ASSESSING CLIMATE CHANGE IMPACTS ON THE BLUE RIVER BASIN OF OKLAHOMA

Christopher N. Bednarczyk[1], Yang Hong[2], Lu Liu[2], Jonathan J. Gourley[3], James Hocker[4], Mark Shafer[4]

[1]National Weather Center Research Experiences for Undergraduates Program
and
Valparaiso University

[2] Department of Civil Engineering and Environmental Science, University of Oklahoma, Norman, OK

[3] National Severe Storms Laboratory, NOAA, Norman, OK

[4]Oklahoma Climatological Survey, University of Oklahoma, Norman, OK

ABSTRACT

A 16 GCM ensemble was used to assess the future climate of Oklahoma and its Blue River Basin under three IPCC emissions scenarios. Output from the models was then applied to a monthly water balance model to predict changes in the hydrologic cycle. By the end of the century ensemble median warming is predicted to be 2.2 to 4.6 °C for the state depending on the scenario. Precipitation trends depended on the emissions scenario, with the state experiencing almost no annual change. The Blue River Basin is expected to receive slightly more precipitation under the lower emissions scenario and less under the higher scenario. Change in temperature along with little change in precipitation led to predicted increase in both potential evapotranspiration and actual evapotranspiration. Soil moisture and runoff are both expected to decrease significantly. Runoff changes by 2100 ranged from ensemble mean of -9.6% for the lower emission scenario to -29.8% for the higher.

1. INTRODUCTION

Potential modifications to the hydrologic cycle associated with climate change are an important topic of study. Continued population growth will put even more strain on water resources in the coming future. Coupled with the changing climate, there could be extreme alterations to the water cycle around the world. Being able to predict and anticipate these changes on a regional level will be vital to the sustainability of current societies worldwide.

In 2002 the Central Oklahoma Water Authority looked into pumping water from the Arbuckle-Simpson Aquifer to cities outside the area. This aquifer is located in south central Oklahoma, where from which several communities get portions of their water supply. The Blue River is one stream that is fed in part by the groundwater from the aquifer. Oklahoma law considers groundwater to be private property, so it can be extracted for use by any landowner who resides in the area of the aquifer. However, concern over the potential effects of pumping large amounts of water away for use in other communities led to legislative action, which put a moratorium on permits to extract water for use outside of the county where the aquifer is located. This will last until it can be determined how much water can be removed without negatively affecting streamflow in the area's rivers and streams (OWRB 2003).

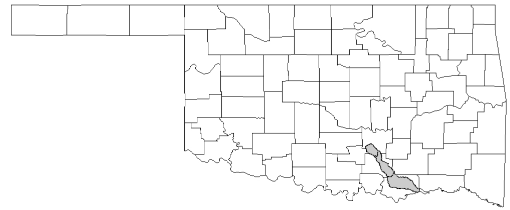
Changes in the water cycle from climate change would also have an impact on streamflow and should certainly be considered. Similar studies have been done in other basins worldwide (Barnett et al. 2004; Elsner et al. 2010; Li et al. 2008; Maurer et al. 2009; VanRheenen et al. 2004). The Blue River is a smaller basin than what is studied in other research, but it is important on the local level. Several communities get water from the river, and it is tied to the Arbuckle-Simpson Aquifer. Planning for climate change should also be taken into account when determining where to secure water in the future.

2. DATA AND METHOD

An ensemble of 16 general circulation models (GCM) was used to assess the future state of Oklahoma climate (see Appendix). The output were made available through the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. GCM output is too coarse of a resolution to do a regional study, so the data are bias-corrected and spatially downscaled climate projections derived from CMIP3 data and served at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/, described by Maurer et al (2007).

There are essentially two types of downscaling: dynamic and statistical. The former applies a regional climate model (RCM) using a GCM for the boundary conditions. These are useful in capturing local specifics such as topography, but they require an extensive amount of computing power. The latter option, statistical, is much more efficient in use of computing resources. One potential disadvantage is it assumes the statistical relationships that exist for the present will continue to apply in the future. Wood et al. (2004) compared three different statistical downscaling techniques: linear interpolation, spatial disaggregation, and bias-correction and spatial disaggregation (BCSD). The BCSD method was shown to perform the best at downscaling GCMs with a hydrologic focus.

The CMIP3 data is downscaled to a spatial resolution of 0.125° longitude/latitude (~12km). Available output is monthly temperature and precipitation for 1950 through 2099. Three IPCC emissions scenarios are considered: B1, A1B, and A2. Each represents a different storyline of greenhouse emissions depending on factors such as population growth, economic development, and technological change. B1 is the most conservative with CO_2 emission levels increasing to approximately 12 gigatons per year by 2040 and by 2100 decreasing to about 5 gigatons per year. Under A1B carbon levels increase for the first half century to about 15 gigatons per year and begin to slowly decline afterwards to slightly less than mid century levels. A2 is the most aggressive scenario with CO_2 levels continuously increasing to reach near 30 gigatons per year by the end of the century (IPCC 2000). Several GCMs have multiple runs, so the total model runs for each scenario are: 37 for B1, 39 for A1B, and 35 for A2.

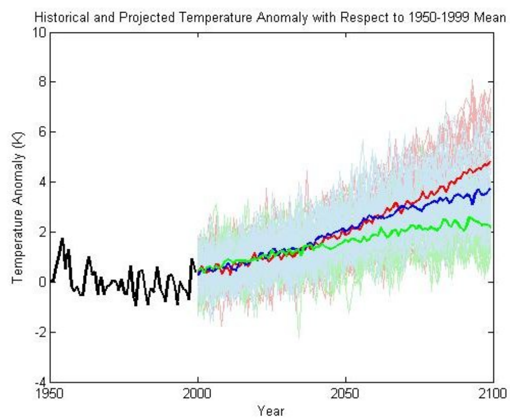


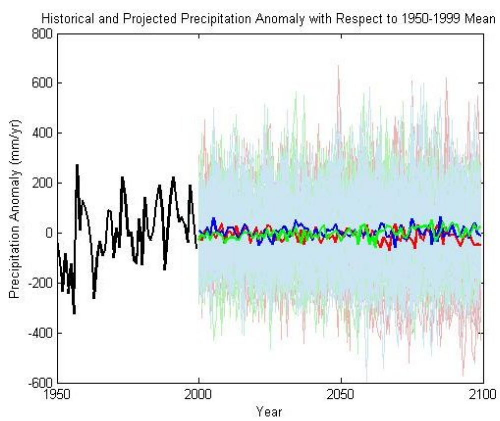
For comparison of historical with future GCM projections, the CMIP3 dataset also provides gridded observations for the area of study, which are used for assessing the state of Oklahoma. Changes in temperature and precipitation were analyzed on both annual and monthly levels. Both spatial and period averages were calculated to examine temperature and precipitation change distributions.

For the Blue River Basin other data sources were used for comparison (see Appendix). Basin average temperature was obtained by averaging four stations' values from NCDC. Precipitation observations come from 17 NWS Cooperative Observers. Discharge observations are collected from the USGS Water Data Station near Blue, Oklahoma in Bryan County (USGS 07332500). This station is not located at the mouth, so predictions only apply to the drainage area above the collection site, which is approximately 1230 km^2 (476 mi^2).

The temperature and precipitation projections were applied to study the Blue River Basin. Basin average was determined by computing the mean of the grid points that the basin lies in (see Appendix). A hydrologic model was used to simulate monthly water resources and their potential changes. The model used for this study was the Thornthwaite monthly water balance model driven by a graphical user interface. It is named after C.W. Thornthwaite who used water budget in climate classification (Thornthwaite 1948). A description is given by McCabe and Markstrom (2007). Input is monthly temperature and precipitation. Output is potential evapotranspiration (PET), soil moisture, actual evapotranspiration (AET), snow storage, surplus, and runoff total. The Hamon calculation is used for PET, which is dependent on only temperature and time of year (Hamon 1961). Manual calibration of the monthly water resources model was done to get the best agreement between observed and modeled runoff for the period June

1936 through August 2006. The parameters used modeled the calibration period well with the Nash-Sutcliffe coefficient of efficiency being 0.778 and a root mean square error of 12.9. When comparing the modeled with observed for the historical period, there was some bias. This was corrected on monthly scale for the GCM projections.





3. RESULTS

3.1 OKLAHOMA

The historical climate of Oklahoma has a wide annual range with warm summers and cool winters. January, on average, is the coldest month at 3 °C (~37 °F). July is the hottest with an average temperature of 27 °C (~81 °F). The statewide average annual precipitation is a little over 750 mm. Winter is the driest season with January receiving about 36 mm. May is the wettest at just over 100 mm. There is a secondary peak in precipitation in early fall with September receiving over 80 mm on average.

For the period 1950-1999, a cooling trend has actually been observed in Oklahoma. Models do not predict that to continue though. Figure 1a shows the time series of the historical and projected temperature anomaly with respect to the 1950-99 mean. The three scenarios tend to agree for most of the first half century, which is tied to the emissions trends defined by the IPCC. For the next ten year period (2010-19), ensemble median warming is projected to be 0.8 °C for B1, 0.7 °C for A1B, and 0.7 °C for A2. It appears that the scenarios diverge around the year 2040, with the B1 temperature increasing at about the same rate as before. A1B and A2 accelerate in warming. The period 2040-49 is expected to experience mean warming of 1.4, 1.9, and 1.7 °C. The A1B and A2 scenarios remain near each other until about 2070, where the A1B starts to level off and the A2 continues at the same rate. For 2090-99, mean warming is projected to be 2.3, 3.4, and 4.5 °C.

Future trends in precipitation are not expected to be as clear as temperature. Figure 2b shows the annual anomaly time series. There has been an increasing trend for 1950-99, but it is not certain if that will continue. There is no clear agreement among models to what will occur with precipitation. For 2010-19, the projected mean precipitation change is -3.2% for B1, -0.6% for A1B, and -1.4% for A2. The 2040-2049 decade is expected to change -1.8, -1.2, and -3.4%. Potential mean changes for the 2090-99 period are -0.04, -1.5, -5.3%. The data shows that not one of these decades indicates a significant decrease in precipitation relative to the 1950-99 mean.

Figure 3a shows the model distribution of projected warming for each month of the period 2010-19. It can be seen that the vast majority of models agree that there will be an increase in average temperature for Oklahoma in all months. The months of spring and summer are expected to warm more than those in fall and winter. There are some models that predict some cooling for this period, but those are all below the 25th percentile. The monthly breakdown for the 2040-49 period (Fig 3b) starts to show the difference between B1 and A1B/A2. The greater warming during the summer becomes more accentuated. The 2090-

99 period (Fig 3c) shows the most dramatic differences among the scenarios. The cooler months still show impressive warming for this period though.

Again on the monthly scale, the trend in precipitation is not as clear because there is large disagreement among the models. The 2010-19 period (Fig 4a) shows that there is perhaps an increase in precipitation for spring and summer and a decrease for fall and winter. However, for most months the models stretch far on both sides of zero. For 2040-49 (Fig 4b), the possible trend observed for the previous time period appears to become more emphasized. It is clear there is still wide model disagreement, but January, February, and October in particular show good consensus of less precipitation. By the end of the century (Fig 4c), the same pattern persists. January and October still show strong cases for less precipitation.

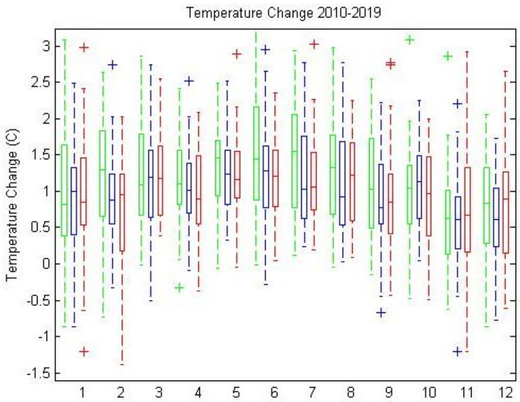
The spatial distribution of temperature change averaged over the century, there is projected to be more warming in the northern and western parts of Oklahoma for all scenarios. The panhandle region in particular shows the most warming, which could be related to a transition towards a more arid climate. The distribution of precipitation change looks a little more interesting. Scenarios B1 and A1B show average precipitation to be greater than the 1950-99 mean across much of the state except for the panhandle and southeast. Under the A2 scenario this difference is larger and covers much more area, which—like in the other scenarios—is centered in the panhandle and southeast regions. Increasing precipitation is sparse with it occurring in the north and northeastern parts of the state.

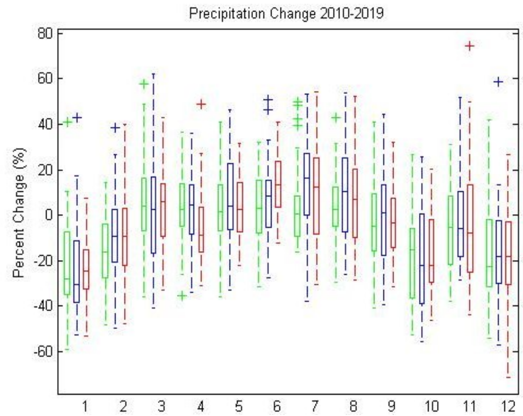
3.2 BLUE RIVER

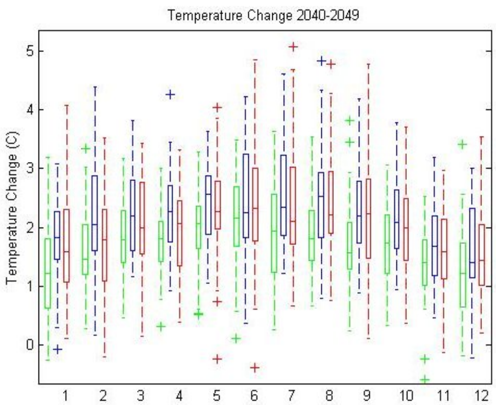
The climate of the Blue River Basin is relatively warm and wet. Average temperatures range from 5 °C (41 °F) in the winter to about 28 °C (82 °F) in the summer. There is strong seasonality in precipitation. January, on average, receives the least precipitation at around 50 mm (~2 in). May is the wettest month averaging over 140 mm (~5.5 in). July and August are fairly dry, and then there is a secondary peak in precipitation for the month of September. Annually, the basin averages about 1040 mm (41 in). Frozen precipitation does occur in the cold season, but it does not play the same role in the water cycle as in other parts of the United States due to temperature usually averaging high enough for melting to occur relatively quickly.

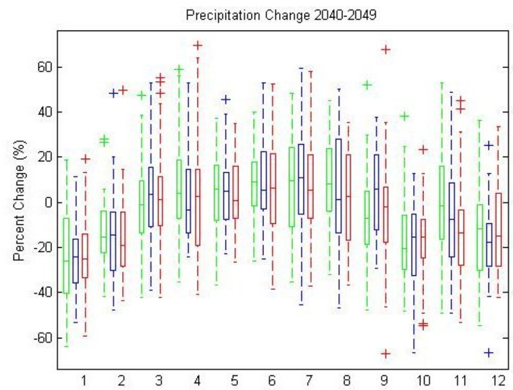
The time series of the next century's temperature anomaly for the Blue River Basin looks nearly identical to that of Oklahoma. The basin is expected to warm slightly less than the state average (~0.1 °C). The precipitation anomaly time series is different however. For Oklahoma, there were no large trends in precipitation for any scenario when looking at each ensemble mean. This is due to trends averaging out when considering larger areas. The Blue River Basin annual precipitation anomaly trends were 43 mm/century for B1, -14 mm/century for A1B, and -33 mm/century for A2. However, these are still not large relative changes. A 43 mm increase is approximately a four percent change. These potential changes in precipitation would have impacts on the water cycle, although they would most likely be small. Monthly breakdown of precipitation change is shown in Figure 5. It can be seen that monthly trends are not as obvious as for the state.

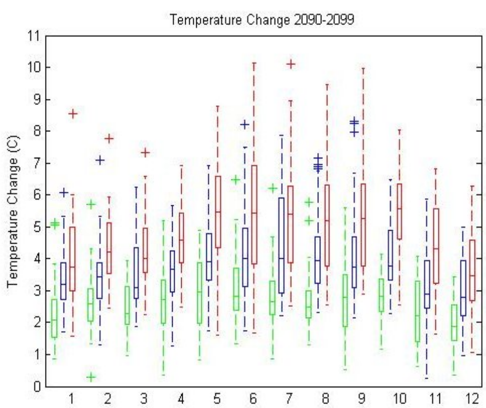
Monthly PET trends follow that of temperature because of how it is calculated in the water balance model. Historically, PET is at its lowest in the winter at about 20 mm, and it increases to almost 170 mm in the summer. Total annual PET averages approximately 930 mm. AET is related to other variables like precipitation and soil moisture. It is approximately PET for the first five months and last two months of the year. On average its lowest value is about 19 mm winter and highest is about 135 mm in summer. Annual average of AET is a little less than 800 mm. Future trends in PET and AET are not identical. PET follows the same trend as temperature with mean annual percent change for the next decade being 6.7% for B1, 5.5% for A1B, and 5.5% for A2. By 2040-49, mean change is predicted to be 10.6, 14.2, and 12.9%. At the end of the century, mean PET increase is projected to be 16.6, 26.4, and 35.6%. AET does not follow the same trend because it is tied to the actual water present from precipitation and in the soil. There is still an increasing trend for all scenario means. For 2010-19, B1 mean is predicted to increase 1.7%, A1B 3.4%, and A2 3.5%. By 2040-49, ensemble means increase to 4.3, 5.9, and 3.8%. For 2090-99, mean changes are 7.5, 7.9, and 6.0%. The larger increases for the lower emissions scenarios are most likely due to more water being available for evapotranspiration than under the higher scenario. From Figure 6 it can be seen that all months are expected to experience increased AET except for July and August. This is due to soil moisture being so depleted that there is none left to evaporate or transpire.

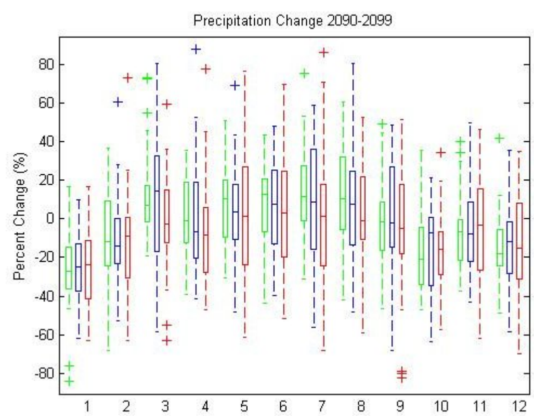

Temperature Change 2010-2019
Temperature Change (C)
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
1 2 3 4 5 6 7 8 9 10 11 12

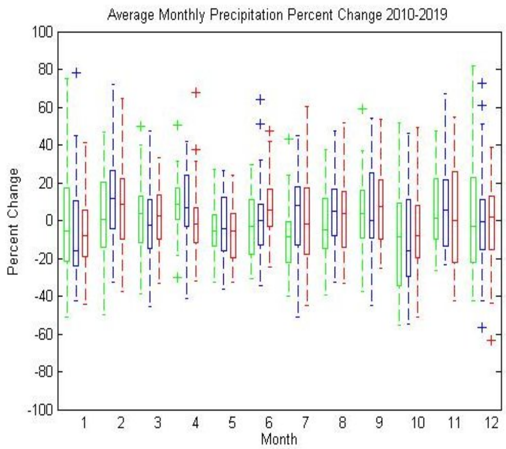

Precipitation Change 2010-2019
Percent Change (%)
80
60
40
20
0
-20
-40
-60
1 2 3 4 5 6 7 8 9 10 11 12

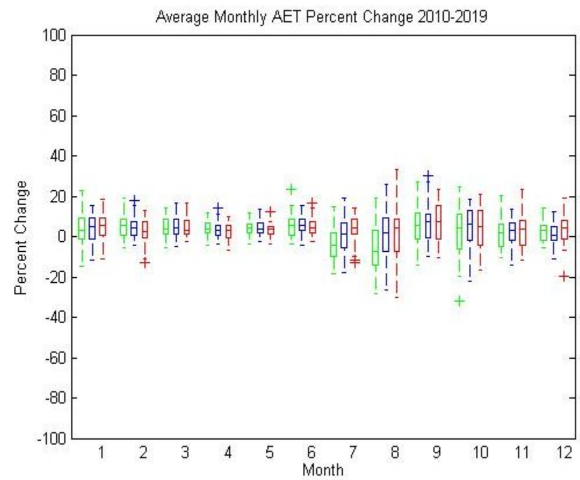

Temperature Change 2040-2049
Temperature Change (C)
5
4
3
2
1
0
1 2 3 4 5 6 7 8 9 10 11 12

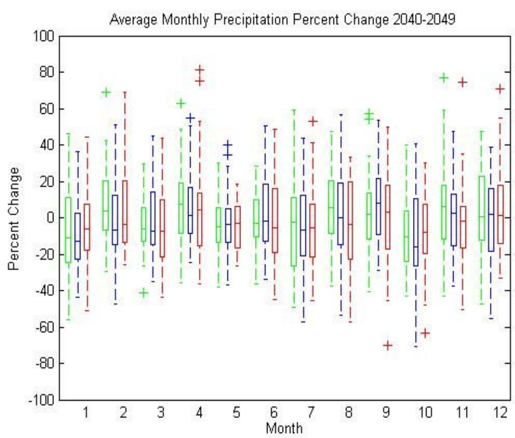

Precipitation Change 2040-2049
Percent Change (%)
60
40
20
0
-20
-40
-60
1 2 3 4 5 6 7 8 9 10 11 12

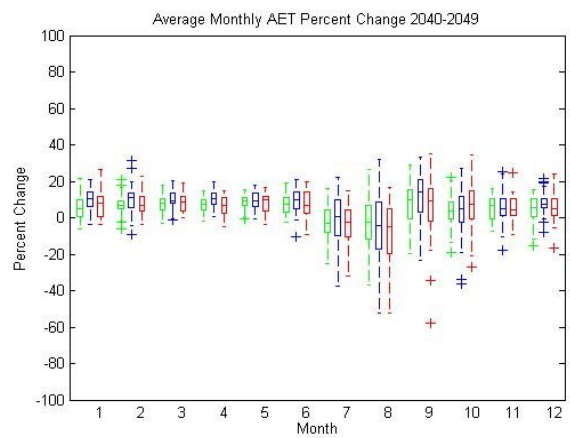

Temperature Change 2090-2099
Temperature Change (C)
11
10
9
8
7
6
5
4
3
2
1
0
1 2 3 4 5 6 7 8 9 10 11 12

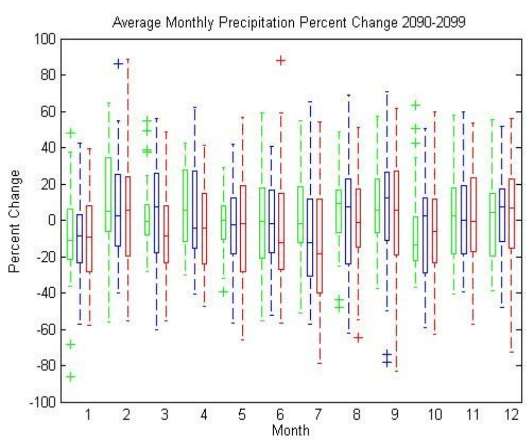

Precipitation Change 2090-2099
Percent Change (%)
80
60
40
20
0
-20
-40
-60
-80
1 2 3 4 5 6 7 8 9 10 11 12

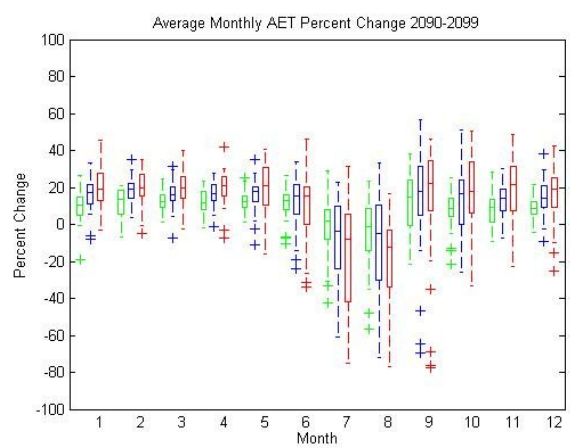

Average Monthly Precipitation Percent Change 2010-2019
Percent Change
100
80
60
40
20
0
-20
-40
-60
-80
-100
1 2 3 4 5 6 7 8 9 10 11 12
Month

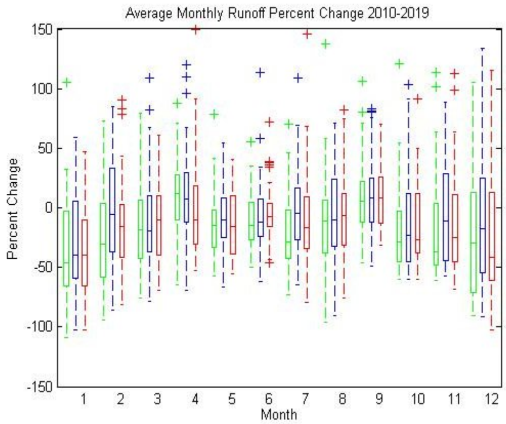

Average Monthly AET Percent Change 2010-2019
Percent Change
100
80
60
40
20
0
-20
-40
-60
-80
-100
1 2 3 4 5 6 7 8 9 10 11 12
Month

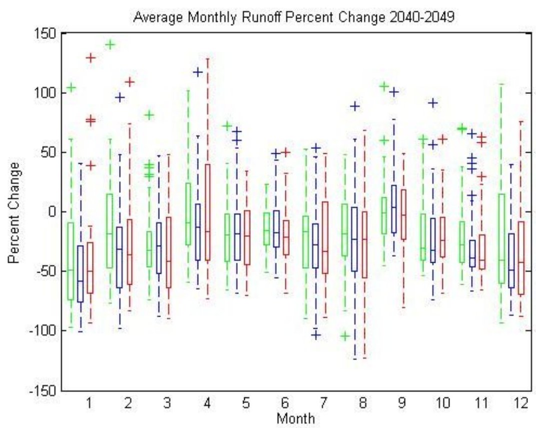

Average Monthly Precipitation Percent Change 2040-2049
Percent Change
100
80
60
40
20
0
-20
-40
-60
-80
-100
1 2 3 4 5 6 7 8 9 10 11 12
Month

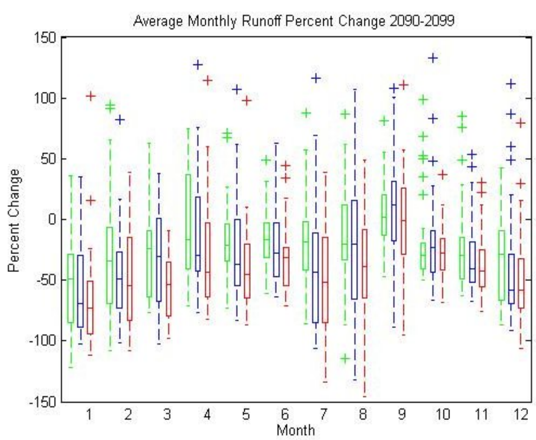

Average Monthly AET Percent Change 2040-2049
Percent Change
100
80
60
40
20
0
-20
-40
-60
-80
-100
1 2 3 4 5 6 7 8 9 10 11 12
Month


Average Monthly Precipitation Percent Change 2090-2099
Percent Change
100
80
60
40
20
0
-20
-40
-60
-80
-100
1 2 3 4 5 6 7 8 9 10 11 12
Month


Average Monthly AET Percent Change 2090-2099
Percent Change
100
80
60
40
20
0
-20
-40
-60
-80
-100
1 2 3 4 5 6 7 8 9 10 11 12
Month







Annual runoff totals show large changes by 2100. Ensemble mean percent change for 2010-19 is -3.5% for B1, 2.5% for A1B, and -1.9% for A2. By 2040-49 the scenario means agree on the direction of change with -6.3, -11.7, and -10.5%. At the end of the century the changes in runoff have grown substantially to -9.6, -16.2, and -29.8%. Figure 7 shows the monthly distributions among the models. It can be seen that outliers are affecting the means for each time period. Values below -100 occur because of the bias correction, so they can be interpreted as -100%. The time period 2010-19 has only 2 months for which the median is above zero for B1 and A1B (April and September). A2 only has one month (September). It appears that January shows the most likelihood to exhibit lower runoff. The period 2040-49 shows increased agreement among months of the lower runoff tendency. By 2090-99 the differences between the scenarios can be observed with A2 showing the largest decrease in runoff for most months. September shows the most resistance to lower runoff. On average this has been the month with the second lowest runoff value (August is the lowest).

Soil moisture fraction is a measure of water content relative to field capacity with a range of zero to one. Historically, it peaks in late spring near a value of 0.90. By August it is at its minimum with an average value of less than 0.25. Soil moisture recharge occurs for the rest of the year until the following spring. The average annual value is 0.65. Expected changes in the fraction for 2010-19 are ensemble means of -10.5, -5.7, -5.0%. For 2040-49, mean change is expected to be -12.9, -12.5, -15.8%. By 2090-99, change in ensemble mean is predicted to be -17.1, -25.0, -35.4%.

4. CONCLUSIONS

A three IPCC emission scenario GCM ensemble was used to analyze future projections of temperature and precipitation for Oklahoma and the Blue River Basin. Significant warming is predicted with the most conservative scenario (B1) being 2.3 °C above the 1950-99 mean by the last decade of the century. A1B and A2 predicted 3.4 and 4.5 °C warming, respectively. The summer months are expected to experience more warming than winter. Agreement was not as strong among models in the prediction of precipitation changes. There was some consensus that projected winter months to experience less precipitation and summer months more.

The Blue River Basin is expected to warm similarly to Oklahoma. Precipitation trends were stronger than for the state as a whole. Both A1B and A2 predicted decreasing trends on average, while B1 predicted an increasing trend. However, the monthly distribution trend observed for Oklahoma was not as clear for the basin.

PET and AET are both expected to increase for all scenarios. PET is strongly related to temperature, so its trend looks nearly identical. AET is related to available water, so it does not increase as much as PET. Because it is tied to precipitation, there was less distinction between the scenarios. AET under B1 was expected be the largest increase due to the larger precipitation increase. A2 had the smallest because although temperature increases the most, precipitation actually decreases.

Soil moisture showed large changes, particularly in later summer and early fall. Runoff shows a dramatic decrease by 2100. With some months showing greater than 50% decrease, there could be years in the future that the Blue River is almost completely dry in parts.

Because precipitation is not expected to change significantly, the decrease in runoff is likely related to the increase in evapotranspiration. If rainfall is constant, then a larger percent is evaporated leading to a lower fraction available for runoff. Although transpiration is an important factor to consider, it was assumed to remain unaltered due to its relation to vegetation.

The predicted changes in the hydrologic cycle will have important consequences for the region. Since several local communities receive water from the Blue River, there is a strong possibility that alternative water sources will need to be secured. Most likely this will include further extraction of groundwater, but that supply is not guaranteed to last long. Growth of nearby cities metropolitan areas such as Oklahoma City and Dallas-Fort Worth will also demand more water, so action will need to be taken to protect local water resources.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. ATM-0648566. We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy. We thank the Remote Sensing Hydrology Group of the University of Oklahoma for their support.

REFERENCES

Barnett, Tim, Robert Malone, William Pennell, Detlett Stammer, Bert Semtner, and Warren Washington, 2004: The Effects of Climate Change on Water Resources in the West: Introduction and Overview. *Clim. Change*, **62**, 1-11.

Elsner, Marketa M., Lan Cuo, Nathalie Voisin, Jeffrey S. Deems, Alan F. Hamlet, Julie A. Vano, Kristian E. B. Mickelson, Se-Yeun Lee, and Dennis P. Lettenmaier, 2010: Implications of 21st century climate change for the hydrology of Washington State. *Clim. Change*, doi: 10.1007/s10584-010-9855-0.

Hamon, W.R. (1961) Estimating potential evapotranspiration. *JHydraul Div Proc Am Soc Civil Eng* **87**,107–120.

IPCC, 2000: Emissions Scenarios.

Li, Li, Zhen-Chun Hao, Jia-Hu Wang, Zhen-Hua Wang, and Zhong-Bo Yu, 2008: Impact of Future Climate Change on Runoff in the Head Region of the Yellow River. *J. Hydrol. Eng.*, 347-354, doi: 10.1061/(ASCE)1084-0699(2008)13:5(347).

Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy, 2007: Fine-resolution climate projections enhance regional climate change impact studies, *Eos Trans. AGU, 88*(47), 504.

Maurer, E.P., J.C. Adam, and A.W. Wood, 2009: Climate model based consensus on the hydrologic impacts of climate Change to the Rio Lempa basin of Central America. *Hydrol. Earth Syst. Sci.*, **13**, 183-194.

McCabe, G.J., and Markstrom, S.L., 2007: A monthly water-balance model driven by a graphical user interface: U.S. Geological Survey Open-File report 2007-1088, 6 p.

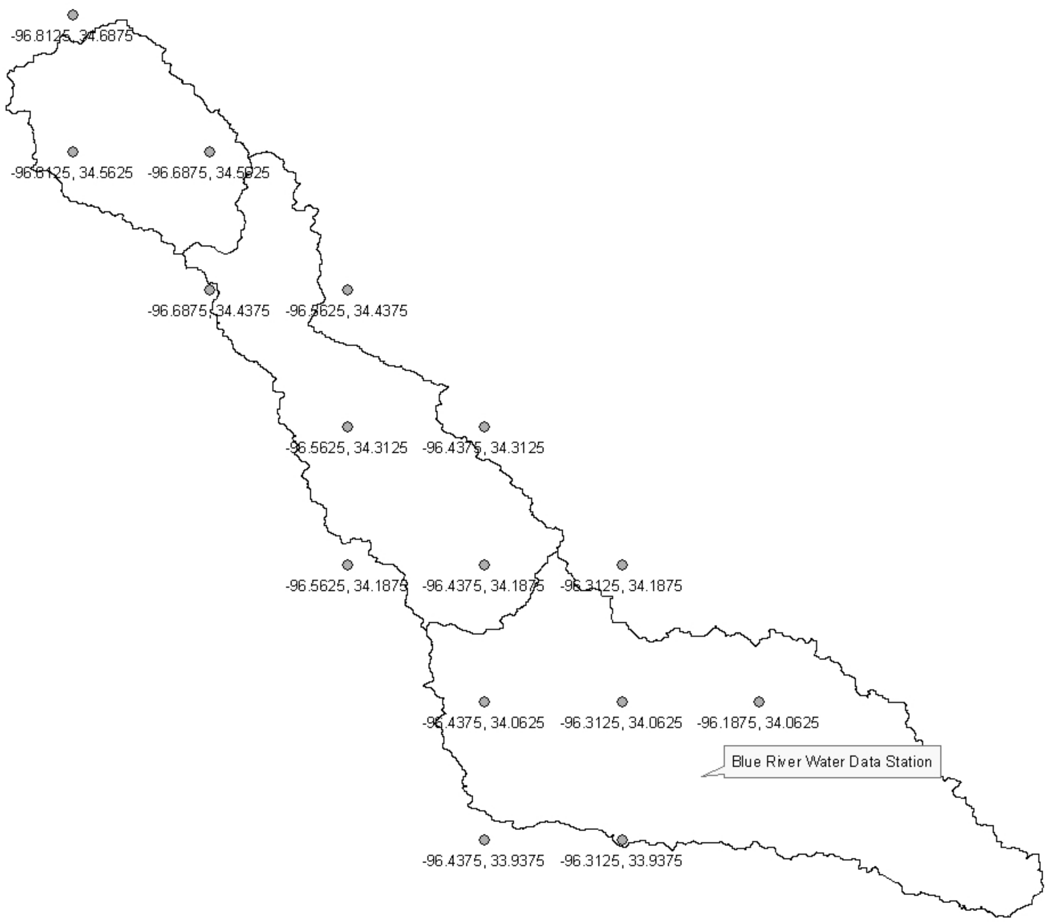
OWRB, 2003: The Arbuckle-Simpson Hydrology Study.

Thornthwaite, C.W., 1948: An Approach toward a Rational Classification of Climate. *Geographical Review*, **38**(1), 55-94.

VanRheenen, Nathan T., Andrew W. Wood, Richard N. Palmer and Dennis P. Lettenmaier, 2004: Potential Implications of PCM Climate Change Scenarios for Sacramento–San Joaquin River Basin Hydrology and Water Resources. *Clim. Change*, **62**, 257-281.

Wood, A. W., L. R. Leung, V. Sridhar, and D.P. Lettenmaier: Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs, *Clim. Change*, 62, 189–216, 2004.

Bjerknes Centre for Climate Research	BCCR-BCM2.0
Canadian Centre for Climate Modeling & Analysis	CGCM3.1 (T47)
Meteo-France / Centre National de Recherches Meteorologiques, France	CNRM-CM3
CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1
NASA / Goddard Institute for Space Studies, USA	GISS-ER
Institute for Numerical Mathematics, Russia	INM-CM3.0
Institut Pierre Simon Laplace, France	IPSL-CM4
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	MIROC3.2 (medres)
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA	ECHO-G
Max Planck Institute for Meteorology, Germany	ECHAM5/ MPI-OM
Meteorological Research Institute, Japan	MRI-CGCM2.3.2
National Center for Atmospheric Research, USA	CCSM3
National Center for Atmospheric Research, USA	PCM
Hadley Centre for Climate Prediction and Research / Met Office, UK	UKMO-HadCM3


-96.8125, 34.6875
-96.8125, 34.5625
-96.6875, 34.5625
-96.6875, 34.4375
-96.5625, 34.4375
-96.5625, 34.3125
-96.4375, 34.3125
-96.5625, 34.1875
-96.4375, 34.1875
-96.3125, 34.1875
-96.4375, 34.0625
-96.3125, 34.0625
-96.1875, 34.0625
Blue River Water Data Station
-96.4375, 33.9375
-96.3125, 33.9375
