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Seasonal trends in air temperature and precipitation in IPCC AR4 GCM output for Kansas, USA: evaluation and implications

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ABSTRACT: Understanding the impacts of future climate change in Kansas is important for agricultural and other socio-economic sectors in the region. To quantify these impacts, seasonal trends in air temperature and precipitation patterns from decadally averaged monthly output of 21 global climate models under the Special Report on Emissions Scenarios A1B scenario used in the Intergovernmental Panel of Climate Change Assessment Report 4 are examined for six grid cells representing Kansas. To ascertain the performance of the models, we compared model output to kriged meteorological data from stations in the Global Historical Climate Network for the period from 1950 to 2000. Agreement between multimodel ensemble mean output and observations is very good for temperature (r^2 all more than 0.99, root mean square errors range from 0.84 to 1.48 °C) and good for precipitation (r^2 ranging between 0.64 and 0.89, root mean square errors range from 322 to 1144 mm). Seasonal trends for the second half of the 20th century are generally not observed except in modelled temperature trends. Linear trends for the 21st century are significant for all seasons in all grid cells for temperature and many for precipitation. Results indicate that temperatures are likely to warm in all seasons, with the largest trends being on the order of 0.04 °C/year in summer and fall. Precipitation is likely to increase slightly in winter and decrease in summer and fall. These changes have profound implications for both natural ecosystems and agricultural land uses in the region. Copyright © 2009 Royal Meteorological Society

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1. Introduction

The central plains region of the United States is one of the largest agricultural producing areas where food production has significant implications to the global economy and food security. This was recognised during the MINK study (Easterling *et al*., 1993). Therefore, understanding the potential ramifications of climate change in the region is vitally important for understanding future global food and possibly fuel security. Understanding potential future impacts of greenhouse gas (GHG) emissions on the climate of the mid-western United States is critical to understanding how climate change will affect the United States in terms of its food production and agricultural economy (Easterling *et al*., 1993; US Global Change Research Program USGCRP, 2001; USGCRP forthcoming, 2009). At the same time, the atmospheric dynamics that regulate the climate over the Midwest are such that they make this one of the most difficult areas in the world for assessing potential climate impacts.

This article will set out to assess how climate model projections based on GHG emission scenarios will affect temperature and precipitation conditions across the Midwest precipitation gradient found, primarily focusing on an area encompassing the state of Kansas. The Intergovernmental Panel on Climate Change (IPCC, 2007) projects that subtropical regions are likely to be most affected by GHG emissions, with significant negative climate outcomes likely to reach into the Midwest of the United States. To assess climate change over the region, we will compare climatologies for the last 50 years against historical global climate model (GCM) simulations to assess how the models simulate the climate of the last 50 years. Following on this assessment, we will assess potential outcomes of future GCM climate change projections for the IPCC Special Report on Emissions Scenarios (SRES) A1B scenario. The SRES A1B scenario assumes that in the near term, emissions will continue to increase, but that by mid century, reductions will take place; thus, it represents an intermediate emissions path into the future (IPCC, 2000).

While we will make an assessment of climate impacts as simulated by GCMs, we also recognise that assessing the impacts of future climate change on agriculture is problematic. Such an assessment must not only consider the impact of climate on crop production but it must also consider additional human drivers, such as cropping choices and world demand for food (Olesen and Bindi,

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2002; Howden *et al*., 2007). It must also recognise that, in their current state, GCMs do not simulate all possible human–climate interactions. For example, certain land use characteristics (e.g. irrigation, fire management and fertiliser use) or in many of the models observed land use change that affect local and global biophysical and biogeochemical processes (e.g. Claussen *et al*., 2001) are not included in the global simulations. Yet there is evidence that these land use changes have a significant impact on climate and ecological processes in the Midwest (Bonan, 1999; Changnon *et al*., 2002; Mahmood *et al*., 2004).

2. Background

The grass lands of the Midwest are one of a number of global grassland ecosystems that occur as a plant adaptation to a high-variable climate conditions. Globally, grassland ecosystems comprise approximately 40% of the total land surface (Samson and Knopf, 1994), and account for most of the world's agricultural production. These ecosystems are particularly important for regulating biosphere–atmosphere interactions with respect to the transport of energy and mass in both natural and agricultural landscapes (Easterling *et al*., 1993; USGCRP, 2001). In addition, they are vital to the global food economy, and their societal importance may further increase as the discussion regarding biofuels for fuel production continues in the future (USGCRP, 2001). Therefore, understanding the impacts of global climate change on these regions is vitally important for food security and to improve our ability to adapt to new conditions.

Characterising and understanding the climate of the Midwest have been a much discussed topic beginning with the earliest climate classification systems. The original Köppen classification drew its boundaries based on the vegetation maps of de Candole (Köppen, 1900; Carter and Mather, 1966). The decision to draw climatic boundaries based on vegetation maps led to a number of problems when characterising the climate over the region encompassing a region like Kansas. For example, shallow soils over the Flint Hills region reduce the ability of vegetation to endure drought conditions (e.g. Park *et al*., 2005). Thus, the forest-grassland ecotone is shifted eastward compared with locations with a similar temperature and precipitation statistics but deeper soils. Such complexities contributed to multiple attempts to redraw the boundaries of the Köppen classification system (e.g. Trewartha and Horn, 1980). Thornthwaite devised his climate classification systems (while at the University of Oklahoma) specifically to avoid determining boundaries on ecotones, but his and follow up systems still are unable to incorporate the problems of the soil boundary conditions (Thornthwaite, 1943, 1948; Feddema *et al*., 2005). To truly understand the future impacts of climate change on the region, researchers need to integrate not only changes in the drivers of climate change but also how local conditions, such as soils and local climate feedbacks associated with human land cover change, can exacerbate or compensate for some of the impacts.

While early researchers such as Köppen and Thorntwaite mapped climates based on average statistics, they also recognised that these boundaries are dynamic and that the annual range and interannual climate variability a characteristic of grassland. This large natural interannual climate variability contributes to the difficulty of detecting and projecting climate change impacts on these regions. Although the relatively short droughts in the 1910s, the 'Dust Bowl' in the 1930s and the 1950s in the American Midwest, form a strong social image of climate impacts in the Midwest, longer observation periods (10–30 year averages) show that the climate has been relatively stable for most of the 20th century (e.g. Skaggs, 1978). Skaggs (1978) used different time averages of the Palmer Drought Severity Index (Palmer, 1965) to illustrate that for different averaging periods, there was no significant climate trend in the first 75 years of the 20th century. Grundstein (2009) shows a general warming and moistening of the eastern United States, with a gradual shift in the zero moisture index line (where potential evapotranspiration equals precipitation) to the west. This is further supported by evidence of a significant wet period in the last quarter of the 20th century (Garbrecht and Rossel, 2002; Garbrecht *et al*., 2004). However, this wet period from about 1980 to 2000 shows some evidence of declining in the southern parts of the Midwest in the first decade of the 21st century (Garbrecht *et al*., 2004). In terms of temperatures, a number of studies suggest that temperatures have been warming in the region (USGCRP, 2001; IPCC, 2007; Patterson, 2008). Robeson (2004) demonstrates that much of the change in temperature has been linked to increases in the winter time daily minimum temperatures. This is further supported in global trends of annual decreases in the number of cold nights and a commensurate increase in the number of annual warm nights (Alexander *et al*., 2006).

In aggregate, most assessments of Midwest climate change point to an accelerated warming in the last few decades accompanied by an increase in precipitation (e.g. Grundstein, 2008). However, it is also clear that the climate of the Midwest has seen much larger climate anomalies prior to the instrumental record. Tree ring evidence suggests more extensive and intense drought episodes (Woodhouse and Overpeck, 1998). At the same time, other evidence suggests not only the potential for severe droughts but also significant shifts in wind patterns, as observed from sand dune orientation patterns in the Sand Hills region of Nebraska (Venkatatamana *et al*., 2006). These studies raise the question of what mechanism might have been responsible for such past climate change and whether such changes might be possible in the future or if they could be triggered by anthropogenic GHG-forcing scenarios. Observations show that anomalous sea surface temperatures in both the North Atlantic and Pacific Ocean could trigger such events (McCabe *et al*., 2004). GCM experiments support this hypothesis, with the most intense drought simulated with forced SST anomalies in both locations simultaneously (Feng *et al*., 2008). However, Feng *et al*.

(2008) were not able to replicate the observed wind patterns associate with the historical events, suggesting this may not be a definitive explanation of the observed historical drought events.

Other recent work points to specific weather anomalies that could explain some of the high interannual climate variability observed over the region. Persistent drought over Mexico, extending into the southwestern United States in the beginning of the 21st century, has possible links to anthropogenic warming associated with GHG emissions and a consequent weakening of the Hadley Circulation (Stahle *et al*., 2009). At the same time, severe flooding in 1993 and 2008 to the north of the study area has been linked to the 'Maya Express' a mechanism by which moisture from the Gulf of Mexico near the Yucatan Peninsula is transported northward as a result of a persistent weather pattern (Dirmeyer and Kinter, 2009). Although it is not clear whether these later mechanisms can be simulated in a GCM, we propose to assess how GCMs simulate future decadal scale temperature and precipitation patterns over the region. Perhaps these conflicting trends are an indication of increased climate variability as is projected in the IPCC fourth assessment report (AR4) (IPCC, 2007).

Assessments of future climate change based on the multimodel IPCC AR4 approach suggest that near surface air temperature in the central United States will likely warm on the order of 4 °C for the SRES A1B scenario (IPCC, 2007). Consequences of increases in minimum air temperature potentially may lead to decreases in productivity of the C_4 grasses and crops as well as increased productivity by C_3 forbs (Alward *et al*., 1999). The distinction between C_3 and C_4 photosynthesis pathways relates to the ability to close the stomata during warmer periods of the day and therefore C_4 generally being better at conserving water. In agricultural regions, such as Kansas, this is significant for grazing and fodder for meat production. Another potential implication of climate change is longer growing seasons. While this may seem beneficial for agricultural production, this is not always the case. Longer growing seasons may not result in increased CO_2 assimilation if water becomes a limiting factor (Sacks *et al*., 2007).

Different grassland ecosystems respond differently to climate change, particularly in response to water availability via soil moisture (Frank and Inouye, 1994). The role of water limitation on vegetation responses varies across grassland ecosystems at relatively small spatial scales (hundreds of kilometers). In the Great Plains region, for example, limited water availability in the eastern portions of the grasslands may indicate that C_4 species will become more abundant (Knapp *et al*., 2001).

In addition to altering the species composition in natural grasslands, a change in the regional precipitation regime has implications for agriculture. Through the Clausius–Clapeyron relationship, due to the strong temperature dependence of saturation vapour pressure, slight increases in precipitation could still result in effectively drier conditions. Warmer, drier conditions will affect the economic viability of agricultural production (via crop selection) and will necessitate effective adaptation mechanisms such as increasingly more efficient irrigation technology and/or new crop varieties.

In terms of productivity, grassland ecosystems are the most sensitive to rainfall variability (Knapp and Smith, 2001). Productivity of C_4 grasslands is known to be sensitive to the frequency of precipitation events largely through a modulation of the soil moisture under both rainfall manipulation studies (Fay *et al*., 2003) and natural conditions (Nippert *et al*., 2006).

One important component of understanding the impact of climate change on grasslands is to understand the importance of feedback cycles between the biotic and climate systems. The role of soil moisture–precipitation feedbacks has been shown to vary spatially (Koster *et al*., 2004; Brunsell, 2006). Through a modelling study, Jones and Brunsell (2009b) show the existence of a positive soil moisture–precipitation feedback in Kansas via an energy balance partitioning (evaporation versus sensible heat flux) mechanism. This implies that any biological control over trends in soil moisture within this region may be amplified by shifts in precipitation. A related mechanism, particularly within the western regions of the state is the role of irrigation. Irrigation is known to affect both the local carbon assimilation (Volk *et al*., 2000), but it also affects atmospheric boundary layer dynamics such as cloud formation (Marotz *et al*., 1975), surface energy fluxes (Adegoke *et al*., 2003, 2007), near surface air temperatures (Mahmood *et al*., 2004) and precipitation (Segal *et al*., 1998).

Compounding the effects of air temperature and water use impacts under global warming scenarios is the biological control exhibited by vegetation. It is generally proposed that there is a positive feedback between climatic warming and biospheric processes (Luo, 2007). The role of the biosphere has been shown to have a positive feedback between global warming and the carbon cycle in a coupled carbon-climate model (Cox *et al*., 2000). In addition to the impacts on air temperature, there are biological implications for the hydrological cycle. Under enriched CO_2 conditions, grasslands appear to conserve soil moisture through a reduction in the stomatal conductance and reduced transpiration (Volk *et al*., 2000). Thus, assessing the response of grassland ecosystems to climate change necessitates understanding of precipitation and temperature impacts in addition to the effect of increased CO_2 conditions.

More generally, land use/land cover modifications have a large potential to either exacerbate or alleviate the effects of global climate change through microscale impacts on water and energy cycling. These impacts are not clearly understood due to many feedbacks as well as how to accurately parameterise land use at GCM resolutions (Feddema *et al*., 2005a, 2005b). To further complicate the issue, the underlying human decision-making processes that control land cover are not well understood at this point (Heistermann *et al*., 2006). To accurately assess mitigation and socio-economic implications of climate change, it is essential that these processes are included in the analysis; particularly in agricultural lands (Olesen and Bindi, 2002; Hopkins and del Prado, 2007; Howden *et al*., 2007).

Thus, it is important for a number of reasons that we understand the implications of climate change within the state of Kansas and the U.S. Central Plains in general. Therefore, the questions to be addressed in this research are (1) what are the seasonal trends in air temperature and precipitation observed during the second half of the 20th century and how do these match the IPCC AR4 simulations? (2) What are the future trends and implications of climate change for the state of Kansas in the 21st century?

3. Methods

GCM output air temperature and precipitation for decadally averaged monthly values were obtained from 21 models used in the IPCC AR4 IPCC, 2007 (multi-model data obtained from the National Center for Atmospheric Research – also available from Program for Climate Model Diagnosis and Intercomparison). A listing of the models used is given in Table I. The spatial resolution of the models used in this analysis varied (IPCC, 2007: Chapter 11), but for this study, all model results were interpolated to the identical T42 GCM grid resolution. All models were run using the SRES A1B scenario.

Rather than establish which models perform particularly well or poorly in this region, we focus on the intermodel variability and the multimodel ensemble mean to assess the seasonal impacts of climate change in the region. In many cases, the use of the multimodel ensemble has been shown to outperform individual models (for a review, see Tebaldi and Knutti, 2007).

The multimodel ensemble means are calculated using decadally averaged monthly mean air temperature and total precipitation. Six grid cells cover the state of Kansas and are used in this analysis (Figure 1). We use linear regression techniques on seasonally averaged temperature and total precipitation model output to test for trends.

To evaluate the seasonal trends in the GCM output for the region, we compare the trends to meteorological station data from the Global Historical Climate Network (GHCN; Peterson and Vose, 1997; Peterson *et al*., 1998). While we acknowledge that many of these stations may be either located in less than ideal locations (Pielke *et al*., 2007) or may exhibit microscale climatic influences that are not representative of the region in general (Pielke *et al*., 2002), our hope is that by using enough stations a realistic understanding of the regional climatic conditions is achieved. Therefore, a total of 337 stations are used for evaluation (Figure 1).

Table I. List of the global climate models used in this analysis.

Number	Group	Name	Country
1	Canadian Centre for Climate Modelling & Analysis (T47)	CGCM3.1(T47)	Canada
2	Canadian Centre for Climate Modelling & Analysis (T63)	CGCM3.1(T63)	Canada
3	National Center for Atmospheric Research (CCSM)	CCSM3	US
4	Météo-France/Centre National de Recherches Météorologiques	CNRM-CM3	France
5	CSIRO Atmospheric Research	CSIRO-Mk3.0	Australia
6	US Department of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	GFDL-CM2.0	US
7	US Department of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	GFDL-CM2.1	US
8	NASA/Goddard Institute for Space Studies	GISS-AOM	US
9	NASA/Goddard Institute for Space Studies	GISS-EH	US
10	NASA/Goddard Institute for Space Studies	GISS-ER	US
11	LASG/Institute of Atmospheric Physics	FGOALS-g1.0	China
12	Institute for Numerical Mathematics	INM-CM3.0	Russia
13	Institut Pierre Simon Laplace	IPSL-CM4	France
14	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	MIROC3.2(hires)	Japan
15	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	MIROC3.2(medres)	Japan
16	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group.	ECHO-G	Germany/Korea
17	Max Planck Institute for Meteorology	ECHAM5/MPI-OM	Germany
18	Meteorological Research Institute	MRI-CGCM2.3.2	Japan
19	National Center for Atmospheric Research	PCM	US
20	Hadley Centre for Climate Prediction and Research/Met Office	UKMO-HadCM3	UK
21	Hadley Centre for Climate Prediction and Research/Met Office	UKMO-HadGEM1	UK

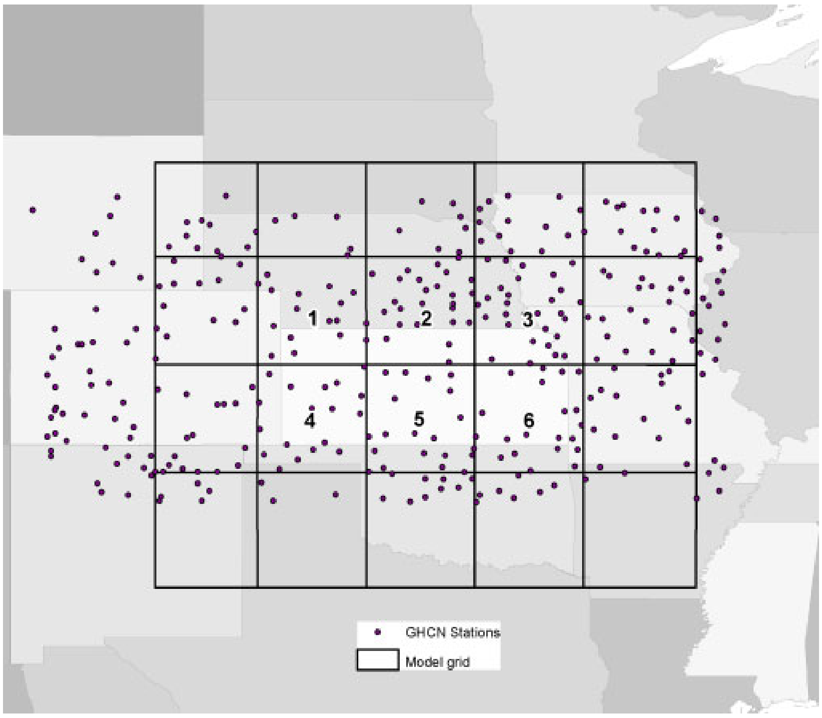

Figure 1. Depiction of global climate model grid cells and Global Historical Climate Network station locations used in this analysis. This figure is available in colour online at www.interscience.wiley.com/ijoc

Rather than compare an individual station or a group of stations with the model output, we interpolated the monthly mean air temperature and total precipitation GHCN data to the grid resolution of the GCM models using kriging (Figure 1). These monthly interpolated values were averaged for each decade to compare with the GCM output using mean absolute differences (|GHCN – GCM|). Seasonal and overall trends were evaluated using linear regression on the decadally averaged monthly temperature and precipitation values.

4. Results

4.1. Comparison of observations and model results

There is large variability between the various models over the region, particularly with respect to summer precipitation (Figure 2). However, when using the ensemble average, the agreement with interpolated station data is quite good (Figure 3). Table II shows the slope, r^2 and root mean square error (RMSE) values for the agreement between the kriged station data and the ensemble mean GCM output for both monthly precipitation and air temperature. For temperature, the RMSE ranges from 0.84 to 1.48 °C, with all r^2 being 0.99 or higher. The slopes for temperature are also quite close to the optimal value of 1. The values for precipitation are more variable, with r^2 ranging from 0.72 to 0.89, corresponding to RMSE ranging approximately between 322 and 1144 mm, with slopes range between 0.52 and 1.16.

The distribution of seasonal precipitation mean absolute differences for each grid cell between the GHCN data and GCM output (|GHCN – GCM|) is shown in Figure 4. The largest absolute differences occur during the high precipitation seasons (spring and summer), with summer having the greatest variability in model estimates. Mean spring differences are about 80 mm, while summer demonstrates a slight spatial trend with mean absolute differences decreasing from west (cells 1 and 4) to east (cells 3 and 6). The mean annual rainfall for Kansas is approximately 700 mm, thus this difference represents approximately 10% of the annual total. This spatial trend is reversed in fall and winter where the difference increases from the western cells (1 and 4) to those covering eastern Kansas (3 and 6). Differences in the fall generally lie between 40 and 60 mm, while the winter differences are on the order of 20 to 40 mm.

The mean absolute differences for seasonal temperatures are shown in Figure 5. All grid cells generally experience between 1 and 2 °C for each season. Unlike the precipitation differences, there is no clear spatial trend in the differences from west to east.

The intermodel distributions of linear trends in seasonal precipitation for 1950–2000 are shown in Figure 6 for each grid cell. There is a large variance in each cell, for each season. In general, the mean slope is near zero and typically agrees with observed trends (shown as triangles). The ensemble mean slopes and associated r^2 values are shown in Table III. None of the values are statistically significant at the $p < 0.05$ level. The slopes derived from the GHCN data contain four values that are significant: an increase in winter and spring precipitation at points 5 and 6 (Table III). The r^2 values are low (on the order of 0.1), but the slopes are significant at the 0.05 level.

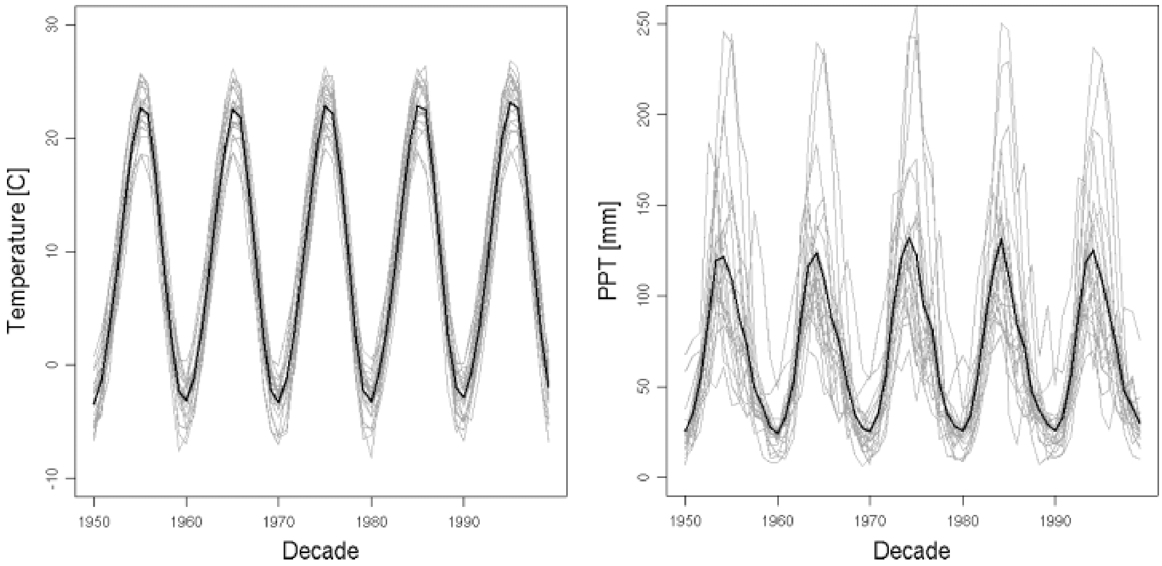

Figure 2. Temperature and precipitation intermodel variability (light grey) and ensemble mean (black) at point 1 for 1950–2000.

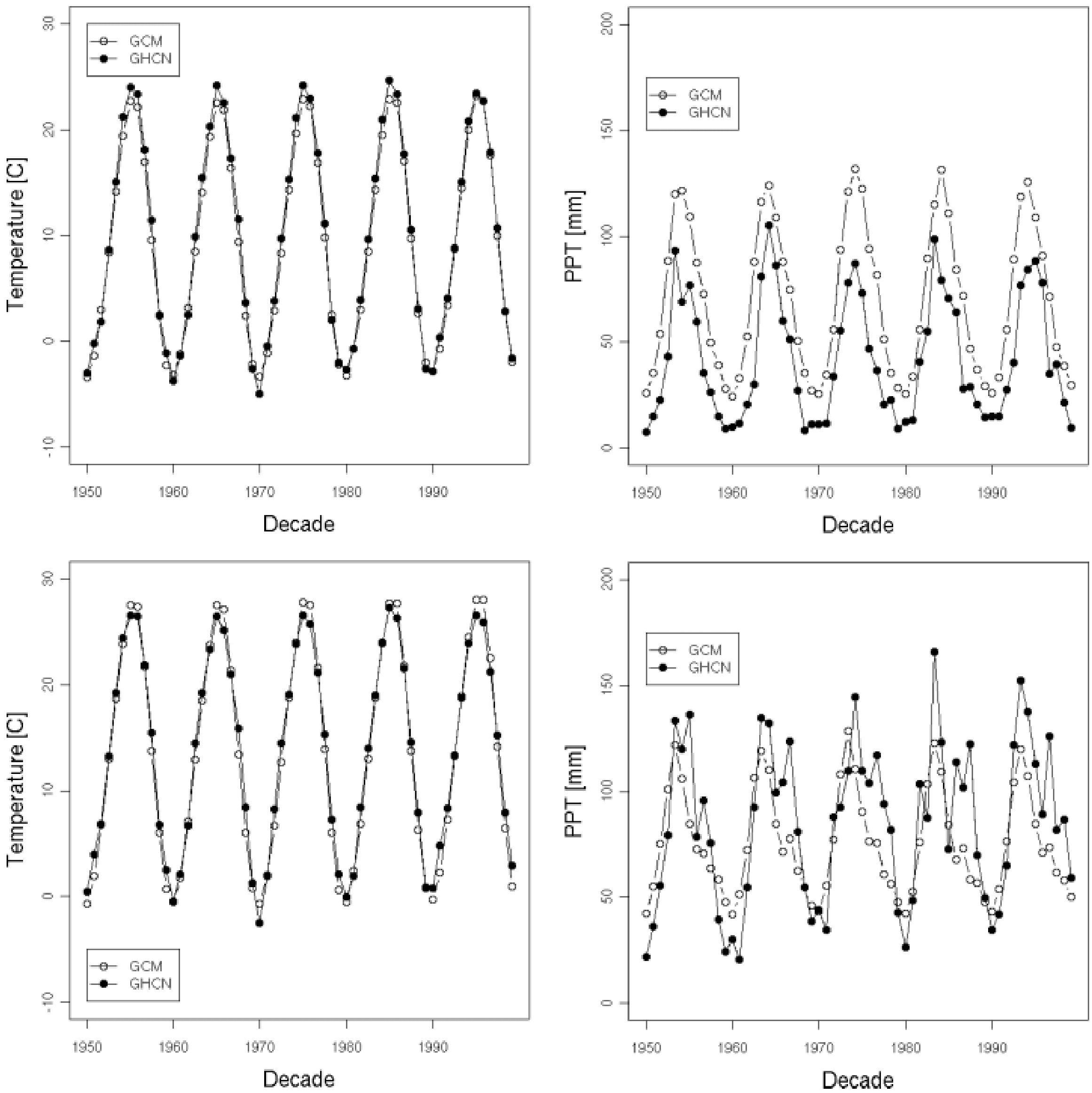

Figure 3. Comparison of ensemble mean global climate model output and Global Historical Climate Network for 1950–2000 for temperature and precipitation (Point 1 top, Point 6, bottom).

Table II. Comparison of monthly Global Historical Climate Network and ensemble mean global climate model output for 1950–2000. All slopes are significant at the $p < 0.05$ level.

Point	Precipitation		RMSE (mm)	Temperature		RMSE (C)
	Slope	r^2		Slope	r^2	
1	1.1615085	0.8932721	909	0.95583941	0.99538582	1.0112948
2	0.7919187	0.8429086	322	0.96111321	0.990856	1.0663241
3	0.6068054	0.7157585	427	1.0061186	0.99015711	1.0493043
4	1.0331864	0.809247	1144	1.0023816	0.99345731	1.4767391
5	0.7517395	0.7742958	356	0.99911581	0.99238609	0.8439416
6	0.5231561	0.6359778	614	1.0664531	0.99005011	1.2201517

RMSE, root mean square errors.

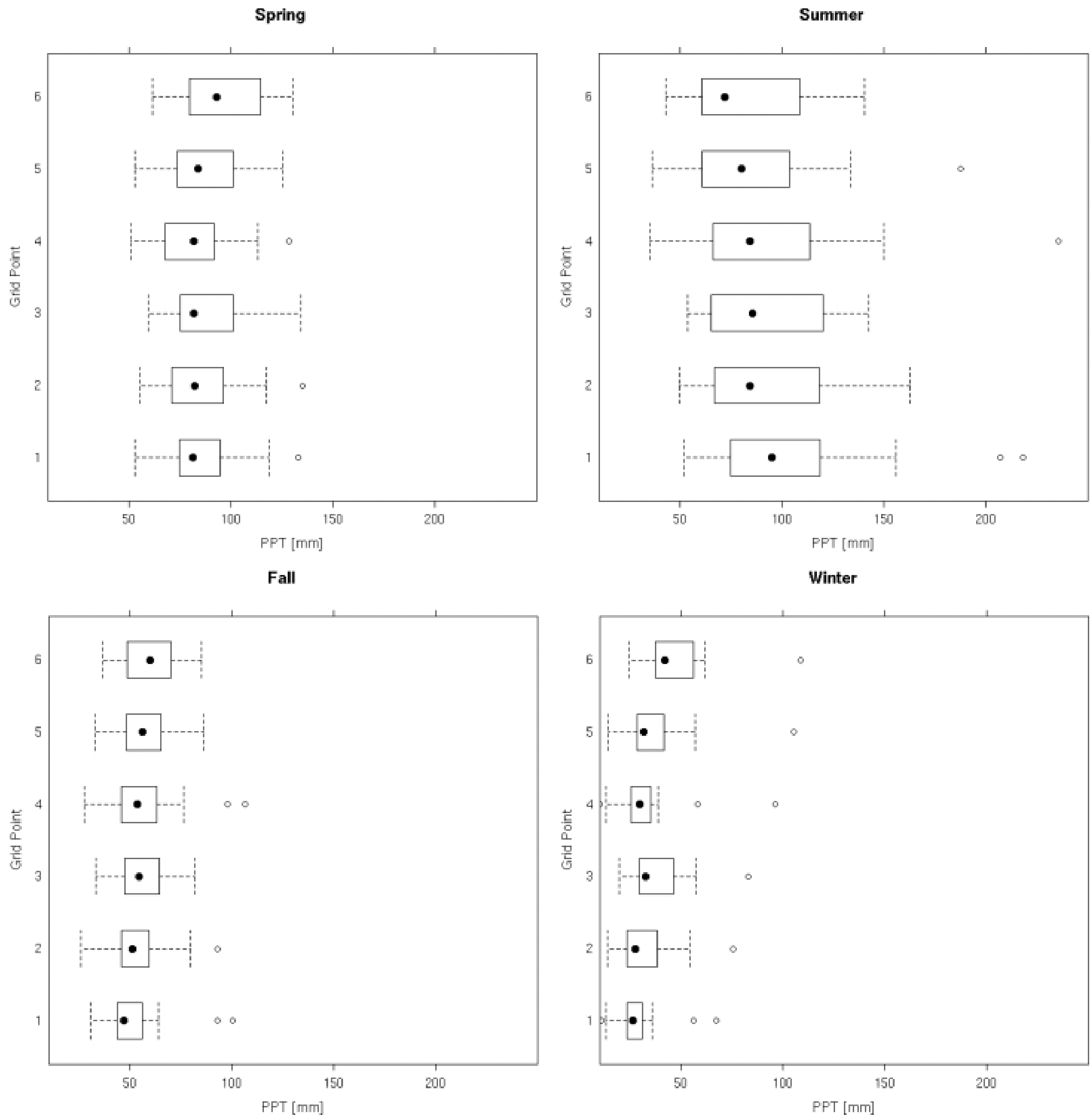

Figure 4. Seasonal precipitation distributions of mean absolute difference between the Global Historical Climate Network and global climate model output for 1950–2000 for each grid cell.

The distributions of linear slopes in seasonal temperatures are shown in Figure 7. All seasons show mean values between 0.01 and 0.02 °C/year (Table IV). All of the seasonal trends are significant ($p < 0.05$) for the ensemble mean GCM output. Along the southern edge (cells 4–6), there is a general trend of temperatures

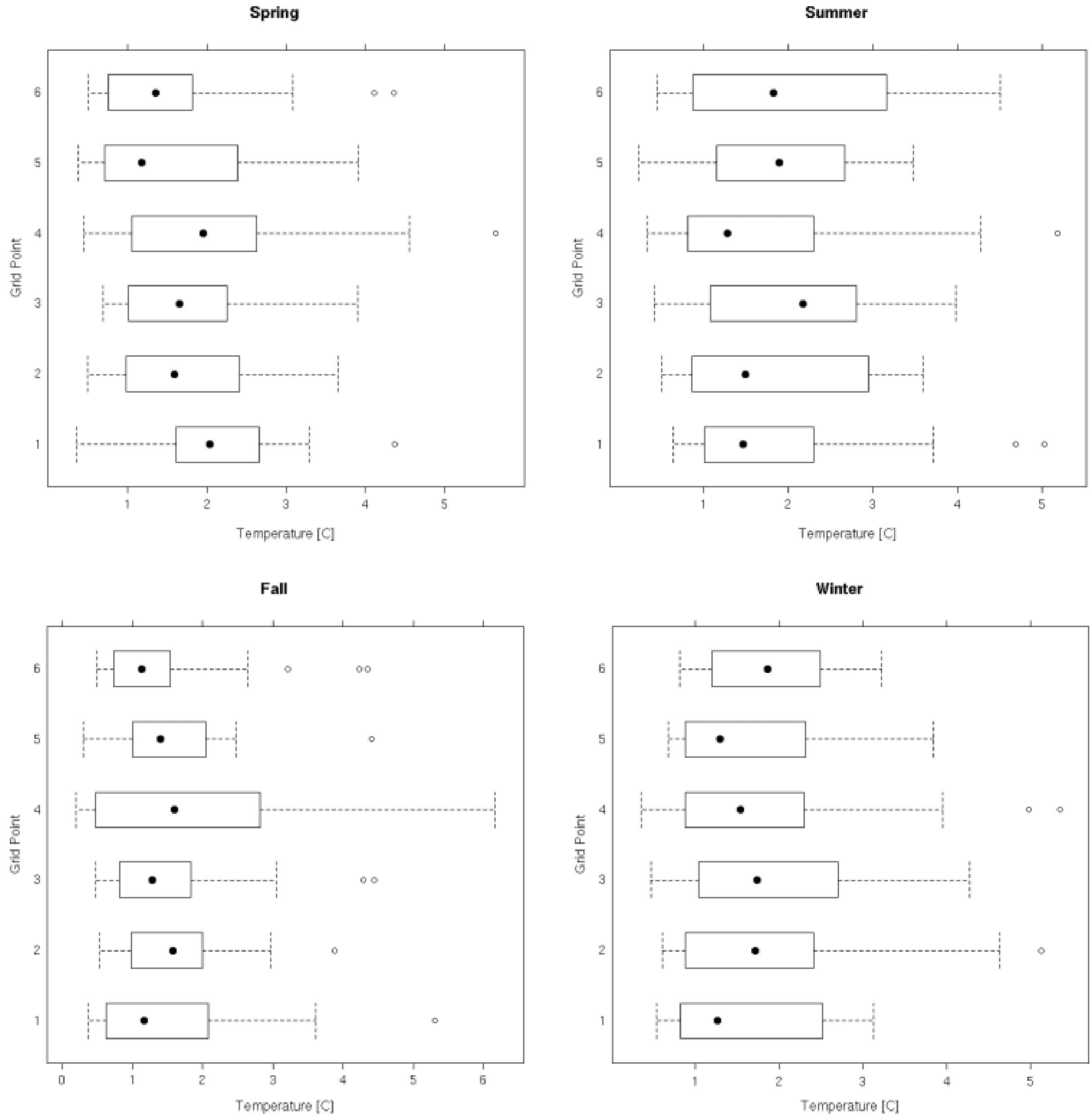

Figure 5. Seasonal temperature distributions of mean absolute difference between the Global Historical Climate Network and global climate model output for 1950–2000 for each grid cell.

increasing more in the western portions of the state for spring, summer and fall. In winter, this trend is reversed with a higher slope in the eastern portion of the state.

The modelled trends are generally larger than the observed trends (shown as triangles), particularly in the Fall when all of the observed trends are lower than the GCM trends. One possible explanation for the discrepancy concerning the Fall temperature trends may be the role of irrigation and land cover change in the region. This will be covered in more detail in Section 4. The observed Spring trends are slightly lower than the majority of GCM derived trends across the region, and (with one exception) the same is true in Winter. The Summer temperature trends generally fall within the majority of GCM trends.

4.2. Future trends in precipitation and temperature

Figure 8 shows an example of the intermodel variability for temperature and precipitation, in this case for grid cell 1 for the 21st century. Ensemble mean precipitation for this cell ranges from approximately 25 mm in the winter to about 125 mm in the summer. Temperature shows an increasing trend with time; particularly for winter and summer mean temperatures.

To examine the seasonal trends in the GCM output, box and whisker plots of the seasonal trends in precipitation between 2010 and 2100 are shown in Figure 9. Spring exhibits a clear west to east gradient, increasing from west (cells 1, 4) to east (cells 3, 6). Across the southern portions of the state, the southwestern grid cell (4) exhibits a negative mean trend, but the variability among models is large, while the eastern cell (6) shows

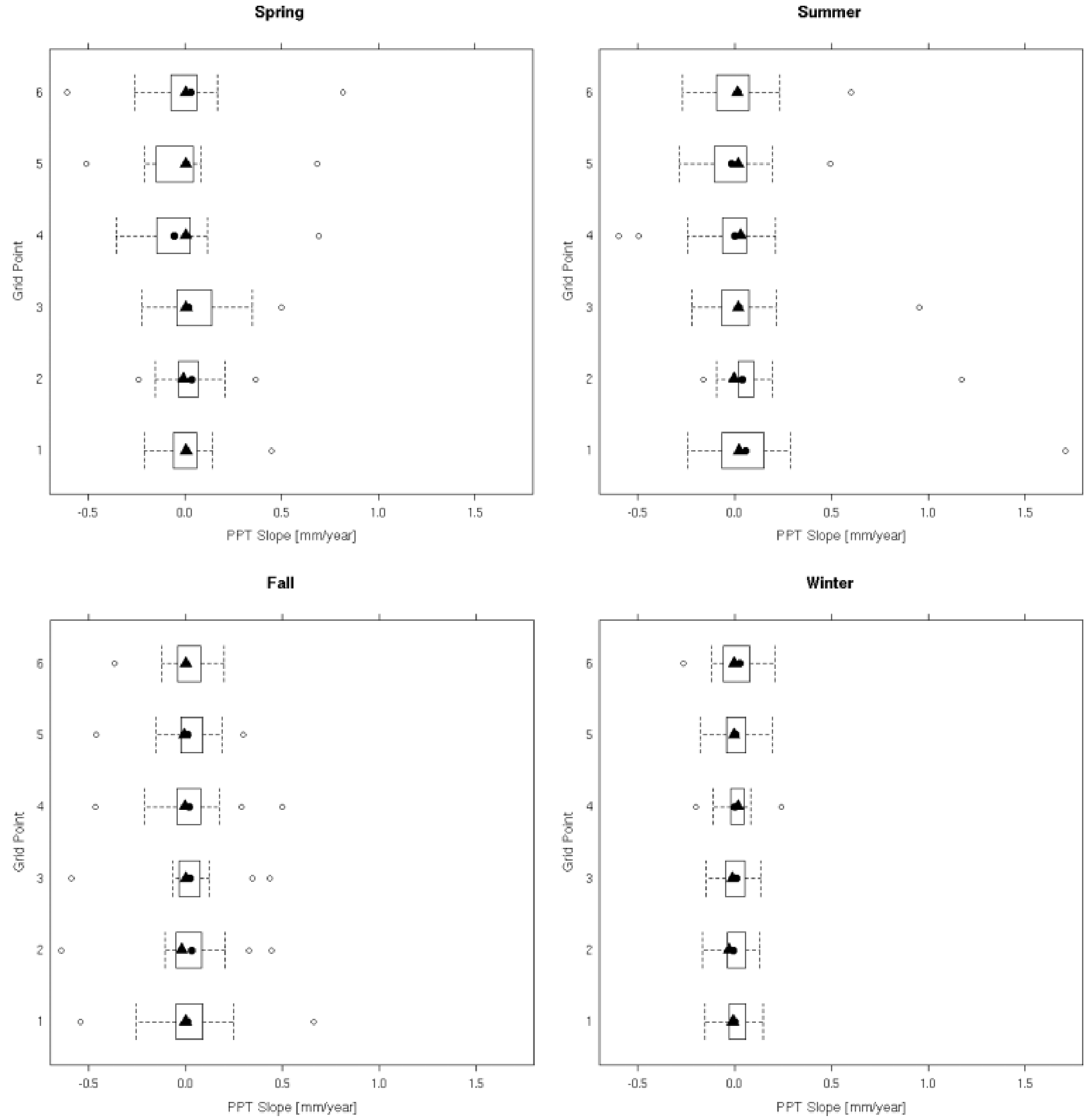

Figure 6. Distribution of seasonal slopes in global climate model precipitation (1950–2000) for each grid cell. Triangles denote observed trends.

a mean of approximately zero. Across the northern half of the state, the mean trend is approximately zero in the west to a slight increase in the east (Table III). Grid cells 2, 3 and 4 exhibit statistically significant trends for spring precipitation.

Summer precipitation exhibits the largest variance between models (Figure 9), but all cells except 4 (southwestern Kansas) exhibit statistically significant decreasing trends in the ensemble mean (Table III). Fall precipitation shows significant decreasing trends in all grid cells. Winter precipitation is generally increasing (all but southeastern Kansas) and is significant across the northern half of the state.

The ensemble mean of air temperature exhibits statistically significant increasing trends for all seasons in all grid cells (Table IV). Winter and spring increases are on the order of 0.035 to 0.04 °C/year. Summer and fall trends are higher, on the order of 0.042 to 0.048 °C/year, respectively.

The distributions of seasonal trends in temperature are shown in Figure 10 for 2010–2100. As with the 1950–2000 model output, there is no clear spatial organisation to the trends along either latitude or longitude. While there is seasonal variation in the mean value, the general range of model temperatures is relatively constant across season.

5. Discussion

For the period of 1950–2000, GCM output for air temperature matches observations extremely well (Table II). The observed trends from 1950 to 2000 in the region

Table III. Linear precipitation trends (mm/year) and associated r^2 values.

Grid Cell	Decadal		Winter		Spring		Summer		Fall	
	Trend	r^2	Trend	r^2	Trend	r^2	Trend	r^2	Trend	r^2
GHCN (1950–2000)										
1	8.54E-2	0.00	5.86E-2	0.02	2.37E-2	0.00	1.38E-1	0.01	1.22E-1	0.02
2	5.47E-2	0.00	−9.18E-2	0.02	1.76E-1	0.01	−2.74E-2	0.00	1.62E-1	0.01
3	−1.22E-1	0.00	−3.37E-2	0.00	−4.28E-2	0.00	−4.94E-1	0.04	8.20E-2	0.00
4	1.86E-1	0.01	8.74E-2	0.04	1.94E-1	0.02	2.68E-1	0.02	1.97E-1	0.05
5	3.11E-1	0.02	**2.27E-1**	**0.09**	**6.09E-1**	**0.10**	1.39E-1	0.00	2.69E-1	0.03
6	4.33E-1	0.04	**4.18E-1**	**0.11**	**6.54E-1**	**0.09**	4.31E-2	0.00	6.16E-1	0.05
GCM (1950–2000)										
1	1.86E-2	0.00	3.32E-3	0.01	1.70E-2	0.05	1.20E-1	0.27	2.00E-2	0.04
2	1.34E-2	0.00	−1.36E-3	0.00	2.63E-2	0.15	9.08E-2	0.26	2.45E-2	0.20
3	1.20E-2	0.00	7.88E-4	0.00	5.32E-2	0.45	5.82E-2	0.12	2.44E-2	0.22
4	−2.58E-2	0.00	2.36E-3	0.01	−4.34E-2	0.17	−4.94E-2	0.46	1.31E-2	0.03
5	−2.45E-2	0.00	−5.53E-3	0.02	−2.12E-2	0.04	9.47E-5	0.00	8.16E-3	0.02
6	−2.54E-2	0.00	8.71E-3	0.03	9.22E-3	0.01	1.23E-2	0.01	4.04E-3	0.01
GCM (2010–2100)										
1	−1.11E-8	0.17	**3.41E-2**	**0.74**	−1.56E-3	0.00	**−7.34E-2**	**0.65**	**−4.38E-2**	**0.65**
2	−9.08E-9	0.16	**2.38E-2**	**0.52**	**3.60E-2**	**0.46**	**−7.18E-2**	**0.62**	**−4.76E-2**	**0.72**
3	−4.99E-9	0.12	**2.37E-2**	**0.70**	**7.48E-2**	**0.82**	**−6.05E-2**	**0.53**	**−4.05E-2**	**0.46**
4	−1.69E-8	0.22	1.46E-2	0.28	**−6.06E-2**	**0.59**	−8.44E-2	0.44	**−4.79E-2**	**0.84**
5	−1.69E-8	0.23	3.56E-3	0.02	−9.68E-3	0.03	**−8.88E-2**	**0.61**	**−6.08E-2**	**0.81**
6	−1.70E-8	0.24	−6.16E-3	0.04	2.03E-2	0.06	**−8.64E-2**	**0.57**	**−5.49E-2**	**0.61**

GHCN, Global Historical Climate Network; GCM, global climate model.
Bold values indicate significant at $p < 0.05$.

are weak, whereas all of the GCM trends are significantly increasing temperatures over the same simulated time period. The precipitation also agrees well between the ensemble mean and observations, but not quite as well as the temperature; with few trends being significant for the observations and none for the model output. These trends agree well with the observed literature (e.g. Grundstein, 2008)

Overall, we have confidence in the model ensemble for simulating the Kansas climate. There are several potential mitigating factors that will complicate the agreement between the models and reality. One factor is that the GHCN station data may not accurately represent the true climate of the region due to site location (Pielke *et al.*, 2007) or general representativeness of the site (Pielke *et al.*, 2002). In addition, the act of kriging the station data can potentially induce error in the composite values.

Another factor that may decrease the agreement between the observations and model output is the representation of the land cover in the GCMs. In eastern Kansas, there has been a trend toward both increasing urbanisation as well as increased woody encroachment (Heisler *et al.*, 2003). These factors will contribute differently toward temperature trends through changes in surface radiation budget (albedo, heat capacity) and water cycling (evapotranspiration). In western Kansas, the dominant land use is agriculture, with a significant portion of this being irrigated (on the order of 25%). Generally, irrigation is not simulated in GCMs, preventing them from simulating climate impacts associated with this process (e.g. Moore and Rojstaczer, 2001). This means that the models also cannot simulate the resultant influx of atmospheric moisture following evapotranspiration. Irrigation will likely result in cooling (or reduce warming) in the GHCN observations over western Kansas, and could result in an increase in the eastern Kansas precipitation dependent on regional circulation patterns.

The 21st century simulations show temperature trends approximately double the increases simulated for the 1950–2000 period. All of these values are statistically significant. In addition, many of the precipitation trends are significant particularly for the summer and fall.

Thus, we can begin to examine the impacts on regional climate in Kansas from the multimodel ensemble mean temperature and precipitation seasonal trends. Based on the multimodel GCM simulations, the state will warm in all seasons. Winter temperatures will likely see a transition to above freezing mean temperatures by the end of the century (Figure 8). This will have a profound impact on the propagation of diseases in the region (IPCC, 2007 Report II chapter 5, section 5.4.1.4), perhaps even more so if this continues the observed trend of greatest increases in minimum temperatures (Robeson, 2004; Alexander *et al.*, 2006); something that will increase the costs of agricultural production. Winter precipitation will likely increase slightly also following observed trends (Garbrecht *et al.*, 2004; Grundstein, 2008, 2009).

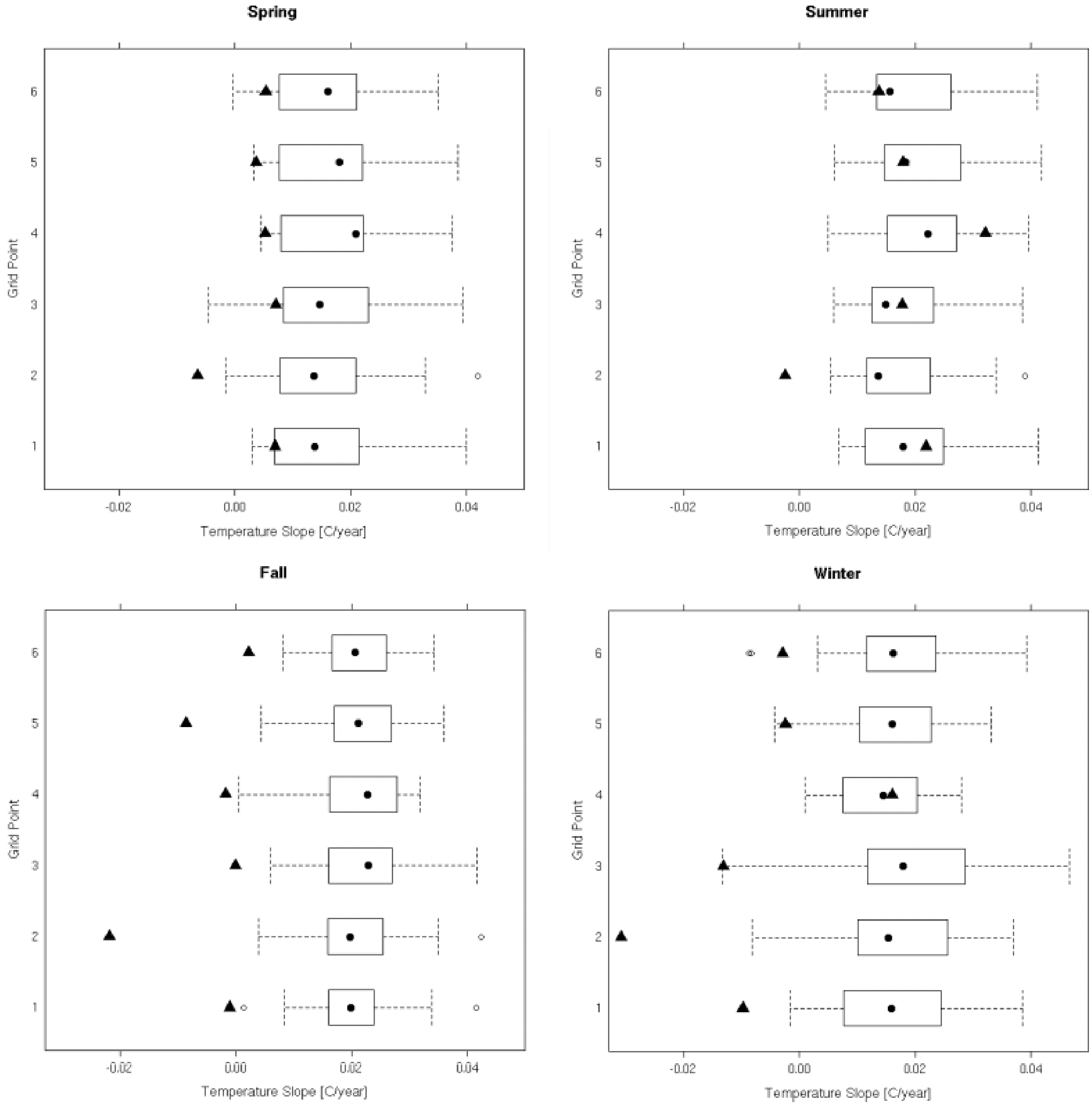

Figure 7. Distribution of seasonal slopes for global climate model temperature (1950–2000) for each grid cell. Triangles denote observed trends.

Spring precipitation in the western regions of the state will likely decrease. This, in combination with increased air temperatures, will likely result in a greater water deficit compared with current conditions. The decrease in precipitation becomes larger in the summer, which accompanied by the rising simmer temperatures will lead to sufficient increases in moisture deficits to likely affect agricultural productivity negatively. Fall temperatures increase by similar magnitudes as the summer, but the precipitation decreases at a lower rate. For agricultural production in the region, these changes over the growing season signify greater water requirements assuming crop types are not changed to species requiring less water. Although these results suggest a lengthening of the growing season and increases in growing degree days for the region, these potential improvements in crop productivity are offset by reduced water availability for the increased transpiration need (Sacks *et al*., 2007).

Water availability in western Kansas is not a certainty; therefore, adaptation by increasing irrigation rates may not be an option. The region already draws heavily from groundwater (the Ogallala Aquifer), where it has been shown that more efficient irrigation does not necessarily result in decreased depletion because of increases in the total area of irrigation (McMahon *et al*., 2003; Scanlon *et al*., 2005). Alterations in land use may also result in changing groundwater quality, primarily through increased chloride and nitrate concentrations (Scanlon *et al*., 2005). The combination of altering subsurface hydrology and precipitation events will likely have a negative impact on aquatic ecosystems in the region (Covich *et al*., 1997; Dodds *et al*., 2004).

Table IV. Linear temperature trends (°C/year) and associated r^2 values.

Grid Cell	Decadal		Winter		Spring		Summer		Fall	
	Trend	r^2	Trend	r^2	Trend	r^2	Trend	r^2	Trend	r^2
GHCN (1950–2000)										
1	4.48E-3	0.00	6.92E-3	0.00	2.19E-2	0.07	−1.13E-3	0.00	−9.83E-3	0.02
2	−1.54E-2	0.00	−6.47E-3	0.00	−2.51E-3	0.00	**−2.18E-2**	**0.09**	**−3.08E-2**	**0.14**
3	2.93E-3	0.00	7.11E-3	0.00	1.78E-2	0.04	−1.26E-4	0.00	−1.31E-2	0.03
4	1.29E-2	0.00	5.24E-3	0.00	**3.21E-2**	**0.13**	−1.77E-3	0.00	1.60E-2	0.04
5	2.64E-3	0.00	3.63E-3	0.00	1.79E-2	0.04	−8.60E-3	0.02	−2.37E-3	0.00
6	4.59E-3	0.00	5.35E-3	0.00	1.37E-2	0.03	2.19E-3	0.00	−2.88E-3	0.00
GCM (1950–2000)										
1	2.99E-2	0.067	**1.61E-2**	**0.88**	**1.53E-2**	**0.705**	**1.93E-2**	**0.852**	**2.03E-2**	**0.81**
2	3.15E-2	0.067	**1.66E-2**	**0.817**	**1.53E-2**	**0.639**	**1.86E-2**	**0.861**	**2.09E-2**	**0.78**
3	3.37E-2	0.067	**1.79E-2**	**0.828**	**1.55E-2**	**0.626**	**1.89E-2**	**0.882**	**2.18E-2**	**0.77**
4	2.97E-2	0.066	**1.48E-2**	**0.836**	**1.75E-2**	**0.774**	**2.22E-2**	**0.862**	**2.09E-2**	**0.82**
5	3.05E-2	0.065	**1.50E-2**	**0.78**	**1.64E-2**	**0.702**	**2.03E-2**	**0.854**	**2.12E-2**	**0.79**
6	3.13E-2	0.065	**1.56E-2**	**0.779**	**1.53E-2**	**0.666**	**1.92E-2**	**0.849**	**2.10E-2**	**0.76**
GCM (2010–2100)										
1	4.03E-2	0.131	**3.59E-2**	**0.995**	**3.49E-2**	**0.985**	**4.67E-2**	**0.981**	**4.27E-2**	**0.984**
2	4.16E-2	0.128	**3.82E-2**	**0.995**	**3.53E-2**	**0.986**	**4.73E-2**	**0.979**	**4.31E-2**	**0.983**
3	4.30E-2	0.125	**4.07E-2**	**0.994**	**3.62E-2**	**0.987**	**4.75E-2**	**0.978**	**4.35E-2**	**0.982**
4	4.06E-2	0.13	**3.44E-2**	**0.995**	**3.79E-2**	**0.982**	**4.77E-2**	**0.981**	**4.39E-2**	**0.985**
5	4.14E-2	0.128	**3.57E-2**	**0.995**	**3.67E-2**	**0.982**	**4.86E-2**	**0.978**	**4.42E-2**	**0.983**
6	4.18E-2	0.126	**3.64E-2**	**0.995**	**3.55E-2**	**0.985**	**4.89E-2**	**0.979**	**4.37E-2**	**0.983**

Bold indicates significant at $p < 0.05$

In terms of natural grasslands in Kansas, the increased temperature and decreased precipitation will likely result in an increase in C_4 grass species (Knapp *et al.*, 2001). In fact, this is already being observed at the Nelson Environmental Study Area, north of Lawrence KS, where C_4 grasses have increased in the last 5 years (Foster *et al.*, in press). When combined with the urbanisation and continued woody encroachment, the future for water cycling in the eastern portions of the state is uncertain.

A mitigating factor for the interactions between natural grasslands and woody encroachment will be the role of soil moisture. Using a regional climate model, we (Jones and Brunsell, 2009a, 2009b) have shown that the area experiences positive soil moisture–precipitation feedbacks. This implies that alterations to the precipitation regime will likely be exacerbated. One of the dominant factors that will likely determine the propagation of C_4 species in the region will be alterations to the timing of precipitation events. Since we are focusing on seasonal trends in precipitation, we are unable to examine the likely changes beyond seasonal magnitudes. However, changes in natural species composition will have agricultural significance due to the large amount of cattle and bison production in the state.

Future trends in precipitation and temperature will also be heavily influenced by changes in local land cover (Feddema *et al.*, 2005b). Urban heat island affects and accelerated runoff rates associated with urbanisation in eastern Kansas may become more significant. These will likely cause the temperature trends presented here to be low (assuming that current trends in population and urbanisation continue). Urbanisation is known to alter regional air temperatures (Oke, 1982), precipitation patterns (Rozoff *et al.*, 2003) and carbon cycle dynamics (White *et al.*, 2002). Again, these issues are not specifically addressed here, but are likely to exacerbate the local expression of the trends in the GCM output.

6. Summary

Understanding the impacts of future climate change in Kansas is important for agricultural and other socioeconomic sectors. To quantify what some of these impacts are, we examined seasonal trends in air temperature and precipitation patterns from 21 GCMs used in the IPCC AR4. To ascertain the performance of the models, we compared model output to kriged meteorological station data from 1950 to 2000. Then, the linear trends for the 21st century were examined.

Results indicate that temperatures are likely to warm in all seasons, with the largest trends being on the order of 0.04 °C/year in summer and fall. Precipitation is likely to increase slightly in winter and decrease in summer and fall. These changes have profound implications for both natural ecosystems and agricultural land uses in the region.

GCMs are a simplification of the natural world, and therefore many processes are either missing or are not adequately represented. However, many of the factors that are currently dominating local land–atmosphere

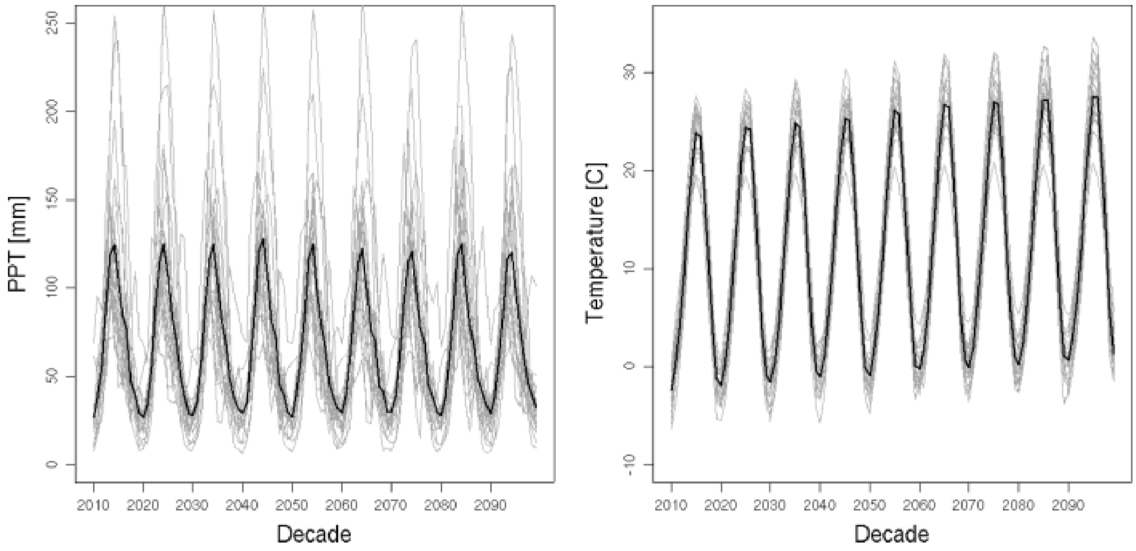

Figure 8. Intermodel variability for 2010–2100 for precipitation and temperature at point 1 (light grey), and ensemble mean (black).

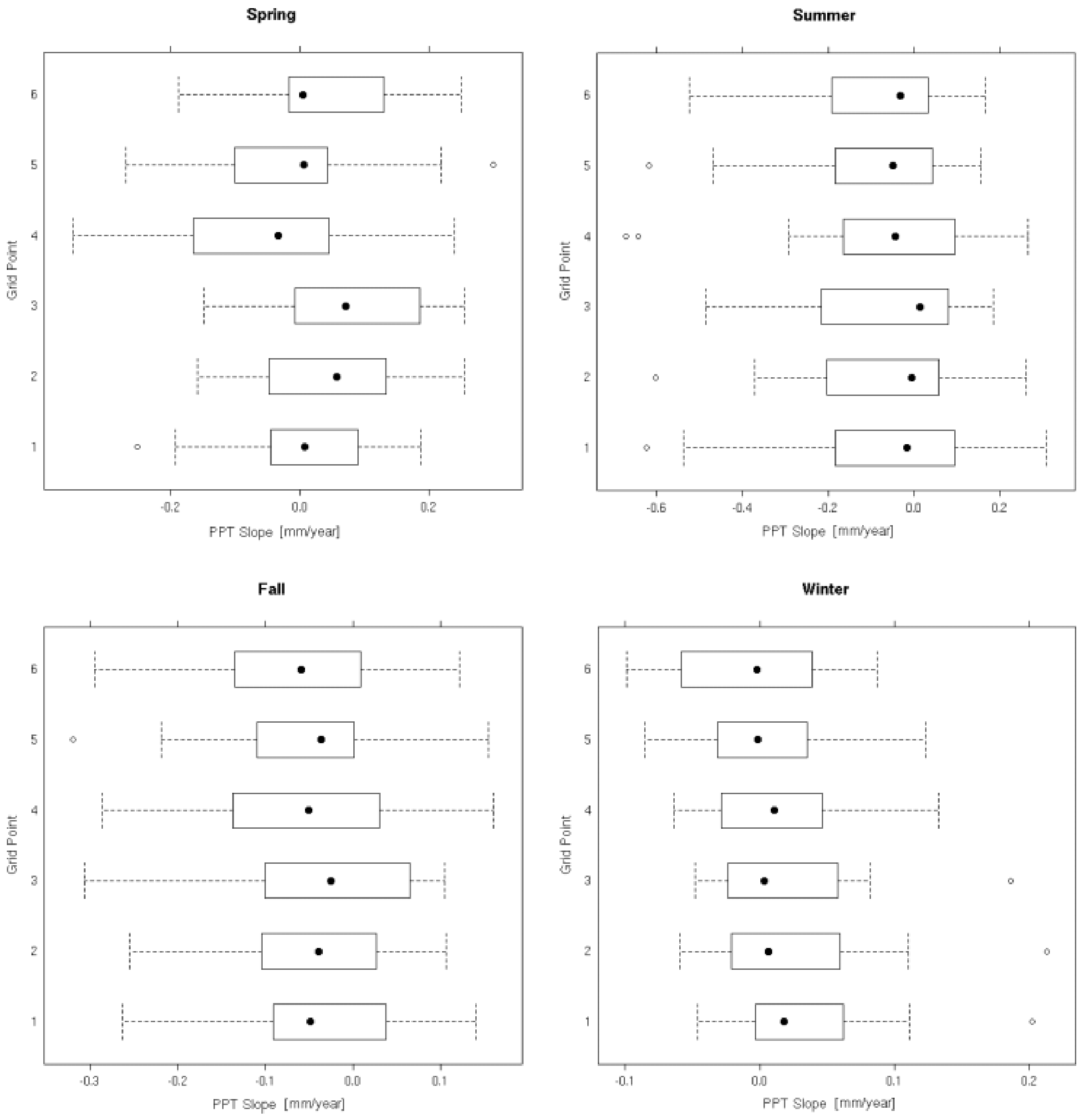

Figure 9. As Figure 6, for 2010–2090.

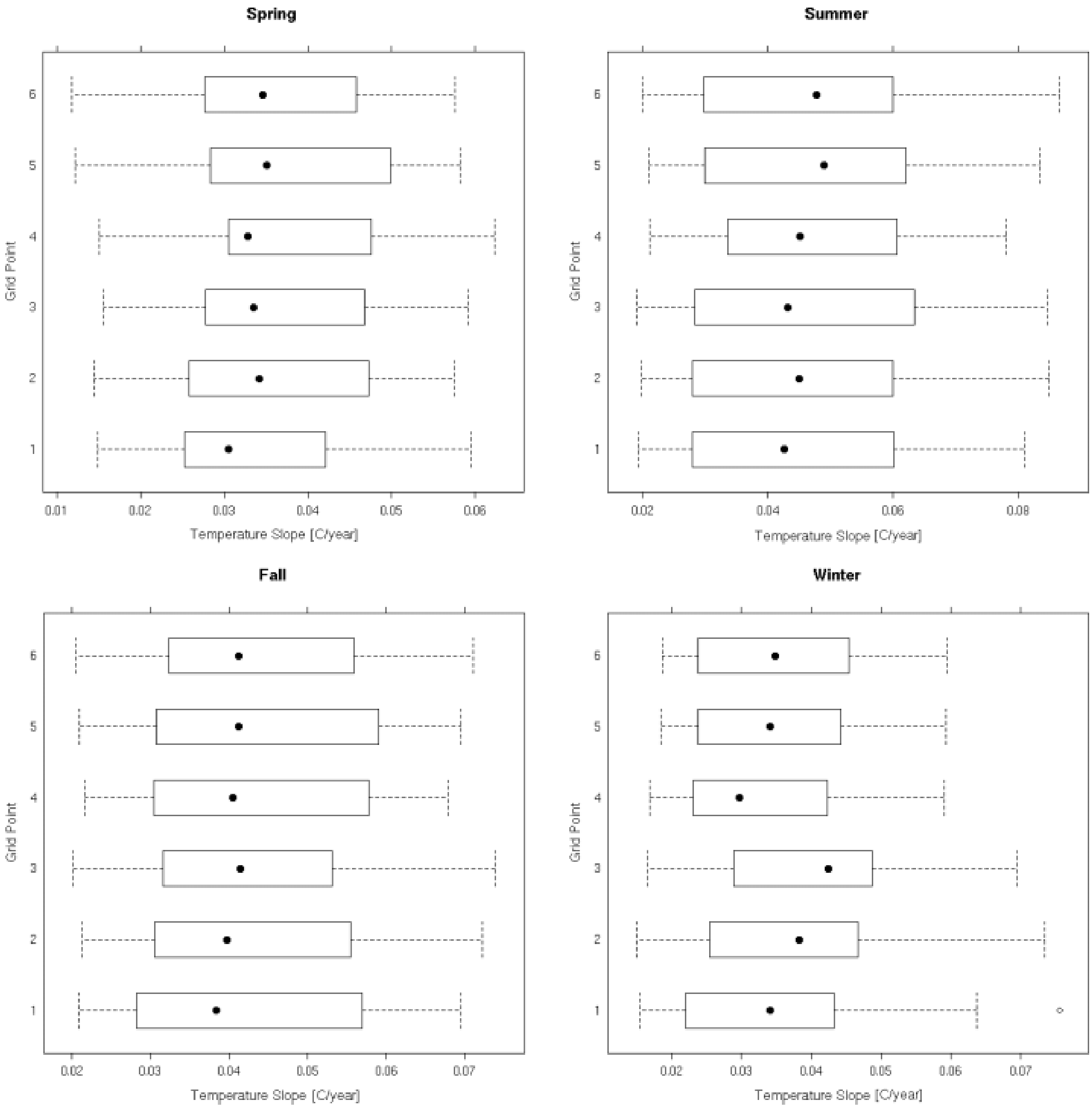

Figure 10. As Figure 7, for 2010–2090.

interactions in Kansas (e.g. urbanisation) are likely to enhance the predicted trends rather than offset them.

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