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Impact of urban heat island on the variation of heating loads in residential and office buildings in Tianjin

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ABSTRACT

Urban heat island (UHI) significantly affects the energy demand of buildings. Therefore, it is important to consider UHI effect when evaluating the real energy demand of buildings in urban and rural areas. Based on hourly data observed over the past ten years from automatic weather stations and four representative rural weather stations selected by remote sensing method, the impact of the UHI intensity (UHII) on the building loads at fine time scales (i.e. day and hour) were evaluated by simulating the hourly loads during whole year of the typical residential and office buildings in urban and rural areas. UHII was found to be the main climatic factor affecting the variations in heating load in both residential and office buildings. With a heating-period mean UHII of 2.1 °C in the ten years, the daily heating load in urban areas is significantly lower than that in rural areas, which is 10.1 and 7.5% less for residential and office buildings, respectively. For residential and office buildings, the daily heating load has decreased by 34.2×10^{-3} and 27.7×10^{-3} kWh/m^2, respectively, for every 1 °C increase in UHII. For both types of buildings, the period of high energy consumption in both urban and rural areas was from late December to late January of the following year. The hourly load in residential buildings was high at night and low during the daytime, and the opposite was founded in office buildings. For residential buildings, the period from 18:00 one day to 07:00 the next day was the high load period in both urban and rural areas, whereas the high load period in office buildings was from 07:00 to 19:00. The peak load in residential and office buildings was founded from 05:00 to 07:00 and from 07:00 to 11:00, respectively. Overall, the daily and hourly heating load variations in residential and office buildings response to UHI should be fully considered to improve the fine-level of heating operation regulations, especially in urban areas, to reduce the energy consumption of buildings.

1. Introduction

China experienced a rapid urbanization process in the past few decades, which has increased the demand for energy and the exploitation of the environment and resources [1,2]. The impact of urban heat island (UHI) on energy consumption in buildings has attracted considerable attention from both academia and relevant government departments. The UHI effect is one of the most prominent features of urban climate [3,4], and has become an important climatic and environmental issue in the 21st century. In 2016, the total energy consumption of buildings in China was 899 million tons of standard coal, accounting for 20.6% of the country's total energy consumption [5]. In the total operation energy consumption of building, heating and cooling energy consumption account for approximately 60–70% [6], which is directly related to the outdoor climate conditions [7]. In particular, the heating and cooling energy consumption are significantly affected by UHI effect [8–10]. Therefore, it is important to study the impact of UHI on the heating and cooling energy consumption of buildings to reduce the energy consumption and emission of pollutants.

Many studies have shown that UHI effect has a significant impact on the energy consumption of buildings [11–13]. The heating and cooling loads of buildings include envelope, indoor, and fresh air cooling loads, and the increase in the temperature caused by UHI effect has a significant impact on the envelope and fresh air cooling loads [14]. A study of representative global cities showed

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that the UHI effect reduces the heating energy consumption by 3–45% and increases the cooling energy consumption by 10–120% [15]. A study on the impact of UHI on the electricity consumption in buildings indicated that actual building power consumption increases by 0.5–8.5% for every 1.0 °C increase in the temperature [16]. Moreover, the impact of UHI on energy consumption in buildings is different at different time scales. Some studies reported that the UHI effect was stronger in winter than in summer [17,18], which reduced the heating energy demand in winter and increased the cooling energy demand in summer [19,20]. Memon et al. [21] found that the UHI intensity is stronger in the daytime than at night, and the cooling degree day (CDD) is maximum when the heating degree day (HDD) is minimum; they pointed out that this phenomenon was directly related to the UHI effect. Further, the impacts of UHI on the energy consumption of buildings are different in different climate zones. Sun et al. [22] pointed out that when the UHI effect is ignored, the total energy consumed of buildings in cold climate zones is overestimated, that in hot climate zones is underestimated, and that in mild-climate zones is not affected.

However, the impacts of UHI on the variations in the heat consumption of buildings at fine-time scales (e.g. hour or day) have remained unclear. It is difficult to accurately evaluate these effects from statistical analysis methods (e.g. the degree-days method) because they do not consider multi-climatic factors and the characteristics of the buildings themselves. The energy consumption simulation method is commonly used to study the impact of urban climate on buildings' energy consumption because it considers both the dynamic variations in multi-meteorological factors and the characteristics of buildings. Many studies have used alternative methods or interpolation methods to obtain hourly meteorological data [7,23] due to lack of hourly data from multi-year observation. Furthermore, the selection of rural weather stations is crucial to study the impact of UHI on energy consumption. To accurately evaluate the impact of UHI on the energy consumption of buildings, it is necessary to select rural weather stations using more objective methods.

In this study, we analyzed the daily and hourly variation of heating loads in urban and rural areas on both residential and office buildings based on hourly meteorological data collected in Tianjin to evaluate the impact of UHI on the variation of buildings' heating loads at fine-time scales. First, we selected rural weather stations using remote sensing method. Second, we simulated the hour-by-hour loads of residential and office buildings during the past ten years. Finally, we tested the response of the daily and hourly heating loads to UHI. The results of this study will be useful in developing hourly heating regulations in Northern China.

2. Materials and methods

2.1. Study area

The study area is Tianjin (38°33′–40°15′ N, 116°42′–118°03′ E), China (Fig. 1). It is located in the lower reaches of the Haihe River, with a population of approximately ten million people in 11,919 km^2 [24]. Tianjin has experienced rapid urbanization, owing to the growing urban population, expanding urban areas, increasing anthropogenic heat emission and environmental pollution. The six districts in the center of the city (i.e. Heping, Hexi, Hebei, Hedong, Nankai, and Hongqiao) are rapidly urbanizing areas (Fig. 1), and the urbanization has expanded to the four districts (Xiqing, Dongli, Jinnan, and Beichen) around the urban center in recent years.

2.2. Selection of rural weather station

Firstly, based on the station selection method developed by Ren & Ren [25] and Yang et al. [18], MODIS satellite data (MOD11A2) were used to calculate the distribution of land surface temperature. Then, considering the relative location of the automatic weather station in the surface temperature field, the four stations of Tai Tou (TT), Cai Gongzhuang (CGZ), Nan Wangping (NWP), and Xi Ditou (XDT) were selected as the alternative rural weather stations (Fig. 2).

Secondly, using the Land Use/Land Cover (LULC) data, the percentage of urban land use area around the alternative rural weather station was calculated in a buffer circle with 4 km as radius (Fig. 3). The results showed that the percentages of the urban and other construction land areas in the buffer circles of TT, CGZ, NWP and XDT stations were all less than 10%, indicating that they can be used as rural weather stations. The land use/land cover dataset of mainland China is provided by the Resources and Environmental Sciences Data Center (RESDC), Chinese Academy of Sciences (CAS) (http://www.resdc.cn).

Finally, the four stations, including TT, CGZ, NWP and XDT around the urban center, were selected as rural weather stations after the overall consideration for actual environment information near the stations (Fig. 1). These stations are located in different locations around the city center in uncovered areas or artificial vegetation areas, away from the influence of tall buildings or other artificial infrastructure. The average altitude of all four rural stations is 1.0 m (Table 1), the same with the central urban area, so it does not need to make a correction of air temperature lapse. The meteorological observation station (i.e. the only urban climate monitoring station in Tianjin) is located in the urban center and was selected as the urban weather station (Fig. 1).

2.3. Definition of UHI intensity and absolute humidity

In this study, the UHI intensity (UHII) was estimated by calculating the difference between the air temperatures of the urban and rural stations, as follows:

$$UHII = T_u - T_r \quad (1)$$

where T_u is the temperature of urban station (°C), and T_r is the mean temperature of the four rural stations (°C).

The absolute humidity was calculated by Eq. (2) given below:

$$\rho_v = \frac{e}{R_v T} \quad (2)$$

where ρ_v is the absolute humidity (kg/m^3), e is the water vapor pressure (Pa, Pa = N/m^2, N = kg·m/s^2, N represents Newton), R_v is the specific gas constant of water vapor (the value of R_v is 461.5 J/(kg·K), J = kg·m^2/s^2), and T is the temperature (K).

The heating period is from the 15th of November to the 15th of March of the following year, as stipulated by the local government of Tianjin City.

2.4. Simulation of the energy consumption of buildings

The hour-by-hour building loads for a ten-year period (2009–2018) were simulated using TRNSYS (Transient System Simulation Program). TRNSYS is software with a modular structure and includes the modules Simulation Studio, TRNBuild, and TRNEdit. These can be combined and connected to form a simulation system for specific studies. TRNSYS is commercial software widely used to study the energy consumption of buildings in the construction industry [15,20]. It can be considered reliable in evaluating the impact of climate on energy consumption [26] and has been used for studies on many provinces of China (e.g. Harbin, Tianjin, Shanghai, and Guangzhou) [27–29].

In our previous work [24,30], the TRNSYS model and data from the meteorological stations in Tianjin were used to simulate the

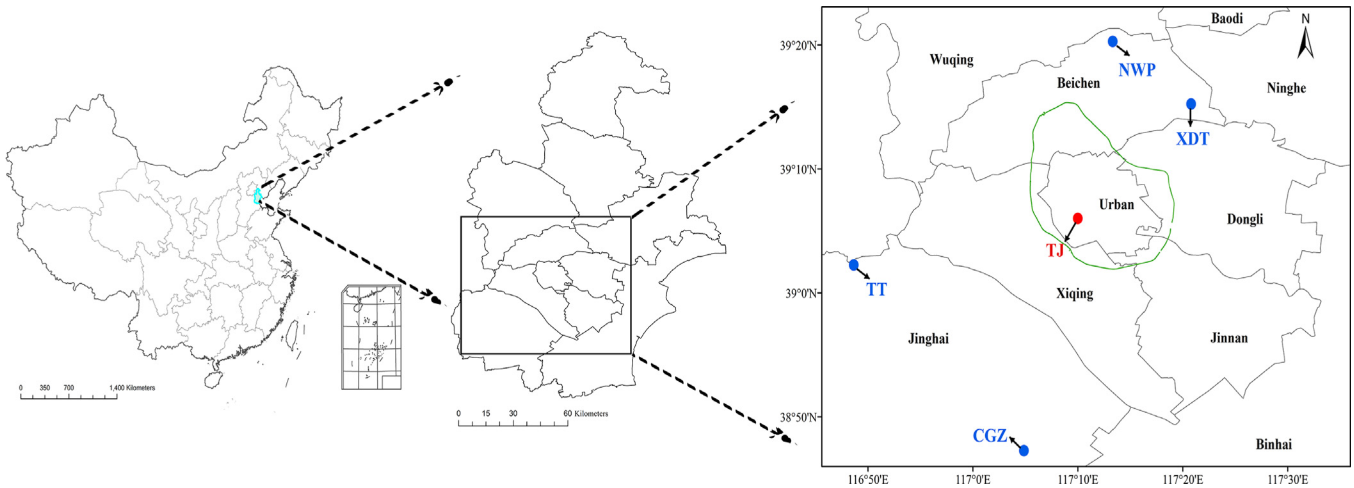

Fig. 1. Study region and the distribution of the weather stations in this study, including the urban station (red dot) and the rural weather stations (blue dot). Note: TJ: Tian Jin station, TT: Tai Tou station, CGZ: Cai Gongzhuang station, NWP: Nan Wangping station, XDT: Xi Ditou station, the same below. The green line represents the outer ring road which surrounds the dominant urban built-up area of Tianjin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

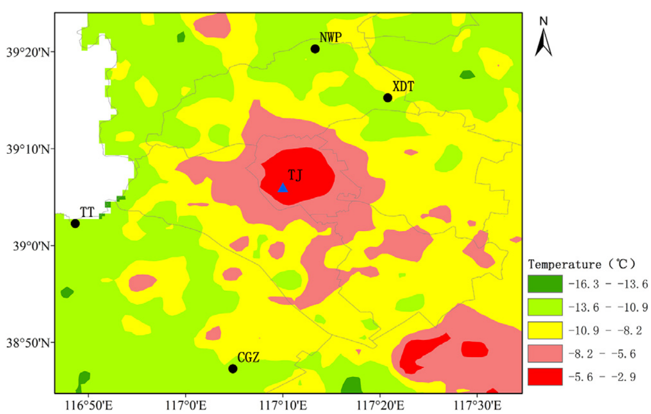

Fig. 2. Distribution of surface temperature and the alternative rural weather stations around urban center in Tianjin.

building energy consumption. Meanwhile, we carried out the actual measurements. We founded that the simulated values were in good agreement with the actual measured values, with errors of less than 15%, indicating the energy consumption simulation could efficiently and reliably reflect the real energy consumption in Tianjin area. This research focused on the variation of building energy consumption in Tianjin area, therefore, we simulated the energy consumption using the TRNSYS directly based on the previous work [28,31].

Meteorological data and building design parameters are needed to simulate the heating loads in buildings. The hourly meteorological data, including the direct normal solar radiation, total solar radiation, surface air temperature (1.5 m), relative humidity, wind speed and wind direction (10 m), used in this study were collected from 2009 to 2018 by automatic weather stations (AWS) in Tianjin. These data were from the National Meteorological Information Center, and have undergone a strict quality control to ensure their reliability and accuracy [32].

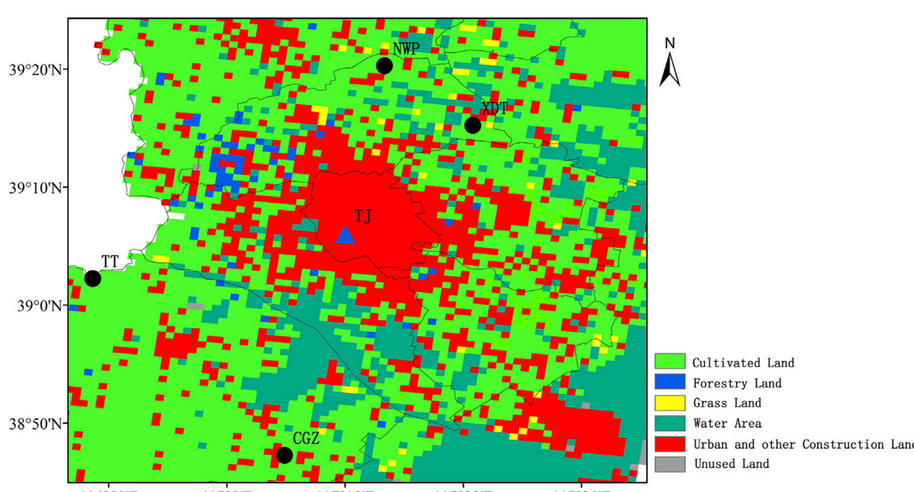

Fig. 3. Distribution of Land Use/Land Cover in study area.

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

	Station code	Station name	Longitude (°E)	Latitude (°E)	Altitude (m)
Urban station	54517	TJ	117.20	39.07	2.2
Rural station	A2565	TT	116.81	39.04	1.0
Rural station	A2566	CGZ	117.08	38.79	1.0
Rural station	A3405	NWP	117.22	39.34	1.0
Rural station	A3465	XDT	117.35	39.25	1.0

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

$$\begin{cases} I_N = K_n I_0 \\ K_n = A_1 A_2^{A_3 A_2^{-A_4 K_t}} \\ K_t = \frac{I_h}{I_0 \cdot \sinh} \\ A_1 = -0.1556\sin^2 h + 0.1028\sinh + 1.3748 \\ A_2 = 0.7973\sin^2 h + 0.1509\sinh + 3.05 \\ A_3 = 5.4.07\sin^2 h + 7.2182 \\ A_4 = 2.990 \end{cases} \quad (3)$$

where I_N is the direct normal irradiation, I_0 is solar constant and h is solar altitude.

In this study, the generic residential and office buildings were used to acquire the heating loads. The building design parameters used for the TRNSYS simulation included the building envelope, indoor design condition, internal load density, and window-to-wall ratio and so on, which were determined according to the JGJ26-2010 standards for residential buildings and GB 50189-2005 standards for office buildings, respectively. The key building design parameters considered are summarized in Table 2.

3. Results

3.1. Variation characteristics of climatic factors during heating periods

3.1.1. Daily variation

The daily variation of the climatic factors, i.e. UHII, absolute humidity, and wind speed, in urban and rural areas, as well as the difference of each climatic factor between urban and rural areas, during the heating period are shown in Fig. 4. It can be seen from the figure that the daily variation in the urban and rural temperatures have the same trend. UHI phenomenon appeared in the heating periods in the last ten years, with an average UHII of 2.1 °C. The strongest UHII occurred from late December to late January, with the highest value of 2.8 °C (January 9). The temperature showed a low value on January 22–23. Strong cold waves appeared on January 22–23 in 2012, 2016, and 2018, resulting in a sharp drop in temperature. During the heating period, the absolute humidity in the urban areas was a little smaller than that in rural areas: the average value in the urban areas was 2.46 g/m^3, while that in the rural areas was 2.52 g/m^3. The wind speed were small in urban areas and large in rural areas. The average daily wind speed in the urban areas was 1.4 m/s, while that in the rural areas was 2.4 m/s.

3.1.2. Heating loads response to climatic factors

We analyzed the correlation between the differences of the heating loads and the differences of climatic factors (i.e. temperature (UHII), absolute humidity (△AH), and wind speed (△W)) between urban and rural areas during the heating period in residential and office buildings, respectively, and the results are shown in Table 3. The UHII entered into the regression model among all climatic factors in residential (R^2 = 0.768) and office (R^2 = 0.704) buildings. The UHII explained 76.8% and 70.4% of the variations of the heating load in residential and office buildings, indicating that UHII was the predominant factor in the heating loads of the residential and office buildings. That is, the heating loads of residential and office buildings were dominantly affected by UHII.

3.2. Impact of UHI on the variations in the residential and office building's heating loads

3.2.1. Residential buildings

(1) Daily variation in residential buildings' heating load
The daily variations in the residential buildings' heating loads in urban and rural areas during the heating period are shown in Fig. 5 and Table 4. The variation trend of the heating load in urban areas was similar to that in rural areas: generally, a single peak distribution. The average daily heating loads were 568.7 × 10^{-3} and 632.7 × 10^{-3} kWh/m^2 in urban and rural areas, respectively, indicating that they were 10.1% less in urban areas than in rural areas (Fig. 5a). High

Table 2
Design parameters of residential and office buildings used in this study.

Building type	Building envelope [W/(m^2 °C)]			Thermal inertia index			Window-to-wall ratio			
	Wall	Roof	Window	Wall	Roof	Floor	East	South	West	North
Residential	0.60	0.45	2.50	4.00	4.50	3.50	0.28	0.41	0.28	0.41
Office	0.60	0.55	2.30	6.50	4.00	3.00	0.06	0.38	0.06	0.51

Building type	Indoor design condition (winter)			Internal load density			Solar radiation absorption coefficient	
	T [°C]	RH [%]	ACR [m^3/h]	Occupancy [m^2/person]	Lighting [W/m^2]	Equipment [W/m^2]	Wall	Roof
Residential	18	35	30	32	5	5	0.48	0.74
Office	20	35	30	6	10	13	0.50	0.69

Note: HTC, heat transfer coefficient; T, Temperature; RH, Relative humidity; ACR, Air change rate.

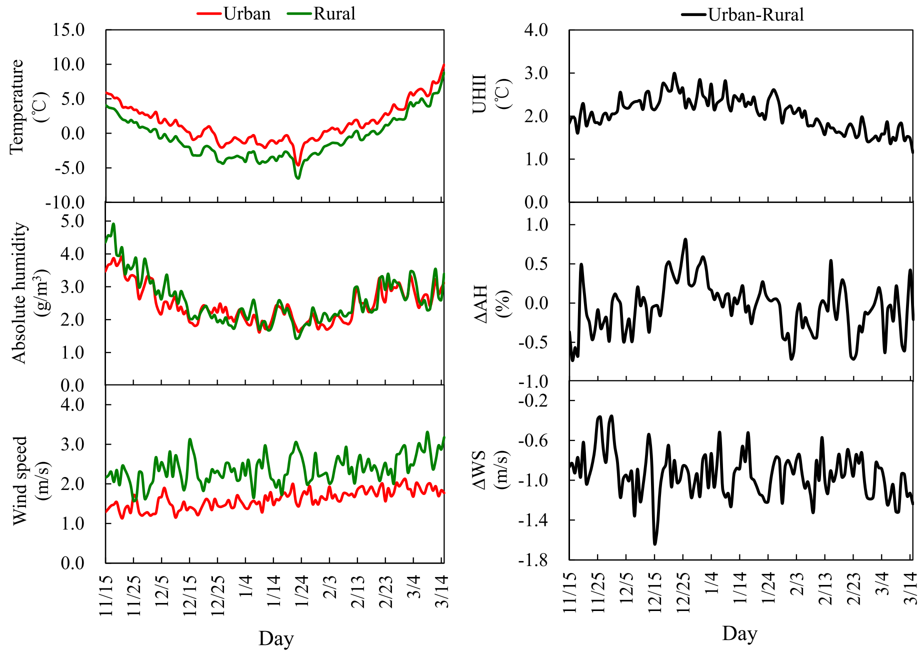

Fig. 4. Daily variations in temperature, absolute humidity, and wind speed, and their difference between urban and rural areas during the heating period.

Table 3
Multivariate regression on daily (n = 1089) heating load differences for residential and office buildings against the climatic factor differences.

Residential buildings	Model 1	Office buildings	Model 1
	−40.402 × UHII		−35.463 × UHII
Constant	19.740	Constant	8.700
R^2	0.768***	R^2	0.704***

Note: R^2, the coefficient of determination; ***, indicated significance $P < 0.001$; UHII, the difference of temperature of urban and rural; △AH, the difference of absolute humidity of urban and rural; △WS, the difference of wind speed of urban and rural.

loads in both urban and rural areas were observed from December 24 to January 26 of the following year, and the average load in urban areas was 10.3% lower than that in rural areas. Low loads were observed from March 11 to 15, when the average load in urban areas was 11.0% lower than that in rural areas (Table 4). According to the correlation analysis between UHII and the difference in the heating load, the daily heating load of residential buildings decreased by 34.2 × 10^{-3} kWh/m^2 every 1 °C increase in UHII (Fig. 5b).

(2) Hourly variation in residential buildings' heating loads

The hourly variations in the heating loads of residential buildings in urban and rural areas are shown in Fig. 6 and Table 5. The average hourly loads were 23.7 × 10^{-3} and 26.3 × 10^{-3} kWh/m^2 in urban and rural areas, respectively, during the heating period. The 24 h load in buildings in both urban and rural areas showed a single peak distribution pattern (Fig. 6a). The heating loads were high at night and low in the daytime and always lower in urban areas than in rural areas. There were two stable periods and two sharply changing periods. A smooth period of the high load was observed from 18:00 on one day to 07:00 the next day: during this period, the load in urban areas was 11.5% lower than that in rural areas (Table 5). The other smooth low load period was from 11:00 to 15:00, when the load in urban areas was 4.2% lower than that in rural areas. The two sharply changing periods included periods of fast increase from 15:00 to 18:00 and fast decrease from 07:00 to 11:00. For every 1.0 °C increase in UHII, the hourly heating load of the residential buildings decreased by 1.3 × 10^{-3} kWh/m^2 (Fig. 6b).

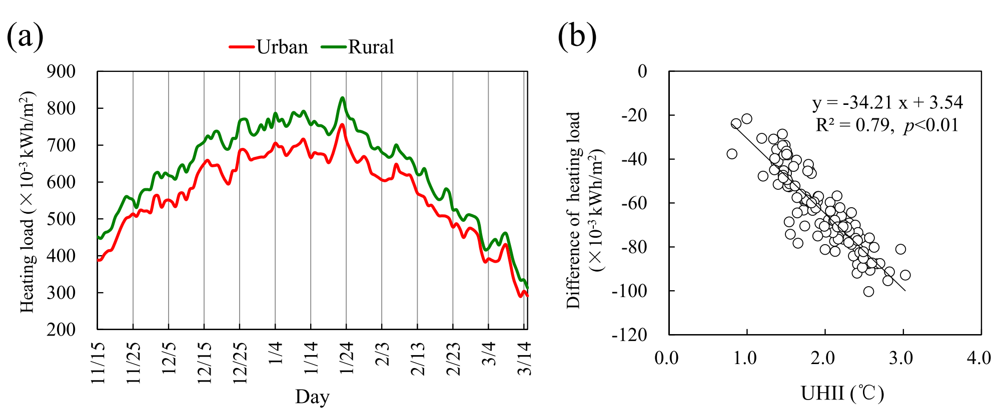

Fig. 5. Daily variations in the heating load of residential buildings and correlation between the heating load and UHII.

Table 4
High/low load periods and average daily loads of residential buildings.

	Urban	Rural	Percentage
High load period	December 23 to January 26 of the following year	December 24 to January 26 of the following year	
Average daily high load ($\times 10^{-3}$kWh/m^2)	683.5	761.8	10.3%
Low load period	March 11 to 15	March 11 to 15	
Average daily low load ($\times 10^{-3}$kWh/m^2)	307.4	345.4	11.0%

(3) Hour-day distribution of the heating load of residential buildings
The variations in the heating loads of residential buildings during heating period can be seen clearly in Fig. 7. The distributions of urban and rural heating loads were generally similar. A maximum heating load period in urban and rural areas was observed at approximately 05:00–07:00 on the 50–70th day (i.e. from late December to late January in the following year; Fig. 7a, b); this was also the period in which there was the maximum difference between urban and rural heating loads (Fig. 7c). Low heating loads were observed mainly at noon every day, especially at the beginning and end of the heating period (i.e. November and March, respectively). The maximum hourly loads were 38.9 $\times$ 10^{-3} and 43.1 $\times$ 10^{-3} kWh/m^2 in urban and rural areas, respectively, and appeared at 06:00 on the 70th day (January 23) of the heating period. The minimum hourly loads were 3.5 $\times$ 10^{-3} and 3.7 $\times$ 10^{-3} kWh/m^2 in urban and rural areas, respectively, and appeared at 13:00 on March 13 (Fig. 7a, b).

3.2.2. Office buildings

(1) Daily variation in office buildings' heating loads
Fig. 8 and Table 6 show the daily variations in the office buildings' heating loads in urban and rural areas during the heating period. All the heating loads in urban and rural areas showed a similar trend with a single peak. The average daily heating loads were 799.9 $\times$ 10^{-3} and 864.8 $\times$ 10^{-3}kWh/m^2 in urban and rural areas, respectively, which indicate that they were 7.5% lower in the urban areas compared to the rural areas (Fig. 8a). As can be seen from Table 6, the high-load period in both urban and rural areas was observed from December 25 to January 29 of the following year. The low-load period was observed from March 11 to 15, when the average load in the urban areas was 7.6% lower than that in the rural areas. The daily heating load of office buildings in the urban area decreased by 27.7 $\times$ 10^{-3}kWh/m^2 every 1 °C increase in UHII (Fig. 8b).

(2) Hourly variation in office buildings' heating loads
The average hourly loads of office buildings were 33.3 $\times$ 10^{-3} and 36.0 $\times$ 10^{-3} kWh/m^2 in urban and rural areas during the heating period from 2009 to 2018, respectively. Different from the residential buildings, the heating loads of office buildings were large at daytime and low at night and were smaller in urban areas than in rural areas (Fig. 9a). The loads were very low between 21:00 and 4:00 the next day in urban and rural areas, and the two curves almost coincide. The high-load period was observed from 07:00 to 19:00, when the load in the urban areas was 6.4% lower than that in rural areas (Table 7). The heating loads increased sharply from 04:00 to 07:00 and decreased sharply from 19:00 to 20:00. For every 1 °C increase in UHII, the hourly heating load of office buildings in urban areas decreased by 0.6 $\times$ 10^{-3} kWh/m^2 (Fig. 9b).

(3) Hour-day distribution of office building heating load
The hour-day distribution of the office buildings' heating loads is shown in Fig. 10. We did not consider the loads in the period from 20:00 to 07:00 the next day owing to their small values. The maximum heating load period was from 07:00 to 11:00 on the 30th–70th day (i.e. from December 14 to January 23 of the following year) of the heating period in urban areas and on the 20th–100th day (i.e. from December 4 to February 23 of the following year) of the heating period in rural areas (Fig. 10a, b). The peak period was also the period of maximum difference between urban and rural heating loads (Fig. 10c). The other high load period was from 17:00 to 19:00, but, in this period, the heating leads were weaker than those in the period from 07:00 to 11:00 (Fig. 10c). The low heating load period was the same as that of residential buildings. The maximum hourly loads were 81.0 $\times$ 10^{-3} and 85.5 $\times$ 10^{-3}kWh/m^2 in urban and rural areas, respectively, which were observed at 07:00 on the 70th day (January 23) of the heating period. The minimum hourly load was observed at 13:00 on March 13 (Fig. 10a, b).

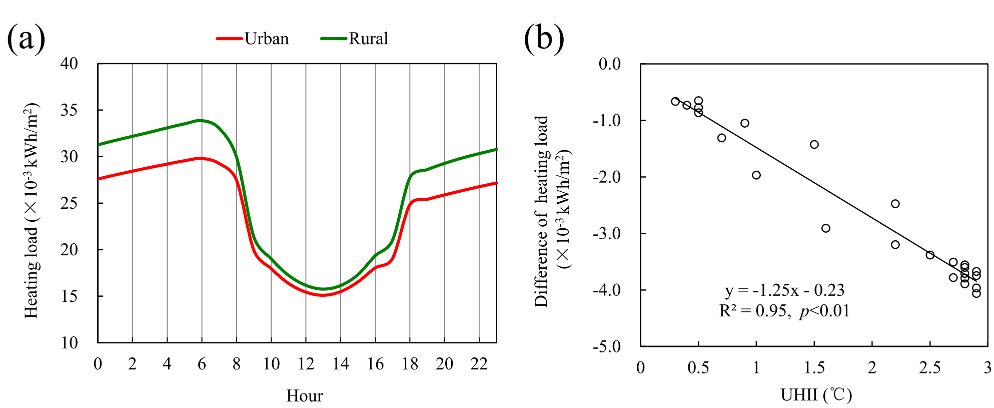

Fig. 6. Hourly variations in the diurnal heating loads of residential buildings in the urban and rural areas.

Table 5
High/low load periods of the diurnal cycle and average hourly loads of residential buildings.

	Urban	Rural	Percentage
High load period	18:00 ~ 07:00 the next day	18:00 ~ 07:00 the next day	
Average hourly high load ($\times10^{-3}$kWh/m^2)	27.7	31.3	11.5%
Low load period	11:00 ~ 15:00	11:00 ~ 15:00	
Average hourly low load ($\times10^{-3}$kWh/m^2)	15.8	16.5	4.2%

4. Discussion and conclusions

The acceleration of urbanization in China has enhanced the UHI effect, which has a significant impact on the energy consumption of buildings, particularly in terms of heating and cooling [22,33]. The spatial distribution of UHI in cities is not homogeneous [18,34], resulting in a difference in the energy consumption demand between urban areas and the countryside. Accordingly, a clearer understanding of the impact of UHI on the energy demand in urban and rural areas is the basis for controlling heating and cooling to reduce energy consumption.

UHI also affect other meteorological factors, which, in turn, affect the energy consumption [20,27]. Studies indicated that the surface UHI intensity has linearly increased in 155 cities across China over the past 30 years [35], which has an interaction with the frequent heat wave in summer [36,37]. We found the UHI phenomenon was very apparent in the past ten years in Tianjin and found that the highest average daily UHII was 2.8 °C in winter. The strong UHI was comparable to those reported for Beijing City [18,38]. The high UHII are related to the rapid development of the city and the high-density buildings in urban areas, as well as the dry climate of winter and the anthropogenic heat emission [20,39]. Moreover, The average daily absolute humidity in urban areas was found to be a little lower than that in rural areas, whereas the wind speed in rural areas was found to be higher than that in urban areas. A correlation analysis between building loads and meteorological factors showed that UHII was the predominant factor in the heating loads of residential and office buildings.

The load of a building is defined as the amount of heat that needs to be added or removed to maintain a comfortable indoor temperature [40]. In general, UHI reduce a building's heating energy consumption and increase its cooling energy consumption [41,42]. In this study, the daily and hourly heating loads of residential and office buildings were evaluated quantitatively.

Because the temperature in urban areas is higher than that of rural areas due to the UHI in winter, people have a lower heat demand in urban areas than in rural areas. Compared with the rural areas, the daily heating load of residential and office buildings in urban areas has decreased by 10.1% and 7.5% during the heating period of the past ten years in this study, respectively. This trend is consistent with the findings of Ding et al. [43], who reported that the residential building load decreased under the strong UHI effect in Qingdao, a city located in the seaside in North China. We also

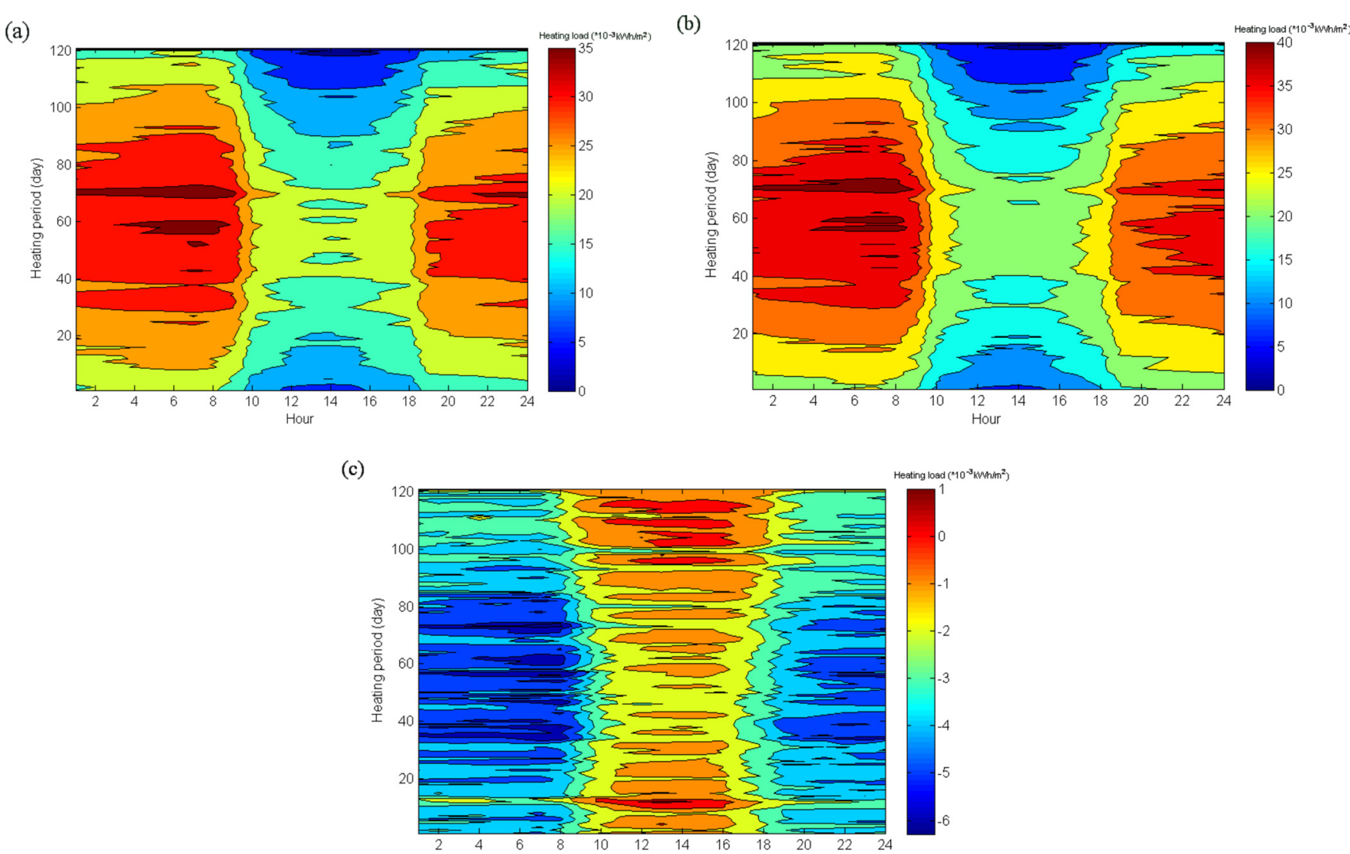

Fig. 7. Hour-day distribution of heating loads of residential buildings in (a) urban and (b) rural areas, and (c) difference between urban and rural heating loads. Note: November 15th was the first day and March 15th of the following year was the last day of the heating period. The same for figures below.

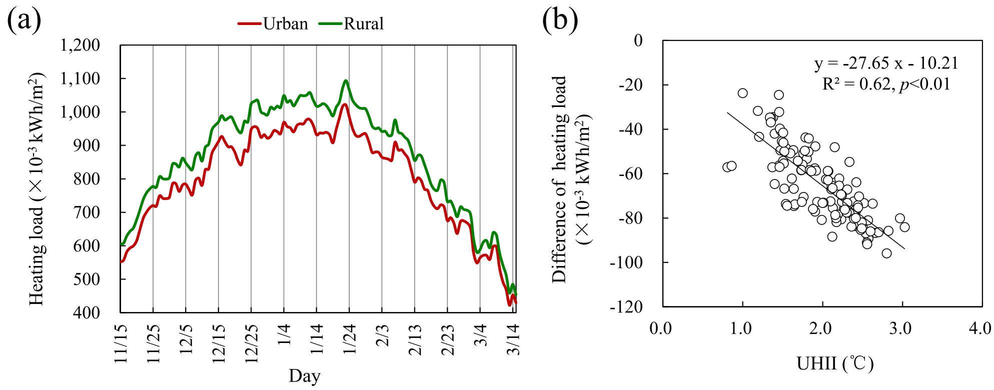

Fig. 8. Daily variations in the heat load of office buildings and correlation between the heating load and UHII.

Table 6
High/low load periods and average daily loads of office buildings.

	Urban	Rural	Percentage
High load period	December 25 to January 29 of the following year	December 25 to January 29 of the following year	
Average daily high load ($\times10^{-3}$kWh/m^2)	950.3	1026.9	7.5%
Low load period	March 11 to 15	March 11 to 15	
Average daily low load ($\times10^{-3}$kWh/m^2)	453.0	490.0	7.6%

found that for a 1.0 °C increase in UHII, the daily heating load of residential and office buildings decreased by 34.2 $\times$ 10^{-3} and 27.7 $\times$ 10^{-3} kWh/m^2, respectively. A previous study showed that the heat loads of residential and office buildings in Guangzhou City decreased by 1.22 and 0.99 kWh/m^2, respectively, for every 1.0 °C increase in UHII [44]. The reason for the difference with our results may be related to the location of the two cities. Tianjin is located in cold climate zone in northern China, while Guangzhou is located in hot summer and warm winter climate zone in southern China; the higher heating demand in cold climate zone (Tianjin) results in a much larger heating load.

Lee et al. [45] showed that the UHI effect increased the minimum temperature at night in urban areas, which would be beneficial for energy saving in urban areas. In this study, the nighttime heating load of residential buildings in urban areas was higher than that in rural areas, which is consistent with the results of Lee et al. [45]. The daily heating loads of residential and office buildings were found to be characterized by a consistent single-peak distribution in both urban and rural areas. The urban and rural heating loads of residential buildings were strong at night and weak at daytime; however, the heating loads of office buildings were strong at daytime and weak at night. The period of high load was observed between late December and late January of the following year on both types of buildings. During this period, people have a higher demand for heating, especially during cold weather events. Therefore, special attention should be paid to increase the heat provided at this time.

The 24 h variation in the heating load was found to have different patterns in residential and office buildings. In urban and rural areas, the period from 18:00 on one day to 07:00 the next day was the high load period for residential buildings, whereas the period from 07:00 to 19:00 was the high load period for office buildings. This may be because demand for heating in residential buildings was higher from one night to the next morning, but that in office buildings was the highest in the daytime. Furthermore, the peak heating load of residential buildings in urban and rural areas was observed at 05:00–07:00, which was also the period with the largest difference between urban and rural heating loads. The low load period occurred at noon and in the afternoon. Liu & Ren [46] studied the characteristics of the heating intensity in Harbin using the degree-hours method. They found that the average hourly heating intensity in Harbin was the highest at 06:00 and the

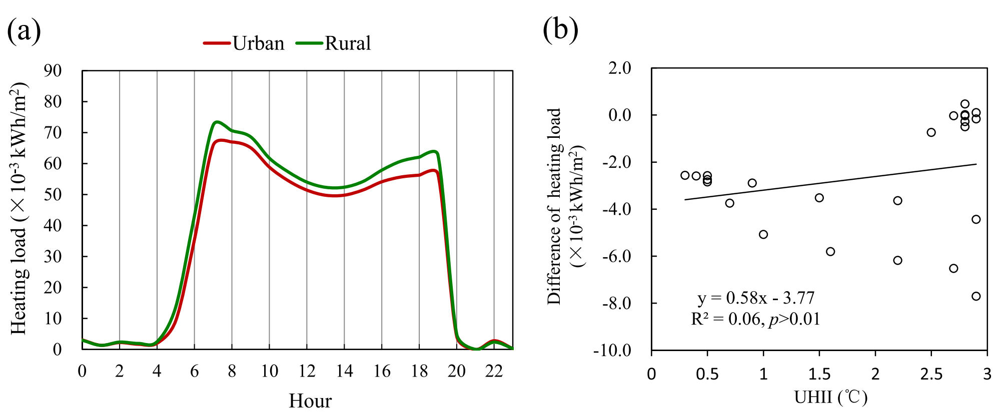

Fig. 9. Hourly variations in the diurnal heating loads of office buildings in the urban and rural areas.

Table 7
High/low load periods of the diurnal cycle and average hourly loads of office buildings.

	Urban	Rural	Percentage
High load period	07:00 ~ 19:00	07:00 ~ 19:00	
Average hourly high load ($\times 10^{-3}$kWh/m^2)	56.7	60.6	6.4%
Low load period	20:00 ~ 04:00 the next day	20:00 ~ 04:00 the next day	
Average hourly low load ($\times 10^{-3}$kWh/m^2)	2.0	2.1	4.8%

lowest at 14:00, which is consistent with the results of this study. For office buildings, the peak load was observed at 07:00–11:00 in both urban and rural areas and the load difference between the two areas was the largest when strong UHI occurred. Urban areas may not need as much heating as rural areas to meet demands for heating during peak-load periods. Accordingly, urban and rural heating should be controlled differently during these periods to utilize the UHI effect to save energy. Although UHI would decrease the heating load of buildings in urban areas in cold climate zones, UHI should not be allowed to develop uncontrollably especially in some southern cities due to the possible effect on cooling load during summertime. New measures to save energy in buildings and reduce their carbon emissions (e.g. application of new energy-saving building materials, clean energy, and green building techniques) should be considered to develop eco-friendly cities.

CRediT authorship contribution statement

Fanchao Meng: Conceptualization, Data curation, Methodology, Formal analysis, Validation, Writing - original draft, Writing - review & editing, Funding acquisition, Project administration. **Jun Guo:** Conceptualization, Investigation, Supervision, Writing - review & editing, Funding acquisition. **Guoyu Ren:** Writing - review & editing, Methodology, Formal analysis. **Lei Zhang:** Data curation, Methodology, Validation. **Ruixue Zhang:** Methodology, Software.

Declaration of Competing Interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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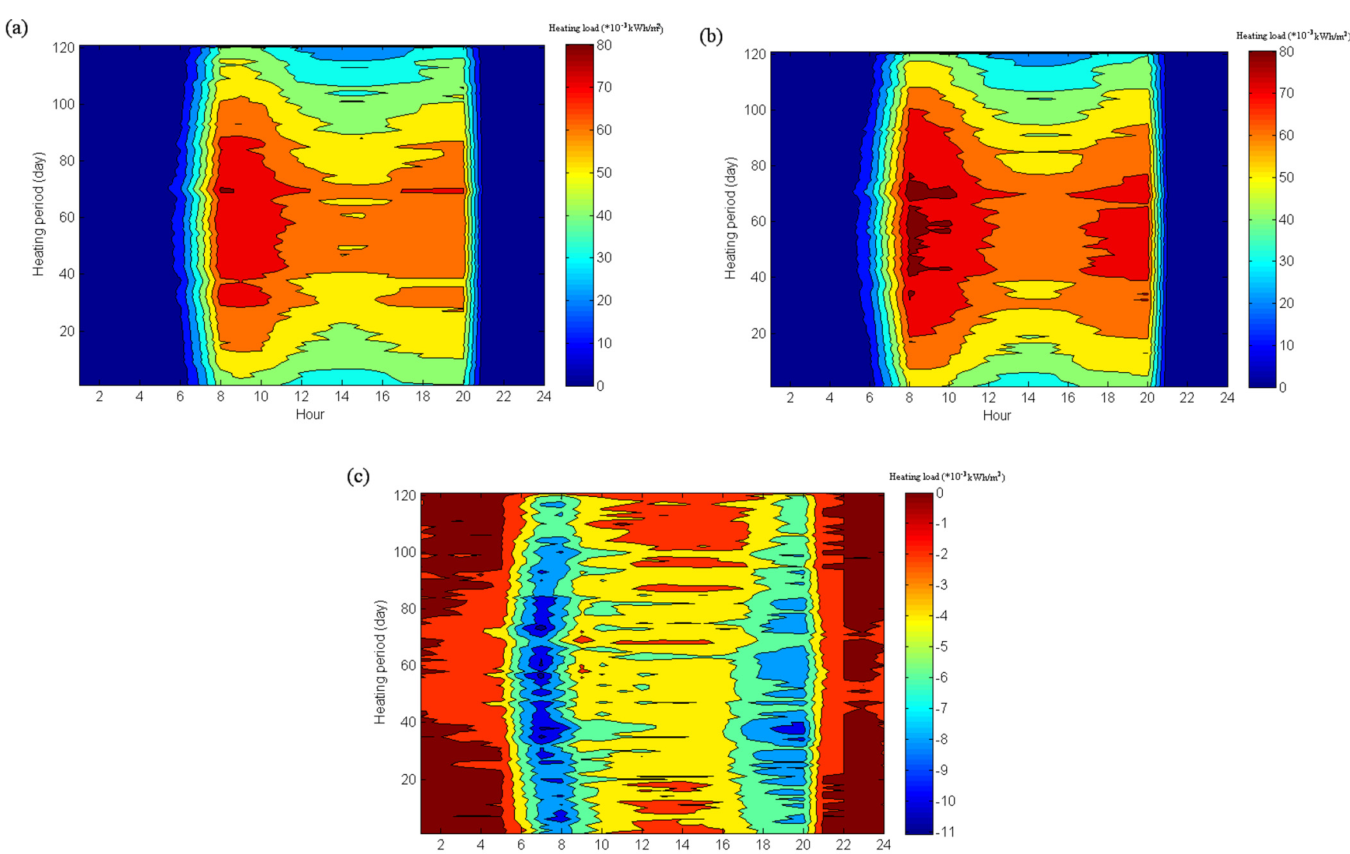

Fig. 10. Hour-day distribution of heating loads of office buildings in (a) urban and (b) rural areas, and (c) difference between urban and rural heating loads.

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