Impact of the urban heat island on residents' energy consumption: a case study of Qingdao

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Abstract. This paper examines impact of urban heat island on residents’ energy consumption through comparative analyses of monthly air temperature data observed in Qingdao, Laoshan and Huangdao weather stations. The results show effect of urban heat island is close related with urbanization speed. Recently, effects of urban heat island of Laoshan and Huangdao exceed that of Qingdao, consistent with rapid urbanization in Laoshan and Huangdao. Enhanced effect of urban heat island induces surface air temperature to rise up, further increase electricity energy consumption for air conditioning use in summer and reduce coal consumption for residents heating in winter. Comparing change of residents’ energy consumption in summer and winter, increments in summer are less than reduction in winter. This implicates effect of urban heat island is more obvious in winter than in summer.

1. Introduction
Urbanization obviously impacts on local climate. Howard, a British scientist, paid attention to temperature was higher in London than that in the suburbs in 1883[1]. In 1958, Manley first proposed the concept of the Urban Heat Island (UHI)[2]. Since then, a large number of observations and studies have shown that the UHI is a common phenomenon in the whole world, regardless of city size, latitude, location either coastal or inland, and terrain[3-5]. Whatever the environment, there are always some urban heat island effects of differing degrees. The urban temperature is usually higher than that of the suburbs, especially when it is sunny and windless[6, 7].The UHI is one of the most typical manifestations for a city of climate change caused by urbanization. The process of urbanization leads to increase in local temperatures. The UHI is closely related to city size, population density, energy consumption and building density[8-10], and may have a significant impact on public health, air quality and energy consumption[11,12].

Large cities in North China also show an obvious heat island effect. Through an analysis for 95 countries of national basic/reference station temperature observation data, from 1961 to 2000, Ren found that the UHI warming rate is 0.11°C/10a[13]. The UHI has had a significant influence on the energy consumption of urban residents in North China. Through the analysis of Shi et al, we find that compared to the 1960s, the average annual amount of heating in East China has decreased by 7.1% while the amount of cooling has increased by 16.7%, in the first 7 years of the twenty-first century[14]. Against this backdrop, this study taking Qingdao as example, which is one of the fastest growing economies in the North china with extremely high rate of urban expansion and a rapid increase in electricity consumption. This study aims to quantify the effects of the UHI in the on local energy consumption by taking into consideration the air temperature and energy consumption.
2. Date resource and study area

2.1. Date resource
The temperature data is the monthly mean temperature provided by the Qingdao meteorological station. In this paper, winter refers to the period from December to February, while summer refers to the period from June to August. The data for population and construction of Qingdao are provided by the statistical yearbook and statistical bulletin of the Qingdao Bureau of Statistics. Electricity consumption data is provided by the Qingdao power supply company.

2.2. Study area
Figure 1 shows the study area. This paper contrasted the strength of the UHI in Qingdao station which located in the urban area, and the Laoshan station which located in the suburb, and the Jiaonan station which is an emerging city located in seaside. Comparing change of residents’ energy consumption in summer and winter caused by the UHI, we can assess the impact of the UHI in Qingdao. It should be noted that this evaluation was a case study of Qingdao, and the results are applicable only to the Qingdao metropolitan area.

3. Methods

3.1. The calculation methods of UHI in Qingdao
Qingdao station and Jiaonan station are both about 1km distant from the shore, so the degree of the influence of the oceans upon these two station temperatures can be thought of as being the same. To calculate the warming range caused by UHI in Qingdao, we can eliminate the influence of the ocean by comparing the mean seasonally temperature of the two stations. The method is as follows:

\[ \Delta T = \bar{T}_q - \bar{T}_j \]
\[ T_U = \Delta T - \Delta T^{\text{avg}} \]

Here \( \Delta T \) is the mean seasonally temperature of Qingdao, \( \bar{T}_q \) is the mean seasonally temperature of Qingdao station, \( \bar{T}_j \) is the mean seasonally temperature of Jiaonan station, and \( T_U \) is the warming range caused by the UHI over the years.

3.2. The calculation methods of energy consumption of UHI in winter
The energy consumption generated by the temperature change in Qingdao in winter is mainly central heating of coal, and at present, the consumption of winter coal in Qingdao is also dominated by central heating. Moreover, there is no major technological change in the coal-fired central heating in Qingdao in recent years, and thus the change in energy consumption due to the heat island effect in Qingdao in
winter can be calculated directly from statistics of the change in the coal-fired amount in winter. The calculation method of total standard coal consumption in Qingdao in winter is as follows

\[ TSC = k_W T_U S \]  

where \( TSC \) is total standard coal consumption (t), \( k_W \) is standard coal consumption coefficient for heating 1 degrees per 10000 square meters of heating \((t/10000 \text{ square meters})\), \( S \) is the central heating area in Qingdao city.

3.3. The calculation methods of energy consumption of UHI in summer

\( L \), the change of residents’ electricity consumption in summer, is caused by both \( L_t \) which represents the long-term change of electricity consumption caused by economic development and \( L_P \) which represents the meteorological electricity consumption caused by the change of meteorological factors. The meteorological load is the difference between the total load and the long-term change of the load, with the mathematical formula expressed as:

\[ L_P = L - L_t \]  

In order to compare the energy consumption difference of winter and summer caused by the urban heat island in Qingdao, this study converts the increase of air-conditioning refrigeration electricity consumption due to the summer heat island into the standard coal weight to compare with the winter coal reduction due to the UHI. According to the energy consumption conversion coefficient provided by the National Development and Reform Commission, the average coal consumption for power supply per kWh of the thermal power plant is 360 g standard coal. The conversion formula between the electric energy and standard coal is as follows:

\[ TSC = T_U k k_s \]  

\( k \) is the converted electric energy coefficient of every ton of standard coal \((t/\text{million kWh})\), \( k_s \) is acquired from the statistical relation between meteorological power load, \( L_P \), and temperature variations, which means the increase in meteorological power load with the rise in each \(^\circ\text{C}\) in Qingdao in summer \((\text{million kWh/\^\circ\text{C}})\).

4. Results and discussion

4.1. Urban development in Qingdao

From the time of the onset of China’s reform and opening to the outside world, the economic development and urban construction of Qingdao increased rapidly. In 2002, compared with 1991, the population of Qingdao increased by 23.2% (excluding the floating population), and the urban area increased by 25.0%. During the 21st century, the floating population has been growing rapidly. As an economically developed cities, the floating population is growing much faster than the permanent population in Qingdao. At the same time, with the acceleration of urbanization and the vigorous development of the real estate market, the Qingdao urban area is increasing rapidly, and the construction area in 2012 has expanded by 157% compared with 2003 (Figure 2).

The increase in urban buildings, the increase of hardened city underlying surfaces and roughness, the urban population increase, industrial concentration, the decrease in green space and water areas, urban wind speed decreases, and so on, are the main factors affecting the form of the UHI[15]. In general, the temperature of asphalt and cement is more than ten degrees warmer than the air temperature, which has the obvious effect of absorbing solar radiation and storing energy[16]. Through the analysis of Pang et al, we find that the UHI in Qingdao is significant, especially in winter. There is a good correspondence between the urbanization process and the enhancement of the heat island effect[17].
4.2. The urban heat island effect in Qingdao

It is important to analyze the urbanization process of Qingdao, Laoshan station, Jiaonan station. The location of Laoshan station (Figure 2), Licun, was formerly the Laoshan County town, which developed slowly before the process of reform and openness. After the process of reform and opening up, the urbanization development of Licun made rapid progress and became a district of the city. Around Qingdao station, located in Shinan District, nearby urban construction has caused little change as yet.

The influence of the heat island effect on the new urban area is more significant than that of the old district. Compared with the annual average temperature of Qingdao station, the difference of warming rate of Qingdao station, Laoshan station, Jiaonan station is not significant before 1980, while the warming range of Laoshan station became significantly higher than that of Qingdao station after 1980, and moreover, the warming rate of Laoshan station is showing a tendency to accelerate even further (Figure 3). The warming rate of Jiaonan station, which located in Huangdao District, is lower than that of Qingdao.

The urban temperature of the big cities has been between 0.3 ~ 0.7 °C higher than that of nearby country temperatures in the 1980s[18], while the urban temperature of Qingdao station is only 0.07 °C higher than that of Laoshan station. Thus, the Qingdao heat island effect is weak compared with the national situation. It should be noted that the influence of nearby oceans upon climate will weaken the UHI[19].

From the mean seasonally temperature of Qingdao station subtract that of Jiaonan station, which should not be affected by global climate change and marine influence. From this difference value, subtract a seasonal temperature difference without the influence of any difference in geographical position, yielding warming range caused by UHI in Qingdao. According to this analysis, the UHI is more obviously in winter. The temperature change in summer is irregular, and from the inter-annual point of view, the positive and negative offsets are larger, and the trend is less obvious than in winter (Figure 4).
4.3. Analysis of residents’ energy consumption in Qingdao

Refer to heating energy consumption data in the statistical yearbook published by the Qingdao Bureau of Statistics website (http://www.stats-qd.gov.cn/statsqd/index/index.shtml), then compare to winter.
average temperatures in Qingdao to analyse the strength of the UHI. As can be seen from Figure 5, the basic trend of winter heating energy consumption and winter average temperature is that as the temperature rises, the energy consumption decreases.

![Figure 5. The relationship between residents’ heating energy consumption and winter average temperature (Year: 2000-2010)](image)

Increased energy consumption by air conditioners is frequently identified as a serious impact of UHIs, and large-scale energy-evaluation studies have investigated the temperature sensitivity of energy consumption to predict energy demand and evaluate climatic conditions [20-22]. Deducting the electricity consumption caused by economic development from daily electricity consumption, we can obtain the residents’ meteorological electricity consumption $L_P$. In summer, the relationship between $L_P$ and the temperature is that as the temperature rises beyond 20°C, power consumption begins to rise exponentially, especially after temperature exceeds 29°C when the rising trend becomes even more obvious (Figure 6).

![Figure 6. The relationship between residents’ cooling energy consumption and average temperature (Year: 2005-2013)](image)

4.4. Using Qingdao station climate change as a baseline to calculate residents’ energy consumption
To calculate the effect of UHI, we filter out the impacts of global climate change by using the method described in 3.1. Considering that the urbanization process of Qingdao has accelerated since the 1990s, using the temperature data from 1961 to 1990, the average rate of change of temperature caused by the UHI was 0.72°C/10a in winter, and it was 0.08°C/10a in summer.
The winter average temperature was 0.1 °C, then 10 years later it increased to 0.82 °C, the calculation being based on average heating coal consumption in Qingdao, saving 22 tons of standard coal / 10000 square meters per year in comparison with the coal consumption at 0.1 °C, and estimating the total heating area in Qingdao as 120 million square meters, this implies a saving of 260000 tons of standard coal a year by the 10th year.

Using 25 °C as the baseline of electricity consumption during summer, Qingdao electricity consumption increases by 1361.6 million kWh in its 10th year, or about 4901.76 tons of standard coal.

4.5. Using Laoshan station climate change as the baseline to calculate residents’ energy consumption
While the temperature of Qingdao station is clearly regulated by proximity to the ocean, Laoshan station is relatively far from the ocean and thus is less affected by the ocean. To calculate the heat island effect for Laoshan station, we can use Qingdao station as the baseline to filter the effects of global climate change. The average change rate of temperature caused by the UHI in winter was 0.8°C /10a, and in summer is 0.7°C/10a. Qingdao heating saved 290,000 tons of standard coal a year by its 10th year. Air conditioning power consumption in the summer increased to 11914 million kWh, or about 42890.4 tons of standard coal.

The UHI caused winter heating energy consumption reduction is greater than the increase in summer cooling power consumption, which means that the heat island effect has the potential to save energy consumption costs of urban residents. However, through the comparison of the energy consumption difference between Qingdao Station and Laoshan Station, it is found that with the increase of heat island, the amount of coal consumed by air-conditioning refrigeration increases, and the energy saving effect of urban heat island in Qingdao area decreases.

5. Conclusions
The urban area of Qingdao is expanding rapidly and has a significant influence upon the UHI. The influence of the heat island effect on the new urban area is more significant than that of the old district, and the heat island effect is more obvious in winter. The results of this study show that total energy consumption is decreased by the effects of the UHI; decreases in warming energy consumption were larger than the increase in cooling-energy consumption. It should be noted that the evaluation method proposed in this paper are applicable only to the Qingdao area because of the differences between urban landforms, construction types, energy saving facilities and so on.

Energy consumption is also an environmental problem and is associated with global warming and the depletion of fossil fuels. we are not recommending that the UHI be actively increased, even if the UHI would decrease local energy consumption. Qingdao, as an important seashore tourist city in the north, must make a full assessment of the city’s energy consumption and select appropriate emission reduction measures cautiously. Measures such as choosing new types of energy-saving building materials, subsidizing energy-conservation enterprises for environmental protection, developing new energy sources to reduce carbon emissions, properly planning urban construction and increasing the green area will be conducive to the construction of eco-friendly city.

Next, we will try to explore the use of thermal remote sensing data and divide different architectural types to build more detailed urban heat island and energy consumption models which could provide more valuable information for developing appropriate policies to address both the UHI and energy use. Continuous efforts are needed to prevent irreversible anthropogenic impacts on the environment.

References
[1] Howard L. 2012 *Cambridge University Press* 1833 348
[2] Manley G 1958 *Quarterly Journal of the Royal Meteorological Society* 84(359) 70-72
[3] Zhao Q, Myint S. W, Wentz E A and Fan, C 2015 *Remote Sensing* 7(9) 12135–12159
[4] Li X, Li W, Middel A, Harlan S L, Brazel A J and Turner B L 2016 *Remote Sensing of Environment* 174 233–243
[5] Zhao Q and Wentz E A 2016 Data 1(1)
[6] Seaman N L, Ludwig F L, Donall E G, Warner T T and Bhumralkar, C. M 2010 Journal of Applied Meteorology 28(8) 760-781
[7] Ulrickson B L 1992 Monthly weather review 120(10) 2264-2279
[8] Estes M, Quattrochi D, Stasiak E, 2003 PUBLIC MANAGEMENT- LAWRENCE THEN WASHINGTON 85(3) 8-12
[9] Rosenzweig C, Solecki W D, Parshall L, Chopping M, Pope G and Goldberg R 2005 Global Environmental Change Part B: Environmental Hazards 6(1) 51-62
[10] Arnfield A J 2003 International Journal of Climatology 26(1) 15-18
[11] Quattrochi D A, Luvall J C, Rickman D L, Estes M G J, Laymon C A and Howell B F 2000 Photogrammetric Engineering and Remote Sensing 66(10) 1195-1207
[12] Stone B, Norman J M 2006 Atmospheric Environment 40(19) 3561-3573
[13] Ren G Y, Chu Z Y, Zhou Y Q, Xu M Z, Wang Y, Tang G L and Guo J 2005 Climatic and Environmental Research 10(4) 701-716 (in Chinese)
[14] Shi J, Chen B D, Cui L L 2011 Plateau Meteorology 30(5) 1415-1421 (in Chinese)
[15] Zhang S Y 2002 Meteorological Monthly 28(10) 18-21 (in Chinese)
[16] Zhou L, Dickinson R E, Tian Y, Fang J Y, Li Q X, Robert K K, Compton J T and Ranga B M 2004 Proceedings of the National Academy of Sciences of the United States of America 101(26) 9540-9544
[17] Pang H J, Gao J, Li C, Sheng L F 2007 Journal of Nanjing Institute of Meteorology 30(4) 524-529 (in Chinese)
[18] Chen L X, Zhou X J, Li W. L 2004 Acta Meteorologica Sinica 62(5) 634-646 (in Chinese)
[19] Qu X S, Yu J M 1993 Journal of the Meteorological Sciences 13(3) 320-326 (in Chinese)
[20] Sailor DJ, Muñoz JR 1997 Energy 22(10) 987-998
[21] Hirano Y, Fujita T 2012 Energy 37(1) 371-383
[22] Radhi H, Sharples S 2013 Applied Energy 112(4) 371-380