Climate Change in Colorado: Supplementary Material on Methods and Figure Sources

Version 1   28 January 2009

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Funding from the Colorado Water Conservation Board of the State of Colorado to the CIRES Western Water Assessment

Summary

The report "Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation" summarizes Colorado-specific findings from peer-reviewed regional studies, and presents new analyses derived from existing datasets and model projections. This supplementary material lists sources for figures that were obtained from other studies and describes the methods and data sources used for the "new analyses" that the team of authors generated. Figures and Tables are listed in the order that they appear in the report. All references are to be found in the bibliography of the report except where the full reference is given in the text.

1. Introduction

Figure 1-1 Climate and Extreme Events

Source: IPCC Fourth Assessment (AR4), Working Group I (WGI) report (IPCC, 2007).

2. The Observed Record of Colorado Climate

Figure 2-1 Annual Average Temperature and Precipitation in Colorado (1950-99)

Data source: PRISM (Di Luzio et al., 2008, www.prism.oregonstate.edu). Annual average temperature is computed as the average of the daily minimum and maximum temperatures. The climatology was computed from monthly-average data available at the PRISM website.

Figure 2-2 Temperature at Nine Observing Stations, and

Figure 2-3 Water Year Precipitation at Nine Observing Stations

Nine observing stations (Table S-1) were selected from a larger set of 40 "better quality" stations compiled by the Colorado Climate Center (Nolan Doesken, CCC) and Western Water Assessment (Klaus Wolter, WWA) as having comparatively fewer identified problems with station moves, millins observations, and measurement and instrumentation changes. The nine stations shown in these figures were chosen because of their 90-year or longer period of record in both temperature and precipitation, and because they are distributed across the state. Monthly data for these stations is available online at the CCC website along with further documentation. The original sources of the data are the National Climatic Data Center (COOP station data, unadjusted) and the Colorado Climate Center. The starting points for computing annual averages are time series of monthly total precipitation and monthly average maximum temperature (Tmax) and minimum temperature (Tmin).

Missing data was handled as follows. For temperature, monthly anomalies from the long-term (period of record) monthly climatology were computed. Annual averages, taking into account the different lengths of the months, were computed from the monthly anomalies for calendar years with at least ten months of available data. The annual mean anomaly was then added back to the average long-term climatology to produce the average temperature for each year. Finally, the average temperature was computed by taking the mean of the average minimum and maximum temperatures for each year. For precipitation, the total precipitation for the Water Year (October 1 – September 30) was calculated by summing the individual monthly totals. All months were required to have data in order to form the annual total.

The 30-year, 50-year, and 100-year linear trends ending in WY 2007 were computed from the annual precipitation time series. If fewer than 100 years of data were available, the full period of record was used to calculate the trend. First, ordinary least-square linear trend was computed along with the statistical significance assuming Gaussian distribution and uncorrelated data (Table S-2).

For precipitation no significant trends were found with the following exceptions: 50-year upward trends were seen Lamar (p<0.025), Grand Junction (p<0.05) and Trinidad (p<0.05). There were no other statistically significant trends with p<0.1) for the other stations and for the other periods. Low autocorrelation from year to year means that standard t-test of significance was adequate. Because of the absence of a pattern of significant trends in precipitation we show the 10-year moving average to emphasize the slower variations that can be of great importance to the reliability of Colorado's water supply. The ten-year moving average of available data within a ten-year window (centered between years) was calculated. The moving average line is not shown for years where data is missing. The first and last 5 years of the moving average are were computed with the data available, and thus comprise averages of fewer than ten years.

For temperature, year-to-year autocorrelation in the data (typically in the range of 0.2 to 0.3) can be a problem.). Based on our experience with more sophisticated signifigance testing of the experimental climate division timeseries (below), and based on the fact that these timeseries have similar autocorrelations and probability distributions to the experimental climate division temperature data, a 97.5% level of significance here corresponds to about a 95% level of significance for the more stringent tests.

Seasonal temperatures are not analyzed here, the absence of a significant trend in the annual mean does not imply the absence of a trend in individual months or seasons.

Table S-1 *Primary stations for climate change assessment in Colorado Station ID, Name, Latitude, Longitude, Elevation, New Climate Division (CD) that includes the station, climate variable (T=Temperature, P=Precipitation), beginning and end of period of observation and number of full years in the record, up to and including 2006. Correlation coefficient of the station time series to its assigned climate divisions time series are shown for 3-month "sliding seasons" (moving averages). Correlations were computed with standardized anomalies, standardized by each season to the period WY 79-06. Statistical significance of the correlation coefficient is shown. These correlations show how representative the variations at an individual station are of variations in the climate division average.*

Stn ID	Name	Lat	Lon (W)	Elev	CD	Var	Begin	End	Yrs	Corr	Stat Sig
CO-7936	STEAMBOAT SPRINGS	40.49	106.81	2023	44	P	1909	2007	94	0.800	>95%
CO-7936	STEAMBOAT SPRINGS	40.49	106.81	2023	44	T	1910	2006	85	0.876	
CO-3488	GRAND JUNCTION	39.13	108.53	1481	45	P	1892	2007	115	0.868	~100%
CO-3488	GRAND JUNCTION	39.13	108.53	1481	45	T	1899	2007	106	0.904	>95%
CO-5722	MONTROSE NO 2	38.49	107.86	1763	45	P	1896	2007	111	0.773	~100%
CO-5722	MONTROSE NO 2	38.49	107.86	1763	45	T	1905	2007	97	0.912	>95%
CO-8429	TRINIDAD	37.17	104.48	1838	46	P	1899	2007	108	0.645	100%
CO-8429	TRINIDAD	37.17	104.48	1838	46	T	1900	2006	88	0.917	
CO-3005	FORT COLLINS	40.61	105.11	1525	48	P	1889	2007	118	0.804	100%
CO-3005	FORT COLLINS	40.61	105.11	1525	48	T	1889	2006	117	0.968	>95%
CO-0109	AKRON 4E	40.15	103.13	1384	52	P	1905	2007	102	0.774	~100%
CO-0109	AKRON 4E	40.15	103.13	1384	52	T	1918	2006	82	0.950	>90%
CO-1564	CHEYENNE WELLS	38.82	102.34	1295	96	P	1897	2005	109	0.725	~100%
CO-1564	CHEYENNE WELLS	38.82	102.34	1295	96	T	1898	2005	98	0.932	>90%
CO-7167	ROCKYFORD 2SE	38.04	103.68	1271	96	P	1888	2007	118	0.854	>95%
CO-7167	ROCKYFORD 2SE	38.04	103.68	1271	96	T	1893	2005	105	0.945	>90%
CO-4770	LAMAR	38.09	102.61	1106	97	P	1889	2007	118	0.751	~100%
CO-4770	LAMAR	38.09	102.61	1106	97	T	1897	2007	106	0.933	>95%

Table S-2 *Statistical significance (p-value) of temperature and precipitation trends differing from zero for stations shown in Figures 2-2 and 2-3. The trend is determined from an ordinary least squares analysis for the 30-year, 50 year and 100-year period (or period of record, for shorter timeseries) ending in 2007. P-values are computed assuming a normal distribution and uncorrelated values in time. P-values less than 0.025 (sometimes referred to as being significant at the 97.5% level) are highlighted in red (increasing trends) and blue (decreasing trends). Based on our experience with more sophisticated signifigance testing of the experimental climate division timeseries, and based on the fact that these timeseries have similar autocorrelations and probability distributions to the experimental climate division data, a 97.5% level of significance here corresponds to about a 95% level of significance for the more stringent tests.*

Stn ID	Name	Precipitation			Temperature		
		30yr	50yr	100yr	30yr	50yr	100yr
CO-7936	STEAMBOAT SPRINGS	0.784	0.243	0.970	0.067	< 0.0001	0.000183
CO-3488	GRAND JUNCTION	0.730	0.042	0.594	0.439	0.133	0.007
CO-5722	MONTROSE NO 2	0.930	0.305	0.791	0.185	0.0024	0.000141
CO-8429	TRINIDAD	0.153	0.045	0.389	0.0001	< 0.0001	0.00012
CO-3005	FORT COLLINS	0.380	0.555	0.433	< 0.0001	< 0.0001	< 0.0001
CO-0109	AKRON 4E	0.147	0.328	0.112	0.0096	0.122	0.0026
CO-1564	CHEYENNE WELLS	0.924	0.821	0.869	0.001	< 0.0001	0.00175
CO-7167	ROCKYFORD 2SE	0.290	0.180	0.993	0.0003	< 0.0001	< 0.0001
CO-4770	LAMAR	0.199	0.023	0.242	0.645	0.48	0.0019

Figure 2-4 Colorado Regional Temperature Trends, and

Table 2-1 Seasonal Temperature Trends in the Northern Colorado Mountains and the Arkansas Valley

Data source: Klaus Wolter, WWA. The original sources of the observational data are NCDC and the Colorado State Climatologist, Nolan Doesken.

Recently defined cluster-based experimental climate divisions (Wolter and Allured, 2007, http://wwa.colorado.edu/forecasts_and_outlooks/docs/WWA_Jun_2007_feature.pdf) were chosen to represent the regional variations in temperature trends within Colorado. The clustering algorithm that was used to define the new divisions is based on similarity of year-to-year variations in temperature and precipitation in the data, whereas traditional climate divisions defined by the National Climatic Data Center (NCDC) are based on geographical and political regions. Therefore it is thought that these new divisions better represent the effects of regional climate processes within the state. In addition, there was a concern among the authors that the averaging procedures used to create time series for the traditional climate divisions might be susceptible to the changing observational network in the Colorado Rockies.

Average seasonal (three month averages: DJF, MAM, JJA, SON) temperature anomalies for the new climate divisions were computed using the "better" stations described above, of which there were between two and seven per division. Only stations in Colorado were used in these averages, even in divisions that span more than one state. Division averages using all available station data were also computed, but are not shown.

The ordinary least squares linear trend was computed, and is shown in Figure 2-4 and Table 2-1. Trends that have a p-value less than 0.05 (95 % significance level) are highlighted. To test the robustness of our statistical significance levels, we performed a non-parametric trend analysis for selected divisions (Helsel et al, 2005 "Computer Program for the Kendall Family of Trend Tests", USGS Scientific Investigations Report 2005-5275). When this method is applied to our data it yields similar trend magnitudes to OLS. (Tables S-3 and S-4). A Mann-Kendall test for significance of the trend (compared to no trend) was used in these cases. Because the time series contain serial correlation (that is, there is some persistence of temperature anomalies from year to year), a "pre-whitening" procedure was used (Yue et al., 2002, "The influence of autocorrelation on the ability to detect trend in hydrological series" Hydrol. Process. v. 16, pp. 1807-1829). As expected, the p-values were somewhat higher when serial correlations (typically 0.2-0.3) were taken into account, but do not qualitatively change the results. (For more information on issues regarding trend analysis see, for example, von Storch, H (1995) Misuses of statistical analysis in climate research. In: von Storch H, Navarra A (eds) Analysis of climate variability applications of statistical techniques. Springer-Verlag, Heidelberg, p 11–26 , or CCSP SAP 3.3, Appendix A). Of all the values tested, only the summer trend in Tmax for the Arkansas Valley dipped below the $p = 0.1$ level when the more stringent analysis was applied.

Table S-3 *Trends and p-values for seasonal and annual trends for the divisions shown in Table 2-1. This computation uses a non-parametric estimate of the trend, and the p-value is calculated using a pre-whitening procedure to account for serial correlations in the data. P-values are shown for all trends with $p < 0.1$ (90% significance level).*

Division	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Annual
Arkansas Valley					
Tmax	+2.4	+3.9 (0.0036)	+0.1	+1.2	+2.1 (0.0042)
Tmin	+3.3 (0.0071)	+2.9 (0.0002)	+1.9 (0.0042)	+1.3 (0.079)	+2.3 (0.0000)
North Central Mountains					
Tmax	+1.2	+4.6 (0.0004)	+1.3	+0.03	+2.2 (0.0067)
Tmin	+2.7 (0.0734)	+4.8 (0.0000)	+3.1 (0.0001)	+2.7 (0.0027)	+3.1 (0.0000)

Table S-4 *As in Table S-3, but for trends in the annual mean temperature as shown in Figure 2-4.*

Trend Period	Arkansas Valley	North Central Mountains
75-year	+1.0 (0.0370)	+1.0
50-year	+2.1 (0.0003)	+2.7 (0.0001)
30-year	+2.2 (0.0060)	+1.7 (0.0295)

Figure 2-5 Colorado Annual Mean Temperatures (1930-2007).

Data source: State monthly average temperature anomalies, National Climatic Data Center. The statewide averages are available from the NCDC website (www.ncdc.gov) and are based on the NCDC Climate Division data. The annual average was computed from the monthly data. The anomaly from the 1950-1999 baseline average is shown. The period 1930-present was chosen for two reasons. First, before 1930 climate division data is determined from a linear regression procedure rather than a weighted average of station data. Second, for the experimental climate divisions, sufficient “better” station data to compute division averages was only available back to 1930 for most divisions. Note that prior to 1930 much of the Western United states experienced a prolonged cool period.

The trends noted in the text were computed as follows. The ordinary least squares trend was computed from the timeseries of annual mean temperature for the NCDC data. The alternate computation of the statewide trend was obtained by a weighted average of the experimental climate division trends reported in figure 2-4. The weights used for each division are shown in Table S-5.

Table S-5 *Area weighting factors for experimental climate divisions.*

Experimental Climate Division	Area Weighting Factor
North Central Mountains	0.19
North Front Range	0.11
Northeast	0.08
Arkansas Valley	0.23
Lower Arkansas Valley	0.05
South Front Range	0.04
San Luis Valley	0.09
Southwest	0.09
Grand Junction/Gunnison	0.13

Figure 2-6 Temperature Trend and Elevation

Source: Diaz and Eischeid 2007.

Figure 2-7 Trend in March Average Minimum Temperature (1949-2004)

Source: Knowles et al. 2006.

Figure 2-8 Trend in Snow vs. Rain in Winter

Source: Knowles et al. 2006.

Figure 2-9 Reconstruction of Streamflow for the Colorado River at Lees Ferry

Source: Meko et al. 2007.

3. A Primer on Climate Models, Emissions Scenarios, and Downscaling

Figure 3-1 Hydrologic Component of GCMs

Sources: Adapted, simplified, and redrawn based on original figures in Milly and Shmakin 2002 and Oleson et al. 2008. Deep groundwater component that is part of the current generation of the NCAR CCSM land surface model is not shown as this is a new addition was made after the CMIP3 model runs were completed.

Figure 3-2 Model Grid for the Atmosphere Component

Source: NOAA (http://celebrating200years.noaa.gov/breakthroughs/climate_model/welcome.html)

Figure 3-3 Global Mean Surface Temperature and Model Projections

Source: IPCC AR4 WG1 2007.

Table 3-1 Effect of Climate Change on Reliability of Boulder's Water Supply

Source: Joel Smith, Stratus Consulting, Boulder, Colorado. The Boulder Study is a collaboration of Stratus Consulting, the City of Boulder, the University of Colorado, and AMEC Consulting.

Figure 3-4 Elevation on Global and Regional Climate Model Grids

Data sources: NCAR CCSM website (CCSM 3.0 T85-resolution model grid downloaded from ccsm.ucar.edu). WRF RCM (48 km resolution, Chris Anderson, Iowa State University). Graphics were plotted from the elevation data used by the models on the native model grids. Note that the NCAR CCSM, though typical of the resolution of present-day (2009) GCMs was one of the higher resolution models in the CMIP3 archive.

Table 3-2. Seasonally Averaged Climate Biases of the IPCC AR4 WG1 Climate Models in Temperature and Precipitation for Colorado

Monthly mean climatology for 1950-1999 for 22 CMIP3 climate models were interpolated from the native model grid to the 4-km PRISM grid. The difference between each model climatology and the observed was then computed for each gridbox. The biases for all the 4-km gridboxes in state of Colorado were averaged to get the statewide bias. The bias was calculated for each model and for each season. The median (50th percentile) value of the all the model biases for each season is shown in the table. The values of the median bias for the Central North America and Western North America regions are taken from IPCC AR4 (2008) Chapter 11 Supplementary Material.

Table 3-3 Strengths and Weaknesses of Statistical Versus Dynamical Downscaling

Source: This table was constructed with the help of Dr. Levi Brekke (Bureau of Reclamation) based on Fowler et al, 2007.

Figure 3-5 The Progression of Data and Models form Climate Models to Streamflow

Adapted and expanded by Bradley Udall and Joseph Barsugli from a diagram in Udall and Bates 2007.

4. Climate Attribution

Figure 4-1 Observed Annual Average North American Surface Temperature (1950-2007)

Data source: Hadley Center CRUTEMv3 global monthly gridded temperature data. This data is on a 5x5 degree grid and was interpolated to a 1x1-degree grid. The ordinary least squares linear trend was computed from annual averages for the period 1950-2007 for each 1 degree gridbox and the resulting total temperature change over the 57-year period (the trend in degrees per year multiplied by the number of years) was contoured. The annual temperature anomaly from the 1971-2000 reference period average was spatially averaged over the land areas of North America to obtain the timeseries plot. The smoothed curves in figures 4-1 through 4-4 were computed using a 9-point filter with Gaussian weights (0.01 0.05 0.12 0.20 0.24 0.20 0.12 0.05 0.01). The frequency response of this filter is very similar to that of a 5-year moving average.

Figure 4-2 Modeled Annual Average North American Surface Temperature (1950-2007)

Data source: CMIP3 Data Archive. All model runs for which both a 20-th century and an A1B scenario output in the archive were used. This totaled 48 runs from 22 models. The multi-model mean was computed treating each run with equal weight. The model output was processed as in Figure 4-1.

Figure 4-3 Intensity and Extent of Drought in Colorado (1895 – 2007)

Data source: NCDC Climate Division monthly Palmer Drought Severity Index data (available from www.ncdc.gov) . There are five climate divisions in Colorado, each with a different total land area. The area-weighted average value of the PDSI is shown in the upper curve. The percentage of area in severe drought in the lower curve is calculated as the sum of the areas of the climate divisions with annual average PDSI < -3 divided by the total area of the state. A value of 100% means that all five climate divisions were in drought, but not necessarily every location within these climate divisions was in drought in every month of the year.

Figure 4-4 Precipitation and River Flow in the Upper Colorado Basin

Data sources: Precipitation: PRISM 4-km monthly data, spatially averaged over the Upper Colorado River Basin, and then averaged over the Water Year. Annual naturalized streamflow at Lees Ferry is taken from the 59th Annual Report of the Upper Colorado River Commission, dated September 30, 2007. Note that the figure caption erroneously states the Bureau of Reclamation as the source for this data. The data shown here are very similar to the annual averages of the naturalized flows presented in Prairie, J. and R. Callejo (2005), "Natural flow and salt computation methods", U.S. Dept. of Interior, Salt Lake City, Utah, Update through 2006 available from the Bureau or Reclamation at www.usbr.gov/lc/ . The differences between the two datasets in the annual total flow would not be visible in the graphic shown here. However, the UCRC data starts at an earlier date allowing comparison to the full record of the precipitation data.

4. Climate Projections

Figure 5-1 Temperature and Precipitation Changes over North America Projected for 2050

Data source: CMIP3 Model Archive. The multi-model mean was computed from 48 runs of 22 climate models for the A1B emissions scenario. Each run was weighted equally. Model output was first interpolated to a common "T42" model grid (about 2.8 degrees in extent) before averaging. Seasons are defined from the monthly-average data as follows: Winter as the December, January, February (DJF) mean, and Summer as the June, July, August (JJA) mean. The annual mean is computed from all months.

The top two rows show the difference of the multi-model average for the period 2040-2060 from the average of the 20-th century model runs for the baseline period of 1950-1999. This graphic is based on based on Figure 11.12 in the IPCC AR4 WG1 (2008) report. However, compared to the IPCC figure, we consider projections for 2050 rather than 2090, and zoom into the conterminous United States showing state boundaries. There also may be small differences due to the equal weighting of model runs rather than individual models. The lower row of panels was computed by selecting only one run for models that had more than one ensemble member, and simply counting the number, out of 22 models, that show an increase in precipitation.

Figure 5-2 January Observed and Projected Temperatures, and

Figure 5-3 July Observed and Projected Temperatures

Data source: CMIP3 Model Archive (models) and PRISM (observations). The projections are computed by taking the multi-model mean temperature change (analogous to those shown in Figure 5-1, but for the individual months of January and July) and adding it to the 4-km PRISM climatology for those months. This figure is illustrative of what an approximately 4°F rise in temperatures would mean for Colorado's climate compared to the existing north-south and elevational gradients of climate in the state. There are a number of unknowns about how Colorado's climate will evolve at any given location – as some local effects may reduce, or amplify the large-scale pattern of widespread warming that is projected over the Western United States.

Figures 5-4, 5-5, 5-6, and 5-7 Projected Monthly Temperature and Precipitation near Grand Junction, Steamboat Springs and La Junta CO.

Data sources: Statistically Downscaled WCRP CMIP3 Climate Projections (Maurer et al, 2007 and references therein) available at gdo-dcp.ucllnl.org/downscaled_cmip3_projections (used for the projections, monthly climatology and temperature range). CMIP3 Model Archive (used for the correction to downscaled precipitation) and NCDC COOP data (estimated range of 20-year means).

The observational climatology was calculated from the downscaled historical simulations for the period 1950-1999. Because of the bias correction used, this climatology is nearly identical to that calculated from the observational dataset used in the downscaling procedure.

The 2040-2059 average of temperature and precipitation were calculated for each of 39 model runs (representing 16 climate models). Both projections and observations were averaged over a 5x5 rectangle of downscaled values. The area over which these small-region averages are taken is shown in Figure 5-4.

The downscaled precipitation projections have been corrected for a slight bias between the percentage changes at the GCM and the downscaled grids. This bias is introduced by the percentile-mapping technique used in the downscaling. Because it does not reflect any known physical processes, we chose to implement a correction that requires the percentage change in the annual total precipitation to be the same in the GCM data (interpolated to each location) and the downscaled data. The correction consists of a small percentage adjustment (typically zero to two percent) that is applied equally to all months of the precipitation projection data for a given model. This correction is being implemented by the "Reconciling Future Projections of Colorado River Stream Flow" project, and results in a slightly drier climate – and greater flow reductions -- in the future than the uncorrected data would suggest.

The 10^{th} and 90^{th} percentiles of monthly temperatures and precipitation for the historical period were calculated from the distribution of downscaled, bias-corrected historical simulations, and should reproduce the range historical observations used for the downscaling procedure.

Because the projections were calculated as 20-year averages, we wanted to compare the range of model projections to the range of variability in 20-year averages of observed precipitation. To do this we needed to use a different observational dataset, as the 50 years of the Maurer 2007 data would be insufficient. We estimate the variability of 20-year means from the long (> 90 years) observational timeseries shown in Figure 2-3 for Steamboat Springs, Rocky Ford (near La Junta) , and Grand Junction (see Table S-1). The range of 20-year means for each month's precipitation was calculated using a block-resampling technique. 4-year means were randomly sampled from the historical record and used to construct 1,000 synthetic 20-year means. Finally, the 10^{th} and 90^{th} percentile values were expressed as a percentage of the monthly climatology at the observing station, and these percentages were then applied to the downscaled monthly climatology shown in the figure. This estimation technique proved to be relatively insensitive to the block-size.

Figure 5-8 Projected Changes in Annual Runoff (2041-2060)

Source: P. C. D Milly www.gfdl.noaa.gov/~pcm/project/runoff_change.ppt, which is a supplement to the Milly, 2005 article. (See further discussion under Table 5-1 below).

Table 5-1 Projected Changes in Colorado River Basin Runoff or Streamflow in the Mid-21st Century from Recent Studies

The articles summarized in this table did not present their data in a consistent manner. Some of the numbers came directly from the text of the report while others were drawn from tables or directly from figures. The ranges shown are those reported in the source material. Some notes on individual studies are given below, but it is strongly suggested that you consult the original articles for more information.

Milly 2005 The values shown in the table come from our Figure 5-8. The Upper Colorado basin is shown as lying in the "10-20% reduction" category, so the range of values shown does not result from considering any specific percentile values. A similar figure by Milly is shown in the CCSP SAP 4.3, (2008) report, with slightly different categories (10-25% reduction), and it is in that figure that the 96% agreement among model runs on the sign of the change is given. According to Dr. Milly (pers. comm.) the two figures were based on slightly different choices for model averaging (that is, whether individual runs for a model are first averaged together, or whether all runs of all models are given equal weight). The original data on GCM runoff changes is shown in the referenced article in Nature (Milly, 2005).

Hoerling and Eischeid, 2006 – The range is taken from the graphic in their paper. The authors have since tempered their conclusions by noting that the large spatial scales used in their analysis probably over-estimate the sensitivity of runoff to rising temperatures compared to analyses that use a finer-scale hydrology.

Christensen and Lettenmaier 2007. The range of runoff changes represents the 5th and 95th percentiles of the 30-year means and is taken from the tabular data in their paper, the same data shown in our Figure 5-9. It should be noted that this range of values includes both model uncertainty and model-simulated natural variability.

Seager et al. 2007 These results were only presented graphically in their paper. We drew a smooth line through the, 25-th, median, and 75-th percentile curves of P-E (precipitation minus evaporation) and interpolated the P - E changes to 2050. The values found were -0.025, - 0.048, and -0.075 mm/day respectively. The total multi-model mean P-E is reported as 0.3 mm/day in this region, yielding 8%, 16%, and 25% change. It should be noted that their averaging area (125°W to 95°W, 25°N to 40°N) includes relatively wet regions such as eastern Kansas and Texas, and excessively dry areas such as the Sonora Desert in Mexico. The averaging area leaves out substantial areas of the headwaters of the Colorado River.

Figure 5-9 Range in Temperature and Precipitation Projections for the Upper Colorado River Basin

Source: Plotted for this report from tabular data in Christensen and Lettenmaier, 2007.

Figure 5-10 Projected change in Colorado River Basin Snowpack

Source: Redrawn from the figure in Christensen and Lettenmaier, 2007.

Figure 5-11 Projected Soil Moisture Changes in the Upper Colorado River Basin for 2050 for April, May, June and July

Data source: Dennis Lettenmaier, University of Washington. Soil moisture output from the Variable Infiltration Capacity (VIC) hydrology model forced by 11 different GCM climate change scenarios that have been bias corrected and statistically downscaled to the 1/8 degree VIC grid (see Christensen and Lettenmaier 2007 for details on the model and the scenarios considered). Because modeled soil moisture in not directly comparable to observations, an analysis of relative changes in terms ofpercentiles was suggested by Prof. Lettenmaier and carried out by Joseph Barsugli for this report.

For each GCM and for each month of the year, the distribution of monthly mean soil moisture for the 50 years of the historic period was calculated. The median monthly value of soil moisture of the period 2040-2059 was then found for each model. The future median value of soil moisture was then expressed in terms of its percentile in the historical distribution for each model run. The average of this number across all model runs was then computed. The maps show the multi-model average change in percentile ranking from the historical period (50^{th} percentile, by construction) to the future period. The change ranges from -50% (the future median is lower than any year in the historical record) to +50 % (the future median is higher than any year in the historical period).

Figure 5-12 Projected Changes in Snow Covered Area, Aspen

Source: Joel Smith, Stratus Consulting

6. Implications of Changing Climate for Colorado's Water Resources

Table 6-1 Challenges Faced by Water Managers, and Projected Changes

Numerous sources.

Figure 6-1 Approaches to Climate Change Assessment

Source: Yates and Miller 2006