3B.3

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

Ahira Sánchez-Lugo *, Jay H. Lawrimore, and David Wuertz
NOAA National Climatic Data Center, Asheville, North Carolina

Kevin Hamilton
Department of Meteorology and International Pacific Research Center (IPRC)
University of Hawai´i at Manoa

1. INTRODUCTION

It has long been recognized that weather and climate have a significant impact on the nation's energy demand. Understanding the factors that affect the national consumption of energy is vital in gauging future energy needs. 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) when temperatures are higher (lower) than normal. This strong relationship between residential energy demand and climate anomalies has been previously documented (Quayle and Diaz, 1980; Le Comte 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.

Most earlier studies of heating demand have based their analysis on the standard reference temperature of 65°F (Quayle and Diaz, 1980; Le 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). Also, it is well known that the U.S. has a broad range of climates and it is reasonable to assume that residents of one region are "comfortable" with conditions that may 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.

This paper describes the development of an objective technique to relate the seasonal residential consumption of natural gas in the U.S. to atmospheric temperature and its fluctuations, focusing on the cold part of the year when residential demand is dominated by heating. This technique improves on previous work through the use of a new analysis method to better gauge the impact of daily weather extremes. The method employed here is based on the calculation of days below a specified temperature threshold as determined with percentiles ("days below percentile" or DBP). DBP, being the number of days below a certain temperature threshold unique for each local area, allows for the selection of an appropriate reference temperature for each station used in the analysis.

Even in the absence of climate change, it is reasonable to expect trends in the U.S. residential natural gas consumption. The Energy Information Administration (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 projected that the climate of the U.S. will warm over the next century in response to the increase of greenhouse gases (e.g. IPCC 2001). This will be a factor that should act to reduce cold-season residential natural gas consumption.

This paper 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. 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). This paper 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.

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* *Corresponding author address:* Ahira M. Sánchez-Lugo, NOAA National Climatic Data Center, 151 Patton Avenue, Asheville, NC 28801; e-mail: Ahira.Sanchez-Lugo@noaa.gov.

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 (Hasumi and Emori, 2004) is used together with our statistical gas demand model.

2. DATA

2.1 *Observed Temperature*

The daily temperature data used to calculate percentiles and days below percentiles (DBP) are from the DSI-3200 data set of daily maximum and minimum temperatures available from NCDC. This data set provides information for a total of 23,000 stations in the nation, of which 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).

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 it was decided to use daily mean temperature data. 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.

Although mean temperature is not included in the DSI-3200 dataset an approximation to the daily mean was computed by averaging the maximum and minimum temperature for each day.

$$Mean \approx \frac{Max + Min}{2} \qquad (2.1.1)$$

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 DSI-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 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 (Figure 1).

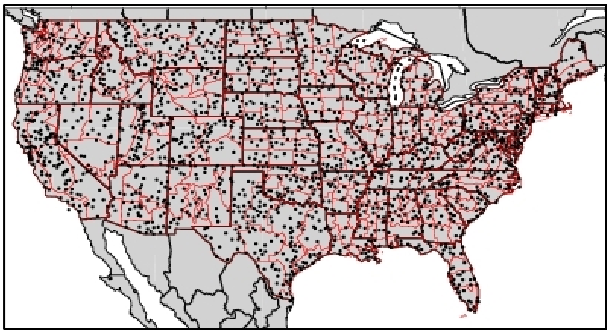

Figure 1. Distribution of stations that passed the Menne and Williams (2005) statistical homogeneity tests over the contiguous U.S.

2.2 *Natural Gas*

The residential natural gas consumption data used were provided by the EIA, which offers values of both state and national level residential consumption. The national monthly residential natural gas consumption data are available from 1973. Since the main focus of this study was to determine a relationship between residential natural gas consumption and wintertime temperature, the analysis was focused on the data from 1987 to 2003 for the contiguous U.S. since the pre-1987 year’s residential natural gas consumption pattern was strongly affected by non weather related variables.

2.3 *Model Projections*

While the historical temperatures and natural gas consumption data are used to determine the statistical relationship between temperature and natural gas demand, modeled temperature projections for the late 21st century are used in order to determine the climate-change related contribution to residential natural gas consumption that may be anticipated.

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 to determine the possible influence of climate change over the 21st century on the U.S. residential natural gas consumption. Specifically, the gas consumption model developed 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. This paper 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. Figure 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. Results from just one model, the so-called MIROC high resolution model were used. 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). 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.

The atmospheric component of the high resolution version of MIROC employed was run as a spectral model in spherical harmonics with triangular truncation at wave number 106 (T106) and results are saved on a 1.125 degree latitude-longitude grid. The raw data used are daily mean values of the surface temperature at all grid points in the contiguous U.S. (Figure 3). 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) were employed.

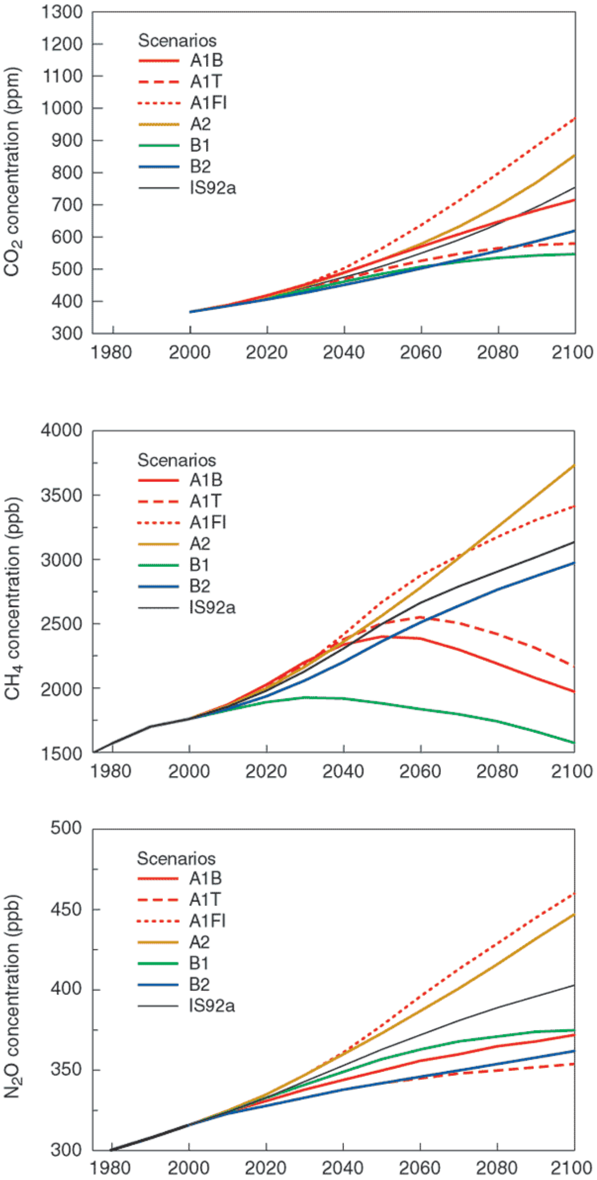

Figure 2. Atmospheric concentrations of CO2, CH4, and N2O resulting from the SRES scenarios. (Source: IPCC)

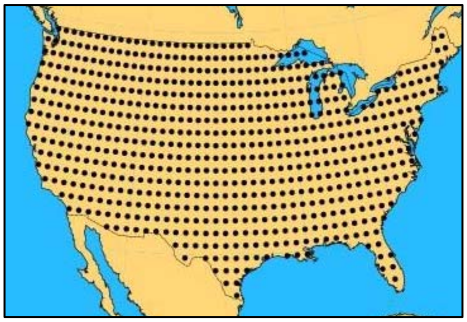

Figure 3. MIROC 3.2 grid points within the contiguous U.S.

3. METHODOLOGY

3.1 *Calculating Days Below 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 from the 5th percentile to the 90th percentile using a 5 percent increment for each station using daily mean temperature data from 1949-2003. 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).

After computing the temperature thresholds for each percentile and for each station for a particular season (winter or cold season) calculation of the days below percentiles (DBP) for the time period of 1987-2003 followed. This was accomplished by aggregating or adding the days that were below a particular percentile threshold for a given season.

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:

$$SDBP = \frac{\sum_{i=1}^{n} (DBP_i)(POP_i)}{\sum_{i=1}^{n} (POP_i)} \qquad (3.1)$$

Where SDBP = State level DBP

n = number of population grid boxes within a state

DBP_i = days below percentiles for the nearest station to population grid box i

POP_i = 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:

$$NDBP = \frac{\sum_{i=1}^{48} (SDBP_i)(CON_i)}{\sum_{i=1}^{48} (CON_i)} \qquad (3.2)$$

Where *NDBP* = National level DBP

CON_i = long-term mean (1989-2003) residential natural gas consumption for state i.

3.2 *Correlations*

Correlations were computed in order to examine the relationship between NDBP and the nation's raw residential natural gas consumption over the period 1987-2003 (Table 3.1). 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.

Table 3.1 shows the correlations of NDBP for daily mean temperature and the raw national residential natural gas consumption for different threshold percentiles. High correlations for mean temperatures ranged from 0.660 to 0.830 for the cold months with the exception of November. Correlations for November were as high as 0.928. 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.

The raw national residential natural gas consumption values display an increasing trend during 1987-2003 (Figure 4). 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 Figure 4, where they are compared with the time series of NDBP values for the 40th percentile threshold. After this detrending of the national residential natural gas consumption values, correlations with the NDBP time series were re-computed (Table 3.2). The correlations improved by detrending the residential natural gas consumption indicating a strong relationship between the nation's residential natural gas consumption and the wintertime temperatures. 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 NDBP for both winter and cold season was judged subjectively to provide the best overall fits for the various months and seasonal periods.

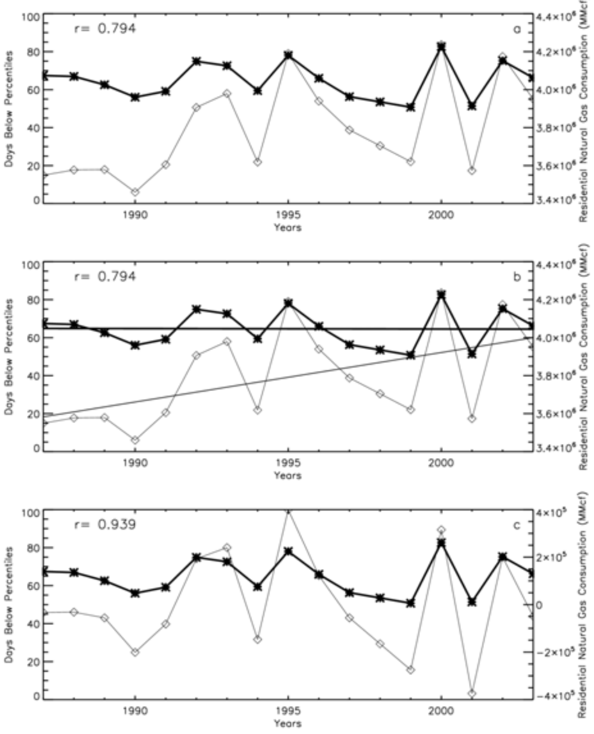

Figure 4: (a) Time series of raw national natural gas consumption in million cubic feet (MMcf) units and weighted NDBP for the 40th percentile for the cold season (November-April). (b) Similar to (a) with trends plotted. Thick line is the NDBP trend and thinner line is the natural gas consumption trend. (c) Time series of nation's detrended natural gas consumption and weighted NDBP. Asterisk (*) represents the NDBP and diamond (◊) represent the national natural gas consumption.

3.3 *Statistical Linear Regression Model*

Detrended time series of yearly values are 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 (1987-2003) means for the appropriate season to the detrended time series. 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:

$$Percent\ \ departure = \frac{(AV - MAV)}{MAV} * 100 \quad (3.3)$$

Where *AV* = Adjusted value of the detrended residential natural gas consumption
MAV = Mean of the adjusted values

The time series of consumption expressed as percent 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 (Figure 4.1.1).

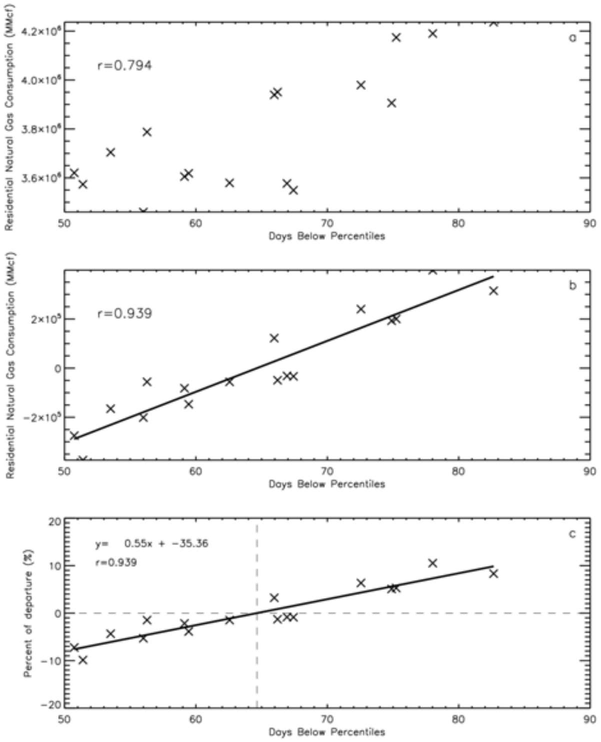

Figure 5: (a) Scatter plot of national residential natural gas consumption versus weighted NDBP at the 40th percentile for mean temperature. (b) Scatter plot of detrended residential natural gas consumption versus weighted NDBP. (c) Linear regression model. All plots represent the cold season (November-April).

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.

The statistical model for the winter season and cold season are represented by the following equations, respectively:

$$Percent\ \ departure = 0.75x - 23.37 \quad (3.4)$$

$$Percent\ \ departure = 0.55x - 35.36 \quad (3.5)$$

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 (Figure 6). 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) (Figure 7).

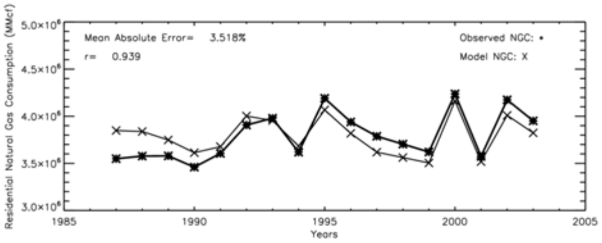

Figure 6: Time series of the national residential natural gas consumption for the cold season for 1987-2003. Asterisk (*) represents the observed consumption, meanwhile the X represents the modeled consumption.

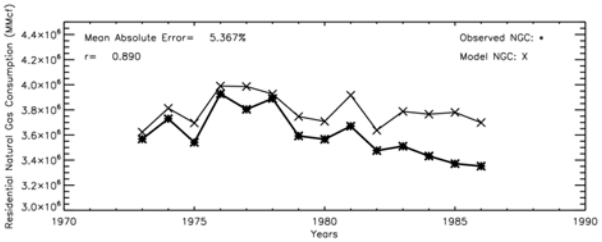

Figure 7: Time series of the national residential natural gas consumption for the cold season for 1973-1986. Asterisk (*) represents the observed consumption, meanwhile the X represents the modeled consumption.

4. LATE 21ST CENTURY PROJECTIONS

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).

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 (Figure 3). 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 with a triangular truncation at wave number 32-42 [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.

5. REFERENCES

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P 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 3.1: Correlations between the monthly/seasonal NDBP and monthly/seasonal raw 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 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 3.2: Correlations between the nations monthly/seasonal NDBP 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 NDBP were calculated using mean temperatures.