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Assessing the effect of land use/land cover change on the change of urban heat island intensity

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With 6 Figures

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Summary

Due to rapid economic development, China has experienced one of the greatest rates of change in land use/land cover during the last two decades. This change is mainly urban expansion and cultivated land reduction in urban growth regions, both of which play an important role in regional climate change. In this paper, the variation of the urban heat island (UHI) caused by urbanization has been evaluated with an analysis of land use change in China. First, meteorological observation stations were grouped by different land cover types (dry land, paddy field, forest, grassland, water field, urban, rural inhabitable area, industrial and mineral land, and waste land) throughout China. These stations were subdivided into urban and non-urban classes. Then, a new method was proposed to determine the UHI intensity from the difference between the observed and the interpolated air temperature of urban type weather stations. The results indicate that the trends of UHI intensity in different land use change regions are spatially correlated with regional land use and its change pattern. During 1991–2000, the estimated UHI intensity has increased by 0.11 °C per decade in the spring and has fluctuated in other seasons throughout China resulting from land use change.

1. Introduction

In recent years, scientists have recognized that land cover/land use changes induced by human activities have large impacts on regional climate (Esserl, 1989; Grunblatt et al., 1992; Wei and Fu, 1998; Lambin et al., 1999; Hillel and Rosenzweig, 2002; Gao et al., 2003). The urban heat island (UHI) effect, the phenomena where air and surface temperatures of urban areas are higher than those of its surrounding rural areas, has been rigorously researched (e.g. Oke, 1982; Owen, 1998). UHI was described by Roth et al. (1989) as "one of the most clearly established examples of inadvertent modification of climate." Numerous studies have shown that urbanization can produce radical changes in the radiative, thermodynamic, and water processes of the land surface and modify local climate in terms of for example, temperature, precipitation, and cloudiness (Carlson and Arthur, 2000; Huff and Changnon, 1972; Oke, 1974). There is increasing evidence that global warming is a result of anthropogenic activity during the past fifty years (IPCC, 2001). Global warming can be partitioned into (1) the urban heat island effect, (2) the effect of deforestation, (3) the effect of secular micro-climate shift, (4) the influence of general global warming with particular reference to the tropics (Harger, 1995). It is therefore important to eliminate the urban heat island effect from observed temperature records in order to assess monthly, seasonal, and annual averaged long-term temperature trends (Karl et al., 1988; Jones et al., 1990; Wang et al., 1990; Matsushita et al., 2004). For example, a reanalysis of global temperature data over the past 50 years that is insensitive to surface dynamics has been produced (Kalnay et al., 1996; Kistler et al., 2001) and the data have been used to assess the long-term climate change, its causes and its impact on carbon and water cycles.

The intensity of the urban heat island (UHI) is directly related to the rate of urbanization, land use patterns, and building density. It can be assessed in several ways: measuring the UHI by comparing present to earlier pre-urban conditions (Lowry, 1977), measuring the UHI through the urban-to-rural temperature difference (Lowry, 1977; Karl et al., 1988); and measuring the UHI in terms of surface (or skin) temperature through the use of airborne or satellite remote sensing (Roth et al., 1989; Gallo and Tarpley, 1996; Streutker, 2003). The selection of the most appropriate method depends mainly on the observed data available.

China, the biggest developing county in land area, has experienced rapid urbanization in recent years (Liu et al., 2005a, b). Some recent studies have shown the effect of large scale urbanization on regional temperature change in China (Zhang et al., 2003; Zhou et al., 2004), but they failed to directly estimate the temporal and spatial variability of the UHI intensity impacted by the real land use change (especially urban sprawl). Using the National Land Cover Dataset (NLCD) of China, which is derived from high resolution remote sensed data and covers the period from the end of the 1980s to 2000 (Liu et al., 2003, 2005a), this study develops a new method of estimating how the intensity of the UHI has changed during this ten year period and how much was the result of land use change.

2. Data sources

The intensively validated NLCD are used as land use change background for this study. The NLCD contains land use data in vector format with a scale of 1:100,000 and gridded land use percentage data at a one square kilometre resolution. The NLCD, constructed by the Chinese Academy of Sciences and the Ministry of Science and Technology, is based on remote sensed data – Landsat TM/ETM (Thematic Mapper/Enhanced Thematic Mapper) covering three periods: the end of the 1980s (1985–1990), 1995/1996, and 2000 (Liu et al., 2003). According to quality assessment, the accuracy of classification for urban areas is 96.32% and the bias of polygon boundaries for each land use type is less than 45 m (Liu et al., 2003). The gridded percentage of land use represents the areal composition of each land use type within each one square kilometre unit (Liu et al., 2002). To characterize the spatial pattern of variability in intensity of UHI from land use change, the map of national land use change zoning (Liu et al., 2003) was used as regional divisions.

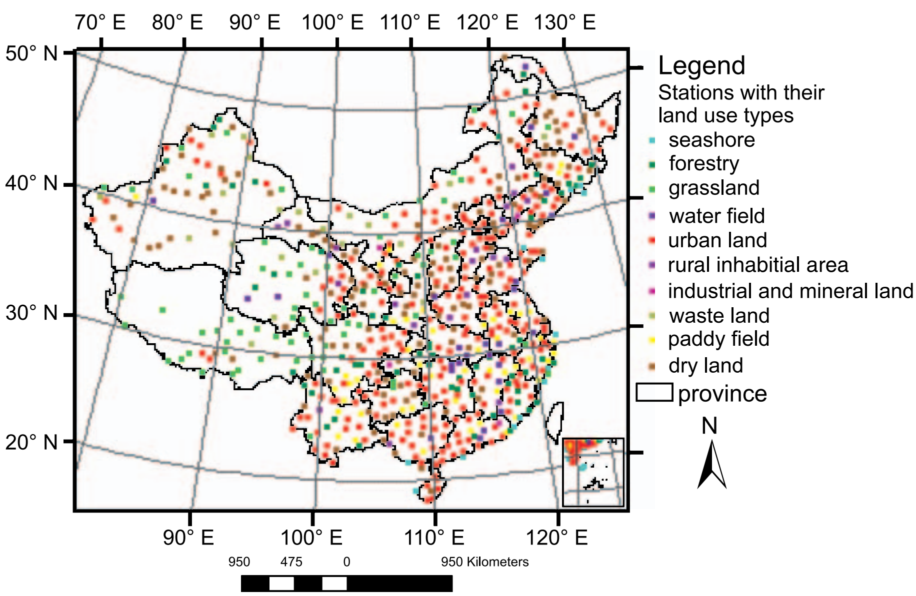

Fig. 1. Spatial distribution of meteorological observation stations and their corresponding ground surface land use types

Daily temperature data used in this study are collected from the 673 meteorological stations of the China Historical Climatological Network and include records from 1991 to 2000 (China Meteorological Administration, http://211.147.16.25/ywwz/constitute/wls01.php). At first, the tabular air temperature data are converted into spatial data with point vector format in Geographical Information Systems (GIS). Then, by overlaying the station point vector layer with the NLCD land use layer, the satellite-based land use classes (dry land, paddy field, forest, grassland, water field, urban, rural inhabitable area, industrial and mineral land, and waste land) are designated to meteorological observation stations. Stations with the urban land use feature are defined as urban type weather stations, and those with other land use features are classed as non-urban types. According to this definition, 273 stations (40% of total numbers) were urban in 2000. There were 46 weather stations experiencing urbanization (from non-urban to urban) from 1991 to 2000, accounting for 6% of the total stations (Fig. 1). In this study, observations are used to identify which stations (urban type) are affected by the UHI effect and which are not, with the exception of the 46 weather stations experiencing urbanization.

3. Methods

3.1 Estimation of UHI intensity at the regional scale

As previously described, the traditional methods used to estimate the intensity of UHI required improvement and extension in order to eliminate uncertainty and to discover the effect of regional land use change over a long time period by using high resolution data. In general, significant spatial differences (elevation and latitude) would exist between urban and non-urban pair stations if their distance is over 100 kilometres (km). Unfortunately, many urban stations in China are far from the surrounding non-urban stations. It is difficult to find enough urban and non-urban pairs to estimate the intensity of UHI at a national scale. Here, a new method is proposed to assess the intensity of UHI. It identifies the difference between the observed air temperature by an urban weather station and the interpolated temperature by non-urban stations. The interpolated temperatures from non-urban stations are set as background temperature of the urban station. The estimated intensity of UHI (*HI*) for one urban station can be expressed as

$$HI = T_u - T_b \quad (1)$$

where T_u is the observed temperature of the urban station; T_b is the background temperature of the urban station. Figure 2 describes the definition of urban background temperature of the urban station. The interpolation method is from Thornton et al. (1997) which is based on the spatial convolution of a truncated Gaussian weighting, i.e.

$$T_b = \frac{\sum_{i=1}^{n} W_{i,r}[T_i + \beta_0 + \beta_1 \times (z_b - z_i)]}{\sum_{i=1}^{n} W_{i,r}} \quad (2)$$

$$W_{i,r} = \begin{cases} 0; & r > R_b \\ \exp\left[-\left(\frac{r}{R_b}\right)^2 \alpha\right] - e^{-\alpha}; & r \leq R_b \end{cases} \quad (3)$$

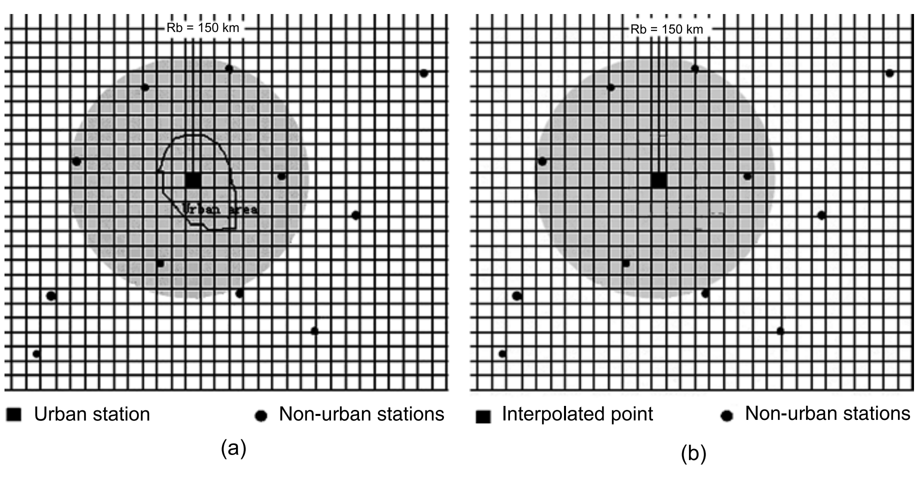

Fig. 2. (**a**) Urban and its neighbor non-urban stations (**b**) calculation of urban background temperature of urban station

where T_i is the observed temperature around the non-urban station i; z_b is the elevation of the predicting urban station; z_i is the elevation of the non-urban station i; $W_{i,r}$ is the filter weight of the non-urban station i that related with radial distance r from the predicting site; R_b is the truncation distance from the predicting site; α is a unit-less shape parameter of the Gaussian function; n is the total number of non-urban weather stations that have a distance less than R_b from the predicting urban station; β_0 and β_1 are the coefficients of linear regression, which is calculated from station pairs by the 2-stage least squares approximation method to reflect the altitude effect on temperature. R_b is assigned as 150 km and α as 3.0 after many tests to achieve the least extrapolation error. In the processing of interpolation, weighting averages of the temperature of non-urban stations within 150 km of the urban station will remove the effects of latitudinal differences, and the calculated vertical temperature reduction rate of elevation will reduce the elevation effects on the interpolated temperature.

In this paper, we calculated the variability of UHI intensity for each urbanization affected weather station by seasonal average air temperature for the periods: Dec.–Feb. (winter), Mar.–May (spring), June–Aug. (summer) and Sep.–Nov. (autumn).

3.2 *Analysis of statistical features of estimated UHI intensity*

In order to estimate regional UHI intensity effectively, a discrete mathematics method is used. At first, for each site in each season, the estimated UHI intensity is transformed from float format into integer format so that only 0 or 1 is assigned (Eq. 4).

$$D_{i,j}^{k} = \begin{cases} 0, & HI_{i,j}^{k} \leq 0 \\ 1, & HI_{i,j}^{k} > 0 \end{cases} \tag{4}$$

where k represents each season; i represents each year; j represents each urban weather station. Then, the frequency of the UHI effect (F_j^k) (i.e. UHI intensity is 1) at each station for each season during 1991–2000 is calculated.

$$F_j^k = \sum_i D_{i,j}^k \tag{5}$$

Finally, the probability distributions of the number of UHI affected sites (P_m^k) for each season at the regional scale is calculated.

$$P_m^k = \sum_j \begin{pmatrix} 1, & \text{if } F_j^k = m \\ 0, & \text{else} \end{pmatrix} \tag{6}$$

where m represents the number of years that site j represented positive UHI intensity in season k, the value scope of m is from 0 to 10. The probability of (P_m^k) is equal to $P_m^k/$sum of urban stations.

3.3 *Validation of the method*

To validate this method, we camed out experiments to randomly select urban and non-urban stations upon which to calculate UHI intensities for the study period. A station is defined as an urban type based on the possibility of an urban effect within a certain distance from the station. A one kilometre distance is selected as the buffering radius around the station to run the overlay procedure with NLCD urban layer by GIS. If the urban area covers more than 75% of the buffering zone of the station, the station is re-classified as an urban type, otherwise, as a non-urban station.

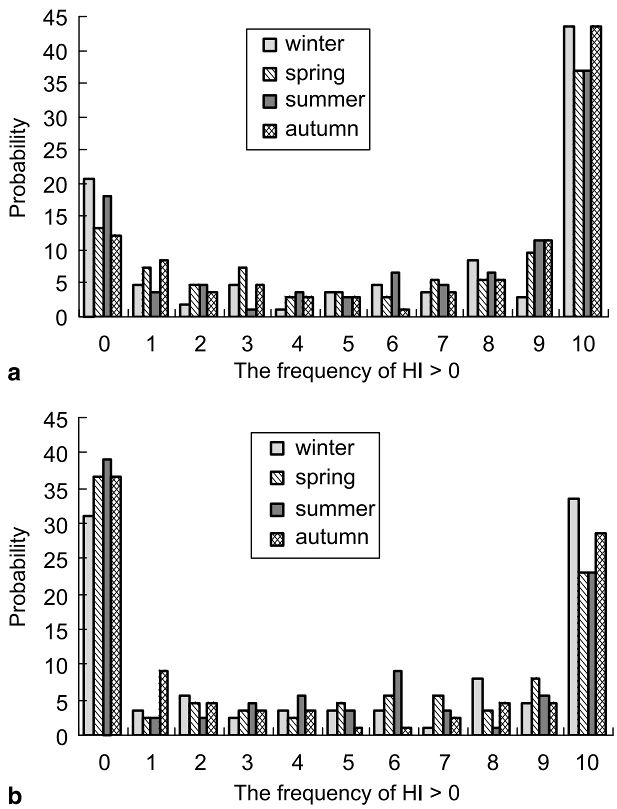

Fig. 3. Statistical distributions of P_m^k for both urban type (**a**) and non-urban type (**b**) stations

The statistical distributions of P_m^k for both urban and non-urban type stations are then calculated. Significant differences between them are found. For urban stations, when $m = 10$, the probability of P_m^k is the largest in all m and when $m = 0$, the probability of P_m^k is small; while for the non-urban stations, the probability distribution of P_m^k is close to the ideal situation that P_m^k is equal to $m = 0$ and $m = 10$ (Fig. 3). This indicates that our method effectively detects the UHI effect.

4. Results

4.1 The trend and seasonal variability of UHI intensity in China

The intensity of UHI varies seasonally. The urban effect on temperature is more significant in winter and autumn than that in spring and summer. For example, more stations have large UHI intensity in the first two seasons (Fig. 4). For each season, we found no significant trend in HI except in spring with an increasing rate of 0.11 °C per decade ($y = 0.011x + 0.605$, $R^2 = 0.517$) (Fig. 4). HI fluctuated from 1.0 to 1.2 °C (mean 1.1 °C) in winter, from 0.6 to 0.8 °C (mean 0.66 °C) in spring, from 0.6 to 0.7 °C (mean 0.65 °C) in summer, and from 0.7 to 0.8 °C (mean 0.76 °C) in autumn.

4.2 The spatial pattern of UHI intensity and its relationship with land use

To study the relationship between UHI intensity and land use change, we linked the variability of UHI intensity at the station level with land use change zoning maps (Liu et al., 2003) (Fig. 5). Table 1 describes the change area of main land use types in different land use change zones. From the percentage of urban stations intensively affected by UHI (we refer to the value of P_{10}^k from formula 6) in each zone, the spatial differences in urbanization effect on temperature would be discovered. Our results show that Zone 4 (Huang-Huai-Hai and Yangtze River delta cultivated land to urban land transform area) has the strongest UHI effect from 1991 to 2000 (Figs. 5 and 6).

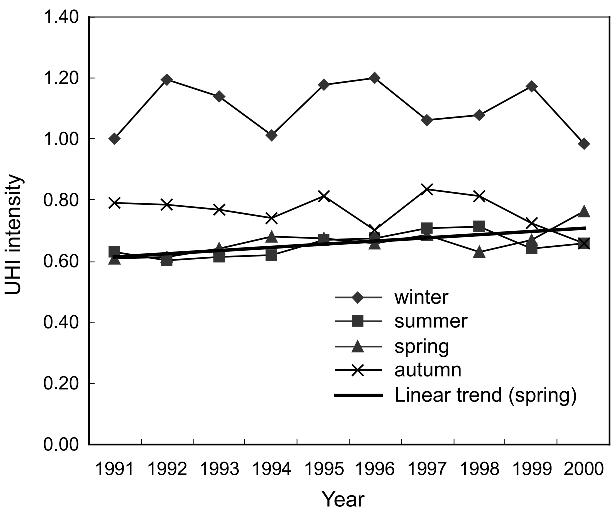

Fig. 4. Urban heat island intensity distributions in different seasons during 1991–2000 (unit: °C)

Our study also shows that the variability of UHI intensity is correlated with land use change during the period of 1991 to 2000 (Fig. 6). The greatest increase in UHI intensity took place in the area with rapid urbanization. Urbanization is a widespread phenomenon in China due to its fast economic growth and the increasing desire by people for an urban life style. During this study period, remote sensing data discovered that more than 70% of the increased urban area is located in Region 4 (Huang-Huai-Hai and Yangtze River delta region), Region 5 (Sichuan basin region), and Region 11 (East-southern seaside of China) (Liu et al., 2003, 2005a). Table 2 gives the urban area change ratios of the four main urban growth regions every five years during 1990–2000. Most of the newly increased urban area in Region 4 (about 1100 thousand hectares) is from farmland that has been cultivated for a long time. The urbanization process has greatly affected the local environment and climate systems in the last decade as has been shown in this study in the case of temperature in Regions 4, 6 and 7. The urban weather stations with greatest UHI effect are broadly distributed across these areas. In North China and the Loess Plateau region (Region 6), a large area covered by natural vegetation (reduction 1,695,820 ha.) and water (reduction 116,348 ha.) has been transformed into cropland and urban areas. This would induce significant environmental risks because of the fragile physical background (Zhang et al., 2003). The main feature of land use change in Central China (Region 8) is the transformation of paddy fields, pothole pools, bottomland and lakes and the expansion of urban land. In the southeastern hill forest, the land/cultivated land transformation area (Region 9), farmland and forestland re-

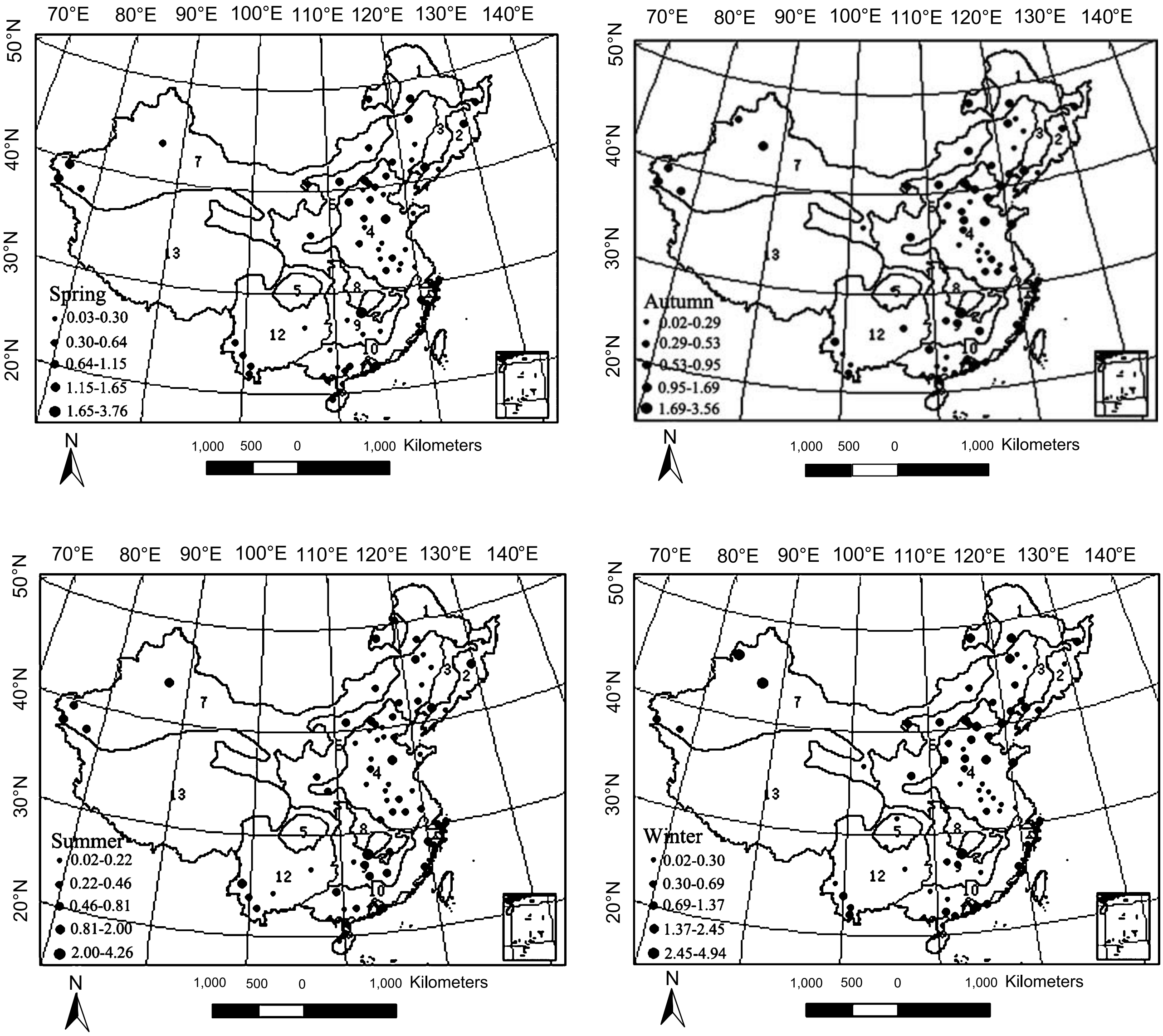

Fig. 5. The distribution map of urban stations which are affected by UHI overlaying with land use change zoning map in four seasons. The black dot represents urban station; the size of them represents the seasonal average UHI intensity of urban station; the number of polygon is the code of land use change zone, which are, *1* north-east China Da/xiao xing an mountains forestry/grass land → cultivated land transform area, *2* east part of north east China forestry/grass land → cultivated land transform area, *3* north-east China plain dry land → paddy field transform area, *4* Huang-Huai-Hai and Yangtze river delta cultivated land → urban land transform area, *5* Sichuan basin cultivated land → urban transform area, *6* north China/Loess Plateau farming and herding grass land → cultivated land transform area, *7* north-west China cultivated land expansion and waste land transform area, *8* central China interchange between paddy fields, pothole pools, bottomland and lakes and urbansprawl area, *9* south eastern hill forest land → cultivated land transform area, *10* south eastern seaside grass land → man made forestry transform area, *11* south-east seaside urban sprawl area, *12* south-western forest-grass land and forest grass land → cultivated land transform area, *13* Qinghai-Tibet Plateau little change area

veal a mixed distribution. Water area changes frequently. Though urbanization expands in these regions, due to the temperature regulation function of water, the climate environment is hardly affected by land use change. Therefore, in Regions 1, 2, 3, 5, 8, 9 and 13 (Qinghai-Tibet Plateau region, belonging to stable and less change areas), urban stations are either not or only very slightly affected by the UHI effect. However, because of development, some urban stations in big cities in these regions have experienced the UHI effect.

Table 1. Land use change area in different land use change zone

Zoning code	Paddy field	Dry field	Forestry	Grassland	Unused field	Water field	Urban
1	24251	905955	−758616	−145228	−42924	10260	6310
2	135401	603078	−319721	−320984	−106383	−4969	17192
3	383507	−39190	−125662	−64958	−137146	−50233	33756
4	−349546	−515504	−21995	−167852	−117955	61636	1093214
5	−54034	−19745	−8560	969	23	599	80747
6	271146	1709757	96903	−1695820	−329079	−116348	63506
7	13292	311202	5275	−872812	331655	126592	84802
8	−53126	−30327	1348	−3249	6417	30863	48079
9	−24611	−12394	−4305	−20030	−66	27748	33665
10	−56231	−6342	249235	−275544	−7268	36323	59455
11	−131076	−76699	2786	−9142	−789	41739	192767
12	−17632	11745	−208705	155929	−313	15901	43064
13	0	9066	2520	−18080	23609	−20100	2987

Unit: Ha. Positive value means increase, negative value means decrease.

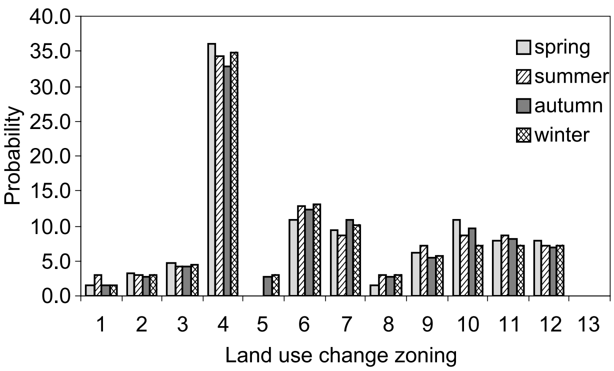

Fig. 6. The relationship between UHI spatial distribution and the land use dynamic change spatial distribution

5. Discussion

UHI is a special meteorological phenomenon in urban areas but is controlled by the physical characteristics and structure of the land surface within and around the urban area such as soil moisture, vegetation communities and impervious surface coverage. Detecting the UHI effect relies on the availability of meteorological data and the scale of study. At the regional scale, if urban expansion cannot be successfully detected and considered in analyzing the station data, the bias in estimating the UHI intensity and the temperature trend would be large. The method we used in this study is appropriate in studying the UHI effect when the availability of urban–rural pairs and meteorological stations is limited. At the regional scale, urban land use changes cannot be detected and may cause some bias in UHI studies (Brian et al., 1998). However, we selected the non-urban stations free of the influence of UHI, in some cases; microclimate differences cannot be removed completely within a range of 150 km. Also, the interpolation method itself may introduce some uncertainties because of the sparse distribution of the stations.

In order to evaluate our results we compared our study with that of Weng and Yang (2004) which examines the impact of urban development on UHI through a historical analysis of urban–rural air temperature differences. Weng and Yang (2004) indicates that during 1985–1995 and 1996–2000,

Table 2. Urban area change ratio in main 4 urban growth regions every five years during 1991–2000

Code	Urban area of 1990s	Increased area during 1990–1995	Increased area during 1995–2000	Ratio during 1990–1995	Ratio during 1995–2000
4	1143462.12	418811.35	69101.79	36.63	4.42
5	73057.95	19332.61	21261.72	26.46	23.01
8	135546.88	22887.80	3187.50	16.86	2.01
11	254623.56	101871.23	6541.32	40.01	1.83

Area unit: Ha.

Table 3. The UHI intensity of Guangzhou city measured in two ways

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Weng's result	0.542	0.458	0.492	0.400	0.658	−0.308	−0.125	−0.100	0.058	−0.050
Estimated in our paper	0.548	0.608	0.593	0.718	0.703	−0.203	−0.2	−0.025	0.025	0.12
Diff.	−0.006	−0.150	−0.101	−0.318	−0.045	−0.106	0.075	−0.075	0.033	−0.170

R^2: 0.822

the average intensity of the UHI is 0.7 °C/year and −0.13 °C/year, respectively, in the station located in Guangzhou, a big city in southeast China (Table 3). The intensity measured in Weng's paper is lower than ours and the $R^2 = 0.822$. The main reason for this difference is that the rural station has been affected by UHI after 1990 due to urban area enlargement and the rapid increase of its temperature. The high R^2-value, close to 1, shows that the precision of our estimated UHI intensity at this station is relatively high and reasonable. Those urban stations with negative HI during 1990–2000 are not considered as UHI affected stations in our study. For example, we did not select the weather station located in Guangzhou City as a UHI affected station because its HI was not always positive during 1990–2000. The negative HI may be mainly due to the impact of other land-use changes on non-urban stations (Kalnay and Cay, 2003), or may potentially be related to: (i) the difference of geographic environment (longitude and latitude, elevation, land use type) of the weather stations, or (ii) the location of the weather stations. In Fig. 3, we find that about half of the urban stations show no urban heat island effect (i.e. there are several negative HI in those stations). We did not discuss how to identify and detect whether an urban station was affected by UHI when the station revealed negative HI. Apparently, the estimation of UHI intensity is sensitive to methodology. For different countries and regions, the land use change, especially urbanization, effect on the intensity of the UHI effect is estimated to be 0.11 °C/year–0.91 °C/year (Karl et al., 1988; Wang et al., 1990; Streutker, 2003). We do not assess the effect of UHI on temperature trend series warming as do many studies such as Kalnay and Cai (2003), Zhou et al. (2004), Li et al. (2004). These studies indicate that the UHI effect causes the temperature warming trends of 0.05 °C/decade–0.011/decade depending on different regions and analysis methods.

If the weather station is located at the boundary of an urban area, it may not be detected even though it is surely affected by the UHI. The noise produced by the microclimate of the urban area where weather stations are located may disguise the UHI effect (Karl et al., 1988). Also, environmental variables, such as wind speed, cloud cover, atmospheric aerosol, air pollutions, and water vapor content, would have an impact on the UHI effect. This indicates that many factors can control the UHI effects occurring in an urban area.

Our study has indicated that the pattern of land use change is very important for the dynamics of local climate. For example, both the growth of the urban area and the drastic reduction in lake areas produced significant UHI effect in the urban area (Jazcilevich et al., 2000). In contrast, the expansion of the water surface can buffer the variation of surface temperature and so decrease the UHI effect.

6. Conclusions

It is feasible to estimate the UHI effect on urban weather stations at the regional scale by comparing observed temperature with interpolated background temperatures from near non-urban stations. Our results show that many weather stations were under the UHI effect during all seasons, especially in winter and autumn, and they were broadly distributed during the period of 1991–2000. The intensity of UHI revealed seasonal variation. In winter and autumn the urban effect on temperature was more significant than in spring and summer. The average UHI intensity was 1.1 °C in winter, 0.66 °C in spring, 0.65 °C in summer, and 0.76 °C in autumn during this ten-year period.

The urban stations affected by UHI are broadly distributed in the Huang-Huai-Hai River and Yangtze River Delta areas, Southeast China, the Loess Plateau of North China, and Wulumuqi city-Shihezi city in Northwest China. These areas have experienced rapid urbanization and other intensive land use change during this study period. We found that the variability of UHI intensity has a strong spatial connection with the pattern of land use, i.e. the influence of the UHI effect on urban stations is not only related to land use change type, but also to land use change structures. In regions where land use change type represented the sharp expansion of an urban area and the reduction in water area, the urban stations were often easily affected by UHI. On the other hand, in regions where land use change type was the expansion of urban area accompanied by an increase in water area or vegetation area, the urban stations were seldom affected by UHI. So, reductions in natural vegetation (forest and grass) and water area (such as wetland and lake) would change microclimate patterns of temperature and make the environment more fragile and climate elements more sensitive to global temperature change.

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References

Brian P, Dan Moses S-K, Craig KS, Hashem A (1998) Existing Climate Data Sources and Their Use in Heat Island Research, http://eetd.lbl.gov/EA/Reports/41973/ Existing Climate Data Sources and Their Use in Heat Island Research

Carlson TN, Arthur ST (2000) The impact of land use/land cover changes due to urbanization on surface microclimate and hydrology: A satellite perspective. Global Planet Change 25: 49–65

Esser G (1989) Global land-use changes from 1860 to 1980 and future projections to 2500. Ecol Model 44: 307–316

Gallo KP, Tarpley JD (1996) The comparison of vegetation index and surface temperature composites for urban heat-island analysis. Int J Remote Sensing 17: 3071–3076

Gao XJ, Luo Y, Lin WT, Zhao ZC, Giorgi F (2003) Simulation of effects of land use change on climate in China by a regional climate model. Adv Atomos Sci 20: 583–592

Grunblatt J, Ottichilo WK, Sinange RK (1992) A GIS approach to desertification assessment and mapping. J Arid Environ 23: 81–102

Harger JRE (1995) Air-temperature and ENSO effects in Indonesia, the Philippines and El Salvador. ENSO patterns and changes from 1866–1993. Atmos Environ 29: 1919–1942

Hillel D, Rosenzweig C (2002) Desertification in relation to climate variability and change. Adv Agron 77: 1–38

Huff FA, Changnon SA Jr (1972) Climatological assessment of urban effects on precipitation at St. Louis. J Appl Meteor 11: 823–842

IPCC (2001) Climate change 2001: Working Group I: The Scientific Basis, IPCC third assessment report

Jones PD, Groisman PY, Coughlan M, Plummer N, Wang WC, Karl TR (1990) Assessment of urbanization effects in time series of surface temperature over land. Nature 347: 1669–1772

Kalnay E, Cai M (2003) Impact of urbanization and land-use change on climate. Nature 423: 528–531

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Celliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D (1996) The NCEP/NCAR 40-year reanalysis project. Bull Amer Meteor Soc 77: 437–471

Karl TR, Diaz HF, Kukla G (1988) Urbanization: its detection and effect in the United States climate record. J Climate 1: 1099–1123

Kistler R, Kalnay E, Collins W, Saha S, White G, Woollen J, Chelliah M, Ebisuzaki W, Kanamitsu M, Kousky V, et al (2001) The NCEP-NCAR 50-year reanalysis: monthly means CD-ROM and documentation. Bull Amer Meteor Soc 82: 247–268

Lambin EF, Baulies X, Bockstael N, Fischer G, Krug T, Leemans R, Moran EF, Rindfuss RR, Sato Y, Skole D, Turber BL II, Vogel C (1999) IGBP Report No.48/IHDP Report No. 10: Land-use and land-cover change implementation strategy. IGBP Secretariat, The Royal Swedish Academy of Sciences, pp 75–85

Li Q, Zhang H, Liu X, Huang J (2004) Urban heat island effect on annual mean temperature during the last 50 years in China. Theor Appl Climatol 79: 165–174

Liu J, Tian H, Liu M, Zhuang D, Melillo JM, Zhang Z (2005a) China's changing landscape during the 1990s: Large-scale land transformations estimated with satellite data. Geophys Res Lett 32: L02405, doi:10.1029/2004GL021649

Liu J, Liu M, Tian HQ, Zhuang D, Zhang Z, Zhang W, Tang X, Deng X (2005b) Spatial and temporal patterns of China's cropland during 1990–2000: An analysis based on Landsat TM data. Remote Sensing Environ 98: 442–456

Liu JY, Zhang ZX, Zhuang DF, Wang YM, Zhou WC, Zhang SW, Li RD, Jiang N, Wu SX (2003) A study on the spatial-temporal dynamic changes of land-use and driving forces analyses of China in the 1990s. Geographical research (Chinese version) 22: 1–12

Liu JY, Liu ML, Zhuang DF, Zhang ZX, Deng XZ (2002) Analyses of the recent spatial land use change pattern in China. Sci China Ser D 32: 1031–1040

Lowry WP (1977) Empirical estimation of urban effects on climate: A problem analysis. J Appl Meteor 16: 129–135

Matsushita B, Xu M, Chen J, Kameyama S, Tamura M (2004) Estimation of regional net primary productivity (NPP) using a process-based ecosystem model: How important is the accuracy of climate data? Ecol Model 178: 371–338

Oke TR (1974) Review of urban climatology 1968–1973. Tech Note No. 134, WMO, 132 pp

Oke TR (1982) The energetic basis of the urban heat island. Quart J Roy Meteor Soc 108: 1–24

Owen TW, Carlson TN, Gillies RR (1998) An assessment of satellite remotely-sensed land cover parameters in quantitatively describing the climatic effect of urbanization. Int J Remote Sensing 19: 1663–1681

Roth M, Oke TR, Emery WJ (1989) Satellite-derived urban heat islands from three coastal cities and the utilization of such data in urban climatology. Int J Remote Sensing 10: 1699–1720

Streutker DM (2003) Satellite-measured growth of the urban heat island of Houston, Texas. Remote Sensing Environ 85: 282–289

Thornton PE, Running SW, White MA (1997) Generating surfaces of daily meteorological variables over large regions of complex terrain. J Hydrol 190: 214–251

Wang WC, Zeng Z, Karl TR (1990) Urban heat islands in China. Geophys Res Lett 17: 2377–2380

Wei HL, Fu CB (1998) Study of the sensitivity of a regional model in response to land cover change over northern China. Hydrol Process 12: 2249–2265

Weng QH, Yang SH (2004) Managing the adverse thermal effects of urban development in a densely populated Chinese city. J Environ Manage 70: 145–156

Zhang GY, Dong WJ, Ye DZ, Fu ZB (2003) New proof to validate the effect of vegetation on summer climate in China. Chinese Sci Bull 48: 91–95

Zhou LM, Dickinson RE, Tian YH, Fang JY, Li QX, Kaufmann RK, Tucker CJ, Myneni RB (2004) Evidence for a significant urbanization effect on climate in China. PNAS 101: 9540–9544

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