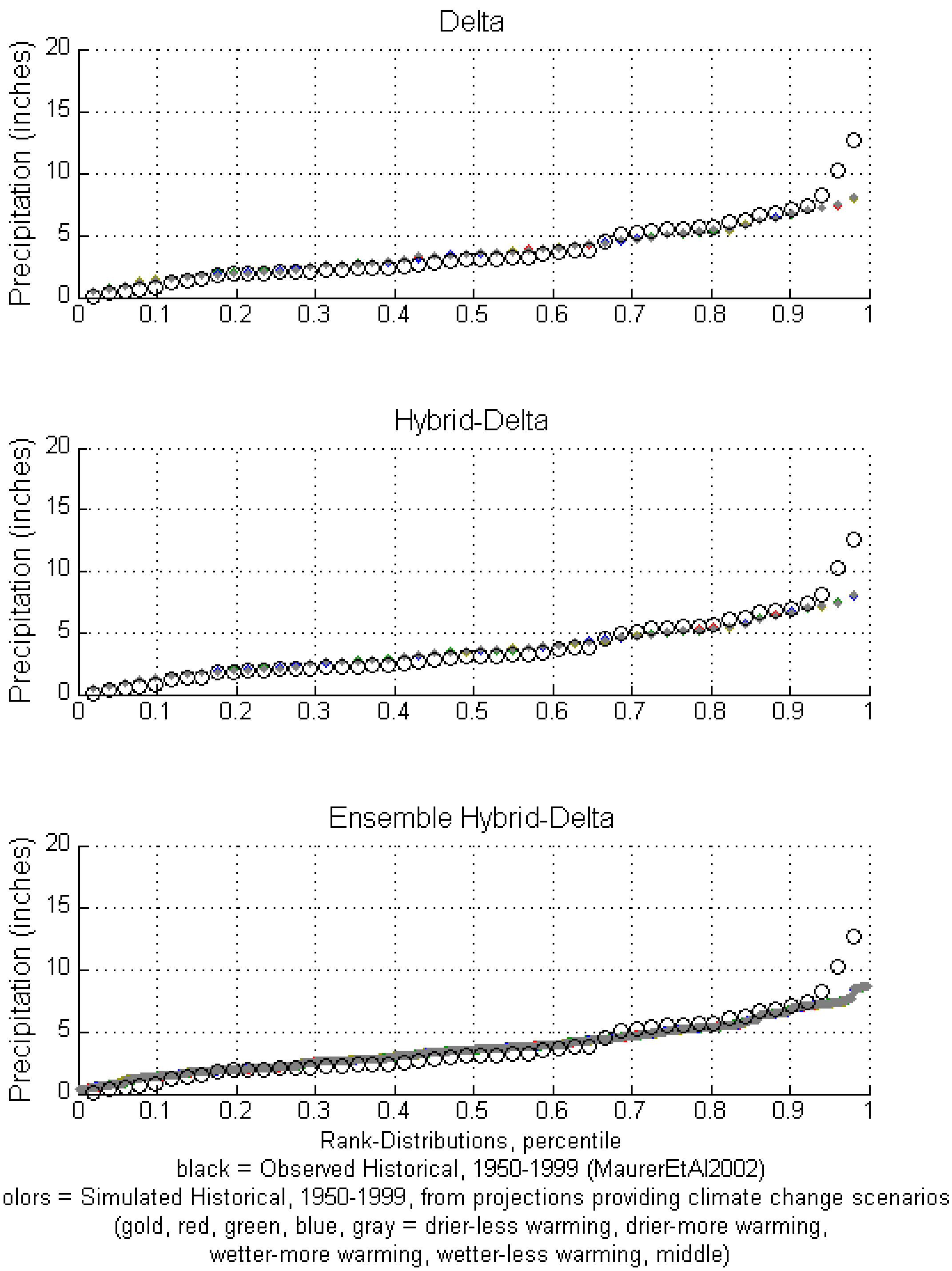

Figure 8. Example Weather Generation – Rank-Distributions of May Precipitation, Observed and Simulated Historical.

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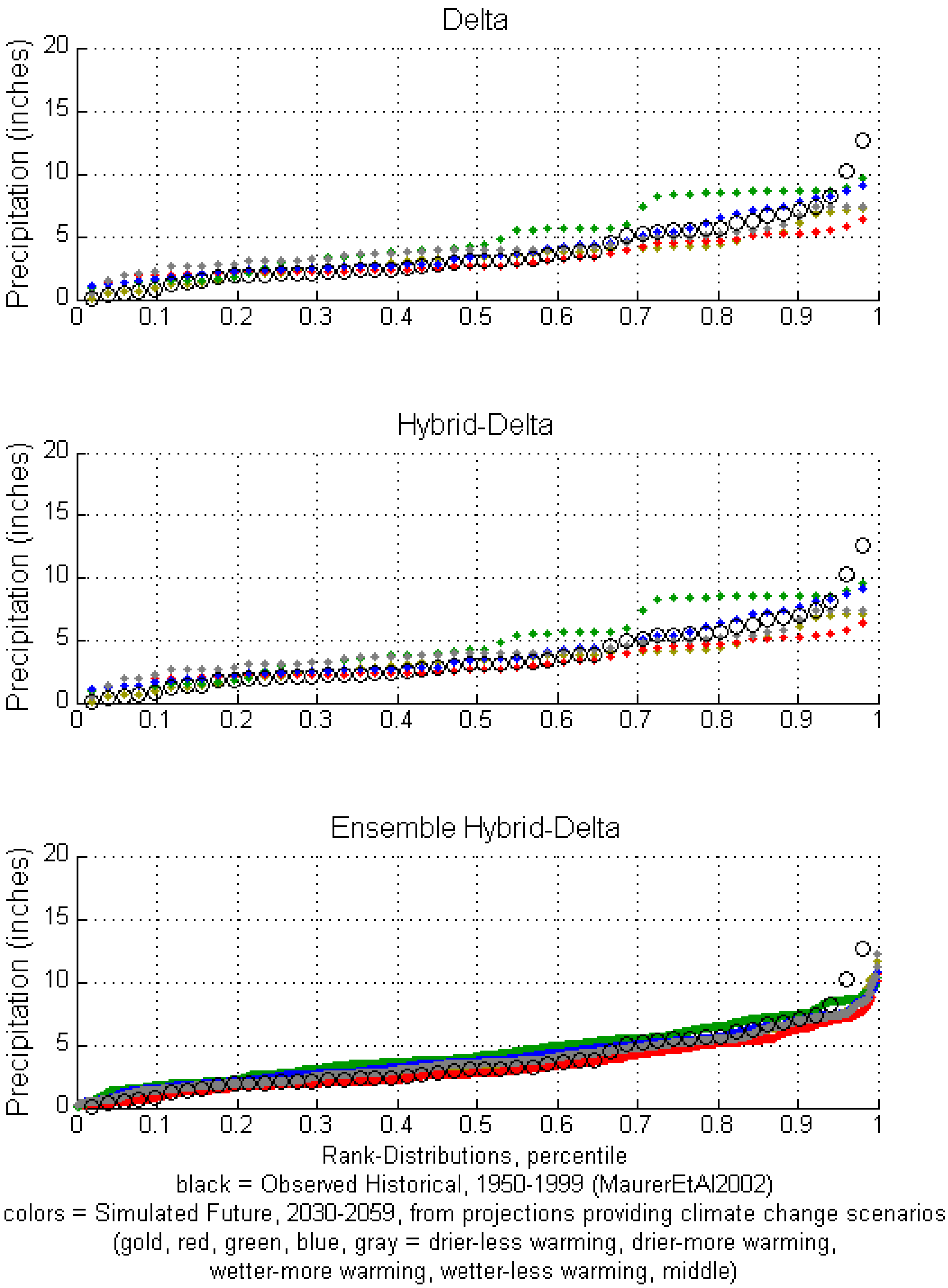

Figure 9. Example Weather Generation – Rank-Distributions of May Precipitation, Observed Historical and Simulated Future.

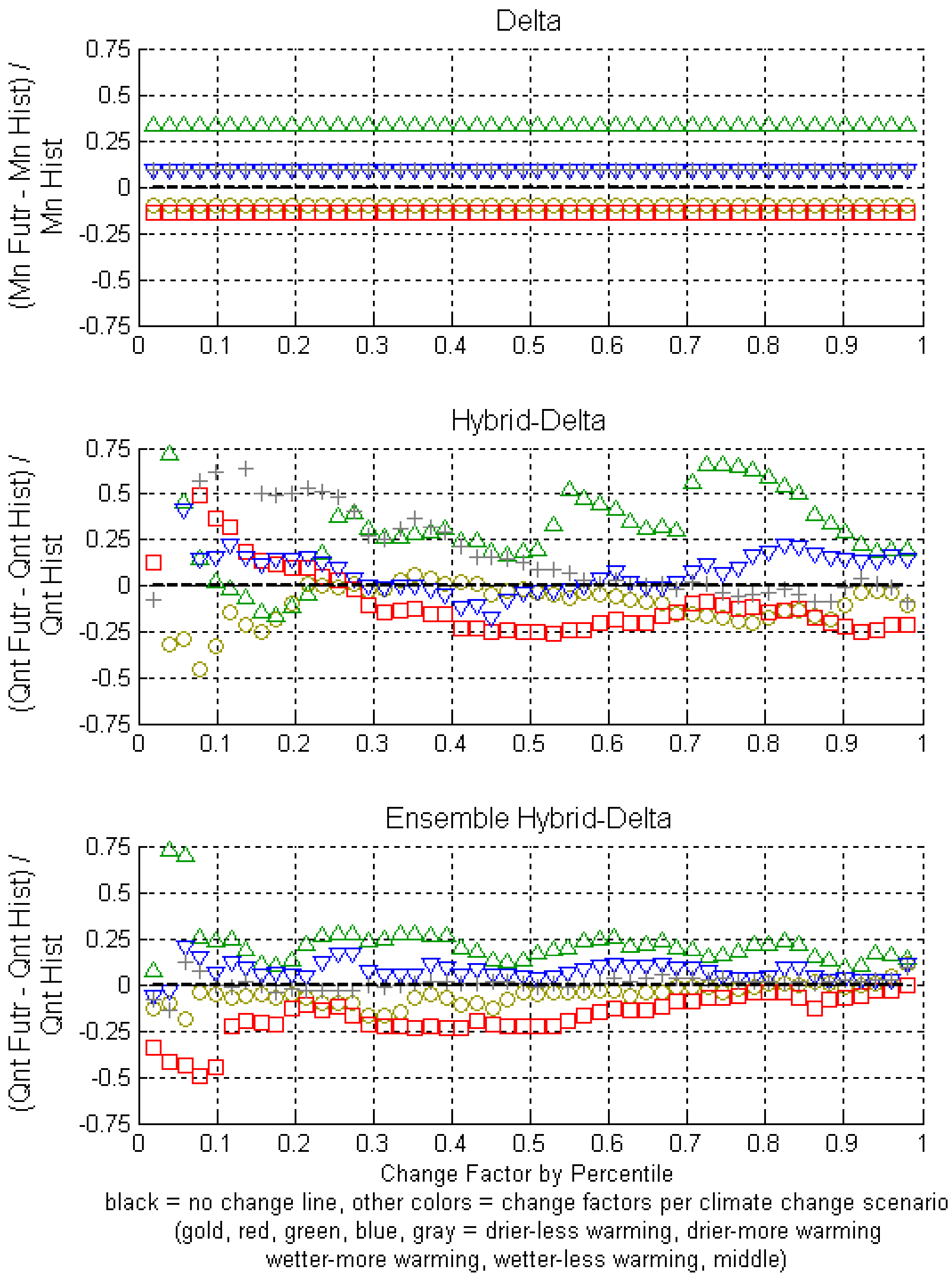

Figure 10. Example Weather Generation – Precipitation Adjustment Factors at Observed Historical May Percentiles.

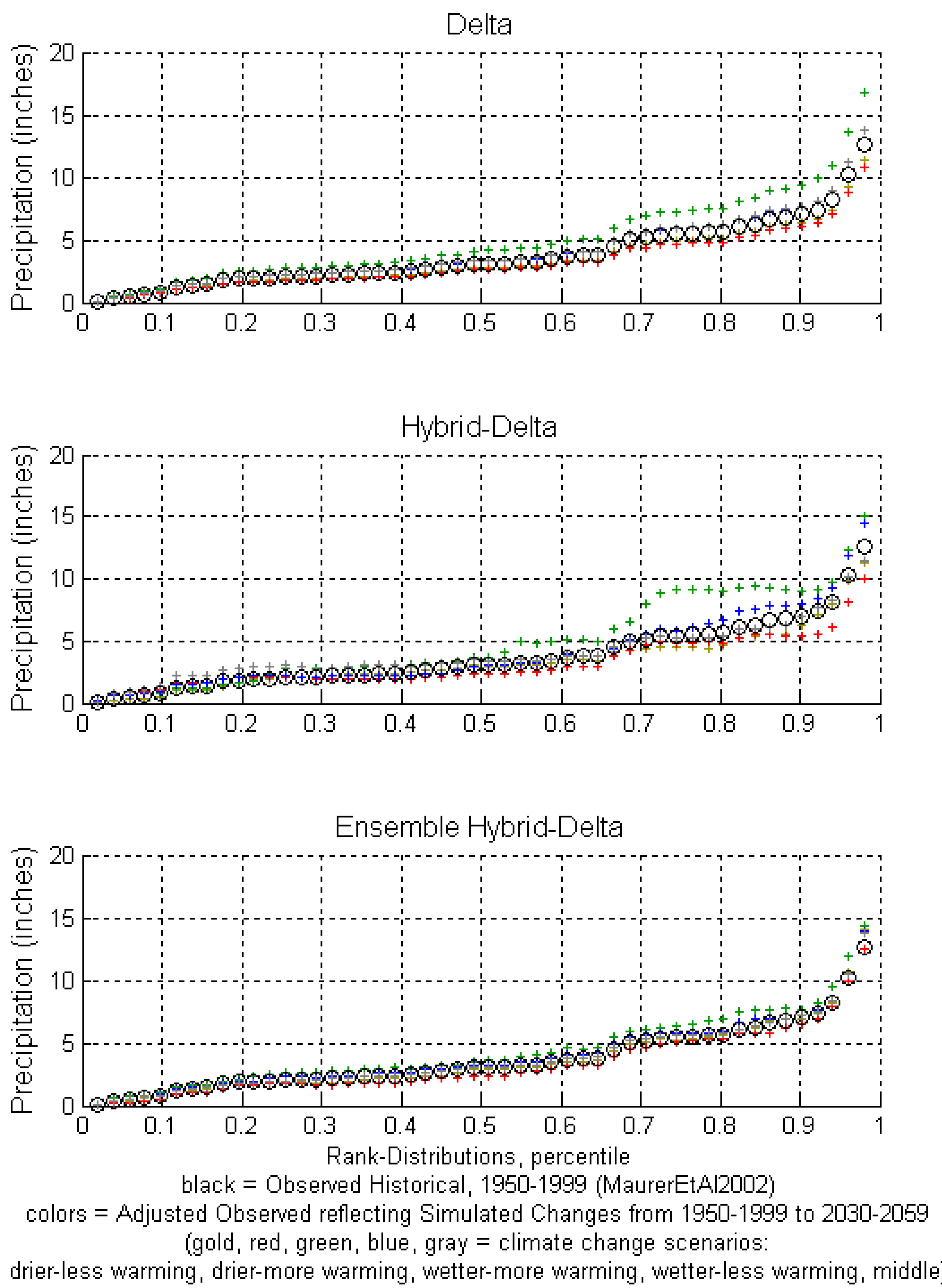

Figure 11. Example Weather Generation – "Future Climate" May Precipitation Reflecting Percentile Adjustments.

For the third panel, the Simulated Historical distributions come from five projection ensembles (Task 1, Approach 2). It may be noticed that the Simulated Historical distributions are identical on all three panels. This is a byproduct of the bias-correction procedure applied to the GCM output feeding the DCP archive used in this study, where GCM outputs were adjusted to be consistent with the 1950–1999 period monthly statistics of Maurer et al. 2002, which also provides the Base weather data used in Task 2. It also may be noticed that the Observed Historical (Base) distribution does not match Simulated Historical at this grid cell. This is a byproduct of the spatial downscaling step of BCSD (section 2.1) that occurs after the GCM bias-correction. The bias-correction is performed at a coarser spatial scale (2º) and forces GCM output to be consistent with Maurer et al. 2002 data aggregated to the 2º scale. The bias-corrected data are then spatially downscaled to 1/8º data using a disaggregation scheme that does not completely translate 2º bias-correction into 1/8º bias-correction.

Figure 9 is similar to Figure 8, except that each panel shows the five Simulated Future distributions reflecting simulated 2030–2059 rather than the Simulated Historical distributions reflecting simulated 1950–1999. As mentioned, each Simulated Future distribution was initially fit to 30 values and then interpolated to the same 50-percentile positions as the Simulated Historical distribution. The top two panels (*Delta* and *HD*) show an identical set of Simulated Future distributions because each set originates from a common set of five climate projections. The third panel (*HDe*) shows a different set of Simulated Future distributions because they each arise from ensembles of projections. In the *HDe* technique, the use of a projection-ensemble to construct the underlying Simulated Future distributions tends to smooth out the pattern of expected May conditions across the percentiles. For example, compare the Simulated Future distributions of *HD* and *HDe* for the "wetter, less warming" scenario (green lines); focusing only on an individual projection (HD), the implication is that nearly 30% of Mays will have at least 8 inches of precipitation, but focusing on a collection of "wetter, more warming" projections (HDe), the implication changes and less than 10% of Mays have precipitation greater than 8 inches.

Moving to the calculation of adjustment factors, Figure 10 shows adjustment factors at the Base distribution's percentile positions.

- Using the *Delta* method, the top panel illustrates how a common adjustment for a given climate change scenario (i.e., underlying climate projection) is applied at all percentile positions of the Base distribution. For example, the "wetter, more warming" climate change scenario (green) involves increasing all Base (Observed Historical) May precipitation totals by 33% whereas the "drier, more warming" scenario (red) involves a -14% decrease.

- Using the *HD* method, the middle panel illustrates how the adjustment factor varies by percentile position, meaning that "climate change" adjustment varies by year-type.

- Using the *HDe* method, the bottom panel illustrates similar information as the middle panel, but showing only adjustment factors at percentile positions from the Base distribution. In the *HDe* technique, the use of a projection-ensemble to construct the underlying Simulated Historical and Simulated Future distributions tends to smooth out the pattern of Adjustment Factors across the percentiles. Note particularly how the "wetter, more warming" scenario of HD (green) experiences a dramatic reduction in positive adjustment during relatively wetter May months (percentiles between 0.5 and 0.9).

Finally, the percentile-vectors of each technique and each climate change scenario are imposed on the Base distribution to construct Future Climate distributions (Figure 11). The theme illustrated on comparison of the adjustment factor vectors (Figure 10) is repeated here, as the *HDe* technique tends to deemphasize large wet-May changes in precipitation suggested by the *HD* technique, which may have been overstated due to its projection-specific view of climate change. Yet, compared to the *Delta* technique, the *HDe* technique still expresses some relatively different adjustments by climate year-type.

3.3 Hydrologic Modeling Results

This section summarizes hydrologic modeling inputs and outputs, with discussion focusing on the runoff outputs that inform yield sensitivity analysis. Results are summarized graphically, focusing on four variables.

- VIC input temperature (Tavg[8])
- VIC input precipitation (Prcp[8])
- VIC-simulated runoff (Q[8])
- VIC-simulated watershed evapotranspiration (Evap[8])

For the first two variables, the gridded daily VIC inputs of daily precipitation, minimum temperature, and maximum temperature are aggregated over each watershed into basin-mean monthly series of precipitation and temperature.[9] For the third variable, daily gridded VIC runoff is routed to the dam locations corresponding to the seven reservoir watersheds (Figure 5), producing a daily

[8] Label for this variable on Figure 12 and Figure 13.

[9] For temperature, the gridded VIC inputs of daily minimum and maximum temperatures are first averaged into a gridded daily mean temperature, which is then subjected to the daily-to-monthly time aggregation and gridded to basin-mean spatial aggregation mentioned above.

runoff series at each location that is then aggregated to monthly runoff for discussion purposes here. For the fourth variable, VIC evapotranspiration is aggregated from daily to monthly and from gridded to basin-mean, just like input temperature and precipitation.

For each watershed and climate (Base historical, five *Delta* future climate, five *HD* future climates, and 5 *HDe* future climates), the monthly mean VIC inputs and outputs were assessed. Figure 12 shows monthly mean conditions for a single basin example, ALTUS. The figure shows 12 plot panels—4 variables (rows) by 3 weather generation techniques (columns). On each panel, there are six patterns of monthly mean condition, corresponding to six climates (Base historical and five futures). For the future climates, the color coding is consistent with that shown on Figure 8 through Figure 11.

Results indicate that the monthly mean conditions can be sensitive to the weather generation technique. This is shown more clearly on Figure 13 where <u>changes</u> in monthly mean condition are shown for the five climate change scenarios, each measured relative to Base historical.

- For temperature, it is clear that warming is expected during all calendar months for each climate change scenario considered. However, it’s also clear that the *HDe* technique portrays smoother month-to-month climate changes relative to those portrayed by *Delta* and *HD* technique. The temperature changes shown for the *Delta* and *HD* techniques are the same because change in monthly mean is being sampled from a common set of underlying projections; however, if the interest was placed on change in monthly distributions, the plot would show differences between the *Delta* and *HD* temperature variabilities (section 3.2).

- For precipitation, the portrayal of month-to-month changes appears to be very sensitive to weather generation technique. The *Delta* and *HD* techniques portray change directions that flip from positive to negative, or vice versa, in more stark and frequent fashion relative to the changes portrayed by the *HDe* technique. As with temperature, the monthly mean precipitation changes from the *HDe* technique follow somewhat smooth month-to-month transitions along a given climate change scenario, emphasizing consensus change information from the ensemble of climate projections informing that scenario. It is noted that, while there do not appear to be months with a consensus sign of precipitation change across scenarios from the *Delta* and *HD* techniques, there does appear to be consensus across scenarios for some months using the *HDe* technique, notably the increase in precipitation during winter months (December–February).

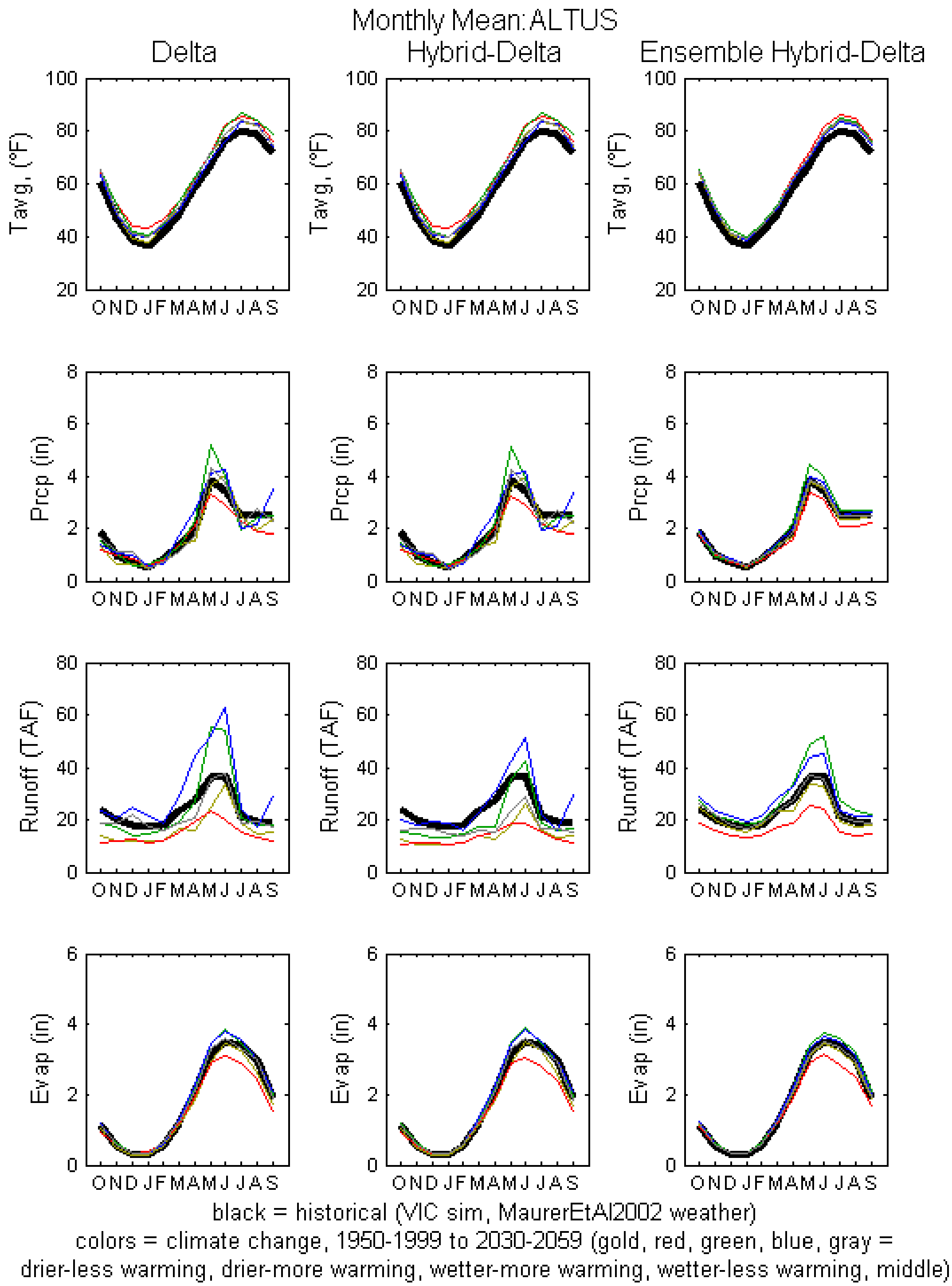

Figure 12. Mean Monthly Temperature, Precipitation, Runoff, and Evaporation – ALTUS.

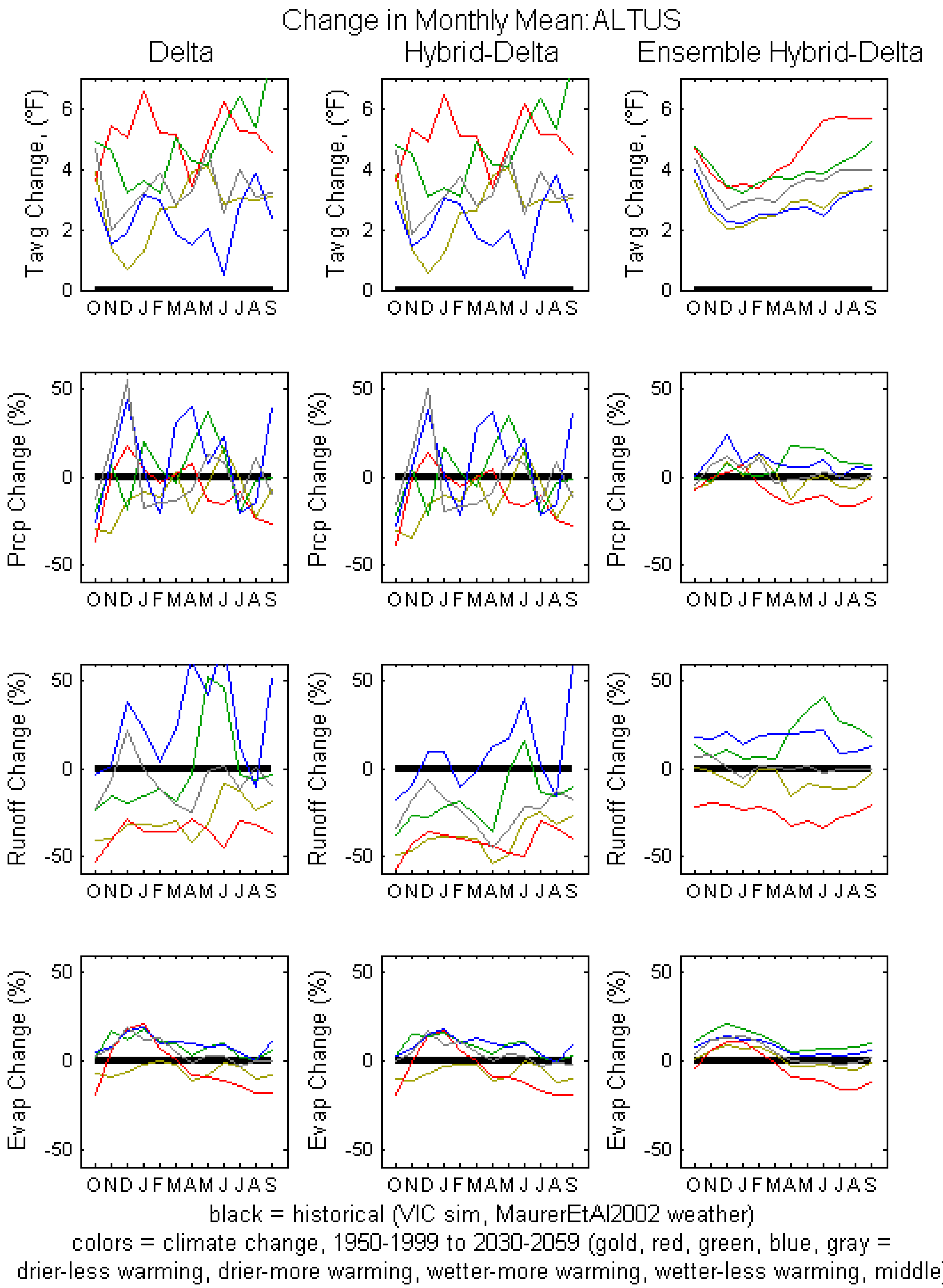

Figure 13. Change in Mean Monthly Temperature, Precipitation, Runoff, and Evaporation – ALTUS.

- For runoff, the portrayal of month-to-month impacts by each technique exhibits similar themes as those discussed for precipitation; the month-to-month runoff impacts reflecting weather generated using the *HDe* technique tend to transition more smoothly than impacts reflecting weather generated using the *Delta* or *HD* technique.

- For watershed evapotranspiration, the themes discussed above also are exhibited. However, it also appears that the amount of evapotranspiration change doesn't necessarily follow the amount of temperature change. This is because the opportunity for evapotranspiration depends not only on the atmospheric demand (related to temperature) but also the soil moisture supply. Increases in winter precipitation should lead to increased soil moisture and increased supply of water for evapotranspiration during those months.

Focusing on runoff, Figure 14 through Figure 16 each show changes in mean monthly runoff for all seven basins corresponding to the three techniques, respectively. Results show that themes found at Lake Altus are similar to themes found at the other reservoir watersheds.

Switching perspective from monthly to annual, Figure 17 shows mean annual conditions for the four variables at each basin, with results specific to variables and weather generation techniques arranged as shown on Figure 12. Figure 18 shows change in mean annual conditions at each basin, also with results arranged by variable and weather generation technique.

3.4 Using Runoff Results in the Yield Sensitivity Analysis

Proceeding to the yield sensitivity analysis, it was understood that either the *Delta*, *HD*, or *HDe* results for changes in 50-year mean-monthly runoff (Figure 14, Figure 15, or Figure 16) would be used to adjust a base sequence of 1926–2008 monthly inflows at each reservoir. Based on the following two reasons, it is recommended that the *HDe* results for change in 50-year mean-monthly runoff be used in the yield sensitivity analysis (Figure 16). The first reason relates to portrayal of month-to-month hydroclimatic changes (temperature, precipitation, and runoff) and an interest in portraying changes that are more consistent when progressing through months. Such portrayal would seem to emphasize monthly climate changes that are more interseasonally coherent. Relative to *Delta* and *HD* results, the *HDe* results show more interseasonal coherency. The second reason is that the *HDe* technique reflects consensus monthly climate conditions in an ensemble of climate projections, whereas *Delta* and *HD* techniques reflect monthly conditions from individual projections.

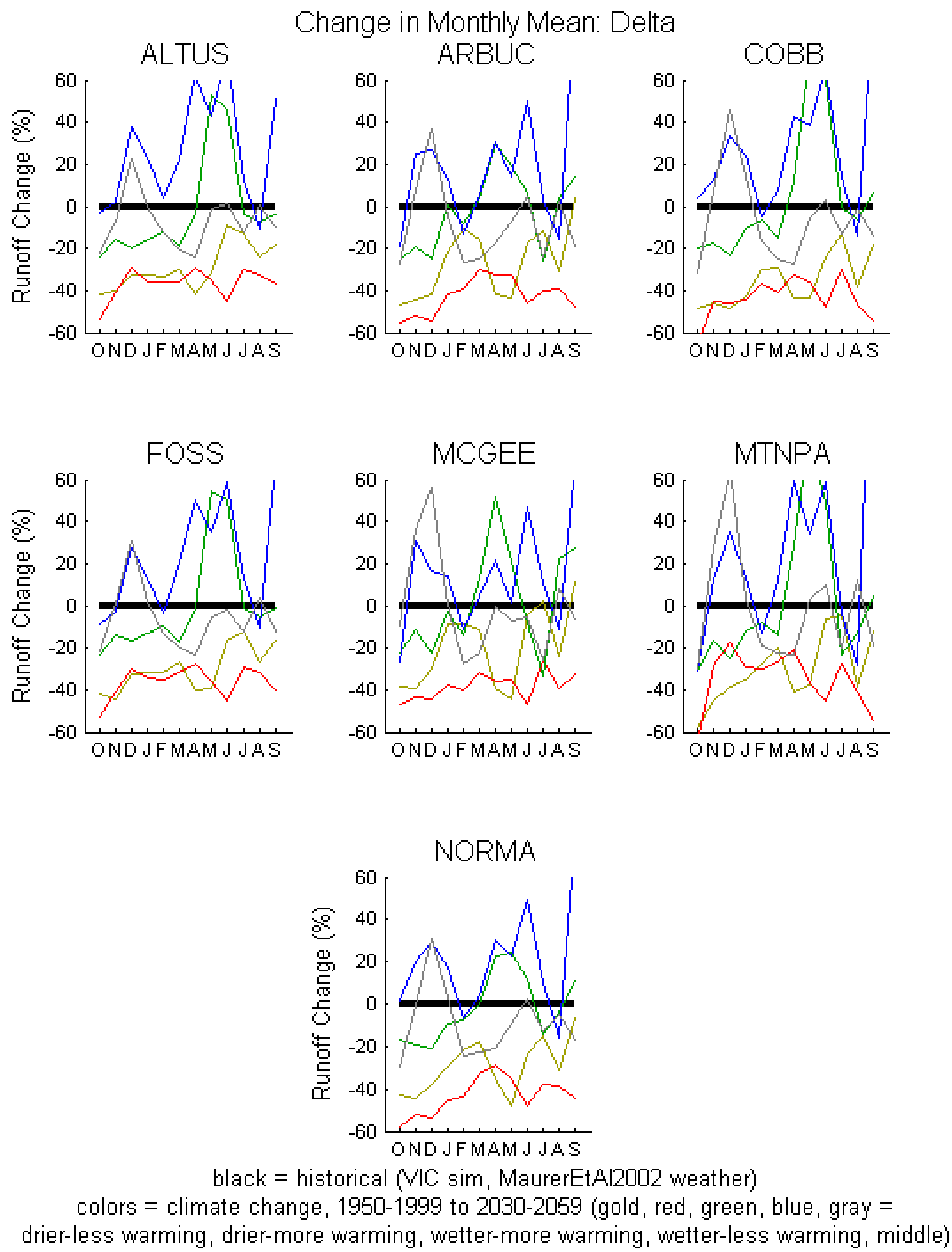

Figure 14. Change in Mean Monthly Runoff – All Basins – Weather Generated Using Delta Method.

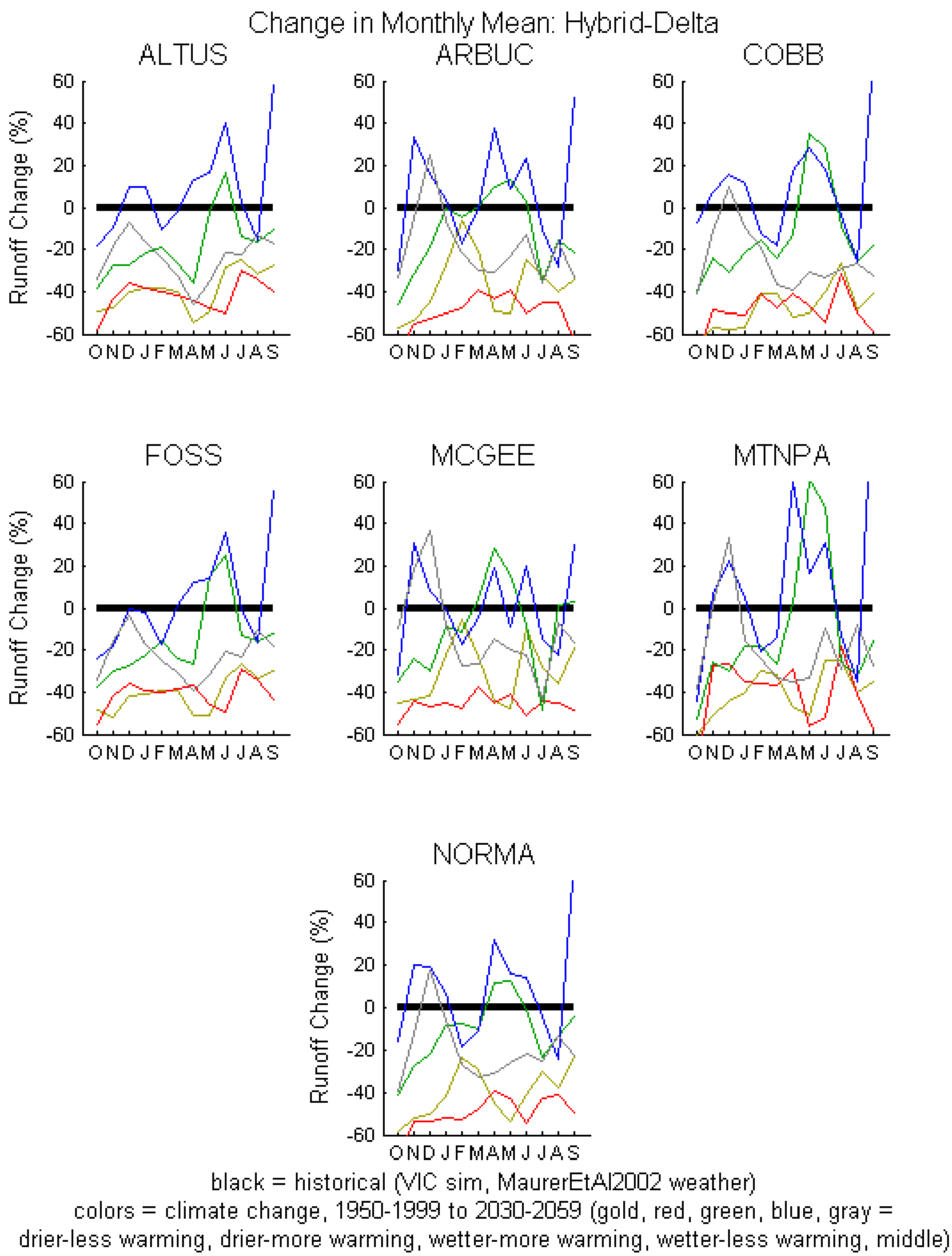

Figure 15. Change in Mean Monthly Runoff – All Basins – Weather Generated Using HD Method.

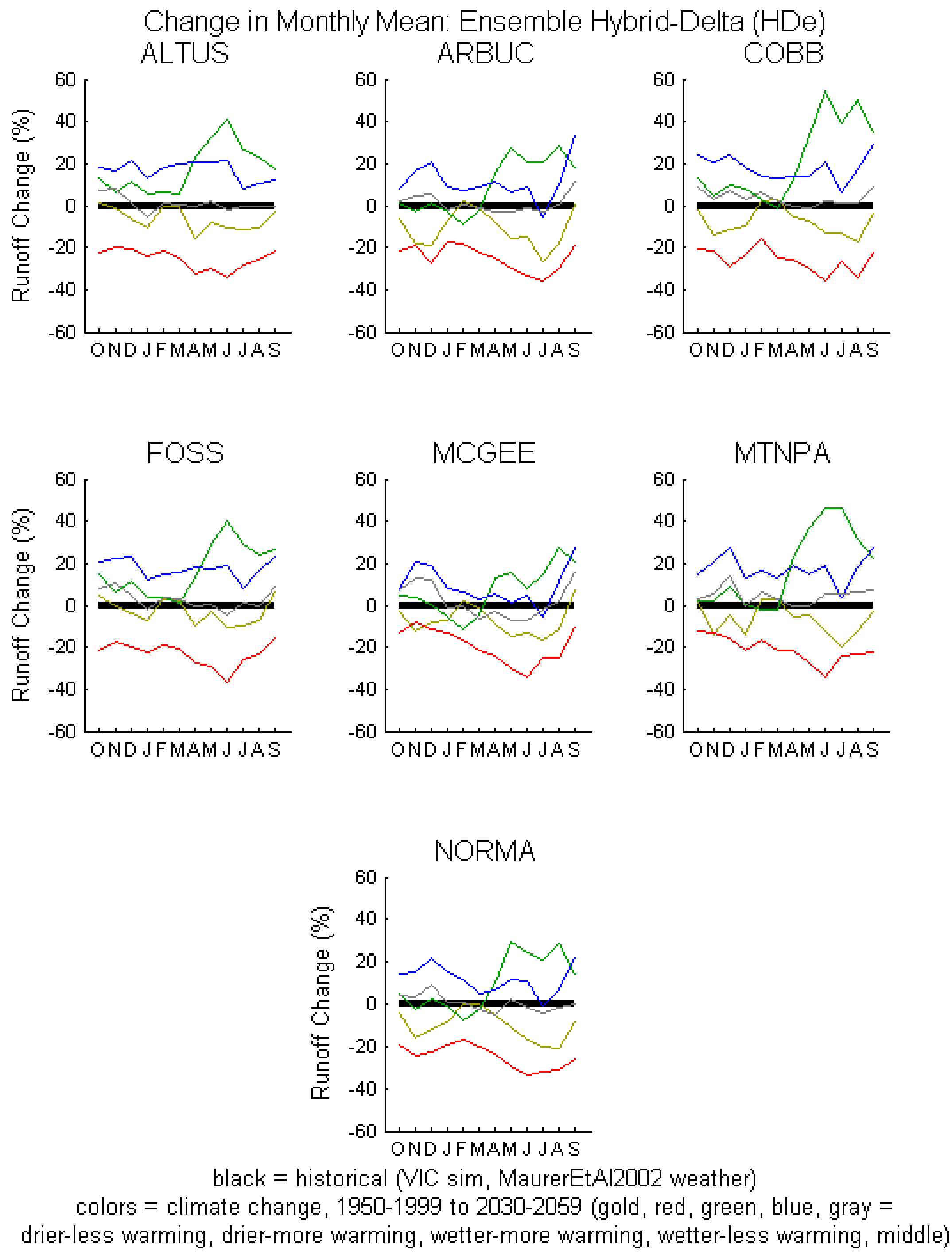

Figure 16. Change in Mean Monthly Runoff – All Basins – Weather Generated Using HDe Method.

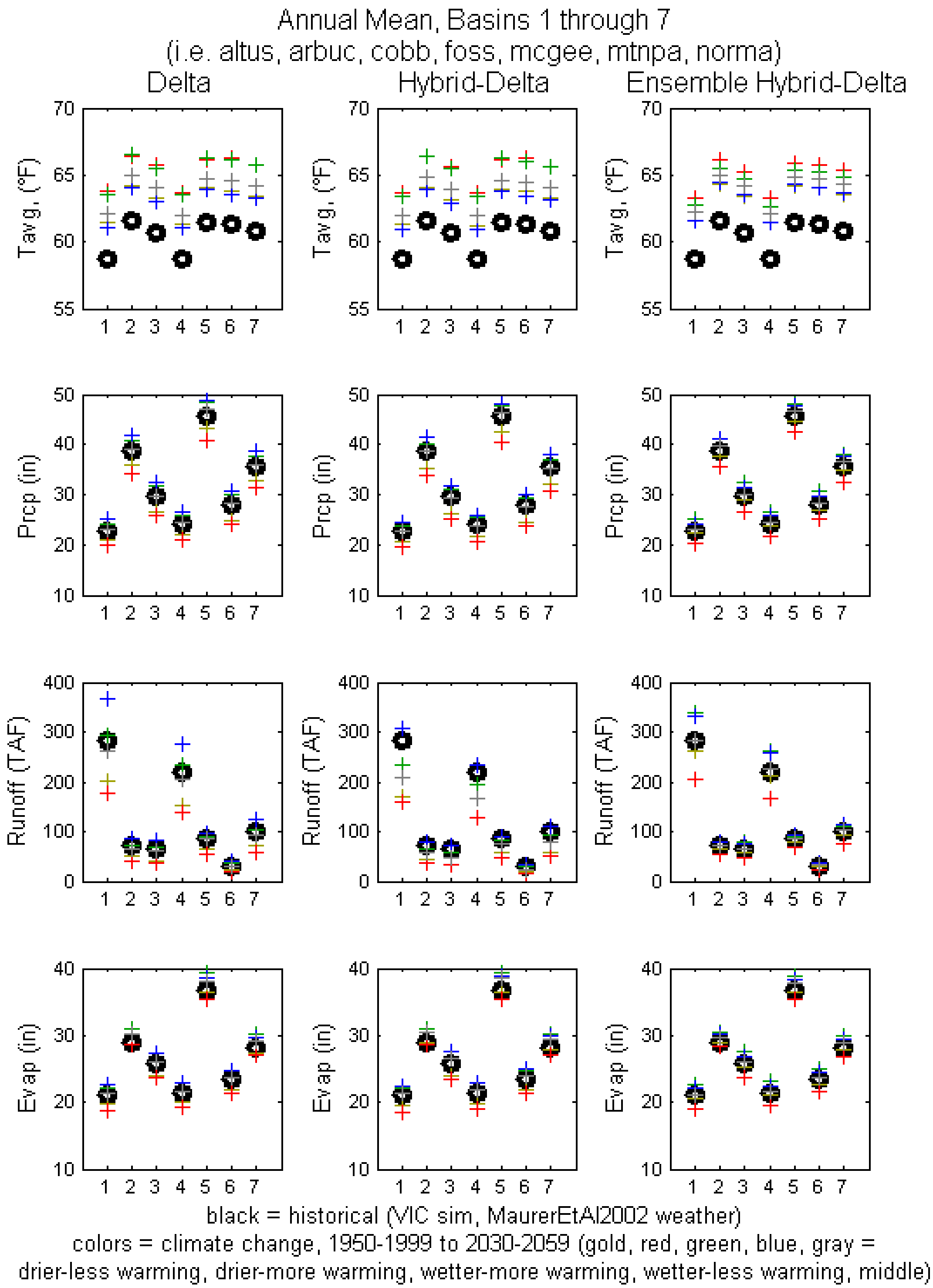

Figure 17. Annual Mean Temperature, Precipitation, Runoff, and Evaporation – All Basins.

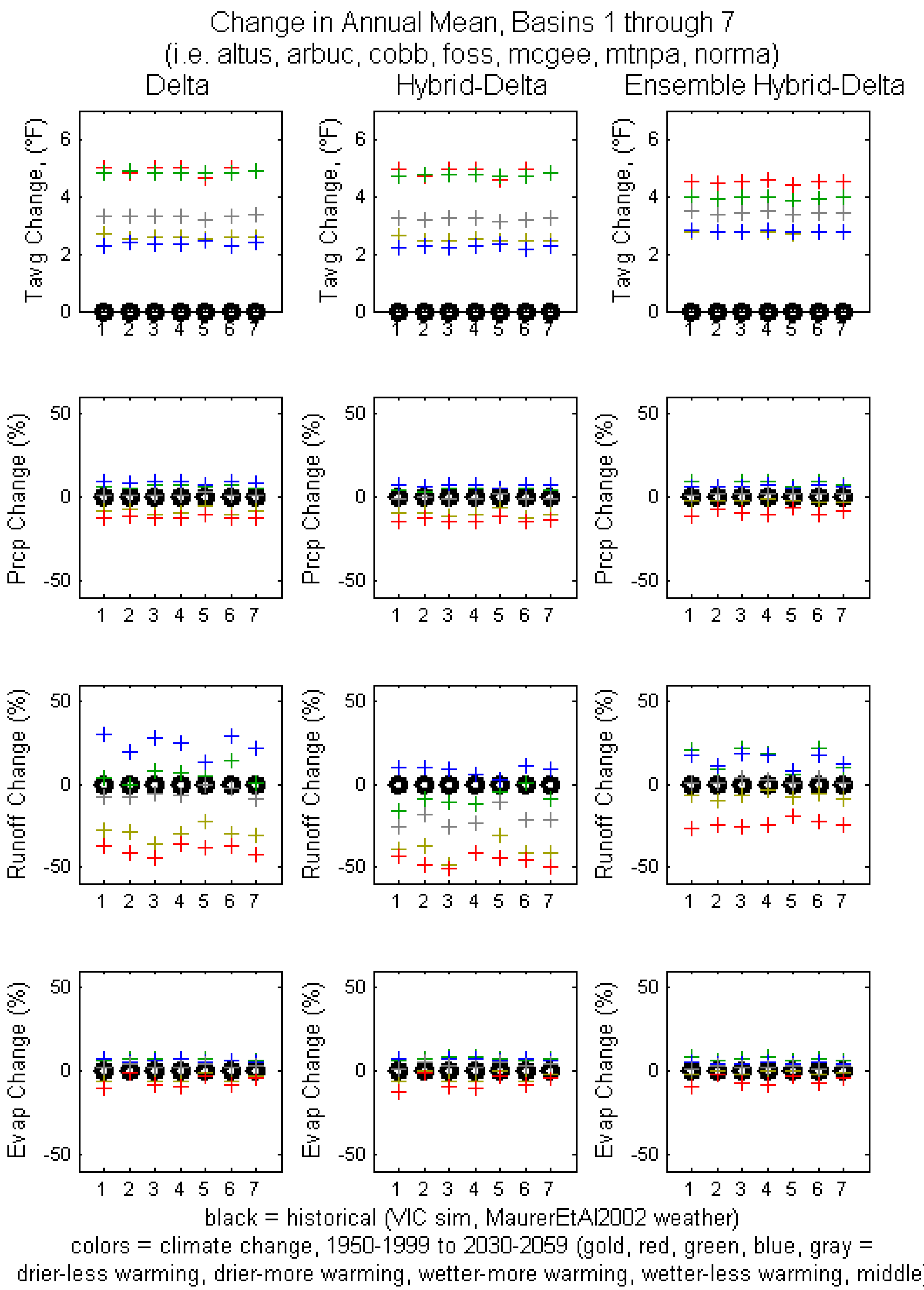

Figure 18. Change in Annual Mean Temperature, Precipitation, Runoff, and Evaporation – All Basins.

It is recommended that, for each scenario, both the changes in mean-monthly and mean-annual runoff be used to adjust the Base monthly reservoir inflow series at a given reservoir used in the yield assessment (i.e., for water years 1926–2008, understanding that this period contrasts with the 50-year duration of Base weather and hydrologic sequences featured in the VIC-simulated hydrologic response assessment just discussed). The need for this two-stage inflow adjustment follows reasoning offered in Reclamation (2008) and arises from how the VIC simulation of historical runoff at a reservoir location is biased relative to the yield assessment's Base historical inflow series at this location during the common historical period. This is because the VIC application was calibrated using historical runoff information that overlapped but did not completely coincide with streamflow and impairments information used to generate the yield assessment's Base inflow series. The consequence of this bias is that when the VIC-simulated changes in mean-monthly runoff are imposed on Reclamation's estimated historical monthly inflows at a given reservoir, then resultant inflow series may express a change in mean annual inflow that differs from VIC-simulated change in mean annual runoff. To reflect the VIC-simulated change in mean annual runoff and, thus, change in long-term water balance, the second inflow series adjustment is necessary and involves scaling the entire series so that the change in 83-year mean annual inflow equals the VIC-simulated change in 50-year mean annual runoff. Ideally, this step would be rendered unnecessary by recalibrating the VIC application to reproduce Reclamation historical inflows (presuming they are natural inflow estimates). However, such model development activity was outside the scope of this effort.

4. Precipitation and Evaporation at Reservoirs

In addition to reflecting runoff impacts, the yield sensitivity analysis is scoped to consider climate change effects on the reservoir precipitation and evaporation conditions. This section describes how time series of reservoir precipitation and evaporation were developed.

4.1 Historical Reservoir Precipitation

Monthly reservoir precipitation estimates have been recorded at each reservoir since time of construction. These data are being used in the yield assessment, which is framed by hydroclimate variability for a period that spans preconstruction to postconstruction conditions: 1926–2008. Reservoir precipitation prior to construction had to be estimated using a data-filling procedure tiering from nearby, or “proxy,” station precipitation and temperature information (P_{pxy} and T_{pxy}). Additionally, there are months of missed reporting in the reservoir precipitation series during the postconstruction period, which meant the data-filling procedure had to address these months also. The goal with data-filling was to produce Base reservoir precipitation series estimated from 1926–2008 that could then be adjusted using the *HDe* change in 50-year mean monthly precipitation over the reservoir watershed to generate Adjusted reservoir precipitation series for the given climate change scenario.

The selected nearby precipitation stations are listed in table 1. These stations have monthly data that span the yield assessment period of 1926–2008. However, these station series also have months of missed reporting, which needed to be filled before filling gaps in the reservoir precipitation data (P_{res}).

Table 1. Proxy Precipitation Stations Used To Fill Gaps in Historical Reservoir Precipitation Series

Reservoir	Proxy Precipitation Station (*Ppxy*)[*]	COOP I.D.
ALTUS	ELK CITY, OKLAHOMA	342849
ARBUC	SULPHUR PLATT NATIONAL PARK, OKLAHOMA	348587
FOSS	HAMMON 1 NNE, OKLAHOMA	343871
COBB	CLOUD CHIEF 2 SE, OKLAHOMA	341927
MCGEE	DAISY 4 ENE, OKLAHOMA	342354
MTNPA	HOBART FAA AP, OKLAHOMA	344204
NORMA	NORMAN 3 S, OKLAHOMA	346386

[*] Each proxy station informed the given reservoir’s Detailed Planning Report (DPR), except for Altus where the DPR does not indicate which precipitation station was used.

The gap filling procedure is a resampling technique that is first operated on the P_{pxy} data and involves steps outlined below. The procedure is applied to a successive pairs of P_{pxy} stations and on a month-specific basis. The ordering of station pairs was influenced by geographic proximity of stations and the need for stations having fewer gaps to be filled first so that they could serve as guides for filling the stations having more gaps. This resulted in the following order of station pairs for mutual gap filling: ALTUS-FOSS, MTNPA-NORMA, MTNPA[10]-FOSS,[10] FOSS-ALTUS,[10] MTNPA-NORMA,[10] MTNPA-COBB,[10] NORMA-ARBUC,[10] and NORMA-MCGEE.[10] For a given station pair and a given month, the following procedure was used:

- Label the stations S1 and S2.
- Identify months when data are reported for S1 (i.e., n1), when data are reported for S2 (i.e., n2), and when these reporting sets intersect (i.e., n1n2). Let n1n2 serve as the set of paired S1 and S2 values from which fill-values are sampled.
- Proceed to fill gap months of S1. Focus on the gap months of S1 for which data were reported for S2. Loop through these S2 values, identifying closest S2 values from the intersect set (n1n2), and identifying the months of these closest values. For these months, get the corresponding S1 values and adopt those values as the fill estimates for S1 during the corresponding gap months.
- Proceed to fill gaps months of S2 in a similar fashion, focusing on the gap months of S2 for which data were reported for S1, etc.

After filling gaps in each P_{pxy} station series, the gap-filling procedure was used again, but this time where S1 and S2 were set to be P_{pxy} and P_{res} data at a given reservoir. In this case, the *S1* series has no gaps, and the procedure only needs to address gaps in S2.

Figure 19 illustrates the results from the procedure, highlighting months where P_{res} at ALTUS was estimated based on P_{pxy} at Elk City, Oklahoma. The figure panels correspond to calendar months, each showing P_{pxy} versus P_{res}. Inspection shows that there is significant error in the relationship between P_{pxy} and P_{res} that, thus, affects gap-fill estimates. Ideally, this procedure would be applied with station-data having a higher correlation with P_{res}. However, due to the period of the yield assessment (1926–2008), the availability of well-correlated P_{pxy} and P_{res} data was limited.

[10] This station's gaps were completely filled after this pairing.

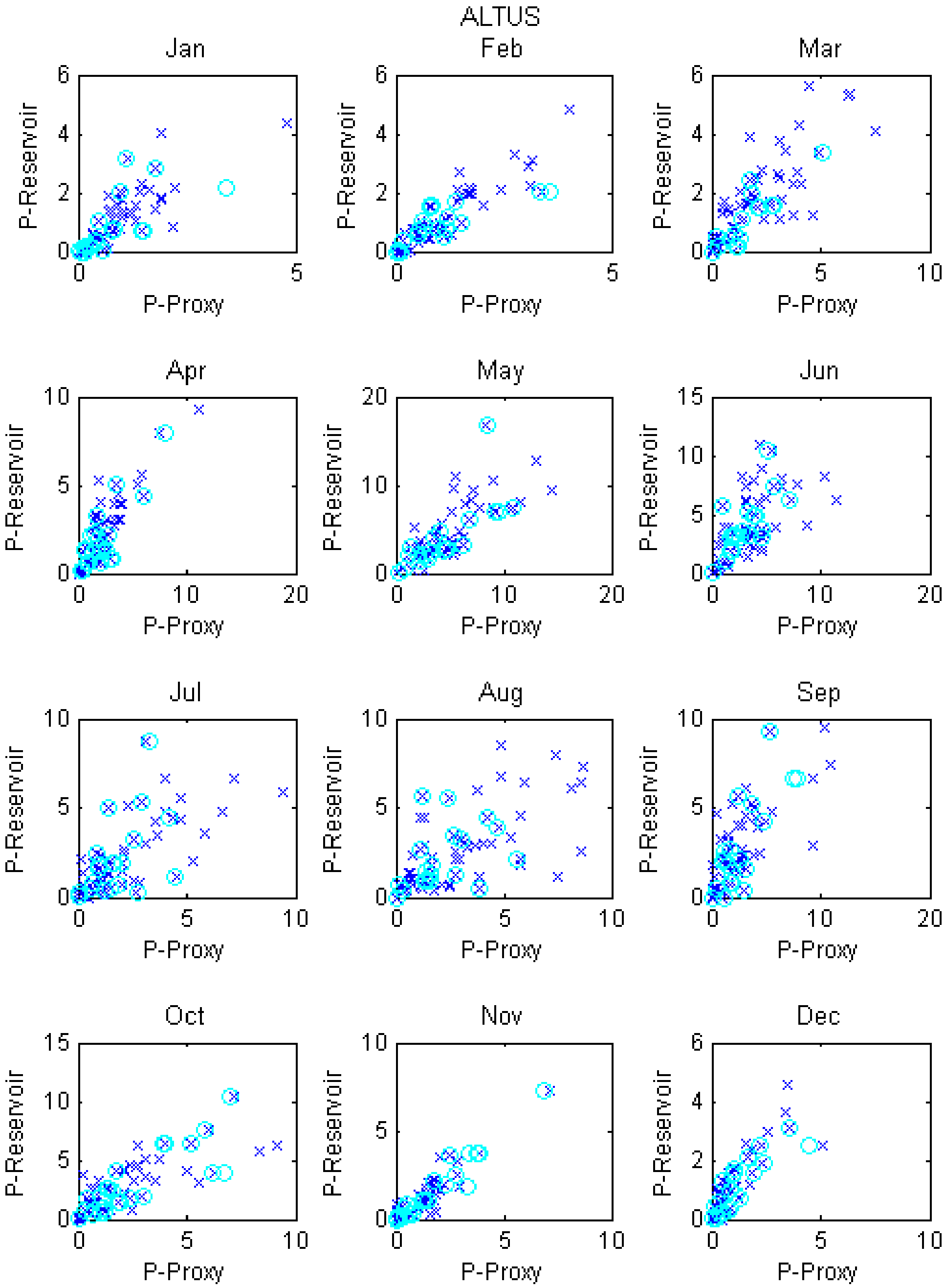

Figure 19. Reservoir Precipitation, Observed and Estimated Based on P_{pxy} data – ALTUS.

4.2 Historical Reservoir Evaporation

As for precipitation, monthly reservoir evaporation estimates have been recorded at each reservoir since time of construction, and there are gaps to fill during the preconstruction period and for months after construction where reports are missing.

The procedure to estimate gaps in the reservoir evaporation series is similar to that used to estimate reservoir precipitation gaps. The key difference is that temperature variability is assumed to be a proxy for evaporation variability, which was done by assuming that reservoir evaporation changes proportionally to temperature change. This assumption is questionable, recognizing that a variety of meteorological conditions affect reservoir evaporation rates (e.g., temperature, radiation, wind speed). However, only temperature data were available for the complete period of 1926–2008; and, therefore, this approximation was used.

Given this presumption, the gap-filling procedure operated on proxy precipitation was applied here to the proxy temperature (T_{pxy}). The gap-filling procedure operated on proxy; and reservoir precipitation was then applied but using proxy temperature and reservoir evaporation (E_{res}). There are two notable caveats in this application:

- Since T_{pxy} data at McGee were not available for the 1926–2008 period, T_{pxy} for Arbuckle were used as a surrogate.

- Also, since E_{res} data for Altus were not availble for the 1926–2008 period, E_{res} from Foss were used as a surrogate.

Given these caveats, the gap-filling for T_{pxy} followed the same succession of proxy station pairs as P_{pxy}, resulting in filled T_{pxy} series. The latter then were used to fill gaps in E_{res}.

Figure 20 illustrates results gap-filling at Lake Altus, where E_{res} at Lake Altus was estimated based on T_{pxy} at Elk City, Oklahoma (green circles). As was discussed for the filling of reservoir precipitation, there is significant error in the relationship between T_{pxy} and E_{res} that, thus, affects gap-fill estimates. Ideally, this procedure would be applied with T_{pxy} having a higher correlation with E_{res}.

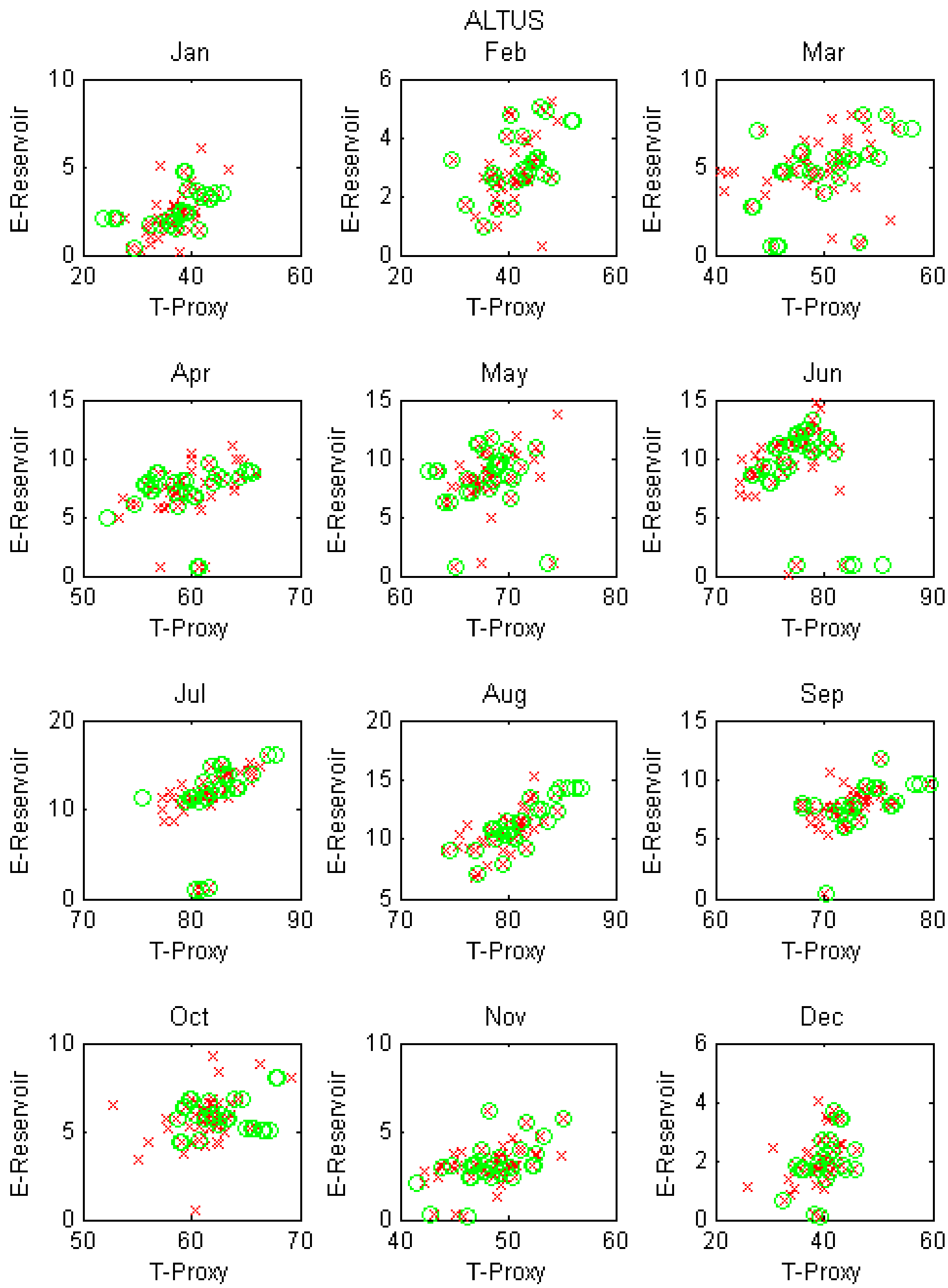

Figure 20. Reservoir Evaporation, Observed and Estimates Based on T_{pxy} Data–ALTUS.

4.3 Estimating Climate Change Reservoir Precipitation and Evaporation

Mean-monthly watershed precipitation and temperature changes from the *HDe* analysis were used to generate "climate change" reservoir precipitation and evaporation series, each tiering from the base 1926–2008 monthly series discussed earlier.

Precipitation was addressed first. For each reservoir and *HDe* climate change scenario, a "climate change" reservoir precipitation series was generated as the Base historical reservoir precipitation series scaled by the ratio changes in 50-year mean-monthly precipitation averaged over the reservoir watershed (Figure 13, right column, second row). This scaling was done on a month-specific basis. Evaporation was addressed next. For each reservoir and climate change scenario, a set of monthly adjustment factors was identified as the product of a given month's "evaporation sensitivity to temperature change" (E_{sens}) and the 50-year mean change in watershed temperature for that month. Development of E_{sens} was based on regression of E_{res} and T_{pxy} data during the historical period.[11] The slopes of these monthly regressions were assumed to be monthly estimates of E_{sens}. Figure 21 shows example estimates of monthly E_{sens} at Lake Altus. "Climate change" reservoir evaporation time series were then estimated as the base E_{res} series incrementally adjusted by the product of E_{sens} and HDe change in watershed temperature. Table 2 summarizes impacts on reservoir evaporation, listing the percentage change in mean monthly depth of evaporative loss, where the mean is computed for all months during 1926–2008 (n = 996).

Table 2. Reservoir Evaporation, Percentage Change in Mean Monthly Loss (inches) by Climate Change Scenario

Climate Change Scenario	ALTUS	ARBUC	FOSS	COBB	MCGEE	MTNPA	NORMA
HDe Drier, Less Warming	6.7	2.6	6.2	6.2	1.7	8.0	3.1
HDe Drier, More Warming	10.7	4.3	10.3	10.4	2.6	13.1	5.2
HDe Wetter, More Warming	9.5	3.8	8.9	9.0	2.3	11.3	4.5
HDe Wetter, Less Warming	6.7	2.6	6.2	6.2	1.7	7.9	3.2
HDe Middle	8.4	3.3	7.9	7.9	2.1	9.9	3.9

[11] Based on graphical inspection of Eres values, there was some concern about some extreme minimum and maximum E_{res} reports at several reservoirs. To eliminate the influence of these extremes on the regression analyses, the regression equations were fit to (E_{res}, T_{pxy}) data pairs involving E_{res} values in between the 10^{th} and 90^{th} percentile E_{res} values.

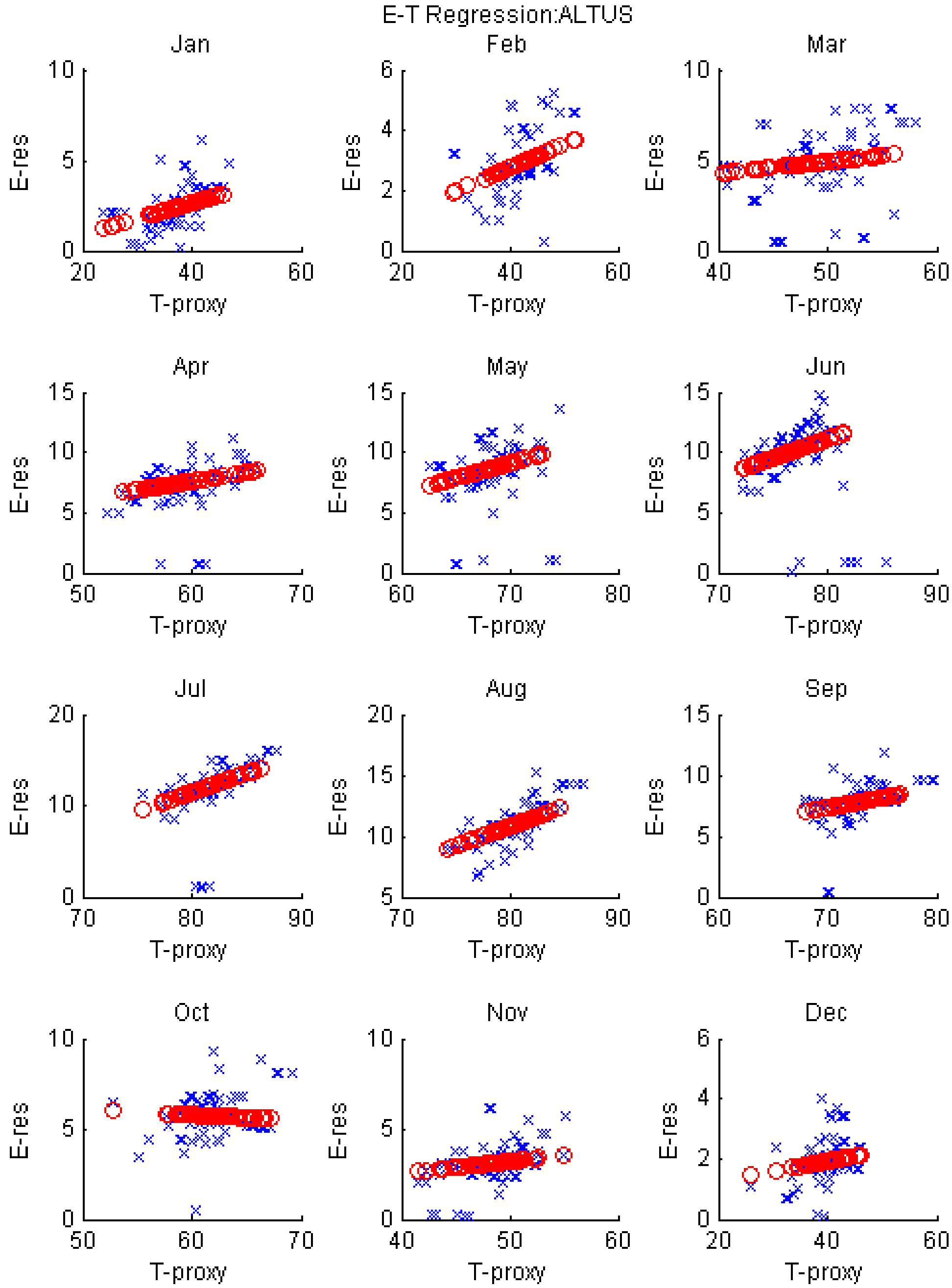

Figure 21. Regression Relationship Between Reservoir Evaporation and Nearby Temperature (*E_{sens}*).

(Figure shows scatter of all paired T_{pxy} and E_{res} data (i.e., E-res and T-proxy), and then the regression fits to all pairs containing E_{res} data within the 10- to 90-percentile range of E_{res} values.)

5. Uncertainties

This analysis is designed to provide some quantitative illustration of how runoff in Reclamation's Oklahoma reservoir watersheds might respond to a range of future climate possibilities. The study was designed to take advantage of best available datasets and modeling tools and to follow methodologies documented in peer-reviewed literature. However, there are a number of analytical uncertainties that are not reflected in study results, including uncertainties associated with the following analytical areas:

- **Global climate forcing:** Although the study considers climate projections representing a range of future greenhouse emission paths, the uncertainties associated with these pathways are not explored in this analysis. Such uncertainties include those introduced by assumptions about technological and economic developments, globally and regionally; how those assumptions translate into global energy use involving GHG emissions; and biogeochemical analysis to determine the fate of GHG emissions in the oceans, land, and atmosphere. Also, not all of the uncertainties associated with climate forcing are associated with GHG assumptions. Considerable uncertainty remains associated with natural forcings, with the cooling influence of aerosols being regarded as the most uncertain on a global scale (e.g., figure SPM-2 in IPCC 2007).

- **Global climate simulation:** While this study considers climate projections produced by state-of-the-art coupled ocean-atmosphere climate models and even though these models have shown an ability to simulate the influence of increasing GHG emissions on global climate (IPCC 2007), there are still uncertainties about our understanding of physical processes that affect climate, how to represent such processes in climate models (e.g., atmospheric circulation, clouds, ocean circulation, deep ocean heat update, ice sheet dynamics, sea level, land cover effects from water cycle, vegetative other biological changes), and how to do so in a mathematically efficiently manner given computational limitations.

- **Climate projection bias-correction:** This study is designed on the philosophy that GCM biases toward being too wet, too dry, too warm, or too cool should be identified and accounted for as bias-corrected climate projections data prior to use in implications studies like this sensitivity analysis. Bias-correction of climate projections data affects results on incremental runoff and water supply response.

- **Climate projection spatial downscaling:** This study uses projections that have been empirically downscaled, using spatial disaggregation on a monthly time-step (following GCM bias-correction on a monthly time-step). Although this technique has been used to support numerous water resources impacts studies (e.g., Van Rheenan et al. 2004, Maurer and Duffy 2005, Maurer 2007, Anderson et al. 2008, LCRA/SAWS 2008, Reclamation 2008, Reclamation 2009), uncertainties remain about the limitations of empirical downscaling methodologies. One potential limitation relates to how empirical methodologies require historical reference information use on spatial climatic patterns at the downscaled spatial resolution. These finer-grid patterns are implicitly related to historical large-scale atmospheric circulation patterns, which presumably would change with global climate change. Application of the historical finer-grid spatial patterns to guide downscaling of future climate projections implies an assumption that the historical relationship between finer-grid surface climate patterns and large-scale atmospheric circulation is still valid under the future climate. In other words, the relationship is assumed to have statistical stationarity. In actuality, it is possible that such stationarity will not hold at various space and time scales, over various locations, and for various climate variables. However, the significance of potential nonstationarity in empirical downscaling methods and the need to utilize alternative downscaling methodologies remains to be established.

- **Generating weather sequences consistent with climate projections:** This study uses three different techniques to generate weather sequences for hydrologic modeling that reflect observed historical climate variability blended with projection information on changes in period monthly conditions. The first two techniques have been demonstrated in previous applications (Delta in Hamlet and Lettenmaier 1999, Miller et al. 2003, and many others; HD in LCRA/SAWS 2008), and the third technique is introduced as an ensemble extension of HD. However, other techniques might have been considered (e.g., generation of weather sequences that conform to the transient development of climate, as featured in Christensen and Lettenmaier 2007). Choice of weather generation technique depends on aspects of climate change that are being targeted in a given study. Preference among available techniques remains to be established.

- **Natural runoff response:** This study analyzes natural runoff response to changes in precipitation and temperature while holding other watershed features constant. Other watershed features might be expected to change as climate changes and affects runoff (e.g., potential ET given temperature changes, vegetation affecting ET and infiltration, etc.). On the matter of land cover response to climate change, the runoff models' calibrations would have to change if land cover changed because the models were calibrated to represent the historical relationship between weather and runoff as mediated by historical land cover. Adjustment to watershed land cover and model parameterizations were not considered due to lack of available information to guide such adjustment.

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Appendix A
Literature Summary on Hydrologic and Water Resources Impacts in the Great Plains Region

This appendix presents a synthesis of climate change literature relevant to hydrology and water resources impacts in the Bureau of Reclamation's (Reclamation's) Great Plains (GP) Region. The summary is a reprint of information originally issued in Reclamation (2009). Summaries generally are divided in terms of studies focused on historical or projected impacts and studies including projected climate change impacts to environmental resources and ecosystems. At present, there is a greater body of literature concerning historical and projected climate and hydrologic changes relative to literature on environmental resources and ecosystem impacts. There is also a greater body of literature concerning impacts in the mountain headwaters and high plains west of the 100th meridian. This section summarizes findings from recent studies (1997–2007) demonstrating evidence of regional climate change during the 20th century and exploring water resources impacts associated with various climate change scenarios.

A.1 Historical Climate and Hydrology

It appears that all areas of the GP Region have become warmer, and some areas received more winter precipitation during the 20th century. Cayan et al. (2001) reports that Western United States spring temperatures have increased 1.8–5.4 degrees Fahrenheit (°F) (1–3 degrees Celsius [°C] () since the 1970s. Based on data from the United States Historical Climatology Network, temperatures have risen approximately 1.85 °F (1.02 °C) in the northern GP to approximately 0.63 °F (0.35 °C) in the southern GP since 1901. That dataset also reveals an increase in annual precipitation of more than 4 percent (%) in the northern GP and 10% in the southern GP over the same time period. The trend was more consistent in the southern GP. Regonda et al. (2005) reports increased winter precipitation trends during 1950–1999 at many Western U.S. sites, including numerous sites in the western GP Region, but a consistent region-wide trend is not apparent.

Coincident with these trends, the western GP Region also experienced a general decline in spring snowpack, reduced snowfall to winter precipitation ratios, and earlier snowmelt runoff. Reduced snowpack and snowfall ratios are indicated by analyses of 1948–2001 snow water equivalent (SWE) measurements at 173 Western U.S. stations (Knowles et al. 2007). Regonda et al. (2005) reports monthly SWE trends during 1950–1999 and suggests that there were statistically significant declines in monthly SWE over roughly half of the Western U.S. sites evaluated for the period 1970–1998. Among those sites, there was no regional consensus among SWE trends over southern Montana to Colorado; however, the regional consensus over western Montana appeared to be a decrease in monthly SWE

These findings are significant for regional water resources management and reservoir operations because snowpack traditionally has played a central role in determining the seasonality of natural runoff. In many GP Region headwater basins, the precipitation stored as snow during winter accounts for a significant portion of spring and summer inflow to lower elevation reservoirs. The mechanism for how this occurs (with precipitation being equal) is that warmer temperatures in these watersheds cause reduced snowpack development during winter, more runoff during the winter season, and earlier spring peak flows associated with an earlier snowmelt.

Warming-induced increases in thunderstorm activity of the GP region (and most of contiguous United States) (Changnon 2001) has led to an increase in heavy precipitation events since 1900 (Groisman 2004). Further, most of that increase has occurred in the last three decades. Garbrecht et al. (2004) found increasing GP precipitation trends led to large increases in streamflow but lesser increases in evapotranspiration (ET).

A.2 Projected Future Climate and Hydrology

Given observed trends in regional warming and declining snowpack conditions, studies have been conducted to relate potential future climate scenarios to runoff and water resources management impacts. Such studies are particularly relevant to the western GP headwaters and the central to northern High Plains. For the GP Region east of the High Plains, and especially in the southern GP, ET demands and warm-season precipitation play a more prominent role in determining local hydrologic conditions relative to water management and generally more so relative to the influence of headwaters snowpack and snowmelt timing.

The findings of six case studies on the sensitivity of water resources to climate change are reported by Lettenmier et al. (1999). One of the case studies was for the Missouri River system. It found that snow accumulation, while important on the western headwaters of the Missouri system, plays only a modest role in total system runoff, and reduced precipitation combined with increasing potential evapotranspiration play a major role in system runoff reductions.

A study by Hotchkiss et al. (2000) addresses the ability to incorporate complex operation rules for multiple reservoirs into a hydrologic model capable of assessing climate change impacts on water resources of large, completely managed river basins. This study was part of an overall effort to address climate change related impacts within the Missouri River Basin. A soil and water assessment numerical modeling tool was used to simulate surface water hydrology that was successfully calibrated to historical conditions; however, its snowmelt component was problematic, thus limiting useful results.

Loáiciga et al. (2000) identified potential impacts of climate change scenarios on management of the Edwards Aquifer system in western Texas. The study reports that the Edwards Aquifer appears to be very vulnerable to warming trends based on current levels of extraction and projected future pumping rates.

Elgaali et al. (2007) and Ojima et al. (1999) report potential climate change impacts on water resources and demands in the GP Region. Changes in agricultural water demands were evaluated based on climate change scenarios using crop consumptive use methods. Both studies project future increases in crop water consumptive use ranging from 20–60% by the end of the 21st century.

Rosenberg et al. (1999) reports impacts on surface water runoff and associated water supplies in the Ogallala Aquifer region under several climate change scenarios, including how changes in atmospheric carbon dioxide impact photosynthesis and ET. Water yield in the Arkansas-White-Red River Basin decreased under all scenarios.

Switching consideration to flood risk management, Lettenmier et al. (1999) reported improved flood control conditions for the Missouri River system under certain climate change scenarios where flood risk is driven by monthly to seasonal phenomena rather than storm or storm pattern phenomena. Hamlet and Lettenmaier (2007) report that simulations suggest that warming over the 20th century has resulted in changes in flood risks in many parts of the Western United States that are broadly characterized by midwinter temperatures and that colder, snowmelt basins typically show reductions in flood risks because of snowpack reductions. In any case, consideration of these results should be complemented by the understanding that many flood risk management situations in the GP Region are driven by potential for local, convective precipitation events. There are still many uncertainties associated with interpreting projected trends in local, convective precipitation potential based on results from current climate models.

A.3 Studies of Impacts on Environmental Resources

Johnson et al. (2005) used a wetland simulation model to predict significant climate change impacts to the northern pothole prairie region. The findings indicate that the most productive habitat for breeding waterfowl would shift to the eastern part of the region under warmer and drier conditions. Conly and Garth van der Kamp (2001) reported wetland and associated wildlife impacts related to climate and land use changes. Wetland water level data were coupled with meteorological data in a numerical model to simulate water level changes resulting from climate change. Poiani and Johnson (1993) also used a numerical model to simulate wetland hydrology and vegetation impacts due to climate change.

Covich et al. (1997) summarizes available information on patterns of spatial climate variability and identifies subregions of importance to ecological processes within the Great Plains. Climate sensitive areas of the Great Plains range from cold-water systems (springs, and spring fed streams) to warmer, temporary systems (intermittent streams, ponds, pothole wetlands, playas).

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