Chin. Geogra. Sci. 2015 Vol. 25 No. 4 pp. 462–471
doi: 10.1007/s11769-015-0764-z

Springer Science Press
www.springerlink.com/content/1002-0063

Change in Urban Wetlands and Their Cold Island Effects in Response to Rapid Urbanization

ZHANG Wei[1, 2], JIANG Jingang[2], ZHU Yubi[3]

(1. *School of Geographical Sciences*, *Southwest University*, *Chongqing* 400715, *China*; 2. *Institute of Remote Sensing and Earth Sciences*, *College of Science*, *Hangzhou Normal University*, *Hangzhou* 311121, *China*; 3. *College of Economics and Management*, *Southwest University*, *Chongqing* 400715, *China*)

Abstract: The cold-island effect of urban wetlands has received increasing attention in recent years due to its important role in the alleviation of urban heat islands. Hangzhou, a representative rapidly urbanizing city with rich wetlands in China, was selected as a case study for researching the changes that the urban wetlands have undergone and their impact on the urban thermal environment. Land surface temperature (LST) was acquired from the thermal infrared data of Landsat 5 Thematic Mapper (TM) images in 1990, 1995, 2000, 2006, and 2010, using the single-channel method. The results are as follows: 1) considering the changes in land use, the urban wetlands located to the west of Hangzhou have decreased significantly during 1990–2010 because of rapid urbanization. In the Xixi Wetland, the change in land use was relatively small and most of the water body and vegetation were preserved. However, to the east of the Xixi Wetland, large areas of water body and vegetation have been replaced by built-up land as a result of the urbanization process; 2) considering the change in LST, it was found from land surface temperature retrieval that the changing spatial pattern of the thermal field was highly correlated with land use changes. Low temperature regions of the eastern Xixi Wetland were gradually eroded by high temperature regions, and the centroid of the heat island in East Xixi was found to be constantly shifting westward. In addition, the difference in LST between the Xixi Wetland and East Xixi has increased; 3) considering the impact factors for this area, land use structure and patch shape were found to have a significant impact on LST, shown by the results of multiple linear stepwise regressions. Increasing the size of the wetlands in urban planning is considered to be the most effective measure in alleviating the urban heat island effect. Moreover, reducing the spatial complexity of landscape patches also contributes to the alleviation of the urban heat island effect.

Keywords: rapid urbanization; cold island effect; heat island effect; Thematic Mapper (TM); Xixi Wetland; Hangzhou

Citation: Zhang Wei, Jiang Jingang, Zhu Yubi, 2015. Change in urban wetlands and their cold island effects in response to rapid urbanization. *Chinese Geographical Science*, 25(4): 462–471. doi: 10.1007/s11769-015-0764-z

1 Introduction

The urban heat island (UHI) phenomenon is one of the most prominent characteristics of urban climate (Xiao *et al*., 2005; Chang *et al*., 2007), and the urban heat island effect has become increasingly notable with the acceleration of global urbanization. This has brought about many negative effects on urban and global ecosystems, including: 1) severely affecting the quality of inhabitation environments in cities. Heat waves can produce many adverse effects on human′s flexibility, consciousness, and behavior, and even healthy people can die of heat exhaustion if exposed to very high temperatures (Kovats and Hajat, 2008; Tan *et al*., 2010); 2) increasing energy consumption. The electricity consumption in cities will increase rapidly due to the greater use of fans, air conditioning and refrigeration equipment. Estimates for major US cities have shown that once temperatures exceed 15℃–20℃, a further 1℃ increase will increase peak electricity demand by 2%–4%. Thus, the additional

Received date: 2014-07-01; accepted date: 2014-11-03
Foundation item: Under the auspices of National Natural Science Foundation of China (No. 41101039, 41371068)
Corresponding author: ZHANG Wei. E-mail: zwei1997@126.com

cooling energy consumption made necessary by UHIs is responsible for 5%–10% of total electricity demand (Cao *et al*., 2010); 3) affecting global climate. The urban heat island effect has significant impacts on many urban climate factors, such as precipitation, wind speed, soil and air humidity, and light (Ren *et al*., 2006), which can affect the overall global climate (Ren *et al*., 2008). As recent research has shown, the influence of the urban heat island effect can extend up to 1000 km away from a metropolis (Zhang *et al*., 2013).

Research into this phenomenon has considered changes in the underlying land surface to be an important cause of the urban heat island effect (Zhou *et al*., 2001; Lin and Yu, 2005; Chen *et al*., 2006), and it is known that wetlands have an important function in climate regulation (Costanza *et al*., 1997; Yang, 2002). Therefore, many scholars have attempted find methods of alleviating the urban heat island effect, through research into wetland's cold island effect. Many of these studies have discussed the range, amplitude and impact factors of urban wetland's cold-humid effect by means of field observation or remote sensing. For example, Saaroni and Ziv (2003) performed field observations, comprising many meteorological parameters, in the daytime hours of the warm season around a 4 ha pond located in Begin Park, Tel Aviv City, Israel. As their results show, in the daytime, even a small pond can bring about a cooling effect with a range of around 40 m. Kim *et al*. (2008) investigated the changes in local thermal environment associated with the restoration of an inner-city stream in Seoul, Korea, using the observational data. They found that the near surface temperature dropped by an average of 0.4℃ after the restoration of the urban stream. Sun *et al.* (2012) investigated the urban cooling islands (UCIs) of ten reservoirs and lakes and five rivers in Beijing using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images, and quantified the UCI intensity as the temperature difference and gradient between the wetlands and their surrounding landscapes.

In previous studies, most of the research into the cold-island effect of urban wetlands has been based on relatively short periods of observation, and long-term research is rare. However, the change of underlying urban surfaces is a long-term process, and urban heat island effect it causes is also an ongoing cumulative phenomenon (Peng *et al*., 2013). Therefore, an analysis of the relationships between urban land use transformations and the change in urban land surface temperature (LST) over a long temporal data series, with accompanying discussion of the relevant impact factors, will help to deepen our understanding of the cold-island effect of urban wetlands and provide a scientific basis for the planning and management of urban wetlands. In Hangzhou, eastern China, two adjacent areas, Xixi Wetland and East Xixi, were chosen as case studies for the analysis of land use changes in urban wetlands and their impacts on LST under the background of rapid urbanization, using Landsat 5 Thematic Mapper (TM) data from 1990 to 2010. In this case study, the questions addressed are as follows: 1) how has the land use in and around urban wetlands changed under the rapidly urbanization process occurring in China? 2) How has the LST difference between preserved wetland (Xixi Wetland) and the occupied wetland (East Xixi) changed over the past 20 years? And 3) what factors are responsible for these changes?

2 Materials and Methods

2.1 Study area

Hangzhou (29º11′–30º33′N, 118º21′–120º30′E) is the political, economic, cultural, financial, and transportation center of Zhejiang Province in the eastern China, which is located in a subtropical monsoon region. Its climate is hot and humid in summer, and cold and dry in winter. The average annual temperature is 17.5℃, the average relative humidity is 70.3%, annual precipitation is 1454 mm, and the total annual sunshine hours are 1765 h.

Historically, tracts of wetland existed in the west of Hangzhou, but most of these wetlands have since been transformed into land used for urban construction during the rapid urbanization of the past 20 years. An exception to this loss of wetland is the Xixi National Wetland Park, which has been strictly protected by the government. Two adjacent areas, Xixi Wetland and East Xixi (Fig. 1), were originally very similar in terms of land topography, climate, hydrology, soil, vegetation, area and shape. However, East Xixi has been transformed from wetland to built-up land during the expanding urbanization of Hangzhou, while the Xixi Wetland has remained unchanged. Therefore, these two regions are ideal contrast analysis test fields for investigating the urbanization of wetland. The present study therefore

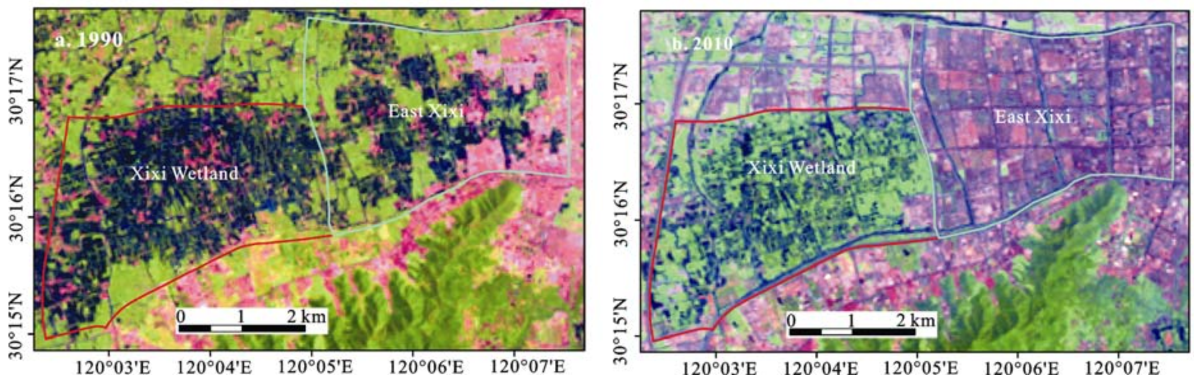

Fig. 1 Land use of study areas in 1990 (a) and 2010 (b). Images were obtained from Landsat 5 TM, with RGB band combinations of 741

selects these two regions as study areas, to analyze the changing land use in urban wetlands and its impacts on LST under rapid urbanization during the past 20 years, and to investigate its respective impact factors.

2.2 Data and processing

The main data source for this study was a set of Landsat TM images acquired on July 20, 1990; August 3, 1995; July 31, 2000; May 29, 2006 and August 12, 2010. The path/row number for each of these images is 119/39; and the pixel resolution of the thermal infrared (TIR) band is 120 m (for land surface temperature retrieval) while that of the other bands are 30 m (for visual interpretation).

Following the aims of this study and the actual situation of the study areas, we obtained the spatial change information of three land use types: water body, vegetation, and built-up area, during the 20-year study period by visual interpretation, using the Arcgis 10.0 and ENVI 4.8 work platforms. After interpretation and land surface temperature retrieval, we conducted the spatial statistics and spatial analysis of land use change and LST data in the study areas using Arcgis 10.0.

2.3 Methods

2.3.1 Land surface temperature retrieval

This paper utilized the generalized single-channel method (Jiménez-Muñoz and Sobrino, 2003; Cristóbal *et al*., 2009; Jiménez-Muñoz *et al*., 2009) for land surface temperature retrieval. This method includes the following steps:

(1) Data preprocessing. This paper used the automated registration and orthorectification package (AROP) developed by Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) for the registration of Landsat 5 images, with the registration error controlled to within 0.5 pixels (Gao *et al*., 2009), and then used the cosine of the sun zenith angle (COST) atmospheric correction model (Chavez, 1996) for the atmospheric correction of Landsat 5 images.

(2) Calculation of emissivity. The emissivity was calculated using the normalized difference vegetation index (NDVI) (Sobrino *et al*., 2008).

(3) Temperature retrieval. The first step was to calculate the at-sensor radiance (L_{sensor}) from digital number (DN) data.

$$L_{\text{sensor}} = G \times DN + B \tag{1}$$

where G and B are the gains and biases of Landsat-5, which are derived from the head files of the images. The second step was to calculate the brightness temperature (T_{sensor}).

$$T_{\text{sensor}} = \frac{c_2}{\lambda \ln\left(\dfrac{c_1}{\lambda^5 L_{\text{sensor}}} + 1\right)} \tag{2}$$

where λ is the radiation wavelength (11.457 μm for TIR data); and c_1 and c_2 are the Planck radiation constants. The final step was to calculate the land surface temperature (T_s).

$$T_s = \gamma\left[\frac{1}{\varepsilon}(\varphi_1 L_{\text{sensor}} + \varphi_2) + \varphi_3\right] + \delta \tag{3}$$

where γ and δ are two parameters of the Planck function; ε is the surface emissivity; and φ_1, φ_2, and φ_3 are the parameters of the atmosphere functions, which can be calculated from the total atmospheric water vapor content which can be derived from MODIS near-infrared water vapor products (MOD05).

2.3.2 Data processing and analysis

In order to analyze the causes of change in temperature difference between Xixi Wetland and East Xixi from 1990 to 2010, we investigated the temperature difference impact factors by means of multiple linear stepwise regression models. We defined the temperature difference between Xixi Wetland and East Xixi from 1990 to 2010 as the dependent variable, and then defined the land use structure and landscape pattern indices of East Xixi as the independent variables.

We calculated the landscape pattern indices using the software of Fragstats 4.1, including Number of Patches (NP), Total Area (TA), Patch Density (PD), Mean Patch Size (MPS), Area-weighted Mean Shape Index (AWMSI), Area-weighted Mean Patch Fractal Dimension (AWMPFD), Shannon′s Diversity Index (SHDI), Largest Patch Index (LPI), Percentage of Construction Land (%CL), Percentage of Water Body (%WL) and Percentage of Vegetation (%VL). The detailed formulae of indices used in this study are included in the help documentation of Fragstats 4.1.

3 Results and Analyses

3.1 Land use change

3.1.1 Land use structure

We obtained the land use data for different years in Xixi Wetland and East Xixi through visual interpretation. As shown in Fig. 2, the land use structure in Xixi Wetland was relatively stable from 1990 to 2010. The percentage area occupied by water body decreased slightly, from 48.61% to 34.89%, with an annual change rate of –0.69%. The percentage area of built-up land increased from 13.12% to 14.94%, with an annual change rate of 0.09%. Finally, the percentage area covered by vegetation increased from 38.27% to 50.17%, with an annual change rate of 0.60%. In contrast, the land use structure in East Xixi changed dramatically during the 20-year study period. Percentage area occupied by water body decreased significantly from 29.50% to 4.45%, with an annual change rate of –1.25%, which is 1.8 times of that in Xixi Wetland. The percentage area of built-up land correspondingly increased drastically from 30.12% to 89.99%, with an annual change rate of 2.99%, 32.8 times of that in Xixi Wetland. Finally, the percentage area covered by vegetation also decreased from 40.38% to 5.57%, with an annual change rate of –1.74%, which is 2.9 times of that in Xixi Wetland. It can therefore be clearly seen that the encroachment of built-up areas into urban wetlands has increased alarmingly, from the comparison of land use structure in Xixi Wetland and East Xixi over the past 20 years. It can be seen from comparison of the two areas that the establishment of a wetland park or wetland reserve is an effective measure in protecting urban wetland from urban development.

3.1.2 Change of centroids

In this section, we introduced the concept of centroid in physics to identify the geographic center for each land use type in Xixi Wetland and East Xixi. Through the calculation of centroids in different years, we could identify the temporal evolution of the each land use type more clearly.

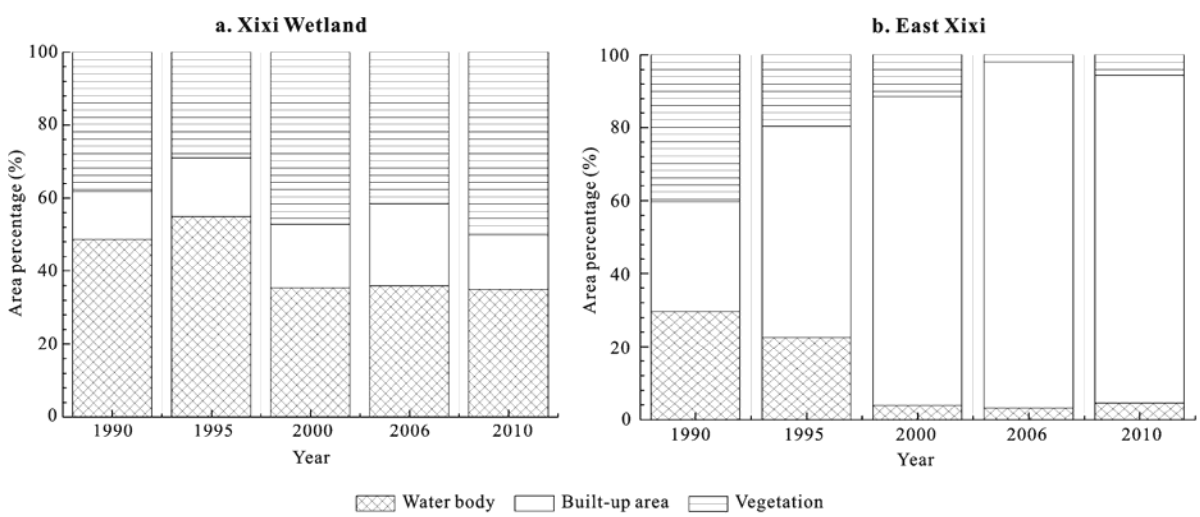

Fig. 2 Land use structure change in Xixi Wetland and East Xixi from 1990 to 2010

As shown in Fig. 3, the centroid positions of each land use type in Xixi Wetland have scarcely changed, remaining in the center of Xixi Wetland during 1990–2010. This indicates that the spatial distribution of each land use type in Xixi Wetland was in a state of equilibrium and stable. However, the centroid positions of each land use type in East Xixi have changed dramatically from 1990 to 2010. In this region, the centroid position of the built-up area has moved almost linearly from east to west. In comparison, the centroid positions of vegetation and water body moved from the center to the southwest at first, then moved back to a central position in 2010. The centroid positions of vegetation and water body moved back to the center of East Xixi in 2010. However, it is worth noting that this phenomenon did not mean that there were significant increases in the sizes of these two land use types, rather it implies that the rapid urbanization process of this area has come to an end. In East Xixi, the urban landscape construction has gradually improved, and the spatial distribution of each land use type has become more stable.

3.2 Change in land surface temperature

3.2.1 Spatial distribution

We can obtain the spatial distribution of LST in the study areas from 1990 to 2010 using the retrieval method described in Section 2.3.1. As shown in Fig. 4, the spatial distribution pattern of the thermal field shows gradual expansion of higher temperatures from the east to the west. In 1990, the land uses in the areas surrounding the Xixi Wetland were farmland to the north and west of Xixi Wetland, farming wetland to the east of Xixi Wetland, and rural residential and town to the south of Xixi Wetland. We carried out a geo-statistical analysis of the land surface temperature within Xixi Wetland and a surrounding buffer of 200 m using Arcgis 10.0. Results showed that the LST of Xixi Wetland was 0.31℃ higher than that at its surrounding areas in 1990. However, by 2010, the land use types in Xixi Wetland's surrounding areas were almost entirely transformed into built-up land. Geo-statistical analysis results showed that the land surface temperature of Xixi Wetland was 7.57℃ lower than that at its surrounding areas by 2010, and that Xixi Wetland represented a typical cold island surrounded by higher thermal field. The thermal field pattern of East Xixi has also undergone tremendous changes. Over the past 20 years, the higher temperature region to the east has gradually eroded the lower temperature region until finally occupying all of East Xixi by 2010.

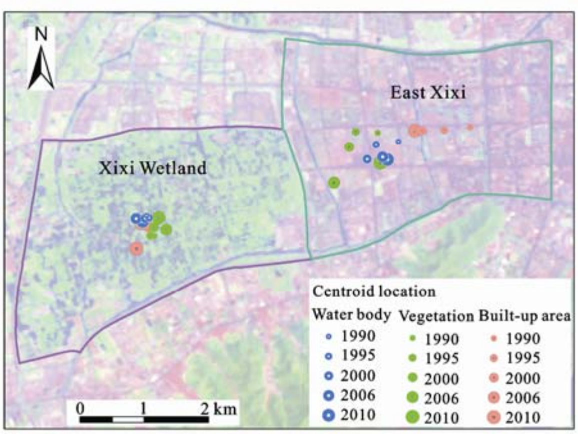

Fig. 3 Temporal evolution of centroid locations for each land use type in Xixi Wetland and East Xixi from 1990 to 2010

These changes are also clearly reflected by the temperature difference between Xixi Wetland and East Xixi (Fig. 5). In 1990, the temperature difference between Xixi Wetland and East Xixi was negligible, and the temperature of vegetation and water body in East Xixi was even lower than that in Xixi Wetland. However, after 1990, the temperature differences between Xixi Wetland and East Xixi have increased almost linearly. From 1990 to 2010, the temperature difference of water body between Xixi Wetland and East Xixi has increased from −1.25℃ to 7.34℃, with a total amplitude of 8.59℃. The temperature difference of vegetation also increased from −1.43℃ to 6.72℃, with an amplitude of 8.15℃. Meanwhile, the temperature difference of the built-up areas was relatively stable, increasing only slightly from 3.53℃ to 5.33℃, with an amplitude of 1.80℃. As a whole, the temperature difference between Xixi Wetland and East Xixi has increased from 0.54℃ to 9.27℃, with an amplitude of 8.73℃.

3.2.2 Change of centroids

In order to reflect the temporal evolution of the thermal field pattern in Xixi Wetland and East Xixi more clearly, we calculated the evolution of heat-island and cold-island centroid positions using Arcgis 10.0 (Fig. 6).

As shown in Fig. 6, from 1990 to 2010, in Xixi Wetland, the centroid position of the heat-island has scarcely changed, and remained in the center of region during 1990–2010. However, the centroid position of the cold-island in Xixi Wetland has moved significantly,

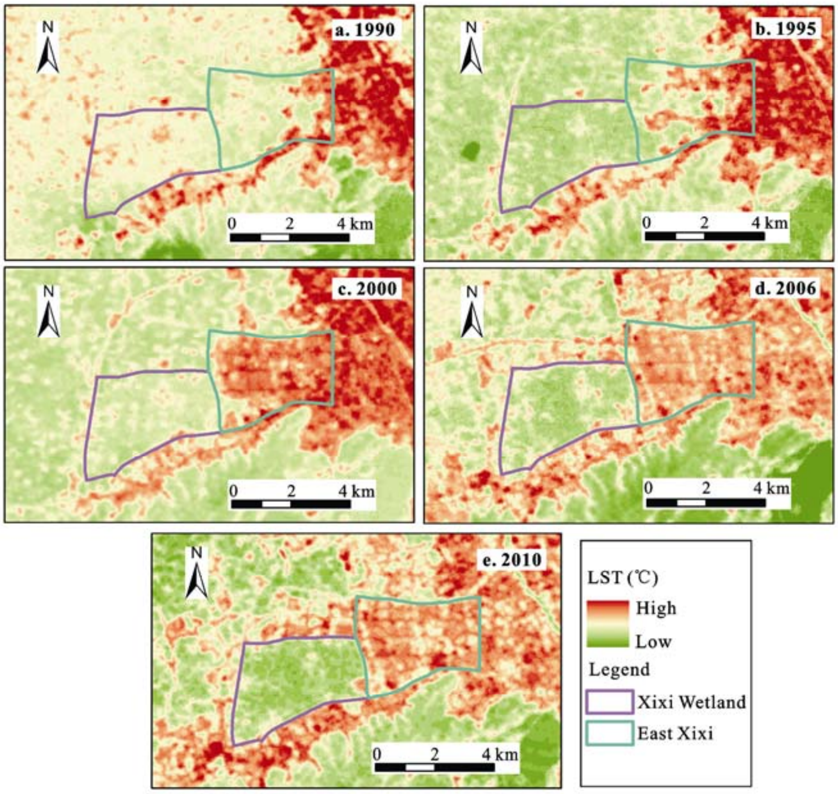

Fig. 4 Spatial distribution changes in land surface temperature (LST) in Xixi Wetland and East Xixi over past 20 years. The analysis of LST of the different images is based on relative values rather than real LST values, due to the fact that images were taken at different times, and thus consideration of real LST values becomes irrelevant. Therefore, discussion herein focuses on the temperature difference between Xixi Wetland and East Xixi in different years

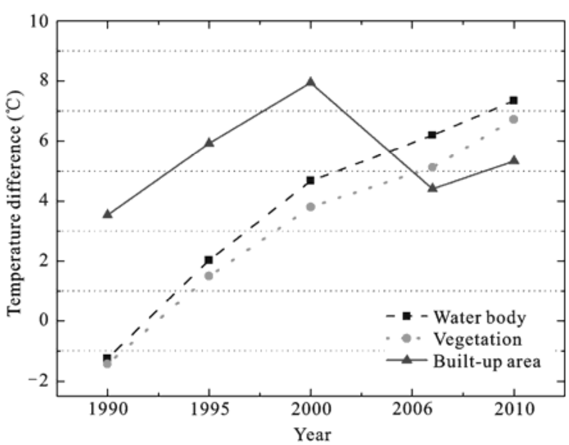

Fig. 5 Temperature difference between Xixi Wetland and East Xixi during past 20 years. Temperature difference is calculated by subtracting the land surface temperature of Xixi Wetland from East Xixi

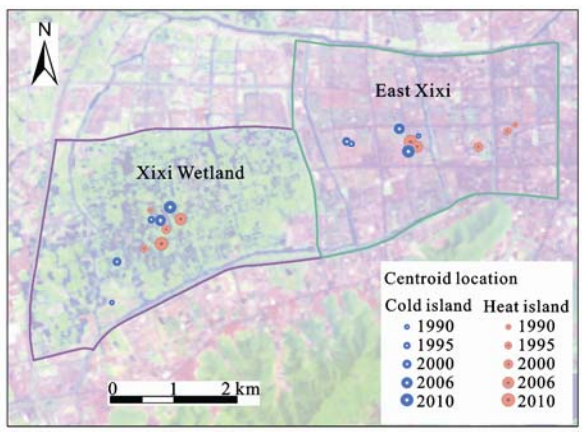

Fig. 6 Temporal evolution of heat-island and cold-island centroids in Xixi Wetland and East Xixi from 1990 to 2010

from the southwest to the regional center. This is the result of urban road construction outside of Xixi Wetland and infrastructure construction within the Xixi Wetland Park as part of the urbanization process. In 2010, the centroids of both the heat-island and coldisland were located in the regional center of Xixi Wetland, indicating that the spatial distribution of the thermal field in Xixi Wetland is at equilibrium and stable. In East Xixi, the changing trends in heat-island and cold-island centroid locations are very similar to those of the land use type centroids. As the centroid position of built-up land moved from east to west, so the centroid position of the heat-island also moved in the same direction. Correspondingly, temporal evolution of the cold-island centroid locations in East Xixi is similar to those of water body and vegetation, which moved from the regional center to the west, and then gradually returned to the center.

3.3 Impact factor analysis

We carried out multiple linear stepwise regressions by means of the ordinary least squares (OLS) method, and built an econometric model as follows:

$$y = -85.948 - 36.437x_1 + 85.209x_2 \quad (4)$$

where y is the temperature difference between Xixi Wetland and East Xixi; x_1 is the area Percentage of Water Body (%WL) in East Xixi, and x_2 is the Area-weighted Mean Patch Fractal Dimension (AWMPFD). The results and test values of this model are shown in Table 1.

It can be seen from Table 1 that all variables passed the F test and multi-collinearity test. The percentage of Water Body (%WL) passed the t test at 99% confidence level, and the Area-weighted Mean Patch Fractal Dimension passed the t test at 95% confidence level. Therefore, the goodness-of-fit of this model is satisfactory.

Land use structure and patch shape have a significant impact on LST, as shown in the results of the multiple linear stepwise regression. The Percentage of Water Body has a negative impact on LST, meaning the greater the percentage area occupied by water body, the lower the land surface temperature. In contrast, the complexity of patch shape has a positive impact on LST, meaning the greater the complexity of the patch shape, the higher the land surface temperature. The standardized coefficient of percentage of water body (1.203) is much larger than that of the Area-weighted Mean Patch Fractal Dimension (0.415), implying that the contribution of the Percentage of Water Body (%WL) to the LST is greater than that of the complexity of patch shape (AWMPFD).

4 Discussion

The urbanization of China has been accelerating along with the development of society and economy since the 1980s. The urbanization rate of China increased from 17.92% in 1978 to 52.6% in 2012, and thus China has completed an urbanization process in 30 years that took hundreds of years in western countries (Yue *et al*., 2013). Joseph E. Stiglitz, Nobel Laureate in economics, has cited urbanization in China as one of the two most important events that will shape global development during the 21st century (Ye and Alfred, 2014). Many recent publications have investigated rapid urbanization and its driving forces in China (Chen, 2007; Liu *et al*., 2010; Zhang Y J *et al*., 2014), and have discussed the negative effects of rapid urbanization on the urban environment (Wang *et al*., 2008; Hubacek *et al*., 2009). The land use changes in western Hangzhou obtained in this study are in line with the large-scale background of China′s rapid urbanization. The results are also consistent with the conclusions of Yu *et al*. (2007) and Yue *et al*. (2013).

Many studies have discussed the relationship between urban heat islands and land use changes, and most of these have cited an increase in the area of impervious urban surfaces, caused by the urban sprawl, as a cause of the increase in sensible heat flux and the Bowen ratio, resulting in an increase in urban land surface temperature (Liu *et al*., 2012; Zhang H *et al*., 2014). There are several notable differences between the present research and previous studies. (1) Research perspective. While urban heat island research based on remote sensing data can easily associate UHIs with the long-term urbanization process, studies have often considered larger spatial scales, such as entire cities (Wang *et al*., 2013). Contrastingly, UHI research based on field observations has

Table 1 Simulation results from multiple linear stepwise regressions

Variable	Non-standardized coefficient	S.E.	Standardized coefficient	t	sig.	VIF
Constant	−85.948	12.356		−6.956	0.020	
x_1	−36.437	1.618	−1.203	−22.524	0.002	1.64
x_2	85.209	10.971	0.415	7.767	0.016	1.64

Notes: where VIF is variance inflation factor; S.E. is standard error; R^2 = 0.997; F(sig.) = 60.327(0.016) often focused on smaller scales, such as specific wetlands, which are difficult to link with long-term regional urbanization processes (Saaroni and Ziv, 2003). This research provides a new perspective to urban thermal environment studies, by associated the cold island effect of wetlands with the rapid urbanization process. In this way, we can analyze the impacts of urbanization on microclimate more directly, which will enable us to propose more targeted strategies for the mitigation of UHI. (2) The reliability of the comparative results. In previous studies, the analyses either compared the mean surface temperature of different land use types across an entire city (Steve *et al.*, 2007), or compared the mean surface temperature of specific wetlands with built-up areas (Kim *et al.*, 2008). Within these comparisons, the objects′ attributes, such as location, topography, landform, microclimate, hydrology, soil, vegetation and shape, are difficult to compare directly, thus reducing the reliability of the comparative results. In this study, two comparative study areas, Xixi Wetland and East Xixi, were very similar in many aspects, meaning that the impacts of other variable factors were minimized, increasing the reliability of the comparative results. (3) Temperature difference. Many publications have discussed the temperature difference of land use types across an entire city. Chen *et al.* (2006) investigated the relationship between urban surface temperature and land cover pattern in Shenzhen, southern China, and found the mean temperature difference between the built-up area and the water body was 2.72℃ on 1 November, 2000. Steve *et al.* (2007) identified the land use types that have most greatly influenced the increase in ambient temperature in Singapore, and found that the mean surface temperature difference between human structures and natural vegetation areas was 4.22℃ on 11 October, 2002. Sun *et al.* (2012) used ASTER images to investigate the urban cooling islands (UCIs) created by wetlands in Beijing, and found the temperature difference between wetlands and built-up areas to be 3.49℃. These results differ considerably, and all are lower than the results of this paper (9.27℃). Because the results of previous researches were very sensitive to the accuracy of land use interpretation, and paid little attention on the influence of vegetation, soil, hydrology, topography and regional location, so the comparative analysis of the mean land surface temperature of each land use type across an entire city maybe is not an accurate approach, and it is likely to result in the underestimation of the cold island effect of urban wetlands. However, the difference between these results may also be derived from differences in local climate, observation time, wetland characteristics and other factors. Further research and more evidence are clearly needed to address this issue.

Many publications have discussed the impact factors controlling the cold-island effect in urban wetlands and parks. These studies took the intensity of park cool islands (PCIs) or urban cooling islands (UCIs) of many urban wetlands and parks during the same period as the dependent variable, and took the shape, area, location, land use structure and other factors of those urban wetlands and parks as independent variables, to discover which factor or factors have the most significant impact on the cold-island intensity (Chang *et al.*, 2007; Cao *et al.*, 2010; Sun *et al.*, 2012). As is shown in this paper, the area and shape of the landscape were important factors influencing the cold-island effect; and these results are consistent with previous research. However, significant differences exist between the present paper and former studies. (1) Two adjacent areas of land, Xixi Wetland and East Xixi, are very similar in many aspects except for the change in land use during the urbanization process. Therefore, these two regions are ideal contrast analysis test fields for investigating the urbanization of wetlands. This paper focused on these two areas of land, and discussed the temperature difference between them over a long temporal series, which can help to provide a new perspective and evidence in the research of the cold island effects of wetlands. (2) This paper further defined direction and amplitude as two major impact factors influencing a wetland′s cold-island effect, using multiple linear stepwise regression, and provided the possibility of predicting changes in land surface temperature in urban areas. Such information is very useful for the planning and management of urban wetlands, and future studies should expand the scope of this methodology.

5 Conclusions

The cold island effect of urban wetland has received increasing research attention as one of the most important countermeasures to alleviate the urban heat island effect. This paper analyzed the urbanization of the Xixi Wetland and East Xixi and its impact on the urban thermal environment in Hangzhou, China, through remote sensing (RS) and Geographic Information System (GIS) techniques.

The wetlands in the west of Hangzhou have become greatly reduced during the process of rapid urbanization of the city. The tendency of the built-up area to expand from east to west gradually encroaching on wetland and vegetation is very clear as shown by the centroid movement of each land use type in East Xixi. Meanwhile, the changes in land surface temperature in Xixi Wetland and East Xixi indicate that the change in the spatial pattern of the thermal field is very similar to the change in land use pattern. Over the 20-year study period, Xixi Wetland was gradually enclosed by a higher thermal field, and the land surface temperature difference between Xixi Wetland and East Xixi increased. Land use structure and patch shape were found to have significant impacts on the change of urban LST, and increasing the size of wetlands during urban planning would prove the most effective measure for alleviating the urban heat island effect, while reducing the spatial complexity of landscape patch will also contribute to reducing urban heating.

In this study, the temperature difference between Xixi Wetland and East Xixi was 9.27℃ in 2010, which is higher than that found in previous studies. It is not very accurate to carry out comparative analysis of the mean land surface temperature of each land use type in an entire city, as was attempted in previous works, and therefore the cold island effect of urban wetlands was probably underestimated in former studies. However, the difference between the present result and previous research may also be associated with local climate, observation time, wetland characteristics and other factors. Further research and more evidence are clearly required to address this issue.

References

Cao X, Onishi A, Chen J *et al.*, 2010. Quantifying the cool island intensity of urban parks using ASTER and IKONOS data. *Landscape and Urban Planning*, 96(4): 224–231. doi: 10.1016/j.landurbplan.2010.03.008

Chang C, Li M H, Chang S D, 2007. A preliminary study on the local cool-island intensity of Taipei city parks. *Landscape and Urban Planning*, 80(4): 386–395. doi: 10.1016/j.landurbplan.2006.09.005

Chavez P S, 1996. Image-based atmospheric corrections-revisited and improved. *Photogrammetric Engineering and Remote Sensing*, 62(9): 1025–1035. doi: 0099-1112/96/6209-1025S3.00/0

Chen J, 2007. Rapid urbanization in China: a real challenge to soil protection and food security. *Catena*, 69(1): 1–15. doi: 10.1016/j.catena.2006.04.019

Chen X L, Zhao H M, Li P X *et al.*, 2006. Remote sensing image-based analysis of the relationship between urban heat island and land use/cover changes. *Remote Sensing of Environment*, 104(2): 133–146. doi: 10.1016/j.rse.2005.11.016

Costanza R, d'Arge R, De G R *et al.*, 1997. The value of the world's ecosystem services and natural capital. *Nature*, 387(6630): 253–260. doi: 10.1038/387253a0

Cristóbal J, Jiménez-Muñoz J C, Sobrino J A *et al.*, 2009. Improvements in land surface temperature retrieval from the Landsat series thermal band using water vapor and air temperature. *Journal of Geophysical Research*: *Atmospheres* (1984–2012), 114(D08): 103. doi: 10.1029/2008jd010616

Gao F, Masek J, Wolfe R E, 2009. Automated registration and orthorectification package for Landsat and Landsat-like data processing. *Journal of Applied Remote Sensing*, 3(1): 033515. doi: 10.1117/1.3104620

Hubacek K, Guan D, Barrett J *et al.*, 2009. Environmental implications of urbanization and lifestyle change in China: ecological and water footprints. *Journal of Cleaner Production*, 17(14): 1241–1248. doi: 10.1016/j.jclepro.2009.03.011

Jiménez-Muñoz J C, Cristóbal J, Sobrino J A *et al.*, 2009. Revision of the single-channel algorithm for land surface temperature retrieval from Landsat thermal-infrared data. *IEEE Transactions on Geoscience and Remote Sensing*, 47(1): 339–349. doi: 10.1109/tgrs.2008.2007125

Jiménez-Muñoz J C, Sobrino J A, 2003. A generalized single-channel method for retrieving land surface temperature from remote sensing data. *Journal of Geophysical Research*: *Atmospheres* (1984–2012), 108(D22): 4688. doi: 10.1029/2003jd003480

Kim Y H, Ryoo S B, Baik J J *et al.*, 2008. Does the restoration of an inner-city stream in Seoul affect local thermal environment? *Theoretical and Applied Climatology*, 92(3–4): 239–248. doi: 10.1007/s00704-007-0319-z

Kovats R S, Hajat S, 2008. Heat stress and public health: a critical review. *Annual Review of Public Health*, 29: 41–55. doi: 10.1146/annurev.publhealth.29.020907.090843

Lin Xuechun, Yu Shuqiu, 2005. Interdecadal changes of temperature in the Beijing region and its heat island effect. *Chinese Journal of Geophysics*, 48(1): 47–54. (in Chinese)

Liu Y S, Liu Y, Chen Y F *et al.*, 2010. The process and driving forces of rural hollowing in China under rapid urbanization. *Journal of Geographical Sciences*, 20(6): 876–888. doi: 10.1007/s11442-010-0817-2

Liu Y, Shintaro G, Zhuang D F *et al.*, 2012. Urban surface heat fluxes infrared remote sensing inversion and their relationship with land use types. *Journal of Geographical Sciences*, 22(4): 699–715. doi: 10.1007/s11442-012-0957-7

Peng Baofa, Shi Yishao, Wang Hefeng *et al.*, 2013. The impacting mechanism and laws of function of urban heat islands effect: a case study of Shanghai. *Acta Geographica Sinica*, 68(11): 1461–1471. (in Chinese)

Ren Chunyan, Wu Dianting, Dong Suocheng, 2006. The influence of urbanization on the urban climate environment in Northwest China. *Geographical Research*, 25(2): 233–241. (in Chinese)

Ren G Y, Zhou Y Q, Chu Z Y *et al*., 2008. Urbanization effects on observed surface air temperature trends in North China. *Journal of Climate*, 21(6): 1333–1348. doi: 10.1175/2007jcli 1348.1

Saaroni H, Ziv B, 2003. The impact of a small lake on heat stress in a Mediterranean urban park: the case of Tel Aviv, Israel. *International Journal of Biometeorology*, 47(3): 156–165. doi: 10.1007/s00484-003-0161-7

Sobrino J A, Jimenez-Munoz J C, Soria G *et al*., 2008. Land surface emissivity retrieval from different VNIR and TIR sensors. *IEEE Transactions on Geoscience and Remote Sensing*, 48(2): 316–327. doi: 10.1109/tgrs.2007.904834

Steve K J, Wong N H, Emlyn H *et al*., 2007. The influence of land use on the urban heat island in Singapore. *Habitat International*, 31(2): 232–242. doi: 10.1016/j.habitatint.2007.02. 006

Sun R H, Chen A L, Chen L D *et al*., 2012. Cooling effects of wetlands in an urban region: the case of Beijing. *Ecological Indicators*, 20: 57–64. doi: 10.1016/j.ecolind.2012.02.006

Tan J G, Zheng Y F, Tang X *et al*., 2010. The urban heat island and its impact on heat waves and human health in Shanghai. *International Journal of Biometeorology*, 54(1): 75–84. doi: 10.1007/s00484-009-0256-x

Wang J Y, Da L J, Song K *et al*., 2008. Temporal variations of surface water quality in urban, suburban and rural areas during rapid urbanization in Shanghai, China. *Environmental Pollution*, 152(2): 387–393. doi: 10.1016/j.envpol.2007.06.050

Wang M N, Yan X D, Liu J Y *et al*., 2013. The contribution of urbanization to recent extreme heat events and a potential mitigation strategy in the Beijing-Tianjin-Hebei metropolitan area. *Theoretical and Applied Climatology*, 114(3–4): 407–416. doi: 10.1007/s00704-013-0852-x

Xiao Rongbo, OuYang Zhiyun, Li Weifeng *et al*., 2005. A review of the eco-environmental consequences of urban heat islands. *Acta Ecologica Sinica*, 25(8): 2055–2060. (in Chinese)

Yang Yongxing, 2002. The 21st century hot point and forward position field of international wetland research from Quebec2000—Millennium Wetland Event. *Scientia Geographica Sinica*, 22(2): 150–155. (in Chinese)

Ye L, Alfred M W, 2014. Urbanization, land development, and land financing: evidence from Chinese cities. *Journal of Urban Affairs*, 36(S1): 354–368. doi: 10.1111/juaf.12105

Yu Minjie, Wu Jianjun, Xu Jianming *et al*., 2007. Studies on the changes of landscape patterns of Hangzhou xixi wetland in 15 years. *Bulletin of Science and Technology*, 23(3): 320–325. (in Chinese)

Yue Wenze, Wang Ruiliang, Fan Peilei, 2013. Spatial patterns analysis of urban expansion in Hangzhou City. *Journal of Zhejiang University* (*Science Edition*), 40(5): 596–605. (in Chinese)

Zhang G J, Cai M, Hu A X, 2013. Energy consumption and the unexplained winter warming over northern Asia and North America. *Nature Climate Change*, 3(5): 466–470. doi: 10. 1038/nclimate1803

Zhang H, Qi Z F, Ye X Y *et al*., 2014. Analysis of land use/land cover change, population shift, and their effects on spatiotemporal patterns of urban heat islands in metropolitan Shanghai, China. *Applied Geography*, 44: 121–133. doi: 10.1016/j.apgeog.2013.07.021

Zhang Y J, Liu Z, Zhang H *et al*., 2014. The impact of economic growth, industrial structure and urbanization on carbon emission intensity in China. *Natural Hazards*, 73(2): 579–595. doi: 10.1007/s11069-014-1091-x

Zhou Hongmei, Zhou Chenghu, Ge Weiqiang *et al*., 2001. The surveying on thermal distribution in urban based on GIS and remote sensing. *Acta Geographica Sinica*, 56(2): 189–197. (in Chinese)