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Impacts of UHI on Heating and Cooling Loads in Residential Buildings in Cities of Different Sizes in Beijing–Tianjin–Hebei Region in China

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Abstract: The heating and cooling energy consumption levels of urban buildings account for a large and rapidly growing proportion of the total end-use energy consumption of society. The urban heat island (UHI) effect is an important factor influencing the spatiotemporal variations in the heating and cooling energy consumption levels of buildings. However, there is a lack of research on the impact of the UHI on the heating and cooling energy consumption of buildings in cities of different sizes in the Beijing–Tianjin–Hebei urban agglomeration, which is the most urbanized region in northern China. We selected rural reference stations using the remote sensing method, and applied an hourly data set from automatic weather stations, to examine the impact of the UHI on the typical residential building heating and cooling loads in three cities of varied sizes in the Beijing–Tianjin–Hebei urban agglomeration through building energy simulation. The main conclusions were as follows. As the UHI intensity (UHII) increased, the heating load difference between urban and rural areas decreased, while the cooling load difference between urban and rural areas increased in the cities. The average daily heating loads in the urban areas of Beijing, Tianjin, and Shijiazhuang were 8.14, 10.71, and 2.79% lower than those in their rural areas, respectively, while the average daily cooling loads in the urban areas were 6.88, 6.70, and 0.27% higher than those in their rural areas, respectively. Moreover, the absolute hourly load differences between urban and rural areas were significantly larger during the heating periods than during the cooling periods, with the former characterized by being strong at night and weak during the day. During the peak energy load period, the contribution of the UHI to the peak load of residential buildings varied between the cities. During the stable high-load period, from 18:00 to 07:00 the next day in the heating periods (from 18:00 to 05:00 the next day in the cooling periods), the hourly loads in the urban areas of Beijing, Tianjin, and Shijiazhuang were 3.15 (2.48), 3.88 (1.51), and 1.07% (1.09%) lower (higher) than those in their rural areas, respectively. Our analysis highlights the necessity to differentiate the energy supplies for the heating and cooling of urban buildings in different sized cities in the region.

Keywords: urban heat island; heating load; cooling load; cities of different sizes; Beijing–Tianjin–Hebei

1. Introduction

The rapid urbanization of the past decades has put enormous pressure on energy, environment and resources [1,2]. The impact of the urban heat island (UHI) effect on building energy consumption has attracted increasingly widespread attention in recent decades. The total life-cycle energy consumption of China's buildings was 2.147 billion TCE in 2018, which accounted for 46.5% of the total national energy consumption [3]. Heating and cooling energy consumption, which accounts for 60–70% of the total energy consumption for building operation, is vulnerable to external meteorological conditions, especially significantly affected by the UHI effect [4]. It is necessary to study the impact of the UHI on building heating and cooling energy consumption for effectively regulating urban building energy and improving the ability of a city to cope with extreme climate events.

Currently, more than 50% of the world's population lives in cities [5,6]. With the influx of population into urban areas and the increase in human activities, a large amount of agricultural land has been converted into urban land, and major urban agglomerations have gradually formed. Rapidly growing urbanization has triggered the UHI effect. It has been reported that more than 400 large cities worldwide have recorded urban overheating [1], which has had a serious impact on urban cooling loads, peak electricity demand, and environmental quality [7]. From 1978 to 2018, the urbanization rate of China's population rose rapidly from 17.92 to 59.58% [8]. Many large cities are facing serious energy pressure for heating and transportation, and environmental pollution [9,10]. Different levels of urban development and cities of different sizes are common among the major urban agglomerations. As a central urban area with dense population and buildings, its massive building energy use is more susceptible to the UHI effect [4,11]. Therefore, it is necessary to comprehensively and quantitatively understand the impact of the UHI on buildings' heating and cooling energy consumption to reduce energy use and increase thermal comfort in different scales cities in urban agglomerations.

The impact of UHI on building energy consumption in different cities has been widely reported in recent years. Studies have concluded that the UHI effect has a significant impact on the heating and cooling energy consumption of buildings [11]. Overall, the UHI effect decreases heating energy consumption and increases the cooling energy consumption of buildings, with the magnitude of the decrease and increase varying from city to city depending on the climatic zone in which they are located and the degree of urbanization development [1,12]. A review summarized the evaluation results of the impact of the UHI effect on building energy consumption in representative global cities in recent decades, suggesting that building cooling energy consumption increased from 10 to 120%, and the heating energy consumption decreased from 3 to 45%, accompanied by the strong UHI effect in central urban areas [11]. For every 1 °C increase in temperature, peak cooling loads are estimated to increase by 0.5 to 8.5% in different cities around the world [13]. In Milan, the UHI reduced the heating load of non-insulated and insulated buildings by 12 and 16%, respectively, while the cooling load increased by 41 and 39%, respectively [14]. In Beijing, from 1961 to 2014, the strong UHI effect resulted in an approximately 16% decrease in building heating load and an approximately 11% increase in cooling load in the urban area compared with the rural area, and a 9% decrease in heating peak load and a 7% increase in cooling peak load in urban areas [15]. In Athens, Santamouris et al. [16] found that the cooling energy demand of a typical office building located in the urban center was almost two times higher than that of a similar building located in the suburban areas, and the peak electricity load was almost tripled. In Barcelona, a simulation study showed that the sensible cooling load of residential buildings increased by approximately 18 to 28%, depending on the UHI intensity (UHII), amount of solar gains and cooling set point [17]. Global warming and the UHI effect are expected to have a significant impact on buildings' energy demands [18,19]. Studies from cities in the American Southwest (Phoenix and Tucson) show that the citywide cooling energy demand is expected to increase two and three times, with approximately 75% of the increase due to urban expansion and approximately 25% due to global warming [20]. Depending on the climate models, the authors of [21] concluded that the U.S. has a 9–20% saving in heating energy consumption and 20–35% increase in cooling energy consumption, while China has a 12–19% saving in heating energy consumption and 37–41% increase in cooling energy consumption. The UHI effect is closely related to energy use and carbon emissions [22]. Without effective controls, the increasing demand for building cooling caused by the UHI effect in urban centers is expected to increase CO_2 emissions by five times by 2050 compared with 2000 [23].

The Beijing–Tianjin–Hebei urban agglomeration, located in northern China, is the political and cultural center of the country and includes cities of different sizes, such as the capital city of Beijing, the coastal city of Tianjin and numerous cities in Hebei province. Since the reform and opening up, the Beijing–Tianjin–Hebei urban agglomeration has experienced an unprecedented and rapid urbanization process, and the UHI effect has been strengthened year by year due to the underlying surface change and the increase in anthropogenic heat emissions. By 2016, the built-up area of the region was about 4466.1 km^2, accounting for 8.2% of the country, and the urban population was about 45.7 million, accounting for 9.6% of the country [24]. The Beijing–Tianjin–Hebei urban agglomeration is very representative due to its high degree of urbanization development, large urban population density, and uneven development of cities of different sizes.

The temperature data used to building energy consumption simulation mainly include: actual observation data from meteorological stations, simulation-generated temperature data with UHI effect [12], and typical meteorological year data representing average climate conditions [25–27], and so on. Due to the lack of multi-year observation data from high-density meteorological station, there are few reports of building energy simulation research using long series observation hourly data. In previous studies, alternative methods or interpolation methods were used to obtain hourly meteorological data for the energy consumption simulation [28–30]. In the late 1990s, China began to set up high-density ground-based automatic weather stations (AWS) [31]. AWS can provide hourly scale actual observation data for building energy consumption simulation. Therefore, the study on the variation characteristics of refined time scale of building loads can be analyzed based on the energy consumption simulation using hour-by-hour observed dataset of multi-year.

It is important to understand the changing patterns and differences in building heating/cooling energy consumption under the impact of UHI in cities of different sizes. However, few studies have been reported the impacts of UHI on building heating/cooling energy consumption in cities of different sizes in large urban agglomerations in northern China. Therefore, we conducted this study in different size cities of Beijing–Tianjin–Hebei urban agglomeration. Based on hourly data observed over the past nine years from AWSs and representative rural weather stations selected by remote sensing method, the impacts of the UHI on the building heating and cooling loads at fine time scales (i.e., day and hour) were assessed by simulating the hourly loads during whole year of the typical residential buildings in urban and rural areas of each cities. This study is expected to helpful to the government for making energy-saving measures in such urban agglomeration as Beijing–Tianjin–Hebei.

2. Methods

2.1. Selection of Study Area and Cities of Different Sizes

The Beijing–Tianjin–Hebei region (36°05′ N–42°37′ N, 113°27′ E–119°50′ E) is located in the northern part of the North China Plain, with the terrain high in the northwest and low in the southeast. To its west and north are the Taihang Mountains and Yanshan Mountains, to its southeast is the northern end of the North China Plain, and to its east is the Bohai Sea. The climate is mainly a temperate continental monsoon climate, with hot and rainy summers and cold and dry winters. The region includes two mega-cities, Beijing and Tianjin, and many cities in the Hebei Province, forming a typical large urban agglomeration in northern China and one of the three major urban agglomerations in China.

With the rapid urbanization in recent decades, the urban area of the Beijing–Tianjin–Hebei region has gradually expanded. Additionally, cities in this urban agglomeration have developed with different sizes and levels. People are flocking to cities, and the urban population is expanding, resulting in dense buildings and obvious overheating in the cities. The permanent resident population (PRP) of Beijing, Tianjin and Shijiazhuang is approximately 18.7, 13.0 and 6.7 million, respectively [32–34]. This paper divided the cities in the Beijing–Tianjin–Hebei urban agglomeration into three categories of representative cities based on the size of their permanent resident populations, i.e., the first category is Beijing (the PRP above 15 million), the second is Tianjin (the PRP between 10 and 15 million), and the third is Shijiazhuang (the PRP below 10 million). This division method is consistent with the population size and urbanization level of cities, which can comprehensively reflect the differences in the cities of the three sizes.

2.2. Selection of Rural Reference Weather Stations

In order to calculate the UHII more accurately, rural reference weather stations (RRWS) were selected. A RRWS selection using remote sensing data developed by Ren and Ren [35] is a relatively objective method as it does not rely on social and economic data. Using the land use/land cover data, the alternative rural weather stations were taken as the center and 4 km as the radius to generate buffer zone data, and the percentages of built-up areas in the buffer zones were calculated. Stations with 0% built-up area in the buffer zones were extracted in cities, based on the calculation results. Furthermore, the RRWS were selected for a comprehensive consideration of the station observation environment, altitude, spatial distribution, and so on. For station selection details, see [35–38]. Yang et al. [36] and Meng et al. [37] selected the RRWS in Beijing and Tianjin, respectively, based on this method and combined with local characteristics. Similarly, the RRWS of Shijiazhuang were selected according to this method in this study. In summary, Mu Jia Yu (MJY), Shan Dong Zhuang (SDZ), Feng Huang Ling (FHL), Pang Ge Zuang (PGZ) in Beijing, Tai Tou (TT), Cai Gong Zhuang (CGZ), Nan Wang Ping (NWP), Xi Di Tou (XDT) in Tianjin, and Sun Cun (SC), Gang Shang (GS), Nan Wang Zhuang (NWZ), Bao Du Zhai (BDZ) in Shijiazhuang, were selected as the RRWS for each city, representing the suburban climate (Figure 1). In this study, the typical meteorological observation stations located in urban centers were selected as the urban stations, i.e., BJ (Beijing) station for Beijing, TJ (Tianjin) station for Tianjin, and SJZ (Shijiazhuang) station for Shijiazhuang, representing the urban center climate (Figure 1). Table 1 summarizes the basic information of the weather stations used.

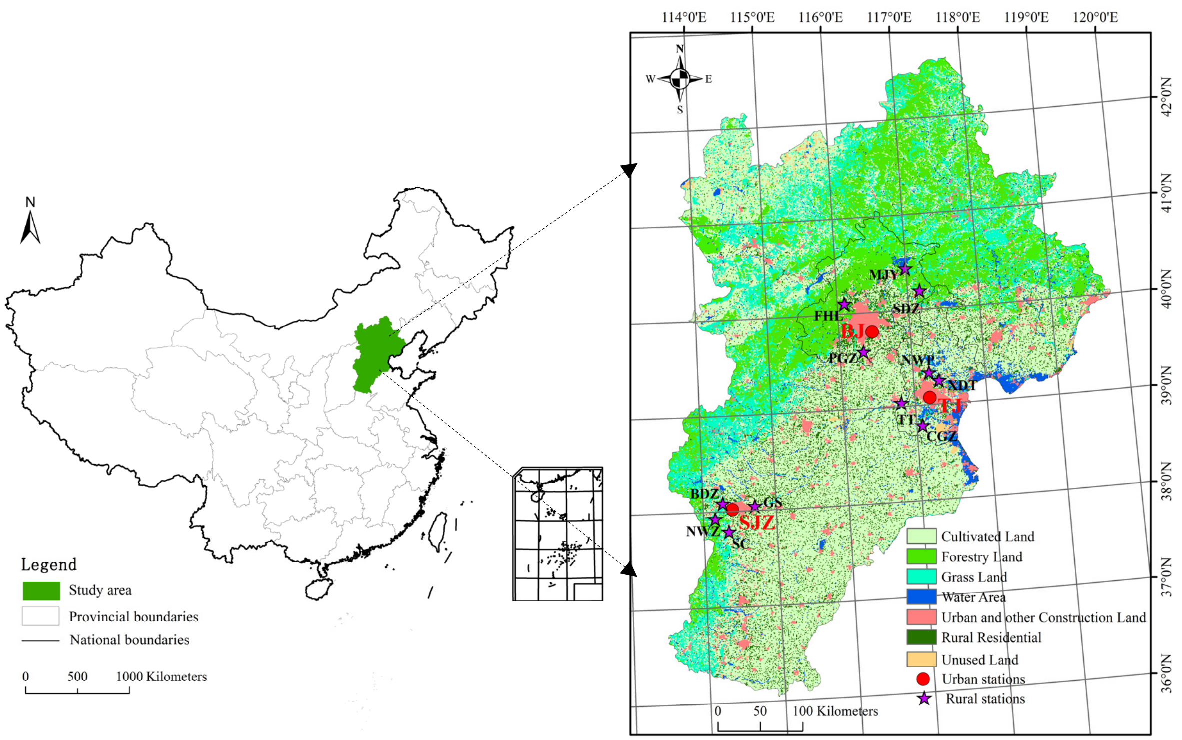

Figure 1. Location of the study area and the distribution of the urban weather station (red dots) and the RRWS (purple stars) in BTH region, China.

Table 1. Information on the weather stations used in this study.

Cities	Station Type	Station Name	Longitude (°E)	Latitude (°E)	Altitude (m)
Beijing	Urban station	BJ	116.47	39.80	31.30
	Rural station	MJY	116.99	40.44	91.00
	Rural station	SDZ	117.17	40.20	74.00
	Rural station	FHL	116.10	40.11	73.00
	Rural station	PGZ	116.33	39.60	25.00
Tianjin	Urban station	TJ	117.20	39.07	2.20
	Rural station	TT	116.81	39.04	1.00
	Rural station	CGZ	117.08	38.79	1.00
	Rural station	NWP	117.22	39.34	1.00
	Rural station	XDT	117.35	39.25	1.00
Shijiazhuang	Urban station	SJZ	114.40	38.02	89.00
	Rural station	SC	114.34	37.79	147.00
	Rural station	GS	114.71	38.05	35.00
	Rural station	NWZ	114.16	37.93	324.00
	Rural station	BDZ	114.27	38.09	380.00

2.3. Calculation of UHII

In the study, UHII is defined as the temperature difference between urban and rural stations (areas). Therefore, UHII can be obtained by the following equation:

$$UHII = T_{\mathrm{u}} - \overline{X}T_{\mathrm{r}} \quad (1)$$

where T_{u} is the temperature of the urban station (°C), and $\overline{X}T_{\mathrm{r}}$ is the mean temperature of the RRWS in each city (°C).

The heating period is from the 15 November to the 15 March of the next year, as stipulated by the local government of BTH. The cooling period is from June to August, which is also the summer in BTH.

2.4. Simulation of the Heating and Cooling Energy Consumption of Buildings and Data Preparation

In this study, Transient System Simulation (TRNSYS) v16 software was used to simulate the heating and cooling energy consumption of residential buildings. This software is one of the most widely used software for building energy consumption simulation study [11,39]. Li et al. [40] used TRNSYS to simulate building energy consumption and monitor the dynamic variations of actual energy consumption in Tianjin, China. A high agreement between simulated and measured energy consumption with an error within 15% was verified, indicating that the simulation results of this software can reflect the real energy consumption variation characteristics and this software is suitable for application in the field of climate impact on building energy consumption [40,41].

Two sets of initial data needed to be input to complete the simulation of building heating and cooling energy consumption. One set was the hourly meteorological data from 2011 to 2019, which was obtained from the Meteorological Information Center of Tianjin Meteorological Bureau and underwent strict quality control [31]. Meteorological parameters mainly included temperature, total solar radiation, direct normal solar radiation, relative humidity, wind speed, wind direction, and so on.

The direct normal solar radiation was calculated by referring to the JGJ/T 346-2014 standards [42] issued by the Ministry of Housing and Urban–Rural Development of China, and the correlative equations are as follows:

$$I_N = I_0 A_1 A_2^{A_3 A_2^{-A_4 K_t}} \quad (2)$$

where I_N is the direct normal irradiation, I_0 is the solar constant. The expression of A_1, A_2, A_3, A_4 and K_t are

$$A_1 = -0.1556 \sin^2 h + 0.1028 \sin h + 1.3748 \tag{3}$$

$$A_2 = 0.7973 \sin^2 h + 0.1509 \sin h + 3.05 \tag{4}$$

$$A_3 = 5.4307 \sin^2 h + 7.2182 \tag{5}$$

$$A_4 = 2.990 \tag{6}$$

$$K_t = \frac{I_h}{I_0 \cdot \sin h} \tag{7}$$

where h is the solar altitude, I_h is the total solar radiation.

The other set is the residential building design parameters related to heating and cooling energy consumption simulation, including building envelope heat transfer coefficient, solar radiation absorption coefficient, indoor design conditions, and so on. The building design parameters were determined according to the JGJ 26-2010 standards [43] for residential buildings in the three cities. Table 2 summarizes the main building design parameters.

Table 2. Design parameters of residential buildings included in this study.

Building Envelope Heat Transfer Coefficient [W/(m^2 × K)]			**Thermal Inertia Index**			**Window-to-Wall Ratio**			
Wall	**Roof**	**Floor**	**Wall**	**Roof**	**Floor**	**East**	**South**	**West**	**North**
0.60	0.45	2.50	4.00	4.50	3.50	0.28	0.41	0.28	0.41

Indoor Design Condition (Summer/Winter)			**Internal Load Density**			**Solar Radiation Absorption Coefficient**	
Temperature [°C]	**Relative Humidity [%]**	**Air Change Rate [m^3/h]**	**Occupancy [m^2/person]**	**Lighting [W/m^2]**	**Equipment [W/m^2]**	**Wall**	**Roof**
26/18	60/35	30	32	5	5	0.48	0.74

3. Results

3.1. Variation Characteristics of UHII in Cities of Different Sizes

In this study, the daily variations of the temperature in urban and rural areas and UHI intensities (UHII) in Beijing, Tianjin, and Shijiazhuang during the period 2011–2019 are shown in Figure 2. The daily mean UHII were calculated from the difference in urban and rural areas using daily mean temperatures from the period 2011–2019. Overall, the daily mean temperature variations in the urban and rural areas of the three cities presented similar trends, with varying degrees of UHII throughout the year. The UHII were generally large in autumn and winter and small in spring and summer, and they were relatively large in Beijing and Tianjin and small in Shijiazhuang. The daily mean UHIIs for Beijing, Tianjin, and Shijiazhuang were 1.5, 1.3, and 0.8 °C, respectively. The highest UHII occurred at the end of December during the heating period (from 15 November to 15 March the next year), with peak values reaching 3.0 °C (27 December), 3.1 °C (31 December), and 1.6 °C (29 December) for Beijing, Tianjin, and Shijiazhuang, respectively. During the cooling period (from 1 June to 31 August), the end of August presented the highest UHII, with peak values reaching 2.0 °C (22, 25 August), 2.0 °C (22 August), and 1.1 °C (31 August) for Beijing, Tianjin, and Shijiazhuang, respectively.

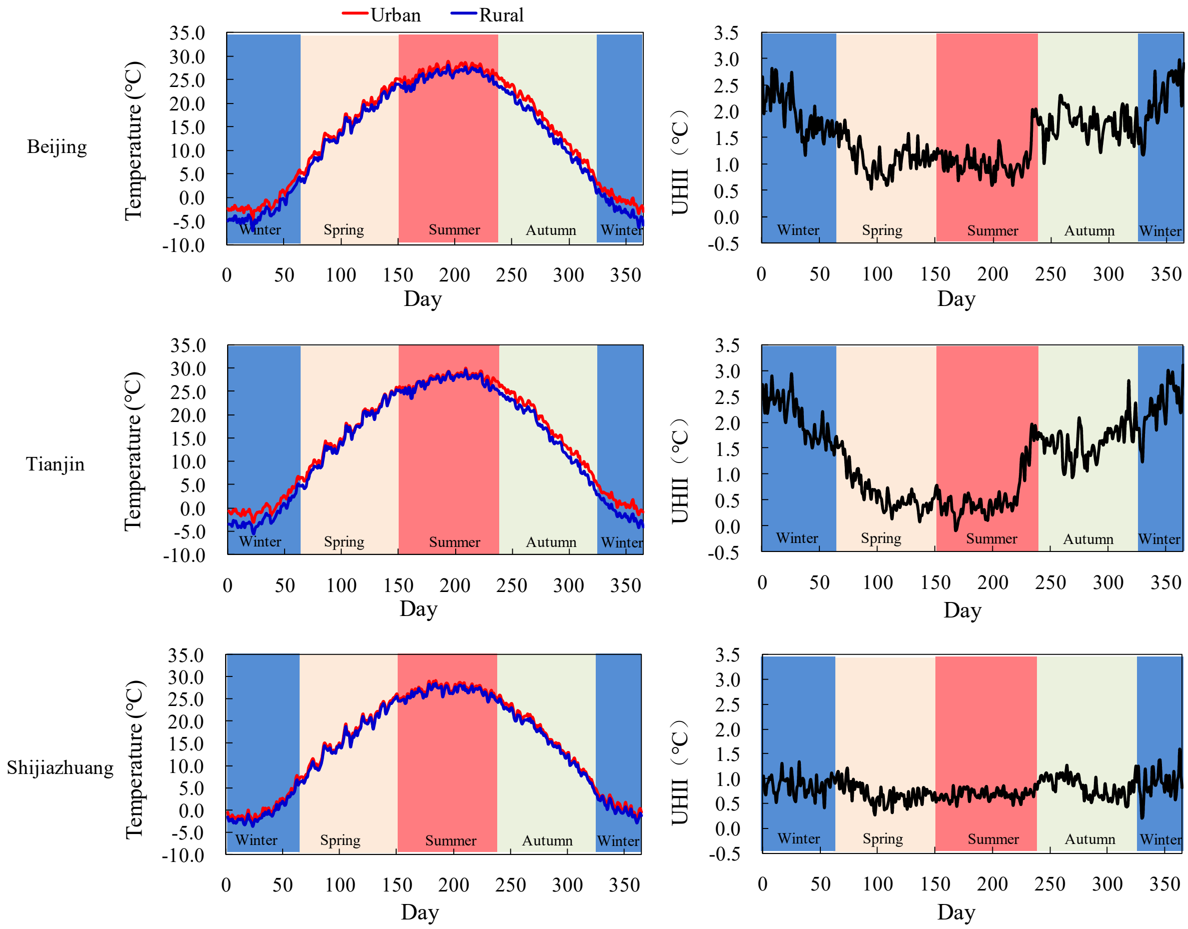

Figure 2. Daily variations in annual mean values of the temperature in urban and rural areas and UHII in Beijing, Tianjin and Shijiazhuang for the period 2011–2019.

3.2. Impacts of UHII on Building Heating and Cooling Loads in Cities of Different Sizes

3.2.1. Daily Load Variations during Heating and Cooling Periods

The daily variations of the annual mean values of the heating/cooling loads and the correlation between the loads and UHII for 2011–2019 are shown in Figure 3 and Table 3. Overall, the variation trends in the heating load in the urban and rural areas of different cities were similar, with the heating load in urban areas being lower than that in rural areas. The average daily heating loads in the urban areas of Beijing, Tianjin, and Shijiazhuang were 8.14, 10.71 and 2.79% lower than those in their corresponding rural areas, respectively (Figure 3A1–A3). The high-heating load period for each city occurred from approximately 25 December to 25 January of the following year (Table 3). A comparison of the average daily loads in urban areas of different cities during the high-load periods showed that Beijing exhibited the highest load, reaching 730.62 $\times 10^{-3}$ kWh/m^2; this load was followed by that of Shijiazhuang, while Tianjin had the lowest value (Table 3). During high-load periods, the average daily loads differed between the urban and rural areas of each city. The average daily loads in the urban areas of Beijing and Tianjin were 8.38 and 10.43% lower than those in their rural areas, respectively, while Shijiazhuang experienced a difference of 1.98%. Low-load periods occurred in each city from March 11 to 15, with the average daily loads in urban and rural areas ranging from 270 to 350 $\times 10^{-3}$ kWh/m^2. The correlations between the UHI and the daily heating load differences in urban and rural areas were analyzed in this study. For every 1 °C increase in UHI, the heating load differences in Beijing, Tianjin, and Shijiazhuang decreased by 30.13, 30.18, and 30.34 $\times 10^{-3}$ kWh/m^2, respectively (Figure 3B1–B3).

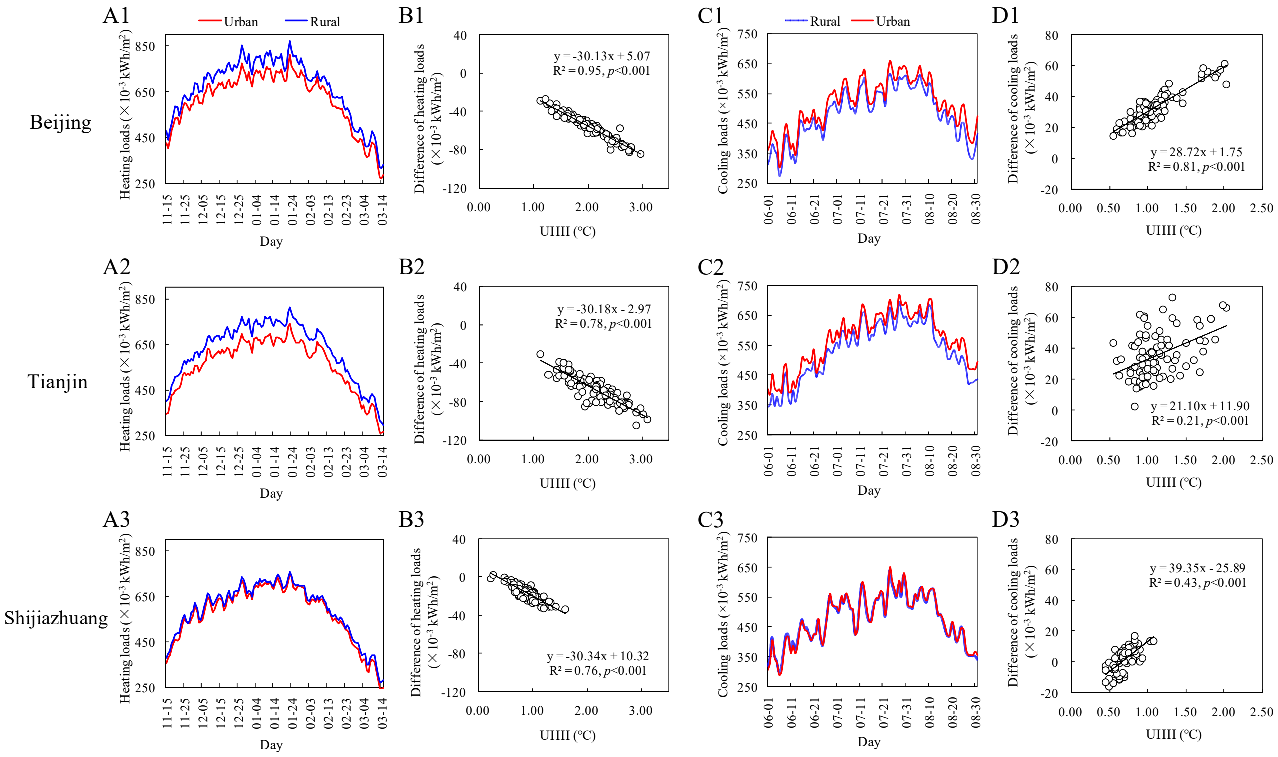

Figure 3. Daily variations in annual mean values of the heating/cooling loads (**A1**–**A3**,**C1**–**C3**) and the correlation between the loads and UHII (**B1**–**B3**,**D1**–**D3**) for 2011–2019.

Table 3. The average daily loads of high/low periods in the heating/cooling period in Beijing, Tianjin and Shijiazhuang for 2011–2019.

Cities	High-/Low-Load Periods	Heating Period			Cooling Period		
		Average Daily Loads in Urban ($\times 10^{-3}$ kWh/m^2)	Average Daily Loads in Rural ($\times 10^{-3}$ kWh/m^2)	Percentage	Average Daily Loads in Urban ($\times 10^{-3}$ kWh/m^2)	Average Daily Loads in Rural ($\times 10^{-3}$ kWh/m^2)	Percentage
Beijing	High-load period	730.62	797.40	8.38%	613.08	583.26	5.11%
	Low-load period	306.99	352.82	12.99%	380.36	344.05	10.55%
Tianjin	High-load period	672.00	750.25	10.43%	671.16	641.37	4.64%
	Low-load period	281.32	328.23	14.29%	418.69	375.98	11.36%
Shijiazhuang	High-load period	692.36	706.32	1.98%	569.08	562.45	1.18%
	Low-load period	269.21	294.05	8.45%	356.45	367.96	3.13%

During the cooling period, the cooling load in the urban area of each city was consistently higher than that in its rural area, due to the UHI effect. The average daily cooling loads in the urban areas of Beijing, Tianjin, and Shijiazhuang were 6.88, 6.70, and 0.27% higher than those in their rural areas, respectively (Figure 3C1–C3). The high-load periods, low-load periods, and their respective average daily loads during the cooling periods are shown in Table 3. The high-cooling load periods in the three cities all occurred from 23 July to 11 August (Table 3). The cooling loads in the urban areas of Beijing and Tianjin were much higher than those of Shijiazhuang. During the high-load periods, the average daily cooling loads in the urban areas of Beijing and Tianjin were 5.11 and 4.64% higher than those in their rural areas, respectively, while this difference was only 1.18% in Shijiazhuang. The low-load periods occurred from 1 to 14 June; there was an urban–rural difference of around 10%, and the average daily loads ranging from 340 to 420 $\times$ 10^{-3} kWh/m^2 in the three cities. According to the analysis of the correlations between the daily cooling load differences and UHI in urban and rural areas, for every 1 °C increase in UHI, the cooling load differences in Beijing, Tianjin, and Shijiazhuang increased by 28.72, 21.10, and 39.35 × 10^{-3} kWh/m^2, respectively (Figure 3D1–D3).

3.2.2. Hourly Variations in Heating and Cooling Loads during Heating and Cooling Periods

Figure 4 and Table 4 show the annual average 24 h heating and cooling load distributions in cities of the three sizes during the heating and cooling periods from 2011 to 2019. Overall, the hourly load differences between urban and rural areas exhibited two stable periods and two sharp-change periods during the heating and cooling periods. The absolute hourly load differences between urban and rural areas were significantly higher in the heating periods than in the cooling periods.

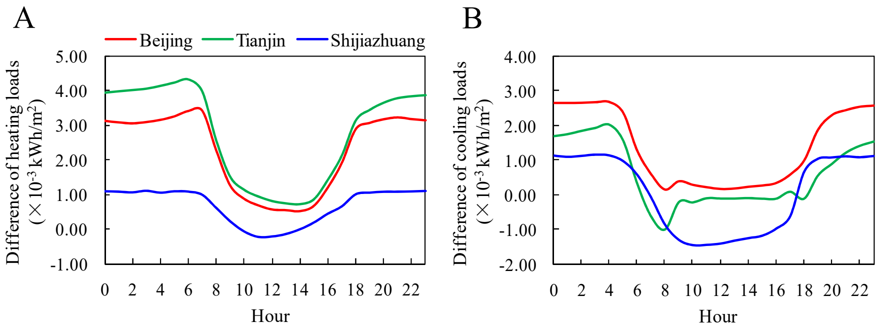

Figure 4. Hourly variations of annual mean values of the heating (**A**) cooling (**B**) load difference between the urban and rural areas for 2011–2019.

Table 4. The average hourly loads of high/low time periods in the heating/cooling period in Beijing, Tianjin and Shijiazhuang for the period 2011–2019.

Cities	High-/Low-Load Periods	Heating Period			Cooling Period		
		Average Hourly Loads in Urban (×10^{-3} kWh/m^2)	Average Hourly Loads in Rural (×10^{-3} kWh/m^2)	Percentage	Average Hourly Loads in Urban (×10^{-3} kWh/m^2)	Average Hourly Loads in Rural (×10^{-3} kWh/m^2)	Percentage
Beijing	High-load period	30.01	33.16	3.15%	22.56	20.08	2.48%
	Low-load period	17.26	17.87	0.60%	17.90	17.62	0.27%
Tianjin	High-load period	27.25	31.13	3.88%	24.37	22.86	1.51%
	Low-load period	15.61	16.42	0.81%	19.39	19.86	−0.46%
Shijiazhuang	High-load period	27.76	28.83	1.07%	21.30	20.21	1.09%
	Low-load period	16.25	16.17	−0.08%	16.44	17.65	−1.21%

The variations in the hourly load difference between urban and rural areas during the heating periods showed regular unimodal distributions in all three cities, with the trends being strong at night and weak during the day. Regarding overall performance, the hourly load differences between urban and rural areas were large in Beijing (2.28 × 10^{-3} kWh/m^2) and Tianjin (2.80 × 10^{-3} kWh/m^2) and small in Shijiazhuang (0.69 × 10^{-3} kWh/m^2) (Figure 4A). During the stable high-load period from 18:00 to 07:00 the next day, the hourly loads in the urban areas of Beijing, Tianjin, and Shijiazhuang were 3.15, 3.88, and 1.07% lower than those in their rural areas, respectively (Table 4). During the stable low-load period from 11:00 to 15:00, the loads in Beijing and Tianjin were similar to each other, while the load in Shijiazhuang was low. There were two sharp-change periods: a sharp decrease from 07:00 to 11:00 and a sharp increase from 15:00 to 18:00.

The variations in the hourly load difference between urban and rural areas in the three cities during the cooling periods were characterized by being strong at night and weak during the day. The hourly cooling load differences between urban and rural areas were large in Beijing (1.37 × 10^{-3} kWh/m^2) and Tianjin (0.60 × 10^{-3} kWh/m^2) and small in Shijiazhuang (0.05 × 10^{-3} kWh/m^2) (Figure 4B). During the stable high-load period from 18:00 to 05:00 the next day, the hourly loads in the urban areas of Beijing, Tianjin, and Shijiazhuang were 2.48, 1.51, and 1.09% higher than those in their rural areas, respectively (Table 4). During the stable low-load period from 09:00 to 17:00, there was a weak negative ratio of urban–rural hourly load demands. The two sharp-change periods included a sharp decrease period from 05:00 to 10:00 and a sharp increase period from 16:00 to 18:00. The hourly load differences between urban and rural areas showed a downward trend from 08:00 to 09:00 (Figure 4B), which may be related to working hours. Many urban residents leave their home for work during this period, resulting in the decreases in the loads of urban residential buildings and the larger urban–rural load differences in the three cities.

3.2.3. Distribution of Correlation between UHII and Hourly Load Difference

Figure 5 shows the variation characteristics of the hourly heating and cooling load differences between urban and rural areas in Beijing, Tianjin, and Shijiazhuang from 2011 to 2019, relative to the UHII. During the heating periods, the hourly heating load differences between urban and rural areas in Beijing, Tianjin, and Shijiazhuang decreased by 0.89, 1.08, and 0.79 × 10^{-3} kWh/m^2, respectively, for every 1 °C increase in UHII (Figure 5A,C,E). During the cooling periods, the hourly cooling load differences between urban and rural areas in Beijing, Tianjin, and Shijiazhuang increased by 0.95, 1.02, and 1.77 × 10^{-3} kWh/m^2, respectively, for every 1 °C increase in UHII (Figure 5B,D,F).

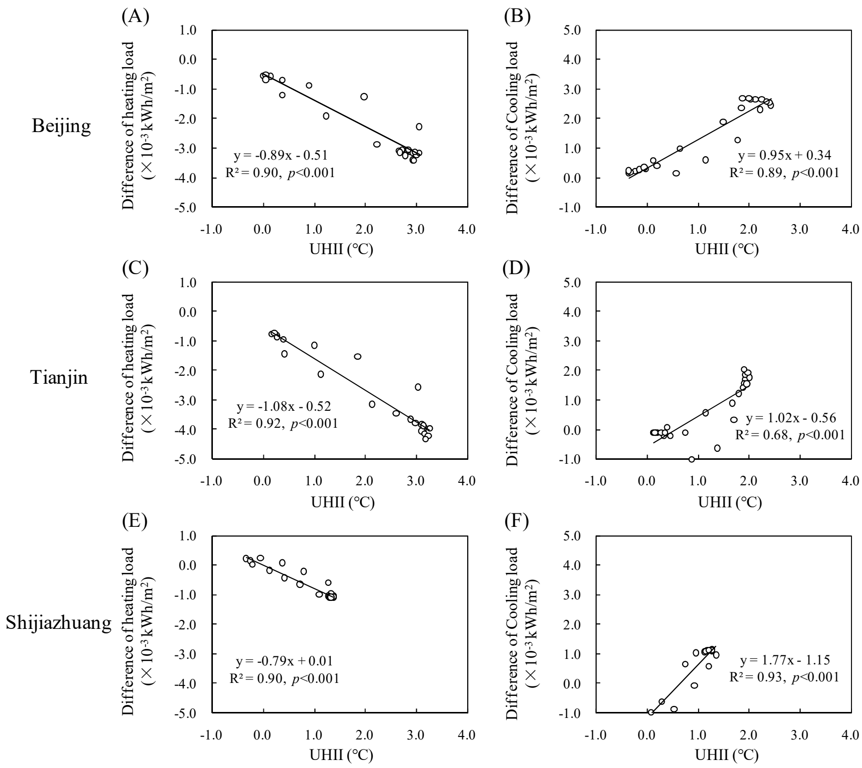

Figure 5. Correlation between the hourly UHII and the hourly heating (**A**,**C**,**E**) cooling (**B**,**D**,**F**) load differences in buildings in Beijing, Tianjin and Shijiazhuang for the period 2011–2019.

When UHII increased from −1 to 4 °C, the decreases (increases) of urban heating (cooling) loads were larger than those of the rural areas in the three cities. In addition, the hourly cooling load difference between urban and rural areas in Shijiazhuang increased more than that in Beijing and Tianjin with the increase in UHII.

4. Discussion

The population density and economic development levels of cities in large urban agglomerations are very different, forming cities of different scales. The Beijing–Tianjin–Hebei urban agglomeration is one of the typical large urban agglomerations in China [44,45]. In recent decades, the UHI effect of the urban agglomeration has become prominent, and the intensity and extent of the UHI have been continuously enhanced with the increase in urban scale and building density [46,47]. This study found that the UHI effect was obvious in Beijing, Tianjin and Shijiazhuang over the period 2011–2019, with UHII being larger in autumn and winter and smaller in spring and summer.

The heating and cooling energy consumption of buildings is significantly affected by global warming and urbanization, especially in the increasingly large urban agglomerations [48,49]. The impact of rising urban temperatures on the buildings' energy demands depends on the magnitude of the urban overheating, the local climate characteristics and the number of buildings, etc. [50]. Moreover, people's thermal comfort is also related to the buildings' heating and cooling energy consumption. The occupants can adapt to rising temperatures by reducing clothing and activity, but when the temperature exceeds 30 °C, the occupants cannot adapt to the environment [51]. Although many factors can affect building energy demand, the UHI effect is relatively significant. The spatial distribution of UHII is heterogeneous [36,52,53], resulting in a difference in energy consumption demand between urban and rural areas. Therefore, taking the Beijing–Tianjin–Hebei urban agglomeration in China as an example, we evaluated the impact of UHI on building heating and cooling loads in cities of different scales in this study.

According to the daily variations in loads during the heating and cooling periods, the trends were generally consistent between the urban and rural areas in different cities. Because of the existence of the UHI phenomenon, the heating loads in urban areas were lower than those in rural areas, while the cooling loads in urban areas were higher than those in rural areas. The average daily heating loads in urban areas of Beijing and Tianjin were 8.14 and 10.71% lower than those of their rural areas, respectively, while this difference was only 2.79% in Shijiazhuang (Figure 3A1–A3). Moreover, Tianjin is close to the Bohai Sea; thus, its urban area is relatively warm in winter, implying decreases in the heating demands of residential buildings and increases in the average daily heating load differences between its urban and rural areas. The high heating load period occurred from 25 December to 25 January of the next year in all cities. During the high-load period, the average daily heating load in the urban area was the highest in Beijing, reaching 730.62×10^{-3} kWh/m^2, followed by that in Shijiazhuang; the load was the lowest in Tianjin (Table 3). During the high-load period, the urban areas were strongly affected by the UHI effect, resulting in the largest difference in loads between urban and rural areas. One study has reported that urban areas did not consume as much energy as rural areas to meet heating demands [37]. Therefore, regulation measures for heating between urban and rural areas should be treated differently in order to fully exploit the UHI effect for energy savings. There is a period when overheating in cities significantly increases the cooling demand [54]. A case study showed that the peak electricity load of buildings could increase by 4.6%, while the total electricity consumption was estimated to increase by 8.5% [13]. In this study, the cooling loads in urban areas were higher than those in rural areas due to the UHI effect, with the average daily cooling loads in the urban areas of Beijing, Tianjin, and Shijiazhuang being 6.88, 6.70 and 0.27% higher than those in their rural areas, respectively (Figure 3C1–C3). The high cooling-load period occurred from 23 July to 11 August for all three cities. The cooling loads in urban areas were high in Beijing and Tianjin and low in Shijiazhuang. The high cooling load in Tianjin was related to its high dehumidification load in summer. A study on the impact of meteorological factors on building energy consumption pointed out that the energy consumption levels of high-rise office buildings were more sensitive to temperature and humidity changes in hot and humid environments than in cold and dry environments [55]. In Tianjin, the urban areas were influenced by the ocean during the summer, thus increasing humidity. Humidity can affect human comfort and increase the dehumidification load in urban areas [56], thereby increasing the total cooling loads of buildings.

The hourly heating/cooling load differences between urban and rural areas were strong at night and weak during the day. The absolute hourly heating load differences between urban and rural areas were significantly higher than the absolute hourly cooling load differences between urban and rural areas. The reason for this phenomenon was that the Beijing–Tianjin–Hebei region is located in a cold climate zone, thus increasing the heating load demand [37,57]. Northern China experiences a strong UHI effect in winter [58,59], and the strong UHI effect at night significantly impacts the energy demands of buildings [60]. During the stable high-load period (from 18:00 to 07:00 the next day) of the heating periods, the hourly loads in urban areas of Beijing, Tianjin, and Shijiazhuang were 3.15, 3.88, and 1.07% lower than those in their rural areas, respectively (Table 4). The hourly load differences at night between the urban and rural areas of Tianjin were higher than those of Beijing. In winter, the temperature in Tianjin, a coastal city, was slightly higher than that in Beijing, an inland city (Figure 2), thus decreasing the heating load in the urban area and increasing the differences in the heating demands between the urban and rural areas of Tianjin. During the cooling periods, the stable high-load period occurred from 18:00 to 05:00 the next day, which was the main resting period for people. During this period, the hourly loads of residential buildings in the urban areas of Beijing, Tianjin, and Shijiazhuang were 2.48, 1.51 and 1.09% higher than those in their rural areas, respectively (Table 4). The stable low-load period occurred from 09:00 to 17:00. This period was the main working time for people in urban areas; thus, the cooling demands in residential buildings decreased, even resulting in a weak negative ratio of urban–rural hourly load demands. We found that the hourly heating load difference decreased while the hourly cooling load difference increased with the increase in UHII in cities of different sizes. For every 1 °C increase in UHII, the hourly heating load differences between the urban and rural areas of Beijing, Tianjin, and Shijiazhuang decreased by 0.89, 1.08, and 0.79×10^{-3} kWh/m^2, respectively, while their hourly cooling load differences increased by 0.95, 1.02, and 1.77×10^{-3} kWh/m^2, respectively (Figure 5). With the increase in UHII, the building load in the urban area of Shijiazhuang in summer will probably increase in the future.

This study had the following limitations. First, the mechanisms of the impacts of UHI on building heating and cooling energy demands remained unclear; thus, an in-depth exploration should be conducted in future studies. Second, we only investigated the impact of UHI on residential building loads, and their impacts on other types of building loads could deserve further investigation. Finally, this study only focused on the impacts of UHI on building loads in a cold climate zone, and further studies should be conducted in other climate zones. In general, this study suggests that it is necessary to differentiate the energy supplies of urban buildings for heating and cooling in different sized cities in regions with a similar climate to Beijing–Tianjin–Hebei, to achieve the purpose of energy saving.

5. Conclusions

In this study, the impacts of UHI on the building heating and cooling loads were assessed by simulating the hourly loads over a whole year for typical residential buildings in urban and rural areas in cities of three sizes in Beijing–Tianjin–Hebei region. The main conclusions are as follows:

1. With the increase in UHII, the heating load difference decreased while the cooling load difference increased in cities of three sizes in the Beijing–Tianjin–Hebei region. Beijing and Tianjin had larger heating load differences between the urban and rural areas than Shijiazhuang. The average daily heating loads in urban areas of Beijing and Tianjin were 8.14 and 10.71% lower than those in their rural areas, respectively, while the difference was only 2.79% in Shijiazhuang. Moreover, because of its proximity to the ocean, Tianjin experienced a relatively warm winter in its urban area, leading to a decrease in the load and relatively large load differences between urban and rural areas. During the cooling period, the loads in urban areas were higher than those in rural areas due to the UHI effect, and the average daily cooling loads in urban areas

of Beijing, Tianjin, and Shijiazhuang were 6.88, 6.70, and 0.27% higher than those in their rural areas, respectively.

2. The period of high heating load occurred from 25 December to 25 January of the next year. The loads of the three cities were significantly affected by UHI, exhibiting different patterns. The average daily loads in the urban areas of Beijing, Tianjin, and Shijiazhuang were 8.38, 10.43, and 1.98% lower than those in their rural areas, respectively. The period of high cooling load occurred from 23 July to 11 August. The average daily cooling loads in the urban areas of Beijing and Tianjin were 5.11 and 4.64% higher than those in their rural areas, respectively, while this difference was only 1.18% in Shijiazhuang.
3. The hourly heating/cooling load differences for residential buildings between urban and rural areas were characterized by being strong at night and weak during the day. The absolute hourly load differences between urban and rural areas were significantly larger in the heating periods than in the cooling periods. During the stable high-load period (from 18:00 to 07:00 the next day/from 18:00 to 05:00 the next day) in the heating (cooling) periods, the hourly loads in the urban areas of Beijing, Tianjin, and Shijiazhuang were 3.15 (2.48), 3.88 (1.51), and 1.07% (1.09%) lower (higher) than those in their rural areas, respectively. With the future increase in UHII, the hourly cooling load differences between urban and rural areas in Shijiazhuang are likely to increase more significantly than those of the other two cities.

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