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Urbanization and its environmental effects in Shanghai, China

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ABSTRACT

This paper analyzes the processes and characteristics of urbanization in Shanghai, focusing on the population and land use and land cover (LULC) change, and its correlation with the evolution of climatic and ecological indicators based on the historical land use data, meteorological station data, social statistical data, normalized difference vegetation index (NDVI) and land surface temperature (LST) data. The possible association between urban heat island (UHI) and urbanization indicators are also discussed. Examination of the population variation indicates a continuously increase of registered population and a rapid increase of floating population that mainly comes from neighboring provinces in recent years. With rapid urban sprawl, a large amount of cultivated lands has been replaced with building lands around urban areas and towns of Shanghai. Urbanization is correlated with the increase of air temperature, hot days and the decrease of relative humidity, wind speed and vegetation NDVI in Shanghai. The growth of UHI in Shanghai has been driven by the continuous increase of buildings, paved roads, buses, population and GDP, as well as the decrease of cultivated land. Boosting the area of green land in urban areas has to a certain extent mitigated the UHI in Shanghai in recent years.

1. Introduction

Urbanization is one of the most powerful and visible anthropogenic forces on Earth (Dawson et al., 2009). Since the second half of the twentieth century, the world has experienced its fastest rate of urbanization, particularly in developing countries (Chadchan and Shankar, 2009). In 1957, 30% of

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the global population lived in urban areas, in 2008, it reached 50% and an estimated 70% is projected to live in cities by 2050 (United, 2007a). Today there are over 400 cities in the world with populations of over 1 million (United, 2007b) and in the foreseeable future, virtually all of the world's population growth will be absorbed by the urban areas of the less developed regions, whose population is projected to increase from 2.4 billion in 2007 to 5.3 billion in 2050 (United, 2007a). Therefore, urbanization has played an important role in the development and modernization of underdeveloped and developing countries, and increasing attention has been paid to cities and urbanization from scientists and policy makers over the last several decades (Hope, 1986; Zhang and Song, 2003; Siciliano, 2012).

Rapid urbanization has greatly accelerated economic and social development, and global cities are engines of economic growth and centers of innovation for the global economy and the hinterlands of their respective nations (De Sherbinin et al., 2007), but urbanization has also created numerous environmental problems ranging from the local to the global scale (Kim and Baik, 2005; Zhao et al., 2006), including increased air and water pollution and decreased water supply (Liu and Diamond, 2005; Shao et al., 2006), local climate alteration and increased energy demands (Zhou et al., 2004; González et al., 2005), insufficient housing and sanitation facilities and traffic congestion (Jago-on et al., 2009), and a major reduction in natural vegetation production and carbon storage/sequestration (Fang et al., 2003; Yuan, 2008). Thus, the identification and assessment of environmental impacts as a result of modern urbanization have become a top priority and many recent studies have been conducted with the goal of better understanding the impacts and issues related to urbanization (Foster, 2001; Chen, 2007; Li and Yao, 2009; Martínez-Zarzoso and Maruotti, 2011).

Shanghai is a coastal modern megacity in East China, with the area of 6340.5 square kilometers and the population of about 23.0 million (Shanghai Municipal Statistics Bureau, 2011). Since China's economic reform in the late 1970s, Shanghai, the country's largest and most modern city has experienced rapid expansion and urbanization (Zhao et al., 2006). The resulting environmental and ecological consequences of urban sprawl have caused considerable concern and several studies have documented some environmental impacts of urbanization, for example, Li et al. (2002) evaluated the influence of urban sprawl and the change of land use on urban climate from 1845 to 1995; Ren et al. (2003) investigated the relationship between water quality and urbanization as well as the changing patterns of land use within Shanghai; Hu et al. (2004) revealed the ways of heavy metal accumulation in soil during rapid urbanization in Shanghai and Zhao et al. (2006) explored the land-use and land-cover changes during 1975–2005, focusing on the impacts of the urbanization process on air and water quality, local climate and biodiversity.

To date, however, long-term (spanning both pre- and post-urbanization periods) and spatially explicit monitoring of the urbanization of the entire Shanghai area, together with comprehensive studies of the climatic, environmental and ecological consequences of rapid urbanization, have not been conducted. The aim of this study is to detect the processes and characteristics of urbanization in Shanghai, focusing on the land use change and population change, and to analyze its correlation with the evolution of climatic and ecological indicators in Shanghai based on the historical land use data, meteorological station, social statistical data, normalized difference vegetation index (NDVI) and land surface temperature (LST) data. We also examine the possible association between urban heat island (UHI) and urbanization indicators in Shanghai in recent years.

2. Datasets and methods

2.1. Study area

Being located on the coast of the East China Sea and at the estuary of the Yangtze River, Shanghai is significantly influenced by humid subtropical monsoon circulation and experiences four distinct seasons, with a mean annual temperature of 15.8 °C and an annual precipitation of 1149 mm. Shanghai has the highest population density in China and is one of the most vigorous economic zones in the world, with 1717 billion Chinese Yuan of gross domestic product (GDP) in 2010 (Shanghai Municipal Statistics Bureau, 2011), accounting for 4.3% of China's total amount. It is administratively equal to a province and is divided into 18 county-level divisions: 17 districts and one county (Fig. 1), of which 9 districts in the core of city are collectively referred to as urban areas, i.e. Huangpu, Luwan, Xuhui,

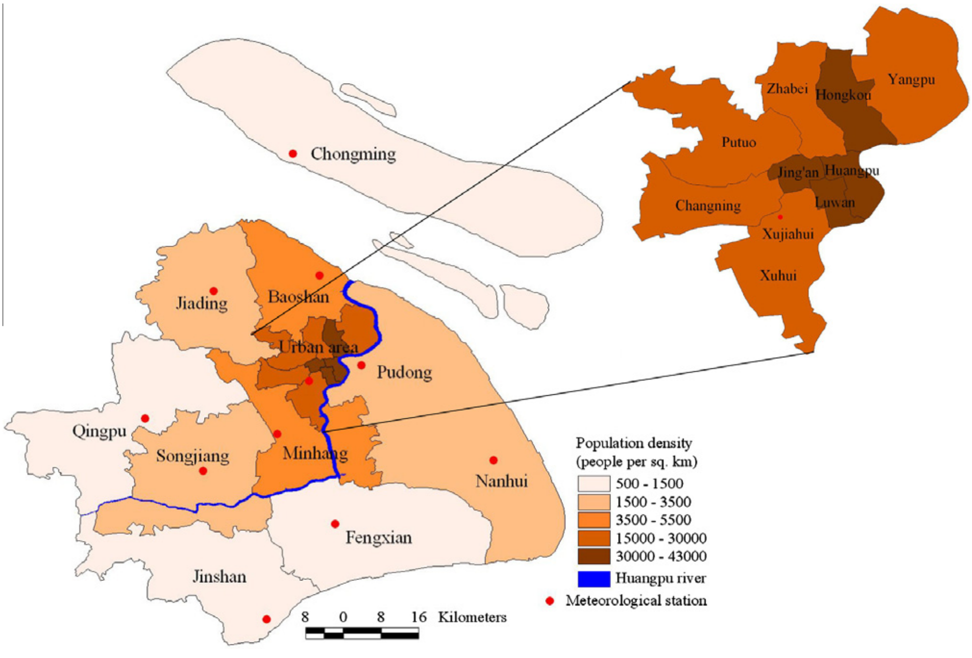

Fig. 1. Study area and the distribution of 11 meteorological stations in Shanghai.

Changning, Jing'an, Putuo, Zhabei, Hongkou and Yangpu district, and other 9 districts further away from the urban areas are Baoshan, Minhang, Jiading, Jinshan, Songjiang, Qingpu, Fengxian, Pudong district and Chongming County. Totally there are 11 meteorological stations in Shanghai, and Xujiahui station is the only representative station of urban areas.

2.2. Data sources

The datasets used in this study include: (1) land use data in 1980 and 2008 derived from cloud-free Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) remote sensing images respectively; (2) annual air temperature, relative humidity, wind speed data and daily air temperature data of Xujiahui and Chongming station in Shanghai from 1960 to 2010 (Fig. 1), which come from Shanghai Climate Center, Shanghai Meteorological Bureau; (3) 10-day composited (maximum-value) SPOT-4 VGT-DN data with 1 km spatial resolution during 1999–2010, which come from the Flemish Institute (http://free.vgt.vito.be/home.php); (4) MODIS near land surface temperature (LST) product on 2 December, 2006 and 18 July, 2007 from Reverb (http://reverb.echo.nasa.gov/reverb/) and ground-based hourly temperature data from 11 meteorological stations in Shanghai; (5) social statistical data, including registered population, gross domestic product (GDP), living space per capita, the area of cultivated land, paved road, building completed and total buildings (including residential and non-residential buildings), water supply and power consumption, sales of gas and liquefied petroleum gas (LPG), the number of operating buses, garbage produced and night soil disposal in Shanghai during 1949–2010, the waste water discharged and waste gas emission during 1991–2010, the use of natural gas during 2000–2010, population density during 1970–2010, population density in 18 districts (or county) of Shanghai in 2000 and 2008, which come from Statistical Yearbook of Shanghai (Shanghai Municipal Statistics Bureau, 2011).

2.3. Methods

In this study, 9 districts in the center of city are regarded as urban areas, all with the population density of more than 15 thousand inhabitants per square kilometer (Fig. 1). According to the population density and the distance to urban areas, five meteorological stations, i.e. Chongming, Qingpu, Jinshan, Fengxian and Nanhui station are regarded as rural stations. Here we define the difference of mean annual temperature between Xujiahui and Chongming station as urban heat island (UHI) index, and the relationships between UHI index and urbanization indicators, including the number of operating buses, area of paved road, building completed and cultivated land, GDP and total registered population are analyzed and discussed.

Remotely sensed images of Landsat TM were interpreted into land use and land cover (LULC) datasets at scale of 1:100,000 after being radiantly corrected, geo-referenced and ortho-rectified. The chosen images were RGB false-color composed correspondent with 4, 3, 2 bands. They were mosaiced together using the county boundary vector data. The major task of pre-processing images was the geometric registration; the latter registration used the quadratic method. The specification for image to image registration is 0.3 pixel in both directions and this accuracy requirement was met for most of the sites. The county land-use vector datasets were created by interpreting TM images in conjunction with the 1:100,000 and 1:50,000 topography maps. During the interpretation process, topography, geomorphology, vegetation, precipitation and temperature datasets were used as the ancillary data.

To analyze the climatic effects of urbanization in Shanghai, two stations, i.e. Xujiahui and Chongming were selected as urban and rural representative station respectively to analyze the difference of the temporal change of mean annual temperature, relative humidity, wind speed and annual hot days during 1960–2010. The hot days are defined as those with daily maximum temperature no less than 35 °C. The near land surface temperature (LST) in typical cloud-free days of winter and summer was also retrieved from MODIS LST product to further explain the temperature effects of different land use types. The MODIS LST product and ground-based temperature data from 11 meteorological stations were collected to build the retrieve equations of daytime LST, and the accuracy of the equation was also validated.

In Shanghai, mean annual normalized difference vegetation index (NDVI) lies in the range 0.1–0.6 during 1999–2010 spatially, so we divided the whole Shanghai into two categories: higher or lower NDVI areas. Regions with mean annual NDVI more than 0.3 were classified as higher NDVI areas and regions with NDVI more than 0.1 but less than 0.3 were classified as lower area. Two time periods, namely 1999–2001 and 2008–2010, were selected to analyze the change of higher and lower NDVI areas under the urbanization and socioeconomic development in Shanghai.

3. Results and discussion

3.1. Urbanization in Shanghai

3.1.1. Change of total population and population density

Economic growth and industrialization have stimulated rapid urbanization and population growth in Asia (Jago-on et al., 2009). From 1949 to 2010, with rapid industrialization and urbanization, Shanghai has experienced a significant change in total population and population density. Registered population has increased continuously from 5.03 million persons in 1949 to 14.12 million persons in 2010 (Fig. 2a), with another 8.98 million persons of floating population that reside in Shanghai for above half year currently (Shanghai Municipal Statistics Bureau, 2011). Ten counties of Jiangsu province along the boundary with Shanghai were incorporated into Shanghai in 1958, so there is a jump of registered population during 1959–1960. Registered population has changed with an increasing rate of 0.72 million persons per decade between 1981 and 2010, and the long-term trend is statistically significant. Since 1993, Shanghai has been the first region of China to have a negative fertility growth rate in its registered population, while the total number of registered people is increasing owing to immigration.

Population density has also significantly increased from 1734 persons per square kilometer to 3632 persons per square kilometer during 1970–2010 in Shanghai, with an increasing rate of 419 persons per square kilometer per decade. During 2000–2008, population density has increased in most districts of Shanghai, with Putuo district has the greatest increase of 4457 persons per square kilometer, followed by three suburban districts, i.e. Baoshan, Minhang and Pudong, with the increase of 3240,

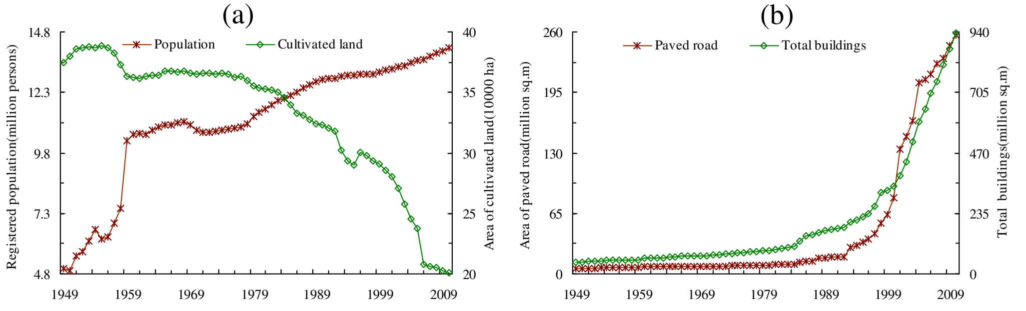

Fig. 2. Change of urbanization indicators in Shanghai (a: registered population and cultivated land; b: paved road and total buildings).

3109 and 2579 persons per square kilometer. In four urban districts, i.e. Jing'an, Luwan, Huangpu and Hongkou population density has decreased, with Jing'an district has the greatest decrease of 13,153 persons per square kilometer (Fig. 3a). This is related to the relocation of residents to suburban areas for major municipal engineering and other construction in Shanghai. With rapid urbanization and economical development around, some people in Chongming County have left their hometown, so the density of population in Chongming has also deceased by 61 persons per square kilometer during 2000–2008.

The increase of population density in Shanghai mainly results from the addition of floating population in recent years. According the Statistical Yearbook of Shanghai (Shanghai Municipal Statistics Bureau, 2011), there are 8.98 million floating population in Shanghai in 2010, with Pudong and Minhang districts have the greatest number of 2.02 and 1.20 million floating population respectively. In urban areas of Luwan, Jing'an and Huangpu districts and Chongming County, floating population is relatively less relevant (Fig. 3b). In China, rural–urban migration has made dominant contributions to urban population growth (Zhang and Song, 2003). As temporary migrant workers, a large proportion of floating population in Shanghai comes from neighboring Anhui province as well as Jiangsu and Zhejiang provinces. Many migrant workers are farmers and farm workers made obsolete by modern farming practices and factory workers who have been laid off from inefficient state-run factories. They include men and women and couples with children. Men often get construction jobs while women work in cheap-labor factories.

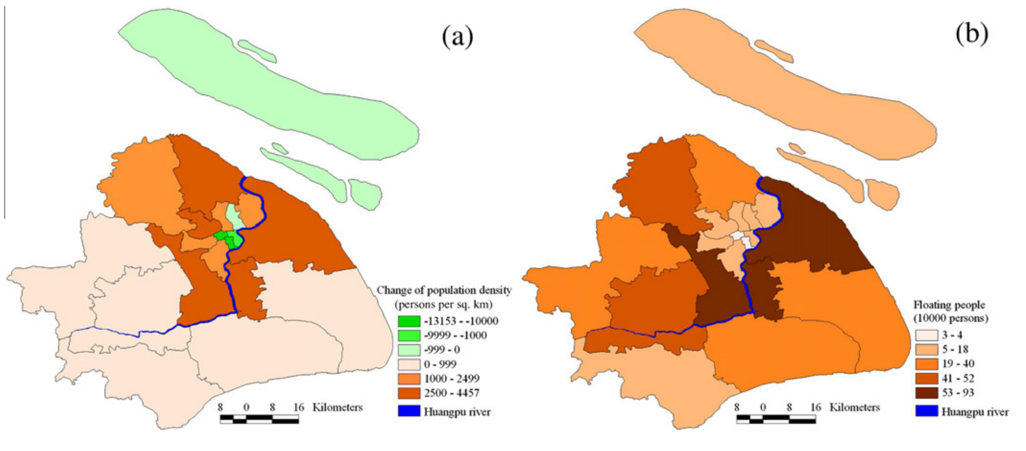

Fig. 3. Change of population density during 2000–2008 (a) and the floating people in 2008 (b) in Shanghai.

3.1.2. Change of land use and land cover

The land resources are confronted with more and more serious space and environment pressure with industrialization, city and town-rization's development in Shanghai. Due to rapid economic development, Shanghai has experienced one of the greatest rates of change in land use and land cover (LULC) during the last three decades, and this change is mainly urban expansion and cultivated land reduction. During the period from 1949 to 2010, cultivated land has reached the largest area with 388.7 thousand hectares in 1955, and it reached the least area with 201.0 thousand hectares in 2010 (Fig. 2a). In the past 62 years, cultivated land has significantly decreased with a rate of 26.7 thousand hectares per decade, especially after 1980, cultivated land has decreased rapidly with a rate of 53.5 thousand hectares per decade.

Fig. 4 shows the land use map of Shanghai in 1980 and 2008. Cultivated land has the largest area, followed by building land and water body, and grassland has the least area during 1980–2008. Compared with that of 1980, land use types have changed significantly in 2008, with building land, including towns, residential and constructional areas, expanding greatly, and a large amount of cultivated land replaced by building land. Moreover, the increase of building land mainly occurred around urban areas and towns of Shanghai. The change of forest land, grassland and water body is less than cultivated land and building land. In 2008, the areas of cultivated land, forest land, grassland, water body and building land are 3735.2, 99.0, 15.3, 474.6 and 2060.5 square kilometers respectively, accounting for 58.5%, 1.6%, 0.2%, 7.4% and 32.3% of the total area in Shanghai.

From 1980 to 2008, the total area of land use change is 3076.2 square kilometers, accounting for 48.8% of the total area of Shanghai. Compared with that of 1980, cultivated land has a net decrease of 1497.8 square kilometers in 2008, accounting for 28.6% of the total cultivated land area of 1980, and building land (including town, residential area and other buildings) has increased 1419.5 square kilometers, accounting for 221.5% of the total building area (Fig. 5). Meanwhile, forest land has increased by 110.6% from 47.0 to 99.0 square kilometers, grassland has increased by 17.7% from 13.0 to 15.3 square kilometers and water body has increased by 28.3% from 370.0 to 474.6 square kilometers. With rapid urbanization and economic development, a large area of high-quality cultivated land has been changed to residential or constructional areas in Shanghai.

Urban expansion and subsequent LULC changes in Shanghai have largely been driven by policy reform, population growth and economic development (Yin et al., 2011). The change of land use types in Shanghai is consistent with other cities of China. Tan et al. (2005) indicated that urban land expansion of the 145 cities in China between 1990 and 2000 mainly occurred on former arable land. Yin et al. (2011) explored the spatio-temporal dynamics and evolution of LULC changes and urban expansion in Shanghai during the transitional economy period (1979–2009) and the results also indicated that urbanization had accelerated at an unprecedented scale and rate during the study period, leading to

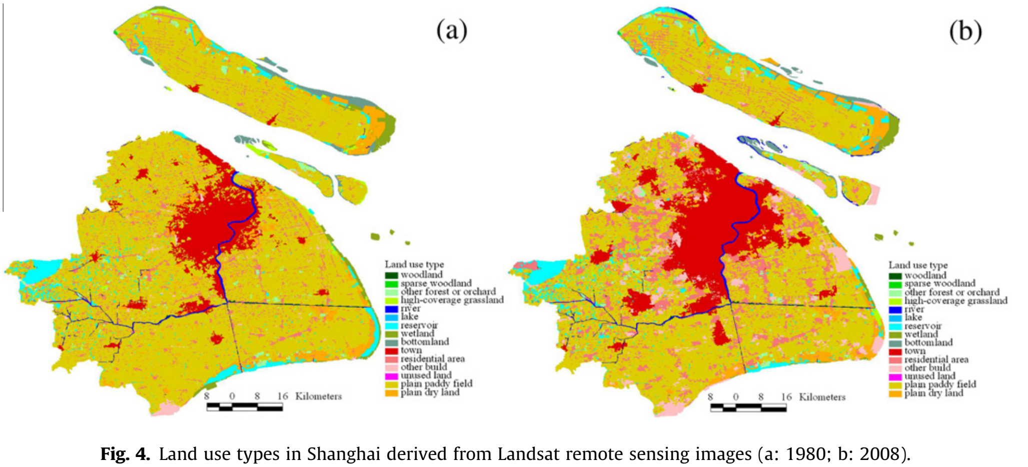

Fig. 4. Land use types in Shanghai derived from Landsat remote sensing images (a: 1980; b: 2008).

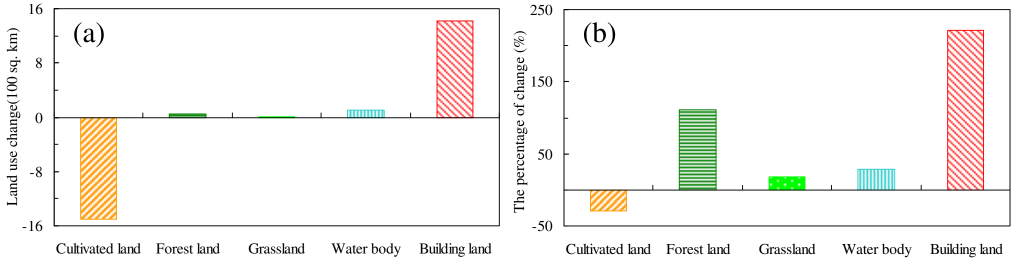

Fig. 5. Absolute (a) and percentage (b) change of land use in Shanghai during 1980–2008.

a considerable reduction in the area of farmland and green land. The increase of water bodies in Shanghai is due to the large-scale coastal development after 2000 (Yin et al., 2011). For enriching the supply of the seafood market and improving the people's livelihood, aquaculture industries have developed rapidly in the southern parts of Shanghai, especially in Fengxian district. Furthermore, the constructions of artificial landscape lake in many newly built communities make a certain contribution to the increase of water bodies in the whole Shanghai (Guo and Hu, 2010).

3.1.3. Change of other urbanization indicators

The process and extent of urbanization in Shanghai are also shown in other respects, such as area of paved road and buildings, GDP, water supply and power consumption, sales of gas and LPG, etc. From 1949 to 2010, the area of paved road in Shanghai has increased significantly (Fig. 2b), especially after 1992, it increases with a rate of 152.8 million square meters per decade. Meanwhile, the total area of buildings (including residential and non-residential buildings) has increased from 46.79 million square meters in 1949 to 935.92 million square meters in 2010, and during 1992–2010, it has increased rapidly at a rate of 433.3 million square meters per decade, with the living space per capita increasing from 6.9 square meters in 1992 to 17.5 square meters in 2010. Since the beginning of the old city reconstruction and Pudong development in 1992, major construction and renovation of the municipal infrastructure has resulted in the fast reduction of cultivated land and growth of buildings and paved roads in Shanghai.

Water supply in Shanghai has increased significantly from 180 to 3090 million cubic meters during 1949–2010, with an increasing rate of 489 million cubic meters per decade (Fig. 6a), of which the volume of tap water sold for living use has increased rapidly from 100 to 1864 million cubic meters, with an increasing rate of 264.2 million cubic meters per decade, and the tap water sold for industrial use has increased from 31 to 580 million cubic meters during 1949–2010, with an increasing rate of 110.5 million cubic meters per decade. Power consumption has also increased significantly from 881 to 129,587 million kilowatt hours during 1950–2010, with an increasing rate of 16,171 million kilowatt hours per decade (Fig. 6a), of which industrial consumption has increased from 756 to 78,661 million kilowatt hours, with an increasing rate of 10,533 million kilowatt hours per decade, and urban residential consumption has increased from 253 to 16,895 million kilowatt hours during 1950–2010, with an increasing rate of 2984 million kilowatt hours per decade.

Total sales of gas have increased significantly from 30 to 1285 million cubic meters during 1949–2010, with an increasing rate of 359 million cubic meters per decade, and in 2003, the total sales of gas is the greatest (2193 million cubic meters) (Fig. 6b). Production use of gas has increased gradually from 6 to 521 million cubic meters during 1949–1987, and after that it decreased gradually. Residential use of gas has increased gradually from 23 to 1884 million cubic meters during 1949–2003, and after that it also decreased gradually. The sales of LPG have increased rapidly from 1993 to 2001 in Shanghai (Fig. 6b). In 2001, the total sales of LPG were 500.9 thousand tons, and after that they also decreased as a whole. The decreasing sales of gas and LPG are related to the intensive use of natural gas in Shanghai at the beginning of this century. The sales of natural gas have increased from 216 million cubic meters in 2000 to 4266 million cubic meters in 2010, of which 779 million cubic meters of natural gas is used for household consumption.

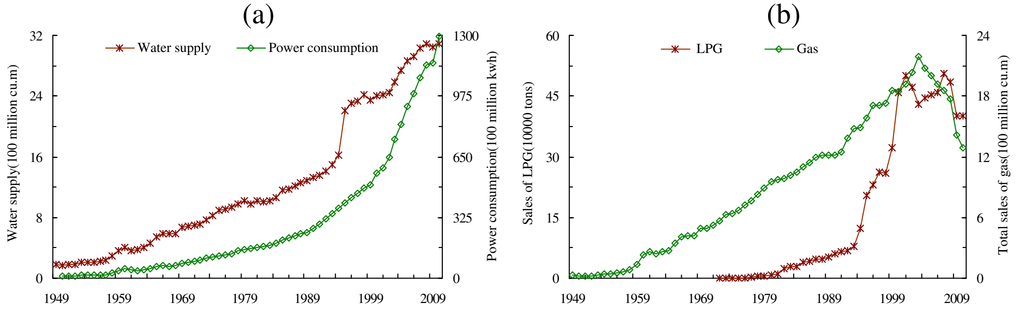

Fig. 6. Change of other urbanization indicators in Shanghai (a: water supply and power consumption; b: liquefied petroleum gas and gas).

3.2. Environmental effects of urbanization in Shanghai

3.2.1. The climatic effects of urbanization

Expansion of cities to accommodate increasing population has global, regional, and local effects on weather and climate because of LULC changes and accompanying effects on physical processes governing energy, momentum, and matter exchange between land surfaces and the atmosphere (Cotton and Pielke, 2007; Zhang et al., 2009). Urbanization significantly impacts regional near-surface air temperatures and wind fields, subsequently influencing air quality, human comfort and health (Grossman-Clarke et al., 2010). Recent studies demonstrate that LULC changes have important impacts on diurnal temperature range (Stone and Weaver, 2003; Balling and Cerveny, 2003; Bounoua et al., 2004) and temperature extremes (Tonkaz and Çetin, 2007; Grossman-Clarke et al., 2010). It is estimated that the mean surface temperature over Southeast China has increased by 0.05 °C per decade under the impact of urbanization (Zhou et al., 2004). Kalnay and Cai (2003) also suggested that half of the observed decrease in diurnal temperature range is due to urban and other land-use changes in the continental United States.

Fig. 7 shows the difference of annual mean temperature, relative humidity, wind speed and annual hot days in urban and rural station during 1960–2010. The differences for four climatic factors between urban and rural station are all significant since 1980s, and as time goes on, the differences increase. The mean annual temperature in Xujiahui station is higher than that of Chongming station with 0.84 °C during 1960–2010, and the difference has significantly increasing trend, with 0.41 °C during 1960–1970 to 1.30 °C during 2001–2010. The mean annual relative humidity and wind speed in Xujiahui station are lower than that of Chongming station with 4.3% and 0.95 m/s during 1960–2010 respectively, and the differences significantly increase from 2.7% and 0.7 m/s during 1960–1970 to 5.0% and 1.6 m/s during 2001–2010 respectively. The annual hot days in Xujiahui station are more than that of Chongming station with 7.7 days during 1960–2010, and the difference has significantly increasing trend, increasing from annual 3.8 days during 1960–1970 to 16.3 days during 2001–2010.

The construction and maintenance of impervious surfaces such as buildings and paved roads are a major human alteration of the land surface that leads to a relatively higher temperature in urban areas comparing to the surrounding rural areas in Shanghai. The waste heat released from urban houses, transportation and industry, further contributes to the development of thermal difference between the urban and the rural areas. In Shanghai, the spatial pattern of land surface temperature (LST) is generally consistent with the land use types either in winter or in summer (Fig. 8). The LST is higher in the urban area, towns and other construction area and lower in Chongming County and the southwestern parts of Shanghai. Generally, the difference of LST is about 8.0 °C in winter and 3.0 °C in summer. In summer, the LST is lower in the southeastern parts of Shanghai and Chongming County. This is due to the summer prevailing wind patterns (southeastern wind) that bring cool air from the East China Sea to Shanghai.

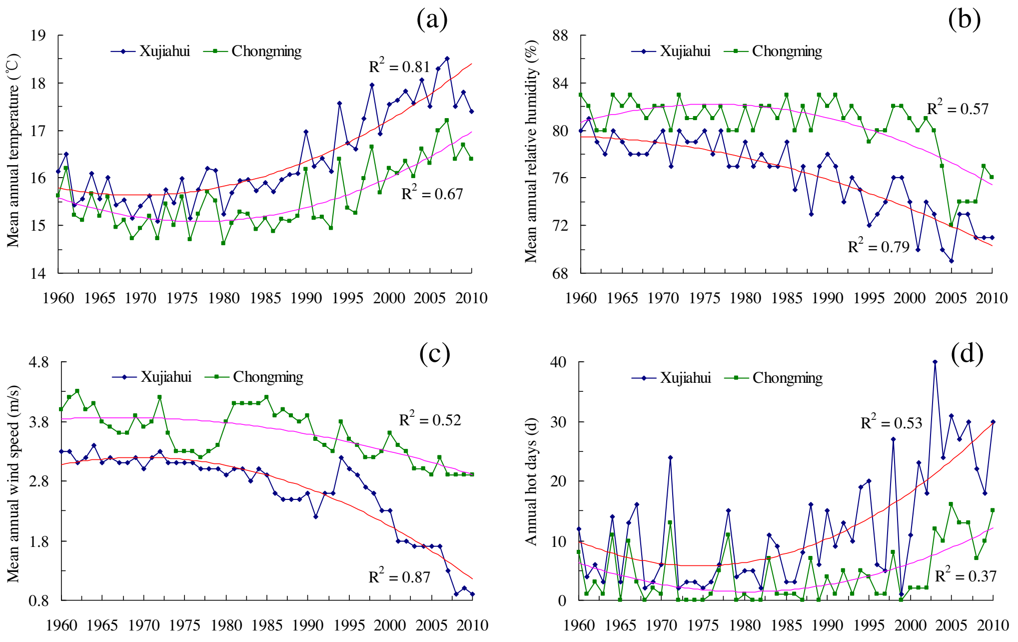

Fig. 7. Variation of mean annual temperature (a), relative humidity (b), wind speed (c) and hot days (d) in urban and rural station during 1960–2010. (The blue and green lines are the annual variation of climatic factors in Xujiahui and Chongming station respectively, the red and pink lines are quadratic polynomial fitted curve, and the R-squared is the coefficient of determination). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

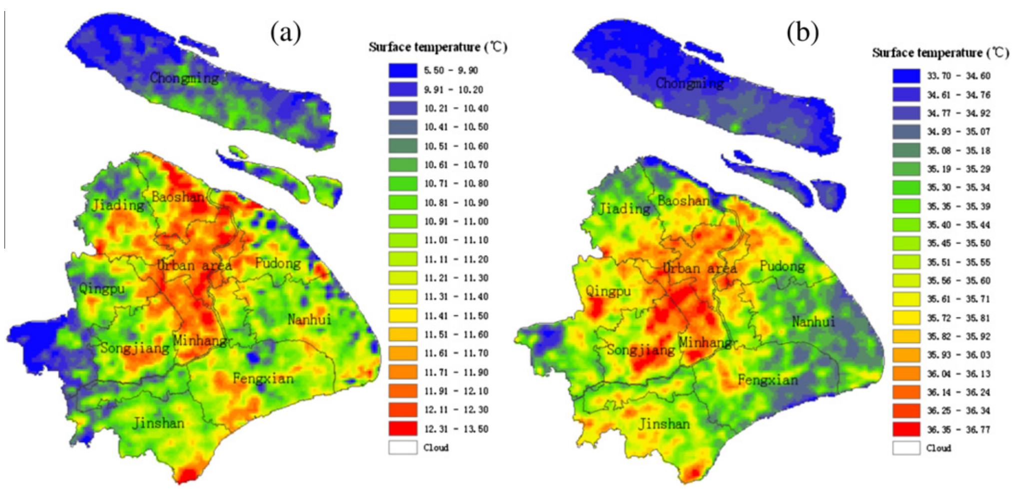

Fig. 8. Spatial pattern of land surface temperature (LST) in winter (a) and summer (b) retrieved from MODIS product in Shanghai.

3.2.2. The pollution effects of urbanization

Urbanization places a heavy burden on the urban atmosphere and water quality. In Asian countries, megacities contribute approximately 16% of the total anthropogenic sulfur emissions (Guttikunda et al., 2003). The results from Ren et al. (2003) reveal that rapid urbanization corresponds with rapid degradation of water quality in Shanghai, and a regression model shows that close to 94% of the variability in water quality classifications is explained by industrial land area. Zhang (2007) indicates that metals have been reduced efficiently, but organic pollutants develop in aggravating trend as human sewage increase in the Huangpu River, Shanghai from 1991 to 2002. The ways of urbanization and urban transformations unfold over the next few decades will have profound implications for the quantity and quality of water resources (Lebel, 2005) and atmospheric environment in Shanghai.

With the acceleration of urbanization and the remarkable improvement of people's living standard, the problems relevant to environmental pollution have become more and more serious in Shanghai. Garbage produced has increased from 960 thousand tons in 1950 to 8900 thousand tons in 2010, with an increasing rate of 1443.7 thousand tons per decade in Shanghai during 1950–2010 (Fig. 9a), of which residential garbage takes a large proportion, with an increasing rate of 1332.1 thousand tons per decade. Night soil disposal has increased from 960 to 4180 thousand tons during 1952–1978, and after that it has decreased mainly due to the increase of septic tanks.

The pollution effects of urbanization in Shanghai also involve in the waste water discharged and waste gas emission. During 1991–2010, total waste water discharged in Shanghai is 41,915 million tons, with mean annual waste water discharged of 2096 million tons (Fig. 9b). Industrial waste water discharged has decreased with an annual rate of 56.0 million tons, while residential waste water discharged has increased with an annual rate of 67.7 million tons. Total waste gas emission has increased with an annual rate of 44.0 billion cubic meters during 1991–2010, of which industrial waste gas emission has increased rapidly, with an annual increasing rate of 43.1 billion cubic meters.

Pollutants can affect human health in many ways with both short-term and long-term effects, and people with health problems such as asthma, heart and lung disease may also suffer more from environmental pollution. Urbanization has become an extremely serious public health challenge, and the increase in coronary heart disease in Asian countries was found to be associated with the growing urbanization (Khoo et al., 2003). Ye et al. (2000) also suggested that the huge increase in the number of motor vehicles associated with the urbanization process had led to serious human health risks in Shanghai. In Shanghai, total patients treated in medical institutions have increased from 5.4 person-times per year-end resident in 2000 to 9.1 person-times per year-end resident in 2010, and in-patients in medical treatment institutions have increased from 7.6 persons per 100 year-end residents in 2000 to 12.4 persons in 2010 (Shanghai Municipal Statistics Bureau, 2011). The increasing percentage of patients in Shanghai is partly attributed to the environmental pollution during urbanization.

3.2.3. The ecological effects of urbanization

The exchange of energy, water, and momentum between the land surface and the atmosphere is strongly influenced by the physical characteristics of vegetation and soils. In the process of urbanization, natural vegetation cover is largely replaced by paved surfaces, and open spaces are maintained for recreational or ornamental purposes, so that the ecosystem dynamics of the remaining green areas

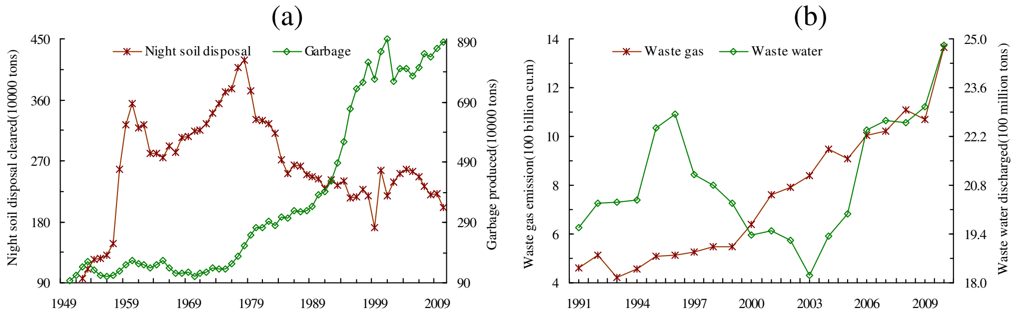

Fig. 9. The change of environmental pollution in Shanghai (a: garbage produced and night soil disposal; b: waste gas emission and waste water discharged).

of the city are usually quite different from those of the open countryside (Shi et al., 2009). Thus, changes in vegetation imply changes in the physical properties of land surface, including surface albedo, surface roughness, leaf-area index, rooting depth, and availability of soil moisture (Lamptey et al., 2005). Research on land surface temperature showed that the partitioning of sensible and latent heat fluxes and thus surface radiant temperature response is a function of varying surface soil water content and vegetation cover (Owen et al., 1998).

Urbanization has great effects on vegetation coverage and NDVI in Shanghai. Fig. 10 shows the mean annual NDVI during 1999–2001 and 2008–2010. During two periods, the area with higher NDVI has decreased, and the area with lower NDVI has increased significantly. During 1999–2001 and 2008–2010, the area of higher mean annual NDVI accounted for 85.8% and 76.2% of the total area respectively, and the area of lower mean annual NDVI accounted for 12.5% and 22.6% of the total area respectively. Moreover, the decrease of NDVI was mainly occurred around the urban areas and towns.

Urbanization is generally associated with an increase in managed green areas, such as street trees, lawns, and parks for urban recreation and these improve both the visual appeal of a city and environmental quality (Attwell, 2000). In parallel with its urban expansion, Shanghai's green areas have continued to increase in size, and the total area of green space has increased from 720 hectares in 1972 to 120,148 hectares in 2010 (Shanghai Municipal Statistics Bureau, 2011). The increase of NDVI in urban areas is related to the rapid increase of urban green area.

As the third largest island in China and the largest alluvial island in the world, Chongming Island was declared as an ecological island by the Shanghai Government in 2003. All development activities that conflict with the protection of the environment will be prohibited on the island. At the same time, the Shanghai Government provides monetary compensation to local communities and encourages local resident participation in the protection of the island (Yuan et al., 2003). So in the past 12 years, vegetation NDVI in Chongming Island has increased and the area with mean annual NDVI more than 0.5 accounts for 29.9% and 54.4% of the total area of Chongming Island during 1999–2001 and 2008–2010 respectively.

3.2.4. The relationship between urbanization indicators and urban heat island in Shanghai

Urbanization leads to alterations of the local climate, and in particular creates a significant urban heat island (UHI) effect (Kalnay and Cai, 2003; Zhou et al., 2004). The rapid urban sprawl and the change of land use have resulted in remarkable heat island phenomenon in Shanghai, China in recent years (Li et al., 2002; Zhang et al., 2010). Urban areas are often jungles of asphalt, concrete, brick and other dark materials for the construction of roads and buildings. All of these man-made materials have a low reflectivity, and function to absorb incident solar radiation (Oke, 1982). In addition, the urban areas have a large population and dense buildings, which results in the large amount of anthropogenic heat release from vehicles, plants, air conditioners, and other heat sources and the heat stored and

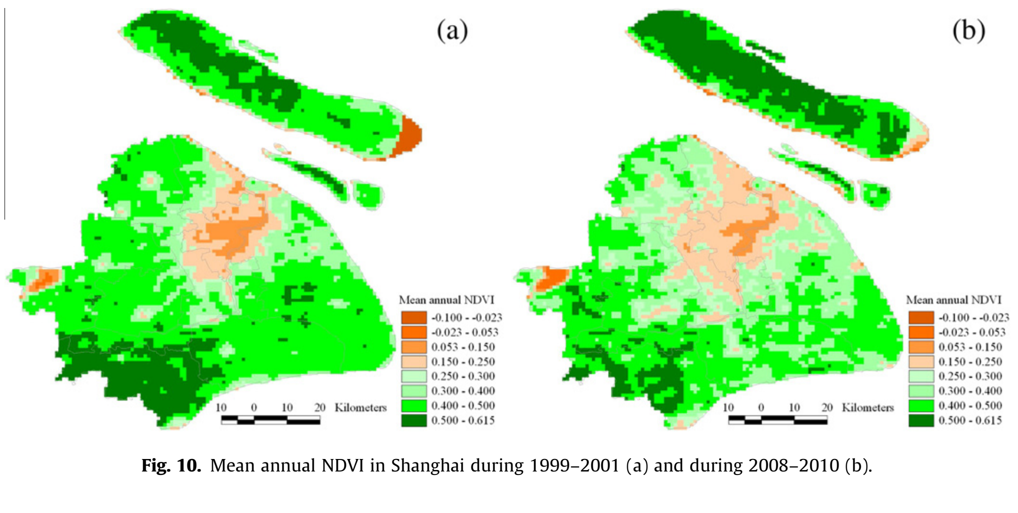

Fig. 10. Mean annual NDVI in Shanghai during 1999–2001 (a) and during 2008–2010 (b).

reradiated by massive and complex urban structures (Rizwan et al., 2008). It is useful to describe the causal factors leading to the existence of UHI so that they can be identified.

There is a close correlation between the UHI index and urbanization indicators in Shanghai during 1960–2010. Significant logarithmic relationships are evident between UHI index and the number of operating buses, area of building completed, area of paved road and GDP (Fig. 11a–d), and significant quadratic polynomial relationships are existed between UHI index and total registered population and the area of cultivated land (Fig. 11e and f). To a significant degree, the growth in UHI has been driven by the continuous increase in area of buildings and paved roads, number of operating buses, expansion of population and rapid increase of GDP, as well as the decrease in area of cultivated land. Cao et al. (2008) also suggested that the growth and agglomeration of population and GDP, the expansion of built-up area and the increase of dwelling house are important drivers of UHI in Shanghai due to their functions on the increase of energy consumption and/or impervious area. Fig. 11f shows that UHI index is negatively correlated with the area of cultivated land. This indicates that the conversion of large areas of cultivated land to urban land accelerates the increase of UHI intensity.

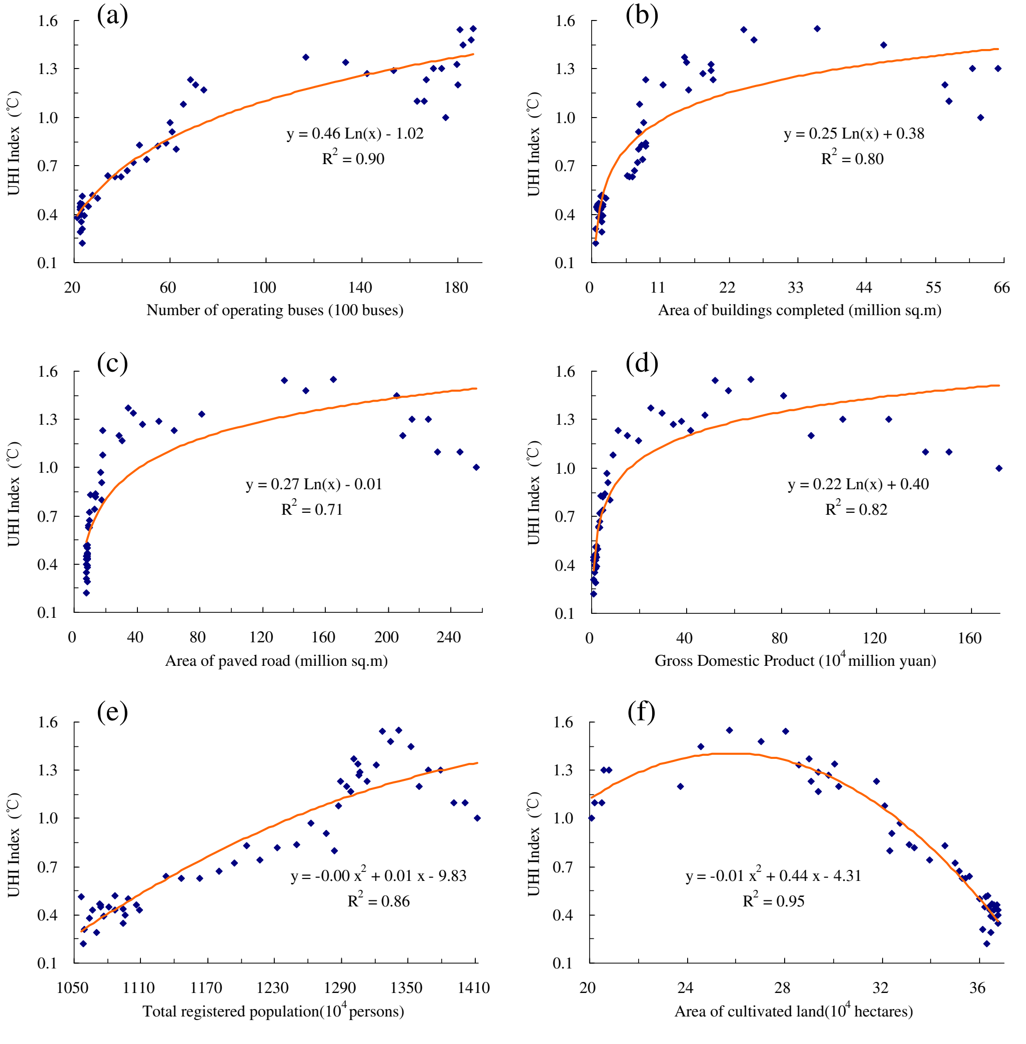

Fig. 11. Relationship between UHI index and some urbanization indicators in Shanghai during 1960–2010.

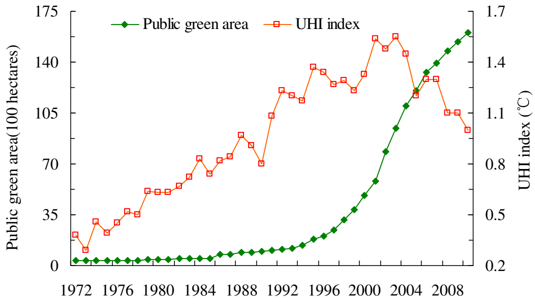

Fig. 12. Variation of annual UHI index and public green area in Shanghai during 1972–2010.

In recent 10 years, some urbanization indicators, such as the GDP, area of buildings and paved roads have increased rapidly, and the area of cultivated land has decreased rapidly in Shanghai. The relationships between UHI index and these urbanization indicators are somewhat not as good as before (Fig. 11). This is mainly attributed to the reduction of UHI index after 2001 (Fig. 12). To cope with the adverse effects of UHI on eco-environment and human living, Shanghai government has make great efforts to launch the large-scale construction of urban green system and strengthen scientific and reasonable urban comprehensive planning in recent years. After 2000, public green area, including parks and roadside green, has increased rapidly from 5820 hectare in 2001 to 16,053 hectare in 2010, with an annual rate of 1103 hectare in Shanghai (Fig. 12). Recent studies (Zhou et al., 2008, 2011) also indicated that boosting the area of green land in urban areas would, to a certain extent, mitigate the heat island.

4. Conclusion

Urbanization is one of the most powerful and visible anthropogenic forces on Earth. With rapid urbanization and economic development, Shanghai has experienced significant change in population, LULC and other socioeconomic indicators. Up to 2010 there are 14.12 million registered populations and another 8.98 million floating populations, and the population density is 3632 persons per square kilometer in Shanghai. The rapid urban sprawl has resulted in a large amount of cultivated lands being replaced with building lands. During 1980–2008, cultivated land has a net decrease of 28.6%, and building land has increased by 221.5%. The urbanization in Shanghai has also shown in the change of other indicators. The area of paved road has increased with a rate of 152.8 million square meters per decade and the total area of buildings has increased with a rate of 433.3 million square meters per decade during 1992–2010.

Urbanization has also created serious environmental problems in Shanghai, including its climatic and ecological effects and environmental pollution. Urban areas have higher air temperature, more hot days, lower relative humidity and wind speed than rural areas by 1.3 °C, 16.3 days, 5.0% and 1.6 m/s respectively during 2001–2010. The spatial pattern of LST is generally consistent with the land use types in Shanghai. The areas with higher NDVI have decreased in Shanghai in recent years, and the areas with lower NDVI have increased significantly due to urbanization and LULC activities. Urbanization has also placed a heavy burden on the atmosphere and water quality and environmental sanitation in Shanghai. Garbage produced has increased with a rate of 1443.7 thousand tons per decade during 1950–2010 and waste gas emission has increased with an annual rate of 44.0 billion cubic meters during 1991–2010.

The growth of UHI in Shanghai has been driven by the increase in area of buildings and paved roads, number of operating buses, expansion of population and rapid increase of GDP, as well as the decrease in area of cultivated land. Significant logarithmic relationships are evident between UHI index and the number of operating buses, area of building completed, area of paved road and GDP, and significant quadratic polynomial relationships are existed between UHI index and total registered population and the area of cultivated land. In recent 10 years, the large-scale construction of urban green system launched by Shanghai government has to a certain extent, mitigated the heat island. In the situation of many urbanization indicators are still developed continuously as before, the correlations between UHI index and urbanization indicators are somewhat weaker than former.

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