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Evaluation of the effects of one cold wave on heating energy consumption in different regions of northern China

Dachuan Jiang, Weihua Xiao*, Jianhua Wang, Hao Wang, Yong Zhao, Baoqi Li, Pu Zhou

State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China

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ABSTRACT

The heating energy consumption per floor area (HECPA) and heating degree days (HDD) are effective indicators in quantifying the energy demand for heating with climate change. Using the heating energy consumption and meteorological data, an attempt has been made to analyse the relationship between the HECPA and HDD in different regions of northern China by the linear regression model. Based on the constructed model, the effects of one cold wave on heating energy consumption in different regions are evaluated. The results show that the HECPA and HDD in Beijing have a positive correlation with a correlation coefficient of 0.68. During the cold wave in 2016, the heating energy consumption in Beijing approximately increases 2.37% compared with 2014. However, no correlation has been found between the HECPA and HDD in the relatively undeveloped regions. It seems that the cold wave has a greater effect on the developed regions than relatively undeveloped ones. It is considered that the reasons for the little effect of one cold wave on heating energy consumption in the undeveloped regions are outdated heating systems, insufficient energy supply for heating and low living standards.

1. Introduction

In recent decades, extreme weather and climate events frequently occur as global warming intensifies, and climate abnormal change causes the abnormal change of heating energy consumption in winter. Heating energy consumption is a major source of energy use and generation of greenhouse gas (GHG) emissions. Thus, it is necessary to estimate the effects of one cold wave on heating energy consumption, which can provide decision makers with objective data for anticipating for energy use and demand.

The relationship between climate change and energy consumption has been a hot topic in international academia. For example, using degree-day index, Roshan et al. [1] simulated the impact of climate changes on the need for energy consumption in household cooling and heating systems, and found that an increase of energy consumption for cooling in households in 2075. Huang et al. [2] evaluated the variation of climate change impact on building energy consumption to spatiotemporal scale, and found that buildings in the warm-humid climate zones showed larger changes than those in other regions. Santamouris [3] thought that the major technological, economic and social forces and policies have to be employed in order to minimize the energy consumption of buildings, eradicate the energy poverty and mitigate the local climate change. Danny et al. [4] conducted a review of the impact of climate change on energy use in buildings, and considered that the most significant impact will occur in warmer climate dominated by cooling demand. A strong correlation was also found between energy use and climate change [5].

There are many methods for estimating the effects of climate change on heating energy consumption [6,7]. As a whole, they rely on either sophisticated simulations [8,9] or simplified calculations [10–13]. Characteristic examples of energy simulation models are Energy Plus and DOE-2/DOE-2.2 developed by the US Department of Energy, and Building Load and Analysis and System Thermodynamics (BLAST) developed by US Army Construction Engineering Research Laboratory and the University of Illinois at Urbana-Champaign [14–16]. Recently, Dirks et al. [8] used the Building Energy Demand (BEND) model, a detailed building analysis platform utilizing EnergyPlus™ as the simulation engine, to evaluate the climate change impact on heating and cooling energy consumption. However, the model is complex, requiring sophisticated software and extensive computing hours. When it comes to

* Corresponding author.
E-mail addresses: xiaoweihua@iwhr.com, xwsen998@163.com (W. Xiao).

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simplifying the calculation methods, there have been some investigations that relate the heating demand regarding to their energy consumption with regression models [17,18]. Among the more common of simplified methods is the degree-days method, which involves cooling degree days (CDD) and heating degree days (HDD) [19,20]. Verbai et al. [13] predicted the energy demand for heating of residential buildings using variable degree days.

Previous studies have concentrated on the effects of climate change on building energy consumption to building type, however, they did not evaluate the effects of climate change on heating energy consumption in different regions. Additionally, they indicated that climate change had an impact on energy consumption, e.g., the relationship between energy consumption and temperature was notably significant in the United States [21,22]. However, they paid little attention to the effects of extreme weather on heating energy consumption, and the evaluation method was complex. Although simplified techniques were also used, e.g., degree-days method, the heating energy consumption used as an evaluation index seems to be inappropriate because the heating energy consumption could be largely affected by the heating area. Therefore, the heating energy consumption per floor area (HECPA) appears to be a useful tool to quantify the changing needs for heating with climate change.

In this study, the effects of one cold wave in January 2016 on heating energy consumption in different regions of northern China were evaluated. The cold wave approximately lasted for 10 days in the entire nation, but the duration was approximately 3 days in each province of northern China. The objectives of this study are to: (i) analyse the characteristics of heating energy consumption and HDD in the different regions of northern China; (ii) construct a linear regression model of the heating energy consumption, which is direct and simple compared with existing literature; and (iii) evaluate the effects of one cold wave on heating energy consumption in different regions of northern China, and analyse the possible reasons for the different effects of one cold wave between the developed and undeveloped regions.

2. Material and methods

2.1. Data and study area

The heating energy consumption data were obtained from China Statistical Yearbook and Beijing Statistical Yearbook, which involved indicators such as heating supply, heating area and heating period. The data of Beijing span the period from January 1, 1979 to December 31, 2014, and other provinces span the period from January 1, 2001 to December 31, 2014. Historical meteorological data were obtained from the daily temperature data of 756 meteorological stations in China from January 1, 1979 to December 31, 2014. The entire meteorological data are available at the China Meteorological Administration Website (see: http://data.cma.cn/site/index.html (in Chinese)).

Central heating is the main heating method in northern China, and the distribution of central heating is shown in Fig. 1. In this study, Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shandong and Henan province were selected to evaluate the effects of one cold wave on heating energy consumption.

2.2. Methodology

2.2.1. Linear regression model

In this study, the HECPA and HDD were used as the indicators to evaluate the relationship between the cold wave and heating energy consumption. The relationship between energy consumption and temperature is commonly assumed to be linear [23]. Thus, the HECPA linear regression model is as follows:

$$Q = Q_0 + \left(\frac{\Delta Q}{\Delta HDD}\right) HDD \tag{1}$$

Where Q (10^3 kJ/m^2) is the HECPA; Q_0 (10^3 kJ/m^2) is the base load of HECPA, which is a constant and independent of the shift in temperature; $(\Delta Q/\Delta HDD)$ ((10^3 kJ/m^2)/°C) is the sensitivity of HECPA to HDD during the cold wave, i.e., the rate of change in heating energy consumption when the value of HDD changes by 1 °C; HDD (°C) is described as follows:

$$HDD = \begin{cases} \sum_{i=1}^{n}(T_0 - T_i) & , T_0 \geq T_i \\ 0 & , T_0 < T_i \end{cases} \tag{2}$$

Where T_i (°C) is the daily mean temperature during the heating period; $T_0 = 5$ °C, the base temperature for heating in China [24]; n (d) is the number of days of the heating period, determined by the local administrative department.

To compare the effects of HDD on heating energy consumption during the cold wave with previous years, the evaluation formula can be expressed as Eq. (3):

$$Q_1 = \left(\frac{\Delta Q}{\Delta HDD}\right)(HDD_1 - HDD_0) \tag{3}$$

Where Q_1 (10^3 kJ/m^2) is the HECPA; HDD_1 (°C) is the HDD during cold wave; HDD_0 (°C) can be described as follows:

$$HDD_0 = \frac{\sum_{i=1}^{n} H_i}{n} \tag{4}$$

Where H_i (°C) is the HDD of previous year i, corresponding to the occurrence time of the cold wave; n represents the years.

The effects of one cold wave on heating energy consumption is the product of Q_1 and the heating area, e.g., a Q_1 value of 36000 means that the heating energy consumption is 36000 kJ per square meter.

2.2.2. Model accuracy

In response to climate change, the evaluation model above can be used to make a short-term prediction for heating energy consumption. However, the correlation coefficient is not enough to evaluate the prediction accuracy, so the Mean Absolute Percentage Error (MAPE) was used to test the prediction accuracy. The parameter is shown as below:

$$MAPE(n) = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{Q_{1i} - Q_{0i}}{Q_{0i}}\right| \times 100\% \tag{5}$$

Where Q_{0i} (10^3 kJ/m^2) is the monitored value of HECPA, Q_{1i} (10^3 kJ/m^2) is the estimated value of HECPA by Eq. (1), and n is the sample size.

3. Results and discussion

3.1. Effects of one cold wave on heating energy consumption in developed regions

3.1.1. Characteristics of heating energy consumption and HDD in Beijing

Fig. 2 shows that before 2000, heating area of Beijing was under 50 million m^2, and it increased to 567.86 million m^2 in 2014. The total heating energy consumption was under 25 million GJ before