

Analyzing projected changes and trends of temperature and precipitation in the southern USA from 16 downscaled global climate models

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Abstract This study aims to examine how future climate, temperature and precipitation specifically, are expected to change under the A2, A1B, and B1 emission scenarios over the six states that make up the Southern Climate Impacts Planning Program (SCIPP): Oklahoma, Texas, Arkansas, Louisiana, Tennessee, and Mississippi. SCIPP is a member of the National Oceanic and Atmospheric Administration-funded Regional Integrated Sciences and Assessments network, a program which aims to better connect climate-related scientific research with in-the-field decision-making

processes. The results of the study found that the average temperature over the study area is anticipated to increase by 1.7°C to 2.4°C in the twenty-first century based on the different emission scenarios with a rate of change that is more pronounced during the second half of the century. Summer and fall seasons are projected to have more significant temperature increases, while the northwestern portions of the region are projected to experience more significant increases than the Gulf coast region. Precipitation projections, conversely, do not exhibit a discernible upward or downward trend. Late twenty-first century exhibits slightly more precipitation than the early century, based on the A1B and B1 scenario, and fall and winter are projected to become wetter than the late twentieth century as a whole. Climate changes on the city level show that greater warming will happened in inland cities such as Oklahoma City and El Paso, and heavier precipitation in Nashville. These changes have profound implications for local water resources management as well as broader regional decision making. These results represent an initial phase of a broader study that is being undertaken to assist SCIPP regional and local water planning efforts in an effort to more closely link climate modeling to longer-term water resources management and to continue assessing climate change impacts on regional hazards management in the South.

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1 Introduction

Future climate will impact the world in every aspect of life. Climate influences the world through changing temperature, precipitation, snowmelt, and a host of other natural phenomenon (Karl et al. 2009). Global climate change

has profound effects on society's physical systems and human activities (IPCC AR4 2007). The Global Climate Change Impacts in the United States Report compiled by the US Global Change Research Program claims that "Climate changes are already affecting water, energy, transportation, agriculture, ecosystems, and health" and additionally finds that the "global temperature has increased over the past 50 years." Regional climate, being a combined product of global climate forcing and also of regional atmosphere-landslide surface feedbacks, localizes the global impacts on society and is closely linked to regional water resources and local hazard management (Karl and Trenberth 2003). The frequency and extent of local extreme weather is of great importance to regional social and economical systems, thus regional climate plays a significant role in policy making and management, which allows more relevant and localized practices (Hellmuth et al. 2007).

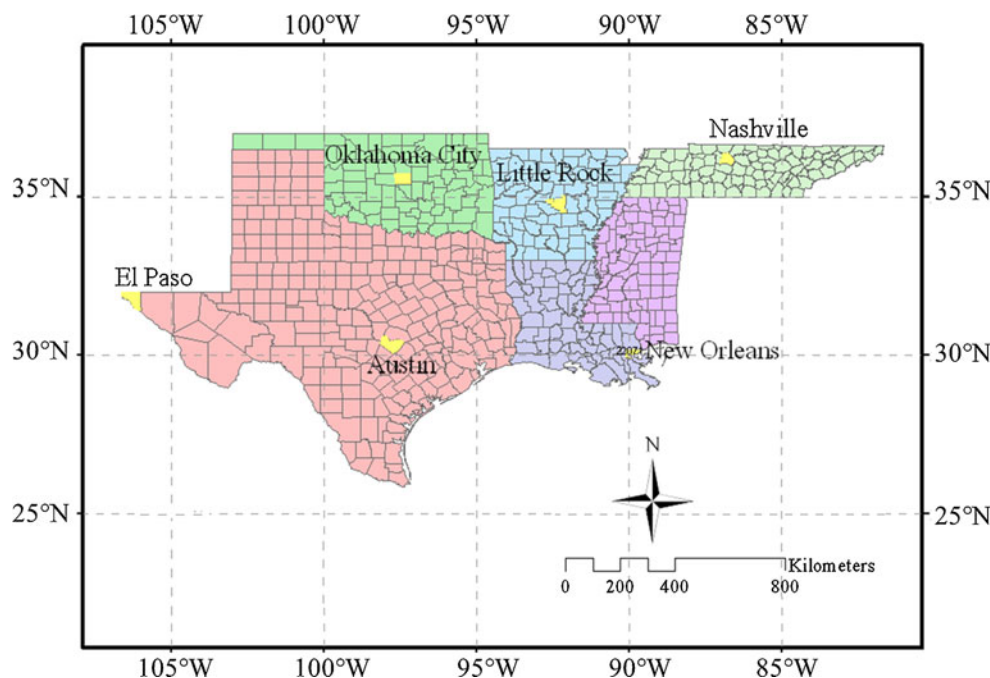
The area of focus for this climate change study is the six-state region of responsibility for the Southern Climate Impacts Planning Program (SCIPP; <http://www.southernclimate.org/>)—Oklahoma, Texas, Arkansas, Louisiana, Tennessee, and Mississippi—hereafter referred to as the SCIPP region (Fig. 1). SCIPP is a southern-USA-focused climate hazards preparedness program that aims to bridge the gap between climate science and local-level climate hazard planning processes. As the ninth addition to the Regional Integrated Science and Assessment (RISA) program, SCIPP strives to continue the success of the RISA program in conducting critical, interdisciplinary research through stakeholder partnerships. The RISA program supports research that addresses complex climate sensitive issues

of concern to decision-makers and policy planners. SCIPP is a collaborative research effort between the Oklahoma Climatological Survey and College of Atmospheric and Geographic Sciences at the University of Oklahoma and the Department of Anthropology and Geography and Southern Regional Climate Center at Louisiana State University.

Global climate studies usually rely on global climate models (GCMs), which simulate past climate and project future climate. GCM outputs have coarse resolutions and perform poorly at smaller scales, making these models inappropriate for regional impact assessment (Maurer et al. 2007). Therefore, downscaling techniques were applied to subset climate data from global scale to the study region. The two primary downscaling methods commonly used are dynamic and statistical (Giorgi et al. 2001; Wilby and Wigley 1997). Dynamic downscaling takes into account regional features by applying Regional Climate Models to the GCMs outputs and as a result performs better at capturing local processes and feedbacks but is relatively expensive to operate (Liang et al. 2006; Lo et al. 2008). Statistical downscaling relates large-scale climate features to local climate using simple statistical relationship which is computationally less intensive, however less physically relevant and depend on the quality of the observational data (Maurer et al. 2007).

This study aims to assess the past 50 years of climate in the South, and predict its future climate based on GCMs projections, while also providing a scientific database for local water planning efforts. Study results are provided at varying spatial scales to quantify climate projections at the regional, state, and local levels. Six high population centers

Fig. 1 Southern Climate Impacts Planning Program (SCIPP) region: Oklahoma, Texas, Arkansas, Louisiana, Tennessee, and Mississippi. The yellow highlighted counties denote six urban areas of interest selected for city-level temperature and precipitation analysis



were selected to specify climate change projections at several locations throughout the region, including El Paso, Austin, Oklahoma City, Little Rock, New Orleans, and Nashville. In addition, further hydrologic research is planned to assist local communities and governments in their water management.

2 Data and methodology

For this study the observational data used were the gridded National Climatic Data Center (NCDC) Cooperative Observer station data, described by Maurer et al. (2007). The data cover the time period 1950 to 1999 in a monthly time step. The World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase3 (CMIP3) multi-model dataset were archived for climate projection analysis after statistical downscaling described in the next paragraph.

Each WCRP CMIP3 climate projection was bias-corrected and spatially downscaled (Wood et al. 2002, Wood et al. 2004, and Maurer et al. 2007). Maurer et al. (2007) states that the result of bias correction is an adjusted GCM dataset that is statistically consistent with observation during the bias

correction overlap period (i.e., 1950–1999 in this application). In other words, before temperature bias correction procedure, the twenty-first century GCM trend is removed and then bias correction is applied to the residual magnitudes to create adjusted GCM. Afterwards, the trend is added back to adjusted GCM (Maurer et al. 2007). Unlike the temperature projections, there is no trend-removal to the twenty-first century precipitation projections prior to bias correction. As a result, the projected precipitation trends are slightly wetter after bias correction for much of the contiguous USA.

Both observation and CMIP3 data have two outputs: surface temperature (°C) and monthly precipitation (millimeters per day). The CMIP3 data cover the continental USA and portions of southern Canada and northern Mexico at a 1/8° (~12 km) resolution spatially downscaled from 2° grid using the Bias Correction and Spatial Disaggregation (BCSD) approach of Wood et al. (2004). Simulations start from 1950 to 1999, and projections under three IPCC AR4 CO₂ emission scenarios start from 2000 to 2099.

The 16 GCMs downscaled data used in this study are listed in Table 1. All models were compared with observations over the SCIPP region for the same time period, and the ensemble mean values were used to run the climate

Table 1 The global climate models used in this study

Model abbreviations, emissions pathways, and projection run numbers					
Modeling group, country	WCRP CMIP3 I.D.	SRES A2 runs	SRES A1b runs	SRES B1 runs	Primary Reference
Bjerknes Centre for Climate Research	BCCR-BCM2.0	1	1	1	Furevik et al. 2003
Canadian Centre for Climate Modeling and Analysis	CGCM3.1 (T47)	1...5	1...5	1...5	Flato and Boer 2001
Meteo-France/Centre National de Recherches Meteorologiques, France	CNRM-CM3	1	1	1	Salas-Melia et al. 2005
CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0	1	1	1	Gordon et al. 2002
US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	1	1	1	Delworth et al. 2006
US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	1	1	1	Delworth et al. 2006
NASA/Goddard Institute for Space Studies, USA	GISS-ER	1	2, 4	1	Russell et al. 2000
Institute for Numerical Mathematics, Russia	INM-CM3.0	1	1	1	Diansky and Volodin 2002
Institut Pierre Simon Laplace, France	IPSL-CM4	1	1	1	IPSL 2005
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)	1...3	1...3	1...3	K-1 model developers 2004
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA	ECHO-G	1...3	1...3	1...3	Legutke and Voss 1999
Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM	1...3	1...3	1...3	Jungclaus et al. 2006
Meteorological Research Institute, Japan	MRI-CGCM2.3.2	1...5	1...5	1...5	Yukimoto et al. 2001
National Center for Atmospheric Research, USA	CCSM3	1...4	1...3, 5...7	1...5	Collins et al. 2006
National Center for Atmospheric Research, USA	PCM	1...4	1...4	2, 3	Washington et al. 2000
Hadley Centre for Climate Prediction and Research/Met Office, UK	UKMO-HadCM3	1	1	1	Gordon et al. 2000

change projection analysis for higher reliability (Maurer et al. 2007; Santer 2009). The three scenarios of the twenty-first century for future greenhouse gas emissions used in CMIP3 data were A2, A1B, and B1, as defined in the IPCC Special Report on Emissions Scenarios (Nakic'enovic'N et al. 2000). Scenario A2 is a higher emission path and describes a higher population world where technological change and economic growth are more fragmented and slower. Scenario A1B is a middle emission path known as business-as-usual and describes a balanced world where people do not rely too heavily on any one particular energy

source. Scenario B1 is a lower emission path in which the economy rapidly changes towards service and information, with an emphasis on clean, sustainable technology.

This study looks at climate change from two aspects: time series change and spatial distribution. Spatial mean and period mean values of CMIP3 data were archived through MATLAB programming, and analysis was done on MATLAB and ArcGIS platforms. Changes of the parameters over time and space are the key outputs in this study, with the emphasis on impacts to regional activities.

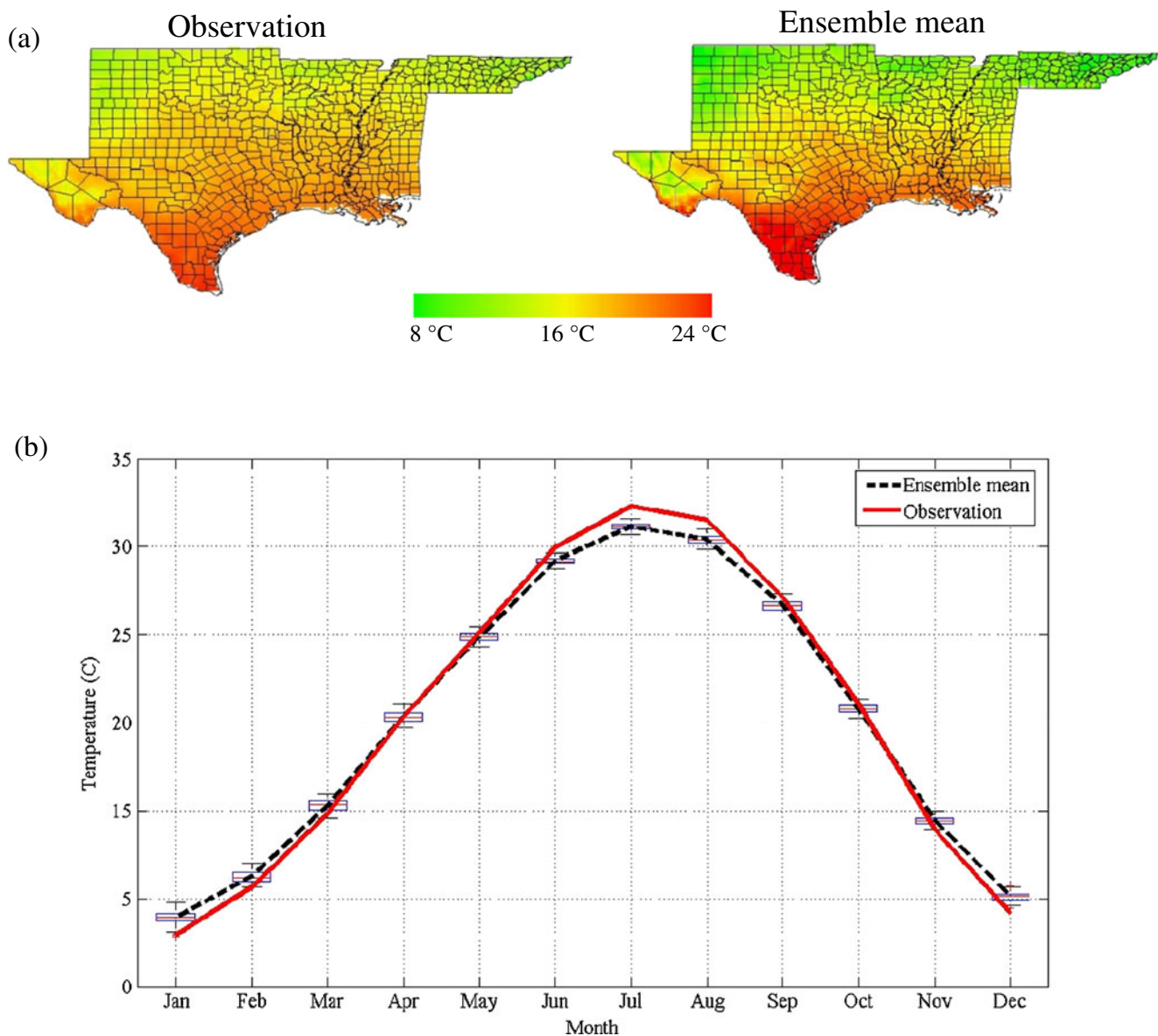


Fig. 2 **a** Spatial observation vs. ensemble mean on temperature for the period of 1950–1999; **b** monthly ensemble mean vs. observation on temperature for the period of 1950–1999. The *blue box plots* are the probability distribution of the multi-model runs

3 Results analysis and discussions

3.1 GCMs validation

GCMs have been applied to simulate past climate and project future climate around the world by climate researchers. GCMs are typically at a very coarse resolution (e.g., Schmidt et al. 2006; Hansen et al. 1983). For some impacts assessments that require much finer resolution of climate information, the model spatial resolutions are not adequate enough. The limitations of their inadequate performance on finer resolution scale constrain their abilities to project future climate

variables, especially precipitation (Felzer and Heard 1999). Precipitation in this region is heavily dominated by smaller scale convective precipitation, something that the global models cannot resolve. The application of statistical downscaling method of GCMs enables finer resolution of climate information, but the nature of more localized, convective precipitation in the South still limits the accuracy of the outputs (Wilcox and Donner 2007). Although GCMs provide the broader scale condition and boundary conditions for the region, research involving higher resolution nested models is highly needed in this region.

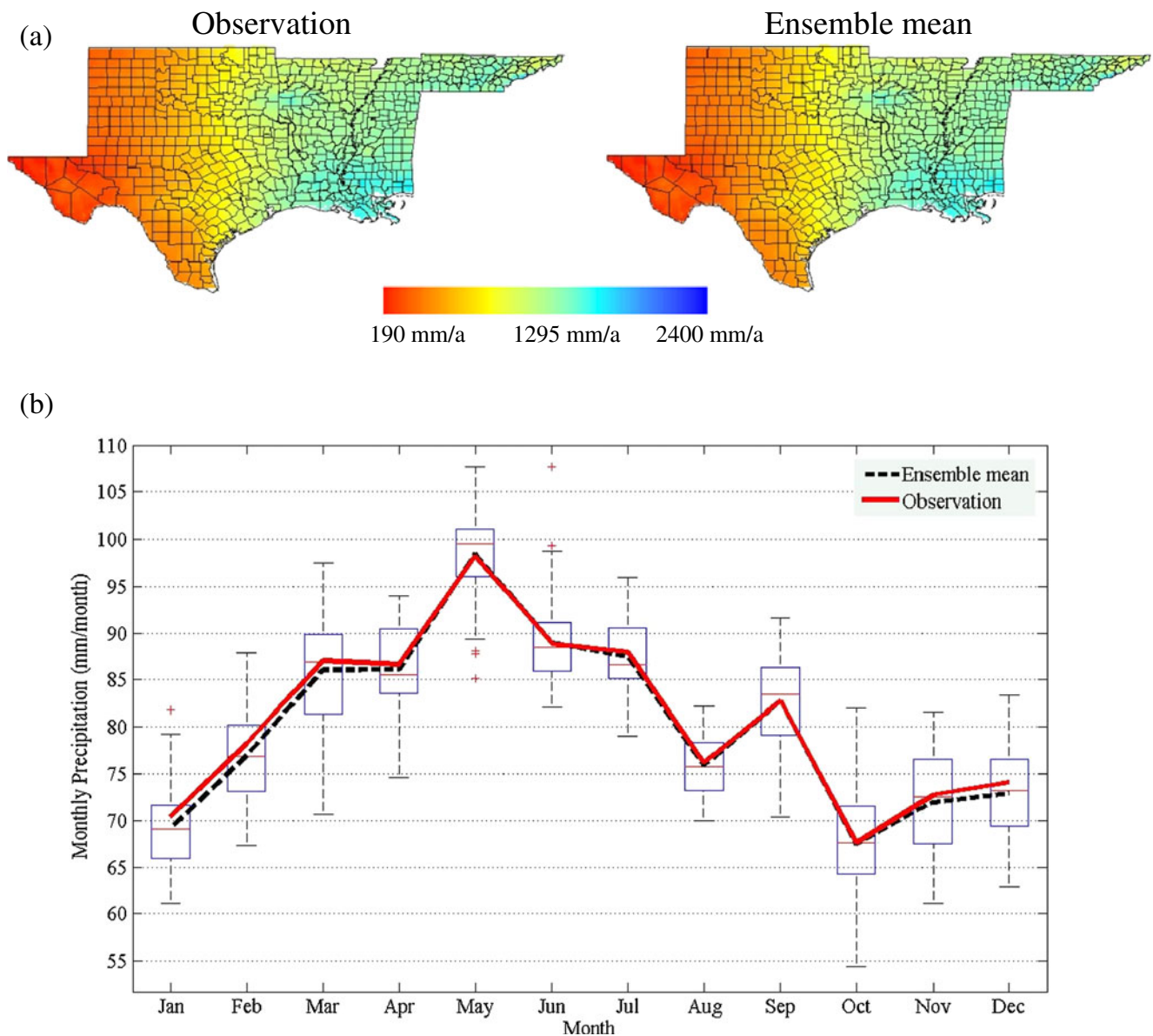


Fig. 3 **a** Spatial difference of ensemble mean vs. observation on precipitation for the period 1950–1999; **b** monthly ensemble mean vs. observation on precipitation for the period of 1950–1999. The blue box plots are the probability distribution of the multi-model runs

Table 1 lists all 16 GCMs used in the CMIP3 dataset. There were 35 runs for the A2 scenario, 39 runs for A1B, and 37 for B1. Each GCM has simulations for temperature and precipitation for the period of 1950–1999. The ensemble mean is a preferred method (Tapiador and Sanchez 2007). Considering the uncertainty of a single GCM output and the restrictions of statistical downscaling methods to the South, a single downscaled GCM could hardly be representative in this case. Therefore, this study implies the projections of the ensemble mean from the 16 GCMs outputs.

Figures 2 and 3 provide a comparison between the ensemble mean for the historical time period and the observed data for the same period. The historical monthly temperature comparison indicates that the GCMs outputs underestimate summer temperature and overestimate winter temperature; however, there is not a significant spatial variation from the observation for the region over a whole year (Fig. 2a). The box plots over the ensemble mean display the simulated temperature ranges of the past 50 years. Temperature does not vary significantly for each month over the past 50 years (Fig. 2b); however, precipitation varies both over time and over space. There is a relatively discernible difference on monthly time scale from 1950 to 1999 (Fig. 3b).

3.2 Climate projections

3.2.1 Temperature

The temperature of the Earth is sensitive to the emission of heat-trapping gases such as carbon dioxide (Karl and Trenberth 2003). The historical temperature distribution across the SCIPP region is characterized by warmer temperatures to the south and cooler to the north. The average temperature for the period of 1950–1999 was 17.4°C, with the Gulf coast region approximately 10°C warmer than the northern portion of SCIPP (Fig. 2a). Climate in the SCIPP

Table 2 Results of trend test and change point analyses of annual temperature in SCIPP

Number	Scenarios	MK trend test for temperature			Pettitt test for temperature Change point (year)
		Z values	Trends	Significance level	
1	A2	13.99	Increasing	–*	2019
2	A1B	13.72	Increasing	–*	2019
3	B1	13.12	Increasing	–*	2019

* $p=0.001$

region is characterized by a peak in the annual temperature during July (~27.3°C) and a minimum in annual temperature experienced during January (~3°C) (Fig. 2b). The 1950 to 1999 period can be analyzed by splitting the period in half. The 1950 to 1975 period exhibited an overall cooling trend, while warming was predominant during 1976 to 2000 (Fig. 4). One potential explanation is that “the influence on climate from increasing greenhouse gas emissions has been greatest during the past five decades” (Karl et al. 2009).

Mann–Kendall Test (MK Test) has been commonly used to assess the significance of trend in hydro-meteorological time series (Kendall and Stuart 1973). In this study, MK Test is applied to analyze the trend and statistic significance of projected temperature and precipitation variability. The non-parametric approach developed by Pettitt (1979) was also used for determining the occurrence of a change point in the temperature and precipitation time series (Table 2 and Table 3).

Model projections indicate an increase in temperatures across SCIPP ranging between 2.3°C and 4.8°C by the end of the twenty-first century depending on the emission scenario (Fig. 4). The second half of the century is projected to be warmer than the first half century by an average of 2.2°C, 1.8°C, and 1°C as projected by A2, A1B, and B1 scenarios, respectively. MK Test (Table 3) shows that the projected

Fig. 4 Surface temperature anomaly relative to 1950–1999 mean over SCIPP from 2000–2099. Light red background is the 16 GCMs’ temperature projection for A2 scenario. Light blue background is the 16 GCMs’ temperature projection for A1B scenario. Light green background is the 16 GCMs’ temperature projection for B1 scenario. Bold color lines are the ensemble means for the corresponding scenarios

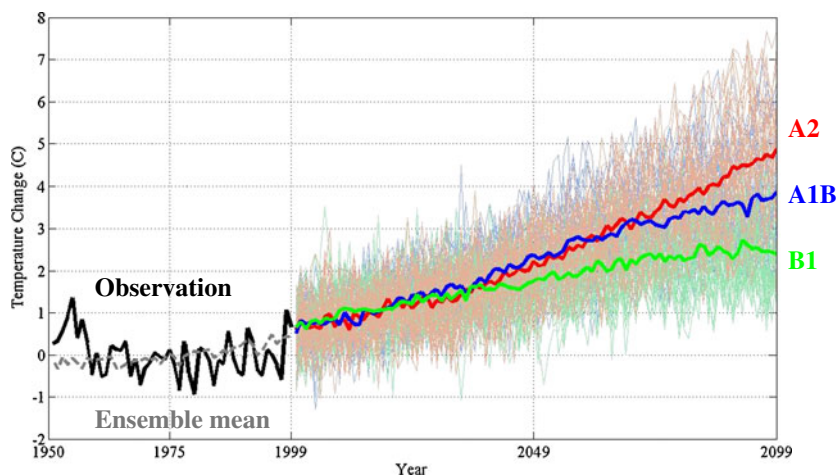


Table 3 Results of trend test and change point analyses of annual precipitation in SCIPP

Number	Scenarios	MK trend test for precipitation			Pettitt test for precipitation Change point (year)
		Z values	Trends	Significance level	
1	A2	-0.99	Decreasing	- ^a	-
2	A1B	2.95	Increasing	-*	2055
3	B1	5.83	Increasing	-**	2050

* $p=0.01$; ** $p=0.05$

^a Means significance level exceeds 0.05

temperature changes under the three scenarios are regarded as significant changes. The change point takes place in the year 2019 under A2, A1B, and B1 scenarios. Figure 5 breaks down the projected changes by the three scenarios by decade. Beginning in 2040–2049, the probability distributions for the different emission scenarios begin to diverge, particularly for the low emission scenario (B1). For example, during the second decade of the twenty-first century, less than 5% of the region is expected to be warmer by 2°C, but by the end of the century, the area increases to almost 15% for the B1 scenario (Fig. 5). Figure 6a provides a spatial representation of future temperature conditions based

on the models. More significant warming is projected in the second half century than the first half. Warming is projected to be more significant across the northwestern portions of SCIPP, with less substantial warming near the Gulf Coast. Further regional characteristics can be seen by assessing the projections on a seasonal basis (Fig. 6b). The most significant changes in temperature are projected to occur in the summer and fall seasons with more warming occurring across the northern portions of the SCIPP region. A warming signal is also present during the spring and winter but is less significant relative to the summer and fall. Figure 7 provides more information on the temperature change on state level and again reveals that average temperature changes more significantly in 2050–2099 than in 2000–2049. Oklahoma is projected to have the greatest warming in the SCIPP region in both half centuries (Fig. 7a). The majority of Oklahoma will potentially increase over 1.4°C in 2000–2049, and over 3.5°C in 2050–2099 by A2 scenario (Fig. 7b). One significant concern regarding the projected increase in surface temperatures is the potential influence on heat-related hazards such as wildfires (Piñol et al. 1998) and drought (Edwards and McKee 1997). Warmer summer conditions could potentially contribute to more “flash droughts”; however, that would be highly dependent on future precipitation conditions.

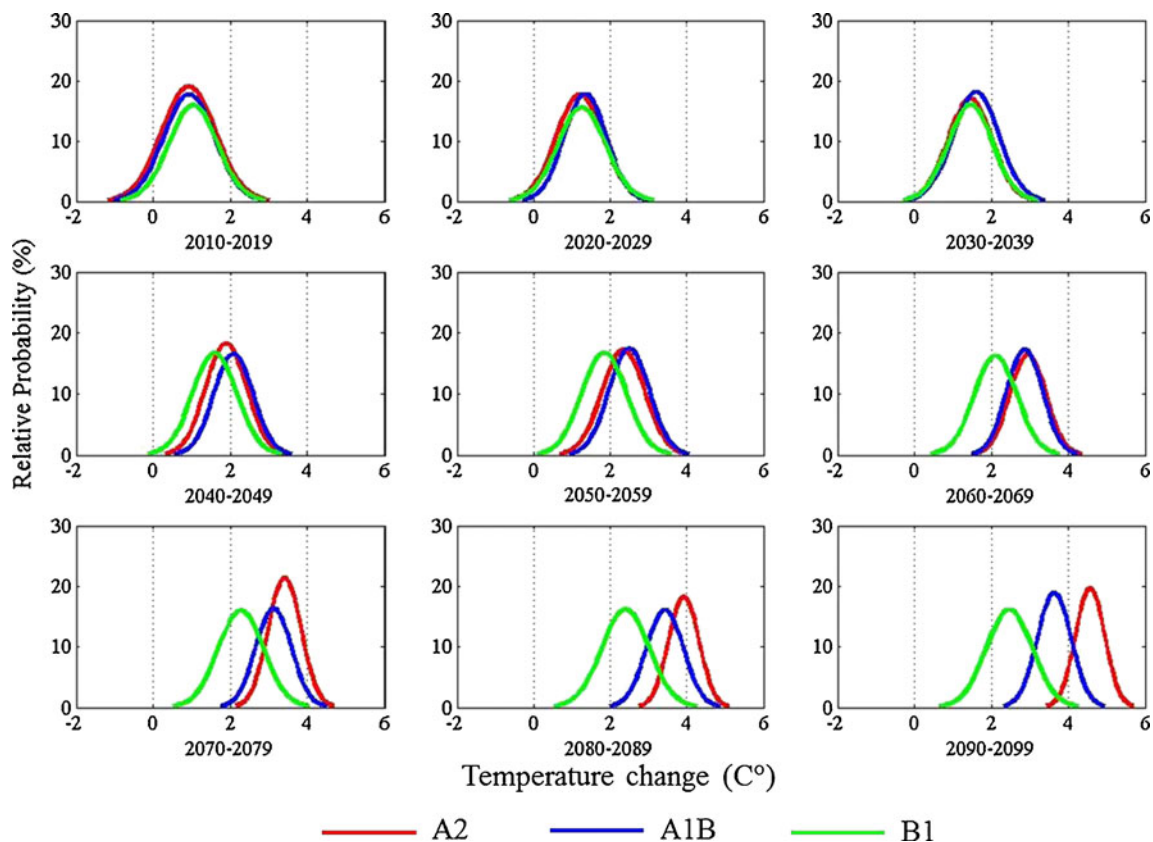


Fig. 5 Projected probability distributions of temperature changes for the period 2010–2099 relative to 1950–1999 mean

Fig. 6 **a** Projected ensemble temperature change distribution for each state within the SCIPP region for the period 2000–2049 and 2050–2099 relative to 1950–1999 mean. **b** Same as **a** except on a seasonal basis (same legend as **a**)

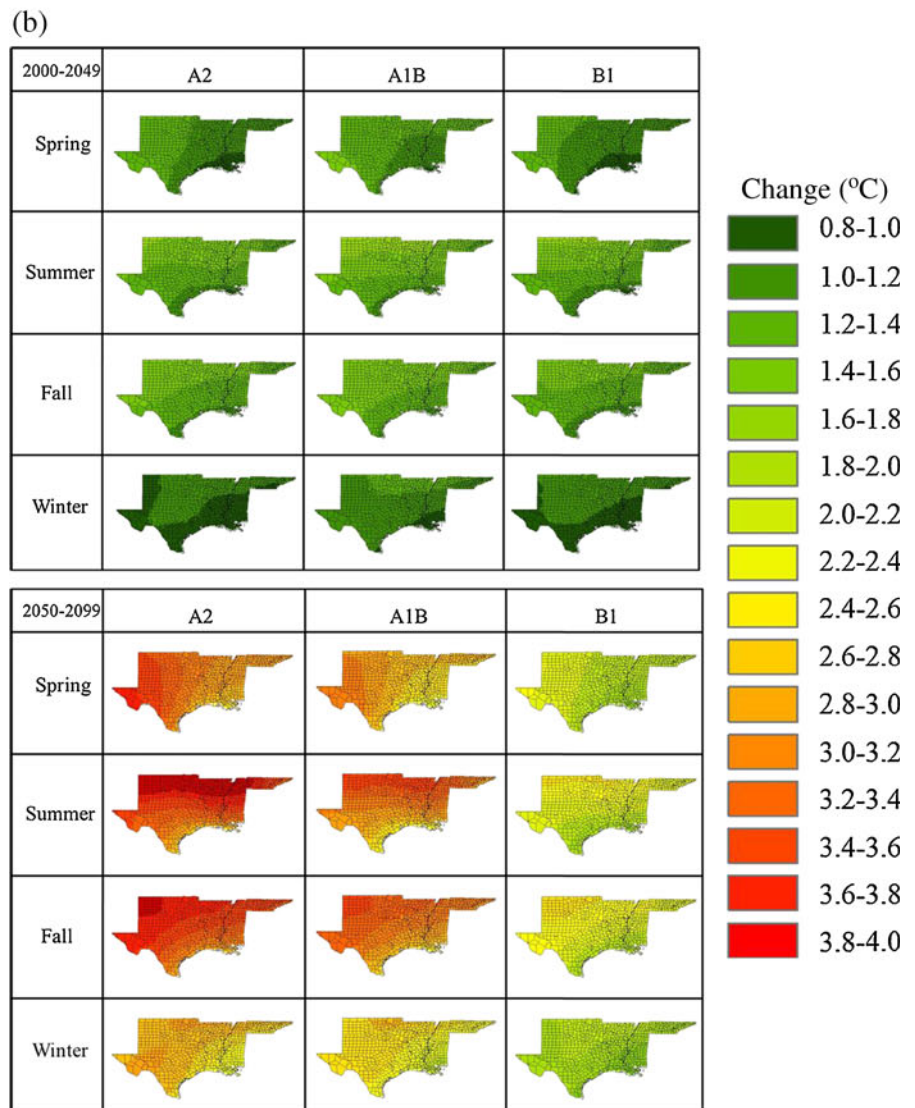
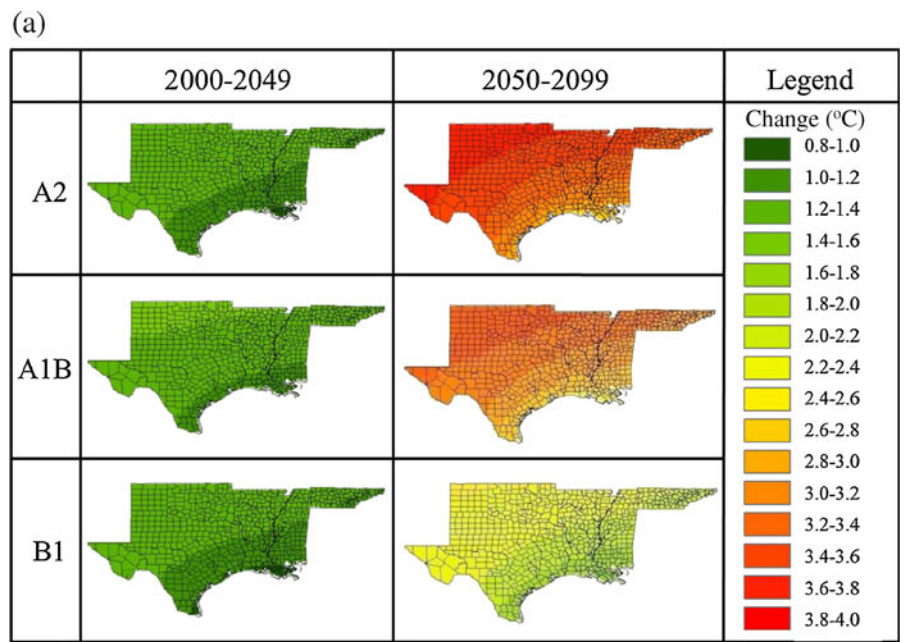
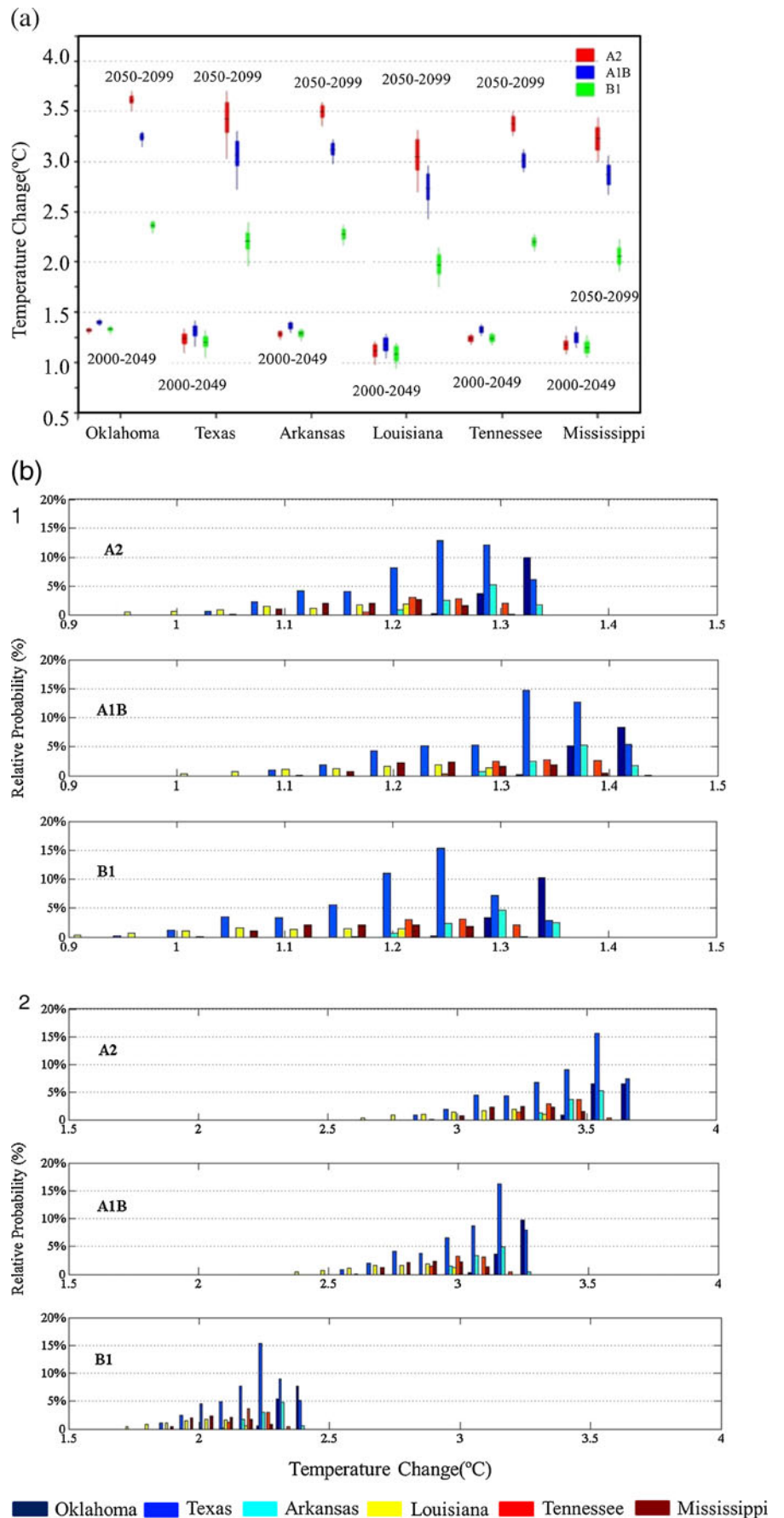


Fig. 7 a Projected ensemble temperature change for each state within the SCIPP region for the period 2000–2099 based on different scenarios. **b** Projected ensemble temperature change distribution for each state within the SCIPP region for different periods (b1: 2000–2049 and b2: 2050–2099) based on different scenarios



Projected temperature for the twenty-first century is highly dependent on the emission scenario with the A2 scenario exhibiting the highest relative increases in temperature, particularly for the summer and fall months (Fig. 8a). The changes in monthly temperature are crucial to numerous sectors including agriculture, water resources, and energy. Studies have found that crop yields are impacted by the rising temperature and less rainfall. A change in climate induces various biological effects that can result in impacts on crop production and supply, which could further impact systems and lead to more economic and social issues (Nelson et al. 2009). The monthly future temperature changes projected by A1B are broken down into every 20 years in Fig. 8b. The changes increase significantly during the last two decades of the century, during which time over 4°C of warming is projected to occur during 6 months of the year. Temperature changes for the six selected cities across the SCIPP region are shown in Fig. 9.

3.2.2 Precipitation

The SCIPP region is a land of contrast, specifically with respect to average annual rainfall. Western portions of the region experience arid conditions and as little as 10 or fewer inches of precipitation per year on average, while southeastern portions of the region (specifically southern Louisiana and Mississippi) receive significantly greater amounts of precipitation totaling greater than 60 inches per year on average (Fig. 3a). One major feature contributing to this major disparity in rainfall is the presence of the Gulf of Mexico, which provides a significant amount of the moisture to the region, particularly to locations closer to the coast.

The historical average annual precipitation across the SCIPP region has been 955.7 mm (38.2 in.) in the past 50 years, and has slightly increased over time. According to USGCRP's Report (Karl et al. 2009), US "precipitation has increased an average of about 5% over the past 50 years." This

Fig. 8 a Projected monthly ensemble temperature change relative to 1950–1999 monthly mean for the period of 2000–2099 based on different scenarios. **b** Projected A1B monthly ensemble temperature change for each two-decade period

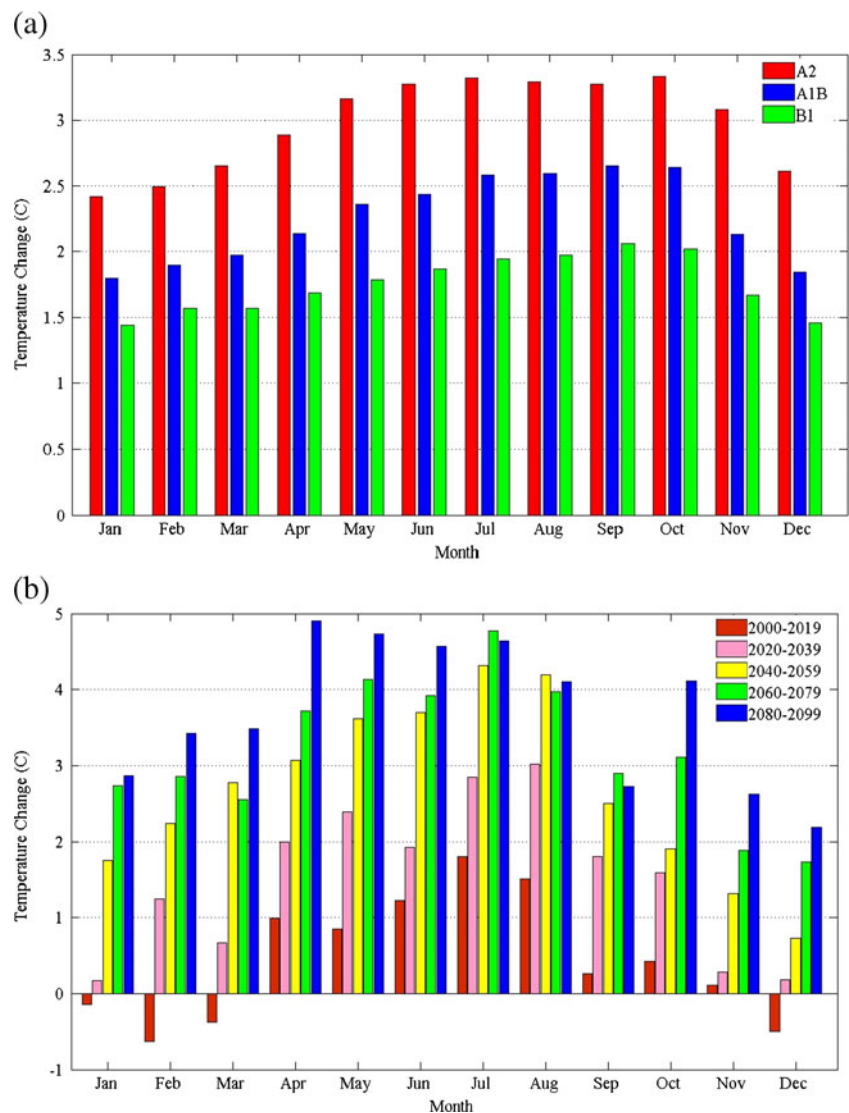
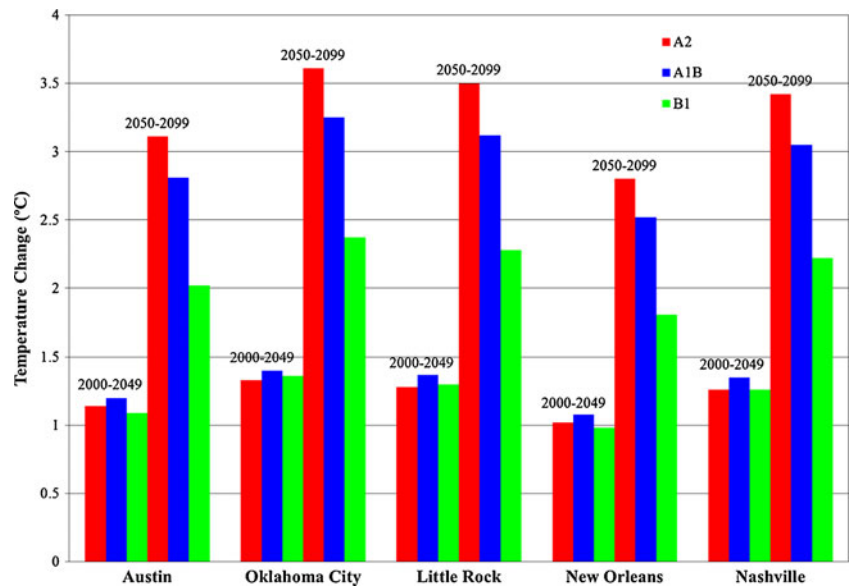


Fig. 9 Projected ensemble temperature change relative to 1950–1999 mean based on different scenarios for cities of interest within SCIPP



study examined the ensemble mean of the 16 GCM model outputs after statistical downscaling to assess possible increases or decreases in future precipitation conditions.

The results of this examination found that future precipitation conditions are not projected to change significantly upward or downward during the twenty-first century (Fig. 10). However, projected precipitation under B1 scenario is tested to have more significant increase overall (Table 3). Future increases are projected in the northeastern portions of SCIPP, with Tennessee having the most significant change (Fig. 11). Southwestern portions of SCIPP are projected to have a drier future, with A2 producing 0.35% less rainfall than the historical

mean during 2050 to 2099 (Fig. 11a), although change is not considered statistically significant (Table 3). Seasonal precipitation variation differed according to the different scenarios; however, common characteristics were found (Fig. 11b). The spring season, which provides a substantial portion of the annual precipitation total to the region, is projected to be drier. Precipitation is projected to increase in southwest Texas and eastern Tennessee during the summer, with a shift towards the Gulf coast during the fall. Winter is projected to be wetter in the northeast and drier in the south.

Rainfall is projected to increase nearly 7% in December relative to 1950–1999 mean according to the A1B scenario

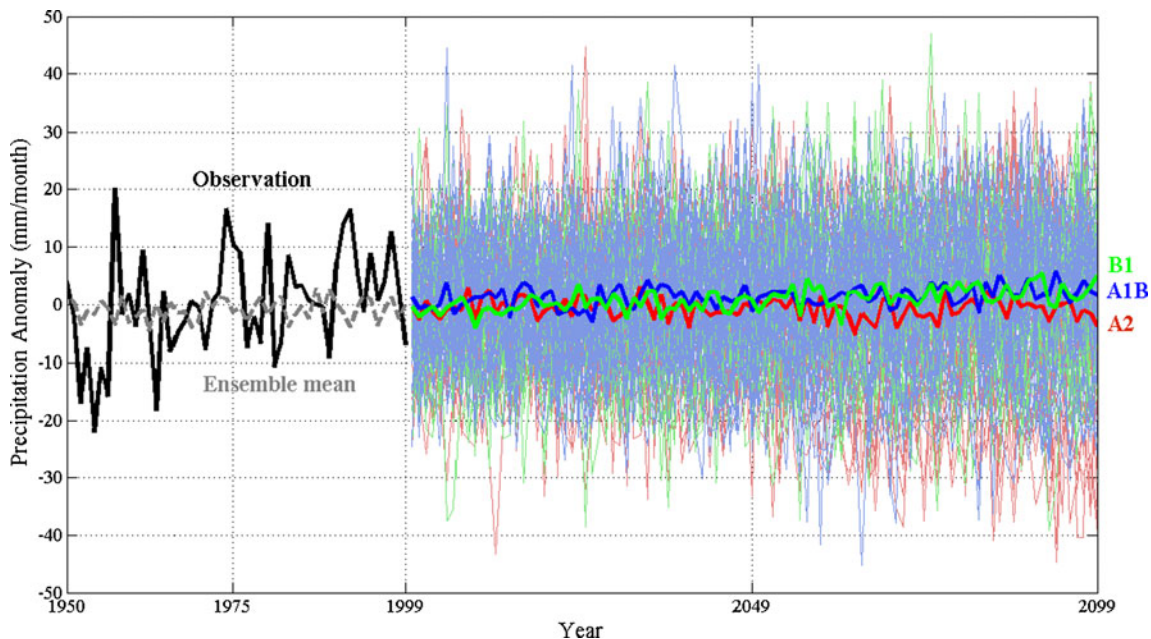
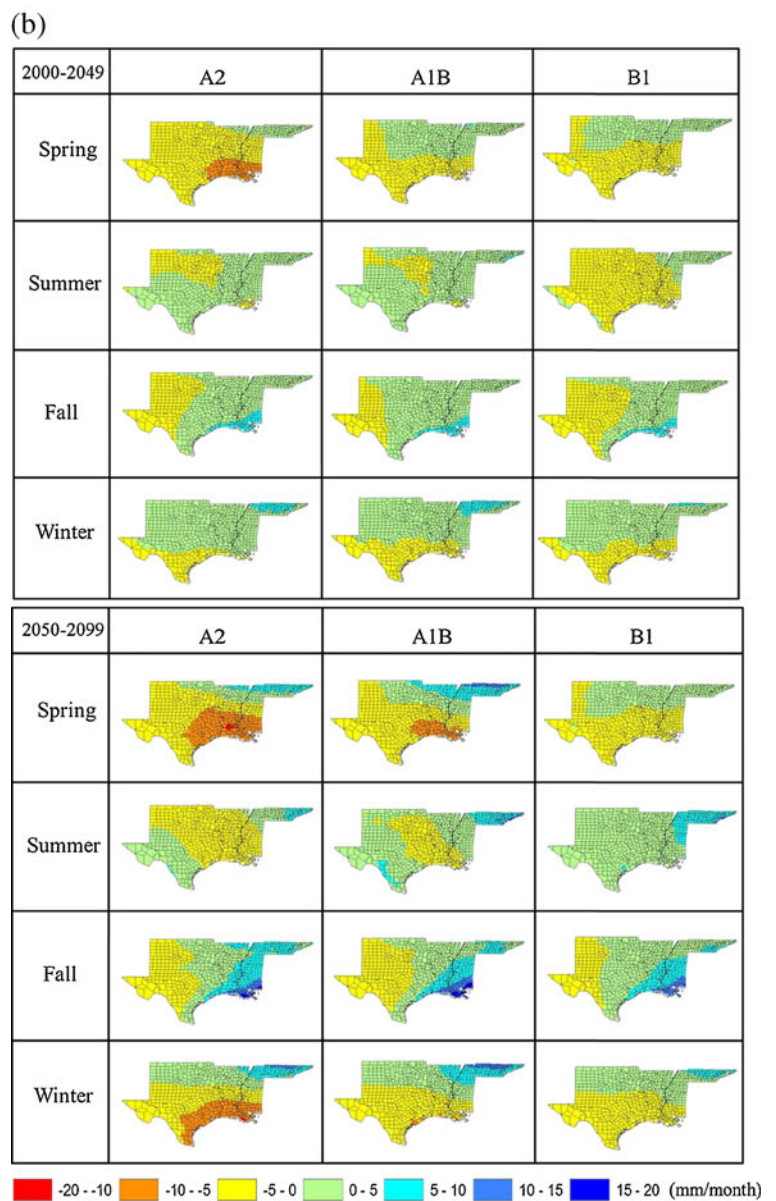
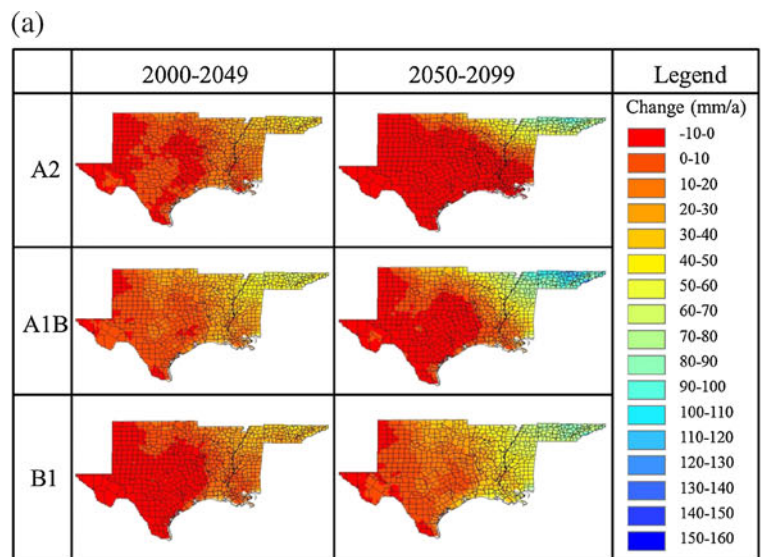


Fig. 10 Precipitation anomaly over SCIPP from 2000–2099. The 16 GCM precipitation projections for the A2 (light red), A1B (light blue), and B1 (light green) scenarios are shown in the background. Bold lines are the ensemble means for the corresponding scenarios

Fig. 11 **a** Projected ensemble precipitation change for each state within the SCIPP region for the period 2000–2049 and 2050–2099. **b** Same as **a** except on a seasonal basis



(Fig. 12a). The change point takes place in the year 2055 (Table 3). However, 7% of increase is not incredibly significant in this case. The three states that exhibited the most noticeable change in Fig. 11a were pulled out in Fig. 12b for further analysis. The state of Tennessee is expected to have 10 to 30 mm of precipitation increase in the winter months from 2050 to 2099. Texas is projected to be drier for most months except for several months during the fall (September and November). Louisiana exhibits tremendous changes throughout the year, with rainfall increases during February and rainfall decreases during January and April. Comparing to state, city level climate projection might have relatively larger uncertainty given its smaller size. Nevertheless, we cautiously selected six major metropolitans within the SCIPP region to examine their precipitation projections, again, using the ensemble mean of the downscaled 16 GCMs outputs rather than one single model. The six selected major cities areas also show interesting trends concerning precipitation (Fig. 13).

This trend is consistent with the geographic pattern over the synoptic SCIPP region: dry areas getting drier while wet areas wetter from the west most El Paso eastward to Nashville. El Paso and Austin both show drier futures. Oklahoma City shows slight increase of precipitation for all scenarios. New Orleans exhibits an overall increase in precipitation with the exception of the A2 scenarios during 2050–2099. Nashville is projected to have the greatest increase in precipitation, followed by Little Rock.

3.3 Uncertainties

In this study we selected the IPCC recommended 16 GCM model outputs under the three emission scenarios, after a rigorous statistical downscaling, and conducted climate assessment over the six-state SCIPP region of southern USA using the ensemble mean of 16 downscaled model results rather than one single model. However, uncertainties about

Fig. 12 a Projected monthly ensemble precipitation change for the period of 2000–2099 based on different scenarios relative to 1950–1999 mean over the SCIPP region. **b** Projected monthly precipitation change for 2050–2099 under A1B scenario relative to 1950–1999 mean over the three states with the most noticeable change

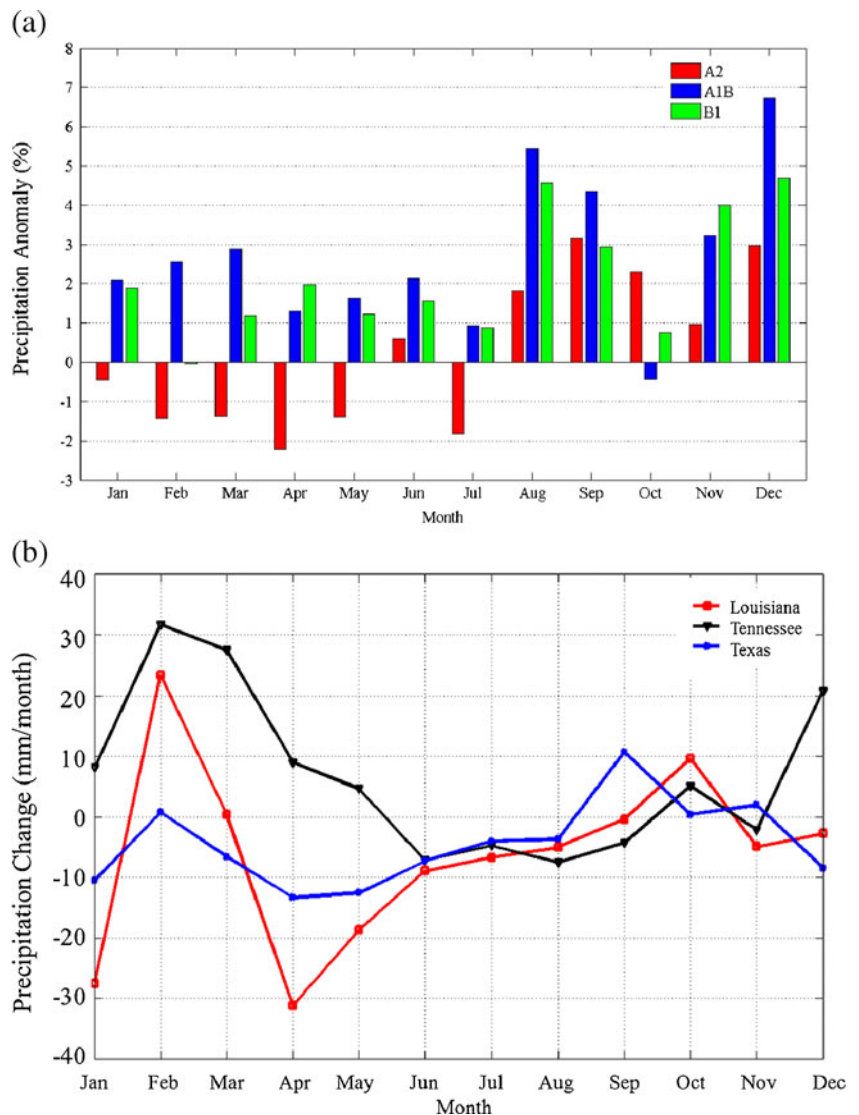
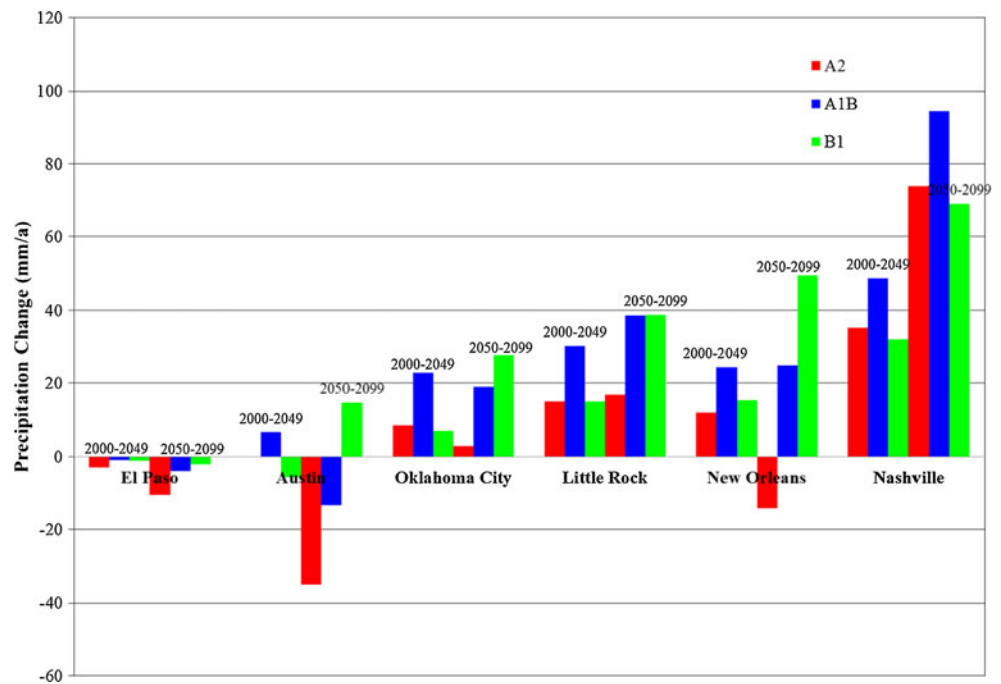


Fig. 13 Projected ensemble precipitation change based on different scenarios for six areas of interest within SCIPP. The order of the cities ranks from dry west to wet east within the SCIPP region



future climate arise from a number of different sources. Here we briefly mention three major uncertainties from climate scenarios, GCMs, and statistical downscaling methods that potentially ask for readers' cautions when interpreting this study.

3.3.1 Scenarios uncertainties

Climate scenarios from IPCC have been widely used in climate change and mitigation research. However, these scenarios still rely on the results from GCM experiments and however complicated the model is, the scenarios alone could only represent some of the uncertainties that relate to the modeling of the climate response to a given forcing condition, but may not include uncertainties caused by the modeling of atmospheric composition for a given emissions scenario, or those related to future land-use change (Mearns et al. 2001). Refer to Mearns et al. (2001) for five key sources of uncertainty relate to climate scenario construction.

3.3.2 GCMs uncertainties

On one hand, the Earth is a complex natural system within which many processes and feedbacks between different components are yet not fully understood by human. Therefore, it is difficult to include these uncertainties in the models until better understanding has been achieved. GCMs today could only be ensured to represent natural processes as known by human as accurate as possible, so the predictions made by the GCMs are as accurate as what current models could reach.

One the other hand, most of the uncertainty in the predictions of future climate is not related to natural processes.

Instead, future human behavior is the most unpredictable component. For example, innovations that limit the amount of greenhouses gases, regulations that change the amount of pollutants, and how the population will be growing in the future all remain somewhat unknown (IPCC 2001).

3.3.3 Statistical downscaling methods uncertainties

Maurer et al. (2007) stated that the principal weakness of any non-dynamical downscaling method is the assumption of some temporal stationarity in how large-scale climate features relate to local-scale surface climate. BCSD method used in WCRP CMIP3 dataset assume that the processes determining how precipitation and temperature anomalies for any two-degree grid box from GCMs distributed to 1/8 degree grid box will be the same in the future as they have been in the past. Also, the bias correction step features the assumption that the biases exhibited by a GCM for the historical period will also remain in the projections. Tests of these assumptions, using historic data, show that they appear to be reasonable, inasmuch as the BCSD method compares favorably to other downscaling methods (Wood et al. 2004).

Application uncertainties of BCSD CMIP3 dataset vary depending on which spatial and temporal aspects of projections are used (Mote et al. 2011). Arguably, statistical descriptions of these projections (e.g., period and spatial statistics) are more reliable than location- or time-step-specific conditions. These projections can be used more confidently to support statements on projected changes in mean-annual temperature over a given region than to describe a specific future month's condition in that region (Maurer et. al 2007).

4 Conclusions

This research assesses future climate change conditions over the SCIPP region using the WCRP CMIP3 bias-corrected and statistically downscaled climate dataset. The projections of climate change are based on the A2, A1B, and B1 scenarios. The study focused on temperature and precipitation change over the southern USA while also going down to the state and city level to provide detailed analysis.

The research used an ensemble mean of 16 GCMs due to the substantial benefits of relying on the output of many models. The results found that there were slight differences between the ensemble mean and past observations.

The average temperature in the SCIPP region is projected to change 2.3°C to 4.8°C by the end of the twenty-first century based on different emission scenarios. Temperature increases more significantly in the second half of the century than the first half. Spatial results revealed that the northern and northwestern portions of SCIPP are projected to warm more significantly than regions closer to the Gulf of Mexico. While the SCIPP region is projected to have increased temperatures in all seasons, summer and fall are projected to have the most significant temperature increases.

Precipitation does not have a discernible upward or downward trend during the twenty-first century based on this analysis. However, the eastern and northeastern portions of SCIPP are forecasted to be wetter. Tennessee exhibited the most significant increase in annual precipitation while Texas is projected to have the greatest decreases in precipitation. The transition from late summer to early winter (specifically the months of August, September, November, and December) is projected to be wetter for the region as a whole.

Uncertainties involved in the future climate are discussed in detail. Basically, uncertainties existed in IPCC climate scenarios, GCMs, and statistical downscaling methods are the major reasons for the disparity and uncertainty of future climate as projected by different GCMs. Even so, the results presented in this research represent an initial phase of a broader study that will investigate the impacts of these climate projections on water resources management through the use of hydrologic models. This study is being undertaken to assist local water planning efforts in an effort to more closely link climate modeling to longer-term planning efforts. Additional research will be carried out in the future to continue assessing climate change impacts on regional hazards management in the South.

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References

- Edwards DC and McKee TB (1997) Characteristics of 20th century drought in the United States at multiple time scales. *Climatology Report Number 97–2*, Colorado State University, Fort Collins, Colorado
- Felzer B, Heard PS (1999) Precipitation differences amongst GCMs used for the U.S. National Assessment. *J Am Water Resour Assoc* 35(6):1327–1339
- Giorgi F et al. (2001) Regional climate information: Evaluation and projections, in *Climate Change 2001: The Scientific Basis—Contribution of Working Group I to the Third IPCC Assessment Report*, edited by J. T. Houghton et al., chap. 10, pp. 583–638, Cambridge Univ. Press, Cambridge, U.K
- Hansen J, Russell G, Rind D, Stone P, Lacis A, Lebedeff S, Ruedy R, Travis L (1983) Efficient three-dimensional global models for climate studies: models I and II. *M Wea Rev* 111:609–662. doi:10.1175/1520-0493(1983)111<0609:ETDGMF>2.0.CO;2
- Hellmuth ME, Moorhead A, Thomson MC, and Williams J (eds) (2007) *Climate Risk Management in Africa: Learning from Practice*. International Research Institute for Climate and Society (IRI), Columbia University, New York, USA
- IPCC (2001) In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Da X, Maskell K, Johnson CA (eds) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p 881
- IPCC (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Core Writing Team, Pachauri, R.K and Reisinger, A., 104 pp, Geneva, Switzerland
- Karl TR, Trenberth KE (2003) Modern global climate change. *Science* 302:1719–1723
- Karl TR, Melillo JM, Peterson TC (2009) *Global climate change impacts in the United States*. Cambridge University Press, New York
- Kendall MG, Stuart A (1973) *The advanced theory by statistics*. Griffin, London
- Liang XZ, Pan J, Zhu J, Kunkel KE, Wang JXL, Dai A (2006) Regional climate model downscaling of the U.S. summer climate and future change. *J Geophys Res* 111:D10108. doi:10.1029/2005JD006685
- Lo JCF, Yang ZL, Pielke RA Sr (2008) Assessment of three dynamical climate downscaling methods using the Weather Research and Forecasting (WRF) model. *J Geophys Res* 113:D09112. doi:10.1029/2007JD009216
- Maurer EP, Brekke L, Pruitt T, Duffy PB (2007) Fine-resolution climate projections enhance regional climate change impact studies. *Eos Trans AGU* 88(47). doi:10.1029/2007EO470006
- Mearns LO, Hulme M, Carter TR, Leemans R, Lal M, Whetton P, Hay L, Jones RN, Katz R, Kittel T, Smith J, Wilby R, Mata LJ, Zillman J (2001) In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press,

- Cambridge, United Kingdom and New York, NY, USA, p 881, Climate Scenario Development
- Mote P, Brekke L, Duffy PB, Maurer E (2011) Guidelines for constructing climate scenarios. *Eos Transactions* 92(31):257–258
- Nakic'enovic'N et al (2000) Intergovernmental panel on climate change special report on emissions scenarios. Cambridge University Press, Cambridge, U.K
- Nelson G et al (2009) Climate change: impact on agriculture and costs of adaptation. International Food Policy Research Institute, Washington, D.C
- Pettitt A (1979) A nonparametric approach to the change-point problem. *Applied Statistics* 28:126–135
- Piñol J, Terradas J, Lloret F (1998) Climate warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain. *Clim Chang* 38:345–357
- Santer B (2009), Climate scenarios 101: Which climate model is “best”, OCCRI Workshop on Scenarios of Future Climate, October 28–29, 2009, Portland
- Schmidt GA, Ruedy R, Hansen JE, Aleinov I, Bell N, Bauer M, Bauer S, Cairns B, Canuto V, Cheng Y, Del Genio A, Faluvegi G, Friend AD, Hall TM, Hu Y, Kelley M, Kiang NY, Koch D, Lacis AA, Lerner J, Lo KK, Miller RL, Nazarenko L, Oinas V, Ja. Perlwitz, Ju. Perlwitz, Rind D, Romanou A, Russell GL, Mki. Sato, Shindell DT, Stone PH, Sun S, Tausnev N, Thresher D, Yao M-S (2006) Present day atmospheric simulations using GISS ModelE: comparison to in-situ, satellite and reanalysis data. *J Climate* 19:153–192. doi:10.1175/JCLI3612.1
- Tapiador JF, Sanchez E (2007) Changes in the European precipitation climatologies as derived by an ensemble of regional models. *J Climate* 21:2540–2557. doi:10.1175/2007JCLI1867.1
- Wilby RL, Wigley TML (1997) Downscaling general circulation model output: a review of methods and limitations. *Prog Phys Geogr* 21:530–548
- Wilcox EM, Donner LJ (2007) The frequency of extreme rain events in satellite rain rate estimates and an atmospheric general circulation model. *J Climate* 20:53–69
- Wood AW, Maurer EP, Kumar A, Lettenmaier DP (2002) Long-range experimental hydrologic forecasting for the eastern United States. *J Geophysical Research-Atmospheres* 107(D20):4429
- Wood AW, Leung LR, Sridhar V, Lettenmaier DP, 62 (2004) Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. *Clim Chang* 15:189–216