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ORIGINAL PAPER

The effects of climate change on heating energy consumption of office buildings in different climate zones in China

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Abstract Climate plays an important role in heating energy consumption owing to the direct relationship between space heating and changes in meteorological conditions. To quantify the impact, the Transient System Simulation Program software was used to simulate the heating loads of office buildings in Harbin, Tianjin, and Shanghai, representing three major climate zones (i.e., severe cold, cold, and hot summer and cold winter climate zones) in China during 1961–2010. Stepwise multiple linear regression was performed to determine the key climatic parameters influencing heating energy consumption. The results showed that dry bulb temperature (DBT) is the dominant climatic parameter affecting building heating loads in all three climate zones across China during the heating period at daily, monthly, and yearly scales ($R^2 \geq 0.86$). With the continuous warming climate in winter over the past 50 years, heating loads decreased by 14.2, 7.2, and 7.1 W/m^2 in Harbin, Tianjin, and Shanghai, respectively, indicating that the decreasing rate is more apparent in severe cold climate zone. When the DBT increases by 1 °C, the heating loads decrease by 253.1 W/m^2 in Harbin, 177.2 W/m^2 in Tianjin, and 126.4 W/m^2 in Shanghai. These results suggest that the heating energy consumption can be well predicted by the regression models at different temporal scales in different climate conditions owing to the high determination coefficients. In addition, a greater decrease in heating energy consumption in northern severe cold and cold climate zones may efficiently promote the energy saving in these areas with high energy consumption for heating. Particularly, the likely future increase in temperatures should be considered in improving building energy efficiency.

Keywords Climate change · Heating loads · Energy consumption · Climate zones · Office buildings · China

1 Introduction

It is generally believed that global climate is changing and the earth surface temperature will rise gradually. An ensemble projection using CMIP5 models (Coupled Model Intercomparison Project Phase 5, a standard experimental protocol for studying the output of coupled ocean-atmosphere general circulation models (GCMs) began in 2009) and a new emission scenario estimates that global-mean surface air temperature (SAT) changes for the periods 2016–2035 and 2081–2100 compared with 1986–2005 will likely be in the range of 0.3–0.7 and 0.3–4.8 °C, respectively (IPCC 2013). Observed surface air temperature, in particular the winter temperature in mid-latitude urban areas, is also increasing and is expected to continue to rise under the combined influence of anthropogenic global warming and urbanization process (Committee on China National Assessment Report on Climate Change 2007; Ren et al. 2008, 2012). Climate change has drawed great attention in recent years in part because of its large impact on many aspects of human society and the natural

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environment (Lam et al. 2010; Wan et al. 2011; Edenhofer et al. 2014; Wang and Chen 2014). Building energy consumption is of the fundamental importance for society and has received wide concern in the world because building energy consumption is especially vulnerable to climate change owing to the direct relationship between outdoor climate conditions and space heating and cooling (Radhi 2009; Huang and Gurney 2016). Many previous studies have concerned the climate impact on building energy usage by simulating energy consumption (Wang et al. 2010; Li et al. 2014), or by using heating/cooling degree days (Chen et al. 2007; McGilligan et al. 2011). Based on these studies, many strategies to improve building energy efficiency have been proposed (Frank 2005; Arima et al. 2016; Invidiata and Ghisi 2016).

In China, as the second largest building energy consumer in the world (Eom et al. 2012), buildings have also played an important role in the total energy requirement because building energy consumption accounts for more than 30% of the total national energy consumption and which is projected to increase to 35% by 2020 (Yao et al. 2005; Wan et al. 2011). In addition to higher energy consumption, many severe haze events have occurred in winter, particularly in northern China, which are largely related to coal consumption using for heating. To lower the building energy consumption and its implications for the environment (e.g., the corresponding aerosol and carbon emissions), improving energy efficiency in buildings is one of the important measures under the conditions of climate change. However, buildings in China generally still have much lower energy efficiency than those of countries with similar climatic conditions (Yao et al. 2005). To a large extent, the lower energy efficiency is due to lack of accurate and detailed information about the response of building energy consumption to climate change (Li et al. 2016). Therefore, efficient energy-saving measures or decision-making for selecting devices of heating, ventilation, and air-conditioning (HVAC) systems under the climate change conditions will not be fully considered to increase building energy efficiency.

The average surface temperature of China increased 1.09 °C during the 1901–2014, being higher than that of the global average (Su et al. 2016). The incremental rise in temperature is even more apparent in most parts of northern China than that in the south China (Zhou and Yu 2006). Based on the previous studies, the large increase in temperature will have huge implications for energy consumption and the environment (Yao et al. 2005; Cai et al. 2009; Li et al. 2015). Building professionals and policy makers have noted the importance of climate change impacts on energy consumption, especially the effects of increasing temperature on reducing energy consumption as well as the possible decrease of haze. Therefore, it is necessary to reveal the climate change effects on building energy consumption, especially for heating energy use. Berger et al. (2014) explored the effects of climate change upon office buildings' performance in Vienna, Austria, and found that heating demands slightly diminished and cooling requirements generally increased remarkably. Frank (2005) explored the potential impacts of climate change on heating and cooling energy demands in Switzerland and predicted a 33–44% decrease in the annual energy demand for heating of residential buildings for the period of 2050–2100. However, it is rather limited concerning the responses of building energy use to climate change or variability in China (Wan et al. 2011; Li et al. 2014, 2016). Particularly, most of these studies have considered energy consumption sensitivities to climate variation in only a single city (Lam et al. 2010; Chan 2011; Yao and Zhu 2011; Li et al. 2014, 2016). Although Wan et al. (2011, 2012) concerned the climate change on energy use in different climate zones, they only reported the yearly changes of energy consumption without considering monthly or daily changes of energy consumption. There are several climatic types that are primarily caused by major physical factors (e.g., mid-latitudinal locations, vast area, and mountainous topography) (You et al. 2011; Yang et al. 2011; Chan and Chow 2014). Previous studies have revealed that the impact of climate change will vary greatly according to geographical region and building types (Wang and Chen 2014). Determining the effects of climate variation on buildings' heating/cooling energy consumption in different climate zones is the foundation of operating and designing more energy-efficient buildings, which will be beneficial to save energy and reduce energy use and pollutant emissions.

In this study, office buildings were selected to determine the effects of climate change on energy consumption. Office building is one of the fastest growing areas of the building sector in China (Wan et al. 2011). According to statistics from the Building Energy Conservation Research Center of Tsinghua University (2010), the total power consumption of office buildings reached 172.6 billion kWh, accounting for 24.1% of the total energy consumption of public buildings in China in 2007. On the basis of per unit area, energy consumption of office buildings with full air-conditioning (A/C) could be 10–20 times than that on residential buildings (Jiang 2006). In short, the energy consumption of office buildings has a direct impact on the total national building energy consumption (Yao and Zhu 2011; Kong et al. 2012) and has become a focus of energy-saving efforts. The impacts of climate change on office building energy use are especially important for energy saving, and thus, office buildings were selected in the present study. The heating load of office buildings during the period of 1961–2010 was simulated with TRNSYS (Transient System Simulation Program) software. The response of the heating load to the changing climate in different climate zones across China was examined by stepwise multiple linear regression. The objectives of this study were (1) to clarify the impacts of key climate parameters on building heating energy consumption in different climate zones across

China at different temporal scales (i.e., day, month, and year) and (2) to examine whether there exist different response patterns of heating energy consumption in different climate zones in China.

2 Methodology

2.1 Study area

According to national standard of the Thermal Design Code for Civil Buildings (GB 50176-93), there are five major architectural climate zones across China, including severe cold, cold, hot summer and cold winter, mild, and hot summer and warm winter climate zones. In the present study, Harbin, Tianjin, and Shanghai were selected to represent the three major climate zones (i.e., severe cold, cold, hot summer and cold winter climate zones) (Fig. 1). The other two climatic zones (i.e. the mild, and hot summer and warm winter climate zones) were not considered owing to no requirement of heating and no limit on the heat transfer coefficient of building envelopes.

2.2 Selection of buildings

Office buildings are an important contributor to energy consumption. In the present study, a generic and fully air-conditioned office building was used to obtain heating load by simulating with TRNSYS software. The design features of the office building comply with the local energy code of buildings and consist with local building stock. The design conditions of buildings, such as the building envelope heat transfer coefficient, indoor design conditions, and internal load density, were set in terms of the design standards for energy efficiency of public buildings (GB50189-2015). A 22-story office building was selected for simulating energy consumption, which has a total construction area of 32,200 m^2 and floor-to-floor height of 98 m. The design and operation features of generic office building envelopes and HVAC systems depend on not only the prevailing architectural and engineering practices but also the local design/energy codes in the three cities. Table 1 shows the summary for key design parameters of selected office buildings.

2.3 TRNSYS simulation program

TRNSYS is a transient system simulation program developed by the Institute of Building Technology and Solar Energy Utilization of Wisconsin University in the USA and has been gradually improved by the joint efforts of several European research institutes. TRNSYS is a very flexible graphically based software environment that can be used to simulate the behavior of transient systems. The modular structure of this simulation program is designed to solve energy system problems by breaking complex problem down into a serious of smaller components (Crawley et al. 2008). The smaller components will be integrated together as a visual interface known as the Simulation Studio of TRNSYS, while building parameters will be inputted through a dedicated visual interface. TRNSYS has become one commercially available model system since 1975 and is extensively used for building energy simulation, which can equally well be used to traffic flow, biological processes, and other dynamic systems.

According to the Inspection Standards of Building Energy Consumption Analysis and Calculation Program developed by the American Society of Heating, Refrigerating and Air-

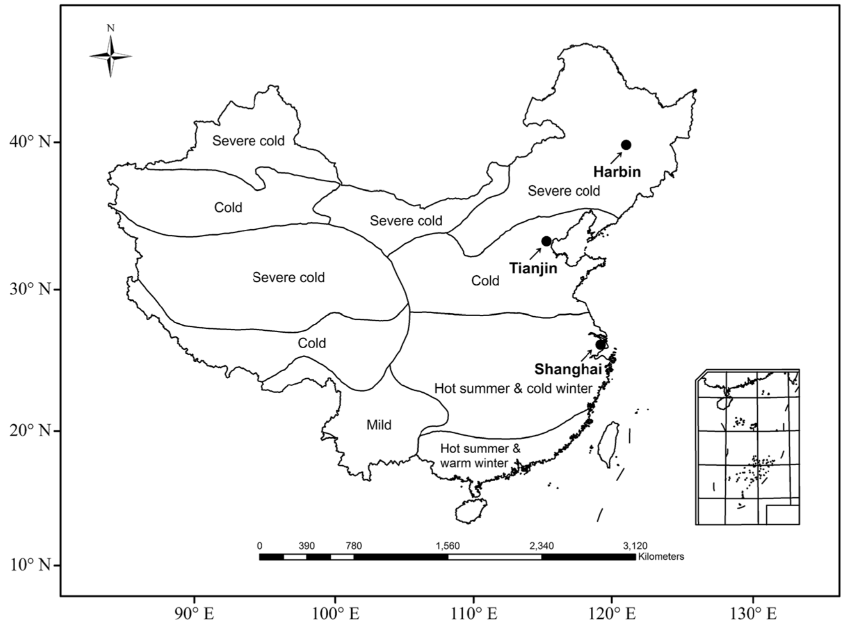


Fig. 1 Distribution of the selected three climate zones and representing cities in China

Table 1 Design data for the selected office buildings in different climate zones of China

Cities	Building envelope HTC (W/m^2/°C)			Indoor design condition (summer/winter)			Internal load density			Window-to-wall ratio			
	Wall	Roof	Floor	T (°C)	RH (%)	ACR (1/h)	Occupancy (m^2/person)	Lighting (W/m^2)	Equipment (W/m^2)	East	South	West	North
Harbin	0.45	0.35	2.00	26/20	60/30	1.5	4	11	20	0.27	0.35	0.27	0.26
Tianjin	0.60	0.55	1.50	26/20	60/30	1.5	4	11	20	0.34	0.40	0.34	0.41
Shanghai	1.00	0.70	1.20	26	60	1.5	4	11	20	0.45	0.50	0.45	0.42

Conditioning Engineers (ASHRAE) in 2004, the accuracy and reliability of this software meets the requirements. There is a certain difference between the simulation and the actual energy consumption due to the effects of residential living habits and economic levels (Lam et al. 2010; Wan et al. 2011; Li et al. 2015, 2016). Li et al. (2015) indicated that the energy consumption simulation could efficiently reflect the real energy consumption. Wan et al. (2011) also considered that this software is very reliable in the study of the impacts of climatic change on energy consumption.

2.4 Multi-year simulation of building energy consumption

For the energy consumption simulation by using TRNSYS, two sets of initial data are needed as inputs (Li et al. 2015). The building parameters (Table 1) are inputted through a dedicated visual interface. In addition to building input data, a weather database was also built into the software as an input file. To obtain the hour-by-hour energy consumption during the past 50 years (1961–2010), hourly data for multiple climatic variables including dry bulb temperature (DBT), relative humidity (RH), solar radiation (SR), wind speed (WS), and wind direction (WD) should be inputted into the TRNSYS software. In order to obtain the information of climate change impacts on energy consumption in the urban area, the meteorological observation stations located in the urban center of the three cities were selected (the meteorological observation stations in Harbin and Tianjin belonging to the national basic meteorological stations of China and the station in Shanghai being a general meteorological station). The climatic data are from National Meteorological Information Center, including DBT, maximum temperature (MAT), minimum temperature (MIT), SR, WD, WS, and wet bulb temperature (WBT) from representative city meteorological stations from 1961 to 2010. The quality control and the homogeneity of the selected meteorological data have been strictly tested to ensure the reliability and accuracy of the data. It can be found that there was no apparent effect of station relocation on the homogeneity of meteorological data. Detailed information on the quality control and homogeneity test can be found in the previous studies (Cao et al. 2017).

Hour-by-hour DBT and RH data before 2006 were generated from the records of four times per day during the period of 1961–2005 (generally having hourly record since 2006) using cubic spline interpolation methods and the WBT were obtained by the corresponding DBT and RH. The hourly SR was calculated by the Collores-Perein and Rabl model based on daily total solar radiation and then were adjusted for three weather conditions (i.e., sunny, foggy, and rainy). WS and WD were directly collected from the observed data. According to our earlier works, the calculated and observed hourly DBT, RH, and SR data exhibit very similar patterns, and the regression coefficients of the calculated and observed values were all above 0.95 with a 0.001 level of significance, confirming the reliability and accuracy of the calculated data (Li et al. 2014, 2016).

According to the relevant governmental heating regulations and the actual conditions of each city, the winter heating period was defined from October 20 to April 20 next year for Harbin, November 15 to March 15 next year for Tianjin, and December 1 to February 28/29 next year for Shanghai.

2.5 Statistical analysis

Both the climatic parameters themselves and their interactions (i.e., a change in one parameter affects the others) are critical for the impact on energy consumption (Li et al. 2016). Therefore, stepwise multiple linear regressions were used to test the dominant parameters affecting office building heating load. In short, stepwise multiple linear regressions on the building heating energy consumption of daily, monthly, and yearly data were performed against the possible climatic parameters, i.e., the mean temperature, MAT, MIT, WBT, SR, and WS, in the heating period. Simple linear regression analysis was used to test the yearly variation in heating loads for office buildings during 1961–2010 and its relationship with dominant climatic parameters. All statistical analyses were performed using SPSS 17.0 for Windows, and significance levels were set at $P < 0.05$.

3 Results

3.1 Response of daily heating load to climatic parameters

The responses of heating load to corresponding climatic parameters in the three climate zones by stepwise multiple linear regression analysis are outlined in Table 2. The heating loads of the selected office buildings were predominantly affected by the DBT at daily scale, which explained 96.3% of the variation in the daily heating load in Harbin, 91.2% in Tianjin, and 89.5% in Shanghai. In addition to the DBT, the other parameters, i.e., SR, MAT, MIT, and WBT, were all entered into the regression models. These parameters contributed less to the variation in heating load in Harbin, as the R^2 value increased slightly from model 2 to model 4 (Table 2). For Tianjin, the combination of the DBT and SR explained 93.2% of the variation in the daily heating load, and the DBT, SR, and WBT could explain 96.0%, indicating that SR and WBT have much less contribution to the variation in the daily heating load (Table 2). Among these parameters, except for DBT, the SR accounted for only a very small part of the variation in the daily heating load in Shanghai, as the DBT and SR could explain 92.6% of the heating load (Table 2).

3.2 Response of monthly heating load to climatic parameters

Monthly heating loads were primarily related to the DBT in all cities (Table 3). In Harbin, the DBT, SR, and MIT were all entered into the regression models but R^2 did not show an obvious increase from model 1 to model 3 (Table 3), indicating that DBT is the main parameter affecting heating load, explaining 99.1% of the variation. For Tianjin, the DBT was still the predominant parameter (R^2 = 0.956, $p < 0.001$), whereas SR and WBT contributed less to the variation in monthly heating load, evidenced by the smaller increase in R^2 from model 1 to model 3 (Table 3). For Shanghai, the DBT explained the variation in the monthly heating load of 94.1% and explained 98.6% together with SR. The WBT was also entered into the regression model, yet R^2 did not increase apparently (Table 3). This indicates the DBT is still the dominant factor in the monthly variation in the heating load in Shanghai, with a small contribution by SR (Table 3).

3.3 Response of yearly heating load to climatic parameters

Table 4 shows the results of the yearly heating load against the climatic parameters in different climate zones. For Harbin, the DBT explained 96.4% of variation in annual heating load. The

Table 2 Results from stepwise multiple linear regression on daily heating load against the climatic parameters of different climate zones

Harbin		Model 1	Model 2	Model 3	Model 4
		−40.190 × DBT	−38.680 × DBT	−36.677 × DBT	−29.455 × DBT
			−6.660 × SR	−6.842 × SR	−6.660 × SR
				−2.004 × MIT	−4.430 × MIT
					−4.888 × MAT
	Constant	745.159	816.986	807.783	820.197
	R^2	0.963***	0.970***	0.970***	0.970***
Tianjin		Model 1	Model 2	Model 3	Model 4
		−42.144 × DBT	−41.323 × DBT	−11.955 × DBT	−8.733 × DBT
			−6.388 × SR	−11.085 × SR	−10.226 × SR
				−32.302 × WBT	−31.745 × WBT
					−3.591 × MAT
	Constant	665.036	722.189	681.92	693.449
	R^2	0.912***	0.932***	0.960***	0.961***
Shanghai		Model 1	Model 2	Model 3	Model 4
		−44.889 × DBT	−46.505 × DBT	−38.550 × DBT	−29.509 × DBT
			−7.031 × SR	−5.118 × SR	−6.268 × SR
				−7.383 × MAT	−7.026 × MAT
					−9.686 × WBT
	Constant	762.208	834.016	843.332	834.521
	R^2	0.895***	0.926***	0.930***	0.931***

R^2 the coefficient of determination, *DBT* dry bulb temperature, *MAT* maximum temperature, *MIT* minimum temperature, *WBT* wet bulb temperature, *SR* solar radiation, *WS* wind speech

***Significance $P < 0.001$

Table 3 Results from stepwise multiple linear regression on monthly heating load against the climatic parameters of different climate zones

Harbin		Model 1	Model 2	Model 3
		−42.426 × DBT	−39.168 × DBT	−37.727 × DBT
			−8.078 × SR	−8.143 × SR
				1.322 × MIT
	Constant	723.063	826.97	810.495
	R^2	0.991**	0.995***	0.995***
Tianjin		Model 1	Model 2	Model 3
		−46.759 × DBT	−41.033 × DBT	−15.706 × DBT
			−10.364 × SR	−13.167 × SR
				−28.693 × WBT
	Constant	647.429	756.997	708.506
	R^2	0.956***	0.987**	0.997***
Shanghai		Model 1	Model 2	Model 3
		−44.375 × DBT	−47.066 × DBT	−29.043 × DBT
			−10.899 × SR	−13.285 × SR
				−19.930 × WBT
	Constant	759.775	865.962	856.613
	R^2	0.941***	0.986***	0.992***

R^2 the coefficient of determination, *DBT* dry bulb temperature, *MAT* maximum temperature, *MIT* minimum temperature, *WBT* wet bulb temperature, *SR* solar radiation, *WS* wind speech

***Significance $P < 0.001$

other parameters, i.e., SR, MIT, and WS, contributed little to the variation in annual heating load, as the R^2 value showed a weak increase from model 2 to model 4 (Table 4), indicating that DBT is the predominant climatic parameter affecting the annual heating load of Harbin. Similarly, DBT is the main climatic parameter in Tianjin, which explained 85.6% of the annual heating load variation. Heating load can be explained 93.1% by the combination of DBT and SR. For Shanghai, the DBT, WBT, SR, and WS were all entered into the regression models (Table 4). The DBT explained 94.1% of variation in the annual heating load, and heating load can be explained 98.4% by the combination of DBT and SR. The WBT and WS were also entered into the regression models but had little effect on the heating load.

3.4 Long-term variation of heating load and its sensitivity to DBT

The annual variation in heating load and DBT in different cities are listed in Fig. 2. Owing to climate change caused by urbanization and probably by anthropogenic global warming, the annual heating load showed a significant decrease ($P < 0.001$) in all three cities during the heating periods over the last 50 years from 1961 to 2010. The increasing rates of DBT were 0.62 °C/10 yr, 0.53 °C/10 yr, and 0.64 °C/10 yr in Harbin, Tianjin, and Shanghai, respectively (Fig. 2). Heating load showed significant decrease in all the selected cities, with the decreasing rates of 14.2, 7.2, and 7.1 W/m^2 in Harbin, Tianjin, and Shanghai, respectively

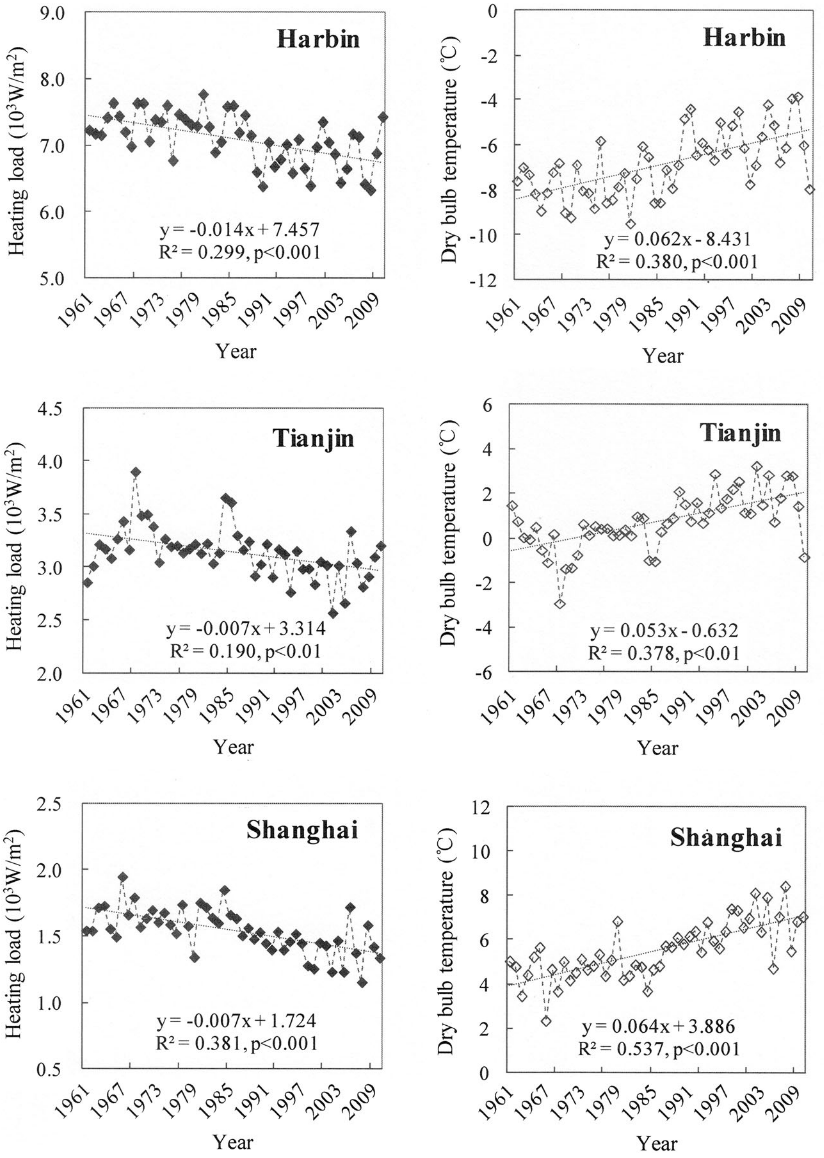
Table 4 Results from stepwise multiple linear regression on yearly heating load against the climatic parameters of different climate zones

Harbin		Model 1	Model 2	Model 3	Model 4
		−253.079 × DBT	−257.453 × DBT	−273.091 × DBT	−279.743 × DBT
			−56.305 × SR	−55.771 × SR	−54.726 × SR
				10.734 × MIT	10.985 × MIT
					−19.247 × WS
	Constant	5361.914	5900.678	6132.394	6151.758
	R^2	0.964***	0.979***	0.985***	0.986***
Tianjin		Model 1	Model 2		
		−177.207 × DBT	−187.578 × DBT		
			69.886 × SR		
	Constant	3274.114	3933.242		
	R^2	0.856***	0.931***		
Shanghai		Model 1	Model 2	Model 3	Model 4
		−126.389 × DBT	−138.263 × DBT	−75.365 × DBT	−91.563 × DBT
			−35.984 × SR	−44.851 × SR	−43.029 × SR
				−74.759 × WBT	−60.029 × WBT
					−11.129 × WS
	Constant	2242.122	2609.242	2599.42	2649.948
	R^2	0.941***	0.984***	0.995***	0.996***

R^2 the coefficient of determination, *DBT* dry bulb temperature, *MAT* maximum temperature, *MIT* minimum temperature, *WBT* wet bulb temperature, *SR* solar radiation, *WS* wind speech

***Significance $P < 0.001$

Fig. 2 Yearly changes of the heating loads of office buildings (*left*) and corresponding DBT (*right*) during the heating period in the three cities



(Fig. 2). The simple linear regression analysis indicated that the heating load was significantly and negatively correlated with DBT in the selected three cities ($R^2 \geq 0.86$, Fig. 3). For Harbin, Tianjin, and Shanghai, the heating load decreased by 253.1, 177.2, and 126.4 W/m^2, respectively, with a 1 °C increase in DBT.

4 Discussion

Building energy use is particularly important and has attracted widespread attention because it not only affects the sustainable development of our society but also has huge implications for the environment (Kharseh et al. 2014). The most severe haze event occurred in winter in northern China during the past several years is, in a large extent, related to the consumption of energy, especially coal consumption for heating. Determining the responses of building energy consumption for heating to climate change is beneficial not only for making energy-saving strategies or measures but also for reducing pollutant emissions (Li et al. 2016). Energy consumption in building is unavoidably influenced by both climate change and socioeconomic factors (e.g., economic development, urbanization, and population increase) (Isaac and van Vuuren 2009; Yang et al. 2014). In this study, the building heating load was obtained by the TRNSYS simulation to remove the socioeconomic impacts because the building parameters were constant while the climatic parameters were variable in the process of simulation. Thus, the responses of heating energy consumption to climate change could be quantified without the consideration of socioeconomic impacts. Moreover, the effects of climatic parameters on heating energy consumption of buildings in different climate zones at different temporal scales (i.e., day, month, and year) could be examined.

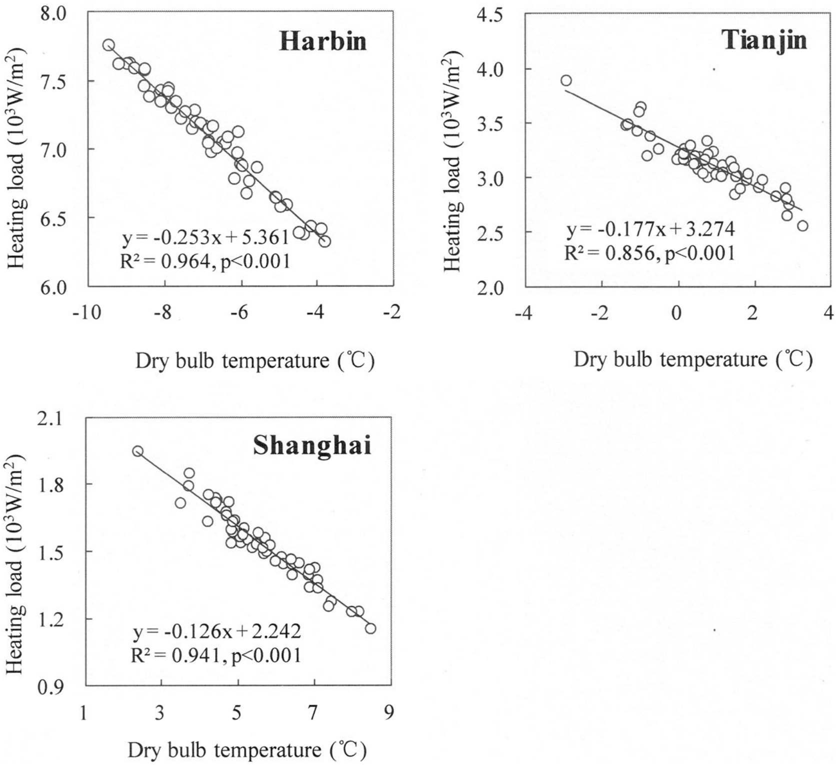


Fig. 3 The relationship of yearly changes of the heating loads of office buildings and its corresponding DBT in the three cities

It was found that building heating load is predominantly related to the DBT in the selected climate zones in China where heating is required. This is consistent with the findings of previous studies (Camilleri et al. 2001; Christenson et al. 2006; Ward 2008; Papakostas et al. 2010; Wan et al. 2012). More importantly, the present study found that the DBT explained 91–96%, 94–99%, and 86–96% of the variations in the daily, monthly, and yearly heating loads, respectively, in the three cities, indicating a strong correlation between building heating load and the DBT, regardless of temporal scales. From a nationwide energy and environmental perspective, it is necessary to be able to evaluate the range of the probable fluctuation in cooling and heating energy demands caused by climatic change in different climate zones (Li et al. 2012). Based on the regression analyses of heating load against climatic parameters in this study, the daily, monthly, or yearly heating loads can be well predicted by the DBT using regression models for different climate zones. This would provide for building professions and decision-makers a good idea of possible changes in heating energy consumption so that appropriate operating measures could be considered. Additionally, although other climatic parameters have little effect on the variation in heating load, they should not be ignored.

The effects of climate change on energy consumption for heating varied in diverse locations because of different climate conditions (Sailor 2001; Radhi 2009). From northern to southern China, with climate zones shifting from those of severe cold to hot summer and cold winter, the heating load of office buildings shows a significant decrease during the heating period by 14.2, 7.2, and 7.1 W/m^2 in Harbin, Tianjin, and Shanghai, respectively, over the last 50 years. In addition, when the DBT increase by 1 °C, the building energy loads for heating decrease by 253.1 W/m^2 in Harbin, 177.2 W/m^2 in Tianjin, and 126.4 W/m^2 in Shanghai. These findings indicate that heating load decreases more sharply with rising temperatures for severe cold climate than for hot summer and cold winter climate. In northern China, located in severe cold and cold climate zones, heating is needed throughout the winter, and severe haze events have often occurred partly due to building heating, particularly the associated coal consumption. Energy use for improving thermal comfort accounts for a considerable proportion of building energy consumption (Lam et al. 2008; Yang et al. 2014). On the other hand, the land area of northern China constitutes for about 70% of total country's area, and its heating energy consumption of buildings contributes to about 45% of the total national urban building energy consumption (Cai et al. 2009). This suggests that the total heating energy consumption in major cities of severe cold and cold climate zones of China may largely decrease under the continuous climate warming in the future, and thus, an appropriate reduction of heating devices in practice could be considered. In contrast, although the heating load of Shanghai (representing hot summer and cold winter climate zone) slightly decreased with rising temperature, the heating load per unit area may not obviously change owing to the short winters and lower overall heating energy consumption.

With continuous warming, heating energy consumption may be expected to decrease significantly in the future (Shi et al. 2016). Northern China witnessed the largest increase in surface air temperature by 0.8 °C/10a over the past 50 years (1951–2001) (Ren et al. 2005; Ding et al. 2007). Most parts of northern China are predicted to become significantly warmer with a 1 °C increment, whereas approximately 0.3–0.6 °C in southern China (Zhou and Yu 2006; Xu et al. 2009). Meanwhile, energy consumption simulations have projected that heating energy consumption will decrease continuously over the service life of buildings as a result of climate warming (Christenson et al. 2006; Wang et al. 2010; Zhou et al. 2013). From these predictions, a warming climate in big cities of severe cold and cold climate zones can be expected to lead to a decrease in energy demand in winter, which may decrease the future energy consumption of building heating to a large extent. However, although temperature shows a long-term increasing trend in winter in China, extreme cold winter events may occasionally occur (e.g., extreme cold winter events in northern China in 2008) due to the large decadal and multi-decadal variability of climate, which will lead to a significant rise in heating energy consumption in cold winters. Therefore, extreme climate events should be taken into account in the design and operation of heating systems.

5 Conclusions

In this paper, the impacts of climate and climate change on the daily, monthly, and yearly heating loads of office buildings were estimated in the representative cities of three climate zones of China. Our results have important implications for energy-saving management policies and buildings' design in the country. Firstly, the DBT is the dominant climatic factor affecting office building heating load in all of the three climate zones at different temporal scales. The daily, monthly, or yearly heating loads can be well estimated by the DBT depended on regression models in different climate zones due to the high determination coefficients. Additionally, other climatic parameters should not be ignored, though they contributed to heating load to a lesser degree. Secondly, the heating load showed a decreasing trend in all of the representative cities under continuous warming over the past 50 years, especially in severe cold climate zone. In other words, corresponding measures for heating energy efficiency of buildings should be made according to different climate zones. The apparent decreasing rate of heating load in severe cold climate zone in northern China is more beneficial to energy saving due to its larger total energy consumption than that in hot summer and cold winter climate zone in southern China. Particularly, likely increasing in temperature should be considered to make energy-saving measures in the process of new buildings' design in the future.

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