Managing the adverse thermal effects of urban development in a densely populated Chinese city

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Accepted 20 November 2003

Abstract

Guangzhou city in South China has experienced an accelerated urban development since the 1980s. This paper examines the impact of the urban development on urban heat islands through a historical analysis of urban–rural air temperature differences. Remote sensing techniques were applied to derive information on land use/cover and land surface temperatures and to assess the thermal response patterns of land cover types. The results revealed an overriding importance of urban land cover expansion in the changes in heat island intensity and surface temperature patterns. Urban development was also related to a continual air temperature increase in the 1980s and 1990s. The combined use of satellite-derived vegetation and land cover distributions with land surface temperature maps provides a potential useful tool for many planning applications. The city’s greening campaigns and landscaping designs should consider the different cooling effects of forest, shrubs and grassy lawns for temperature control and should plant more tall trees.

Keywords: Urban development; Urban heat island; Land surface temperature; Urban and environmental planning; Guangzhou

1. Introduction

Urban development, as a major type of land cover change in human history, has a great impact on the environment. In the process of urbanization, trees are cut and natural vegetation cover is largely replaced by paved surfaces. Open spaces are maintained for recreational or ornamental purposes rather than for the production of food or timber, so that the ecosystem dynamics of the remaining ‘green’ areas of the city are usually quite different from those of the open countryside (Mather, 1986). Moreover, urban areas generally have higher solar radiation absorption and a greater thermal capacity and conductivity because of being covered with buildings, roads and other impervious surfaces. Heat is stored during the day and released during night. Therefore, urban areas tend to experience a relatively higher temperature compared to the surrounding rural areas. This thermal difference, in conjunction with waste heat released from urban houses, transportation and industry, contribute to the development of an urban heat island (UHI). Urban climatologists have long been interested in the differences in observed ambient air temperature between cities and their surrounding rural regions (Landsberg, 1981). The UHI effect is not restricted to large metropolitan areas; in fact, it has been detected in cities with population less than 10,000 people (Karl et al., 1988). Moreover, higher urban temperatures generally result in higher ozone levels due to an increased ground-level ozone production (DeWitt and Brennan, 2001). Higher urban temperatures also mean increased energy use, mostly due to a greater demand for air conditioning. As power plants burn more fossil fuels, they drive up both pollution level and energy costs.

Effective ‘greening’ campaigns may reduce urban heat and alleviate the UHI effect. Properly planted trees seize particulates and reduce nearby air temperatures through both transpiration and shade in the summer and increase temperatures through wind reduction in the winter (McPherson et al., 1998). Tree planting not only can modify microclimate, but also has other ecological as well as economic and aesthetic benefits (Gatrell and Jensen, 2002). Because of the importance of urban trees, many environmentally conscious planning authorities have taken on the strategy of greening campaigns worldwide (Nichol,
1994). In this context, detailed information on the UHI and its relationships with urban growth and with urban forest/vegetation would be very valuable to urban and environmental planners. Knowledge on these relationships can be used by planners to recommend tree planting programs and to evaluate the need for new or revised urban design and landscaping policies for mitigating the adverse thermal effects of building geometry, building mass and poor landscape layouts.

The objective of this study is to investigate the relationship between urban development and UHI in Guangzhou and to discuss the effectiveness that the city’s greening campaigns have brought about to lessen urban temperatures and to dampen the heat island effect. This coastal city in South China has undergone a fundamental change in land use and land cover due to accelerated economic development under the reform policies since 1978. Because of the lack of appropriate land use planning and the measures for sustainable development, rampant urban growth has created severe environmental consequences. Specific questions addressed in this paper include:

1. how has urban land cover changed over the past several decades and what are the temporal and spatial processes of urban expansion? 2. how has such urban growth promoted the UHI effect and altered surface temperature patterns? and 3. what types of greening campaigns have been adopted to mitigate the UHI effect and are they adequate and effective?

2. Guangzhou’s climate and socioeconomic settings

Guangzhou (also known as Canton) is located at latitude 23°08’N and longitude 113°17’E and lies at the confluence of two navigable rivers of the Zhujiang River (literally the ‘Pearl River’) system (Fig. 1). With a population of 3.99 million and total area of 1444 km² (Guangdong Statistical Bureau, 1999), Guangzhou is the sixth most populous city in the nation. It has been the most important political, economic and cultural center in South China. The Guangzhou municipality comprises eight administrative districts in the city proper (Baiyun, Dongshan, Fangcun, Haizhu, Huangpu, Liwan, Tianhe and Yuexiu) and four

Fig. 1. Study area map showing major geographic features and the eight districts, with inset maps of location and the urban core area.
rural counties (i.e. Huadu, Zengchen, Panyu and Conghua). This study focuses on the city proper of Guangzhou.

Guangzhou has a subtropical climate with an average annual temperature of 22 °C. The lowest temperature is normally found in January, averaging 18.3 °C and the highest temperature in July, averaging 32.6 °C. The annual average precipitation ranges from 1600 to 2600 mm. Because of the impact of the East Asian Monsoonal (and less importantly Indian monsoon) circulation, about 80% of the rainfall comes in the period of April to September with highest concentration in spring. The humidity is high in all seasons and the average relative humidity is 80%. This stems principally from the wetland environment and the basin-like terrain of the city. The most uncomfortable season is in the spring’s plum rain period, when the weather is characterized by continuous rain, with rising temperatures, low wind velocity and extremely high relative humidity. Clothes may become moldy and people may feel stifled. Research by Professor Yang at South China Normal University (SCNU), who has been studying the city’s climate for decades using weather station and in situ data, confirms the existence of the UHI (Yang et al., 1984). The combination of high temperature and high humidity creates certain degree of thermal discomfort in the period from May to September and this discomfort becomes extreme in July and August even for people at rest (Yang, 1986).

Guangzhou has a history of urban development spanning across 2000 years (Xu, 1990). It originated as a small village about 300 BC. The city wall was first built in the third century, after China was united in the Qin Dynasty. During the Sui, Tang and Song Dynasties, Guangzhou developed into the largest seaport in the nation as international sea going trade developed rapidly. With the economic development and the population increase, the city wall was expanded several times toward the east and the north. During the Qing Dynasty, the city was further expanded to the south, approaching the north bank of the Zhujiang. Following the establishment of the People’s Republic of China in 1949, Guangzhou’s locational advantages became more prominent, especially with the ending of the Vietnam conflict and the rising prosperity of Southeast Asia (Xu, 1985). The population increased steadily after 1949 with an annual natural increase rate of 14.39 per thousand and the population size has doubled over the 50-year period (Fig. 2). The urban development has progressed at an unprecedented pace, especially after the implementation of the economic reforms in 1978, with the eastward and northward expansion replacing the traditional southern and western expansion. Due to the severe silting of the river, increasing size of ships and the demand for more land, new developments are attracted to the out port in Huangpu, the east end of the city (Xu, 1985). The total area of finished housing covered 12.3 km² in 1949, but increased (by 10 times) to 127.9 km² in 1999 (Fig. 2).

3. Data acquisition and image processing

The temperature data between 1985 and 2000 are obtained from the Central Weather and Chenchun Stations in Gunagzhou, including annual mean temperatures, monthly mean temperatures, monthly mean of low temperatures and monthly mean of high temperatures. The UHI intensity is computed based on the difference of monthly mean temperatures at the Central Station and those at Chenchun Station.

Land surface temperatures were derived from geometrically corrected Landsat Thematic Mapper (TM) thermal infrared (band 6) images dated on December 13, 1989 and August 29, 1997. The TM thermal band has a spatial resolution of 120 m and a noise level equivalent to a temperature difference of 0.5 °C (Gibbons and Wukelic, 1989). The local time of satellite overpass was in the morning (approximately 10:00 a.m.), so that the chance for detecting a weaken UHI is maximized. Since both images were acquired at approximately the same time, a comparative study is feasible. Although the impact of diurnal heating cycle on the UHIs will be an interesting issue to address, no attempt was made to include it in this paper, because TM does not provide day and night infrared images at the same day. A quadratic model was used to convert the digital number (DN) into radiant temperatures (\(T_{\text{rad}}\)) for each channel (Malaret et al., 1985). However, temperature values obtained above are referenced to a black body. Therefore, corrections for emissivity (\(\varepsilon\)) became necessary according to the nature of land cover. Vegetated areas were assigned a value of 0.95 and non-vegetated areas 0.92 (Nichol, 1994). The differentiation between vegetated and non-vegetated areas was made according to the normalized difference vegetation index values, which were computed from visible (0.63–0.69 μm) and

![Fig. 2. Historical trend in population and housing, 1949–1998.](image-url)
near-infrared (0.76–0.90 μm) data of TM images. The emissivity-corrected land surface temperatures were then computed using the equation developed by Artis and Carnahan (1982)

\[
T_s = \frac{T_{\text{MK}}}{1 + (\lambda T_{\text{MK}}/\rho) \ln e}
\]

(1)

where

\[
\lambda = \text{wavelength of emitted radiance (for which the peak response and the average of the limiting wavelengths} (\lambda = 11.5 \mu m) (\text{Markham and Barker, 1985} \text{ will be used}), \]

\[
\rho = \frac{hc}{\sigma} (1.438 \times 10^{-2} \text{ m K}),
\]

\[
\sigma = \text{Stefan Bolzmann’s constant (5.67 \times 10^{-8} W m^{-2} K^{-4} = 1.38 \times 10^{-23} J K^{-1})},
\]

\[
h = \text{Planck’s constant (6.626 \times 10^{-34} J s)} \text{ and}
\]

\[
c = \text{velocity of light (2.998 \times 10^{8} m s^{-1})}.
\]

The source data for mapping urban and built-up areas include a topographic map, a land use and land cover map and satellite imagery. The topographic map was produced by the Chinese government in 1960, based on 1:25,000 aerial photographs taken in 1958. The land use and land cover map was prepared by the Department of Geography, Zhongshan University, based on aerial photographs taken in 1984. The two maps have the same scale of 1:50,000. Urban and built-up areas were delineated from the two maps and manually digitized into computer with ArcInfo computer program.

The satellite images are two Landsat TM images, dated on December 13, 1989 and August 29, 1997, respectively. Each Landsat image was rectified to a common UTM coordinate system based on 1:50,000 scale topographic maps. These images were resampled using the nearest neighbor algorithm, with a pixel size of 30 m for all bands. The resultant root mean square error was found to be 0.77 pixel (or 23.1 m on the ground) for the 1989 image, 0.58 pixel (or 17.4 m on the ground) for the 1997 image.

Land use and land cover patterns for 1989 and 1997 were mapped using Landsat TM data. A modified version of the Anderson scheme of land use/cover classification was adopted (Anderson et al., 1976). The categories include: (1) urban or built-up land, (2) barren land, (3) cropland (rice), (4) horticulture farms (primarily fruit trees), (5) dike-pond land, (6) forest and (7) water. A supervised signature extraction with the maximum likelihood algorithm was employed to classify the Landsat images. Both statistical and graphical analyses of feature selection were conducted and bands 2, 3 and 5 were found to be most effective in discriminating each class and therefore, were used for classification. The accuracy of the classified maps was checked with a stratified random sampling method, by which 50 samples were selected for each land use and land cover category. The reference data was collected from field survey or from existing land use and cover maps that have been field-checked. Large-scale aerial photographs were also employed as reference data in accuracy assessment when necessary. The overall accuracy of classification was determined to be 90.57 and 85.43%, respectively. The KAPPA index was 0.8905 for the 1989 map and 0.8317 for the 1997 map. A detailed accuracy assessment result, including the error matrices and the user’s and producer’s accuracy of the land use and land cover maps, can be found in Weng (2001). The urban and built-up areas were extracted from each land use and land cover map to create the urban maps.


The intensity of UHI is determined by the interaction of several factors, including the degree of urbanization (total built-up area, population size, industrial development and transportation), the geometry of a city, physical environment and human activities (Yang et al., 1984). Whether a city is a metropolis or a county seat, the UHI effect is linked to the composition of the underlying surface, i.e. the pattern and structure of land use and land cover. Urban development has often intensified the degree of UHI. The following text reviews the history of urban development in Guangzhou.

Guangzhou city proper has experienced a series of drastic changes in the administrative boundaries. These changes affect the computation of urban and built-up areas in different periods of time. The current city jurisdiction came into effect in 1988, governing eight urban districts and four adjacent counties. The 1960 and 1984 urban maps cover the urban core area only. The remote sensing-GIS analysis indicates that the urban and built-up land has expanded by more than six times from 1960 to 1997. In 1960, the urban and built-up area was 64.2 km² (Fig. 3a) and 159.6 km² in 1984 (Fig. 3b). During this 24-year period, urban land use (in the rectangular box) increased by 95.4 km², or by 149%. The rectangular box defines the limit of the 1984 aerial photograph survey, which lies between 23°2′30″ and 23°13′40″N in latitude and 113°10′00″ and 113°34′00″E in longitude, covering the then nearly all the urban area. Moreover, the land use and land cover maps derived from the Landsat TM images show that the urban and built-up area was 194.8 km² in 1989 (Fig. 3c) and 295.2 km² in 1997 (Fig. 3d). Urban land use increased by 100.4 km², or by 51.5% in the 8-year period. Overlaying the urban land use maps with a city district boundary and major roads reveals the area extent and spatial occurrence of urban and built-up areas and the expansion trend.

Before the communist took over in 1949, there was an old city core area (the biggest polygon in Fig. 3a) extending from the Haizhu Bridge to some narrow and crowded streets in the Yuexiu and Dongshan Districts. Most of the new developments took place in the suburbs as organized
clusters for accommodating industries, warehouses, or external transportation facilities, aside from a few developments on the outskirts of the old city core (Xu, 1985; Lo, 1994). Huangpu was designated as the out port of the city. New developments were directed to the suburbs in order to contain the growth of the inner city. When a project required a large piece of land, city planners would intentionally locate it in a remote area that had sufficient, less productive land, especially in the eastern and southern suburbs. The built-up area increased from 36 km\(^2\) in 1949 to 56.2 km\(^2\) in 1954 (Guo, 2001). In the late 1950s, there was a significant increment in industrial and residential land uses. Factories were built in selected areas of Haizhu, Fancun and Huangpu Districts, while residential developments spread out in the Tianhe District to house higher education, research and medical units.

During the 1960s and 1970s, urban development was sluggish due to continuous political movements. New factories were built in the Haizhu District and production and port facilities were expanded to the northeast riverbank of Fungcun District. The city’s port function started to shift largely to Huangpu District, where heavy chemical and power industries had been initiated. The stature that Guangzhou was sanctioned as the only foreign trade center in the pre-reform China warranted new housing developments on the northern fringe of Yuexiu District. In addition, a major railway terminus was developed immediately north to the old city core. These developments promoted the city’s northern and northwestern expansion. By 1978, the total built-up area reached 89 km\(^2\).

The 1980s witnessed a dramatic urban development. A triangular Economic and Technological Development Zone (9.6 km\(^2\)) was established in Huangpu District to attract foreign investment in industries. The Huangpu New Port finished building up eight 20,000 tonnage deepwater berths for ships. These constructions, in conjunction with other port facilities, residential and office buildings, hotels, schools, recreational facilities, shaped a modern Huangpu District. Furthermore, the Baiyun International Airport was reconstructed and expanded. New bridges were constructed to link with the island of Ho Nam (Henan), laying the foundation for future southern expansion. Fig. 3c shows that two urban development corridors were becoming visible in 1989, one expanding eastward to Huangpu and the other expanding northward along the expressways.

The urban and built-up areas grew even faster in the 1990s, primarily owing to the development of commercial housing. Commercial housing was initially scattered out in Tianhe District. However, recent development shifted to the northern and southern banks of the Zhujiang. A modern business
and residential zone of 6.6 km², i.e. Zhujiang New Town (Zhujiang Xin Cheng) was developed along the northern waterfronts of the Zhujiang immediately east to the old city core. In terms of industrial land use, there had been substantial developments in Tianhe High-Tech Industrial Park, while heavy industries continued to build up in Huangpu District. By 1997, the urban and built-up area reached 295.2 km². Fig. 3d shows that a west–east-running urban corridor following the northern shore of the waterway has taken shape. In addition, northward urban sprawl along both sides of Baiyun Hill is now a conspicuous feature in the city’s land use. If this trend of urban sprawl continues, the Baiyun Hill will soon become a green island surrounded by a sea of buildings with high-rises striking out haphazardly into the sky.

5. The changing UHI patterns

The magnitude of UHI as measured by the urban–rural air temperature difference ranges from 0.2 to 4.7 °C, depending on the weather conditions. The diurnal variation pattern shows that the UHI normally peaks at 12:00 noon and goes down gradually until reaches the smallest at 14:00 p.m. (Yang et al., 1984). An urban heat sink may be found in the afternoons from 12:00 to 17:00 p.m., when the city is cooler than the surrounding rural areas. The UHI would be maximized during a sunny day, leveling out a difference of 3.9–4.7 °C, while in a rainy day, a weakened UHI tends to be observed with a magnitude of 0.2–0.4 °C (Yang and Zhang, 1985).

The seasonal variation of the UHI is as evident as the diurnal variation. Table 1 shows that the monthly magnitude of UHI between 1985 and 2000 computed based on the monthly average temperatures at the Central Station and those at Chenchun Station. Generally speaking, the UHI is stronger in the fall and winter (September–December) and weaker in the Spring (February and March). This seasonal pattern is particularly true for the observational period between 1985 and 1995, as shown in Fig. 4. The urban–rural air temperature difference continues to increase in the summer and fall and reaches the highest in November, with an average magnitude of 0.7 °C over the 10-year period. The UHI is minimized in February and March, when a small temperature difference of 0.25–0.27 °C may be observed. Several factors favor the development of a weakened UHI in the spring. First, the tropical location of the city and the monsoonal circulation of Eastern China give rise to a visible rainy season. The weather system is often unstable during the rainy season, making it easy for pollutants to spread out and for thermal energy exchange with the surrounding areas. Moreover, the large amount of clouds reduces solar radiation and emitted radiation from the Earth’s surface, so that the green house effect of the urban area becomes relatively insignificant. Finally, moist soil and air help evaporating and have the effect of reducing temperature near the surface. On the other hand, during the summer and fall, China is mainly controlled by a tropical and subtropical maritime air mass. A low-pressure trough co-exists with a shallow high-pressure ridge along the coast in the upper troposphere between 70° and 80°E (Zhao, 1994). The pressure systems near the ground are characterized by the Indian warm low pressure over most parts of Eurasia, coupled with the maritime high pressure over the Pacific and Indian Oceans (Zhao, 1994). Therefore, the warm, moist southern and southeastern monsoons dominate the lower troposphere over China. This stable monsoonal weather system favors the development of a stronger UHI in Guangzhou.

This seasonal pattern of UHI has no longer existed after 1996, as shown in Table 1 and Fig. 4. Temperatures measured at Chenchun Station are consistently higher than urban temperatures measured at the Central Weather Station of Guangzhou. The urban–rural temperature difference yielded

Table 1

<table>
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<tr>
<th>Year</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
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The urban heat island intensity is computed based on the monthly mean temperatures at the Central Station and those at Chenchun Station.
as large as −0.8 °C (in January 1998), with a 5-year monthly average of −0.13 °C (1996–2000). The abnormally high rural temperatures are primarily a result of continuous urban building up around Chenchun Station in the 1990s. The station is indeed submerged in a sea of buildings and has turned into a typical urban station. In contrast, there are more open spaces and lawns surrounding the Central Station, leading to relatively lower average temperatures comparing with those measured at Chenchun Station.

However, these relative lower temperatures are by no means an indicator of a decreasing urban temperature in the city. As a matter of fact, Guangzhou’s urban temperature has kept a continual, wavyly increase since the 1950s (Fig. 5). During the period from 1960 to 1985, annual mean temperature, as measured at the Central Station, ranged between 21.5 and 22.5 °C. A significant increase became apparent after 1986, leveling out to 22–23 °C for the period of 1986–1998. The mean temperature in the coldest month, i.e. January, has shown a similar tendency of increase, with a sharp increase occurring after the mid-1980s (Yao, 2001). This pattern of temperature increase was also observed at Chenchun Station. Clearly, the increase in urban temperatures is attributed to the city’s accelerated urban development in the 1980s and 1990s.

6. Interpreting land surface temperature patterns

A choropleth map (Fig. 6) was produced to show the spatial distribution of emissivity-corrected land surface

![Fig. 5. Annual mean air temperature in the urban area, 1960–2000.](image-url)
temperatures in 1989 and 1997. The statistics of land surface temperature on December 13, 1989 indicates that the lowest temperature was 16.98°C, the highest temperature 25.23°C and the mean 21.17°C, with a standard deviation of 1.72. From Fig. 6, it becomes apparent that all the urban or built-up areas have a relatively high temperature. Some ‘hot spots’ (the highest temperature class) can be clearly identified. In 1989, the most extensive hot spot was found in the western part of Haizhu District, an industrial region in the city. Another noticeable hot spot was detected in the southeast corner of the city proper, where Guangzhou Economical and Technological Development Zone is located. There were also many small hot spots throughout the Tianhe District, which are related to the sparsely distributed industries in the region. However, there did not exist an extensive hot spot in the old urban areas.

Fig. 6. Geographical distribution of land surface temperature in 1989 and 1997. The boundary of districts is superimposed. W–E, S–N and SW–NE profiles (transaction lines) are indicated.
such as Liwan, Yuexiu and Dongshan Districts, in spite of their high construction density. Apparently, commercial and residential areas are less effective to increase land surface temperature. The lowest temperature class (16.98–19.45 °C) appeared in the following three areas: (1) the eastern part of Baiyun District around Maofeng Mountain; (2) Baiyun Hill and (3) the southeastern part of Haizhu District. These areas were substantially rural at one time and were mostly covered by forest. Both the northwest Baiyun District and west Fangcun District have a moderate temperature range 19.45 to 21.17 °C, where cropland and dike-pond land prevailed.

The spatial pattern of land surface temperature on August 29, 1997 is markedly different from that of December 13, 1989, as seen from Fig. 6. The difference reflects not only the differences in solar illumination, the state of vegetation and atmospheric influences of remotely sensed TM data set, but also changes in land use and land cover. The 1997 image was taken in the hottest month. The average temperature was 31.93 °C, with a range between 27.62 and 39.62 °C. The standard deviation was also larger (2.54 °C) than that in 1989, indicating that the surfaces experienced a wider variation in land surface temperature. The urban and rural areas can easily be distinguished from Fig. 6. The urban areas showed a high temperature of over 34.47 °C, while the rural settlements a minimal temperature of 31.93 °C. A major hot spot expanded eastward from the urban core areas of Liwan, Yuexiu, Dongshan to Huangpu, forming a high temperature corridor. A major hot spot to the south of the Pearl River seemed to stretch out from the eastern Haizhu to Fangcun District. In addition, two large hot spots newly emerged, one centered at Guangzhou Railroad Station and Baiyun International Airport and the other to the east of Baiyun Hill. Both areas had undergone a rapid urban sprawl since the 1990s. Numerous strip-shaped hot spots were also detectable along the northward highways such as Guangzhou–Huaxian, Guangzhou–Huandong and Guangzhou–Conghua Highways.

The distinctive land surface temperature patterns are associated with the thermal characteristics of land cover classes (Lo et al., 1997; Weng, 2001). To better understand the impact of urban development on land surface temperatures, the thermal signature of each land cover type was obtained by overlaying a land surface temperature image with a land use and land cover map in the same year. The average value of land surface temperature by land cover type is summarized in Table 2. It is clear that urban or built-up land exhibited the highest surface temperature (22.50 °C in 1989 and 34.75 °C in 1997), followed by barren land (22.16 °C in 1989 and 32.94 °C in 1997). This implies that urban development did bring up surface temperature by replacing natural vegetation with non-evaporating, non-transpiring surfaces such as stone, metal and concrete. The standard deviations of the surface temperature values were relatively small for urban cover, indicating that urban surfaces did not experience a wide temperature variation because of the dry nature of non-evapotranspirative materials. The lowest surface temperature in 1989 was observed in forest (19.77 °C), followed by dike-pond land (20.18 °C) and water bodies (20.35 °C). On August 29, 1997, the lowest surface temperature was found in forest (29.88 °C), followed by cropland (30.96 °C) and horticultural farms (31.24 °C). Forests showed considerably lower surface temperatures, because dense vegetation can reduce amount of heat stored in the soil and surface structures through transpiration. Water bodies tended to get warm slowly during the day owing to high thermal inertia and convection. Cropland and horticulture farms had an intermediate level of surface temperature, as they owned sparse vegetation and exposed bare soil.

7. Implications on planning—managing the urban heat?

An examination of the linkage between urban development, the UHI phenomenon (based on urban–rural meteorological station comparisons) and satellite-derived land surface temperatures provides a conceptual model of the dynamics of an urban thermal environment, which can be used as an informative basis for urban planning decisions. Based on the results of this study, the following planning implications can be derived:

(1) Continuous urban building up promoted the UHI effect. The magnitude of the UHI ranged from 0.2 to 4.7 °C, subject to seasonal variations and weather conditions. The abnormal urban heat sink phenomenon after 1986 is primarily a result of the continued urban

<table>
<thead>
<tr>
<th>Land cover</th>
<th>1989-12-13 (standard deviation)</th>
<th>1997-8-29 (standard deviation)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban or built-up land</td>
<td>22.50 (1.23)</td>
<td>34.75 (2.09)</td>
<td>27.07</td>
</tr>
<tr>
<td>Barron land</td>
<td>22.16 (1.33)</td>
<td>32.23 (2.05)</td>
<td>26.06</td>
</tr>
<tr>
<td>Cropland</td>
<td>21.30 (1.26)</td>
<td>30.96 (1.72)</td>
<td>25.17</td>
</tr>
<tr>
<td>Horticulture farms</td>
<td>21.71 (1.83)</td>
<td>31.24 (1.90)</td>
<td>25.52</td>
</tr>
<tr>
<td>Dike-pond land</td>
<td>20.18 (0.26)</td>
<td>32.83 (2.46)</td>
<td>25.21</td>
</tr>
<tr>
<td>Forest</td>
<td>19.77 (1.74)</td>
<td>29.88 (1.15)</td>
<td>23.82</td>
</tr>
<tr>
<td>Water</td>
<td>20.35 (0.72)</td>
<td>31.34 (1.45)</td>
<td>24.02</td>
</tr>
</tbody>
</table>
built-up around the rural Chenchun Station and its change into an urban station.

(2) The expansion of urban/built-up area resulted in an increase in air temperatures. Urban temperature has shown a continual, wavy increase with the expansion of built-up area. This trend became more noticeable after the mid-1980s, when accelerated urban development occurred.

(3) Satellite imagery can be used to derive information on land cover and land surface temperatures at high spatial and temporal resolutions, so that the thermal response of each land cover type and the thermal effect of spatial arrangement of different land cover types can be understood. This understanding has at least two folds of applications. One is to identify the optimal location, size and shape of a park, a green island, a corridor, or a buffer zone, so as to minimize the adverse thermal effects. The other is to model the thermal impact of a proposed land use/cover change, e.g. residential or commercial development.

(4) The results indicate that vegetation plays a significant role in reducing the amount of thermal radiation upwelling into the atmosphere. Therefore, the benefits of maintaining and enhancing urban forest can be proved and the effectiveness of the city government’s greening campaigns can be evaluated.

(5) Different types of vegetated surfaces vary greatly in inputting and mitigating upwelling thermal energy into the atmosphere. The fact that forest (trees) was found more efficient than horticultural farms (mainly shrubs and grasses) and cropland may be used to provide a justification and to assess the success for the city’s annual tree planting campaign.

(6) Satellite imagery show that besides tree-line roads, water bodies appeared as another type of cool linear features. This indicates a need to keep the water bodies clean, particularly the Pearl River and may require more rigid controls over water pollution.

(7) It is noted that industrial uses yielded much higher land surface temperatures than residential and commercial uses, even for high-density ones. This proves the importance of locating/relocating the majority of the industries away from the inner city.

(8) There is an intimate relationship between air temperature and land surface temperature (Oke, 1976). Although a precise transfer function between the ground surface temperature and the near ground air temperature is not yet available, Byrne (1979) has observed a difference as much as 20 °C between the air temperature and the warmer surface temperature of dry ground. It is true that impervious surfaces are hotter and generate warmer air temperatures. The planning strategies such as the city’s greening campaigns would contribute to damping and mitigating of the UHI in spite of ambiguous understanding of its mechanisms.

Guangzhou municipal government has been pursuing and implementing various types of greening and other costly landscaping policies since its establishment in 1949 (GZCLCCC, 1995). It is estimated that the total area of parks, gardens and other green areas in the urban area went up from 37.36 km² in 1978 to 83.5 km² in 1999 (Guangzhou Statistical Bureau, 1999) yielding an annual increase rate of 3.9% (Fig. 7). However, the amount of increase in green space did not keep up with the pace of urban development, which possessed an average annual increase rate of 5.69% during the same period (Fig. 7). Similarly, road construction exhibited a much higher rate of increase than roadside green belt. The total area of paved roads was 4.47 km² in 1985, but elevated to 25.56 km² in 1999 (Guangzhou Statistical Bureau, 1999) yielding an annual rate approximately of 13.26% (Fig. 7). In contrast, the coverage rate of roadside green belt merely rose by 5.64% between 1985 (2.18 km²) and 1999 (4.7 km²) (Fig. 7), far below the road construction rate (Guangzhou Statistical Bureau, 1999). This implies that a large proportion of roadside areas became and remained as barren land for many years. The remote sensing analysis indicates that barren land had a higher land surface temperature than any other land cover types except for urban/built-up land. By converting forestland into barren land, land surface temperature would be amplified by approximately 8% in the summer and by 12% in the winter. Urban development without sufficient greening efforts explains in part why the UHI in Guangzhou has been intensified and air temperature steadily rose.

The majority of the greening campaigns and landscaping efforts that Guangzhou Municipal government sponsored have focused on the primary objective of beautification.

Fig. 7. Statistical indicators of urban development and greening efforts, 1985–1999.
The city has a nickname of 'flower city' for long. In recent years, this view has been strengthened. Grass lawns and various types of flowers are especially favored in urban design and landscaping, while trees are neglected to a large extent. The effectiveness of expensive greening and landscaping policies can hardly be judged empirically by their direct impacts on the modification of microclimate or easing of the UHI effect and thus environmental sustainability. Professor Yang of SCNU and Wang, an official from the city’s Bureau of Parks, Gardens and Green Area Administration conducted a research in 1987 on the ecological effect of greening and tree planting in the city. It was concluded that the greening areas consistently generated lower air temperatures than non-vegetated streets in terms of daily mean temperatures, daily high temperatures and duration of temperatures \( \geq 30^\circ C \). Trees in the parks can generally reduce under-canopy temperatures by 2.1 \( ^\circ C \), while afforested streets and residential areas lowered daily mean temperatures by 0.9 and 0.5 \( ^\circ C \), respectively, compared with their non-vegetated counterparts (Yang and Wang, 1989). Moreover, greening areas displayed a higher relative humidity and the difference between greening and non-greening areas ranged from 9 to 12%, but may reach a maximum of 25%. They further measured transpiration rates of eight most popular tree species in the city (kapok, magnolia, broad-leaf banyan, small-leaf banyan, candlenut tree, cordate telosma, Chinese azalea and sweet-scented oleander). The average rate of leaf transpiration from these trees was 27.5 g m\(^{-2}\) h\(^{-1}\) at daytime and 1.26 g at night-time, which translated into a daily transpiration of 421.2 g m\(^{-2}\) h\(^{-1}\) for an average tree (Yang and Wang, 1989). Assuming that the total built-up area of the city is 200 km\(^2\) and that the thickness of the urban canopy layer (the air just below roof level; Oke, 1979) was 100 m, it would require an afforested land of 50 km\(^2\) full of the trees to completely get rid of the UHI intensity of 2 \( ^\circ C \) (Yang and Wang, 1989). The city produced a total amount of heat at 37.87 \( \times 10^8 \) MJ (Mega Joule) daily, which included 62.5% of heat from solar radiation and 37.5% of waste heat released from urban houses, transportation and industry. To balance the heat-off, 4.31 million of trees with an average crown size of 70 m\(^2\) must be planted, i.e. 21,550 trees per km\(^2\) (Yang and Wang, 1989). Although the city had a total greening area of 83.5 km\(^2\), the majority was occupied by grass lawns, gardens and shrubs, which were not as effective as big trees in damping urban heat. From this viewpoint, Yang and Wang’s 1989 report recommended to plant more big trees. The present study reveals that the municipal government did not follow the recommendation and put it into practice, however.

**8. Conclusion**

The effectiveness of combined use of remote sensing, GIS and in situ air temperature data has been demonstrated for deriving information regarding to land use and land cover, land surface temperatures and for examining the thermal effect of urban development. The urban/built-up area in Guangzhou has expanded by more than six times between 1960 and 1997 and the urban development has altered the magnitude and pattern of UHI, as measured by the urban–rural air temperature differences. Application of Landsat TM thermal infrared data to the study of land surface temperatures suggests that different land cover types have distinctive thermal responses. The conversion of natural and vegetated surfaces into urban uses will raise the temperatures and increase the spatial variability of land surface temperatures. Satellite-derived land use/cover maps showing the vegetation distribution can be used in conjunction with land surface temperature maps to assess the effectiveness of the city’s greening campaigns. Since forest, shrubs, grassy lawns have different cooling effects, urban planners can utilize this knowledge as a tool of temperature management in landscaping efforts.

The Guangzhou municipal government has no intention to neglect its environmental problems and thus the creation of ecological cities has been advocated. The city planning department frequently put the policies of afforestation, greening and landscaping that build green belts, gardens and parks in the urban areas into practice. However, this research has demonstrated that these policies have not been effective in keeping the level of greenness with the pace of urban development and making the environment sustainable by minimizing the adverse thermal effect of urban development. It is suggested that more trees, not grassy lawns and shrubs, should be planted to keep the city 'cool'.

Improvements in this study would involve conducting survey of ground and air temperatures during the time of satellite overpasses. This would provide on-the-ground air temperatures for image calibration, so that the transfer function(s) between them can be determined. If land surface temperatures can be used as a surrogate for air temperatures, then urban planners can utilize satellite-derived measures to indicate the need for new or revised urban design and landscaping policies for mitigating the UHI effect (Nichol, 1996). Moreover, higher resolution spatial and spectral images would be crucial in order to differentiate more categories of vegetation type, so that the effect of vegetation’s biophysical properties on the urban thermal environment can be investigated. By using multi-season remote sensing data, it will be possible to monitor the changing patterns of UHI and their interface with vegetation dynamics and urban development.

**Acknowledgements**

The authors would like to thank the National Geographic Society for providing a grant (Grant number: 6811-00) to sponsor this research. The constructive comments
and suggestions of two anonymous reviewers are greatly acknowledged to help improving this paper.

References


