International Journal of
Climatology

U.S. Regional Climate Change and Impacts 2010-2050: Temperature and Population Weighted Degree-Days

Journal:	*International Journal of Climatology*
Manuscript ID:	Draft
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	
Complete List of Authors:	Cohen, Judah; AER, Inc. Salstein, David; AER, Inc. Hoffman, Ross; AER, Inc. Connor, Tom; AER, Inc. Ganeles, Curt; Cornell University, Atmospheric Sciences
Keywords:	Climate Change, Regional Impacts, Degree-Days, Energy Consumption

Full Title: U.S. Regional Climate Change and Impacts 2010-2050: Temperature and Population Weighted Degree-Days

Short Title: Impact of Projected U.S. Regional Temperature Change

To be submitted to *International Journal of Climatology*

February 13, 2010

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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 simulating this system. This paper utilizes a sub-set of this information, from coupled atmosphere-ocean models, to develop projections of surface temperature change for six U.S. regions, and then estimates population weighted heating and cooling degree-days, common metrics used to estimate energy requirements for space temperature control.

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 0.7 ºC and that summer temperatures will warm further by 0.6 ºC by the 2040s. For both seasons the warming will be greatest in the central and western part of the country. 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 greater the uncertainty. It is anticipated that these uncertainties will be reduced as climate change science advances over the next several years. By the middle of the century, U.S. northern regions will experience energy consumption decreases from space heating that exceed 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 approximately 5%.

Key Words: Climate Change, Regional Impacts, Degree-Days, Energy Consumption

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 appear to be unprecedented, with the most recent decade of the 2000s being the warmest ever observed. 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 overall temperature. Additional greenhouse gases (GHGs) have supplemented the heating due to CO_2. Nevertheless the climate 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; variations in atmosphere and ocean regional circulations on time scales of years to decades can dominate regional temperature change.

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 to our economy. Of primary importance is the impact of the change in temperature on heating and cooling of residential and commercial 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 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 Programme, 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 50 years, based on linear fits to observed or modeled data and conclude with projected changes in heating and cooling degree-days, which are referenced to 65 °F (18.3 °C).

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 area weighted global mean, annual temperature since 1950. The last nine years (2001-2009) plus 1998 are the ten warmest years within the record.

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). Most of the regions in the world have had a positive temperature trend, with the largest increases 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, or even some cooling. Alaska, as noted, has the largest U.S. observed increases, between 1 and 3 °C. Figures like Fig. 2 for each season (not shown) show that the Northern Hemisphere winter, December-January-February (DJF), experienced the largest trends of the four seasons. Studying temperature trends at finer temporal and spatial scales is important to energy use because of varying implications of inhomogeneous temperature increases during different seasons and different regions for heating and cooling.

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 that act in concert with CO_2 are methane, nitrous oxide, chlorofluorocarbons, and ozone. CO_2 is approximately 36% higher than in pre-industrial times. 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%.

The IPCC and others have concluded that it is probable that warming temperature 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.

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. The properties of the atmosphere or ocean - temperature, winds or currents, and humidity or salinity, are defined at a fine three-dimensional grid network covering the global domain. Discretized equations are used to advance these quantities into the future. 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. Furthermore, GHGs interact with the flows of solar and thermal (i.e., infrared) energy, and change the heat balance of 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.

GCMs have been developed at several of the world's major weather centers, government laboratories and universities, including ones in the U.S., Canada, Japan, China, 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 taken as the best estimate from the modeling approach as a whole, although the superiority of an ensemble mean has been questioned (Reifen and Toumi, 2009). The spread amongst the models provides an estimate of uncertainty, a large spread reducing the confidence in the mean result.

We have accessed 13 coupled atmosphere-ocean model runs (see Table 1), all for the A1B scenario, in which CO_2 increases 1% per year, until its concentration doubles. These model results are those that were most readily available for our analysis from the archives of the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007a, b). 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 is a moderate future scenario in which there is rapid economic growth, a mid-century population peak and advanced technology with a balance of energy sources (Meehl et al., 2007b).

Previous studies have analyzed regional temperature projections for the United States (U.S.). The IPCC report did present temperature and precipitation projections at a regional level. In Chapter 11 (Christensen et al., 2007), surface air temperature projections are presented for North America. The Report divides North America into five regions and presents regional temperature differences between the decades 1980-1999 and 2090-2099. In this article we present somewhat finer resolution dividing the U.S. into six regions and we present temperature differences between the decades 1990-1999 and 2040-2049. A recent paper by Brunsell et al. (2009) looked at projected temperature and precipitation trends during the 21st century for Kansas in the central U.S.; their results indicate likely increasing temperatures for all seasons, with the largest trends being on the order of 0.04 °C/year in summer and fall. Finally the impact of temperature changes in nine different regions of the U.S. on 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.

To determine and evaluate the changes over the regions of the continental U.S., we use a 13-member 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 six regions based on energy usage. These are the Northeast, Southeast, Great Lakes, Upper Midwest, Northwest and Southwest, as depicted in Fig. 3. The Northeast dominates the heating oil market. The Great Lakes and Upper Midwest are mostly heated with natural gas. In the Southeast and Southwest, air conditioning is the greatest energy concern.

For each model, we extracted the surface temperature at each model grid-point in the six U.S. regions (Fig. 3). 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 years were 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 affected by temperature. Winter and summer are the seasons showing the largest and smallest temperature increases, respectively, during the latter half of the 20th century.

b. U.S. temperature trends and differences

As context, we first present in the panels of Fig. 4 the long-term trend (estimated 50-year change) from the observation for winter and summer. As 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). At the end of the 20th century, the

U.S. experienced warming across most if not the entire country. In the areas in the North Central U.S. in the winter months of DJF, trends were typically between 1 and 2 °C (Fig. 4a) while the JJA season had a considerably smaller increase, or a decrease, throughout the middle of the U.S. of -0.5 – 1.0 °C (Fig. 4b). Cooling did occur in both seasons in parts of the south central U.S. As we will show below, the models predict that the general warming trend observed during the second half of the 20th will accelerate during the first half of the 21st century.

Results for the mean and range of the change in temperature between the 1990s and 2040s for the six regions and the U.S. as a whole, for both the DJF and JJA seasons, are given in Table 2. There is considerable spread of projections from these 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 estimated regional increases in temperatures for the 50-year period are all within the range of 0.5 to 1.1 °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 0.7 °C, with individual projections ranging from as low as -0.3 °C to as high as 2.1 °C. For the JJA season, the ensemble mean projection is an increase of 0.6 °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 computed the mean temperature change and trend of the ensemble of models in the mid-season months of DJF and JJA during the periods 2040-2049 and 1990-1999, given as the mean temperature change over the 50-year period. The change is not uniform, though; in fact, the 2040s see a decrease from the 2030s in the DJF season due to natural variability. Both analyses show similar results so therefore we will only show the trends over the periods between 2040-2049 and 1990-1999 in °C per 50-year change (Fig. 6). In both the DJF and JJA seasons, the largest trends of expected increase in the models are in the central and western part of the country, centering on the Great Plains and intermountain west. The maximum value for temperature trend in JJA was around 1.2 °C per half century, somewhat less than the 1.4 °C per decade for DJF. Away from the maximum situated over the Rockies and the Plains, the values reduce steadily. At the southeast Atlantic coast for example, both seasons have values closer to 0.6 °C per half century.

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 here. Nevertheless, temperature increases are expected in all regions at all future times examined. Results are discussed in most detail for temperature changes through the 2040s.

In the Northeast, for winter temperatures in the 2040s, the ensemble mean projection is an increase of 0.5 °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. 7). Results for summer are similar (Fig. 8). For summer temperatures in the 2040s, the ensemble mean projection is an increase of 0.6 °C with a range of –0.9 to +2.3 °C.

Other studies indicate that the number of hot days will also increase (Frumhoff et al., 2007). 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).

In Fig. 7 we also include winter temperature projections for the Southeast, the Great Lakes, the Upper Midwest, the Northwest and the Southwest, and in Fig. 8 we show summer temperature projections for all regions. Results for the winter and summer are qualitatively the same as for the Northeast. Though in general the range is greater across the Northern U.S., especially the Upper Midwest, and less in the Southern U.S.

For comparison we refer to the results from an earlier study by the U.S. Climate Change Science Program, based on 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, which is 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.

3. Impacts of temperature changes on regional space heating and cooling

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. Here we focus on the sensitivity of current heating and cooling requirements to temperature change projected by our ensemble of climate models.

a. Computing energy consumption for heating and cooling

In order to estimate current and projected future energy consumption we calculate population weighted heating (winter) and cooling (summer) degree-days. Population weighted degree-days are generated by taking the population fraction for a climate division (the climate divisions are used by the National Climate Data Center for compiling climate statistics and producing forecasts), multiplying by the degree-days for that climate division, and summing this quantity for all the climate divisions in each of the six regions. This technique will weight a degree-day total in a densely populated area more heavily than for a non-populated area within the same region.

Degree-days are defined as the number of degrees that the daily mean temperature is observed above (cooling degree-days or CDDs) and below (heating degree-days or HDDs) 65 ºF (18.3 ºC) at a given location. Thus degree-days are directly related to the energy consumption to heat and cool residences and offices. However, the AR4 model data is stored as monthly means and we further averaged monthly means into seasonal means for our analysis. Therefore, we followed the technique of Thom (1964) to compute seasonal mean CDDs and HDDs. However, during the winter and summer seasons when daily mean temperatures are much above or below 65 ºF, using the seasonal mean temperature to calculate the seasonal degree-days is very close or exactly the same as using the daily mean temperatures to calculate seasonal degree-days.

The technique outlined by Thom assumes that daily temperature is described by a normal distribution, which implies that monthly and seasonal temperatures are also distributed normally. Degree-days in cases where the monthly temperature is well above or below the base of 65 ºF are also described by a normal distribution. However, when the monthly average temperature is close to 65 ºF, the degree-day distribution is described by a mixed population of zero degree-days and greater than zero degree-days. Thom derived the following relationship between the seasonal mean temperature and HDDs and CDDs respectively:

$$HDD = N(65 - \overline{T} + \sqrt{N}\sigma_m l^*)$$

$$CDD = N(\overline{T} - 65 + \sqrt{N}\sigma_m l_*)$$

Where:

HDD is the estimated total degree-days accumulated for the winter season

CDD is the estimated total degree-days accumulated for the summer season

N is the number of days in the period

σ_m is the standard deviation of the seasonal average temperature

T is the seasonal average temperature

l^* is the truncation coefficient for degree-days above a base (HDD)

l_* is the truncation coefficient for degree-days below a base (CDD)

The climate division HDD and CDD truncation coefficients are found by substituting the 30-year average temperature and degree-day values for each climate division for the season into the relationships above, and solving. For the population weighting, the following relationship was used:

$$DD_R = \sum_{i=1}^{i=N_R} W_{R,i} \times DD_{R,i}$$

where:

DD_R is the population weighted degree-day (winter or summer) for the region

R is one of the six U.S. regions

N_R is the number of climate divisions in the region

$W_{R,i}$ is the fraction of the climate division population to the region population

b. Estimating 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 depends on the characteristics 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. 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.

Using the ensemble mean regional temperature projections and our estimation of population weighted degree-days, we estimate current and projected consumption of energy due to heating and cooling of residential and commercial spaces. We have limited ourselves to the peak winter and summer months because during those months the monthly temperature anomaly nearly or exactly equals the monthly degree-day anomaly. We compared temperature anomalies with absolute degree-days for selected cities and the variation in both is almost exact. In Panel 9a we show the correlation between winter temperature anomalies and heating degree-days for Atlanta and in Panel 9b we show the correlation between summer temperature anomalies and cooling degree-days for Chicago. The correlation in both cases is nearly equal to one in both Atlanta, which experiences relatively moderate temperatures in the winter and Chicago, which experiences relatively moderate temperatures in the summer. However, during the shoulder months when mean temperatures approach 65 °F, that relation often breaks down.

In Table 3 we show the population-weighted HDDs (DJF) for the U.S. and the six regions for the 1971-2000 base period and for the 2040s. We assumed a steady population so that any changes in population-weighted degree-days are due to changes in temperature alone.

In Table 4 we show the same for population weighted CDDs (JJA). From the tables we see that the models are predicting a decrease in HDDs and an increase in CDDs for the U.S. and for all regions by mid-century. In Figures 10 and 11 we plot the absolute and percentage difference in HDDs (DJF) and CDDs (JJA) between the 1971-2000 base period and the 2040s, respectively. Regionally we project a decrease in peak HDDs ranging between 4-7% and nationally a decrease of around 5%. For peak CDDs, we project a much greater range with an increase regionally between 11-65% and nationally an increase of approximately 16%. HDDs and CDDs are strongly correlated with energy usage (Day, 2005). In Panel 9c we correlate variations in HDDs and residential energy consumption and in Panel 9d we correlate variations in CDDs and residential energy consumption for the years 1973-2009. In both seasons, degree-day variability explains a significant fraction of the variance in energy consumption, though the relationship is stronger in winter than in summer. In what follows, we assume that energy consumption will change in the same proportions as HDDs and CDDs.

To approximate energy consumption for heating and cooling spaces we tabulated monthly energy consumption data for the residential and commercial sectors from the Energy Information Administration (EIA, 2009). According to the Monthly Energy Review of the EIA, 12.1 Quads of energy were consumed by the residential and commercial sectors in the winter months of DJF and 9.7 Quads of energy in the summer months of JJA from the most recent year of data—2008/09. The total energy consumed for the most recent available year, 2008, was within a few percentage points of the total energy consumed during the late 1990s. A 5% decrease in heating by the 2040s (Fig. 10) translates into a decrease of 0.6

Quads of energy consumed for heating while a 16% increase in cooling (Fig. 11) translates into an increase of 1.5 Quads of energy consumed for cooling in the summer. This yields a total annual net increase of approximately 1 Quad or 5% consumed for heating and cooling by the 2040s due to projected temperature change alone. This approximation ignores changes such as energy efficiency to commercial and residential buildings.

c. Discussion of energy use trends

Overall in the U.S., Scott et al. (2005) projected a reduction between 4% and 20% in the demand for residential heating 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 0.7 ºC in the winter months in the U.S.; our result concurs in this regard with Scott et al. (2005) as well as with the earlier results of Rosenthal et al. (1995). Based on the ensemble mean, we have a reduction by about 5% in the space heating requirements of the U.S. during the peak winter months. Based on 0.7 ºC of warming in the winter, costs for heating of commercial buildings will decrease, but the amount of energy savings as a percentage will depend on fuel type. Decreases of about 3% for electricity and natural gas are projected, but overall, in areas where fuel oil is prevalent, a reduction of 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. On the other hand, given the changes in climate regime and possible economic conditions, households may decide to make relevant alterations, including their fuel choice, improvements to buildings, or the temperature to which they condition their spaces (Mansur et al. 2008). There is additional uncertainty due to the spread of the climate model projections. While we only present CDDs, HDDs, and changes in energy consumption for the ensemble mean projection for the 2040s, it is clear that the uncertainty (i.e., the ensemble spread) in temperature projections described earlier for the continental U.S. and the six regions, which can be noted in Figs. 7 and 8 and summarized in Table 2, would propagate through to substantial uncertainty in projected CDDs, HDDs, and changes in energy consumption.

Balancing the heating reduction, 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. For comparison, our analysis predicts a mean summer increase of 0.6 °C by the 2040s from the ensemble model mean, which is equivalent to approximately a 16% increase in energy from air conditioning during the peak summer months.

Much of the industrial consumption of energy is not related to the ambient temperature, with the obvious exceptions of heating and cooling of 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 annual increase in temperature in the U.S. of 0.7 °C will create approximately an increase of 0.9 to 1.0% in energy used for air-cooling in commercial buildings.

Our projection is that the overall energy use for space heating and cooling will increase by about one Quad of energy by the 2040s or almost a 5% increase in the total number of Quads currently being used for space heating and cooling in the U.S. Of course, a number of more energy efficient technologies are being developed that may dramatically reduce the energy needed in many areas, including space heating and cooling, as well as 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 Northeastern U.S., warming was found at all but two 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 U.S. 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 U.S. in each of its regions throughout the first half of the 21st century in both winter and summer. The spread in the set of models indicates substantial uncertainty in this projection. Space heating energy requirements will be reduced and air-cooling requirements will be increased in all regions of the U.S., though the net effect will be energy savings in the North and energy increases in the South and West. Overall, we estimate that future energy consumption for space heating and cooling to increase for the U.S. by approximately 5% by the 2040s. Temperature increases impact a number of other activities including energy production by power plants, hot water heating, and transportation.

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 (Titus et al., 2004), storminess (Piacorek et al., 2002) and the water cycle (USCCP, 2008). These factors may have additional impacts on energy production. 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 (USCCSP, 2008). Increased storminess will additionally impact offshore oil platforms in the Gulf of Mexico. Water supplies required to cool 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.

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 specifying GHG scenarios remains a major challenge.

Acknowledgements

We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

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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 12 degrees of freedom are significant at the 90, 95, and 99% level if the t-statistic exceeds 1.356, 1.782 and 2.681, respectively.

Table 3. Population weighted heating degree-days for the U.S. and the six regions for the base period 1971-2000 and based on model predicted temperatures the 2040s for the winter months DJF.

Table 4. Population weighted cooling degree-days for the US and the six regions for the base period 1971-2000 and based on model predicted temperatures the 2040s for the summer months JJA.

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 six 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 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 (DJF) and b) summer (JJA). The values shown are in °C/50 years.

Figure 7. Temperature change for an ensemble of climate models for the six U.S. regions a) Northeast, b) Southeast, c) Great Lakes, d) Upper Midwest, e) Northwest and f) Southwest the for the winter months (DJF) as in Fig. 5.

Figure 8. Same as Fig. 7 except for the summer months (JJA).

Figure 9. Scatter plots for the relationship between a) temperature anomalies and winter HDDS in Atlanta, b) temperature anomalies and summer CDDs in Chicago, c) winter population weighted HDDs and residential energy consumption and d) summer population weighted CDDs and residential energy consumption. Data for energy consumption is from the Energy Information Administration (EIA).

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

Figure 10. Projected changes in energy required for heating as departures from the base period 1971-2000. Absolute values shown in boxes (scale on left) and percentage shown in whiskers (scale on right). Negative values correspond to decreased energy usage.

Figure 11. Projected changes in energy required for cooling as departures from the base period 1971-2000. Absolute values shown in boxes (scale on left) and percentage shown in whiskers (scale on right). Positive values correspond to increased energy usage.

TABLES

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

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
IPSL	Institut Pierre Simon Laplace	France
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
UKMO	United Kingdom Meteorological Office	England

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 12 degrees of freedom are significant at the 90, 95, and 99% level if the t-statistic exceeds 1.356, 1.782 and 2.681, respectively.

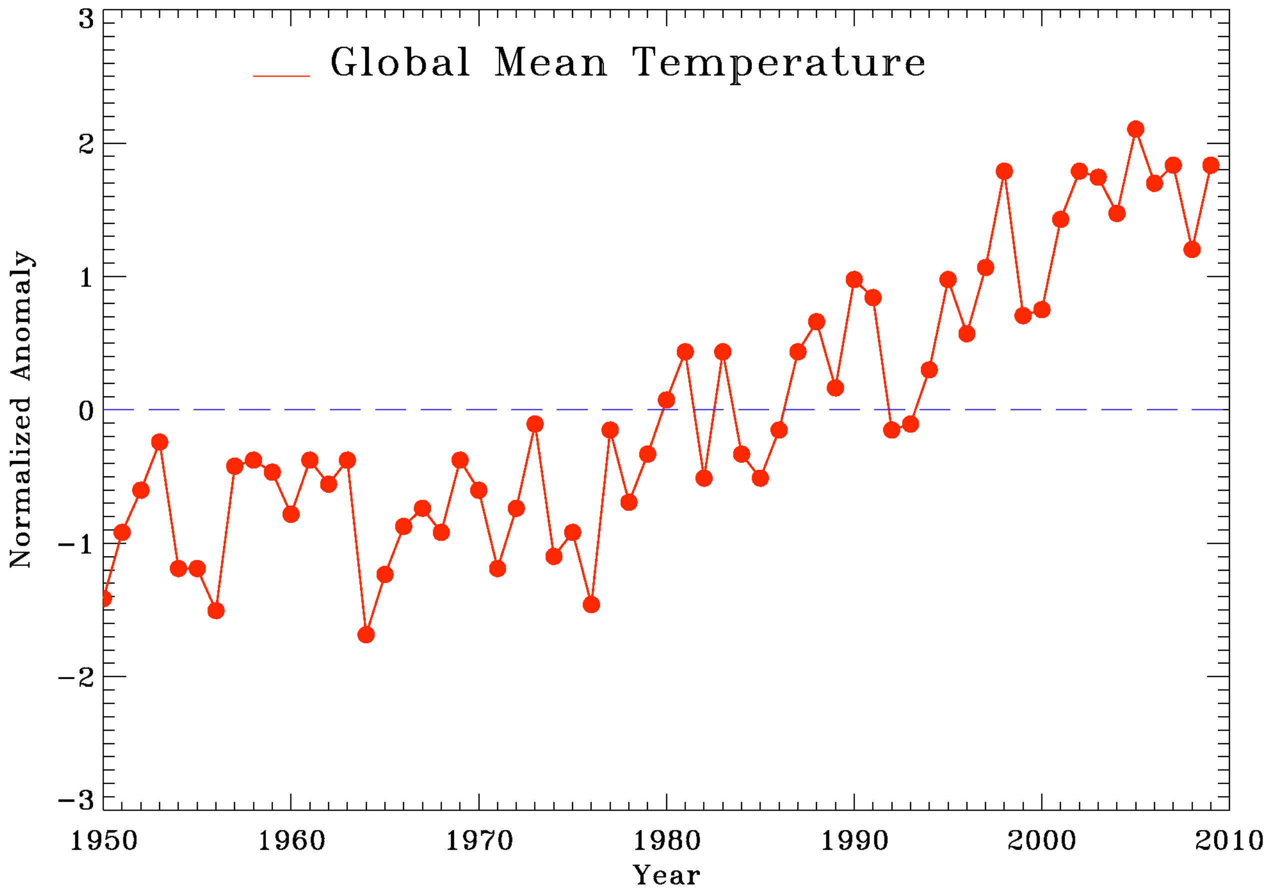
Region	**DJF Mean**	**DJF Range**	**t-statistic**	**JJA Mean**	**JJA Range**	**t-statistic**
Northeast	0.5	-0.8 – 2.6	1.8	0.6	-0.9 – 2.3	2.2
Southeast	0.6	-0.3 – 2.2	2.4	0.7	-0.3 – 1.9	2.8
Great Lakes	0.6	-0.6 – 2.6	2.2	0.6	-0.8 – 2.5	2.3
Upper Midwest	0.9	-1.5 – 2.4	2.9	0.5	-1.5 – 2.4	1.7
Northwest	1.1	-0.5 – 2.6	4.3	0.6	-0.5 – 2.7	2.1
Southwest	0.9	0.2 – 2.3	4.0	0.6	-0.4 – 2.5	2.5
CONUS	0.7	-0.3 – 2.1	3.4	0.6	-0.4 – 2.3	2.5

Table 3. Population weighted heating degree-days for the U.S. and the six regions for the base period 1971-2000 and based on model predicted temperatures the 2040s for the winter months DJF.

sCast Region	Normal Population Weighted HDD for Climate Period 1971 to 2000	Forecast Average Population Weighted HDD for 2040 Based on Trend
North East	3151	3034
South	1631	1487
Great Lakes	3473	3338
Upper Midwest	3717	3574
South West	1017	947
North West	860	812
National	2465	2335

Table 4. Population weighted cooling degree-days for the U.S. and the six regions for the base period 1971-2000 and based on model predicted temperatures the 2040s for the summer months JJA.

United States Region	Normal Population Weighted CDD for Climate Period 1971 to 2000	Forecast Average Population Weighted CDD for 2040 Based on Trend
North East	557	676
Great Lakes	597	735
Upper Midwest	760	905
South West	543	615
North West	79	129
South	1288	1433
National	832	965



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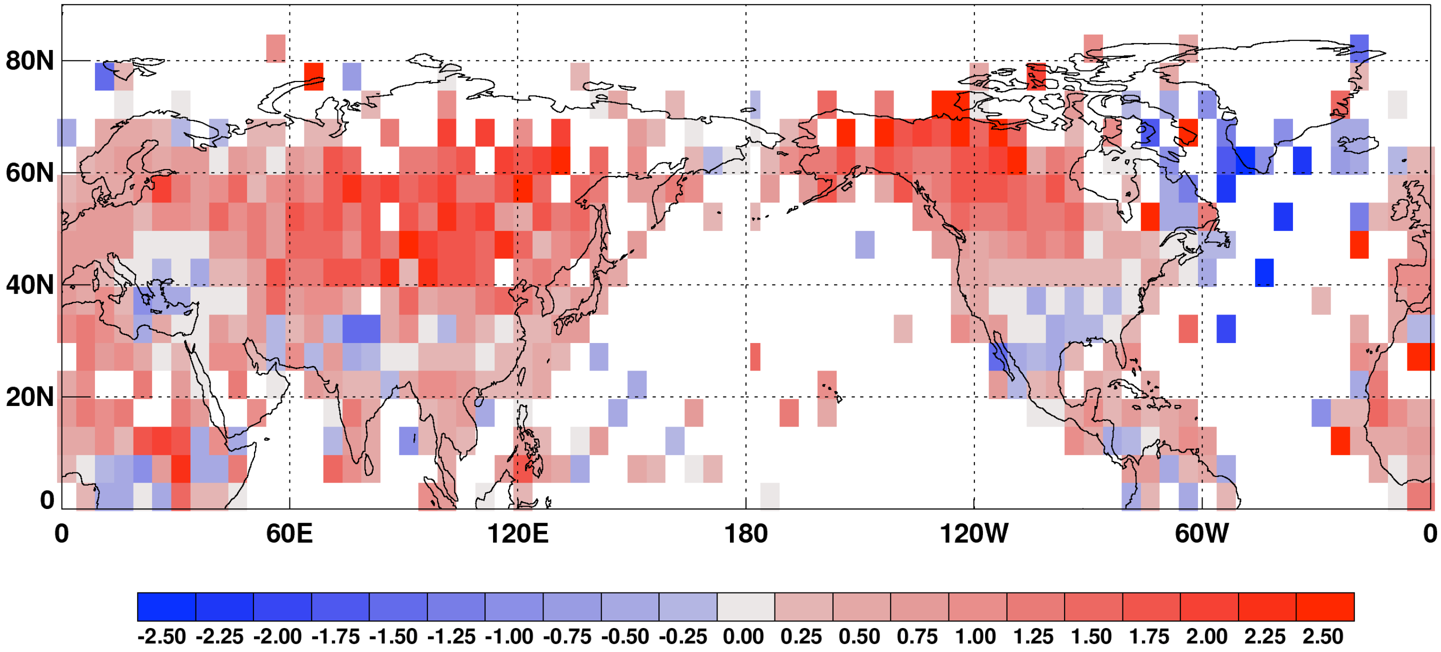

Figure 2. Trends in annual average surface temperature (1950-1999). These trends are based on a linear in time fit to the gridded observation data set of the Climate Research Unit (University of East Anglia, U.K.) CRUTEM3 land-surface temperature data set (Brohan et al. 2006). Units are °C/50 years.

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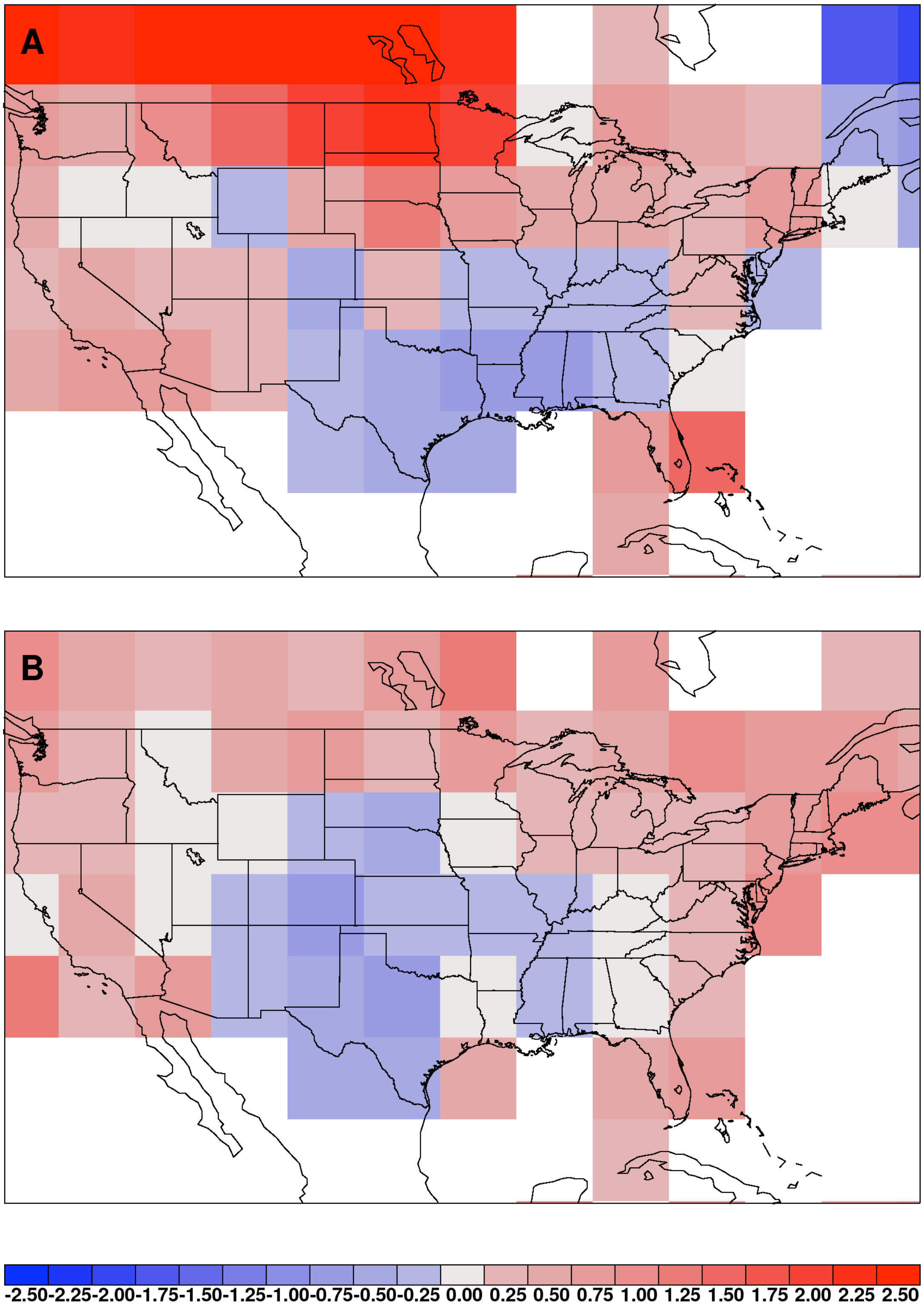

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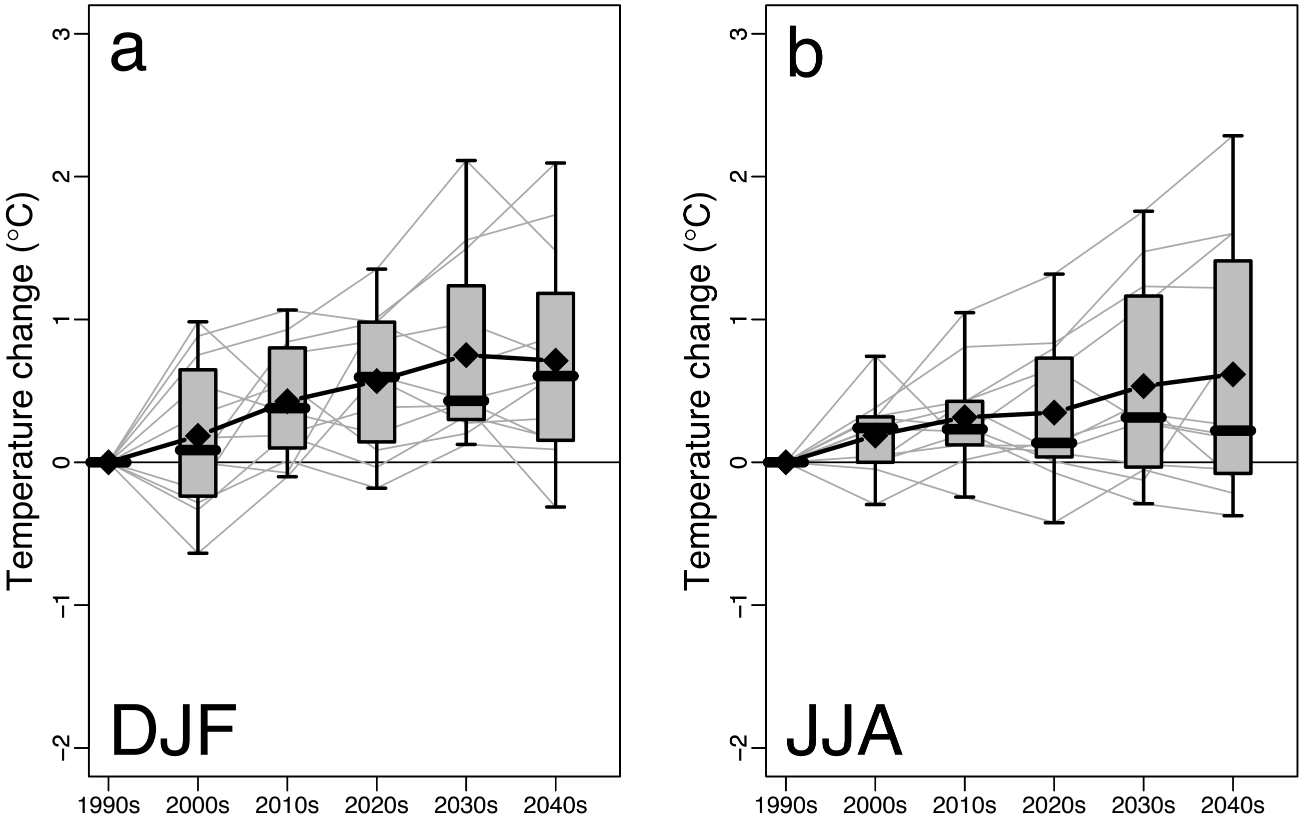

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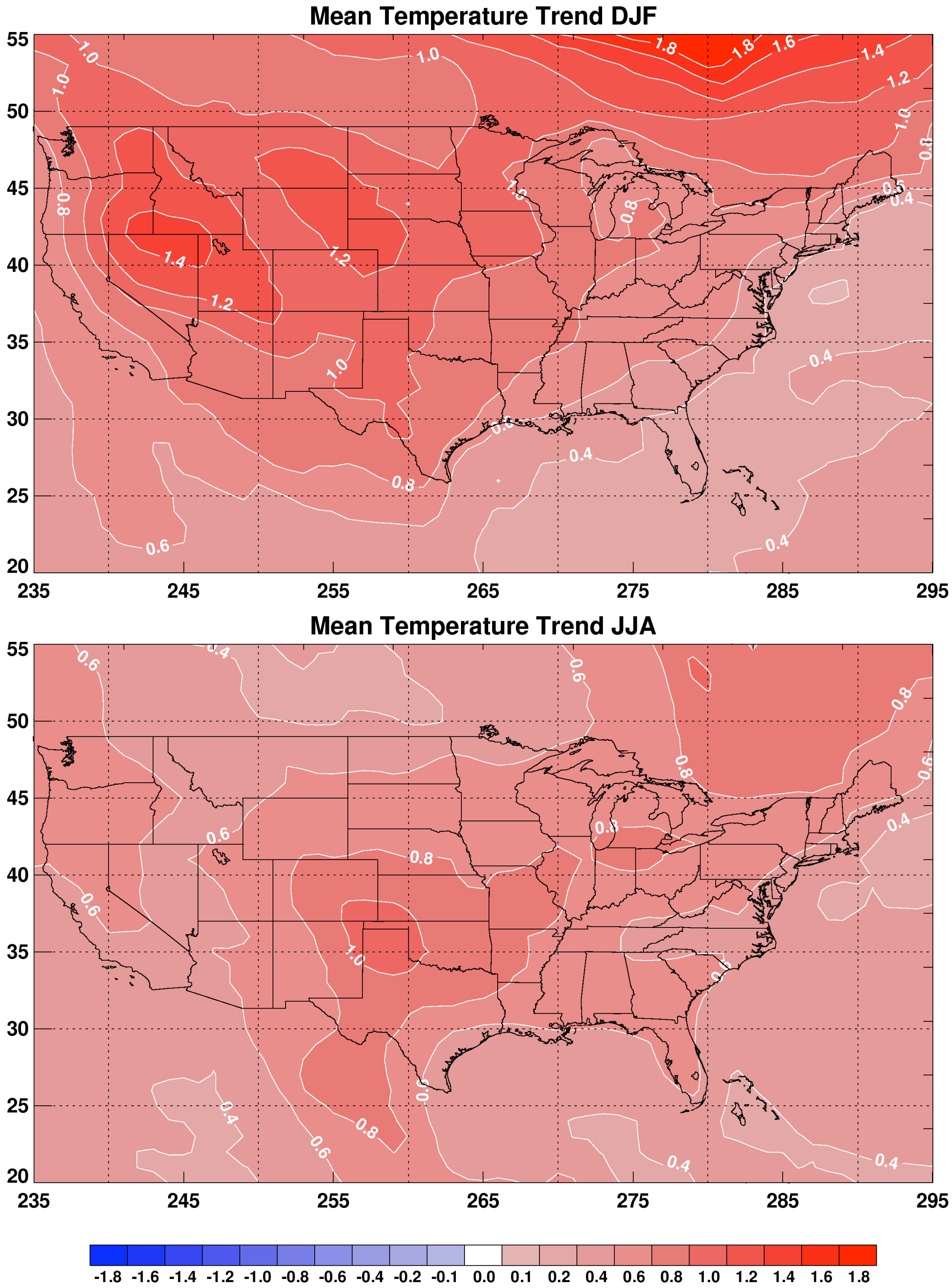

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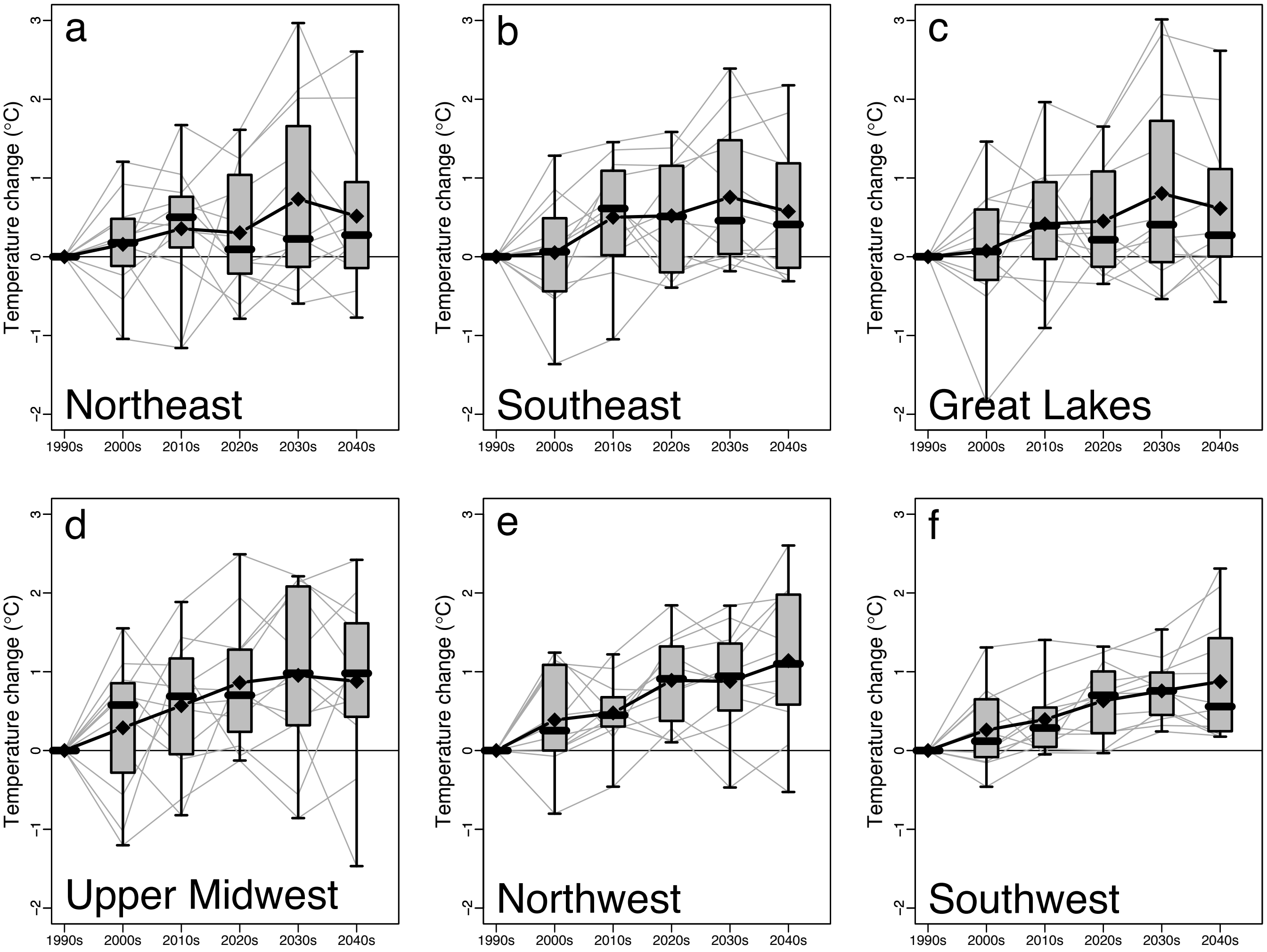


Figure 7. *Temperature change for an ensemble of climate models for the six U.S. regions a) Northeast, b) Southeast, c) Great Lakes, d) Upper Midwest, e) Northwest and f) Southwest the for the winter months (DJF) as in Fig. 5.*

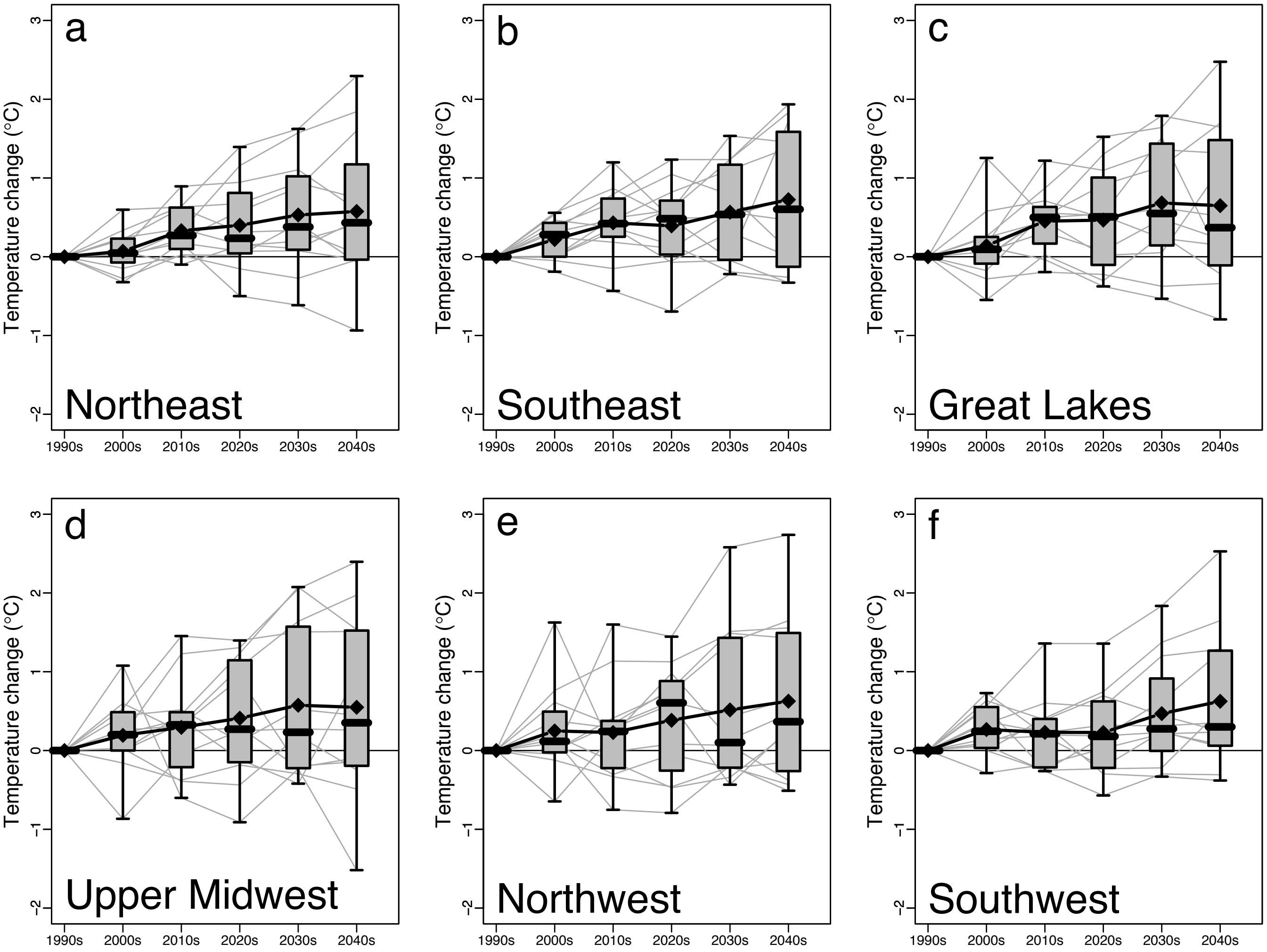
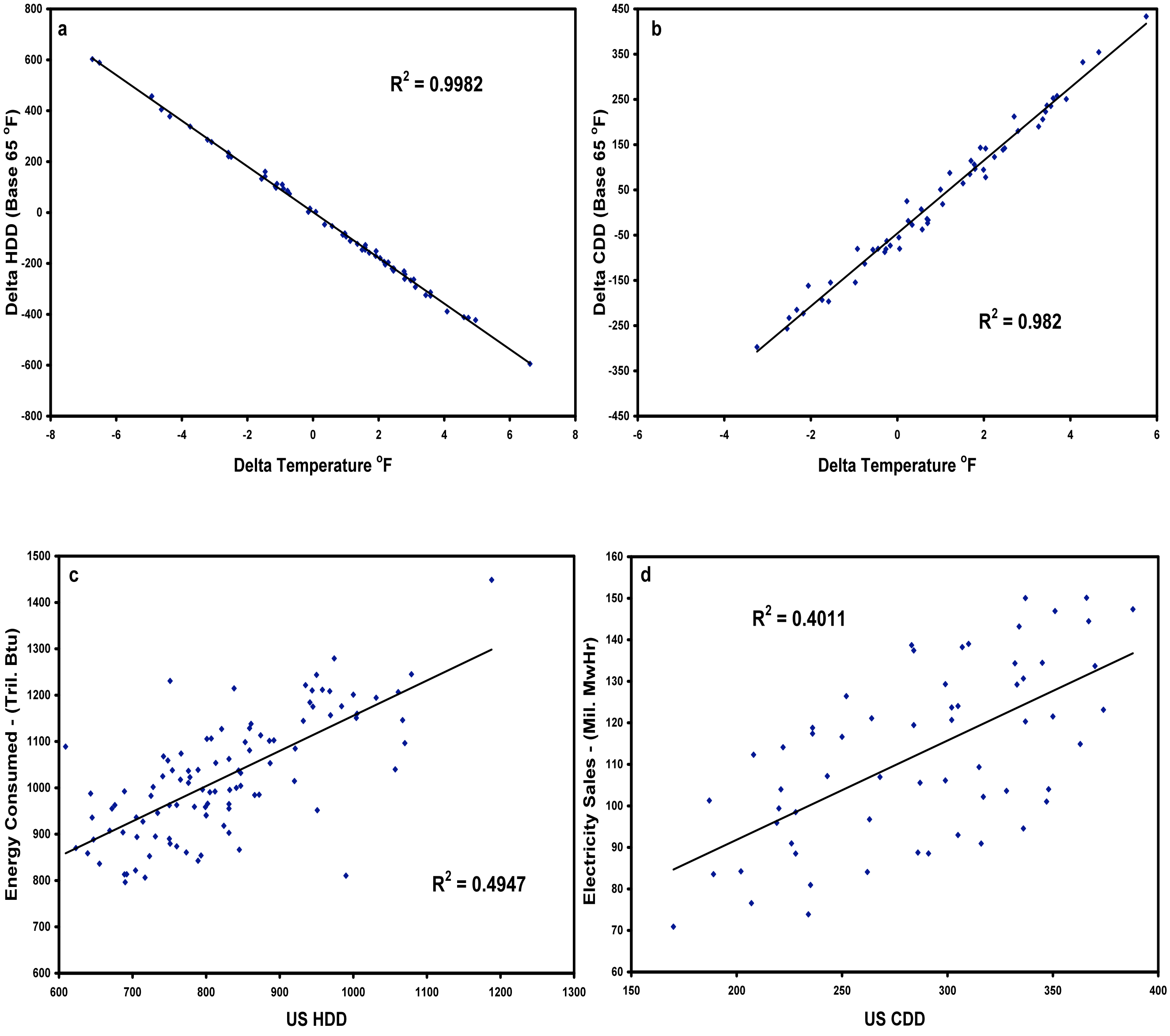


Figure 8. *Same as Fig. 7 except for the summer months (JJA).*



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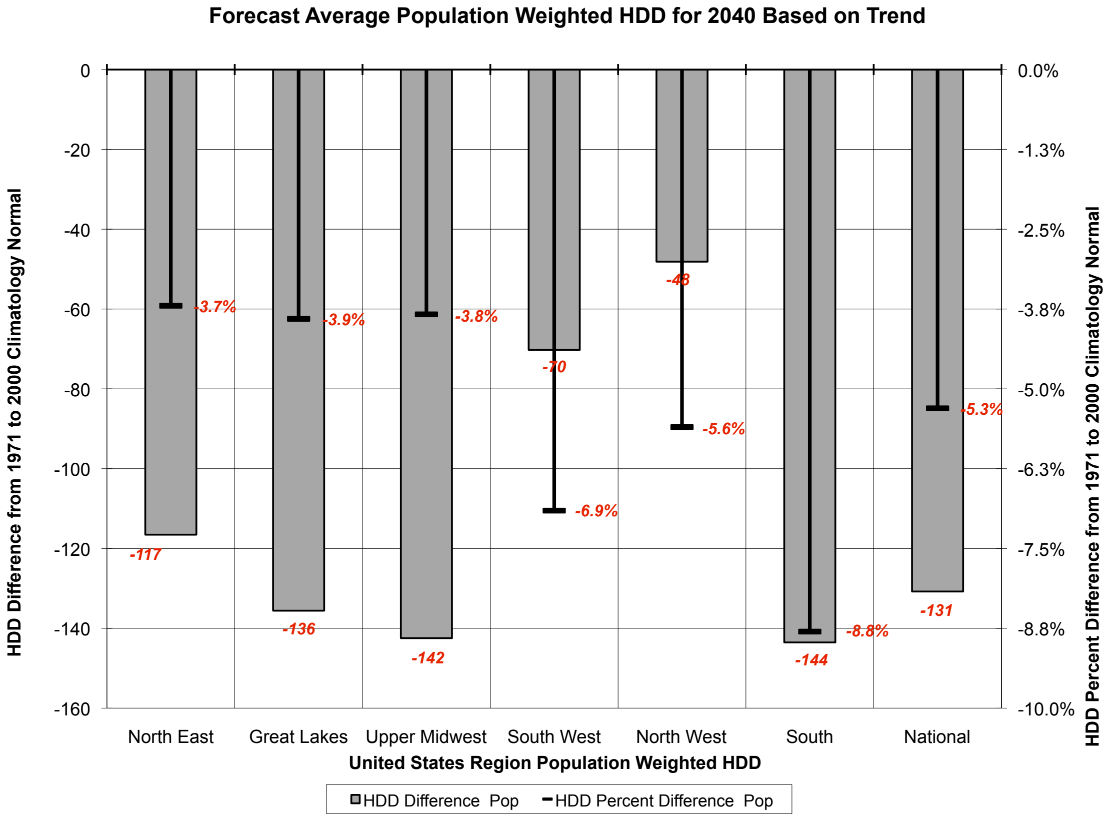

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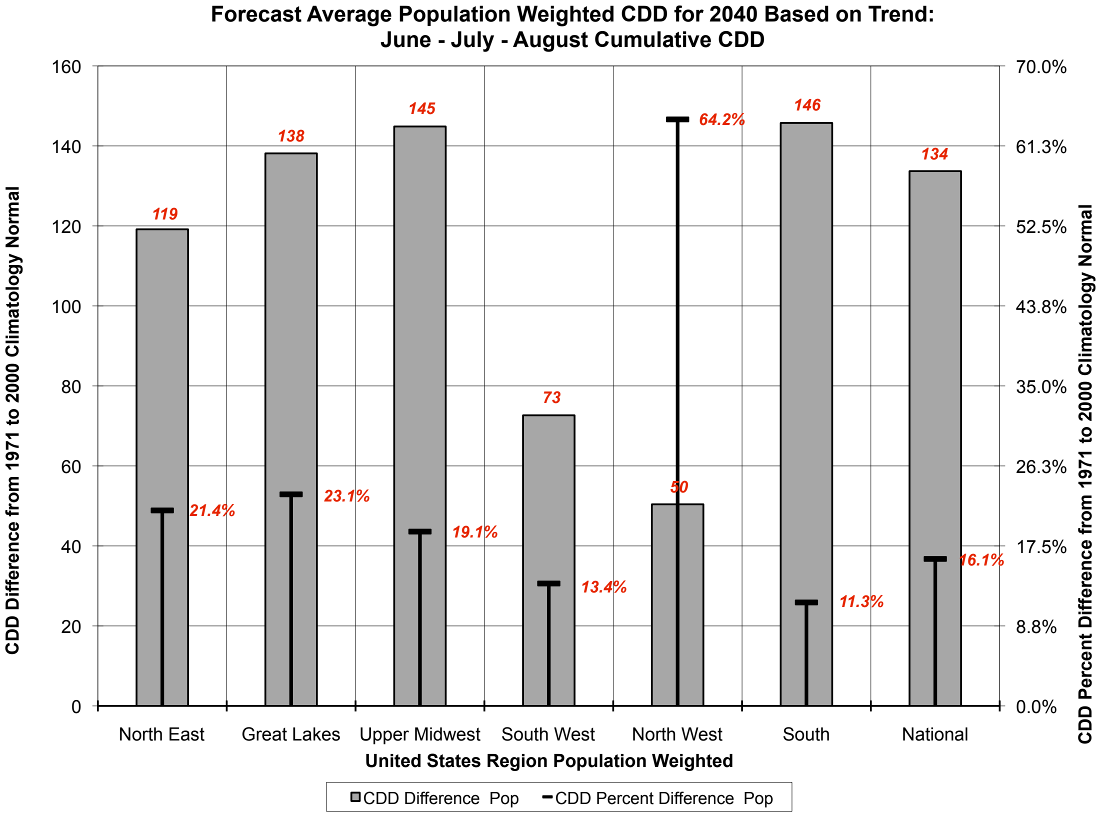

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