# AN INDEX TO MEASURE THE INFLUENCES OF CLIMATE ON RESIDENTIAL NATURAL GAS DEMAND

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# ABSTRACT

Quantifying the relationship between temperature fluctuations and energy usage can be useful for many aspects of planning for ongoing operations and future economic development. This thesis describes work to develop an objective technique to relate the monthly and seasonal residential consumption of natural gas in the U.S. to atmospheric temperature fluctuations, focusing on the cold part of the year when residential demand is dominated by heating. It improves on previous work through the use of a new analysis technique to better gauge the impact of daily weather extremes. The objective is to quantify the relationship between daily temperature fluctuations and monthly residential natural gas demand with the specific goal of creating a statistical model that predicts how anomalous temperatures affect natural gas demand on monthly and seasonal timescales. The model provides estimates of the percent departure of natural gas demand from the long-term average given appropriate forecasts of temperature variations. The approach is based on calculation of days below a specified temperature threshold that is different for each location, and thus differs from conventional "heating degree day" approaches. The threshold for each station is determined as a percentile boundary in the daily temperature distribution observed over a control period (1987-2004). A national index for a given month or group of months is then constructed by weighting each station temperature by the estimated long-term mean gas consumption of the surrounding region. It is shown that this index does an excellent job of explaining year-to-year fluctuations in the observed U.S. residential natural gas consumption, at least when long-term trends in consumption are removed. Such trends are likely related principally to non-meteorological factors such as population growth and changes in consumer preferences.

This study also addresses the extent to which natural gas demand will change in the future based on long-term projections of the atmospheric warming expected to result from anthropogenic forcing. Specifically the results of a forecast of temperature in the late 21st century versus late 20th century made by the MIROC3.2 "high-resolution" global climate model is used together with the statistical gas demand model developed here. The results suggest that, holding non-climate-related factors constant, the U.S. cold season residential natural gas consumption can be expected to decline substantially over the next century due to global warming. The climate model data are available at daily temporal resolution and at fairly fine spatial resolution (~100 km), and results of an investigation of the sensitivity of the natural gas consumption forecast to the time and space resolution of the temperature data employed are presented.

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# CHAPTER 1
# INTRODUCTION

## 1.1 Weather Effects on Residential Natural Gas Consumption

It has been long recognized that weather has a significant impact on the nation's economy. The U.S. Department of Commerce's Bureau of Economic Analysis estimates that 42% of the nation's economy is climate sensitive (National Research Council, 1998).

The National Climatic Data Center (NCDC), the world's largest active archive of weather data, has as a task to track and evaluate climate events in the U.S. that have great economic and societal impacts. For the period 1980-2005, NCDC computed that the U.S. has had 67 weather related disasters that accounted for a total of losses of approximately $540 billion. It has been determined that the nation's weather-related losses are mainly due to hurricanes, floods, severe thunderstorms, effects of excessive moisture and temperature on crops, tornadoes, winter storms, hail, and windstorms (Changnon and Hewings, 2001).

Energy demand, one of the economy's most important aspects, has received a great deal of attention because it is directly affected by weather and climate anomalies (Warren and LeDuc, 1981). It is well understood that when cold season temperatures are lower (higher) than normal, energy demand for residential heating increases (decreases). In the warm season demand for air conditioning increases (decreases) with temperatures higher (lower) than normal. This strong relationship between residential energy demand and climate anomalies has been previously documented (Quayle and Diaz, 1980; LeComte and Warren, 1981; Warren and LeDuc, 1981; Downton et al, 1988; Lehman and Warren, 1993; Changnon et al, 1999; Heim et al 2003). Most studies have related residential energy consumption to accumulated heating and cooling degree-days (HDD and CDD respectively), which are defined in terms of the deviation from a reference temperature (Downton et al 1988).

The HDD concept is based on the notion that heating is not necessary when the daily mean temperature is above or equal to a reference temperature. This reference temperature is thought to be a "comfortable" temperature, so that when the daily mean is below the "comfortable" temperature some residential heating is required (Downton et al, 1988). Similarly the CDD approach assumes that when daily mean temperatures are below or equal to a reference temperature residential cooling is not necessary.

The majority of previous studies of heating demand have based their analysis on the standard reference temperature of 65°F (Quayle and Diaz, 1980; Comte and Warren, 1981; Downton et al, 1987; Heim et al, 2003), although it has also been suggested that due to conservation methods and changes in standards of comfort it might be more appropriate to use a lower reference temperature (Downton et al, 1988).

Quayle and Diaz (1980) showed that HDD is a useful measure for estimating energy demand. They computed correlations between monthly electric energy consumption and total HDD for the cold season of November through May for the period 1966-1977. The correlations were as high as 0.84 suggesting that the primary variable controlling the fluctuations in residential heating is temperature. This proved that an increase in HDD means an increase in energy demand and usually an increase in energy price (Quayle and Diaz, 1980).

With the understanding of how climate anomalies affect the energy demand, accurately forecasted seasonal temperatures can be used in gauging future energy needs. An example of this is provided by a study completed by researchers at Northern Illinois University (NIU). Their objective was to assist the university's heating plant manager with NIU's natural gas purchase decisions for the fall of 1997. Since the deregulation of the natural gas market, consumers have the option to "lock in" a current price for a fixed period or pay for natural gas based on its continuous price adjustments to the market (Changnon et al 1999). Using a statistical model, the group forecasted a warmer than average winter due to the presence of a very strong El Niño, which they then predicted would lead to a lower demand in natural gas and thus lower natural gas prices. So the researchers encouraged the heating plant manager to "ride the market". By doing so, the heating plant manager bought natural gas incrementally at a falling rate and thus saved NIU a total of $500,000.

With the understanding that a climate impact indicator would be beneficial for those who manage climate risks, NCDC has developed an index to enhance the understanding of weather and climate's impact on U.S. energy demand (Heim et al, 2003). The Residential Energy Demand Temperature Index (REDTI), a national level index based on monthly and seasonal population weighted HDD and CDD, is computed using historical data on year to year fluctuations in temperature and energy demand for residential heating and cooling. To determine how well the index would capture these year to year changes, the REDTI was correlated with the U.S. residential energy consumption for the period 1980-2000. The correlation for the winter season was 0.75

(Heim et al. 2003). However, the current study was motivated by a belief that the quantification of the relationship between temperature and energy usage can be improved through the use of new analysis techniques to better gauge the impact of daily extremes.

The current study generalizes the original Heim et al. work through the creation of a new index that measures the impact of anomalous weather and climate conditions on residential energy consumption using temperature data of higher temporal resolution to better account for daily variations. The objective of this study is to quantify the relationship between daily temperature fluctuations and energy demand, particularly natural gas consumption used for residential heating, with the goal of creating a statistical model that improves the understanding of how anomalous daily temperatures affect residential natural gas demand on monthly and seasonal timescales. The model will provide estimates of the percent departure of residential natural gas demand from average and can be used retrospectively to help separate the influences of climate from other market forces. It can also provide improved estimates of future residential natural gas demand when combined with seasonal forecasts of temperature.

Although it has been previously shown that HDD are useful in estimating energy demand, the present study will apply a different approach for estimating residential natural gas demand. The technique is based on the calculation of days below a specified temperature threshold as determined with percentiles ("days below percentile" or DBP). The basis for this method is as follows.

It is well known that the U.S. has a broad range of climates and it is reasonable to suppose that residents of one region are "comfortable" with conditions that can differ greatly from those in other regions with different climates. For this reason an appropriate reference temperature of HDD for energy demand analyses should differ from region to region, yet 65°F is commonly used for all regions. DBP, being the number of days below a certain temperature threshold unique for each local area, allows us to select an appropriate reference temperature for each station used in the study. Thus in the present study the relationship between the length of anomalously cold periods, defined by the DBP, and residential cold season natural gas consumption is analyzed.

This study also addresses the extent to which U.S. cold season residential natural gas demand will change in the future due to possible climate change. It is known that atmospheric concentrations of many greenhouse gasses are rising in response to human activities and also that anthropogenic effects contribute to trends in atmospheric aerosol concentrations. The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report stated the current widespread consensus that these changes in atmospheric composition are driving already observable global climate changes and that under plausible scenarios for continuing anthropogenic changes the global mean climate may be expected to warm quite significantly by the end of the century (IPCC 2001). The present study will combine the indices for relating residential natural gas consumption to temperature along with a forecast of late-21st century atmospheric warming from a global atmosphere-ocean climate model to make one possible prediction for the climate-related component of future residential natural gas consumption. In addition the issue of how sensitive such a forecast is to the spatial and temporal resolution of the climate model simulation data will be investigated.

## 1.2 Background on U.S. Natural Gas Consumption

Natural gas, one of the nation's most important energy sources, was once considered a mystery to mankind. It is a combustible composed by a mixture of light hydrocarbons gases, primarily methane, and when burned it gives off a great deal of energy. As early as 500 BC the Chinese first discovered its usefulness as a source for heating salt water to separate the salts from the water and make it drinkable. In 1816 natural gas was first introduced as an energy resource in the U.S. But due to limitations on transportation, natural gas initially delivered only locally within the municipality it was produced and was exclusively used as source of light. Once practical means of transportation were developed, its use became much more widespread.

In the early stages of the natural gas industry, local governments feared the development of monopolies. They believed that, in the absence of competition, a company would take advantage of its position and charge overly-high prices. Due to this fear of possible abuse, the Natural Gas Act (NGA) of 1938 was established, regulating the natural gas market. This act gave authority to the Federal Power Commission (FPC) to monitor and set "reasonable" rates for the sale of natural gas. During this period, interstate pipeline companies would generally purchase the natural gas from producers and transport it to the local distribution companies, which in turn distributed and sold to customers (Jess 1997). Although the FPC imposed "reasonable" rates for pipeline services, it did not regulate prices of natural gas from the producers to the pipelines. It was not until 1954 that the Supreme Court decided that natural gas producers that sold the product to interstate pipelines would fall under the FPC regulations, regulating the prices at the wellhead as well. This price control had negative consequences that became quite visible in the early 70's.

Since the price of natural gas was below the market value, producers saw no reason to explore for new reserves. In view of the fact that the FPC only regulated wellhead prices for the interstate market, producers sold the natural gas at a much higher price to the intrastate market. This resulted in a successful intrastate market satisfying the natural gas demand yet resulted in a number of shortages and price irregularities in the interstate market. It was taken as a sign that a regulated market was not optimal for either the industry or consumers. As a consequence the natural gas market moved towards deregulation, resulting in a greater and healthier competition in the market. Since the deregulation of natural gas, customers have the option to purchase the natural gas from producers at a "lock in" price or "ride the market" price which is continuously adjusted. Thus it is of great importance to quantify the relationship between temperature and natural gas demand.

Today, natural gas is considered to be the nation's fastest growing energy source. According to the Energy Information Administration (EIA), natural gas accounted for 23% of world energy production in 1999 and it accounts for 24% of total energy consumed in the United States. Although there are many different applications for this fossil fuel (e.g. commercial, residential, and industrial), the focus of this research is on its use for residential heating.

In 2000, the American Gas Association (AGA) estimated that about 52% of the nation's households use natural gas to heat their homes. It has become one of the most popular energy sources for residential heating and as years pass by more homes prefer natural gas as their primary source of heating. Due to its versatility, efficiency, environmentally friendliness and cost, the EIA projects an increase in demand of about 40% by 2025 (Natural Gas Facts, 2006).

Natural gas is an efficient fossil fuel due to the fact that about 90% of natural gas produced is delivered to consumers as useful energy, while only about 27% of energy converted to electricity reaches consumers (American Gas Association, 2006). Historically it has been one of the cheapest forms of energy available to residential consumers. In 2002, the Department of Energy (DOE) conducted a study in which they estimated that natural gas has had the lowest cost of all energy sources available for residential use (American Gas Association, 2006). It is considered an environmentally friendly source owing to the fact that it emits lower levels of potentially harmful byproducts into the air compared to other fossil fuels. For example, the EIA estimated that natural gas produces 117,000 pounds of carbon dioxide per billion Btu; meanwhile, oil produces 164,000 pounds of carbon dioxide per billion Btu and coal produces 208,000 pounds of carbon dioxide per billion Btu. Because $CO_2$ is the primary long-lived, anthropogenic greenhouse gas, the EPA, the United Nations Intergovernmental Panel on Climate Change and others have suggested energy consumers change to natural gas to help alleviate global climate change (American Gas Association, 2006).

# CHAPTER 2
# DATA

This chapter provides a detailed description of the temperature and residential natural gas consumption data used to conduct this research. Also provided is a description of the climate model and the integrations used in this study in projecting changes in atmospheric temperature during the 21st century.

## 2.1 Temperature Data

The daily temperature data used to calculate percentiles and days below percentiles (DBP) are from the DSI-3200 data available from NCDC. This data set provides information for a total of 23,000 stations in the nation but only about 8,000 of these are active. The period of record for each station varies among states but the majority began collecting data during 1948 (NCDC DSI-3200). A variety of parameters are provided in this data set such as maximum and minimum temperature, snowfall, and 24 hour precipitation totals. We will focus on the analysis of maximum, minimum, and mean temperatures which are given in degrees Fahrenheit with an estimated precision to the nearest $\pm$ 0.1°F. Although mean temperature is not included in the TD-3200 dataset an approximation to the daily mean was computed by averaging the maximum and minimum temperature for each day.

$$Mean \approx \frac{Max + Min}{2} \tag{2.1}$$

This approximation has been used throughout the U.S. for many years as a result of the ready availability of daily maximum and minimum temperatures of stations across the nation (WMO, 1983). However, it has been recognized that the averaging of hourly values would be ideal (Guttman and Lehman, 1992).

To begin the process of the analysis, a subset of the TD-3200 dataset was selected by identifying the stations with the most homogeneous time series within the nation. Inhomogeneities in a station record can be caused by various factors, such as changes to the observation schedule, changes in the instrumentation and/or changes in land use/land cover in the surrounding area that might cause a break point or a spurious local trend (Menne and Williams 2005). The stations used for this study were those that passed the Menne and Williams (2005) statistical homogeneity tests. By doing so a total of 2,082 stations over the contiguous U.S. that had the fewest moves and instrumental changes detected were identified and data from these stations are the basis of the present analysis (see Figure 2.1.1).

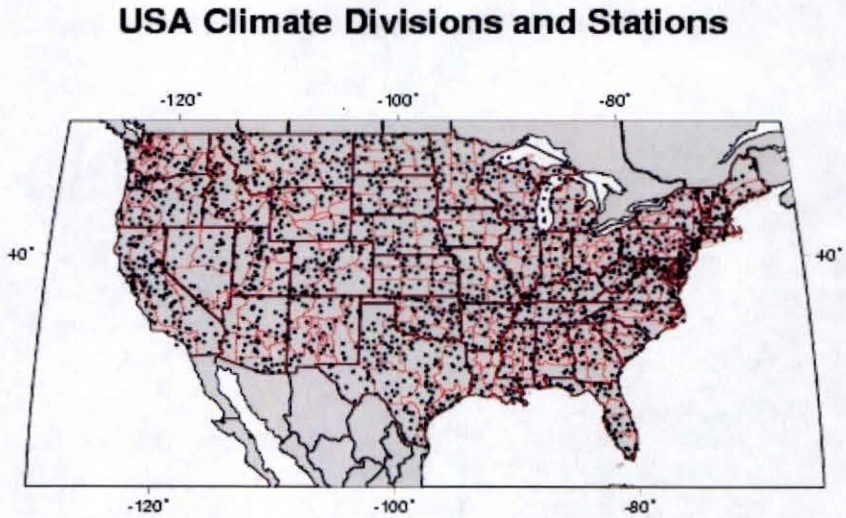

Figure 2.1.1: Distribution of stations that passed the Menne and Williams (2005) statistical homogeneity tests over the contiguous U.S.

## 2.2 Residential Natural Gas Consumption Data

The residential natural gas consumption data used in this study were provided by the Energy Information Administration (EIA), which offers values of both state and national level residential consumption. The national monthly residential natural gas consumption data are available from 1973, but the state monthly residential natural gas consumption data are only available from 1989. In this study we will concentrate initially on analyzing data from 1987 to 2004, but will also use the full 1973-2004 data.

In most areas of the nation some residential heating is necessary during the cold season months of November through April. Thus the present study is focused on the winter and cold seasons which have been defined as follows: the winter season is comprised by December through February and the cold season is comprised by November through April. The national residential natural gas consumption was available on a monthly basis and the computation of the seasonal natural gas consumption was accomplished by aggregating the consumption for each month that composed a particular season. For example, winter of 1987 is the sum of residential natural gas consumption for December 1987, January 1988, and February 1988. Since data from 2005 was not available at the time the study was initiated, the focus of the seasonal analysis is on the seasonal periods for years 1987-2003 (i.e. using data from November 1987 through April 2004).

As previously mentioned, due to fear of possible abuse in the natural gas market the Natural Gas Act (NGA) was established to regulate the market. The NGA gave the Federal Power Commission (FPC) the authority to monitor and control the price rates of the natural gas. The FPC regulated the wellhead prices for the interstate market to be lower than the market value, benefiting the customers but causing losses to the producers. Given that the wellhead prices were not regulated in the intrastate market, producers began to sell natural gas at higher prices that would benefit the market in the states that natural gas was produced, leaving the consumer states with limited supplies; as a result consumption declined sharply in the early 70's to mid 80's (see Figures 2.2.1 and 2.2.2). It was then immediately understood that a deregulated market would lead to much healthier competition in the market and thus would benefit both consumers and the industry. Since the main focus of this study is to determine a relationship between residential natural gas consumption and wintertime temperature, the analysis of this study will focus on the data from 1987 to 2004 for the contiguous U.S. since the pre-1987 year's residential natural gas consumption pattern was strongly affected by non weather related variables.

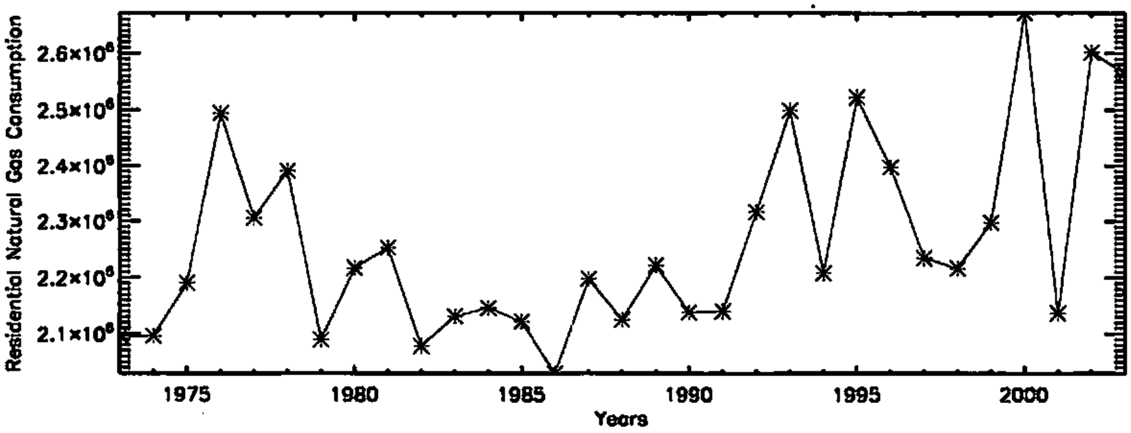

Figure 2.2.1: Time series of the nation's natural gas consumption for the winter season (December – February) for the period of 1973-2003.

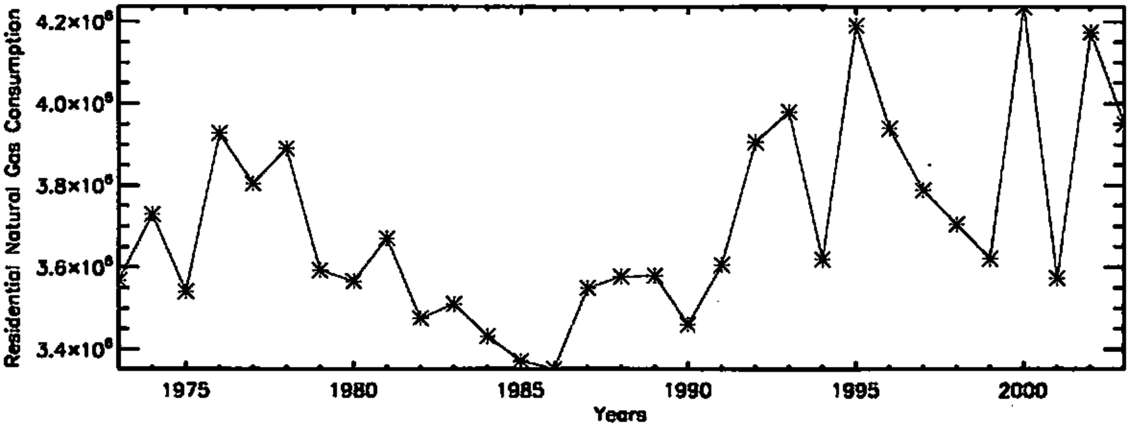

Figure 2.2.2: Time series of the nation's natural gas consumption for the cold season (November – April) for the period of 1973-2003.

The national residential natural gas consumption obtained from the EIA website includes Hawaii and Alaska. Table's 2.2.1-2.2.2 give the monthly values of gas consumption for November through April each year for 1989 to 2004 in Alaska plus Hawaii and the entire U.S., respectively. Since our study emphasizes the contiguous U.S. there were no adjustments performed on the residential natural gas data since the total consumption of Hawaii and Alaska constitutes less than 1% of the national residential natural gas consumption and such a correction would only be possible after 1989.

| Alaska and Hawaii Residential Natural Gas Consumption Data | | | | | | |
|---|---|---|---|---|---|---|
| Year | Jan | Feb | Mar | Apr | Nov | Dec |
| 1989 | 1,844 | 2,200 | 1,616 | 1,273 | 1,520 | 1,702 |
| 1990 | 1,794 | 2,142 | 1,811 | 1,231 | 1,631 | 2,264 |
| 1991 | 1,981 | 1,897 | 1,526 | 1,309 | 1,400 | 1,737 |
| 1992 | 1,828 | 1,983 | 1,812 | 1,392 | 1,484 | 1,732 |
| 1993 | 2,130 | 2,189 | 1,523 | 1,336 | 1,307 | 1,819 |
| 1994 | 1,868 | 1,816 | 2,004 | 1,531 | 1,544 | 2,245 |
| 1995 | 2,112 | 1,975 | 1,964 | 1,623 | 1,454 | 2,339 |
| 1996 | 2,103 | 2,470 | 1,971 | 1,473 | 1,749 | 2,225 |
| 1997 | 2,300 | 1,667 | 1,813 | 1,218 | 1,726 | 2,207 |
| 1998 | 2,293 | 1,768 | 1,574 | 1,288 | 1,898 | 2,227 |
| 1999 | 2,717 | 2,271 | 2,119 | 1,361 | 2,163 | 2,508 |
| 2000 | 2,403 | 1,935 | 1,812 | 1,280 | 1,791 | 2,058 |
| 2001 | 1,933 | 1,871 | 1,867 | 1,230 | 2,230 | 2,832 |
| 2002 | 2,106 | 1,981 | 2,163 | 1,455 | 1,447 | 2,122 |
| 2003 | 2,267 | 1,755 | 2,094 | 1,374 | 2,363 | 2,476 |
| 2004 | 3,199 | 2,095 | 2,108 | 1,458 | 2,047 | 2,514 |

Table 2.2.1: Total Natural Gas Consumption Data for Alaska and Hawaii

| U.S. Residential Natural Gas Consumption Data (MMcf) | | | | | | |
|---|---|---|---|---|---|---|
| Year | Jan | Feb | Mar | Apr | Nov | Dec |
| 1989 | 751,166 | 743,050 | 645,859 | 414,487 | 405,314 | 790,934 |
| 1990 | 788,596 | 642,665 | 551,987 | 399,624 | 375,652 | 630,275 |
| 1991 | 843,832 | 664,218 | 573,093 | 372,922 | 459,455 | 658,449 |
| 1992 | 785,718 | 696,082 | 573,979 | 431,401 | 436,771 | 717,170 |
| 1993 | 830,874 | 768,365 | 703,183 | 449,738 | 457,330 | 705,034 |
| 1994 | 952,520 | 841,815 | 630,616 | 392,153 | 391,460 | 638,175 |
| 1995 | 815,547 | 754,491 | 600,034 | 418,820 | 488,812 | 757,844 |
| 1996 | 933,642 | 830,912 | 705,207 | 473,842 | 502,981 | 737,722 |
| 1997 | 902,399 | 757,457 | 605,856 | 433,073 | 497,310 | 731,030 |
| 1998 | 812,108 | 691,819 | 647,619 | 407,752 | 398,094 | 615,913 |
| 1999 | 911,162 | 689,687 | 669,270 | 420,192 | 371,595 | 659,606 |
| 2000 | 862,900 | 775,235 | 550,261 | 400,886 | 482,600 | 914,339 |
| 2001 | 976,677 | 780,482 | 681,884 | 400,728 | 360,721 | 609,025 |
| 2002 | 815,227 | 712,863 | 660,430 | 415,196 | 483,192 | 771,634 |
| 2003 | 945,975 | 884,238 | 674,582 | 414,495 | 413,663 | 738,596 |
| 2004 | 966,158 | 859,539 | 592,332 | 380,466 | 408,781 | 727,918 |

Table 2.2.2: Total Natural Gas Consumption Data for the nation.

## 2.3 Model Data for Future Climate Projections

Even in the absence of climate change, it is reasonable to expect trends in the U.S. residential natural gas consumption. As mentioned earlier, the EIA predicts an increase of about 40% in the U.S. consumption by 2025 simply due to the economic and other practical factors that will promote demand. However, it is also reasonable to expect the climate of the U.S. to change significantly over the next century in response to anthropogenic changes in atmospheric composition, most notably in the concentration of carbon dioxide (e.g. IPCC 2001). This will be a factor that should act to reduce cold-season residential natural gas consumption. One aim of the present study is to estimate the effect of projected 21st century climate change on the U.S. residential natural gas consumption, assuming all other factors affecting demand are held constant.

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body providing authoritative reviews of climate science. As part of the preparation of their Fourth Assessment Report (AR4), the IPCC oversaw an intercomparison project for global coupled atmosphere-ocean models. Groups at about 15 centers worldwide contributed data from a set of prescribed model integrations, and the IPCC have made these data available for analysis. Of particular interest here are (i) the simulations meant to be representative of the 20th century (so-called "20c3m" runs), and (ii) simulations that begin from the 2000 results in the 20c3m runs and continue through the 21st century, employing projected scenarios of long-lived greenhouse gas concentrations and sulphate aerosol concentration.

The present interest is in determining the possible influence of climate change over the 21st century on the U.S. residential natural gas consumption. Specifically, the gas consumption model developed here will be applied to projected late 21st century atmospheric temperatures. The AR4 data base provides results for several different 21st century scenarios and integrations from many models. The present study will consider results using the so-called IPCC SRES (Special Report on Emission Scenarios) A1B scenario. The basic economic and political assumptions that enter the formulation of the A1B scenario are a future world of new and efficient technology, rapid economic growth and a global population that peaks in mid-century and then declines afterwards. Fig. 2.3.2 shows the projected concentrations of carbon dioxide, methane and nitrous oxide in the SRESA1B scenario along with a number of other scenarios proposed by the IPCC SRES. The A1B scenario is roughly in the middle of the range of plausible scenarios proposed by SRES, in terms of projected greenhouse gas concentrations.

Even assuming a specific scenario for projected atmospheric composition, the various climate models in the AR4 intercomparison produce different forecasts of global warming. Generally for the SRESA1B scenario models will display between roughly 2°C and 4°C warming of the global-mean surface air temperature over the 21st century. For the present study results from just one model, the so-called MIROC high resolution model will be used. This was chosen because it was the AR4 model that had the finest spatial resolution simulations (typically 2 or 3 times finer than most of the other AR4 models). The fine MIROC model resolution is valuable since one of the key advantages of the present method for relating gas consumption to weather conditions is the ability to employ very fine spatial resolution daily temperature data.

MIROC is an acronym for Model for Interdisciplinary Research on Climate, and this is a coupled global atmosphere-ocean simulation model developed jointly by the University of Tokyo Center for Climate System Research, the Japanese National Institute for Environmental Studies and the Frontier Research Center for Global Change (Hasumi and Emori, 2004). It has existed in various versions, but the version MIROC3.2 was used for the IPCC AR4 runs and this is described at:

http://www-pcmdi.llnl.gov/ipcc/model_documentation/MIROC3.2_hires.htm.

The atmospheric component of the high resolution version of MIROC employed here was run as a spectral model with T106 truncation and results are saved on a 1.125 degree latitude-longitude grid. The raw data used here are daily mean values of the surface temperature at all grid points in the contiguous U.S. (Figure 2.3.1). Results from 20 years of the 20c3m run (January 1981 through December 2000) and from the last 20 years of the SRESA1B run (January 2081 through December 2100) will be employed.

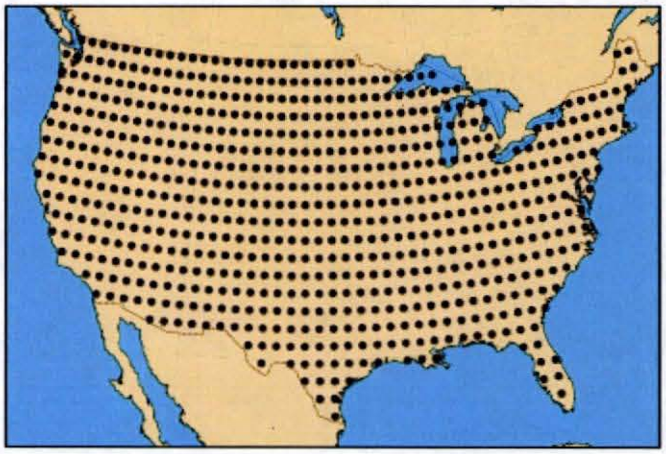

Figure 2.3.1: MIROC 3.2 grid points within the contiguous U.S.

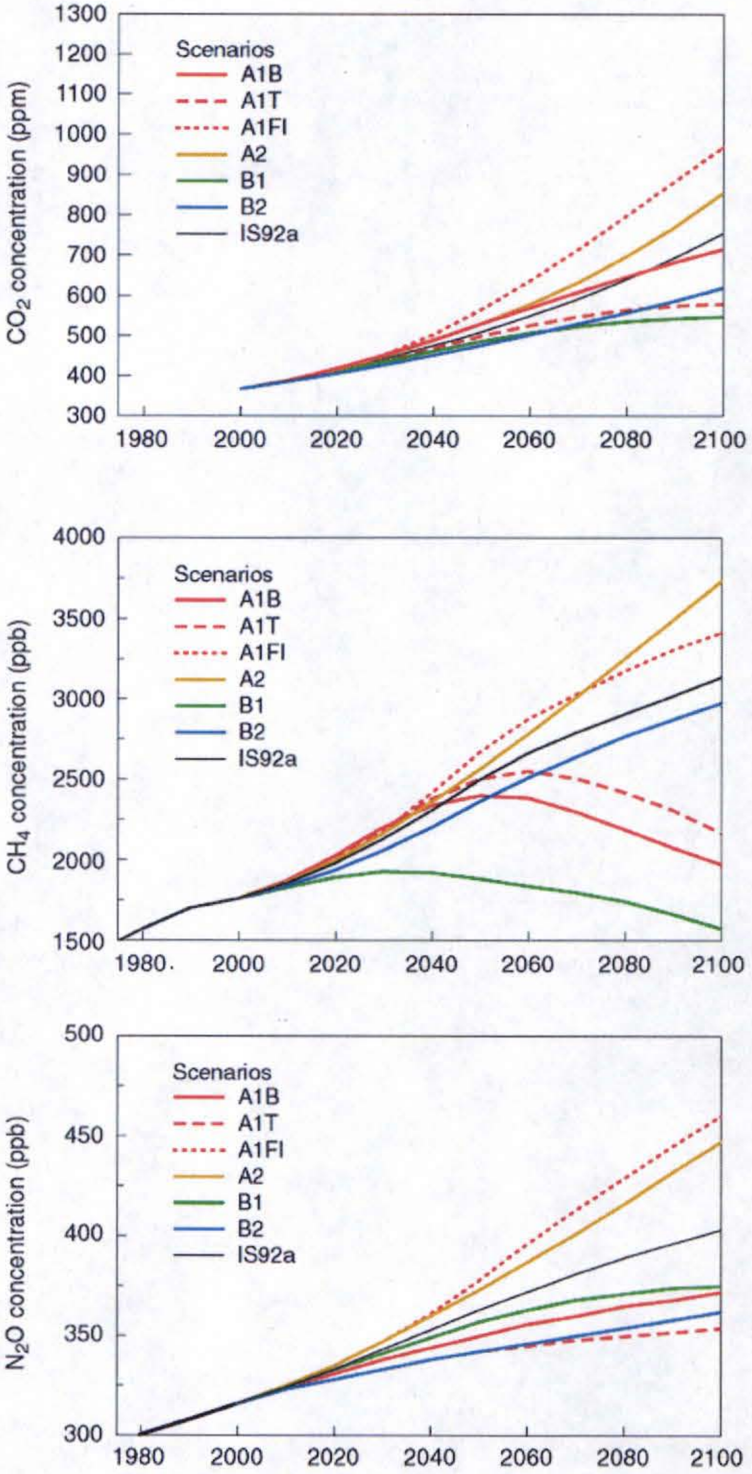

Figure 2.3.2: Atmospheric concentrations of $CO_2$, $CH_4$, and $N_2O$ resulting from the SRES scenarios. (Source: IPCC)

While computing the mean monthly warming for each grid point, a further step was taken to estimate the contiguous U.S. warming predicted to occur in the late 21st century. By averaging the daily estimated warming over the grid points located in the contiguous U.S., monthly warming was obtained. Table 2.3.1 displays the MIROC forecast of projected surface air temperature warming averaged over the contiguous U.S. for each month. It is interesting to compare these results with the map of forecast surface warming recently published online by the IPCC AR4 Working Group 1 in their Summary for Policymakers. This is based on the multimodel ensemble (i.e. an average over the results for all roughly 20 models used in preparing the report) and shows the annual-mean warming of 2091-2100 over 1981-1999 in the SRESA1B. Over the continental U.S. the multimodel warming estimate is between 3.5 and 4.5°C (approximately 6.5-8°F) which is somewhat less than in the MIROC model. In the model comparisons performed for the 2001 IPCC assessment (the earlier version of) the MIROC model was also found to predict stronger warming than most other models.

| | |
|---|---|
| January | 10.07°F |
| February | 9.69°F |
| March | 11.34°F |
| April | 9.74°F |
| May | 9.23°F |
| June | 9.81°F |
| July | 10.62°F |
| August | 11.72°F |
| September | 11.42°F |
| October | 10.27°F |
| November | 7.96°F |
| December | 8.90°F |

Table 2.3.1: Estimated monthly warming to occur in the late 21st century.

# CHAPTER 3
# METHODOLOGY

A detailed description of the methodology employed in calculating monthly and seasonal days below percentiles (DBP) is presented in this chapter. An explanation of the weighting process used to maximize the DBP correlation with respect to residential natural gas consumption is offered followed by a description of the process for generating the linear statistical regression model. In addition, the methodology for applying the Global Climate Model (GCM) daily mean data in this study can be found within this chapter.

## 3.1 Days Below Percentiles

The initial step taken to quantify the relationship between winter temperatures and residential natural gas consumption was the computation of percentiles. Percentiles are defined as thresholds or boundary values in frequency distributions. For example, the 20th percentile is the value which marks off the lowest 20 percent of the observations from the rest. The 50th percentile is the median, and the 80th percentile exceeds all but 20 percent of the values (Wilks 1995).

The percentile boundaries were calculated for each station and for each temperature element (daily max, min, and mean) from the 5th percentile to the 90th percentile using a 5 percent increment. These percentiles were computed by extracting all non-missing data for all months and those that composed the winter season (December through February) and the cold season (November through April).

The non-missing data for each season (winter and cold) were extracted from the daily temperatures during the years 1949-2003 and sorted in ascending order. The temperature threshold for each percentile, e.g. 50th percentile, was computed by determining which temperature surpassed 50 percent of the sorted values. It can also be described as the daily temperature value that exceeded a random member of the total days found in the season for the period of 1949-2003, with a probability of 0.5 or 50 percent (Wilks, 1995).

Figure 3.1.1 shows illustrative results from a single station. The frequency distribution plotted in this figure used real station daily observations for the period of 1981-2000 (this period was chosen for comparison purposes explained in Chapter 5) for the winter season. For this example the 20th percentile has as a temperature threshold of 24°F, while the 50th percentile has a temperature threshold of 34°F, and the 80th percentile has as a threshold 43°F.

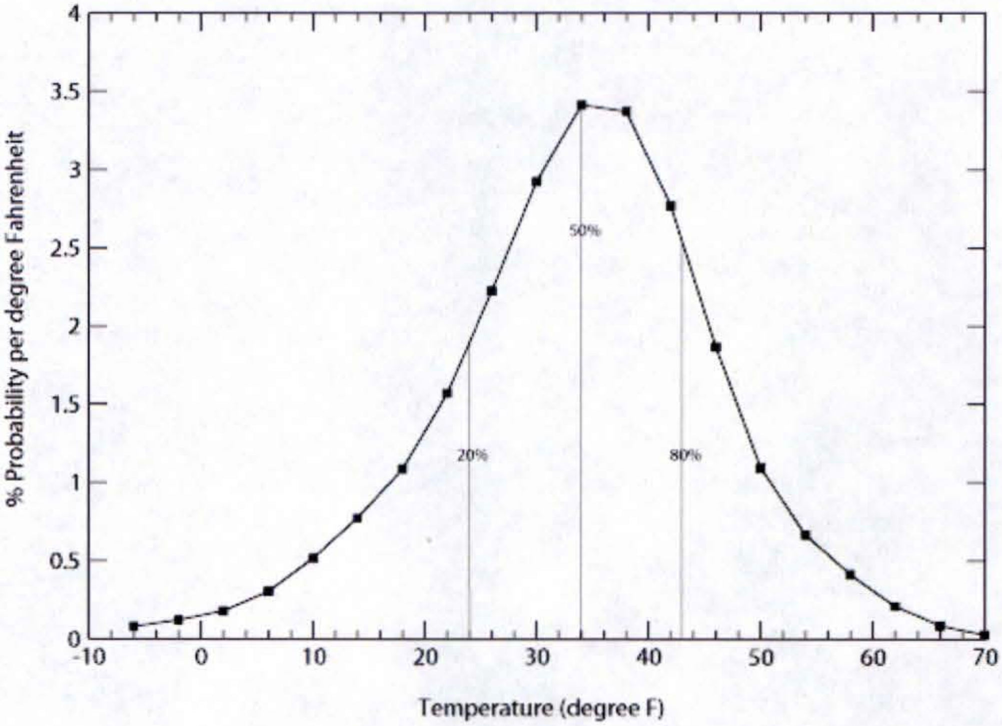

Figure 3.1.1: Frequency distribution for the winter season of a station located in the Southeast climate division in Illinois.

After computing the temperature thresholds for each percentile, for each station, and each temperature element for a particular season (winter or cold season) calculation of the days below percentiles (DBP) followed. Even though data for the nation's residential natural gas consumption was available for 1973 to 2004, the time period for this analysis was 1987-2004 (see chapter one). Hence, the calculation of the total number of days below a percentile or temperature threshold, for all selected stations within the contiguous U.S. began in 1987 and ended in 2004 (seasonal analysis ended in 2003). This was accomplished by aggregating or adding the days that were below a particular percentile threshold for a given season. Again this calculation is performed for all temperature elements.

In calculating the national index, a weighting method was employed to give more significance to those stations that are located in more heavily populated areas. This was based on the assumption that areas with greater population density would have a greater influence on the residential natural gas consumed within a state compared to areas with less population.

To pursue the calculation of the state level weighted DBP for each season; a high-resolution (1km x 1km) 2000 population data set was used. The process of calculating population weighted (state level) DBP for all states involved selection of the nearest station to each population grid point that was located in a particular state. The equation used for weighting the DBP within each state is as follows:

$$SDBP = \frac{\sum_{i=1}^{n}(DBPi)(POPi)}{\sum_{i=1}^{n}(POPi)} \tag{3.1}$$

where $n$ represents the number of population grid boxes within a state, *DBP* represents days below percentiles for the nearest station to population grid box $i$ and *POPi* represents the population in grid box $i$. By doing so, the state days below percentiles (*SDBP*) are calculated. Lastly, the days below percentiles for the nation were calculated by weighting the SDBP by the mean residential natural gas consumption, to give more significance to those states that contribute the most to the national residential natural gas consumption. The equation used is as follows:

$$NDBP = \frac{\sum_{i=1}^{48} (SDBPi)(CONi)}{\sum_{i=1}^{48} (CONi)} \tag{3.2}$$

where *NDBP* represents the nation's DBP and *CONi* is the long-term mean (1989-2004) residential natural gas consumption for state *i*.

In Chapter 4 the time series of national DBP for each month and year will be correlated with measures of the national residential natural gas consumption. Three different measures will be used: (i) raw consumption values (plotted in Figures 2.2.1, 2.2.2 and again in Figures 3.1.2 and 3.1.3), (ii) detrended consumption values, and (iii) percent departure from the mean values.

The time series of the national residential natural gas consumption for each season during 1987-2003 are plotted in Figures 3.1.2 and 3.1.3. Examination of the time series of the nation's residential natural gas consumption reveals a positive trend in the consumption and suggests that a detrended time series may better reflect the year-to-year climate-related fluctuations. Residential natural gas consumption has been increasing through the late 1980's and 1990's due both to overall economic growth and increased favor among consumers due to its reputation as a clean, efficient, safe, and economical energy source. This distorted the relationship between the weighted DBP and the residential natural gas consumption. The linear least-squares trend for the 1987-2003 period is shown in Figures 3.1.2 and 3.1.3. Detrended time series of yearly values are then computed simply as the difference from the least-squares fit. Another quantity which will be referred to as the "adjusted values" are computed by simply adding the long-term

(1987-2004) means for the appropriate season to the detrended time series.

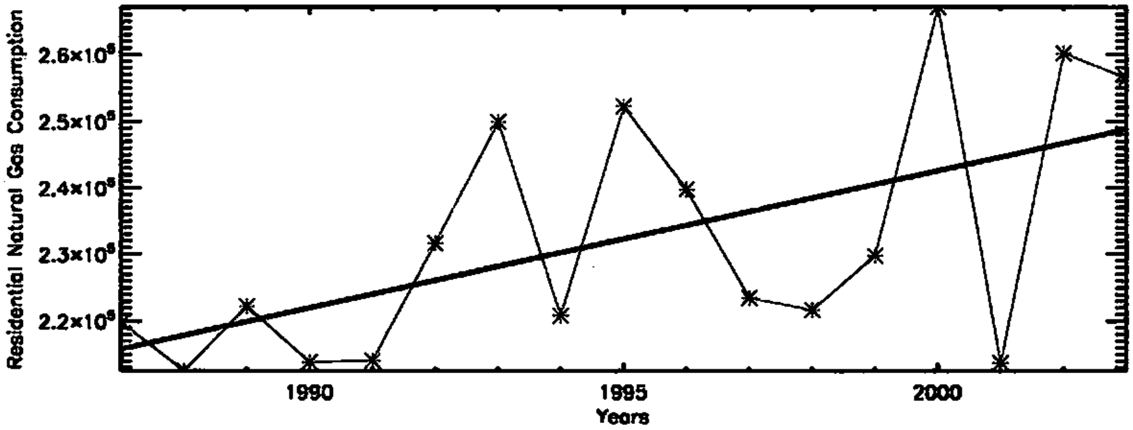

Figure 3.1.2: Time series of the total national natural gas consumption for the winter season (December to February).

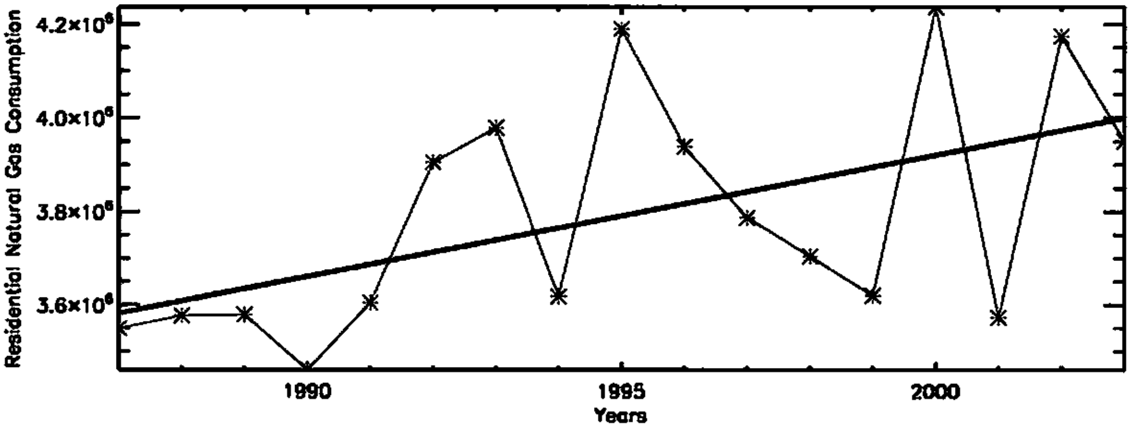

Figure 3.1.3: Time series of the total national natural gas consumption for the cold season (November to April).

Then the deviation of these adjusted values of residential natural gas consumption from the long term mean was computed. Finally, these deviations were divided by the mean residential natural gas consumption, and multiplied by 100 to obtain deviations in terms of percent of the long-term mean. The following mathematical equation illustrates this process:

$$Percent\ of\ departure = \frac{(AV - MAV)}{MAV} * 100 \qquad (3.5)$$

where $AV$ is the adjusted value of the detrended residential natural gas consumption and $MAV$ is the mean of the adjusted values.

### 3.2 Application to Projected Warming Data

The procedures outlined in Section 3.1 provide a technique to estimate the national gas consumption over a particular season given the daily temperatures over a fine grid of stations covering the contiguous U.S. If similar time series of temperatures for an altered climate could be determined, then the technique could be applied to estimate the change in gas consumption that could be attributed to the climate change. As noted in Section 2.3 the MIROC AR4 SRESA1B simulation gives an estimate of the expected surface warming of late 21st versus late 20th century. However the 20th century simulation in the MIROC model will have significant biases relative to actual observations (like all such models), and this prevents the most straightforward application of the results to calculate the gas consumption change. In this study the late 20th century gas consumption calculation will be based on the actual daily temperature observations while the 21st century temperatures will be based on the real daily data plus the warming inferred from the model calculation.

This approach requires that the model and real data are available at the same set of stations. In this study the real station temperature observations from 1981-2000 were interpolated onto the MIROC grid and then the predicted model warming (SRESA1B minus 20c3m) at each grid point was used to generate time series of late 21st century daily temperatures. More details will be provided in Chapter 5.

# CHAPTER 4
# RESULTS FOR RETROSPECTIVE DATA

A detailed analysis of the correlations computed between the national weighted DBP and residential natural gas consumption is found within this chapter. The creation of the statistical model is explained and two procedures to estimate the reliability of the model are also described.

## 4.1 Correlation analysis

Although previous studies have shown that the heating degree days (HDD) index is a useful measure for estimating energy demand, the present study will apply a different approach in estimating residential natural gas demand. The method employed was the calculation of days below a specified temperature threshold determined with percentiles (DBP). The method of calculating DBP, which represent the length of anomalously cold periods, were described in the previous chapter (see Section 3.1). The technique allows the computation of appropriate DBP for individual states (SDBP) and for the nation (NDBP) as a whole.

Correlations were computed in order to examine the relationship between NDBP and the nation's raw residential natural gas consumption over the period 1987-2004 (1987-2003 for seasons). The calculations were repeated for different values of the threshold used to define the DBP, with the aim of finding the threshold that leads to the largest correlation of NDBP and residential natural gas consumption.

| P<br>S | 25th | 30th | 35th | 40th | 45th | 50th | 55th | 60th | 65th | 70th |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.662 | 0.685 | 0.707 | 0.719 | 0.721 | 0.711 | 0.692 | 0.672 | 0.649 | 0.629 |
| 2 | 0.701 | 0.737 | 0.750 | 0.757 | 0.755 | 0.750 | 0.741 | 0.729 | 0.714 | 0.680 |
| 3 | 0.822 | 0.828 | 0.823 | 0.822 | 0.810 | 0.807 | 0.793 | 0.787 | 0.772 | 0.742 |
| 4 | 0.642 | 0.637 | 0.651 | 0.645 | 0.654 | 0.627 | 0.593 | 0.555 | 0.515 | 0.477 |
| 11 | 0.851 | 0.871 | 0.891 | 0.911 | 0.924 | 0.928 | 0.925 | 0.920 | 0.909 | 0.889 |
| 12 | 0.653 | 0.697 | 0.722 | 0.753 | 0.774 | 0.803 | 0.812 | 0.812 | 0.815 | 0.806 |
| 13 | 0.655 | 0.699 | 0.734 | 0.743 | 0.752 | 0.759 | 0.765 | 0.766 | 0.756 | 0.740 |
| 14 | 0.727 | 0.754 | 0.782 | 0.794 | 0.798 | 0.802 | 0.789 | 0.778 | 0.763 | 0.728 |

Table 4.1.1: Correlations between the national monthly/seasonal DBP and monthly/seasonal residential natural gas consumption. The first column gives the number of the calendar month considered (1-12) or 13 (December - February) or 14 (November – April). The weighted DBP were calculated using daily mean temperatures (estimated by eq. 2.1).

| P<br>S | 25th | 30th | 35th | 40th | 45th | 50th | 55th | 60th | 65th | 70th |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.664 | 0.675 | 0.680 | 0.656 | 0.634 | 0.598 | 0.557 | 0.531 | 0.522 | 0.510 |
| 2 | 0.754 | 0.769 | 0.770 | 0.763 | 0.756 | 0.752 | 0.737 | 0.721 | 0.701 | 0.660 |
| 3 | 0.848 | 0.848 | 0.843 | 0.839 | 0.828 | 0.814 | 0.796 | 0.782 | 0.751 | 0.715 |
| 4 | 0.631 | 0.616 | 0.607 | 0.589 | 0.564 | 0.549 | 0.550 | 0.512 | 0.445 | 0.399 |
| 11 | 0.893 | 0.904 | 0.915 | 0.916 | 0.924 | 0.925 | 0.919 | 0.912 | 0.898 | 0.881 |
| 12 | 0.707 | 0.754 | 0.793 | 0.814 | 0.831 | 0.837 | 0.841 | 0.834 | 0.819 | 0.802 |
| 13 | 0.731 | 0.762 | 0.776 | 0.788 | 0.787 | 0.783 | 0.777 | 0.764 | 0.745 | 0.720 |
| 14 | 0.815 | 0.826 | 0.826 | 0.812 | 0.796 | 0.780 | 0.761 | 0.744 | 0.727 | 0.698 |

Table 4.1.2: Correlations between the national monthly/seasonal DBP and monthly/seasonal residential natural gas consumption. The first column gives the number of the calendar month considered (1-12) or 13 (December - February) or 14 (November – April). The weighted DBP were calculated using maximum temperatures.

| P<br>S | 25th | 30th | 35th | 40th | 45th | 50th | 55th | 60th | 65th | 70th |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.617 | 0.647 | 0.672 | 0.689 | 0.695 | 0.700 | 0.689 | 0.686 | 0.681 | 0.680 |
| 2 | 0.737 | 0.736 | 0.726 | 0.715 | 0.704 | 0.678 | 0.657 | 0.623 | 0.584 | 0.538 |
| 3 | 0.717 | 0.714 | 0.691 | 0.671 | 0.638 | 0.625 | 0.619 | 0.622 | 0.639 | 0.633 |
| 4 | 0.567 | 0.617 | 0.635 | 0.646 | 0.680 | 0.667 | 0.655 | 0.636 | 0.592 | 0.548 |
| 11 | 0.789 | 0.805 | 0.824 | 0.844 | 0.859 | 0.870 | 0.868 | 0.860 | 0.849 | 0.833 |
| 12 | 0.623 | 0.647 | 0.677 | 0.691 | 0.696 | 0.706 | 0.714 | 0.730 | 0.735 | 0.738 |
| 13 | 0.609 | 0.647 | 0.660 | 0.666 | 0.669 | 0.669 | 0.665 | 0.664 | 0.661 | 0.647 |
| 14 | 0.628 | 0.637 | 0.637 | 0.655 | 0.657 | 0.662 | 0.673 | 0.686 | 0.694 | 0.681 |

Table 4.1.3: Correlations between the national monthly/seasonal DBP and monthly/seasonal residential natural gas consumption. The first column gives the number of the calendar month considered (1-12) or 13 (December - February) or 14 (November – April). The weighted DBP were calculated using minimum temperatures.

Table 4.1.1 shows the correlations of NDBP for daily mean temperature and the raw national residential natural gas consumption for different threshold percentiles. Tables 4.1.2 and 4.1.3 show the same correlations, but for DBP computed for daily maximum and minimum temperatures, respectively. High correlations for mean and maximum temperatures were similar, ranging from 0.660 to 0.830 and 0.680 to 0.850, respectively, for all months with the exception of November. Correlations for November for both mean and maximum temperatures were as high as 0.928 and 0.925, respectively. These high correlations may possibly be attributed to the fact that November is the beginning of the cold season when people may be more sensitive to the cold temperatures and consumers may thus respond closely to the daily weather conditions. The highest correlations for all months/seasons were found within the range of 40th to 50th percentile for mean temperatures while these were within the range of 35th to 40th percentile for maximum temperatures. Minimum temperatures had lower correlations compared to the other elements which ranged from 0.670 to 0.740 for all months/seasons with the exception of November which had a high correlation of 0.870.

As was seen earlier the raw national residential natural gas consumption values display an increasing trend during 1987-2003 (Figures 3.1.2 and 3.1.3). By contrast, the NDBP shows a slight downward trend, which corresponds to the overall atmospheric warming experienced in recent decades. It thus seems reasonable to ascribe the overall trend in consumption to the non-climatic factors such as population, economic growth and consumer preferences. In order to remove these non-climatic influences on the demand for residential natural gas, a linear detrending was applied to the gas consumption time-series and the results are shown as the diamonds in Figures 4.1.1 and 4.1.2, where they are compared with the time series of NDBP values for the 40th percentile threshold.

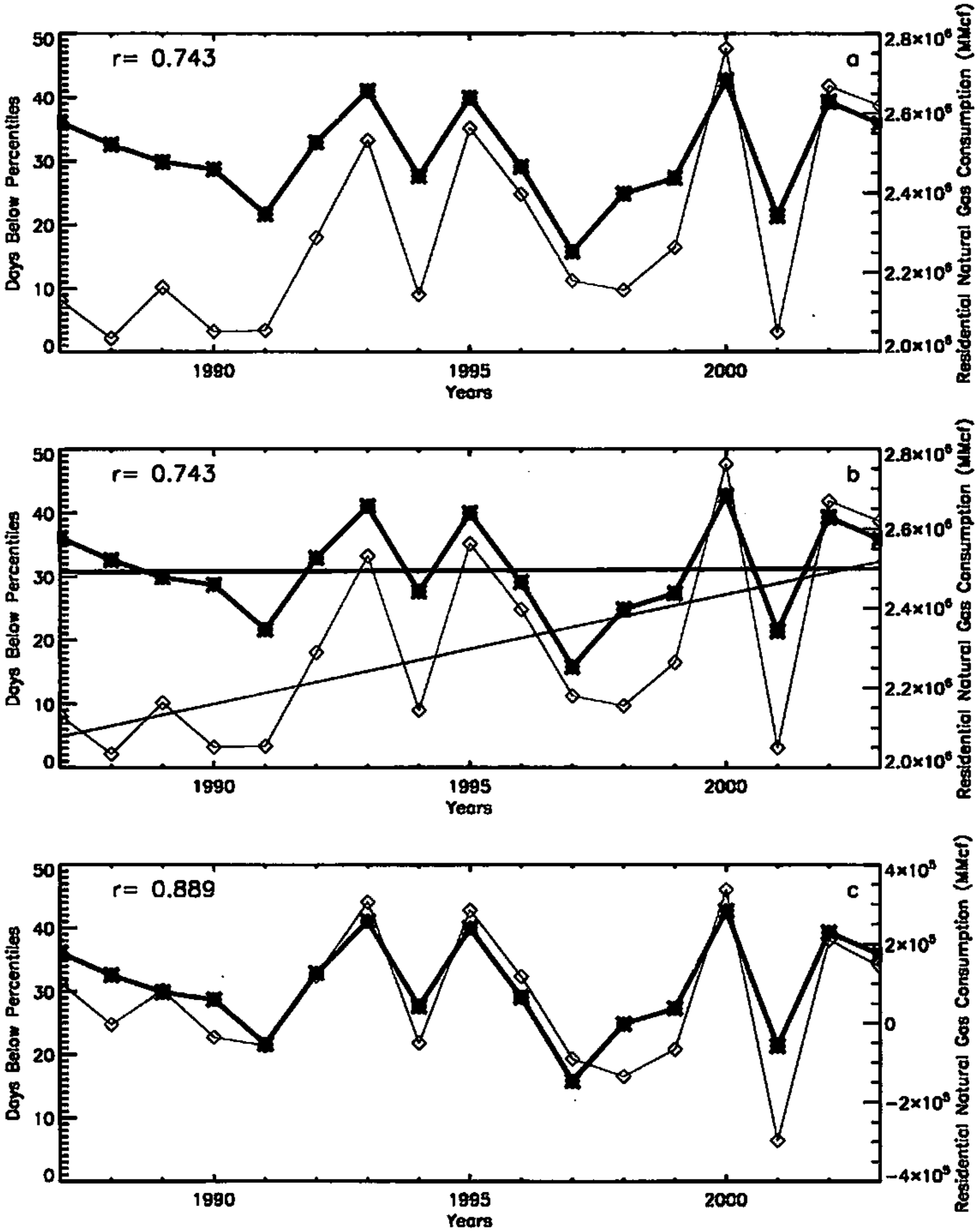

Figure 4.1.1: (a) Time series of raw national natural gas consumption and weighted DBP for the 40th percentile for the winter season (December to February). (b) Similar to (a) with trends plotted. Thick line is the DBP trend and thinner line is the natural gas consumption trend. (c) Time series of nation's detrended natural gas consumption and weighted DBP. Asterisk (*) represents the DBP and diamond (◊) represent natural gas consumption.

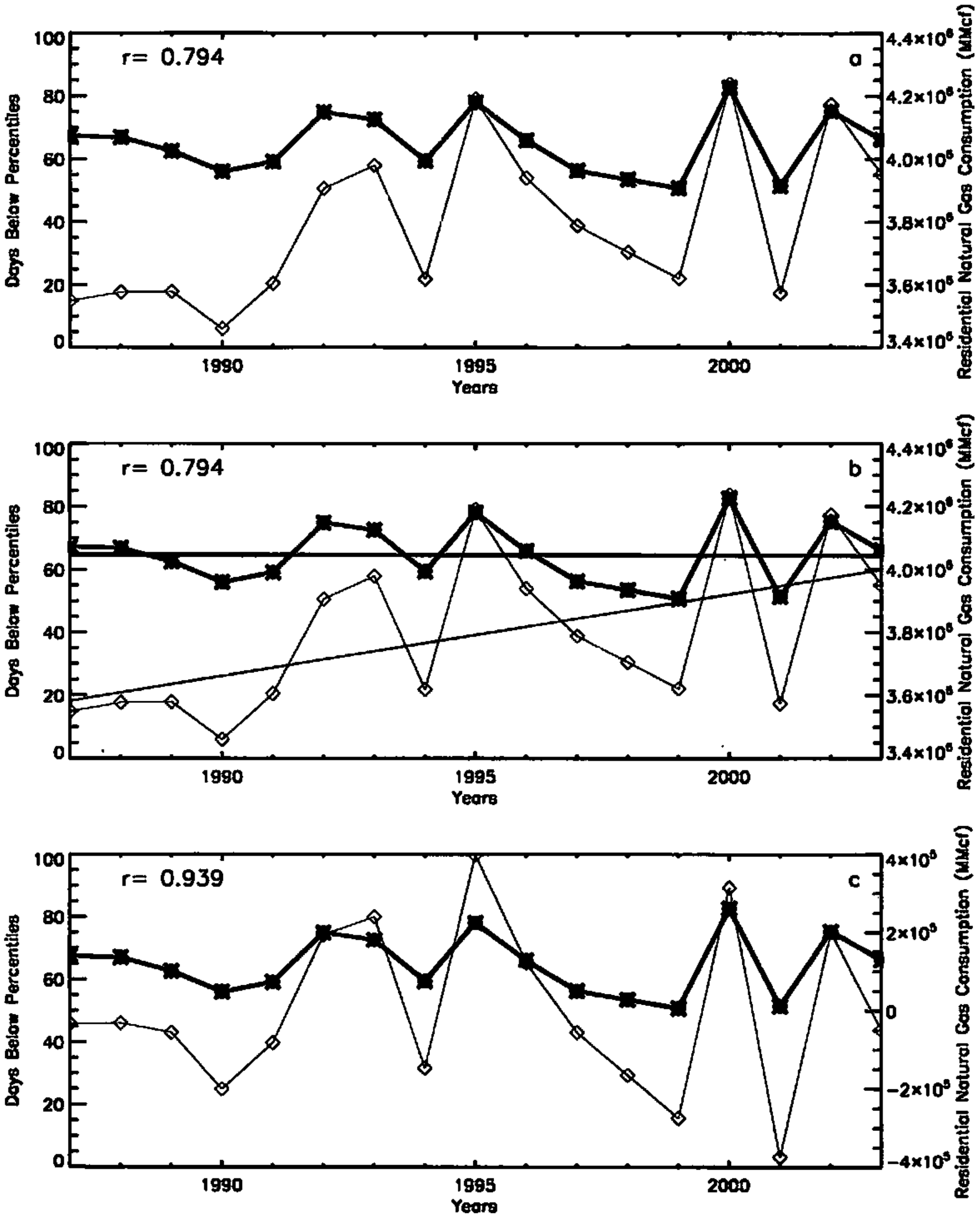

Figure 4.1.2: As in 4.1.1 but for the cold season (November to April).

After this detrending of the national residential natural gas consumption values, correlations with the NDBP time series were re-computed. The results are displayed in Table 4.1.4, 4.1.5, and 4.1.6.

| P S | 25th | 30th | 35th | 40th | 45th | 50th | 55th | 60th | 65th | 70th |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.735 | 0.743 | 0.746 | 0.749 | 0.747 | 0.744 | 0.735 | 0.729 | 0.724 | 0.728 |
| 2 | 0.855 | 0.877 | 0.885 | 0.888 | 0.879 | 0.865 | 0.850 | 0.831 | 0.813 | 0.780 |
| 3 | 0.901 | 0.913 | 0.906 | 0.898 | 0.886 | 0.874 | 0.850 | 0.833 | 0.810 | 0.779 |
| 4 | 0.642 | 0.637 | 0.651 | 0.645 | 0.654 | 0.628 | 0.594 | 0.557 | 0.516 | 0.478 |
| 11 | 0.901 | 0.918 | 0.937 | 0.954 | 0.964 | 0.969 | 0.967 | 0.963 | 0.953 | 0.935 |
| 12 | 0.750 | 0.780 | 0.803 | 0.828 | 0.851 | 0.879 | 0.897 | 0.906 | 0.913 | 0.911 |
| 13 | 0.858 | 0.879 | 0.888 | 0.889 | 0.889 | 0.887 | 0.892 | 0.895 | 0.891 | 0.880 |
| 14 | 0.855 | 0.884 | 0.919 | 0.939 | 0.945 | 0.944 | 0.939 | 0.931 | 0.927 | 0.919 |

Table 4.1.4: Correlations between the nations monthly/seasonal DBP and monthly/seasonal detrended residential natural gas consumption. The number 13 represents the winter season (December through February) and the number 14 represents the cold season (November through April). The weighted DBP were calculated using mean temperatures.

| P S | 25th | 30th | 35th | 40th | 45th | 50th | 55th | 60th | 65th | 70th |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.749 | 0.745 | 0.732 | 0.718 | 0.706 | 0.677 | 0.636 | 0.618 | 0.613 | 0.610 |
| 2 | 0.882 | 0.888 | 0.884 | 0.869 | 0.856 | 0.847 | 0.830 | 0.813 | 0.790 | 0.755 |
| 3 | 0.871 | 0.881 | 0.873 | 0.865 | 0.849 | 0.831 | 0.808 | 0.783 | 0.752 | 0.708 |
| 4 | 0.605 | 0.596 | 0.589 | 0.579 | 0.561 | 0.553 | 0.559 | 0.524 | 0.455 | 0.411 |
| 11 | 0.928 | 0.935 | 0.944 | 0.945 | 0.951 | 0.952 | 0.949 | 0.946 | 0.942 | 0.930 |
| 12 | 0.795 | 0.837 | 0.870 | 0.891 | 0.909 | 0.919 | 0.928 | 0.925 | 0.913 | 0.897 |
| 13 | 0.905 | 0.919 | 0.926 | 0.927 | 0.921 | 0.910 | 0.900 | 0.892 | 0.878 | 0.856 |
| 14 | 0.934 | 0.943 | 0.938 | 0.932 | 0.914 | 0.895 | 0.878 | 0.867 | 0.860 | 0.853 |

Table 4.1.5: Correlations between the nations monthly/seasonal DBP and monthly/seasonal detrended residential natural gas consumption. The number 13 represents the winter season (December through February) and the number 14 represents the cold season (November through April). The weighted DBP were calculated using maximum temperatures.

| P<br>S | 25th | 30th | 35th | 40th | 45th | 50th | 55th | 60th | 65th | 70th |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.777 | 0.786 | 0.791 | 0.795 | 0.795 | 0.799 | 0.800 | 0.811 | 0.822 | 0.832 |
| 2 | 0.864 | 0.863 | 0.854 | 0.847 | 0.836 | 0.815 | 0.792 | 0.759 | 0.721 | 0.677 |
| 3 | 0.795 | 0.790 | 0.770 | 0.746 | 0.715 | 0.690 | 0.676 | 0.658 | 0.675 | 0.660 |
| 4 | 0.576 | 0.628 | 0.647 | 0.658 | 0.686 | 0.676 | 0.665 | 0.647 | 0.602 | 0.556 |
| 11 | 0.857 | 0.873 | 0.891 | 0.904 | 0.915 | 0.924 | 0.927 | 0.923 | 0.916 | 0.909 |
| 12 | 0.731 | 0.747 | 0.769 | 0.775 | 0.776 | 0.783 | 0.794 | 0.809 | 0.815 | 0.825 |
| 13 | 0.826 | 0.838 | 0.841 | 0.838 | 0.835 | 0.828 | 0.822 | 0.818 | 0.813 | 0.809 |
| 14 | 0.793 | 0.806 | 0.813 | 0.832 | 0.842 | 0.860 | 0.882 | 0.902 | 0.918 | 0.929 |

Table 4.1.6: Correlations between the nations monthly/seasonal DBP and monthly/seasonal detrended residential natural gas consumption. The number 13 represents the winter season (December through February) and the number 14 represents the cold season (November through April). The weighted DBP were calculated using minimum temperatures.

It is evident that the correlations for each month and season have improved after detrending the residential natural gas consumption, with the exception of April. When comparing the results of the non-detrended with the detrended correlations, April is the only month that detrending did not have a significant affect. Figure 4.1.3 summarizes the data for April and it is clear that April gas consumption has no particular increasing or decreasing trend. The lack of trend in April (while other months show increasing consumption with time) may reflect a tendency for the increase in consumers over the 1987-2004 period to have been concentrated where population growth was biggest, namely in the southern parts of the nation where heating demand will likely be weak late in the season (e.g. note the result for interstate migration of the U.S. population during recent years presented in Table 20 of the 2007 Statistical Abstract of the United States http://www.stat-usa.gov/online.nsf/vwNoteIDLookup/NT007B8B86/$File/2007_1-pop.pdf?OpenElement)

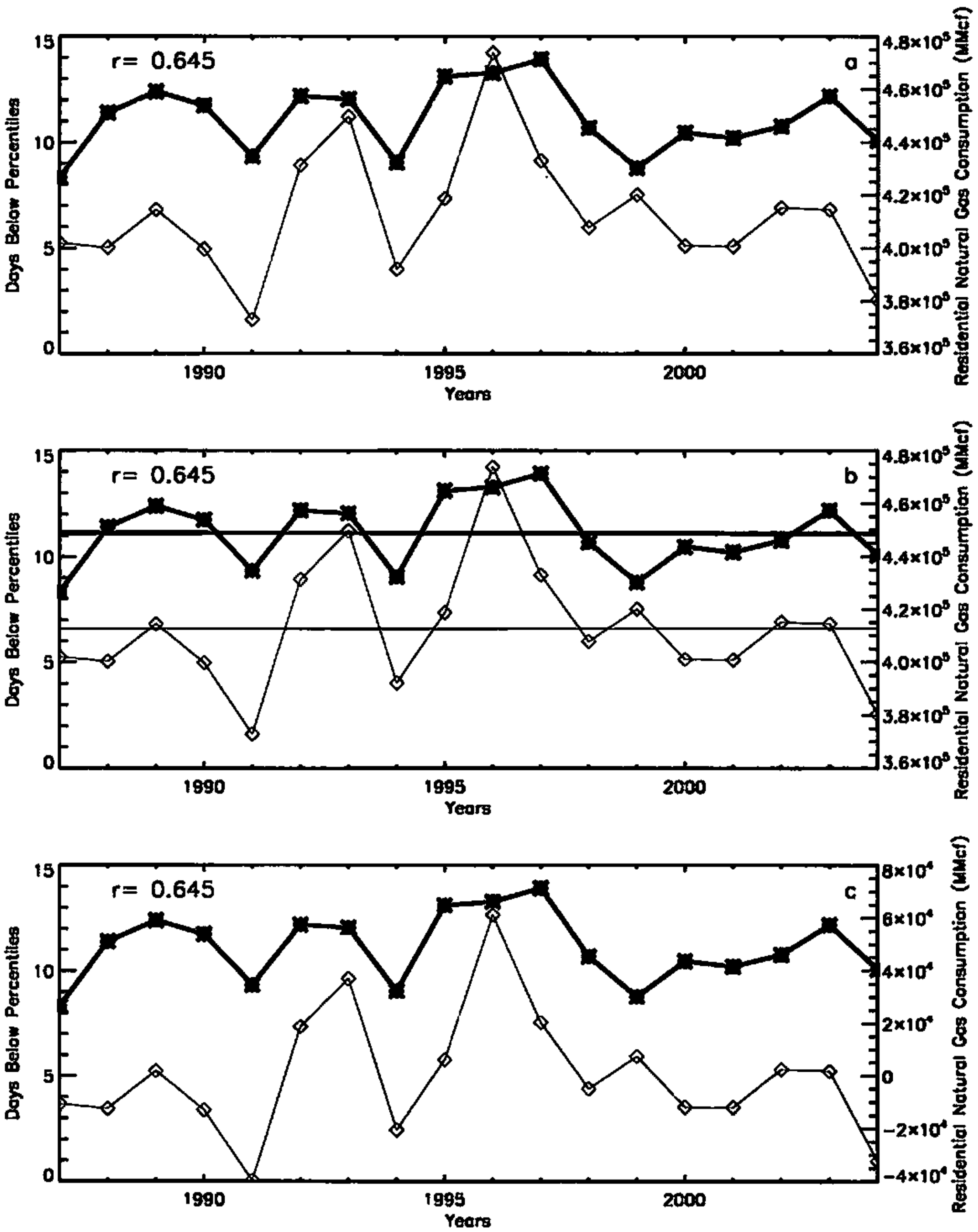

Figure 4.1.3: (a) Time series of national natural gas consumption and weighted DBP for the 40th percentiles for April. (b) Similar to (a) with trends plotted. Thick line is the DBP trend and thinner line is the natural gas consumption trend. (c) Time series of national detrended natural gas consumption and weighted DBP. Asterisk (*) represents the DBP and diamonds (◊) represent natural gas consumption.

When comparing the correlations of consumption with NDBP for each of the temperature elements (mean, maximum, minimum), maximum and mean temperatures led to similar results with the exception of the winter season where maximum temperatures had higher correlations compared to the mean temperatures. Correlations for minimum temperatures were slightly lower than the rest. Overall, the correlations improved by detrending the residential natural gas consumption and were high for all three elements indicating a strong relationship between the nation's residential natural gas consumption and the wintertime temperatures. Although correlations were computed for each daily temperature element (maximum, minimum, and mean) and for all percentiles, the remainder of this study will present only results obtained using the daily mean temperatures. This was done since the ultimate goal is to use the final statistical model along with seasonal climate forecasts to provide improved estimates of residential natural gas demand for the winter and cold seasons, and to predict possible climate change impacts on residential natural gas demand. In practice many operational and climate model projections seasonal forecasts are often provided only for the mean daily temperatures, rather than daily highs and lows. When analyzing the correlations located in Table 4.1.4, it is evident that the best correlations fall in the range of 35th to 50th percentile for all months that correspond to the winter and cold season. To provide a simple analysis the 40th percentile for computation of DBP for both winter and cold season was judged subjectively to provide the best overall fits for the various months and seasonal periods. All further discussion of the statistical model will use the 40th percentile criterion. Results based on the application to the 1987-2004 period are presented in the following section.

## 4.2 Statistical Linear Regression Model

The time series of consumption expressed as percent of departure can also be correlated with the NDBP and this correlation is used as the basis for the statistical model that will be advanced here as the most convenient forecast (or hindcast) of consumption given the temperature data for a season. This statistical model can be used retrospectively to help separate the influence of climate from other market forces and when combined with seasonal weather forecast, it can also provide improved estimates of future residential natural gas demand.

Figure 4.2.1 shows the individual winter values of NDBP (using the 40th percentile) and gas consumption indices for the 1987-2003 period, but now plotted as a scatter diagram. Results for the raw consumption values, detrended consumption values and the percent of departure consumption values are plotted in different panels. Figure 4.2.2 shows the same quantities for the full cold season. The correlation coefficients, of course, in the top two panels of 4.2.1 and 4.2.2 are the same as seen earlier in 4.1.1 and 4.1.2 and the correlation of the percent departure values are the same as for the detrended time series. One can think of the horizontal dashed line (0% departure) as representing the mean consumption for the season that was computed to be 2,323,000 million cubic feet or MMcf in winter and 3,791,000 MMcf in the cold season. The vertical dashed line is drawn at the average NDBP, in this case using the 40th percentile boundary (which was 31 DBP for winter and 64.5 DBP in the cold season).

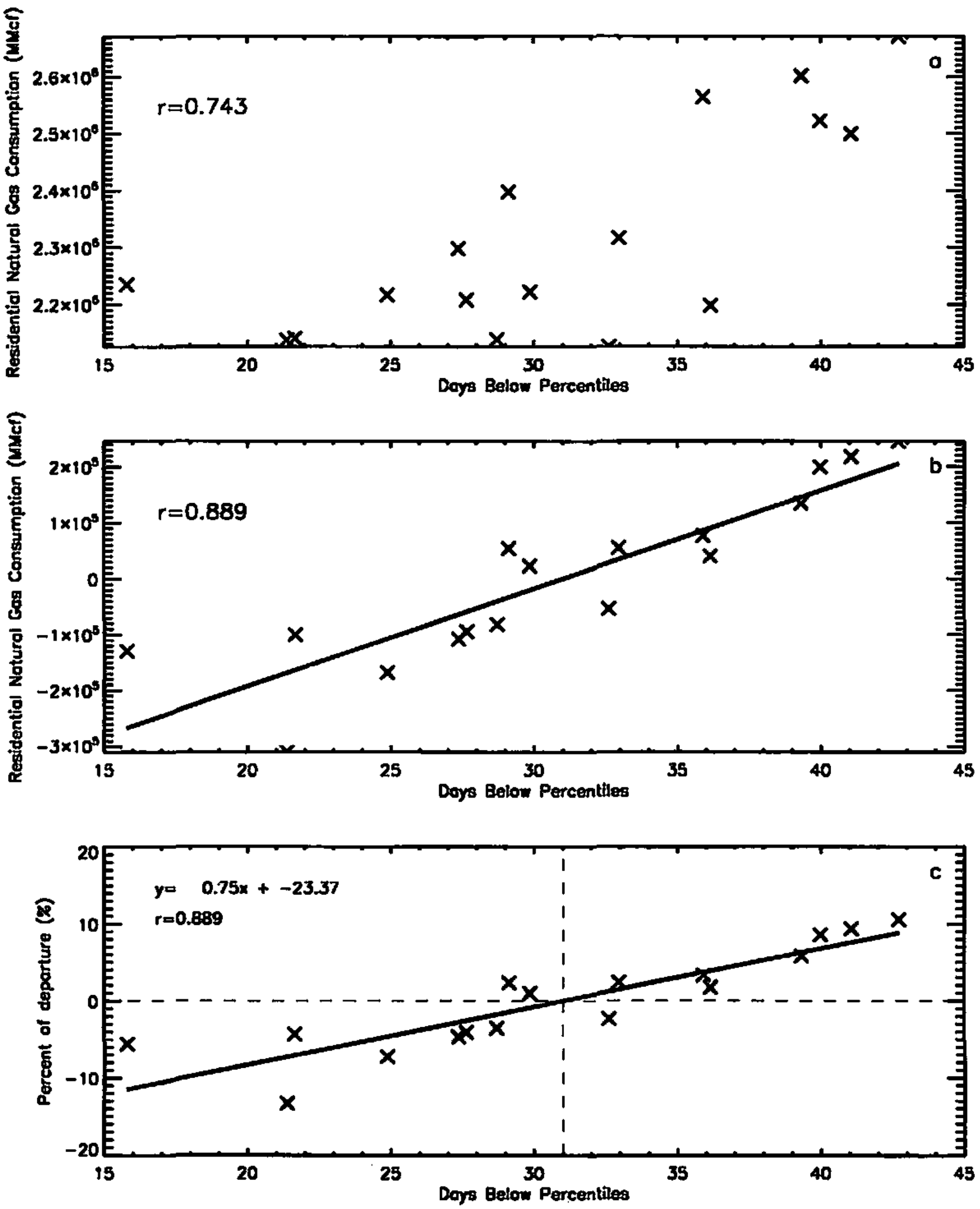

Figure 4.2.1: (a) Scatter plot of national residential natural gas consumption versus weighted DBP at the 40th percentile for mean temperature. (b) Scatter plot of detrended residential natural gas consumption versus weighted DBP. (c) Linear regression model. All plots represent the winter season (December - February).

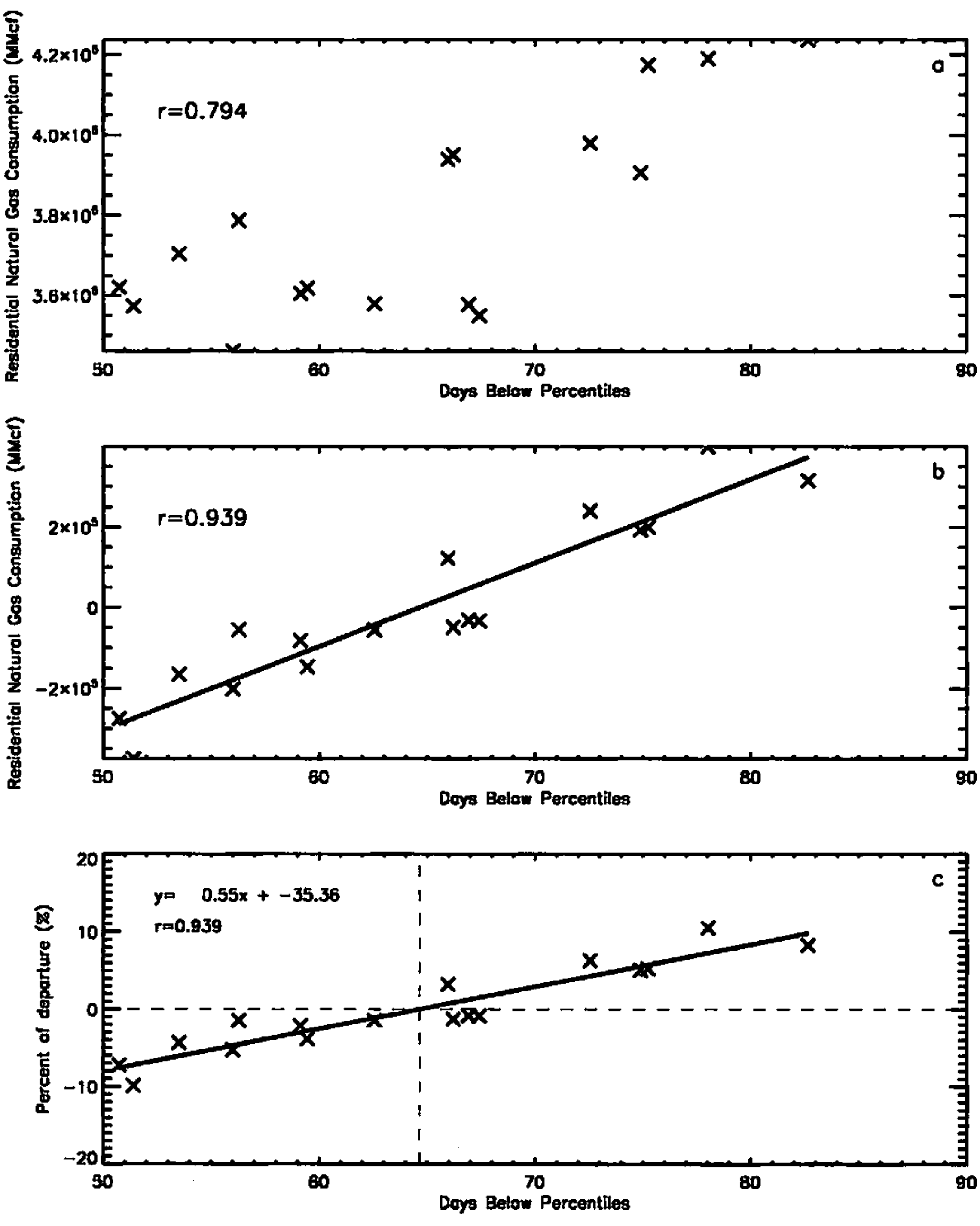

Figure 4.2.2: As in 4.2.1 but for the cold season (November – April).

To quantify the model's overall error in fitting retrospective data the NDBP for the period 1987-2003 were used in the linear regression model to produce a hindcast of the detrended time series of the national residential natural gas consumption. The result now reconstructed for the winter is shown in Figure 4.2.3. Once again the correlation coefficient of 0.889 is exactly as before. In addition the mean absolute error between the observed and hindcasted time series was computed and found to be 4.167%. Figure 4.2.4 shows the same comparison for the cold season and the mean absolute error in the hindcast is only 3.518%. Also note that the correlations of 0.889 and 0.935 are much larger than those obtained by Heim et al (2003) with their HDD-based analysis. Of course, these small absolute percentage errors refer to the ability to predict the total consumption. The year-to-year fluctuations are typically less than 1/5 of the long-term mean consumption, and so the errors are a more significant fraction of the component one actually needs skill to predict.

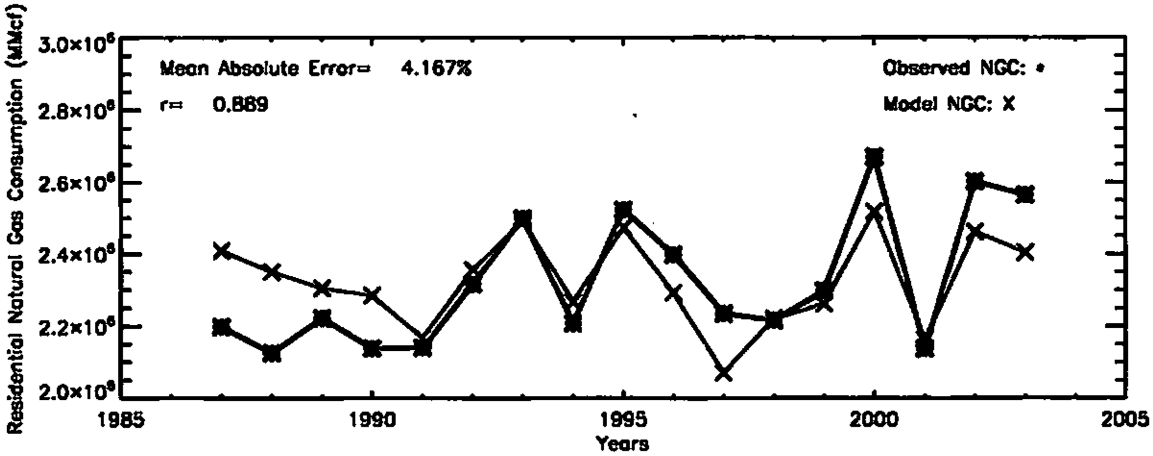

Figure 4.2.3: Time series of the national residential natural gas consumption for the winter season for 1987-2004. Asterisk (*) represents the observed consumption; meanwhile the X represents the modeled consumption.

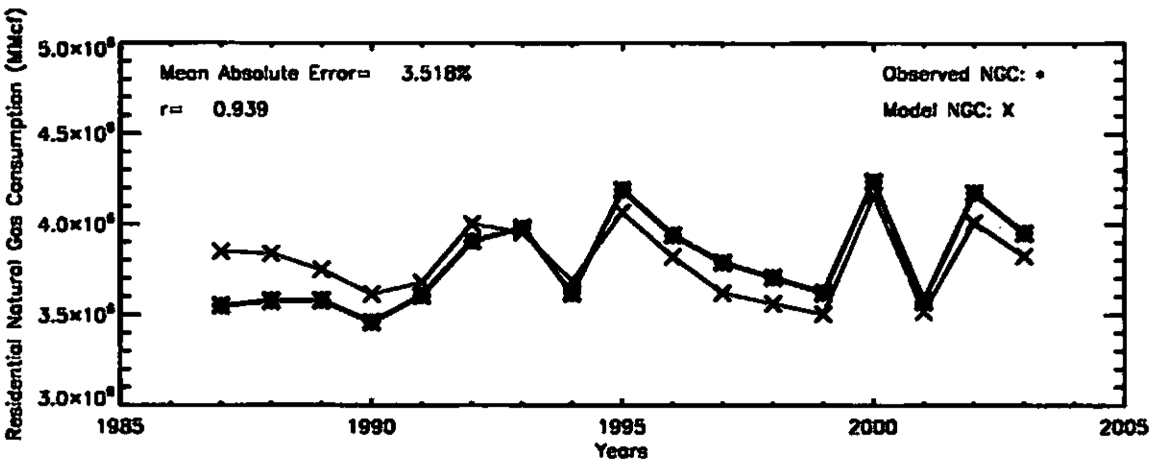

Figure 4.2.4: Time series of the national residential natural gas consumption for the cold season for 1987-2004. Asterisk (*) represents the observed consumption, meanwhile the X represents the modeled consumption.

To further test the statistical model, it was applied to estimate the residential natural gas consumption for the period of 1973-1986. The data for this period were not employed in the development of the statistical model. As noted earlier, during this time period the natural gas market confronted a dramatic regulatory change that led to a change in demand patterns and therefore a decline in residential natural gas consumption (see figure 2.2.1 and 2.2.2) which the present statistical model cannot hope to capture. The actual comparison of observed consumption and statistical model hindcasts for 1973-86 are shown in Figure 4.2.5 for the winter and Figure 4.2.6 for the cold season. For the winter season, the mean absolute percent of error was computed to be 6.252%, meanwhile the correlation was still quite high (0.873). For the cold season, the mean absolute percent of error was computed to be 5.367% and its correlation was 0.890. For both seasons the model overestimated the consumption for this period and understandably did not reproduce the observed downward consumption trend, but it did a reasonable job in capturing the interannual fluctuation of the consumption for this earlier period. This is encouraging and supports the notion that the model is reliable in estimating the fluctuation of residential natural gas demand attributable to weather and climate anomalies.

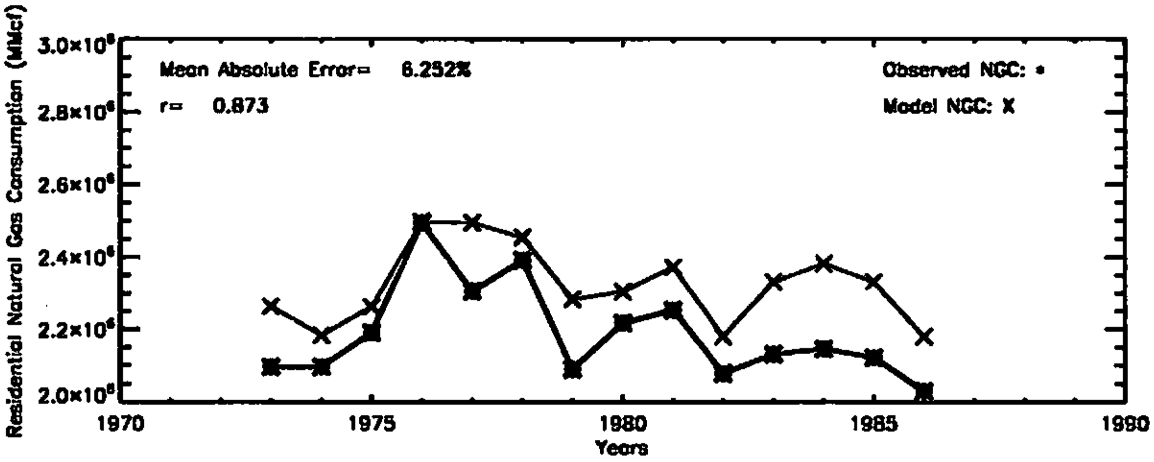

Figure 4.2.5: Time series of the national residential natural gas consumption for the winter season for 1973-1986. Asterisk (*) represents the observed consumption; meanwhile the X represents the modeled consumption.

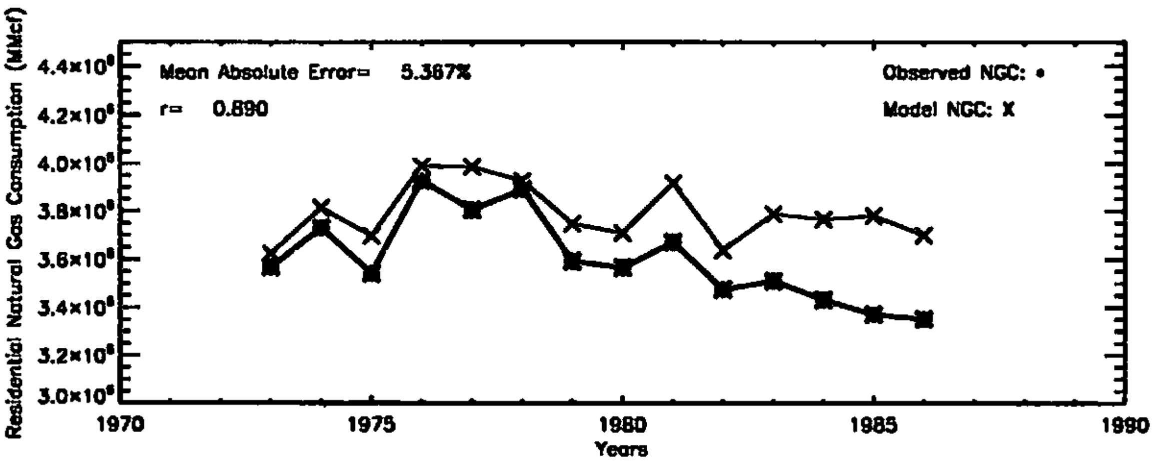

Figure 4.2.6: As in 4.2.5 for cold season.

# CHAPTER 5
# RESULTS FOR PROJECTED DATA

In this chapter the use of the present regression model relating temperature to residential natural gas consumption will be applied to predicted late 21st century conditions, with the intention of determining the climate-change related contribution to residential natural gas consumption that may be anticipated. National DBP are computed for the late 21st century and inserted in the statistical model for the winter and cold seasons. The dependence of the projected change in the nation's estimated residential natural gas consumption using climate projections based on daily versus monthly mean data, and high spatial resolution versus coarse resolution data will also be investigated.

## 5.1 Future Daily Climate Projections

In the previous chapters it has been demonstrated that a strong relationship between energy demand (in this case for residential natural gas) and climate anomalies exists. Overall the relationship is as follows: as NDBP increases (more days below the temperature threshold, meaning colder days) the residential natural gas consumption increases. Conversely, if the NDBP decreases (fewer cold days) the residential natural gas consumption will decrease.

As noted earlier many studies have indicated that a significant increase in global mean temperatures will most likely occur the next century in response to anthropogenic activities. So if an increase in global mean temperatures is expected, a decrease in winter and cold season residential natural gas consumption can be expected as well, assuming all other factors affecting demand remain unchanged (population, technology, perceptions of personal comfort, etc).

This study will estimate the effect of projected 21st century climate change on U.S. residential natural gas consumption. Specifically the effects of temperatures on consumption in 2081-2100 relative to 1981-2000 will be estimated. Data from the high resolution MIROC 3.2 model were used for the climate projection, specifically 20 years of the 20c3m run (January 1981 through December 2000) and the last 20 years of the SRESA1B run (January 2081 through December 2100) were employed. The model output for daily mean surface air temperatures were available and serve as the basis for the 21st century temperatures used in the present study as described below.

The appropriate use of the climate model data to infer the warming is not completely obvious. The temperatures simulated in the 20c3m run have significant biases relative to those observed. As an example, Figure 5.1.1 compares the probability distribution for the observed daily mean temperatures in winter during 1981-2000 with the comparable results for the MIROC 20c3m simulation at a grid-point near the real station location. The model at this grid point has a median temperature about 2°F warmer than does the real station and also has a much narrower distribution, notably with many fewer very cold extremes than in the real station data. In this study the consumption estimates for 1981-2000 are computed using the real temperatures and the 2081-2100 consumption estimates are based on the real temperatures in 1981-2000 with a warming inferred from the model simulations added.

Even once this approach is decided upon, there are different ways the warming data can be used. The simplest approach may be to simply compute a seasonal (or monthly) mean climatological warming from the model simulation and add this to the daily 1981-2000 observations. Results obtained using this approach will be discussed later. This approach does not allow for the possibility that warming affects not only the mean temperature during the cold season, but also the distribution of temperatures. The other extreme is to make daily differences in the temperatures from the model simulations (e.g. January 1, 2081 minus January 1, 1981) and add these to the daily observed temperatures. Results from this approach will be discussed first. In order to add the model's inferred warming and the real daily data, the real station observations from 1981-2000 were interpolated onto the MIROC grid in order that the data be at the same set of "stations".

Figure 5.1.2 shows the distribution of winter temperatures for the same grid point as in Figure 5.1.1, but for the 2081-2100 period in the SRESA1B simulation (shown together with that from 1981-2000 of the 20c3m simulation). The predicted late-21st century temperatures are not only warmer in the mean than those simulated for 1981-2000, but have a noticeably different shape to the distribution.

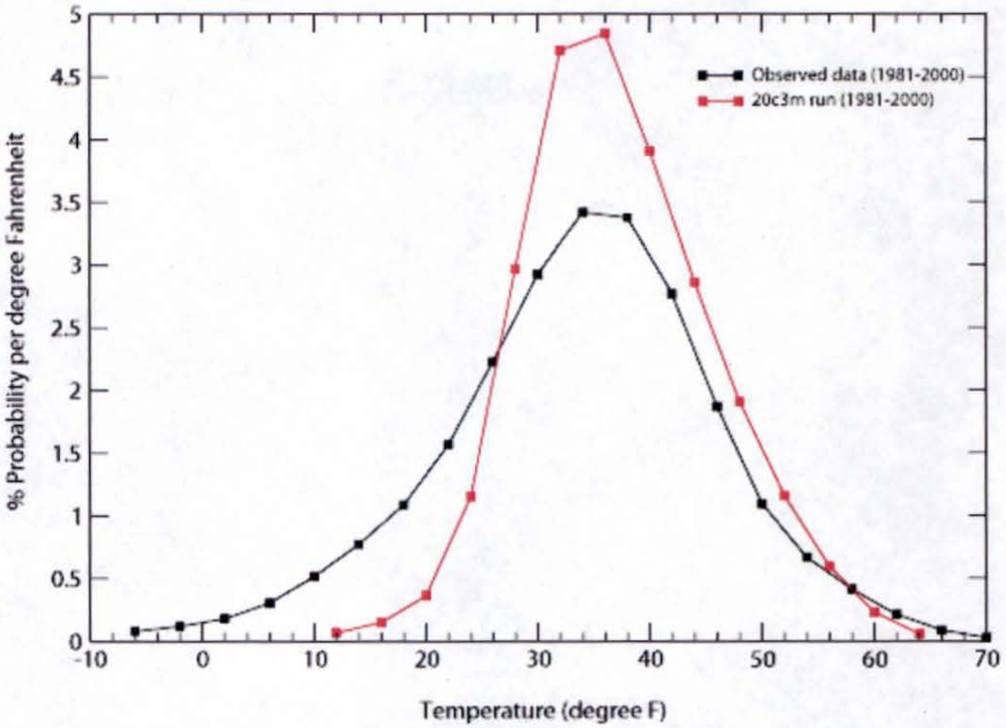

Figure 5.1.1: Frequency distribution using the 20c3m data (January 1981- December 2000) and the real station observation data. For the 20c3m data, the 20th percentile has as a temperature threshold of 31°F, the median is 36°F, while the 80th percentile has 44°F as a threshold. The 40th percentile has 34°F as a threshold.

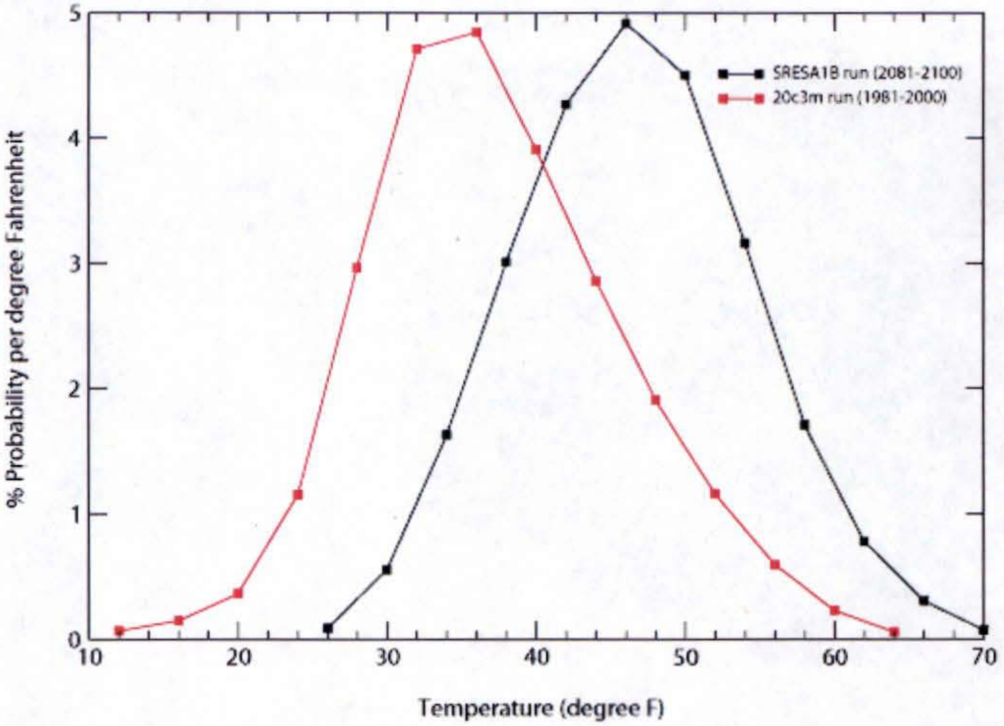

Figure 5.1.2: This figure represents the frequency distribution using the SRESA1B (January 2081- December 2100) data for the winter season of a grid point located in the Southeast climate division in Illinois. The station's 20th percentile has a temperature threshold of 40°F, the median is 46.5°F, while the 80th percentile has 53°F. The 40th percentile has 45°F as a threshold.

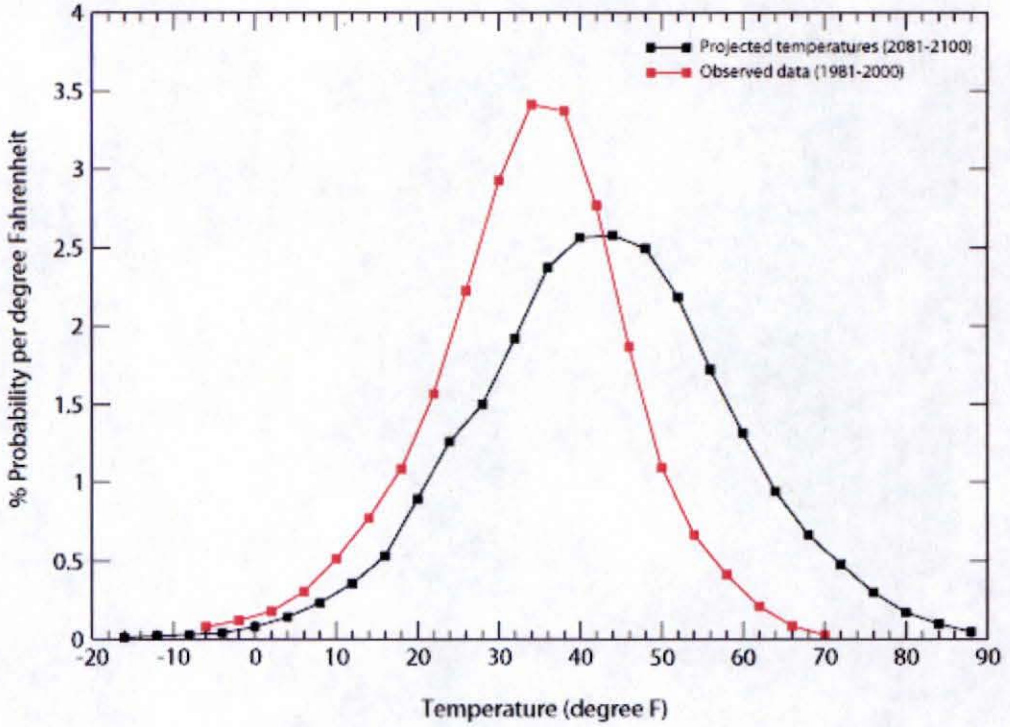

Figure 5.1.3: This figure represents the frequency distribution for the winter season of a grid point located in the Southeast climate division in Illinois for the projected 21st century. The station's 20th percentile has as a temperature threshold of 30°F, the median is 43°F, while the 80th percentile has a threshold of 55°F. The 40th percentile has 39°F as a threshold.

An additional step was undertaken to determine if there is a difference between the statistical model developed using real station data from 1987-2003 period and the version obtained using the real data interpolated onto the MIROC grid. The procedures described in Section 3.1 were repeated using the grid-interpolated real data for 1987-2003. Figure 5.1.4 and 5.1.5 show scatter plots between the individual winter and cold-values, respectively, and residential natural gas consumption for the 1987-2003 period. This figure also shows the linear fit line representing the statistical model computed using the real station data for the period of 1987-2003. The statistical models for the winter and cold season, respectively, based on the 1987-2003 fit to actual station data, are expressed by the following equations:

$$Y = 0.75X - 23.37 \tag{5.1}$$

$$Y = 0.55X - 35.36 \tag{5.2}$$

where $X$ represents NDBP and $Y$ represents the percent departure of the nation's 1987-2003 mean residential natural gas consumption.

While the statistical models for the winter and cold season, respectively, based on the 1987-2003 fit, using the interpolated station data can be expressed by the following equations:

$$Y = 0.73X - 24.27 \tag{5.3}$$

$$Y = 0.51X - 34.85 \tag{5.4}$$

where $X$ represents NDBP and $Y$ represents the percent departure of the nation's 1987-2003 mean residential natural gas consumption. Results are quite similar with the station data or the grid-interpolated data. The results discussed below will be based on (5.1) and (5.2), but results with (5.3) and (5.4) are nearly identical.

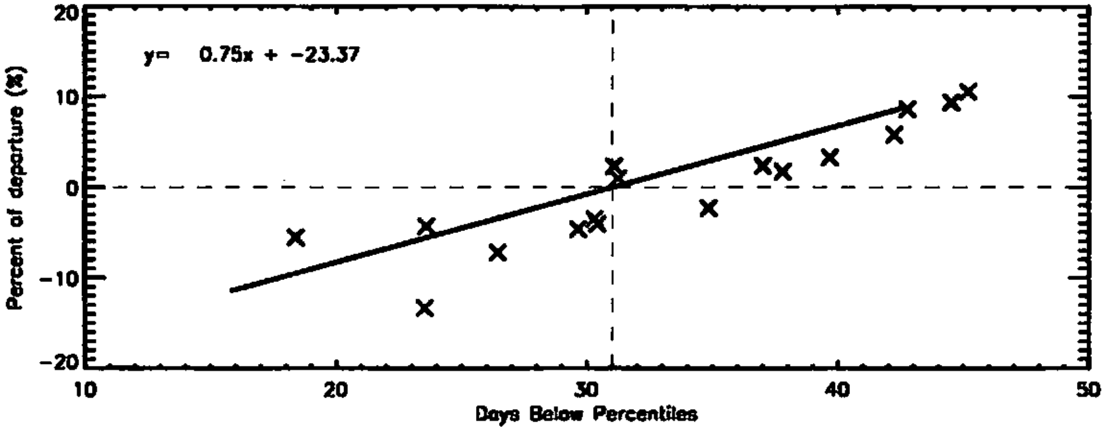

Figure 5.1.4: Scatter plot for the winter season of percent of departure vs. weighted NDBP using the interpolated station data for 1987-2003 period. The linear regression model for the 1987-2003 period using the real station data is depicted as well.

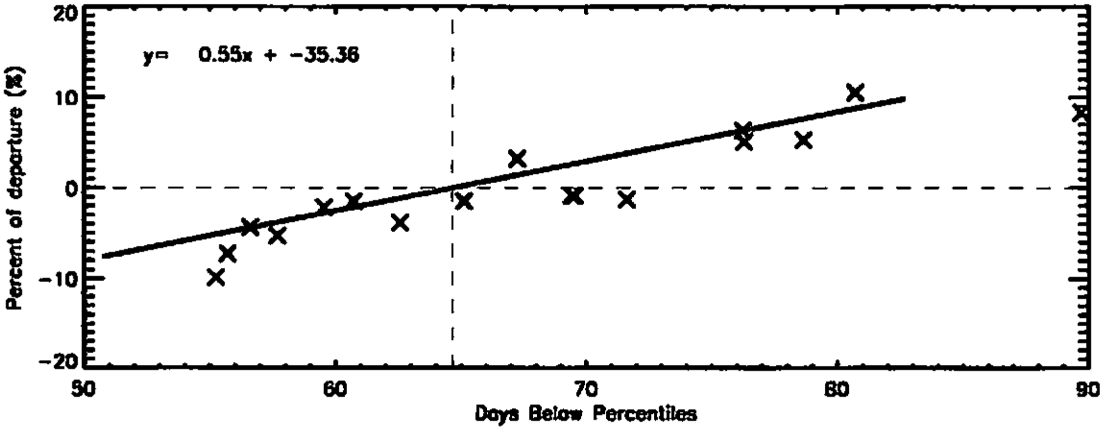

Figure 5.1.5: As in 5.1.4 for the cold season.

After calculating the projected 21st century temperatures, the computation of the NDBP proceeded. All of the model's grid points were treated as individual stations. Thus the procedure used for the computation of NDBP using stations was now applied for each grid point including the weighting methods (population and residential natural gas consumption).

The NDBP were then substituted in the statistical model (illustrated in Figure 5.1.4a and 5.1.5a) to estimate the residential natural gas consumption for individual seasons in the late 21st century. The results are shown as percent departures (from 1987-2003 means) in Figures 5.1.6b (for winter) and 5.1.7b (for the cold season), where each 'X' represents the projected DBP and thus natural gas consumption for the period 2081-2100.

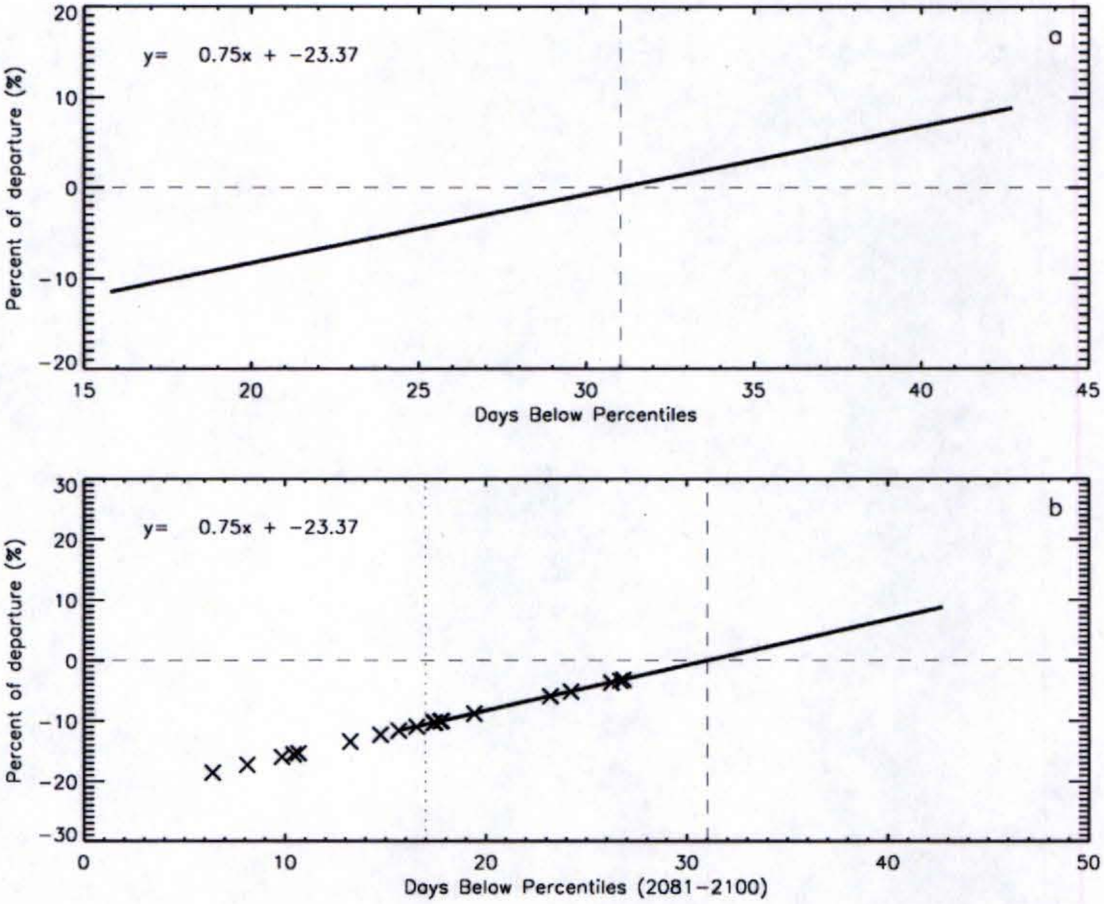

Figure 5.1.6: (a) Linear regression model for the winter season (December - February). Horizontal dashed line represents the nation's mean natural gas consumption for the period 1987-2004. Vertical dashed line represents the nation's mean DBP for the period 1987-2004. (b) Projected DBP for the period 2081-2100 inserted in the statistical model to estimate percent departure from normal for the 2081-2100. The vertical dotted line represents the nation's projected mean DBP for the period 2081-2100.

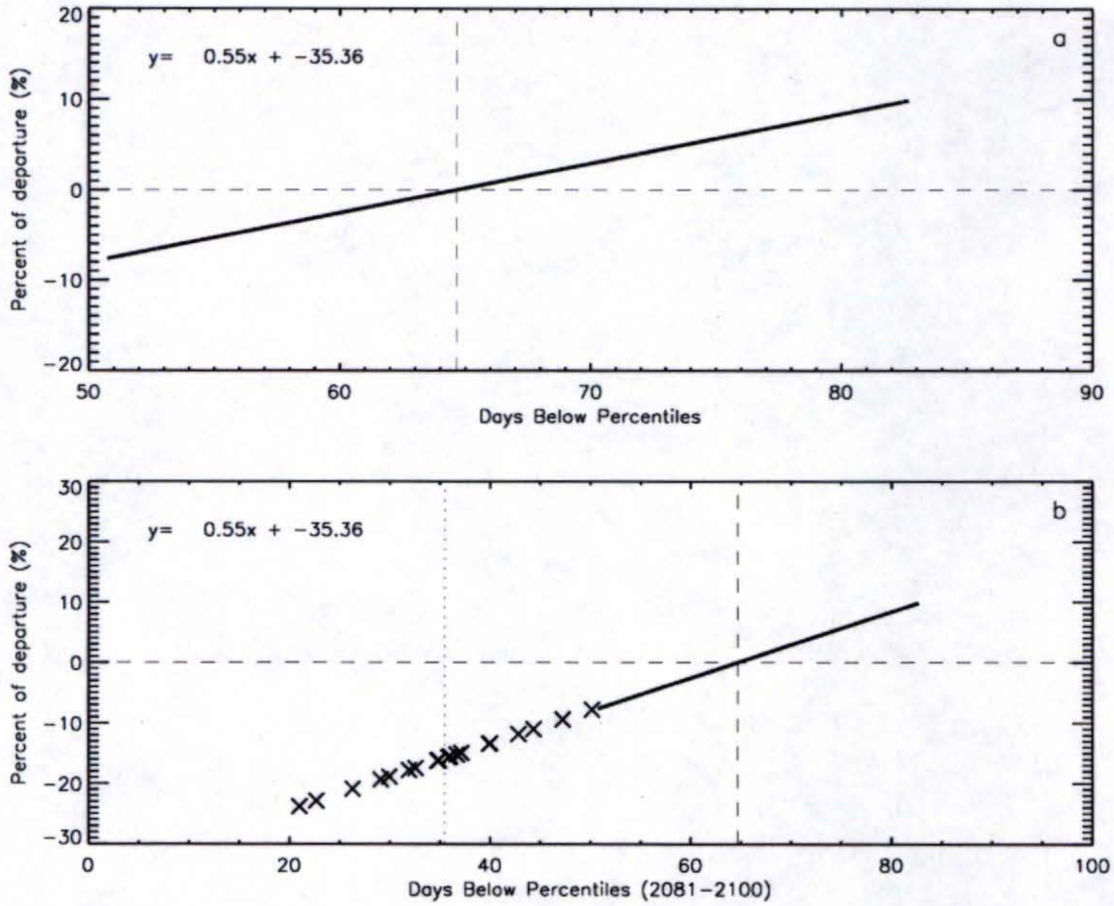

Figure 5.1.7: As in 5.1.4 but for the cold season (November – April).

As seen in Figures 5.1.6b and 5.1.7b, it is evident that the projected climate change will significantly affect the nation's residential natural gas consumption for the winter and cold season.

It is estimated that for the winter season in the late 21st century the mean NDBP will be approximately 17 (represented by the dotted vertical line in figure 5.1.6), which would be 14 days less than the period 1987-2003. This, by itself, is predicted to cause a decrease in the nation's mean residential natural gas consumption of about 11% for the entire period of 2081-2100 relative to 1987-2003.

For the cold season, the NDBP for the period of 2081-2100 is estimated to be 35. When comparing to the period of 1987-2003, there is a predicted decrease of approximately 30 days. The estimated decrease in the nation's mean cold season residential natural gas consumption for 2081-2100 relative to 1987-2003 attributable to anticipated climate change is approximately 17%.

As mentioned previously, there are other factors, besides weather and climate anomalies, that affect the demand on residential natural gas consumption. The results mentioned above are based on maintaining all these other non-climatic factors constant.

## 5.2 Use of Coarse Spatial Resolution Warming Projection

Even though data from a rather fine resolution model were used in the analysis discussed above, the reality is that many current global climate models are run at horizontal resolutions of roughly T32-T42, i.e. much coarser resolution compared to the high resolution MIROC model used here. A coarse resolution model does not represent adequately small features, which is relevant here since extreme daily temperatures perturbations are often associated with relatively small scale weather phenomena. This motivates us to compare the results of the projected climate effect on gas consumption using both fine and coarse spatial resolution climate change projections.

To do so, a spatially smoothed version of the MIROC simulated daily temperature data was prepared by replacing the original temperature value in each grid box with an area weighted average smoothing of the temperatures in a 3x3 matrix of the T106 grid-boxes.

The procedure to calculate the NDBP using the high resolution data was now repeated using the spatially smoothed version of the climate model data. The NDBP calculated using the smoothed version data (effectively representing only the scales resolvable by a T35-resolution model) was substituted in the statistical model for each corresponding season. The results are displayed in Figures 5.2.1 and 5.2.2.

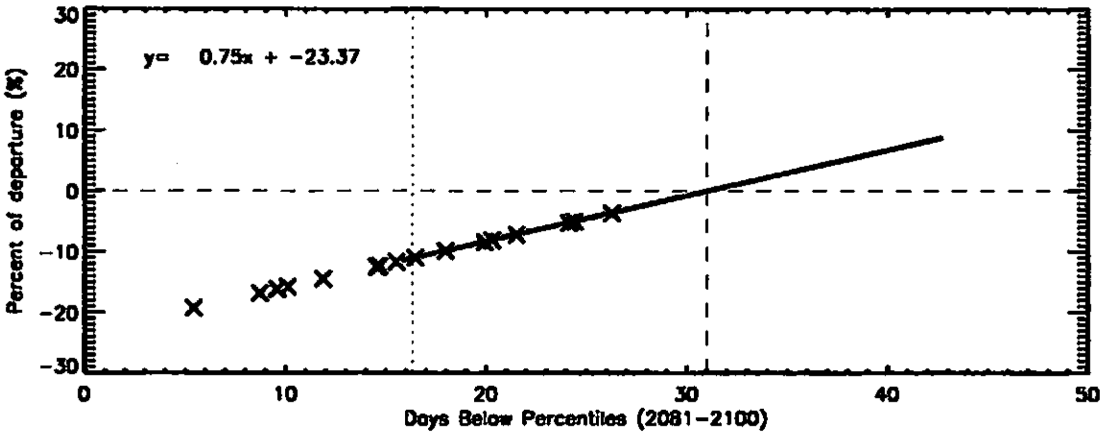

Figure 5.2.1: The NDBP calculated by using the spatially smoothed version was inserted in the statistical model to estimate percent departure from normal for 2081-2100 for the winter season (December - February). Horizontal dashed line represents the nation's mean natural gas consumption for the period 1987-2004. Vertical dashed line represents the nation's mean DBP for the period 1987-2004. The vertical dotted line represents the nation's projected mean DBP for the period 2081-2100.

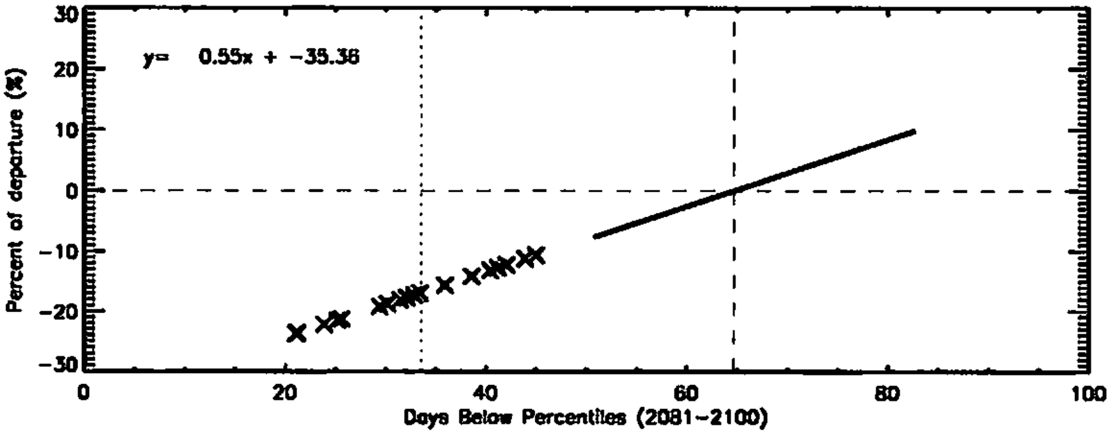

Figure 5.2.2: As in 5.2.1 but for the cold season (November – April)

Comparing Figures 5.2.1 and 5.2.2 with the counterparts using the full resolution climate model data (Figures 5.1.6 and 5.1.7), show that the results are quite close, though clearly different. Notably the spread of the NDBP values for the individual years is reduced when the smoother warming data are employed. However, the mean over the 20 years is rather similar and the actual forecast of decrease in the winter mean consumption is 12% using the smoothed data versus 11% using the unsmoothed data. For the cold season the forecast decrease consumption is 18% using the smoothed data versus 17% using the unsmoothed data.

### 5.3 Use of Future Monthly-Mean Climate Projections

In the previous section, results using the late 21st century daily projected temperatures were discussed. The projected daily temperatures were computed by adding the daily warming calculated by the subtraction of the daily temperatures in the 20c3m run from the daily temperatures in the SRESA1B run (section 5.1). This approach involves a subtle assumption that the warming increment can be regarded as independent of the temperature that is being incremented. At the other extreme, the 21st daily century temperatures could be computed just as the 1981-2000 real temperature plus monthly-mean warming from the model results or even monthly-mean climatological (say 2081-2100 minus 1981-2000) warming. This is also of interest, since many model simulations have archives of only monthly-mean data. In addition, much work now involves using multimodel ensemble simulations, and climate change information from such ensembles makes sense only as averages over reasonably long periods. This section will evaluate how the modeled national residential natural gas consumption will differ from the results discussed in the previous section when only the predicted monthly mean warming for each grid point is used. The procedure is straightforward, with the monthly mean warming for each month in 2081-2100 relative to 1981-2000 taken from the MIROC SRESA1B simulation minus the 20c3m simulation. This warming is then added to the daily observed data to compute the projected temperatures for the period 2081-2100. These calculations were performed using the full spatial resolution model data. Figure 5.3.1 shows the distribution of winter season temperatures for the southeast Illinois location examined earlier computed using the monthly-mean warming.

These daily temperatures were computed for all grid points and the NDBP calculation proceeded as before. Figures 5.3.2 and 5.3.3 display the projected residential natural gas consumption for the years 2081-2100 for the winter and cold seasons, respectively.

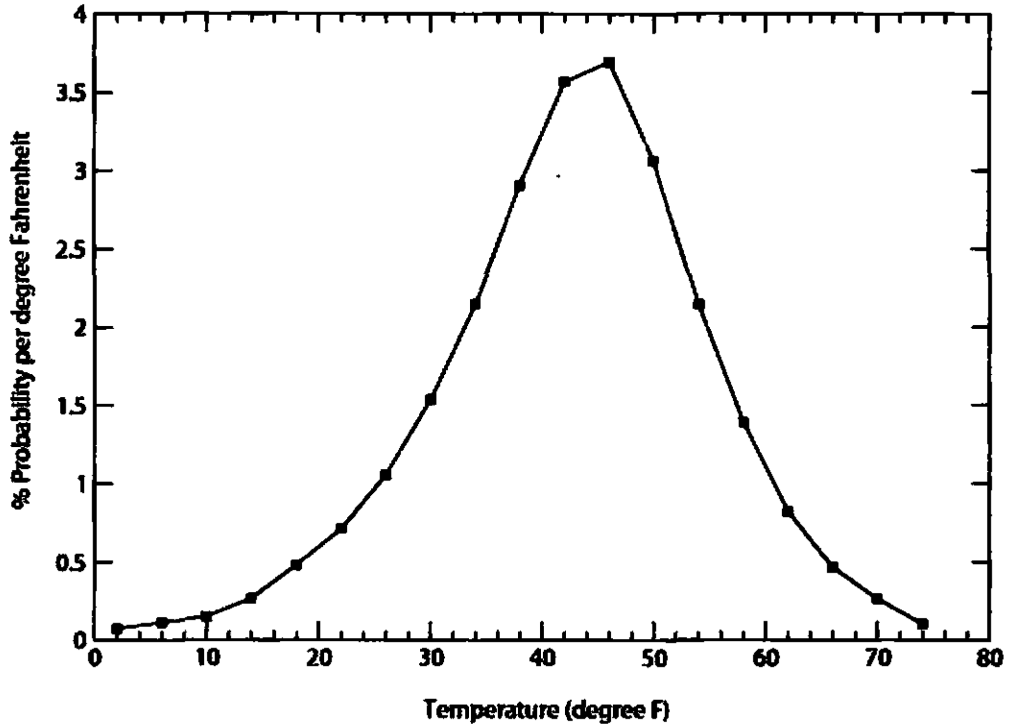

Figure 5.3.1: This figure represents the frequency distribution for the winter season of a grid point located in the Southeast climate division in Illinois for the projected 21st century using monthly mean warming. The grid-point's 20th percentile is 34°F, the median is 43°F, while the 80th percentile is 52°F. The 40th percentile has 41°F as temperature threshold.

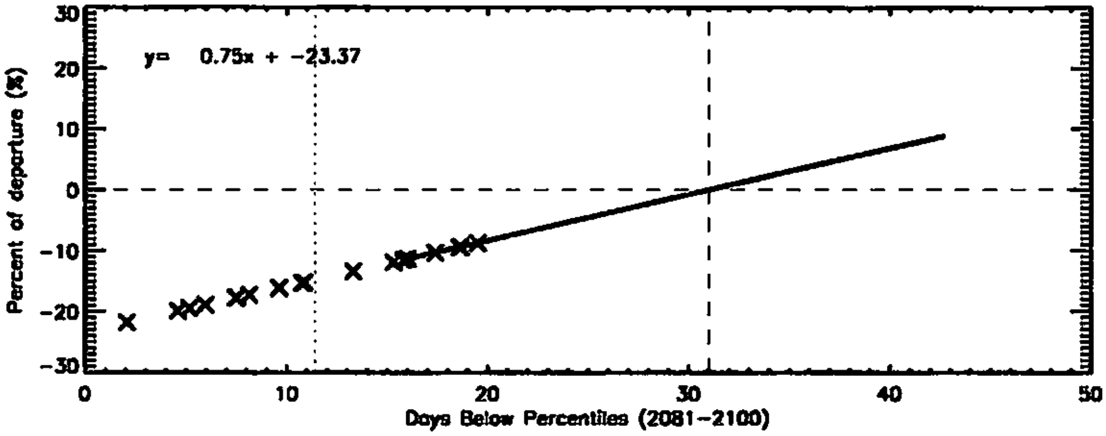

Figure 5.3.2: The NDBP calculated by using monthly mean warming. The NDBP was inserted in the statistical model to estimate percent departure from normal for 2081-2100 for the winter season. Horizontal dashed line represents the nation's mean natural gas consumption for the period 1987-2003. Vertical dashed line represents the nation's mean DBP for the period 1987-2003. The vertical dotted line represents the nation's projected mean DBP for the period 2081-2100.

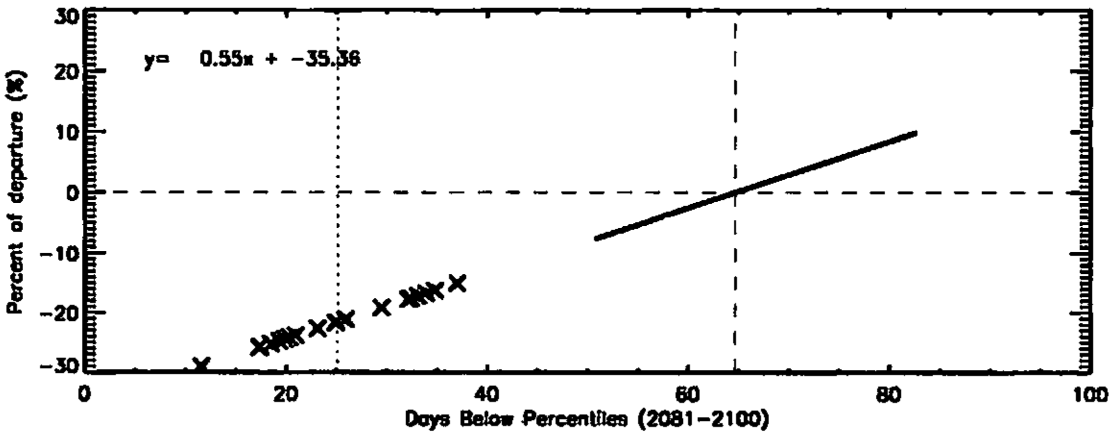

Figure 5.3.3: The NDBP calculated by using monthly mean warming. The NDBP was inserted in the statistical model to estimate percent departure from normal for 2081-2100 for the cold season. Horizontal dashed line represents the nation's mean natural gas consumption for the period 1987-2003. Vertical dashed line represents the nation's mean DBP for the period 1987-2003. The vertical dotted line represents the nation's projected mean DBP for the period 2081-2100.

Results in Figures 5.3.2 and 5.3.3 can be compared with those in 5.1.6 and 5.1.7 which were based on the daily warming increments. The results using the monthly-mean warming increments are similar in that a decrease in residential natural gas consumption for both winter and cold season is predicted, but the magnitude of the projected decrease is larger using the monthly-mean increments (specifically 16% versus 11% for winter, and 22% versus 17% for the cold season).

The difference in results between monthly warming versus daily warming can be explained by the probability distribution. Figure 5.3.4 compares the probability distribution of the projected late-21st century using the two methods of projecting the warming. The distribution of the projected temperatures using the monthly-mean warming has a different shape compared to that obtained using the daily warming increments. Notably, the distribution based on daily increments is broader and hence has more extremes falling below the cold threshold used to model the gas consumption.

These results show that the projected residential natural gas consumption response to a simulated global warming scenario is sensitive to how the warming data is used. The most appropriate way to use the warming predicted from a model which (like any actual model) does not perfectly simulate the present climate needs to be investigated more fully.

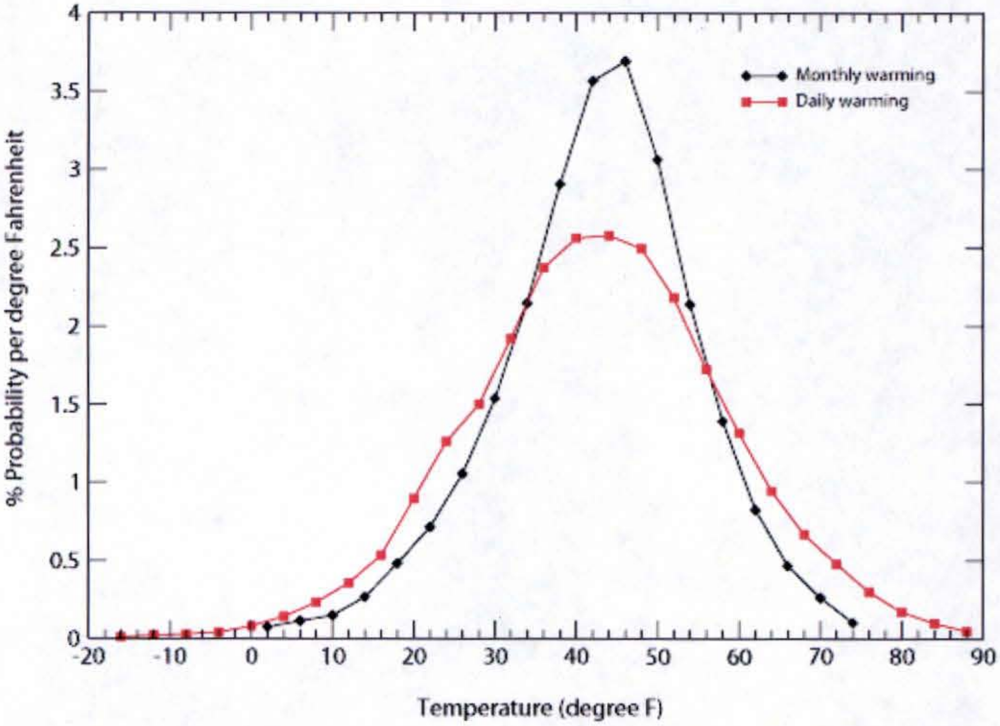

Figure 5.3.4: This figure represents the frequency distribution for the winter season of a grid point located in the Southeast climate division in Illinois for the projected 21st century using monthly mean warming and daily warming.

# CHAPTER 6
# CONCLUSIONS

Energy demand is directly affected by weather and climate anomalies and this has led to numerous earlier studies aiming to quantify this relationship. The present study focused on the quantification of the relationship between energy demand, specifically residential natural gas, and daily temperature fluctuations. The main goal was to create a statistical model that will improve the understanding of how anomalous daily temperatures affect residential natural gas on monthly and seasonal timescales. The model provides estimates of the percent of departure of the U.S. national residential natural gas demand from its long-term average. When combined with seasonal temperature forecasts, it can provide improved estimates of residential natural gas demand a season or more in advance. Also, since continuing increases in mean surface air temperatures in the U.S. are expected as a consequence of global climate change the model can be applied to study the role of climate in the long-term trends of natural gas consumption.

Most earlier energy demand studies have related consumption to heating degree days (HDD) and/or cooling degree days (CDD) based on somewhat arbitrary reference temperatures (typically taken to be 65°F for the calculation of HDD and CDD).

In contrast to previous work, the method employed in this study was based on the calculation of days below a specified temperature threshold determined with percentiles. This method allows the use of a simple objective approach to select a "customized" reference temperature for each individual station. The aim is to characterize the relevant weather-related information as a single national number related to the number of days the temperature was below a specified percentile. A weighting method was employed to give more significance to (i) those stations that are located in more heavily populated areas and (ii) those states that contribute the most to the national residential natural gas consumption. This calculation of an appropriately weighted national days below percentile number was performed for each of the daily maximum, daily minimum, and daily mean temperatures. The procedure was applied to the observations during the "winter" (December – February) and a longer "cold season" (November - April) during 1987-2003.

Residential natural gas consumption is affected by weather and climate anomalies, but as well by non-climatic influences such as economic growth and changes in consumer preference. During the 1987-2003 period a strong overall growth in demand was apparent. The linear detrending of the residential natural gas consumption data over this period was performed in a simple attempt to remove these non-climatic influences that affected the residential natural gas consumption. Correlations between the national days below a specified percentile and the nation's residential natural gas consumption were calculated for the winter and cold season and for all three temperatures elements. Although the number of days below percentiles for all temperature elements had strong correlations, daily mean temperatures were used for the rest of the analysis of this study, as these are most likely to be available in seasonal weather forecasts and climate model projections of future climate change.

After selecting the temperature element used in the analysis, the creation of the statistical model proceeded. Using the 40th percentile as the percentile boundary, statistical models were created for the winter and cold season. The statistical model for the winter season and cold season are represented by the following equations, respectively:

$$\textit{Percent departure} = 0.75x - 23.36 \qquad (6.1)$$

$$\textit{Percent departure} = 0.55x - 35.35 \qquad (6.2)$$

where $x$ represents the days below the 40th percentile. These equations provide an estimate of percent departure from average. For the winter season, the mean consumption for the period 1987-2003 is approximately 2,323,000 MMcf, while for the cold season the mean consumption for the same period is approximately 3,791,000 MMcf. This model does a remarkably good job at fitting the observed year-to-year fluctuations in U.S. residential natural gas consumption during 1987-2003. It was also shown to do a reasonable job at hindcasting the interannual variations in consumption in the earlier 1973-1986 period (although the consumption in these years was affected strongly by nonclimatic effects including changes in the regulatory regime).

Many models and atmospheric composition scenarios have been used to project future climate through the 21st century. The present study used one such climate projection to make an estimate of the possible climate-related changes in U.S. natural gas consumption that can be expected in 2081-2100 relative to the 1981-2000 period. Specifically the results from the Japanese MIROC 3.2 model used in the SRESA1B scenario were employed. The 21st century temperatures for use in the natural gas consumption model were computed by summing the actual 1981-2000 daily temperature observations plus the warming inferred from the model calculation. In order to do this, the real station temperature observations from 1981-2000 were interpolated onto the MIROC grid. Two procedures for using the model simulated warming information were employed. In one the actual daily warming over one century for a particular date was added to the actual temperature for that date. This procedure leads to forecast natural gas consumption during 2081-2100 that is approximately 11% below the 1987-2003 mean consumption in winter and 17% below in the November-April period.

The same process was re-done but instead of using daily warming, a monthly mean warming was calculated and then added to the real daily data from 1981-2000 to estimate the projected temperatures for 2081-2100. Once the national DBP were computed, these were inserted in the winter and cold season statistical model to estimate the consumption of residential natural gas in the late 21st century. The projected drop in U.S. residential natural gas consumption in late 21st century relative to 1987-2003 is now approximately 16% in winter and approximately 22% in November-April. The dependence of the results on how the model warming data and real observations are combined is significant. Other approaches (such as fitting statistical distributions to the observed and modeled temperatures, and then using the climate model projections to infer the change in both the mean and higher-order moments of the temperature distribution) may be investigated in the future.

The MIROC model is notable among current global climate models for its relatively high horizontal resolution (T106). Since most of the current global models are typically run at a coarser resolution (say T32-T42), the same process performed for the high resolution (T106) was executed using a spatially smoothed version of the daily modeled temperature warming data. There were only small differences in the results using the full resolution versus spatially-smoothed projected warming.

The expected increase in the mean surface temperature during the late-21st century will be mainly due to an increase in emission of $CO_2$. Burning of fossil fuels (e.g. natural gas, coal, and oil) is considered a source of $CO_2$ emitted in the atmosphere. The increase in consumption of fossil fuels will lead an increase of atmospheric $CO_2$, which will eventually lead to warmer temperatures. The present work can help quantify the expected negative feedback effect on global warming due to reduced wintertime natural gas consumption as the atmosphere warms.

Although this study has taken a further step in the quantification of the connection between residential energy demand, specifically natural gas, and daily variations of mean temperature, the use of this model is limited to only one energy source and is only applicable to winter and cold seasons. NCDC plans to expand the present study with the purpose of taking into consideration the other energy sources (e.g. heating oil, electricity, propane, other) used for residential heating and cooling as well.

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