Shift in seasonal climate patterns likely to impact residential energy consumption in the United States

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Keywords: energy demand, regional climate change, degree days

Abstract

We develop a highly-resolved ensemble of climate simulations and empirical relationships between weather and household energy consumption to provide one of the most detailed estimates to date for potential climate-driven changes in the United States residential energy demand under the highest greenhouse gas emissions pathway. Our results indicate that more intense and prolonged warm conditions will drive an increase in electricity demand while a shorter and milder cold season will reduce natural gas demand by the mid 21st century. The environmental conditions that favor more cooling degree days in summer and reduced heating degree days in winter are driven by changes in daily maximum temperatures and daily minimum temperatures in the respective seasons. Our results also indicate that climate-driven change can potentially reverse impacts of a projected decrease in rural population on residential energy demand. These projected changes in climate-driven energy demand have implications for future energy planning and management.

1. Introduction

Frequent occurrences of hotter summers and warmer winters across the United States (US) reflect a potentially permanent change in temperature distribution that is progressively reshaping energy demands (EPA US 2014, Petri and Caldeira 2015). In particular, warming trends are the strongest on record in recent decades with seven out of the ten warmest years since 1998 (EPA US 2014). Given the current trajectory of emissions, most recent temperature projections suggest warming of 1.1 °C–2.2 °C across the continental US by the mid 21st century (Melillo et al 2014, Ashfaq et al 2016). Increase in the mean temperatures is the strongest over the higher elevations and the part of US that presently receive significant amounts of cold season precipitation in the form of snow while southwest and southeast are projected to be the hot spots for increases in maximum temperatures. Additional warming will likely exert further influence on the US energy system making adaptation a necessity to meet the challenges of future energy demand.

Changes in ambient temperatures have implications for the two dominant sources of energy that are used for residential space heating and air conditioning in the US. Electricity is the dominant source of energy used for space cooling and therefore temperature increases associated with climate change are anticipated to drive electricity demand associated with greater air conditioning use. A recent study projected that by the end of the 21st century, residential energy costs in relatively warm states (such as Florida) could increase by $200/year (Huang and Gurney 2017). Meanwhile, natural gas is the dominant fuel source for residential space heating. Hence, demand for natural gas is expected to decline in the future as rising temperatures reduce heating demand (CCSP 2007). Nevertheless, given the diversity in the climate characteristics and the magnitude of projected climate change across the US, substantial geographic
heterogeneity in the response of residential energy demand (hereafter RED) to climate change should be expected. This variability will exert contrasting controls on natural gas and electricity demand, leading to inevitable fine-scale variations in the energy system response. A comprehensive investigation of the fine-scale changes in the RED is important for planning future enhancements to the electricity generation and distribution system, as well as the natural gas pipeline network. There are several technological, societal, economic and environmental factors that will frame the future RED. However, given the interdisciplinary nature of these factors and lack of reliable future estimates for many, it is practically impossible to incorporate their combined influences in a single study. Due to these limitations, this study mainly focuses on the influences of climate driven long-term environmental variations on RED within the context of projected population increase. Thus far, a number of studies have investigated potential variations in the US energy system in the future climate, but results to date are relatively limited. Most of the studies either use spatially and/or temporally aggregated data (Sailor and Munoz 1997, Zhou et al 2014, McFarland et al 2015), or have focused on a particular geographic sub-region within the US (Amato et al 2005, Ruth and Lin 2006, Auffhammer and Aronruengsawat 2011). Similarly, most of the studies often have only investigated changes in electricity consumption (McFarland et al 2015, Allen et al 2016, Auffhammer et al 2017), without considering changes in natural gas demand. Likewise, RED investigations at spatially disaggregated scales so far have obtained future climate data either directly from general circulation models (GCMs) (Wang and Chen 2014, Huang and Gurney 2016) or via statistical downscaling of GCMs (Dirks et al 2015). While GCMs remain the most reliable tool for understanding future climate change, a mismatch between their resolution and the scales that are relevant for policymaking preclude their direct use when making reliable estimates of climate change impacts (Diffenbaugh et al 2005, Ashfaq et al 2009, Suggitt et al 2011, Ashfaq et al 2016). Likewise, statistical downscaling has its own limitations given that it cannot refine climate change signal without altering the simulated process-based climate system response in GCMs (Ashfaq et al 2013). Therefore, while computationally expensive and data intensive, regional climate modeling based dynamical downscaling of GCMs remains the most sophisticated methodology for the generation of fine-scale climate projections.

In this study, we seek to build on previous work and provide a more comprehensive and applicable picture of RED in response to climate change. We develop observations based economic models that describe the relationship of RED to human population and climatic conditions. Further, leveraging one of the most detailed (to date) ensemble of climate change simulations over the US (Ashfaq et al 2016), economic models are used to provide estimates for future changes in residential energy use for space heating and cooling in response to changes in climatic conditions. Our analyses provide estimates for future changes in both electricity and natural gas demand for residential space heating and cooling across the US at the county level.

2. Data and methodology

2.1. Data

Observed gridded daily maximum temperature (Tmax) and daily minimum temperature (Tmin) are obtained from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) (Daly et al 2008). Simulated Tmax and Tmin are obtained by bias correcting dynamically downscaled 11-member ensemble of GCMs (see table S1, available online at stacks.iop.org/ERL/14/074006/mmedia) from Coupled Model Inter-comparison Project Phase 5 (CMIP5) (Ashfaq et al 2016) following the approach detailed in Ashfaq et al (2010), (2013). State level natural gas and electricity consumption (EIA US 2016a, 2016b) and residential energy consumption survey (RECS) data for the 10 US census divisions (figure S1) are obtained from US Energy Information Administration (EIA). Population statistics are obtained from US Census Bureau (Census US 2016). Further description of these datasets is detailed in the supplementary information.

2.2. Methodology

The multi-step methodology is detailed in the following subsections and a schematic is provided in figure S2.

2.2.1. Heating and cooling degree days
We use heating degree days (HDD) and cooling degree days (CDD) to quantify the energy requirements for residential heating and cooling respectively. HDD (CDD) is defined as the number of degrees (in degree Celsius; °C) to be heated (cooled) below (above) a given threshold. HDD and CDD calculations use 18.3 °C (65 °F) as threshold and follow the UK Met Office equations (Day 2006). See supplementary information for further details.

2.2.2. Econometric model
Equations (1) and (2) represent the econometric models for residential electricity and natural gas consumption. Each econometric model is based on state level observed EIA energy (electricity or natural gas) consumption, state level degree-days from aggregated PRISM meteorological observations and state level population from Census for 1990–2005.
\[
\log(E_{\text{sh}}^{\text{any}}) = c_e + \alpha_{e0}(HDD_{\text{sh}}^{\text{any}}) + \alpha_{e1}(HDD_{\text{sh}}^{\text{any}})^2 \\
+ \beta_0(CDD_{\text{sh}}^{\text{any}}) + \beta_1(CDD_{\text{sh}}^{\text{any}})^2 \\
+ \gamma_{00}(P_y) + \delta_f + \delta_m + \epsilon_e
\]  

(1)

\[
\log(NG_{\text{sh}}^{\text{any}}) = c_{ng} + \alpha_{ng0}(HDD_{\text{ng}}^{\text{any}}) \\
+ \alpha_{ng1}(HDD_{\text{ng}}^{\text{any}})^2 + \gamma_{ng0}(P_y) \\
+ \delta_f + \delta_m + \epsilon_{ng}
\]  

(2)

RECS-based percentage usage is applied to total residential electricity and natural gas consumption to obtain the relative shares of electricity \((E_{\text{sh}}^{\text{any}})\), used for space heating and cooling, and the natural gas \((NG_{\text{sh}}^{\text{any}})\), used for space heating for state \(s\), month \(m\) and year \(y\).

Similarly, \(HDD_{\text{sh}}^{\text{any}}, HDD_{\text{ng}}^{\text{any}}\) and \(CDD_{\text{any}}\) are HDD fulfilled by electricity, HDD fulfilled by natural gas and CDD for respective state, month and year. \(c_e\) and \(c_{ng}\) are constant terms, \(\alpha_{e0}, \alpha_{e1}, \beta_0, \beta_1, \gamma_{00}, \alpha_{ng0}, \alpha_{ng1}, \gamma_{ng0}\) are coefficients of respective terms as shown in the equations and \(\epsilon_e, \epsilon_{ng}\) are error terms. Additionally, we use \(\delta_f\) and \(\delta_m\) as fixed effects for states and months respectively. Fixed effects were used in a regression model to control for some types of omitted variable bias. The state fixed effects account for the average difference in time-invariant state characteristics. The month of year fixed effects account for common shocks to all states in a month of the year and can capture seasonal patterns unobserved in the data. In this case, inclusion of state and month fixed effects allows control for differences in the magnitude of degree days that arise (i) among states because of differences in population size and (ii) among months because of seasonal variations. It should be noted that while the month fixed effects account for intra-annual differences among the states, the differences between years arising from factors such as macroeconomic fluctuations are not incorporated. Moreover, the electricity model uses all months while summer months (June, July and August) are excluded for the natural gas model. Overall, the econometric models are able to precisely estimate the determinants of electricity and natural gas demand. The R-square values for the models are 0.99 and 0.98 respectively and there are significant t-statistics for all the coefficients at 95% significance level. The F-statistics suggest that the results are jointly as well as individually statistically significant (table S2 and S3). We also perform additional tests to rule out any temporal or spatial correlation in our datasets. First, we perform regressions using Newey-West standard errors with 45 and 34 lags for electric and natural gas models respectively. Second, we estimate these regression using (Driscoll and Kraay 1998) standard errors. These standard errors are robust to very general forms of temporal and spatial correlation with all coefficients being statistically significant at the 1% level.

The fixed effect regression models established in equations (1) and (2) are subsequently applied to each of the RegCM4 ensemble members by replacing the PRISM degree days with the simulated degree days in the 25 years in the historical period (1981–2005) and the 40 years period in the future (2011–2050). For the future models, the population is kept at the 2005 level to isolate the variations in energy demand that arise solely because of climatic changes.

2.2.3. Energy data disaggregation

We have devised a weighting method to disaggregate state-level estimated energy consumption data to the county level. This accounts for differences in the population, heating and cooling requirements across counties within each state. The disaggregation technique is detailed in the supplementary information.

3. Results and discussion

3.1. Historical comparisons

Across the US, residential space heating requirements are generally higher than the space cooling requirements given the higher number of HDD than CDD (figures 1(a)–(d)). Cooler temperatures associated with continental air and higher elevations drive maximum space heating requirements in the north central US (up to >3400 °C) whereas space cooling requirements peak mostly over southern US such as Florida, Texas and parts of the southwest (up to >2000 °C). The spatial variability in the degree days, along with their magnitudes are simulated exceptionally well in the RegCM4 simulations compared to the observations (figures 1(a)–(d)).

Observations exhibit a decreasing (increasing) trend in HDD (CDD) across the US, which is also captured in the simulations (figures 1(e)–(h), S3–4). However, the simulated decrease in HDD (up to 350 °C) is substantially milder than observed (up to 550 °C) over the Rockies, and the strongest observed increase in CDD over the southwest is approximately 1.5 times higher than the simulated trends. The trends in HDD are significant in both the observations and the simulations in most of the western half and parts of the eastern half of the US. However, the increasing trend in CDD is only significant over parts of the southwest and Pacific Northwest in the observations in contrast to the simulations that also exhibit significant trends over the southeast and parts of the northeast. HDD and CDD trends in ten metropolitan regions exhibit similar characteristics in both the observations and the simulations. For instance, both datasets exhibit a decreasing trend in HDD over all ten regions, which is also statistically significant over three regions. Similarly, both datasets exhibit increasing but insignificant trends in CDD over 9 out of 10 regions (figures 1(i), S3–4). Collectively, these comparisons demonstrate that the downscaled data exhibits good skill in the simulation of the mean HDD and CDD, and first-order skill in the...
simulated their historic trends. This is important because historic trends in HDD and CDD provide a precursor for future changes in energy demands in warmer climates.

Driven by the skillfulness of downscaled data in capturing the characteristics of HDD and CDD, simulations-based electric and natural gas demands also compare well with the EIA observations, particularly
at low and medium demand levels (<4000 GWh for electricity and <60 000 MMcf for natural gas) (figures S5–S7). The simulated electric demand also exhibits skill at the metropolitan level where statistically significant trends are simulated across all ten metropolitan regions in both the RegCM4 simulations and the observations (figure 1(i), S5). The trend in simulated natural gas demand compares well with the observations for 7 out of 10 regions (figure 1(i), S6). Both electricity and natural gas demand exhibit an upward trend, due to the rising population over the historical period.

3.2. Future changes in energy demand
To understand the impacts of climate variations on RED, we fix all other factors including population and other economic drivers that may influence energy system response. Such an approach is a standard in the future climate studies. For instance, all RCPs driven GCMs simulations only simulate climate system response to changes in representative concentration pathways. With population kept at 2005 levels, electricity demand is projected to increase across the US with the exception of some parts of western US, which exhibit a decrease of up to 7% in parts of Arizona, Nevada, and California by 2050 (figure 2(a)). The magnitude of increase across the rest of the US is up to 10%. For metropolitan regions considered in this study, an increase in electricity demand is projected for eight out of ten, ranging from approximately 0.5% for Boston–Cambridge Newton, MA to more than 7% for Miami–Fort Lauderdale–West Palm Beach, FL (figure 2(c)). In the case of natural gas, the demand is projected to decrease over most of the US (figure 2(b)) with the exception of parts of some states such as Texas, Arizona, and Florida that exhibit a strong increase. However, these strong percent increases over parts of these states primarily driven by their relatively small natural gas demand during the historical period. Given that natural gas is mainly used for space heating, the decrease in natural gas demand is driven by the changes during the winter months (i.e. September–May). RegCM4 ensemble members show a robust decrease in natural gas demand (up to 4%) across all ten metropolitan centers, which is mainly driven by a decrease in HDD (figures 2(e)–(f)). The decrease is larger during the transition months i.e. April and May in spring, and September and October in fall compared to winter months.

3.3. Driving climate variations
We investigate the factors driving future changes in RED by defining changes in the summer-like (hereafter summer) and the winter-like (hereafter winter) conditions. Summer (winter) conditions are defined as the longest consecutive period when CDD (HDD) is greater than HDD (CDD). Figure 3 shows a comparison of accumulated degree days and degree days per day (CDD for summer and HDD for winter) in the PRISM observations and the RegCM4 simulations for summer and winter respectively. Accumulated CDD (HDD) range from 0 to >1400 (0 to >4000) °C whereas CDD (HDD) per day range from 0 to 10 (0 to 18) °C during summer (winter). The total and per day degree days are based on the timing and duration of summer and winter. Summer starts as early as April in the south and as late as June/July in the north, with a gradual decrease in the duration (>200 to <40 d) and the cooling requirements (>1400 to <200 °C). Winter starts as early as September in the north and as late as December/January in the south, with a gradual decrease in duration (>280 to <40 d) and heating requirements (>4000 to <400 °C) from north to south. This seasonal duration shift intensifies with the increase (decrease) in latitude and/or elevation for summer (winter) (figure S8).

While electricity is used for both space heating and cooling, future changes in the characteristics of summer and winter suggest that the projected increase in the electricity demand is primarily driven by an increase in the cooling demand. A late onset of winter, particularly over the higher elevations, and an early arrival of summer shrink the length of winter conditions (figure S9) by a few days in the parts of the western US, reducing the HDD by 20 °C to as much as 400 °C respectively (figure 4(b)). On the other hand, there is an increase in the length of summer conditions (figure S9c) by a few degree days in the parts of Pacific Northwest and Rockies to as much as a month in most of the southwest, increasing the CDD by 20 °C to as much as 300 °C respectively (figure 4(a)). The per degree day change in heating (cooling) demand that ranges from −0.7 to 0 (0 to 1) °C is mainly driven by changes in minimum (maximum) daily temperature during winter (summer) (figures 4(c)–(f)).

3.4. Socioeconomic drivers
While this study only focuses on the climate driven long-term environmental variations that can potentially influence RED, there are other socioeconomic factors that may reverse, mute or amplify the projected influence of climate-driven changes. We elaborate on such an impact of socioeconomic variations by considering projected changes in population distribution (figure 5(a)) in our economic model. We use 5 yearly population projections data from Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios A2 scenario, which is analogous for RCP8.5 (EPA US (2010)), and linearly interpolate it at yearly time-scale to match the future period (2011–2050). Use of both climate and population changes in our economic model enables comparisons of future changes in energy demand caused by changes in climate (figures 2(a), (b)) with those caused by changes in both population and climate.
With the exception of Texas, California, and Florida where future population increase is projected to be statewide, urban areas are mainly expected to experience population growth. The projected increase in RED due to population increases (figures 5(b), (c)) in these three states and urban areas across the US will outpace the projected increase in RED due to climate (figures 2(a), (b)). On the other hand, most of the rural areas are projected to witness a decline in the population (figure 5(a)); however, climate-driven increase in RED in those rural areas will overwhelm the decrease caused by population changes (figures 2, 5). Compared to climate-driven changes, our results indicate that an increase (decrease) in urban (rural) population can potentially result in as much as 10 fold increase (as low as 5 fold decrease) in residential electricity demand. Similarly, compared to climate-driven changes, increase (decrease) in urban (rural) population can potentially result in as much as 5 fold increase (as low as 5 fold decrease) in natural gas demand.

In addition to changes in the population, economic factors can potentially exert a significant influence on the pace of technological advancements and
residential energy prices. Moreover, a growing economy boosts advancement in technology, resulting in more efficient heating and cooling systems, efficient building designs etc. Likewise, factors such as supply and demand variations and inflation in the energy sector can also drive changes in residential energy prices. However, due to the absence of reliable estimates for the future energy supply and demand, economic conditions and technological innovations, no other socio-economic factors have been considered in this study.

4. Summary and conclusions

This study uses an econometric model and one of the most detailed climate projections over the continental US to investigate future variation in residential energy demand by the mid-21st century in response to increases in radiative forcing. The econometric model (RegCM4) exhibits exceptional skill across the US in the prediction (simulation) of the characteristics of RED (degree days). Future climate is projected to
exhibit an increase in the span of hot conditions due to the early arrival of summer-like conditions and delay in the onset of winter-like conditions, leading to a net increase in the residential electricity demand and a decrease in the residential natural gas demand by the mid-21st century. However, driven by the spatial heterogeneity in the climate change signal and the background cooling and heating demands, there are important variations in the characteristics of future RED. For instance, counties in the southern half of US and parts of Midwest are projected to experience stronger increases in the residential electricity demand as compared to those in the northeast and northwest. Similarly, the decrease in natural gas demand is higher in the parts of southeast and parts of the south as compared to its demand in the northwest and Midwest. The projected shift in the energy needs from natural gas to electricity may affect greenhouse gas (GHG) emissions, depending on the source of electricity generation. Electricity generation from natural gas and coal based thermal plants contributes to GHG emissions, while electricity generation from renewable sources such as hydropower and solar does not. An increase in space cooling requirements will necessitate enhanced electricity generation capacity to meet the electricity demand, which may lead to additional construction and operational costs and higher electric bills.

While keeping the main focus on climate-driven changes in the future RED, this study also highlights the importance of socioeconomic drivers that may either reverse, mute or amplify the impacts of climate change on energy systems. Using the projected population changes as an example, we demonstrate that while urban areas will likely experience a strong increase in the future RED due mainly to the greater influx of migrating population, rural areas may also exhibit an increase in the future RED due to climate-driven changes despite a decline in rural population. However, as previously pointed out, other socioeconomic drivers and technological advancements, which have not been considered in this study, will also be important determining factors of the future changes in energy demand. Lastly, it should also be noted...
that biases arising from methodological choices such as disaggregation technique, statistical model errors, and uncertainties in the future climate projections may also have influenced our estimates of climate impacts on the future RED. Nonetheless, the results presented in this study should pave the way for the development of more rigorous and comprehensive analysis frameworks for understanding the response of RED to future changes in climate and socio-economic conditions.

Acknowledgments

This research was supported as part of the Energy Exascale Earth System Model (E3SM) formerly known as Accelerated Climate Modeling for Energy (ACME) project, funded by the US Department of Energy, Office of Science, Office of Biological and Environmental Research. The research also received support from the Oak Ridge National Laboratory Project Development funds and Regional and Global Climate Modeling program of the US Department of Energy (DOE) Office of Science. Support for model simulations, data storage and analysis is provided by the Oak Ridge Leadership Computing Facility at the Oak Ridge National Laboratory (ORNL), which is supported by the Office of Science of the US Department of Energy (DOE) under Contract No. DE-AC05-00OR22725. This manuscript has been authored by UT-Battelle, LLC, under contract DEAC05-00OR22725 with the US Department of Energy.

Figure 5. (a) Projected future changes in the population under EPA A2 scenario with respect to 2005 Census population. Relative changes in demand (b) electricity (c) natural gas with and without population changes in the future period (2011–2050). The relative change is calculated by dividing the demand projections when econometric model considers both population change and climate change by the demand projections when econometric model only considers climate change.
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