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Responses of energy use to climate change: A climate modeling study

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[1] Using a general-circulation climate model to drive an energy-use model, we projected changes in USA energy-use and in corresponding fossil-fuel CO_2 emissions through year 2025 for a low (1.2°C) and a high (3.4°C) temperature response to CO_2 doubling. The low-ΔT scenario had a cumulative (2003–2025) energy increase of 1.09 quadrillion Btu (quads) for cooling/heating demand. Northeastern states had net energy reductions for cooling/heating over the entire period, but in most other regions energy increases for cooling outweighed energy decreases for heating. The high-ΔT scenario had significantly increased warming, especially in winter, so decreased heating needs led to a cumulative (2003–2025) heating/cooling energy decrease of 0.82 quads. In both scenarios, CO_2 emissions increases from electricity generation outweighed CO_2 emissions decreases from reduced heating needs. The results reveal the intricate energy-economy structure that must be considered in projecting consequences of climate warming for energy, economics, and fossil-fuel carbon emissions. **Citation:** Hadley, S. W., D. J. Erickson III, J. L. Hernandez, C. T. Broniak, and T. J. Blasing (2006), Responses of energy use to climate change: A climate modeling study, *Geophys. Res. Lett.*, *33*, L17703, doi:10.1029/2006GL026652.

1. Introduction

[2] The observed atmospheric CO_2 increase is expected to continue, leading to continued increases in near-surface air temperatures. One little-studied aspect of warming is the change in the amount of energy required for heating and cooling of buildings, and related changes in fossil-fuel carbon emissions. Projecting these interrelated variables into the future requires a quantitative melding of the results of a detailed climate model and a detailed energy economics model, two different modeling areas that have rarely been joined. Here, we present for the first time a linked simulation involving these two types of models. This first attempt can be refined in several ways, but it has revealed some basic considerations that need to be addressed in projecting energy and carbon responses to climate change.

2. Data and Methods

[3] Because our methodology includes complex numerical models of climate and economic factors we here provide an overview with references to the details of both kinds of models. We compared two time periods, 1971–2000 (the most recent 30-year period for which climate normals are calculated) and 2003–2025 (the period covered by the economic model).

[4] For climate simulation, we used the PCM-IBIS (Parallel Climate Model-Integrated BIosphere Simulator) which is a version of the PCM [*Barnett et al.*, 2001; *Meehl et al.*, 2001; *Washington et al.*, 2000] that simulates surface temperature data at latitude-longitude intervals of 2.5 degrees across the globe for every 15 minutes from 1900 to 2100 [*Thompson et al.*, 2004]. We used two PCM-IBIS computer runs a "Low-ΔT" scenario with a low temperature response to CO_2 doubling (1.2°C), and a "High-ΔT" scenario with higher response (3.4°C). Model temperature responses generally depend on parameterizations of energy and water balances, which affect cloud formation and other feedback mechanisms within the climate system.

[5] To make the climate-model output compatible with economics-model input, simulated temperatures across the United States of America (USA) for each year from 1971 through 2025 were aggregated geographically and temporally into monthly averages for each of the nine census divisions defined by the U.S. Census Bureau (Figure 1a) and converted to population-weighted cooling degree days (CDD) and heating degree days (HDD). Because the two scenarios have different responses to CO_2, their historic and projected regional temperature profiles are different; therefore they were calibrated separately against population-weighted temperature values derived from degree-day data obtained from the National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html), under "Data and Products." The conversion formula for the historical data is:

$$T = (CDD - HDD + 65{*}d)/d$$

where T is a population-weighted monthly average temperature (°F), CDD and HDD are, respectively, corresponding values of cooling degree days and heating degree days, 65 is the reference temperature (°F) for calculating degree days and d is the number of days in the month. For each of the nine census divisions, 1971–2000 averages of these population-weighted temperatures for each calendar month were compared with corresponding averages of modeled temperatures, and the differences were used to adjust the modeled temperatures for 2003–2025. This procedure made the modeled temperatures for each scenario comparable to the historical data, and also easily convertible to population-weighted degree days for the economic model. Changes in total population for each division are incorporated into the economic model, to account for general population growth and inter-regional shifts as projected by the U.S. Census Bureau, Population Projections Branch (http://www.census.gov/population/

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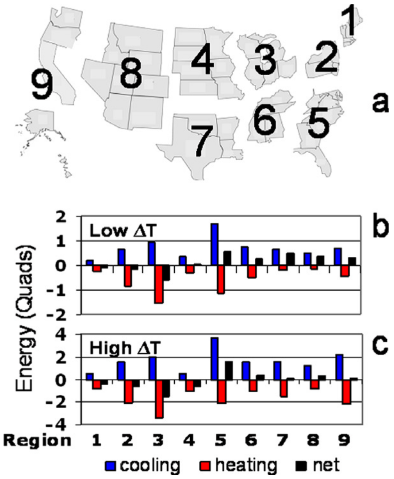

Figure 1. (a) The nine U.S. Census Divisions and their projected cumulative (2003–2025) changes in primary heating, energy, cooling energy, and net changes, as departures from the reference case, for (b) the low ΔT scenario and (c) the high ΔT scenario. The Census Divisions are: (1) Northeast, (2) Middle Atlantic, (3) East North Central, (4) West North Central, (5) South Atlantic, (6) East South Central, (7) West South Central, (8) Mountain, and (9) Pacific including Alaska and Hawaii.

www/projections/projectionsagesex.html). However, it is implicitly assumed in our procedure that population changes in a division will not change the fractional population weighting of any area within that division. Refinements in this area are already ongoing.

[6] From the population-weighted temperatures, we calculated the corresponding CDD and HDD values for 2003–2025. Most months have some days with CDD and other days with HDD, so a series of 30-step (30-day) random walks about 65°F was used to produce a series of daily temperatures from which an initial set of CDD and HDD was calculated. Each daily temperature was then changed by a constant equal to the change in monthly average temperature, and the results were used to obtain corresponding changes in CDD (ΔCDD) and in HDD (ΔHDD). The calculations were repeated for several randomly chosen monthly temperature changes, ranging from −5°F to +5°F, which covered all modeled monthly (population adjusted) temperature changes through year 2025. Because cumulative results of random walks can be highly influenced by the direction of the first step, a wide variety of initial monthly mean temperatures and corresponding changes in CDD and HDD were generated by more than 600 runs of this procedure. The resulting values of CDD, HDD, ΔCDD and ΔHDD, were used to transform modeled monthly temperatures, adjusted for population weightings, into degree-day values.

[7] For economic modeling, the stock of existing buildings and equipment, data on options available, decision procedures, energy prices, etc. need to be available for the model to realistically simulate the purchasing behavior of people. The most widely recognized economic simulation model is the National Energy Modeling System (NEMS) [*U.S. Department of Energy*, 2003a]. The Energy Information Administration (EIA) developed this model to forecast national and regional energy supply and demand through 2025. NEMS models the major end-use sectors of the economy: residential, commercial, industrial, and transportation, including multiple sub-sectors within each. Within the energy sector, it models electricity, oil, gas, coal, and renewable energy production for each of the nine census divisions, providing regional information on energy and economic conditions. The model and assumptions from the reference case of the *Annual Energy Outlook* 2003 [*U.S. Department of Energy*, 2003b, 2000c] were used as our (no-climate-change) reference scenario. The standard NEMS model uses annual cooling and heating degree-day values for each division through the last year of available data and then uses the 1971–2000 average values for all subsequent years. In consultation with staff of the EIA, we modified the model to accept changes in annual temperature-related variables through 2025 and so we refer to the model as DD-NEMS to distinguish it from the standard NEMS model. Temperature changes only directly affect the residential and commercial sectors. However, DD-NEMS also calculated secondary impacts on other sectors such as electricity generation as energy-supply needs change. These effects ripple through other sectors as energy supplies and prices change.

[8] Fuel prices and availability, costs of new power plants, available technologies, and other factors all limit options for drastic changes in energy sources. Although these factors are included in the energy model, it is possible that technological breakthroughs or drastic changes in consumer attitudes will motivate some changes in energy sources which were not anticipated in this study. The NEMS is updated every year so as to include any empirical evidence of such incipient developments. Past NEMS forecasts have been checked each year for accuracy, and the results are posted (http://www.eia.doe.gov/oiaf/analysispaper/forecast_eval.html).

[9] We also checked our carbon emissions estimates for credibility and general accuracy by comparing them with an extrapolation of actuarial experience from 1981 through 2010. After a few years, past experience becomes increasingly risky as a predictor because effects of changes in governing conditions such as supply, demand, and consumer attitudes would become increasingly apparent. We used linear regression to characterize the relationship of USA temperature trends to resulting fossil-fuel carbon emissions, and extrapolated the result to year 2010. This approach was made possible by the development of a monthly data base on USA fossil-fuel carbon emissions [*Blasing et al.*, 2005], allowing seasonal emissions comparisons CDD and HDD. Values of CDD and HDD for states in the USA are available back to 1931, but monthly values of USA per-capita fossil-fuel carbon emissions are available only back to 1981; so data from 1981–2003 were used to estimate trends. Different combinations of months to form the "heating season" and the "cooling season" were tried, and the combination accounting for the most total USA fossil-fuel carbon emissions for each such "season" were selected. Because several months have both CDD and HDD, the seasons may overlap. The "heating season" was thus defined as September–May, and the "cooling season" as June–September. Temporal trends in CDD and HDD from 1981 to 2003 were extrapolated to 2010, providing estimated

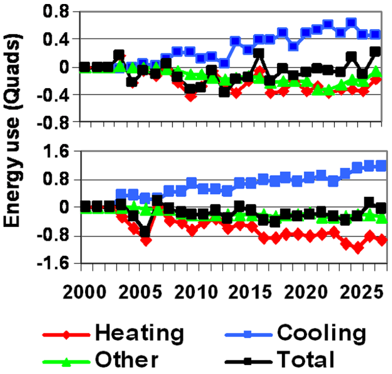

Figure 2. Change in national primary energy use for heating, cooling, other sectors, and totals for the high- and low-ΔT scenarios. Units are quadrillion Btu, or quads, which is a commonly used unit among energy economists. Because one quad equals 1.055 exajoules, one can roughly substitute exajoules for quads when reading the figure.

population-weighted changes of +24 CDD and −82 HDD. These changes were multiplied by 1.23 and 1.01, respectively, to account for proportional emissions increases from cooling (heating) demand during months of each year not included in the heating and cooling seasons defined above. The resulting estimated degree day changes (29.5 CDD and −82.8 HDD) were then applied to regression slopes as follows:

$$CC = 0.22(29.5) = +6.5 \quad \text{and} \quad CW = 0.26(-82.8) = -21.5,$$

where CC and CW are changes in USA per-capita fossil-fuel carbon emissions, in kg of carbon per person per year (kg-C/person-year) during the "heating season" (CW) and "cooling season" (CC). The net result was a projected decrease of 15 kg-C/person-year by 2010. Assuming a USA population of 309 million persons in 2010 (U.S. Census Bureau, Population Projections Branch http://www.census.gov/population/www/projections/projectionsagesex.html), this represents a decrease of 4.9 Tg in annual USA fossil-fuel carbon emissions by that year.

3. Results

[10] The most direct impact of temperature change on energy use involves changes in heating and cooling requirements for residential and commercial buildings. End-use energy demand will depend on the buildings activities, total floor space, fraction that have heating and/or cooling capability, building shell efficiencies, and other factors modeled by DD-NEMS. While end-use energy changes show the direct impact of temperature changes, the change in primary energy (which includes the large thermal energy loss during electricity generation) is more important from the standpoint of emissions. Since electricity is used more for cooling than heating, primary energy (generated from coal, oil, gas, nuclear reactors, or renewable sources) will change by a different amount than will the end-use energy requirements.

[11] Changes in heating and cooling degree days from long-term averages used in the reference scenario will vary from one census division to the next. In general, northern regions of the country are expected to have decreases in end-use heating needs which equal or outweigh their increases in cooling needs, while for southern regions the opposite would be expected. Figure 1 shows the changes in primary energy for the high- and low-ΔT scenarios for each division. The divisions are numbered such that regions of energy savings (1–4) and regions of increased energy use or minimal change (5–9) are grouped together. Northeastern and north-central divisions (1, 2, 3, and 4) do indeed tend to have net decreases in primary use in both scenarios, while the southern regions (5–7) tend to have net increases. Net increases are also seen for the western divisions (8 and 9) which have their large population centers located more to the south.

[12] Primary energy use in the High-ΔT scenario shows greater changes in both heating and cooling demand than does the Low-ΔT scenario (Figure 2). However, energy for heating in the Low-ΔT scenario is relatively constant in the latter years, but continues to decline in the High-ΔT scenario, so that projected *net* energy use in the High ΔT scenario is actually somewhat below that of the Low-ΔT scenario in many years. This partly explains why Low-ΔT projections for 2003–2025 included a cumulative increase in energy use for heating and cooling of 1.09 quads (1.03 Ej) *above* the reference scenario, compared to a High-ΔT projection of 0.82 quads (0.78 Ej) *below* the reference scenario. Cumulative cost increase for all energy uses (in 2001 dollars) is also greater for the Low-ΔT scenario ($14.8 billion) than for the High-ΔT scenario ($6.1 billion). It should be noted that the NEMS accounts for the construction of new combustion turbines to meet increased electricity needs for air-conditioning, and the retirement of older, less efficient, turbines.

4. Fossil-Fuel Carbon Emissions

[13] Changes in national energy use will affect fossil-fuel carbon emissions (as CO_2) to the atmosphere. Projected emissions departures from our reference scenario for High- and Low-ΔT scenarios are shown in Figure 3. In the Low-ΔT scenario, primary energy use increased in the latter years leading to an increase in projected USA fossil-fuel carbon emissions. In the High-ΔT scenario, projected carbon emissions increased as well, although total energy use decreased in most years due to greater warming during the winter months. Carbon-intensive coal use for electricity generation increased while other fuels declined, so net carbon emissions increased despite reduced overall energy use. Although the projected peak increase of 9.4 Tg of fossil-fuel carbon emissions in 2023 represents 0.43% of total USA

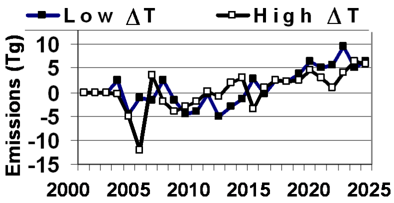

Figure 3. Projected changes in carbon emissions resulting from changes in energy-use patterns for the simulated high and low ΔT departures from the reference case.

fossil-fuel carbon emissions projected for that year, the increasing tend could become more significant in succeeding years.

[14] *Rosenthal et al.* [1995] estimated a decrease of about 8.4 Tg of fossil-fuel carbon emissions/yr in the USA by year 2010. They were projecting 16 years forward while we only projected 7 years in our extrapolation of actuarial experience above. Multiplying their result by 7/16 gives a decrease in annual emissions of 3.7 Tg from 2003 through 2010 to compare with our extrapolation of actuarial experience (4.9 Tg) and our modeling results (Figure 3) which project decreases from the reference scenario of about 4 Tg and 2 Tg for the low and high delta T cases, respectively, in 2010. *Rosenthal et al.* [1995] also speculated that further temperature increases ''will increase greenhouse gas emissions due to the eventual dominance of air conditioning in a very warm climate.'' The question is still open as to when this will happen; our results suggest it will begin around year 2015.

[15] The reasoning of *Rosenthal et al.* [1995] about an ''eventual dominance of air conditioning in a very warm climate'' was supported by our modeling results, which show that our projected emissions changes were mainly due to changes in energy requirements for space cooling/heating. This is seen in Figure 2, where energy-use changes for applications other than heating and cooling are presented in green. These ''other'' changes are roughly the same for both scenarios.

5. Conclusions

[16] Our preliminary analysis provides insights into the interplay between climate change, energy use, economics and fossil-fuel carbon emissions. Cooling is less energy efficient than heating, so an increase in cooling needs (and associated fossil-fuel carbon emissions) can more than offset an equal decrease in heating needs (and associated fossil-fuel carbon emissions). Moreover, coal is more carbon intensive than other fossil fuels, so increased use of coal-derived electrical energy would further amplify carbon emissions. Regional analysis shows increases, or very small changes, in energy for space cooling/heating in the southern and western regions of the USA, while some northern regions have energy and cost savings, and corresponding decreases in fossil-fuel carbon emissions even without mitigation efforts.

[17] Our High-ΔT scenario may not be as likely as one derived from an ensemble of several model outputs. However, by emphasizing winter warming, it clearly revealed some counterintuitive but logical results. For example, even when the warming is concentrated in winter, maximizing the net decrease in energy consumption, projected primary energy production and fossil-fuel carbon emissions still increase due to the nature of the changes in end-use energy demand. More study of the seasonal distribution of climate warming, from model results and from actuarial experience, is recommended. Increased spatial resolution in climate models would also aid in linking them to other models; in this case spatial refinements would provide results that could be more easily matched to the census divisions.

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