U.S. Regional Climate Change and Impacts 2010-2050: Temperature and the Energy Sector

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ABSTRACT

As climate science has advanced, enormous amounts of data have been collected by satellite and *in situ* platforms observing the Earth system and from computer models of this system. This paper utilizes a sub-set of this data to develop projections of surface temperature change for five U.S. regions and summarizes critical findings from past research reported in the scientific literature to provide an outlook for how these changes will affect the energy sector.

Key summary findings are the following. Over the past 100 years, global temperatures have risen on the order of 0.6 ºC. Seasonally the greatest warming has come in the winter months and regions closer to the Poles have warmed at a faster rate than regions closer to the equator. For the U.S. overall, a consensus of climate models predicts that winter temperatures will warm further by 0.8 ºC and that summer temperatures will warm further by 0.7 ºC by the 2040s. For both seasons the warming will be greatest in the central and western part of the country. By the middle of the century, U.S. northern regions will experience energy consumption decreases from space heating that exceed similar increases from cooling of buildings, and the reverse is true in the southern regions. By the 2040s, changes in patterns of energy consumption will be large, but averaged over the annual cycle and over the 48 contiguous states there will be an approximate balance with a net increase of 10% or less.

The uncertainties associated with the projected warming are large. The more specific the prediction, the smaller the effective degree of spatial and temporal averaging, and therefore the uncertainty is greater. It is anticipated that these uncertainties will be reduced as climate change science advances over the next several years.

1. Introduction

The global climate has been changing rapidly over the last century. Although a variety of records from past eras indicate that variations have always occurred, current rates of change are unprecedented. Most of the world's climate scientists have attributed these changes to human activities in the industrial era. In particular, the amount of carbon dioxide (CO_2) added to the atmosphere from the burning of fossil fuels like coal, oil, and natural gas, and from the destruction of once vast forests, has interacted with the Earth's outgoing infrared (radiant) energy to trap heat in the atmosphere and raise the temperature overall. Additional greenhouse gases (GHGs) have supplemented the heating due to CO_2. Nevertheless this is a complex system, and other factors, such as storage of heat in the oceans, have acted to mitigate some of the overall heating. The impact of GHGs is expected to continue in this century and beyond. Yet, the local effects are not uniform; atmosphere and ocean regional circulations can dominate regional temperature change.

Over the last several decades the science of climate change has progressed from a theory, to a search for signs of change, to the development of complex computer modeling of the doubled CO_2 climate, to increasingly definitive evidence of global warming, to climate forecasts for different regions over the next several decades to hundreds of years. While human activities contribute to climate change, a changing climate impacts our health, comfort, safety, environment, agriculture, industry, and transportation. As climate science has advanced, enormous amounts of data have been collected by satellite and in situ platforms observing the Earth system (that is, the atmosphere, ocean, ice sheets, and solid earth) and from computer models of the Earth system. This paper uses a sub-set of the collected data to develop projections of surface temperature change for five U.S. regions and summarizes critical findings from past research reported in the scientific literature to provide an outlook for how these changes will affect the energy sector.

Future projections of climate change are often made using complex models of the atmosphere and ocean that are based on known physical principles. When evaluating a number of such atmospheric models, from the world's principal weather centers and universities, the results, while not identical, typically have a great deal of commonality. Arguably, the average of such model projections provides the best estimate of climate trends. Additionally, from the spread of the model projections we have a measure of the uncertainty of our estimate. Impacts of the expected changes in temperature are important for a host of reasons for our society. How such changes impact the consumption and production of energy is fundamental in our economy. Of primary importance is the impact of the change in temperature on space heating and cooling of residential spaces.

2. Regional Temperature variability and projections

Temperature at the Earth's surface constitutes the climate variable upon which most global change measures have been focused, in part because it is critical to human habitability and to society's energy consumption. Therefore observations of the historical record of surface temperature as well as models simulating the likely future variations in temperature are important records in the evaluation of global change. That the mean temperature over the globe is increasing is documented in a series of reports by the Intergovernmental Panel on Climate Change (IPCC), a body sponsored by the World Meteorological Organization and the United Nations Environmental Panel, to evaluate scientific observations, research, and implications of climate variability.

Solomon et al. (2007) summarize the technical findings of the fourth and most recent report in this series. In what follows, unless otherwise noted, we will report temperature differences (increases or decreases) between a projected decadal average of a future period, usually the 2040s, and observed conditions during the 1990s. We will also report temperature trends in terms of °C per decade based on linear fits to observed or modeled data.

The variability in temperature, as well as in other important climate indices (c.f., Fig. 1.1 of IPCC, 2007), reveals clearly important changes over the last century or longer. For surface temperature, there is a general increase in the last 100 years of approximately 1 °C. Along with records noting the increasing positive trend in general, evidence is mounting that the warming is accelerating. Figure 1 shows that the last eight years plus 1998 are the nine warmest years within since the 1950s. To determine the global mean temperature (as in Fig. 1), measurements are weighted according to area. Similar averages are also often calculated separately for both hemispheres, for land and ocean regions, and for different seasons. It is shown that studying seasonal temperature trends is important to energy use because of varying implications of inhomogeneous temperature increases during different seasons for heating and cooling.

The change over the half-century 1950-1999 comes from temperature increases over many areas of the globe but in particular from the landmasses of the Northern Hemisphere as shown in Fig. 2. These trends are based on a linear in time fit to the gridded observation data set of the Climate Research Unit (University of East Anglia, U.K; Brohan et al. 2006). Whereas most of the regions in the world have had a positive temperature trend, we note that the largest increases are in the high latitude regions in and bordering the Arctic Ocean, particularly areas of Siberia and Alaska. The U.S. has had a positive temperature trend of between 0.5 and 1.5 °C, except that the region around the Gulf Coast shows a smaller warming. Alaska, as noted, has the largest U.S. observed increases, between 1 and 3 °C. Seasonally, the period of Northern Hemisphere winter, December-January-February (DJF), experienced the largest trends of the four seasons, according to the 50-year analysis.

The IPCC and others have concluded that it is probable that the trends are related to human causes, due principally to the amount of GHGs that have been injected into the atmosphere where levels are considerably higher than what they were in pre-industrial times.

The main GHG that has changed is CO_2, which is increasing due to the burning of fossil fuels, deforestation of large areas, and other causes. Other GHGs supplementing CO_2 are methane, nitrous oxide, chlorofluorocarbons, and ozone. CO_2 is approximately 36% higher than in pre-industrial times. From 1990 to 2006 alone the Annual GHG index recently introduced by the U.S. National Oceanic and Atmospheric Administration, shows that from 1990 to 2006 the radiative forcing by all long-lived GHGs has increased by 22.7%.

a. Modeling approach

Global Circulation Models, or Global Climate Models (GCMs), take the basic principles of physics, including conservation of momentum, mass, and energy, and use computer simulations to project the evolving coupled atmospheric and oceanic state in accordance with these accepted principles. Discretized equations are used to advance in time the quantities measuring the properties of the atmosphere or ocean. These properties, the temperature, winds or currents, and humidity or salinity, are defined at a fine three-dimensional grid network covering the global domain. The ocean is an extremely important reservoir of the energy and momentum, as well as

CO_2 for the atmosphere on climate time scales. Various intricacies are important in the modeling effort, including the role of moisture and clouds in the atmosphere.

The evolution of the model depends on atmospheric forcing, such as the incoming solar energy, as well as the chemical composition of the atmosphere itself. The GHGs interact with the flows of solar and thermal (i.e., infrared) energy, and change the heat balance of the atmosphere. Since the beginning of the industrial era, and more so in the recent era, significant amounts of CO_2 and other GHGs have been injected into the atmosphere principally as a result of human activities.

GCMs have been developed at several of the world's major weather centers, government laboratories and universities, including ones in the U.S., Japan, Russia, and Europe. These have been the basis for climate projections reported by the IPCC. Each GCM uses techniques that have been developed by their respective scientists but in many cases are based on the same antecedents and there is a risk that climate models share similar errors. As a result of uncertainties in the models and the data provided to the models, a spread of the projected quantities almost invariably exists. We use the distribution among the ensemble of model results to present the possible climate outcomes. Here a common result or a mean is the best estimate from the modeling approach as a whole. The spread amongst the models provides an estimate of uncertainty, a large spread reducing the confidence in the mean result.

We have accessed 11 coupled atmosphere-ocean model runs, all for a scenario in which 1% increase in CO_2 per year occurs, until the CO_2 concentration doubles; this is one of several IPCC scenarios that have been studied. These model results are from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al. 2007a, b). The models used are listed in Table 1. Since our analysis is based on a single GHG scenario, denoted **A1B**, uncertainties associated with future emissions of GHGs are not accounted for. The various scenarios as described in the IPCC Special Report on Emissions Scenarios (SRES, 2000; summarized on p. 44 of IPCC, 2007) cover a wide range of future economic, population, and technology projections. Scenario A1B describes a future with rapid growth, population peaking by mid-century and advanced technology with a balance of energy sources (Meehl et al. 2007).

To determine and evaluate the changes over the regions of the continental United States, we use an ensemble of such models to study the upcoming several decades until the middle of the 21st century. For projections of trends between now and mid-century, we divide the continental U.S. into five regions—the Northeast, South, Great Lakes, Upper Midwest and West—as depicted in Fig. 3, that are based on energy usage. The Northeast dominates the heating oil market. The Great Lakes and Upper Midwest are mostly heated with natural gas. In the South and West, air conditioning is the greatest energy concern. Note that in the West this energy demand is dominated by the large Southwestern cities.

For each model, we extracted the surface temperature at each model grid point in the U.S. region for each time period, and then assigned them to the five regions (Fig. 3) in which they are located: Northeast, South, Great Lakes, Upper Midwest, and West. The grid-point values were weighted by area, and then averaged within decades: 1990s (i.e., 1990-1999), 2000s, 2010s, 2020s, 2030s, and 2040s. Not all data was available for all models.

We chose the three winter months (December-January-February, or DJF) and summer months (June-July-August, or JJA), as the basis of the study, largely because these capture the extremes in space heating and cooling, the two major energy uses. Winter and summer are also the seasons showing the largest and smallest temperature increases during the latter half of the 20th century.

b. U.S. temperature trends and differences

As context, we first present in the lower panel of Fig. 4 the decadal trend (estimated 50-year change) from the observation data set of the Climate Research Unit. At the end of the twentieth century, the United States experienced warming across most if not the entire country. In the areas in the North Central U.S. in the winter months of December-January-February trends were typically between 1 and 2 °C (Fig. 3) while the June-July-August (JJA) season had a considerably smaller increase throughout the middle of the U.S. of -0.5 – 1.0 °C (Fig. 3). As we will show, this observed warming trend is predicted by the models to accelerate for the first half of the twenty-first century.

Results for the mean and range of the change in temperature between the 1990s and 2040s for the five regions and the U.S. as a whole, for both the DJF and JJA seasons, are given in Table 2. There is considerable spread around each of the means from the ensemble of models. However, treating the set of models as an ensemble, and determining their means, we find that all regions have an increasing trend for both seasons. The regional increases in temperatures for the 50-year period are all within the range of 0.5 to 1.2 °C. A more complete discussion of regional temperature increases and decreases follows in the next section.

For the 2040s and the U.S. region as a whole, the ensemble mean projection during the DJF season is 0.8 °C, with individual projections ranging from as low as 0.1 °C to as high as 2.1 °C. For the JJA season, the ensemble mean projection is an increase of 0.7 °C with a range of -0.4 and +2.3 °C. Fig. 5 shows the distribution of temperature trend for each decade. In Fig. 5, a great deal of decade-to-decade variability is seen in the individual time series of projected temperature.

To examine the regional distribution over the U.S. of projected warming in the two seasons, we first estimate the mean temperature change of the ensemble of models in the midseason months of January and July during the periods 2040-2049 and 1990-1999 in Fig. 6. The differences in both months show values highest in the south-central U.S. (Texas and the southern Great Plains) and the West. Values around 1.5 °F in both seasons are evident.

We then chose one of the models in the middle range of temperature increases to show the trends over the periods between 2040-2049 and 1990-1999 (Fig. 7). This is an example of how a single model may be similar to or different from the ensemble mean. Here we present the results in °C per fifty-year change. In both the DJF and JJA seasons, the largest trends of expected increase in this model are in the middle of the country, centering on the Great Plains. The maximum value for temperature trend in JJA was around 2.0 °C per half century, somewhat less than the 2.25 °C per decade for DJF. Away from the maximum situated over Kansas, the values reduce steadily. At the southeast Atlantic coast for example, both seasons have values closer to 0.8 °C per half century. Comparing Figs. 6 and 7, we see that the mean of the ensemble exhibits smaller spatial scales than the individual ensemble member. Each ensemble member has relatively smooth spatial patterns, but since these patterns do not line up from one model to the next, the mean contains smaller scales.

c. Regional implications

The U.S., a country with a broad geographical spread and large variety of climatic types, is affected in different regions by a variety of external forcing factors. Oceanic circulations, prevailing wind patterns, and proximity to water bodies all affect different parts of the country in different ways. This climatic variability affects how climate change in the upcoming decades of the 21st century will manifest itself in different regions of the country, as described in the following subsections. Nevertheless, temperature increases are expected in all regions at all future times examined. Results are plotted and presented in most detail for temperature changes through the 2040s, but some results for projected changes in precipitation over the next 100 years are also summarized, taken from other studies to provide a more complete picture of anticipated regional climate change.

For comparison we have examined the results from an earlier set of models that were the basis of the study by the U.S. Science Climate Program, in particular the set of model results cited by Ruosteenoja et al. (2003) for the period from 2000-2050. Analyses for three regions, Western, Central and Eastern U.S. (but including parts of Canada) for the first part of the century have DJF means equivalent to 1.6, 1.6, 1.8 °C, and for JJA 1.8, 1.8, 1.6 °C, respectively (USCCP 2008). These values are larger than those in Table 2 for two reasons. First, the Ruosteenoja regions include parts of Canada, closer to the pole, where more pronounced climate change warming is expected. Second, the Ruosteenoja results are based on earlier, somewhat less highly resolved atmosphere-ocean coupled models, which had the physics and resolution that was state-of-the-art prior to 2002.

1) NORTHEAST REGION

For winter temperatures in the 2040s, the ensemble mean projection is an increase of 0.7 °C. However, the individual projections range from a decrease of 0.8 °C to an increase of 2.6 °C. Note that individual models project fluctuations in the intervening decades rather than a steady monotonic increase in temperature (Fig. 8). Results for summer are similar. For summer temperatures in the 2040s, the ensemble mean projection is an increase of 0.7 °C with a range of –0.9 to +2.3 °C.

Other studies indicate that the number of hot days will also increase. By 2100, most New England cities are likely to experience more than 60 days/year with summer temperatures above 90 °F (32 °C), including 14 to 28 days above 100 °F (38 °C). With regard to precipitation, as winter temperatures increase, more precipitation will fall as rain and less as snow. Additionally, late summer and fall droughts are forecast to increase significantly (Frumhoff et al., 2007).

2) SOUTH REGION

For winter temperatures in the 2040s (Fig. 9), the ensemble mean projection is an increase of 0.7 °C. The individual projections range from a decrease of 0.3 °C to an increase of 2.2 °C. For summer temperatures in the 2040s, the ensemble mean projection is an increase of 0.7 °C with a range of –0. to +1.9 °C.

Different models show different changes in precipitation over the next 100 years. The Southeast is currently the wettest region of the contiguous U.S. In the long term, some models, in particular the Canadian model, simulate a 10% reduction in annual average precipitation by 2090, while other models show a nearly 20% increase. Depending on which model is consulted, the Southeast may or may not remain the wettest region of the U.S. (Burkett et al., 2001).

3) GREAT LAKES REGION

For winter temperatures in the 2040s (Fig. 10), the ensemble mean projection is an increase of 0.8 °C. The individual projections range from a decrease of 0.4 °C to an increase of 2.6 °C. For summer temperatures in the 2040s, the ensemble mean projection is an increase of 0.7 °C with a range of –0.8 to +2.5 °C.

Precipitation amounts are likely to increase 10 to 30% across much of the region, with associated increases in both the frequency and intensity of precipitation events. Increased evaporation and lower soil moisture levels throughout the region, combined with greater mean precipitation and increased rainfall intensity, is expected to lead to increased flooding (Easterling and Karl, 2001).

4) UPPER MIDWEST REGION

For winter temperatures in the 2040s (Fig. 11), the ensemble mean projection is an increase of 1.0 °C. The individual projections range from a decrease of 0.4 °C to an increase of 2.4 °C. For summer temperatures in the 2040s, the ensemble mean projection is an increase of 0.6 °C with a range of –1.5 to +2.4 °C. The range for summer is very large. In fact, the 2040s are actually projected to be cooler than the 2030s, but would not be if the one extreme cooling projection were omitted.

For precipitation, earlier estimates showed some increases in the western Plains, along the Rocky Mountains, with the overall average annual precipitation increasing by at least 13%. This increased precipitation will occur in more intense rainfall events, particularly in the southern Plains. Even though rainfall will increase on average, it will not be uniform and because some areas will become drier and everywhere temperatures will be warmer, there will be more intense droughts especially in the lee of the Rocky Mountains where precipitation is predicted to decrease (Joyce, 2001; Schubert et al., 2008).

5) WEST REGION

For winter temperatures in the 2040s (Fig. 12), the ensemble mean projection is an increase of 1.1 °C. The individual projections range from an increase of 0.1 °C to an increase of 2.5 °C. For summer temperatures in the 2040s, the ensemble mean projection is an increase of 0.7 °C with a range of –0.4 to +2.6 °C. Note that the uncertainty for the West region is less than for the other regions.

Models show increased precipitation particularly in winter over California, but drying over parts of the Rockies. Projected annual precipitation changes range from a small decrease (about 7%) to a slightly larger increase (up to 14%) through 2050 and from nearly 0% to up to 50% through the 2090s. While precipitation is expected to increase, so are fires. It is projected that large wildfires will increase10%-40%, with increases as high as 90% in Northern California (Smith et al., 2001).

3. Impacts of temperature changes

Of all the weather elements that impact the way we live and do business—temperature, humidity, precipitation, wind—temperature is most directly related to our heating and cooling needs. Energy required for heating and cooling, as well as for providing hot water, will be impacted as climate changes. Besides direct heat exchange, there are other economic sectors, including transportation and agriculture, in which temperature changes directly impact the amount of energy consumed. Production of energy is also affected in multiple ways by temperature changes. Finally there will be many indirect effects on society because the earth system contains many interacting sub-systems with multitudes of feedbacks—some positive, some negative —operating on a wide range of space and time scales.

a. Energy usage for heating and cooling

Estimates are that 26 Quads (1 Quad = 1 Quadrillion BTUs or British Thermal Units) of energy will be delivered to residential and commercial buildings in the U.S. by the 2030s (USCCSP, 2008). Changes in climate that imply warming will reduce the energy needed for space heating overall in residential and commercial settings. This impact is most important wherever significant heating is required, peaking in the colder northern climate zones of the country. Conversely, the air conditioning that is in use throughout the U.S. during warm weather will demand more energy as temperatures warm.

Whether expected temperature increases will produce an overall net increase or decrease in energy consumption relates to the particulars of a region. The proportional increase or decrease in fuel used in space heating depends in part on the particular energy sources or fuels. Overall, a greater proportion of fuel oil will be saved by the effect of temperature change on heating than for other fuels since fuel oil is basically used only for heating while gas and electric are used for many purposes. For the increase in energy for space cooling used during ambient temperature increase, the dependence of the zone on amount of space cooling generally in use is important. In parts of the country, especially the northern zone or in a maritime city like San Francisco, air conditioning is less prevalent than others. In such locations, increases in the summer temperature will not only raise energy use among people who already use space cooling, but it will lead others to cool their residences when they may not previously have done so. In this case, the impact of an increase in temperature will have a higher proportional effect.

The impact of temperature changes in the regions for space cooling and heating was analyzed by Hadley et al. (2006) for the period through the 2020s based on the Parallel Climate Model-Integrated Biosphere Simulator (Washington et al., 2000), and estimated population and energy statistics from the U.S. Department of Energy. Figure 13 shows results from the Hadley et al. (2006) low temperature change global warming scenario fit to our five regions in terms of energy changes for cooling, for heating, and the net increase in energy usage. Their low temperature change scenario is the one most consistent with our model results. It can be seen that South and West regions have energy increases for cooling larger than energy increases for warming, whereas the Northeast and Great Lakes regions have more energy saved for heating than expended for cooling. The Upper Midwest is roughly in balance with small differences. Overall, for the U.S. approximately 5% more energy will be needed for space cooling and heating combined. We estimate this amount to double by mid-century.

Overall in the U.S., according to Scott et al. (2005), a reduction between 4% and 20% in the demand for residential heating was projected given an expected mean temperature increase in the range between 0.4 and 3.2 °C. By the decade of the 2040s we have projected an overall increase of 0.8 ºC in the winter months in the U.S., according to the ensemble of GCMs; our result concurs in this regard with the earlier results of Rosenthal et al. (1995). Here we have a reduction by about

10% in the space heating requirements of the U.S. Based on 0.8 ºC of warming in the winter, costs for heating of commercial buildings will decrease, but the amount of energy savings will depend on fuel type. Decreases are projected of about 3% for electricity and natural gas, but overall, in areas where fuel oil is prevalent, a reduction up to 12% is anticipated (Mansur et al., 2005). These impacts may vary with region, particularly in the Northeast, which has many older, less efficient commercial buildings,

Balancing the heating mentioned above, the increased surface temperatures will, of course, increase the amount of cooling necessary to reduce the temperature to the same level during periods of the year needing air-cooling. In the U.S., nearly all air conditioning is accomplished using electricity, which is produced by a variety of different energy sources. Increases in air conditioning have a direct impact on peak electricity demand (e.g., Franco and Sanstad 2006 for California). Another factor here is the increase in energy needed in air conditioning due to higher humidity. Warmer air can hold more absolute moisture, and when moisture is removed from the air, energy is used to condense the water vapor in addition to cooling the air, representing a nonlinear relationship between the amount of energy needed for air-cooling and the increase in ambient temperature (Gatley, 2005). As a proxy for humidity, precipitation was used in the study of Mansur et al. (2005); in the average range of values, they noted that a one-inch monthly increase in rainfall would lead to a 7% increase in electricity usage

Again, the air-cooling requirements can be separated into residential and commercial spaces. In residential spaces, Scott et al. (2005) estimated that an increase of 0.4 to 3.2 °C summer temperatures results in a corresponding 8 to 39% increase in national annual cooling energy consumption in residential units. Our measure of mean summer increase by 2040 from the ensemble of models is 0.7 °C, equivalent to approximately a 12% increase in energy from air conditioning.

Much of the industrial consumption of energy is not related to the ambient temperature, with the obvious exceptions of heating and cooling of the buildings. Estimates are that only 6% of the industrial use of energy is related to space conditioning (EIA, 2002). Given the studies cited here, a mean increase in temperature in the U.S. of 0.7 °C will create approximately an increase of 0.6 to 0.9% in energy used for air-cooling in commercial buildings.

On balance, increased use of energy due to air conditioning in buildings throughout the U.S. can exceed the decreased use due to heating, according to some studies, particularly in the southern areas. In the next thirty years, there will be roughly a balance in the amount of energy used. An increase of 0.8 °C will project onto a roughly 15% increase in cooling, assuming the relationships in Scott et al. (2005).

Nationally, we can scale the results we found for the U.S. as a whole to estimate the overall changes in energy usage by region of space heating and cooling, based on the ensemble of model results we developed. We can also to estimate the situation in each region based on the studies and methodology in Scott et al. (2005). For example, for the Northeast, models shows a 0.7 ºC increase in both DJF and JJA, marginally less than the 0.8 and 0.7 ºC increases found for the whole U.S.

As noted, domestic hot water will require less energy for heating, and this will occur in all seasons and all regions. The amount of energy required to raise water temperature from 50 ºF and 120 ºF, (10 °C and 49 °C) a typical scenario, will be reduced by approximately 2%, given that increases in air temperature are mirrored in the input water temperatures.

Our projection is that the overall energy use for space heating and cooling will increase by about two Quads of energy by the 2040s (Fig. 13), almost 10% of the 26 Quads to be used for space heating and cooling in the U.S. Of course, a number of more energy efficient technologies are being developed in the interim that can dramatically reduce the energy needed in many areas, including space heating and cooling, transportation, industry and agriculture. Also, southward population shifts that are occurring now, if continued, will lead to greater overall energy usage since the regions using more energy as temperature increases have faster growing populations.

4. Conclusion

GHGs are the major, widely accepted forcing of global warming, and temperature changes from greenhouse gas forcing will be greatest at higher latitudes. Warming in the 20th century is now known to be greater than initially thought. The annual temperature over the U.S. has actually increased the most in the very recent years, showing a warming acceleration. When a network of stations was examined in the Northeast, warming was found at all but 2 of the 73 stations (Trombulak and Wolfson, 2004). For the globe, even if increases in GHGs had been stopped at year 2000, we are already committed to 0.4-0.6 °C (depending on model) more global warming by year 2100 compared to 0.6°C of warming for the 20th century (Meehl et al. 2005; IPCC 2007) while for the US those values are higher.

We have determined that, based on the average of a set of complex atmospheric model projections, the temperature will increase in the United States in each of its regions throughout the first half of the twenty-first century in both winter and summer. The spread in the set of models indicates a substantial uncertainty in the average amount. Space heating energy requirements will be reduced and air cooling requirements will be increased in all regions of the United States, though the net effect will be energy savings in the North and energy increases in the South and West. Overall, we estimate future energy consumption for space heating and cooling to increase for the U.S. by up to 10% by the 2040's. Temperature increases impact a number of other activities including energy production by power plants, hot water heating, transportation, and demand for electricity.

Though the projected rise in temperatures that we note here have particularly strong impacts for energy, land use, ecology, and the overall economy, these are not the only factors that may be projected to occur in a climate-changed world. Other quantities of note are increases in sea level, storminess and the water cycle. Energy facilities over low-lying areas, including power plants in Florida and elsewhere, and refineries in Texas will be greatly impacted by changes in sea level by mid-century. Increased storminess will additionally impact offshore oil platforms in the Gulf of Mexico. Cooling water supplies for power plants will be affected by changes in the hydrological cycle. Areas in the Western U.S. and elsewhere may be especially affected by changes in the hydrological cycle because the expected precipitation changes may amplify the impacts of social and population changes.

Other economic sectors upon which climate change will have dramatic impacts in the next half-century are transportation and agriculture. Fundamentally, all trends in the different sectors put our society at risk economically. National security risks may also increase as societies around the world are subjected to climate change stresses. It is critical that all such projections be evaluated carefully at the current time as they have great economic and political consequences.

All climate change projections, and hence all climate change impacts, have some degree of uncertainty. Further, many of the elements of weather that make up the climate have large variability. Uncertainties in one aspect of climate science—how raindrops form—can propagate and amplify through the earth system feedbacks to affect many other phenomena—soil moisture, river flooding, etc. Not only are there uncertainties in the input scenarios to the climate change analysis methods and in the climate models, there may be structural uncertainty in the analysis methods and models themselves. In our analyses even for a well-resolved parameter—surface air temperature—we find large uncertainties for regional projections. Improvements to reduce the model component of the uncertainty are anticipated, but prediction of GHG scenarios remains a major challenge.

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Table Legends:

Table 1. Global Circulation Models that produced projections aggregated here.

Table 2. Model projections of the mean and range (maximum and minimum) of the differences between the 2040s and the 1990s. A t-statistic for the ensemble of differences is also presented. For reference, one-sided t-tests with 9 degrees of freedom are significant at the 90, 95, and 99% level if the t-statistic exceeds 1.383, 1.833 and 2.821 respectively.

Figure Legends:

Figure 1. Annual average global surface temperature anomalies relative to the 1951-1980 mean. Data source is the NASA GISTEMP dataset (Hansen et al. 1999).

Figure 2. Trends in annual average surface temperature (1950-1999). These trends are based on a linear in time fit to the gridded observation data set of the Climate Research Unit (University of East Anglia, U.K.) CRUTEM3 land-surface temperature data set (Brohan et al. 2006). Units are °C/50 years.

Figure 3. The five regions of the U.S. considered in this study.

Figure 4. Observed trends in seasonal average surface temperature (1950-1999). As in Fig. 2, but for the U.S. for a) winter and b) summer.

Figure 5. Temperature change for an ensemble of climate models for the entire U.S. The left panel is for DJF and the right panel is for JJA. The ensemble mean is plotted in thick plot lines with diamonds plotted at each decade. The ensemble distribution is shown as a boxplot for each decade. In Fig. 5 and similar figures, a boxplot is displayed for each decade. The boxplot summarizes the key characteristics of the distribution of projected temperature changes. The box itself encloses the data in the 25th to 75th percentile. The median is shown as a thick horizontal bar inside the box. The whiskers extend to the extreme values. The actual time series for each model are plotted as light grey lines.

Figure 6. Ensemble mean trends over the period between the 2040s and 1990s for the U.S. for a) winter and b) summer. The ensemble mean 50-year differences for January and July are shown.

Figure 7. Single model trends over the period between the 2040s and 1990s for the U.S. for a) winter and b) summer. Shown are the trends in ºC/50-years for 3-month seasons.

Figure 8. Temperature change for an ensemble of climate models for the Northeast region as in Fig. 5.

Figure 9. Temperature change for an ensemble of climate models for the South region as in Fig. 5.

Figure 10. Temperature change for an ensemble of climate models for the Great Lakes region as in Fig. 5.

Figure 11. Temperature change for an ensemble of climate models for the Upper Midwest region as in Fig. 5.

Figure 12. Temperature change for an ensemble of climate models for the Western region as in Fig. 5.

Figure 13. Projected changes in energy required for heating and cooling, and the net changes, as departures from a current case for temperature increase scenarios to 2025. Positive values correspond to increased energy usage. (Based on the low temperature change scenario in Hadley et al., 2006.)

TABLES

Table 1.

Abbreviation	Center name	Country
BCCR	Bjerknes Center	Norway
CCCMA	Canadian Center for Climate	Canada
GFDL	NOAA Geophysical Fluid Dynamics Laboratory	US
GISS	NASA Goddard Institute for Space Studies	US
IAP	Institute of Atmospheric Physics	China
INMCM	Institute of Numerical Mathematics	Russia
MIROC HI RES	Meteorological Institute	Japan
MIROC MED RES	Meteorological Institute	Japan
MIUB	Meteorological Institute of the University of Bonn	Germany
MPI	Max Planck Institute	Germany
NCAR	National Center for Atmospheric Research	US

Table 2.

Region	DJF Mean	DJF Range	t-statistic	JJA Mean	JJA Range	t-statistic
Northeast	0.7	-0.8 – 2.6	2.1	0.7	-0.9 – 2.3	2.2
South	0.7	-0.3 – 2.2	2.9	0.7	-0.3 – 1.9	2.4
Great Lakes	0.8	-0.4 – 2.6	2.7	0.7	-0.8 – 2.5	2.3
Upper Midwest	1.0	-0.4 – 2.4	4.0	0.6	-1.5 – 2.4	1.5
West	1.1	0.1 – 2.5	4.3	0.7	-0.4 – 2.6	2.4
CONUS	0.8	0.1 – 2.1	3.6	0.7	-0.4 – 2.3	2.3

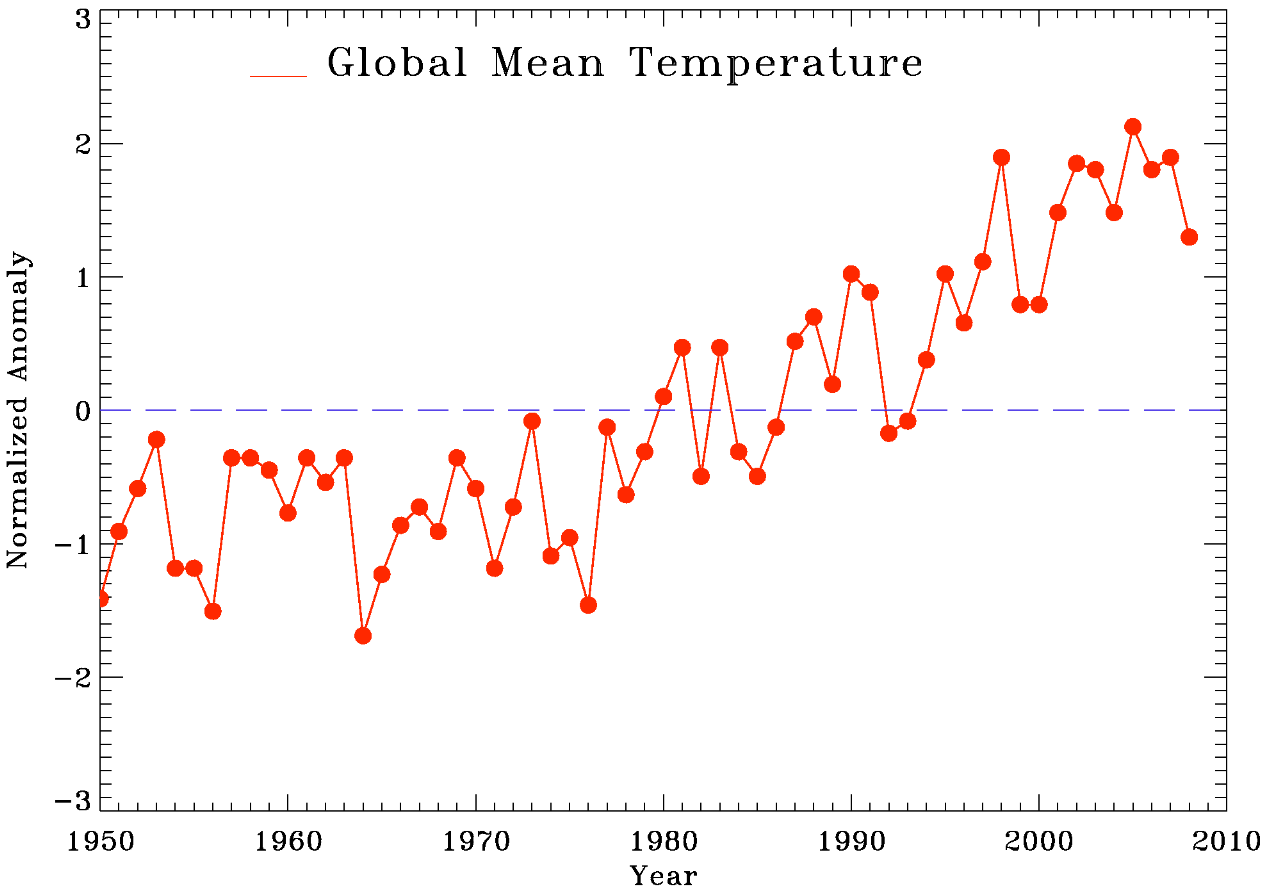
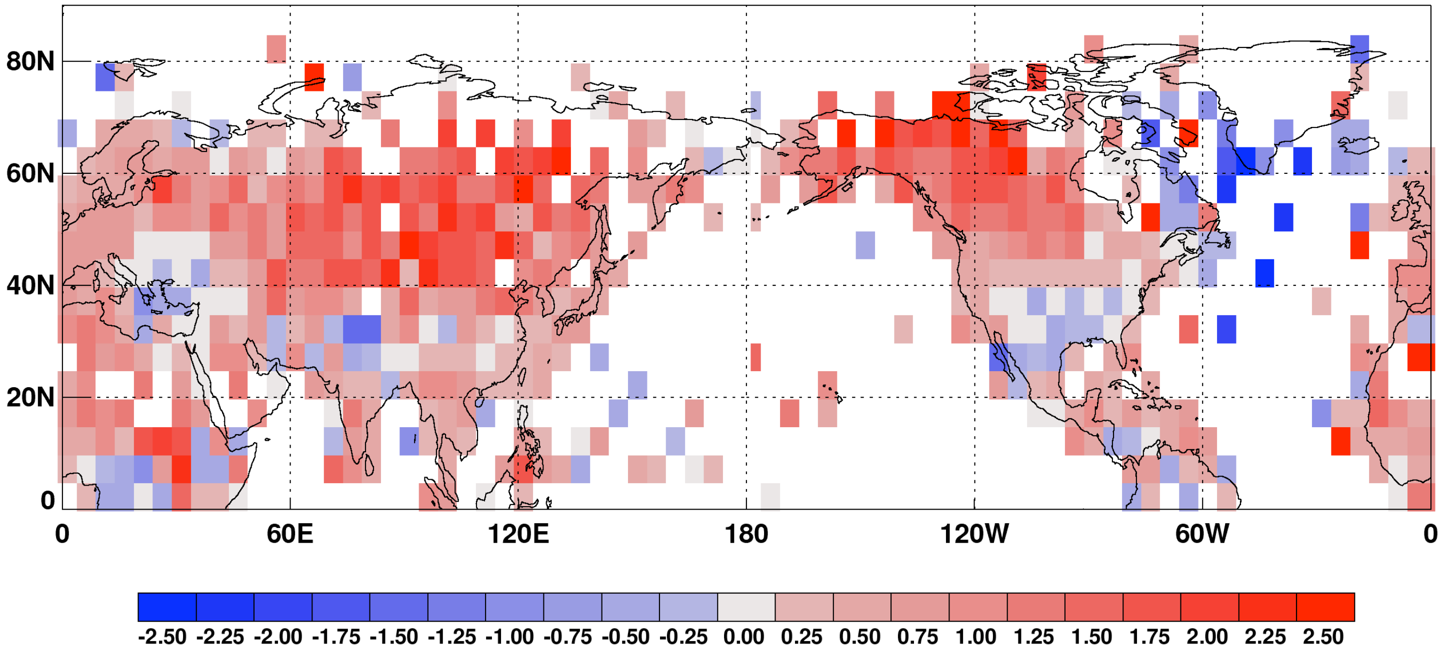

Global Mean Temperature
Normalized Anomaly
Year
3
2
1
0
−1
−2
−3
1950
1960
1970
1980
1990
2000
2010

Figure 1.



80N
60N
40N
20N
0
0
60E
120E
180
120W
60W
0
-2.50
-2.25
-2.00
-1.75
-1.50
-1.25
-1.00
-0.75
-0.50
-0.25
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50

Figure 2.

Figure 3.

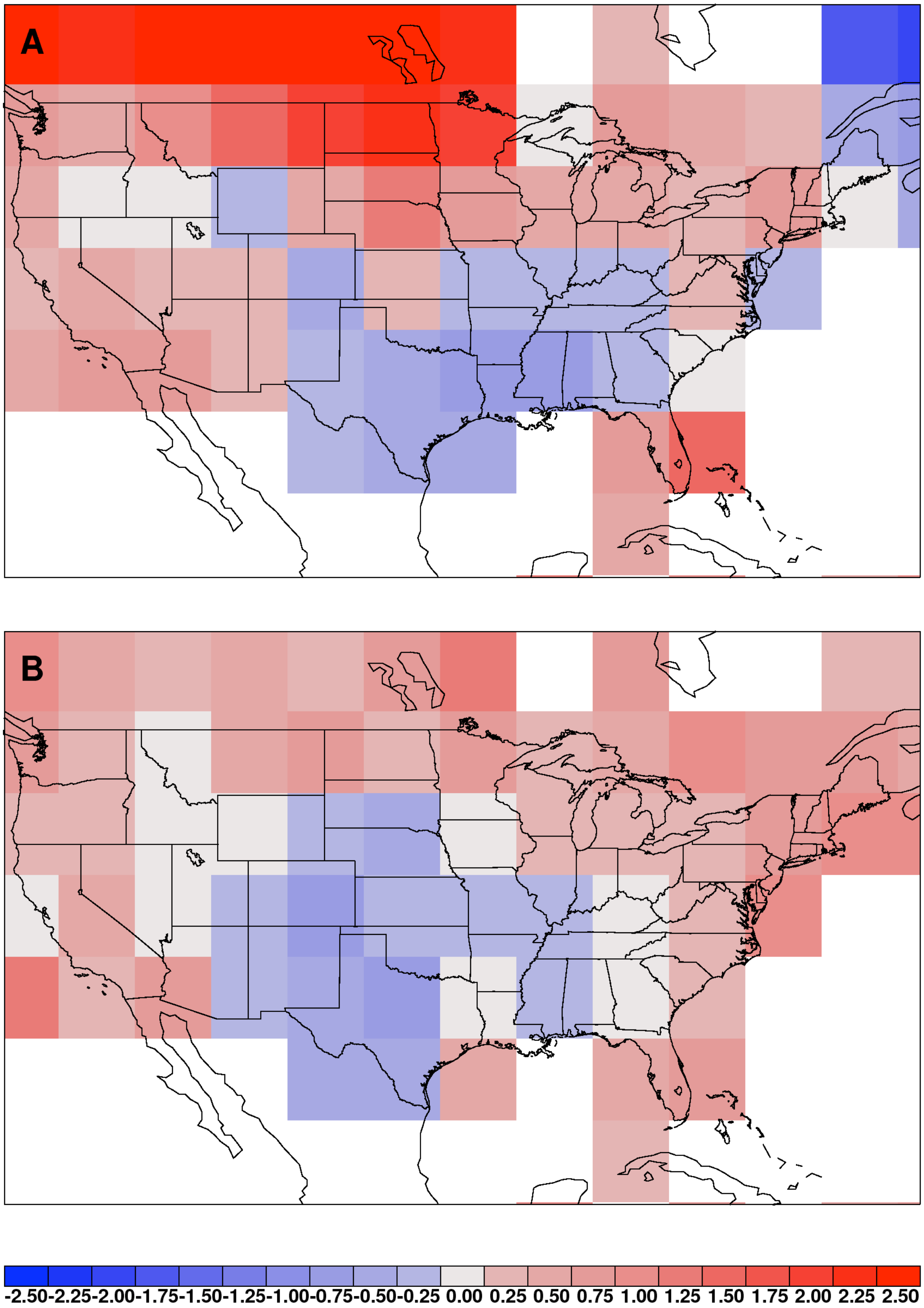

A
B
-2.50
-2.25
-2.00
-1.75
-1.50
-1.25
-1.00
-0.75
-0.50
-0.25
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50

Figure 4.

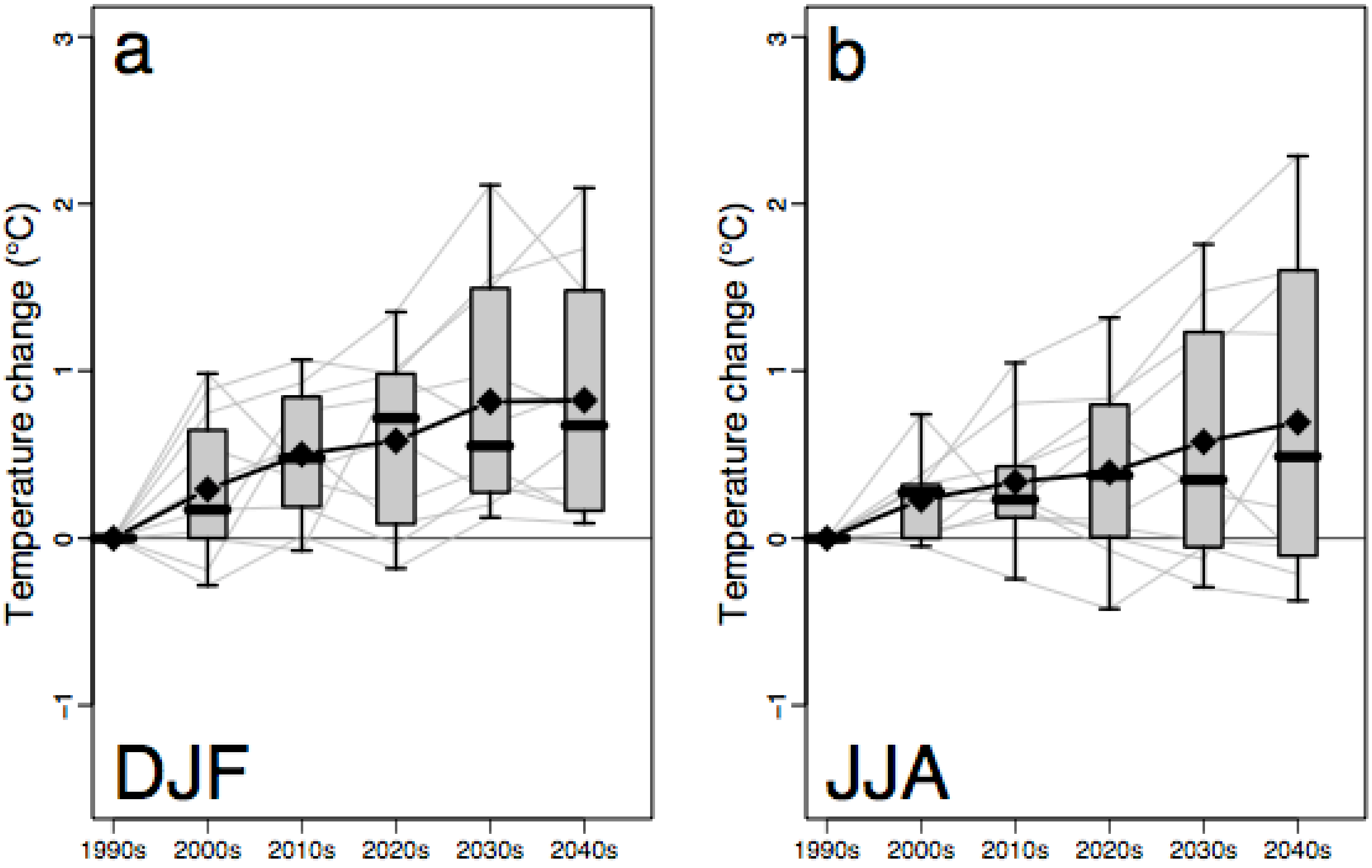

a
b
DJF
JJA
Temperature change (°C)
3
2
1
0
-1
1990s
2000s
2010s
2020s
2030s
2040s

Figure 5.

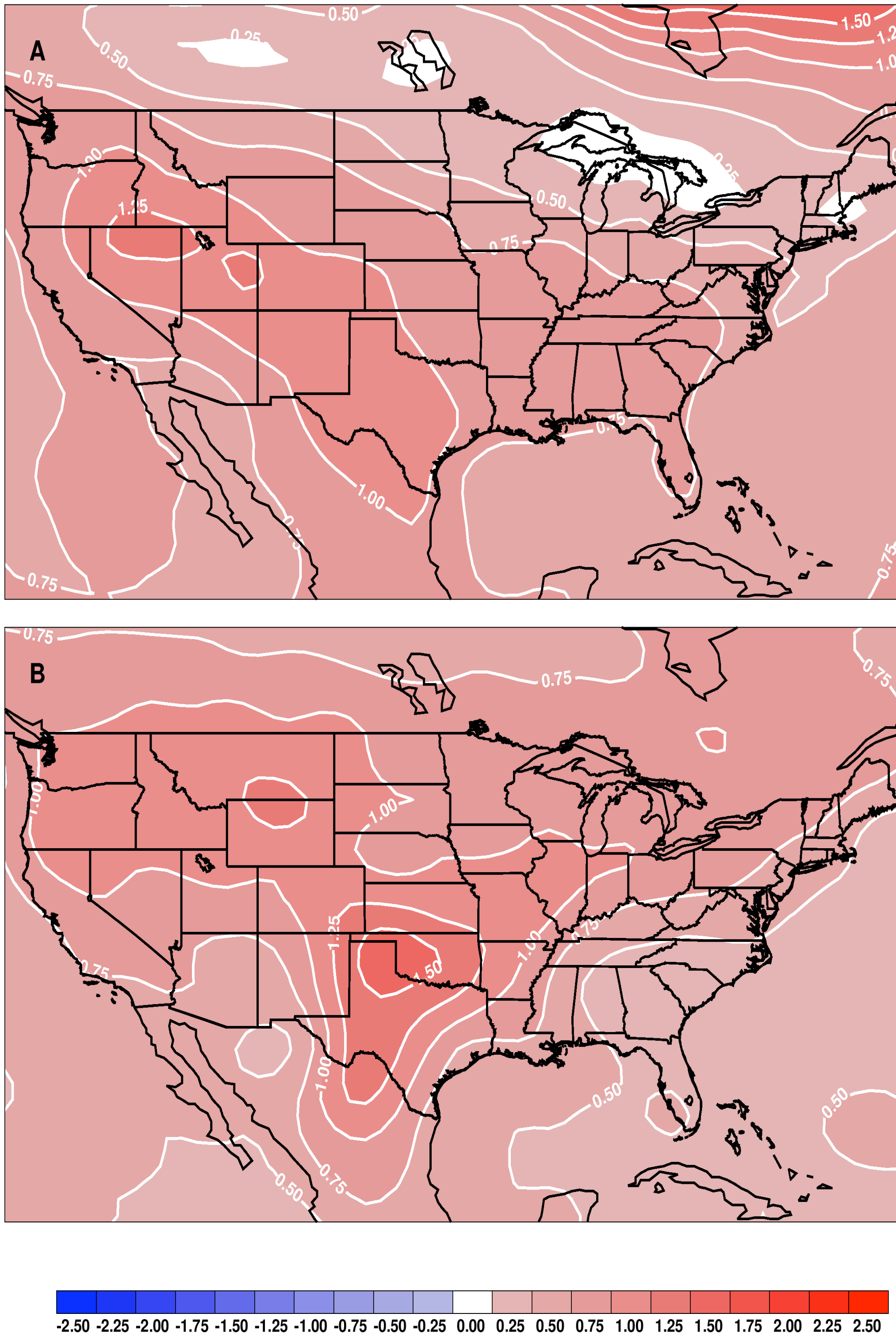

A
B
-2.50
-2.25
-2.00
-1.75
-1.50
-1.25
-1.00
-0.75
-0.50
-0.25
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50

Figure 6.

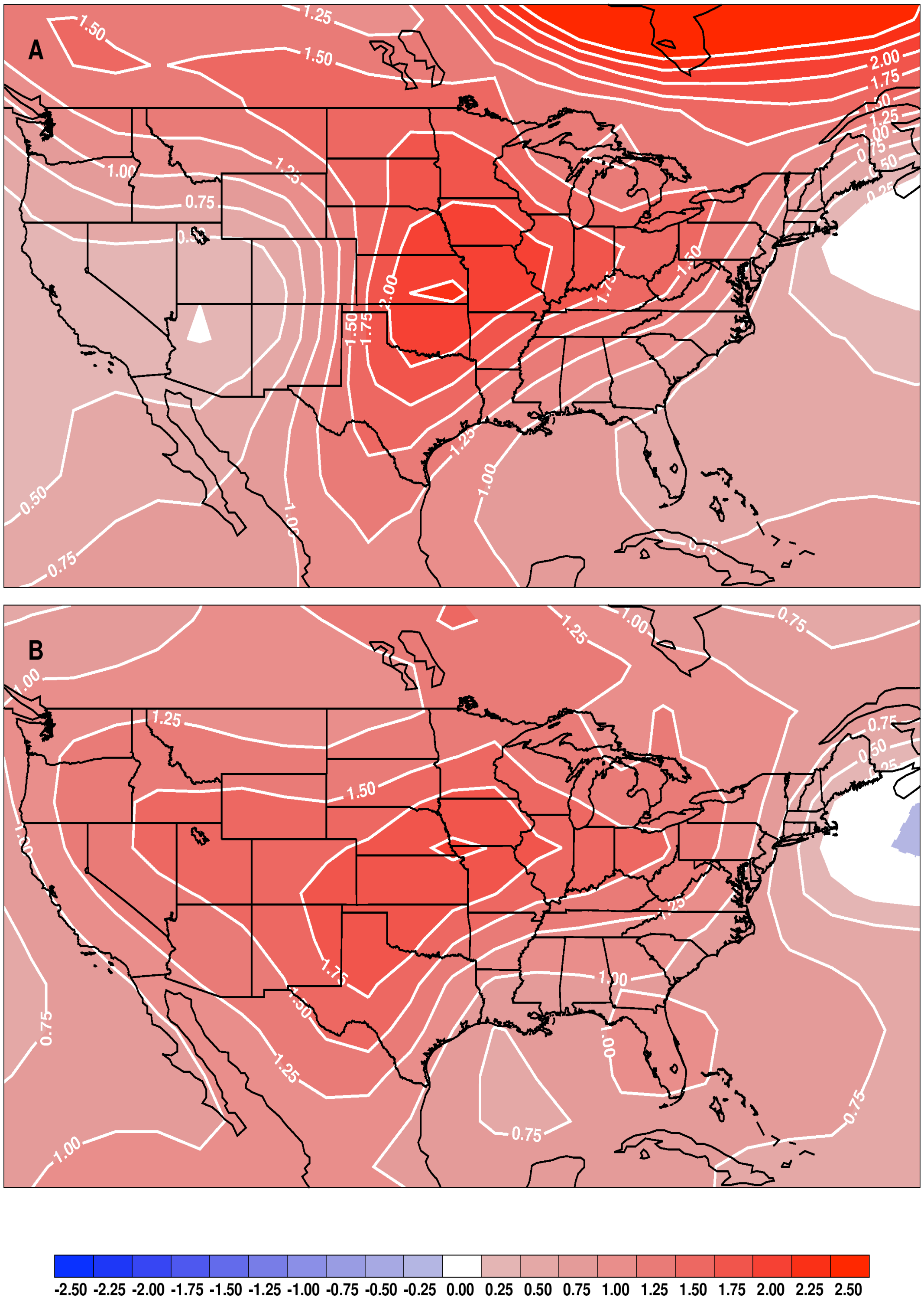

A
B
1.50
1.25
1.50
2.00
1.75
1.25
1.00
0.75
0.50
0.25
1.00
0.75
1.25
2.00
1.50
1.75
1.75
1.25
1.00
1.00
0.50
0.75
0.75
1.25
1.00
0.75
1.00
1.25
1.50
1.75
1.50
1.25
1.00
0.75
0.75
1.00
0.75
-2.50
-2.25
-2.00
-1.75
-1.50
-1.25
-1.00
-0.75
-0.50
-0.25
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50

Figure 7.

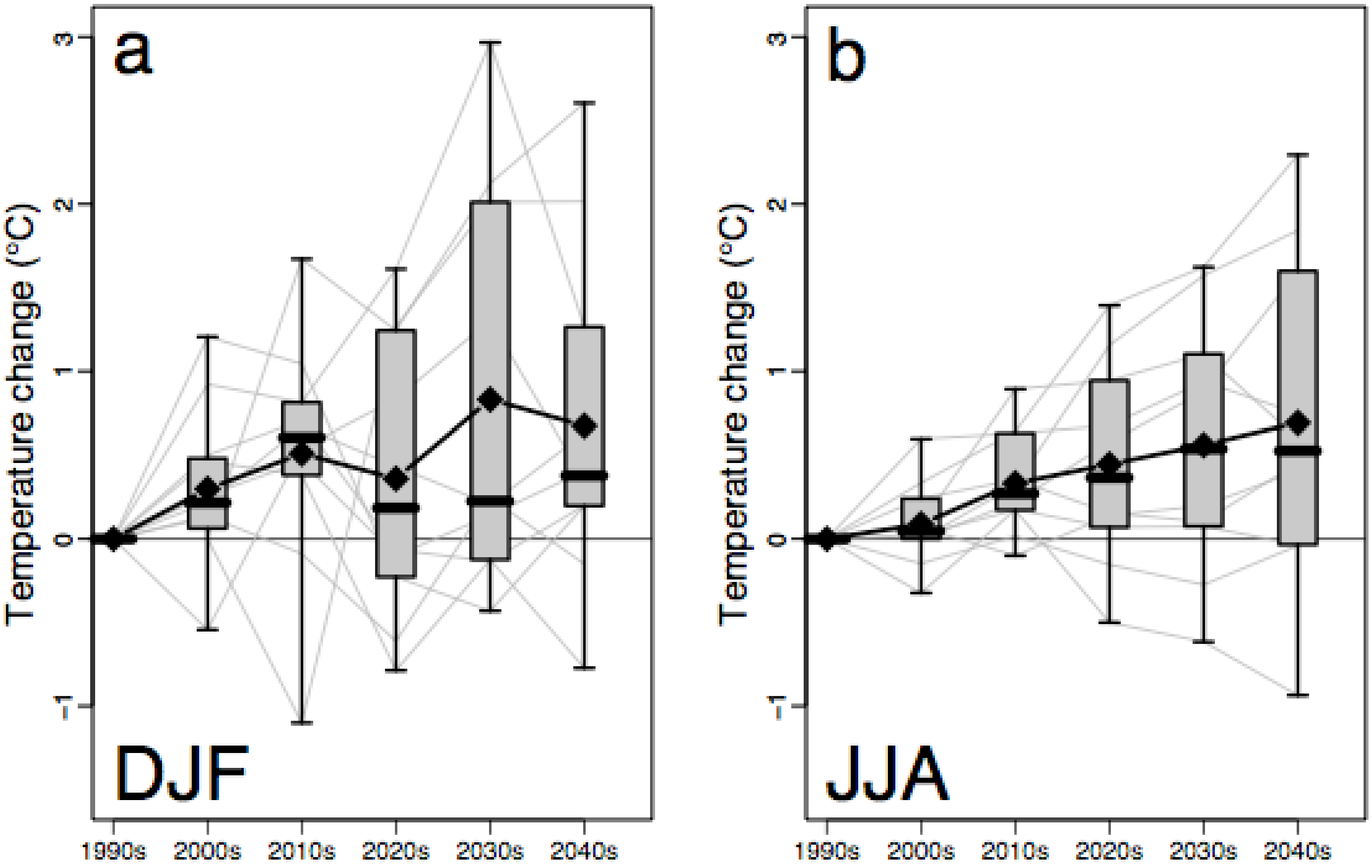

a
DJF
b
JJA
Temperature change (°C)
3
2
1
0
-1
1990s
2000s
2010s
2020s
2030s
2040s

Figure 8.

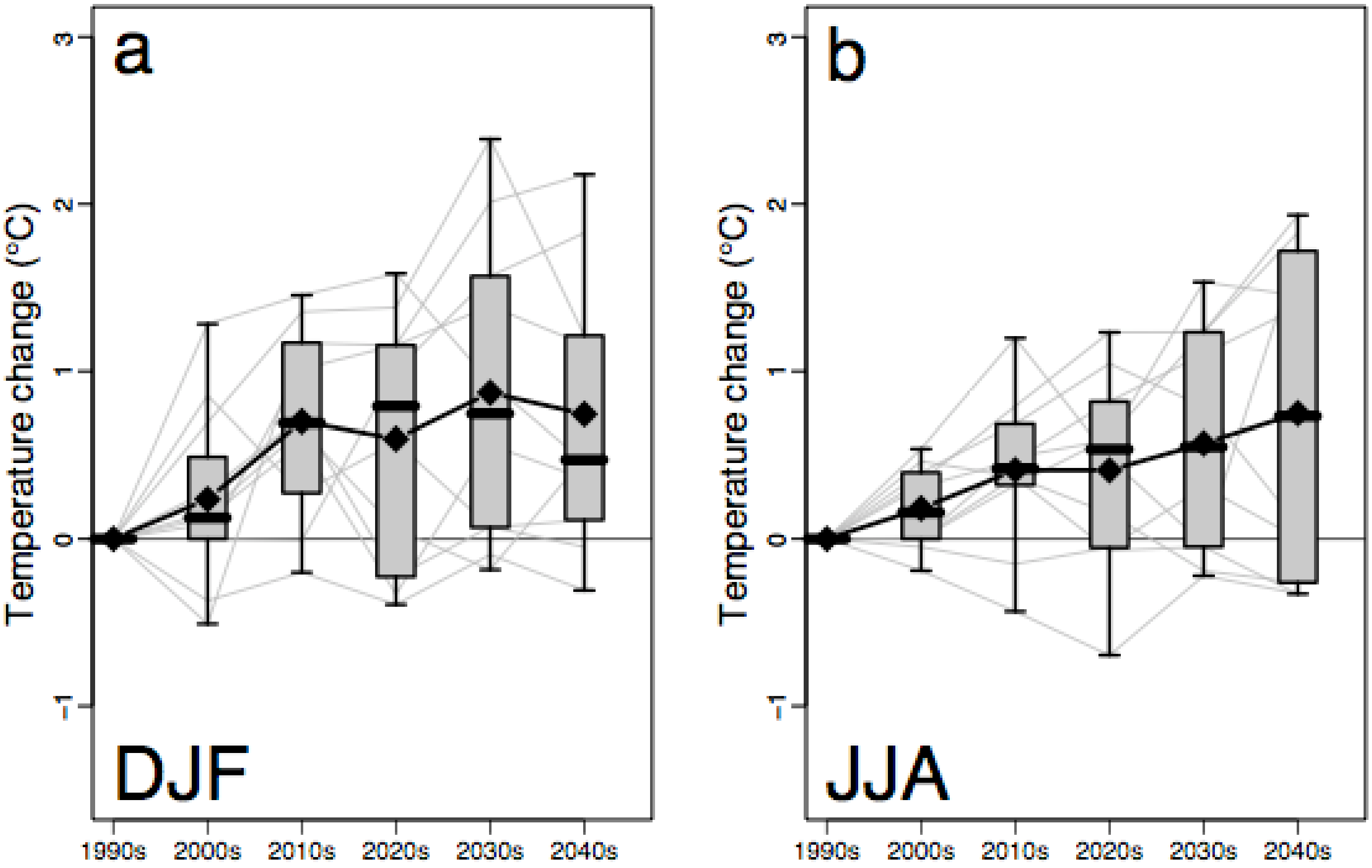

a
DJF
b
JJA
Temperature change (°C)
3
2
1
0
-1
1990s
2000s
2010s
2020s
2030s
2040s

Figure 9.

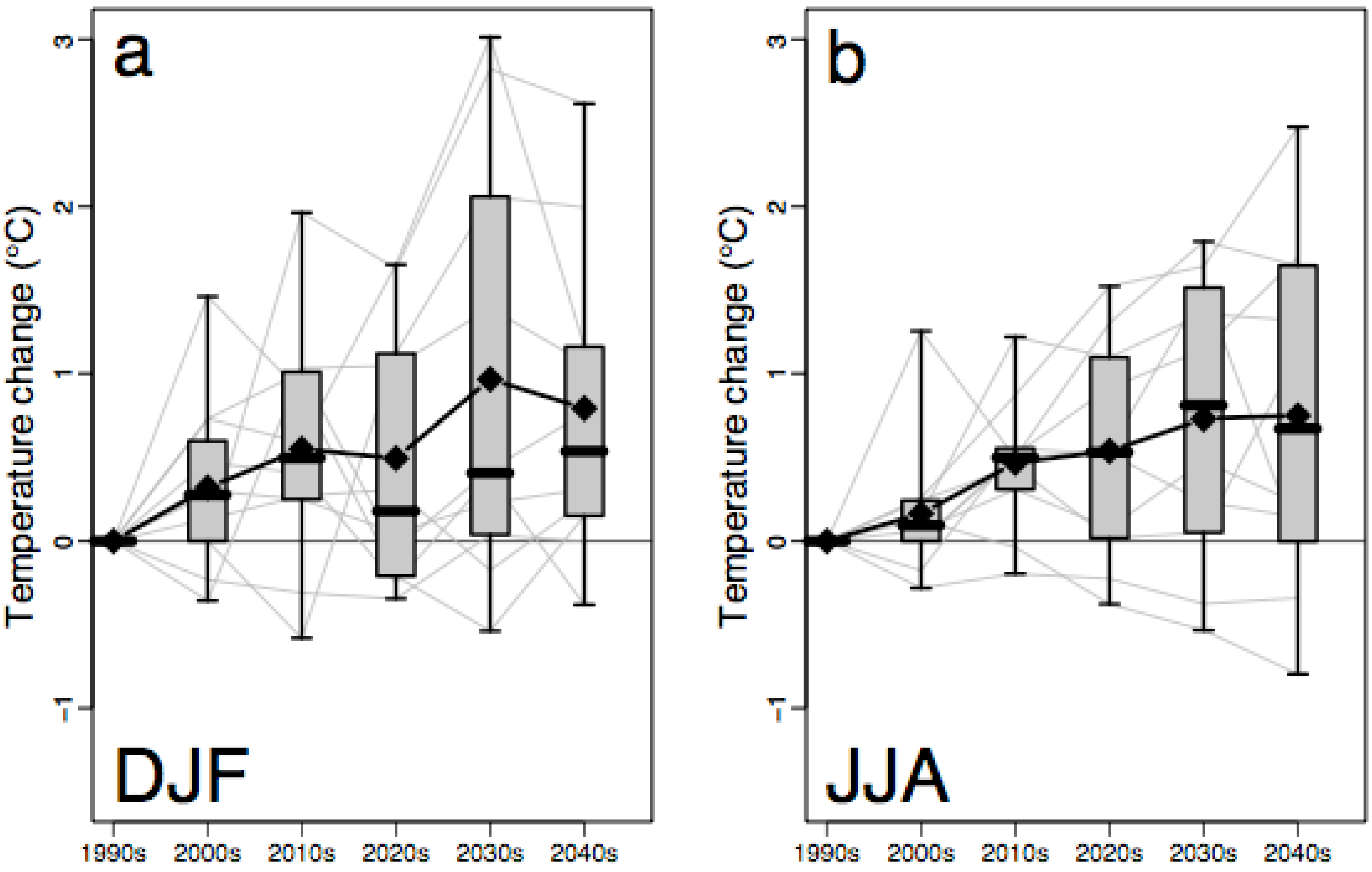
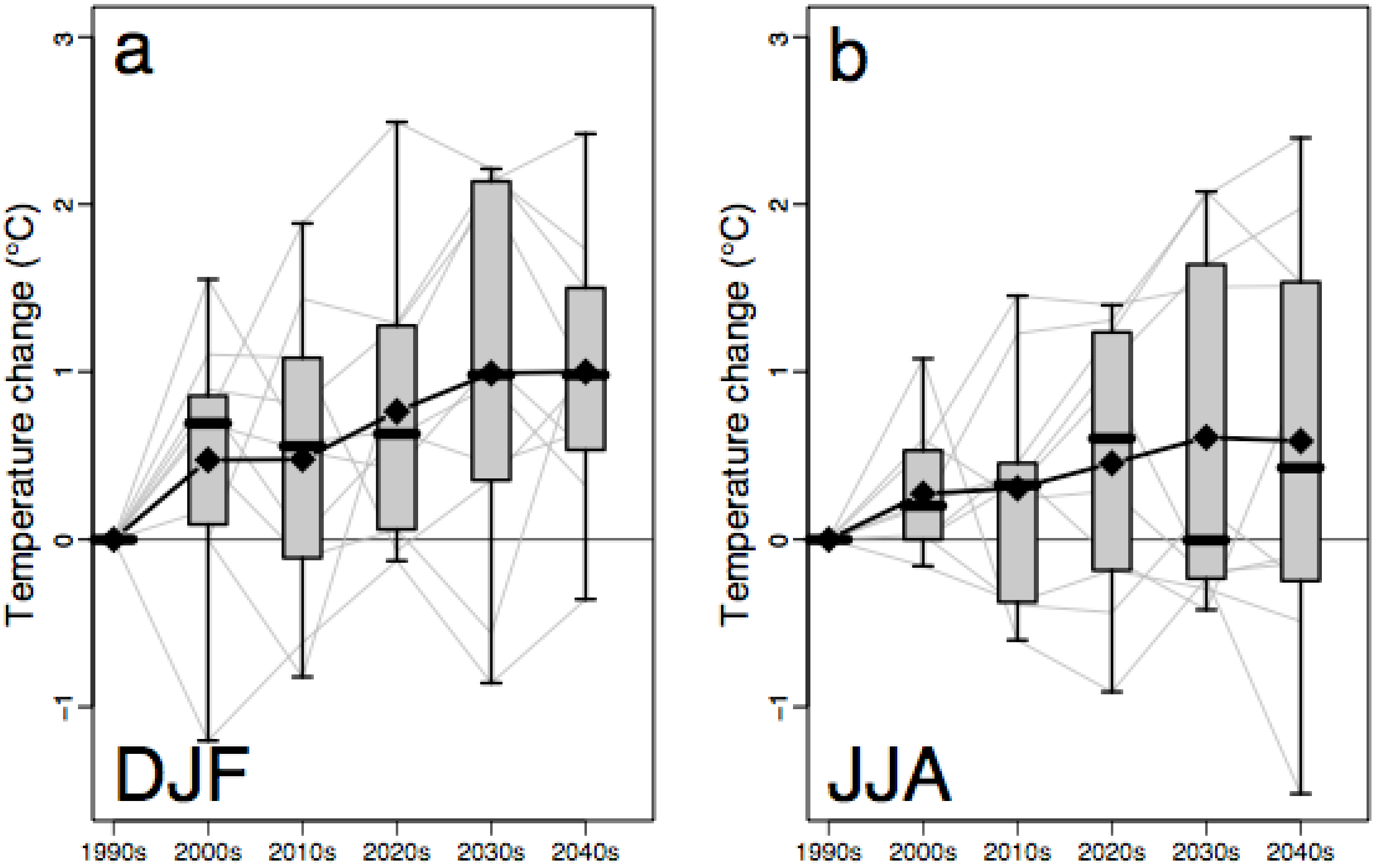

a
DJF
b
JJA
Temperature change (°C)
3
2
1
0
-1
1990s
2000s
2010s
2020s
2030s
2040s

Figure 10.



a
DJF
b
JJA
Temperature change (°C)
3
2
1
0
-1
1990s
2000s
2010s
2020s
2030s
2040s

Figure 11.

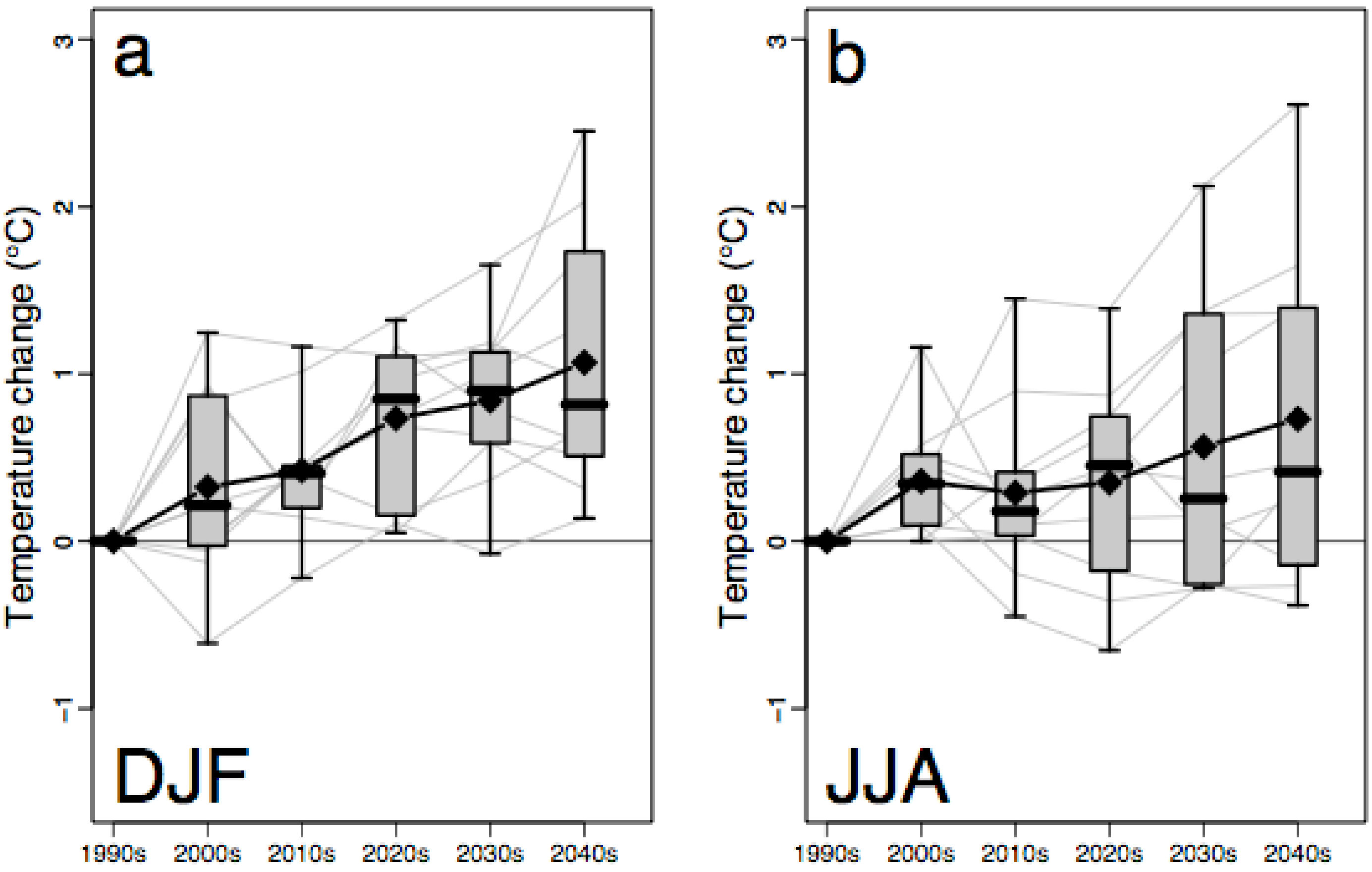

a
b
DJF
JJA
Temperature change (°C)
3
2
1
0
-1
1990s
2000s
2010s
2020s
2030s
2040s

Figure 12.

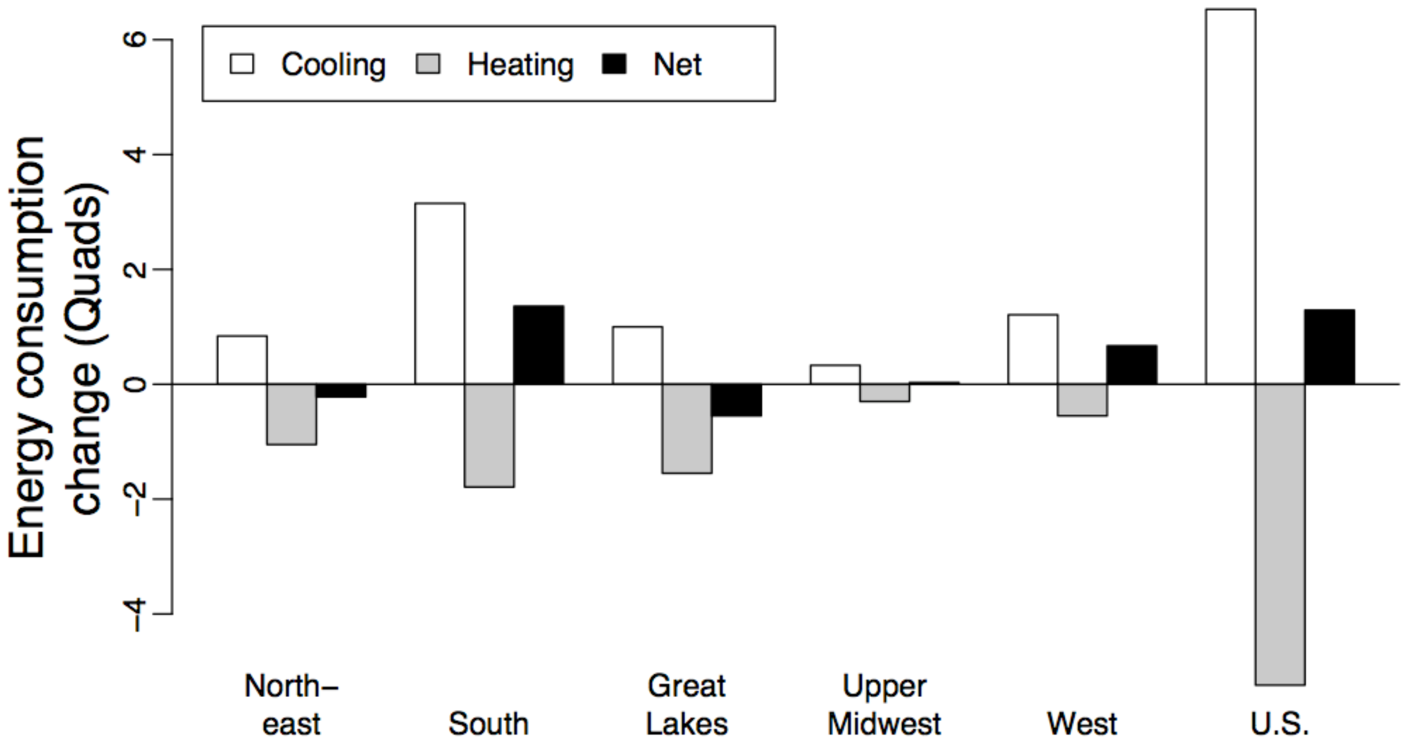

Energy consumption change (Quads)
6
4
2
0
−2
−4
Cooling
Heating
Net
North−east
South
Great Lakes
Upper Midwest
West
U.S.

Figure 13.