

Spatio-temporal pattern analysis of urban thermal environment of different types of cities

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Abstract. Cities with different functions show variable thermal patterns. This study directs at horizontal contrasting the heat island effect of cities and towns in the same latitude. The data source was Landsat TM, by which the thermal infrared bands is used with the algorithm of ARTIS inversion of Heilongjiang Province to acquire the surface temperature of Ha-Qi different types of cities in 1995(1989), 2006 and 2010. In this paper we analyzed the land surface temperature(LST) of temporal, spatial and regional. The results show that a high zone is mainly centralized in the old city and industrial zone. Impervious surface increase leads to temperature rise. Relatively high and low zone fluctuation is due to human activities influence. Climate is one of the key factors to affect the LST, such as precipitation and drought. Through the analysis of urban thermal environment, the process of urbanization can be monitored, to provide accurate information for the quality evaluation of urban thermal environment and heat source survey.

1. Introduction

Since the policy of reform and open door in 1980's, China had accelerated the process of urbanization. The urban heat islands (UHI) effect becomes the focus of scholars. The larger the city scale, the more obvious heat islands effect, and heat islands intensity is greater [1.2]. It was well documented that with the rapid urbanization and population growth, increasing in built-up land and replacing of nature lands with artificial buildings altered surface energy budgets, the hydrological cycle, and could affect local, regional and global climate by changing the surface physical properties [3.4]. Urban expansion has a close relationship with the heat island effect, the thermodynamic characteristics of the underlying surface of the urban region has been largely changed, which also has a certain impact on the global temperature rising [5.6]. Currently studies on UHI effect with remote sensing (RS) for the spatial and temporal scales evolution and distribution law becomes attention hotspot, which mainly pays attention to dynamic change of heat island intensity such as day-night, seasonal distribution as well as spatial distribution [7-10]. However, the analysis of regional difference has not attracted a sufficient attention.

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The development of Ha-Da-Qi Industrial Corridor and urbanization has had a profound impact on urban climate and ecological environment [11].

This paper applied Landsat TM as the basic data source, with the help of remote sensing and geographical information system (GIS), and calculated the land surface temperature (LST) of different functional cities. Harbin and Qiqihar (Ha-Qi) in Heilongjiang Province was used to investigate city's heat islands effect and the spatiotemporal distribution of thermal environment. Two cities can learn from each other by comparing the thermal environmental differences, which provides technical support during the city's construction of ecological environment.

2. Study area

Harbin is located in the belt within $125^{\circ} 42' E$ to $130^{\circ} 10' E$ and $44^{\circ} 04' N$ to $46^{\circ} 40' N$, the capital of Heilongjiang Province. It lies in the east of Songnen Plain, Songhua River winds through the central part of city. Harbin covers an area of $53,100 \text{ km}^2$, with a total of 587.39 million residents. The annual average temperature is 3.2°C , annual precipitation is 400-600 mm. The industrial structure ratio is 14.9:36.8:48.3.

Qiqihar is located in the belt within $123^{\circ} 33' E$ to $124^{\circ} 28' E$ and $47^{\circ} 00' N$ to $47^{\circ} 52' N$, the second largest city of Heilongjiang Province, and laid in the Midwest of Songnen Plain. It covers an area of $43,000 \text{ km}^2$, with a total of 143.9 million residents. The annual average temperature is 3.2°C , annual precipitation is 415 mm. The industrial structure ratio is 24.11:36.55:39.34.

3. Study method

3.1. Data and methodology

Multi-temporal Landsat Thematic Mapper(TM) imageries acquired during 1995 and 2010 were used in this study. All of the images were clear and nearly free of cloud. There are no cloudless images in Qiqihar study area in 1995 and by 1989 instead. The imagery dates of Harbin were 13 September 1995, 27 September 2006, 22 September 2010. While those of Qiqihar were 9 August 1989, 24 August 2006, 2 July 2010, respectively. The City Statistical Yearbook, city and county boundaries and settlements were also collected. The radiometric and geometrical distortions were corrected. The image was extracted by Harbin, Qiqihar administrative region boundaries.

3.2. Retrieval of land surface temperature

- Radiation brightness temperature calculation

$$L_{\lambda} = \text{gain} \times \text{DN} + \text{offset} \quad (1)$$

$$T_6 = K_2 / \ln(K_1 / L_{\lambda} + 1) \quad (2)$$

Where L_{λ} is the radiance of the thermal band pixels, gain is the slope of the radiance/DN conversion function, and offset is the slope of the radiance/DN conversion [12-13]. DN is the digital number of Landsat TM thermal TIR band. Both K_1 and K_2 are pre-launch calibration constants ($K_1 = 60.766(\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1} \cdot \mu\text{m}^{-1})$ 、 $K_2 = 1260.56(\text{K})$).

- Land surface temperature calculation

The temperature values obtained above were referenced to a black body, which is quite different from the properties of real objects. Therefore, the emissivity corrected LST was computed as follows:

$$T_s = \frac{T_6}{1 + (\lambda T_6 / \rho) \ln \varepsilon} \quad (3)$$

Where T_s is the surface radiant temperature in Kelvin (K), T_6 is the black body temperature in Kelvin (K), λ is the wavelength of emitted radiance, herein, $\lambda = 11.5 \mu m$, $\rho = hc / \delta = 1.438 \times 10^{-2} mk = 14380 \mu mk$, $\delta = 1.38 \times 10^{-23} J/k$, $h = 6.626 \times 10^{-34} Js$, $c = 2.998 \times 10^8 m/s$, ε = surface emissivity[14].

- Surface emissivity calculation

In this study, NDVI between 0.157 and 0.721 can use the equation to calculate surface emissivity: $\varepsilon = 1.0094 + 0.047 \times \ln(NDVI)$. And built-up area, water bodies were given the values of 0.923[15], 0.9925[16], respectively.

3.3. Standardization of LST

This paper adopts the robust statistics method to divide the temperature interval, and extract the mean value and standard deviation of the whole region. LST is divided into 5 grades, including high, relatively high, medium, relatively low, and low, respectively.

$$T_s = \frac{T_{si} - \bar{T}_s}{s} \quad (4)$$

Where s is the standard deviation of LST, \bar{T}_s is the mean of LST during the same period, T_{si} is the pixel of LST.

4. Results and discussions

4.1. Temporal changes of the LST

Changes of thermal environmental can be seen from figure 1 of Harbin during the 15 years from 1995 to 2010. For high temperature zone, the extent increased by 61 km² from 1995 to 2006 and 18.6 km² to 2010. Relatively high zone had a growth trend to 2006, the extent increased by 89.6 km² and decreased by 53 km² to 2010 in contrast. In this period, urbanization improved and built-up area expansion. It led to accelerate the high radiation rate such as cement and asphalt increase instead of natural vegetation. Medium zone showed a slow decreasing trend as a whole, the extent decreased by 3.5 km² from 1995 to 2006 and by 18.4 km² to 2010. The reason for this phenomenon is part to relatively high zone and the government pay attention to the other part of urban greening and converted to relatively low zone. For relatively low zone, the extent decreased by 149.3 km² to 2006 and increased by 38.3 km² to 2010. Government occupies the urban green area at the expense of accelerate city construction and then add the artificial afforestation area. For low zone, the extent increased by 2.8 km² from 1995 to 2006 and by 14.1 km² to 2010. Low zone increased mainly because high precipitation in August, 2010, Songhua River water level rose, so that the water area increase. Water is the mainly low LST.

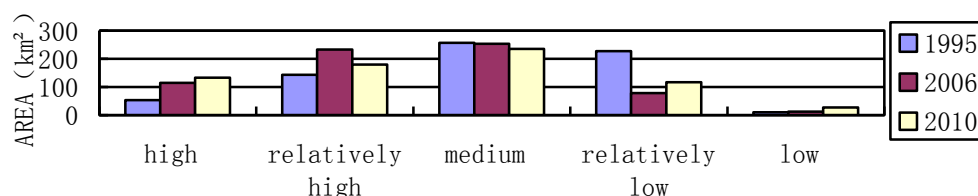


Figure 1. Temporal changes of LST in Harbin from 1995 to 2010

Thermal environment changes of Qiqihar can be seen in figure 2. High zone had a rising trend, the extent increased by 8.6 km² from 1989 to 2006 and then 13.3 km² to 2010. The result indicates that

urbanization accelerated, the impervious layer increased continually, natural vegetation decreased rapidly which were benefit for surface transpiration and evapotranspiration. For relatively high zone, the extent decreased by 89.6 km² to 2006, then it increased by 20.9 km² to 2010. Since the old industrial basis revitalized after 2003, more area were added to the high zone. For medium zone, the extent increased by 5.3 km² to 2006 and then 0.9 km² to 2010. Relatively low zone increased slowly first then decreased rapidly. The extent increased by 8.4 km² to 2006 and decreased by 42.8 km² to 2010. The reasons were due to rapid urban development. Urban constructed at the expense of sacrificing green vegetation area. Low zone area decreased by 8.8 km² to 2006 and increased by 7.5 km² to 2010. It had a trough was caused by the climatic conditions. Drought led to the river border region dry up and point bar increase. As a result, the sand heat absorption capacity increased while low zone decreased. But the whole area didn't change too much.

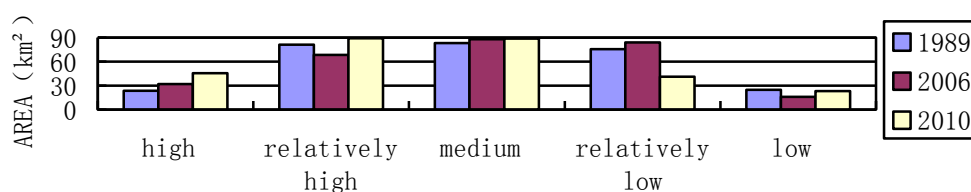


Figure 2. Temporal changes of LST in Qiqihar from 1989 to 2010

4.2. Spatial pattern of LST

4.2.1. Spatial pattern of the LST in Harbin. Figure 3 shows LST of Harbin during 1995-2010. It is clear that spatial extents of urbanization varied significantly among the heat island zone. Most high zone laid in bustling commercial area and high population density areas, industrial heat emissions and along the railway together with the University City construction, transformation of villages which made impervious surfaces, such as cement roads, squares and buildings replace the surrounding green to lift atmospheric temperature. Green construction planning also makes the center part of the high zone and the concentration of heat island decrease. Due to the large scatter, relatively high zone distributed at the high zone, which is mainly found on road side, small residential area and fringe area. The high zone decreased in 2010 which was the result of residential green and shadow area caused by high-rise buildings increased. Medium and low zone was mainly distributed in the banks of river, suburban, small farms and compared with relatively high zone around. Low zone of urban appeared in larger green area such as Botanical Garden, Zhaolin Park, Children's Park, Jianguo Park and both sides of the river. The overall relatively low zone distributed in rivers, paddy fields, large vegetation cover area..

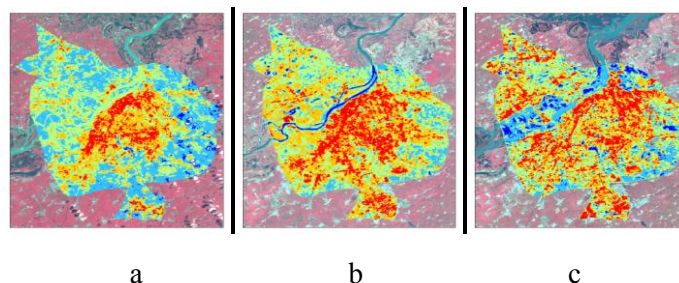


Figure 3. LST classifications of Harbin in 1995, 2006 and 2010

4.2.2. Spatial pattern of the LST in Qiqihar. In 1989, high zone of Qiqihar mainly concentrated in the main city of Jianhua District, Longsha District and Tiefeng District. The city expansion to south from 1989 to 2006, and high zone appeared there. Since the northeastern Unicom Avenue built up, it was

obvious to see the surface temperature increase along the avenue. High zone continued extend to 015 National Highway in north from 2006 to 2010. The extension was basically the same with built-up area. Industrial base of Qiqihar and the location of airport were all in high zones. Relatively high zones mainly distributed in urban center, suburban settlements as well as the surroundings of high zone. The central LST of study area decreased due to bare land covered by vegetation. High and relatively high zone connected into pieces which were basically covering the whole built-up area. Medium and low zones were located in suburbs, bank of rivers and lakes, parks together with vegetation coverage area. Low and relatively low zones of urban center mainly distributed in lake, parks and wetlands.

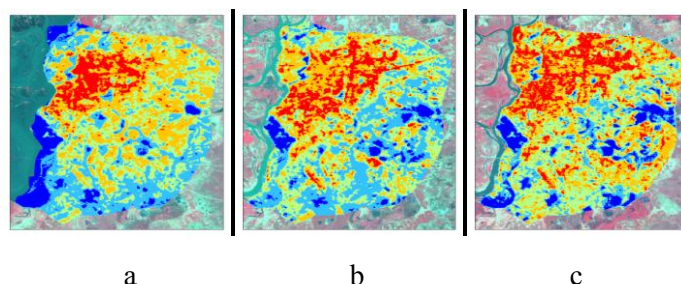


Figure 4. LST classifications of Qiqihar in 1989, 2006 and 2010

4.2.3. Regional collation of LST in Ha-Qi. With the rapid urban development and expansion in 15 years, we can see from figure 1 and figure 2 that high zones in Harbin and Qiqihar were all greatly increased, and they concentrated in the built-up city. The area of medium zone in Harbin had an increase trend, but it was opposite in Qiqihar. The reason for the reverse trend is that Harbin government focuses on city ecological construction which can transfer medium zone to low zone, but Qiqihar pays more attention to the economic development that may lead low to medium zone. Low zone mostly composes of water and larger vegetation coverage area. The rising of Water level in Songhuajiang River caused low temperature zones of Harbin increase in 2010. Qiqihar low zone's reduction in 2006 is the result of drought.

Figure 3 and figure 4 exhibit the relationships between Harbin and Qiqihar. UHI of Harbin expansion is obvious; first of all it develops to southeast, then to north. The expansion of UHI is similar to urban planning of Harbin from 1996 to 2000: urban land develops to south and southeast, forming a palm type extension and group layout. While Qiqihar borders Nenjiang River to the west and 015 National Highway to the north, which will force the development to the south and east. UHI has the same trend with it. Both of the two cities are the start-terminal point of Ha-Da-Qi Industrial Corridor, and the main body of urban economy is industry which mostly in the high zone. UHI of Harbin in 2010 is more fragmentized, while Qiqihar is agglomerative. We should pay more attention to ecological construction in the future.

5. Conclusions

UHI effect concentrated in built-up area in Ha-Qi, which was significantly enhanced and expanded in 15 years. High temperature zones mainly centralized in the old city and industrial zone. Increasing impervious surface leads to temperature rise. High and low zone fluctuation is due to human activities influence. The fluctuations of two cities are not the same because of different development strategy. Climate is one of the key factors affecting the LST, such as precipitation and drought. Low zone increased in 2010 of Harbin is caused by the rise of water level of Songhuajiang River and decreased in 2006 of Qiqihar is for drought. Water can alleviate the heat island effect.

Temporal and spatial variation of thermal environment is thoroughly analyzed by using standardization method and two cities are comparable. Finally, it is noted that the Landsat TM data has provided useful information for studying on UHI, but some limitation inevitably arose due to temporal and spatial discontinuities of satellite data as well as simultaneously measured LST and air

temperature data when the satellite pass over. Thus, MODIS LST product should be beneficial to compare and revise the land surface temperature, which will be the next step work.

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