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The variation of climate change impact on building energy consumption to building type and spatiotemporal scale

Jianhua Huang [a,*], Kevin Robert Gurney [a,b]

[a] School of Life Sciences, Arizona State University, Tempe, AZ 85287, United States
[b] Julie Ann Wrigley Global Institute of Sustainability, Arizona State University, Tempe, AZ 85287, United States

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ABSTRACT

Building energy consumption is vulnerable to climate change due to the direct relationship between outside temperature and space cooling/heating. This work quantifies how the relationship between climate change and building energy consumption varies across a range of building types at different spatiotemporal scales based on estimates in 925 U.S. locations. Large increases in building energy consumption are found in the summer (e.g., 39% increase in August for the *secondary school* building), especially during the daytime (e.g., >100% increase for the *warehouse* building, 5–6 p.m.), while decreases are found in the winter. At the spatial scale of climate-zones, annual energy consumption changes range from −17% to +21%, while at the local scale, changes range from −20% to +24%. Buildings in the warm-humid (Southeast) climate zones show larger changes than those in other regions. The variation of impact within climate zones can be larger than the variation between climate zones, suggesting a potential bias when estimating climate-zone scale changes with a small number of representative locations. The large variations found in the relationship between climate change and building energy consumption highlight the importance of assessing climate change impacts at local scales, and the need for adaptation/mitigation strategies tailored to different building types.

1. Introduction

Energy consumption in commercial and residential buildings accounted for 41% of U.S. primary energy consumption in 2010, of which 37% was used for space heating and cooling. Within the commercial sector, space heating and cooling together account for 31% of building primary energy consumption, while in residential buildings, the share is 43% [1]. Building energy consumption, especially space cooling and heating, is directly influenced by climate change.

Different methods have been utilized to study the impact of climate change on residential and/or commercial building energy consumption [2–4]. These methods can be generally classified into three categories: observation-based regression/prediction, global/regional energy modeling, and individual building energy simulation.

The observation-based regression/prediction approach takes advantage of the historical relationship between energy consumption and climate variables to predict future energy consumption under a changing climate. Because this method is based on historical data, it is self-calibrated when fitted to a model. The output resolution from this approach is usually determined by the resolution of the historical data, and the accuracy of the estimation depends on the quality of the selected regression model (usually evaluated with statistical criteria, such as R^2). This approach has been used to estimate the impacts of climate change on annual/monthly energy consumption [5–8] and peak energy demand [8–11] in some U.S. states. For example, Huang et al. used this method to estimate the building energy demand changes and financial implications of climate change at the state/month scale in the contiguous U.S. [12].

The global/regional energy modeling approach simulates energy consumption in a numerical model composed of multiple variables such as energy demand and supply, economy, technology, population, policy, and climate. The impact of climate change on building energy consumption is assessed through simulated climate change scenarios. Besides climate change, this approach can be also used to study the impact of other key variables such as

* Corresponding author. School of Life Sciences, Arizona State University, Tempe, AZ 85281, United States.
E-mail address: jianhua.huang.1@asu.edu (J. Huang).

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population change, land use change, carbon taxes, and emissions mitigation policy. However, the complexity and flexibility of this method comes at the expense of output resolution. Hence, this method has been employed to estimate the impacts of climate change on building energy consumption at annual timescales and at global, national, and state spatial scales, at the finest [13–18].

The individual building energy simulation approach can be used to simulate high-frequency output (e.g., hourly) for specific building types. However, it usually requires detailed building characteristics and hourly weather data to drive the simulation. Such detailed information (e.g. building characteristics, occupants, operation schedules) is limited. As a result, this approach has been used for a few building types in particular locations only [19–22]. Although Huang [23] and Wang et al. [24] used this approach to evaluate the impact of climate change for the whole U.S., the results are based on building energy simulations in less than 20 cities.

Similar methods have been employed to estimate the impact of climate change on building energy consumption in other countries [25–32] or globally [33–35]. Although the impact of climate change on energy consumption across different building types has been explored down to the monthly temporal scale and for spatial scales down to climate zones (covering several to hundreds of counties) [23,24], the importance of sub-monthly timescales and variation within climate zones has rarely been studied. Given the spatial and temporal heterogeneity of climate change, building energy consumption impact can vary substantially within climate zones at sub-monthly timescales.

In this study we quantitatively explore the impact of climate change on building energy consumption using the individual building energy simulation approach. Our focus is on the variation of impact across different building types at multiple time scales (e.g., annual, monthly, and hourly) and spatial scales (e.g., national, climate zone, and location). We quantify these impacts at over 900 U.S. locations across the 16 U.S. climate zones. We also explore the variation of the impact across 15 commercial building types (each with three different age classes, representing different building technology) and 2 residential building types. High spatiotemporal-resolution combined with building energy consumption simulation at over 900 locations allows us to detect the temporal and spatial patterns of the impacts. Consideration of different building age classes, approximates the sensitivity of climate change impact to variation in building technology. Compared to past research that estimated the impact of climate change on regional building energy consumption using a few locations, the analysis performed here is based on a large number of simulations, offering regional estimates that are more statistically representative.

The remainder of this paper is divided into three parts: methodology, results and discussion, and conclusions. The methodology section includes a description of the building energy simulation model, the weather data and building prototypes used to drive the energy consumption simulations, calibration of results, and the metrics used for comparing results. The variation of building energy consumption impacts to building types/technology at different spatial and temporal scales are explored in the results and discussion section. The main findings, caveats, and the potential for future work are discussed in the conclusions section.

2. Methodology

2.1. Building energy simulation model

EnergyPlus, a well-known building energy simulation tool developed by the U.S. Department of Energy (DOE), is used to simulate building energy consumption. EnergyPlus has been extensively tested and validated for the ANSI/ASHRAE standards and is widely used by engineers and scientists to model building energy consumption [36]. EnergyPlus requires hourly weather data (e.g., temperature, humidity, and solar radiation) and hundreds of building characteristics (e.g., heating, ventilating, and air conditioning system, building materials, and occupancy) associated with specific building prototypes to drive the energy simulations. It produces hourly energy consumption by end use and fuel type for a given building prototype.

2.2. Weather data

The current hourly weather data used in EnergyPlus is retrieved from the third (and the latest) Typical Meteorological Year (TMY3) collection [37]. Each TMY3 file includes hourly weather data in one year duration for a specific location, which is developed based on 1991–2005 weather data or 1976–2005 weather data, if the latter exists. The meteorological data is available for 925 locations in the contiguous U.S., most of which reflect the 1991–2005 weather data. Future monthly weather is derived from the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) [38]. The monthly temperature change between a future time period and the present for each TMY3 location is represented as the average temperature change of its four closest CMIP3 neighbor grid cells. The average temperature change at each location is calculated for two future periods (2040s and 2090s, relative to 1991–2005), each under three IPCC emission scenarios (A2, A1B, and B1 representing high, medium and low emissions respectively [39]) with an ensemble of 15 climate model outputs. These average monthly temperature differences are then added to the current hourly TMY3 temperature data, as a constant, to generate the future hourly weather conditions in each month and location, similar to the approach followed in other studies [19,20,23]. The hourly temperature data generated with this method may not capture the sub-monthly temperature changes, but it ensures that the sub-monthly temperature pattern is consistent with the other climate variables (e.g., humidity and solar radiation) [20].

The projected temperature change for the decades of the 2040s and 2090s are spatially heterogeneous with the temperature change magnitude dependent upon emissions scenario (Fig. 1). Generally, inland locations see larger temperature increases than coastal areas, and high latitude regions show greater differences than low latitude regions. In the 2040s, the temperature increase is less than (or around) 2 °C in all emission scenarios for most locations. In the 2090s, the temperature change shows larger variation across the emission scenarios, with more than a 4 °C increase in most U.S. locations under the A2 scenario and about a 2.5 °C increase under the B1 scenario. The temperature change is always smallest under the B1 scenario, and it is largest under the A1B and A2 scenarios in the 2040s and 2090s, respectively. These spatial patterns are consistent with previous research [40].

2.3. Building prototypes

To specify commercial building characteristics, we used the building prototypes developed by the U.S. DOE. The DOE based these building prototypes on the 2003 Commercial Buildings Energy Consumption Survey (CBECS) data, an effort by the U.S. Energy Information Administration (EIA) to collect building characteristics, occupant schedules, energy consumption and energy expenditures for various commercial building types covering different U.S. regions [41]. The U.S. DOE developed 16 commercial building prototypes for the EnergyPlus model (Table 1), reflecting three different age classes (pre-1980, post-1980, and new-2004), located