An analysis on spatial variation of urban human thermal comfort in
Hangzhou, China

WANG Wei-wu, ZHU Li-zhong, WANG Ren-chao
(College of Environmental and Resource Sciences, Zhejiang University, Hangzhou 310029, China. E-mail: wwwwang@zjnu.edu.cn)

Abstract: Urban human thermal comfort (UHTC) is affected for interacting of weather condition and underlying
surface framework of urban area. Urban underlying surface temperature value and Normalized Difference Vegetation
Index (NDVI) were calculated using image interpreting and supervised classification technique by ERDAS IMAGE
software using 1991 and 1999 Landsat TM images data. Reference to the relational standard of assessing human
thermal comfort and other meteorology data of Hangzhou city in summer, air temperature and relative humidity
variation of different land types of underlying surface were inverse. By choosing discomfort index as an indictor, the
spatial distribution characteristic and the spatial variation degree of UHTC were estimated and mapped on a middle
scale, that is, in six districts of Hangzhou. The main characteristics of UHTC spatial variation from 1991 to 1999 were
revealed using a GIS-based calculation model. The variation mechanism were analyzed and discussed from the
viewpoint of city planning, construction and environmental protection.

Keywords: urban human thermal comfort (UHTC); remote sensing (RS); geographic information system (GIS);
spatial distribution; variation mechanism

Introduction

Urban human thermal comfort (UHTC) is affected for interacting of weather condition and underlying surface
framework of urban area. Air temperature and humidity changes generated by the urban landscape influence people’s
health and comfort as well as energy consumption and air quality. Conventional comfort theory depends on a steady
sited state model where the production of heat equals to the heat losses to the environment, aiming to keep a constant
core body temperature of 37°C. It is thought that human thermal comfort is influenced by the following some main
parameters such as metabolic rate, clothing thermal resistance, mean radiant temperature, air temperature, air
velocity, vapor pressure and so on. Air temperature and humidity are the two most important factors being considered.
Land use/land cover has been known to be a pivotal parameter governing air temperature variation to UHTC
outdoors (Shudo, 1997). It is therefore apparently very important for urban planning and environmental protect
purposes to learn about UHTC variations between different land use categories for both extreme situations and during
average conditions.

Gold in the 1930s and Siple and Passel in the Antarctic in the 1940s, the creators of the wind-chill index, mentioned
thermal comfort outdoors. In the absence of any other similar studies, forty years later Penwarden attempted a more
systematic approach for thermal conditions outdoors, by adding to the steady state model, a term for solar radiation.

In the 1980s a team of researchers at Berkeley worked on thermal comfort outdoors, particularly on implications of
design solutions for the microclimate of San Francisco, which led to the legislation for solar access and wind protection
(Nikolopoulou, 2001). And some mathematical models of the thermoregulatory system were employed for calculating the
comfort conditions.

Urban heat environment has been extensively studied by taking RS and GIS as tools for the last two decades (Aniello,
1995; Ben-Dor, 1997; Gallo, 1993; 1996; Henry, 1989; Roth, 1989; Lo, 1997). Landsat TM with its 30-m spatial
spectral bands makes it possible to identify several discrete urban surface cover materials with characteristic signatures
(Quattrochi, 1983). However, only a few studies about UHTC variations by RS and GIS exist and the data available
appear to be rather deficiency and heterogeneous in comparison with the extent of the area considered often limited to the
some localization of the city concerned or only by meteorological methods. Generally, the comparative studies in different
time are relatively lack.

This paper focuses on an analysis on spatial variation of UHTC by RS and GIS, mainly including the following
aspects: (1) Methods of the conclusive index of UHTC such as brightness temperature and NDVI etc are derived from
Landsat TM image using RS. (2) Brightness temperature and NDVI etc., together with land use information of Hangzhou,
have been used in a spatial analysis model of UHTC. (3) A GIS-based calculation method of the UHTC spatial variation
result of UHTC spatial variation.

1 Study area

1.1 Overview

Hangzhou, a famous historic cultural and tourism city, is situated in the north of Zhejiang Province along the southeast coast of China, on the lower reach of the Qiantang River (Fig. 1). Its northeast and southeast parts belong to northern Zhejiang Plain. About 66% of the total area is hilly, 26% plain, and 8% is covered with lakes, rivers and reservoirs. The natural scenery and cultural accumulation of thousands of years have contributed to the city's world. It consists of one county-level city, seven districts and two counties. It covers a total area of 16596 km² including urban area 688 km² and about built-up area 150 km², and has a population of 5.98 million including 1.63 million urban citizens.

![Map of Hangzhou Area](image)

Fig. 1 District where the study samples were taken and its construction

Characteristic of the inner city are the strictly designed system of streets and man-made canals, which are the result of historic influences such as Sui Dynasty, Qiantang Dynasty and South Song Dynasty. 31% of the area is built-up (of which 2% are the more densely built inner city). Multi-story blocks (9%) and detached houses (9%) characterize the residential neighborhoods. Land use category other built-up occupy another 11%. 60% of the district is forested or used in farming. Another 9% is classified as cemeteries, golf courses or cottage gardens, referred to as green areas (Fig. 1).

1.2 Climate conditions

Situated in a subtropical monsoon climate, Hangzhou City enjoys a temperate climate with four distinct seasons. The annual average temperature of the city is 16.2 degrees centigrade, and about 230–260 non-frost days. It has abundant rainfall and humid air, with annual rainfall of 1500 millimeters. January is the coldest month of the year with the temperature averaging 3.5 degrees centigrade. July is the hottest month with average temperature of 28.6 degrees centigrade. The annual relative humidity is 76%.

1.3 The impact of human activities on UHTC in Hangzhou City

The impact of human activities on UHTC and its spatial distribution and variation characteristic has been recognized as the most important factor during the last decade years. In the Hangzhou City area, this impact has exponentially increased from 1990 until now with the building of new dwellings towards the suburbs and with the construction of city infrastructure (such as transportation, communications, public utilities and so on). In general, this impact has involved in as follows:

As regards the development of real estate in Hangzhou City. From the end of 1998, real estate market of Hangzhou City first accidentally came out the common depression status that existed in whole China. In 1998, 1999, 2000, the sum of money that closed a deal were RMB Yuan 0.97, 6.8, and 10.78 million respectively. The development of new area and old city district revitalization are greatly promoted. The building density and height became increasingly great and some districts even have outrun the limits of urban environmental capacity, especially in some CBDs.

As regards city green land, most green lands of the whole city is concentrated in the scene zone of the West Lake. Green lands cover rate of the whole city can attain to 44.6% when it is calculated embodying the scene zone of the West Lake, but average green land area per cap only is 1.03 m² when excluding a 60 km² region of the scene zone of the West Lake (1996). This value is lower than Beijing, Shenzhen, Zhengzhou which green vegetation cover rate are
already low in China, and even cannot attain 1.20 m² per cap which is the average green land area per cap of Shanghai (1996).

As regards living conditions, radical changes in mentalities and in the life-style of inhabitants have equally contributed to modifying the quality of urban thermal comfort. Among them, we should mention the development of transportation tools and domestic electric equipment responsible for the diffusion of artificial heat. For example, the utilization of cars, and the installation of air-condition facility are becoming increasingly universal to households in Hangzhou City.

1.4 Choosing of sampling area

A sample area with six districts of the city was selected to be representative of the whole city. Fig. 1 shows the location and the construction of study sample area.

These six districts include the most densely populated ones (Xiaocheng District and Shangcheng District) and the ones that contain the possible urban and environmental varieties and peculiarities: outskirts (Xihu District and Binjiang District) and rural areas of the city surroundings, the scene zone of the West Lake (Xihu District), as well as the riverfront (Binjiang District and Xihu District). Fig. 1 shows the overview of the study area and its construction.

2 Data preparation and analysis

The brightness temperature and mean radiant temperature can be derived from Landsat TM image, and certain relativity is figured that existing in between brightness temperature and air temperature. We first prepared the data of land use type and derived the brightness temperature and mean radiant temperature data from TM images.

2.1 Landsat TM image preprocessing

Landsat TM has three visible bands and three infrared bands with a spatial resolution of 30 m and a 120 m thermal band (band 6). Two Landsat TM image data are obtained from acquired on 23 Jul. 1991 and 1 Oct. 1999. The air temperature on that two days ranged from a low of 27.7°C to a high of 36.8°C and from 21.3°C to 33.5°C, average 32.1°C and 26.8°C respectively.

After obtaining satellite data, the image data were extracted using ERDAS IMAGE on a computer that having a Pentium IV CPU. Hangzhou City region mapping is subset from Landsat TM data. Six districts sub-image are obtained as Fig. 1.

Due to the sensitive characteristic of temperature and vegetation to the Landsat thermal infrared, near infrared, red channels data, the 3rd and 4th channels of Landsat TM data are chosen for mapping the distribution of NDVI in Hangzhou. The 6th channel are selected for the study of thermal characteristic.

2.2 Extraction and processing of thermal characteristics parameter—brightness temperature

The Planck function is used for the brightness temperature calculation, and the formula is as follows:

\[ L_{TM} = 0.0056314 DN_{TM} + 0.124. \] (1)

\[ T_B = \frac{k_1}{\ln(k_2/L_{TM} + 1)}. \] (2)

where \( T_B \) is the brightness temperature (K), \( L_{TM} \) is the radiance value after calibration (\( \text{mW} \cdot \text{cm}^{-2} \cdot \text{Sr}^{-1} \cdot \text{pm}^{-1} \)), and \( k_1, k_2 \) equal to 0.56(K), 60.766 (\( \text{mW} \cdot \text{cm}^{-2} \cdot \text{Sr}^{-1} \)) respectively.

Fig. 2 shows the surface brightness temperature of Hangzhou City on a 1991 and 1999 summer day after extraction and processing.

2.3 Preparation of raster format land use type data

Raster format data of land use type are prepared, including raster format data of 1991 and 1999 data in this study. They are obtained by combining image visual interpret technique and supervised classification technique in ERDAS IMAGE. Fig. 3 shows the mapping of urban land use type in 1991 and 1999 from TM image.

---

**Fig. 2.** The mapping of the brightness temperature type on a 1991 and 1999 summer day after extraction and processing.
3 Spatial analysis model of urban human thermal comfort

The urban heat environmental quality distribution analytical conception model is:
\[ Q_s = f(T, S, V, W). \]  
(3)

Where, \( Q_s \) is the analytical result of the urban human thermal comfort in spatial distribution characteristics, which is the function of factors \( T \), \( S \), \( V \), and \( W \). \( T \) is the brightness temperature images from landsat TM; \( S \) is the map of land use type; \( V \) is the vegetation index map of land use and \( W \) is the observed meteorological data.

In order to effectively analyze the distribution and variation characteristics of UHTC, the methods of GIS logic discrimination and stratification analysis are used to establish spatial analytical model. The main idea is to study and establish spatial analytical model for comprehensively analyzing the air temperature and humidity spatial distribution and variation mechanism of UHTC, by using the Landsat TM brightness temperature and NDVI as the main factors with other factors, such as land use classified maps and meteorological data, as supplementary factors.

3.1 The calculation of brightness temperature variation

Using GIS grid module, the brightness temperature mapping of 1999 is first added the last deviation value of each land use type and then is subtracted by the brightness temperature mapping of 1991. Different area with special mark (mask area) is setup from different brightness temperatures variation. The mapping of brightness temperature variation is obtained (Fig. 4).

![Fig. 3 The mapping of urban land use type in 1991 and 1999 from TM image](image)

![Fig. 4 The mapping of the air temperature variation range from 1991 to 1999 and the position after scaled to 0—1](image)

By using data format transfer, geometric precise correction, resampling, radiation correction, and multi-band spectral information combination optimum, the spatial registration and assimilation is solved for the remote sensing and non-remote sensing information of different spatial resolutions.

3.2 Calculating air temperature variation of different media of underlying surface

For deficiency of the quality model to reverse air temperature from the brightness temperature and locating near
Shanghai City. Hangzhou is thought that its characteristics of the underlying surface media resembles with Shanghai. According to the study of the relation between brightness temperature and air temperature in Shanghai summer (Zhou, 2001) (Table 1), the air temperature of Hangzhou is calculated and mapped.

Table 1 The correlated pattern of different ground media between brightness temperature and air temperature

<table>
<thead>
<tr>
<th>Type of ground surface</th>
<th>Underlying surface characteristics</th>
<th>Regression equation</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban built-up areas</td>
<td>Mainly public and residential building</td>
<td>$Y = 11.6 + 0.708X$</td>
<td>0.98</td>
</tr>
<tr>
<td>Combined area between Wood and crop land urban and suburban areas</td>
<td>$Y = 29.976 + 0.158X$</td>
<td>0.97</td>
<td></td>
</tr>
</tbody>
</table>

Notes: * Y stands for air temperature 1.5 meters above ground, X stands for land surface brightness temperature.

Water body is special area, according to relation between water temperature and air temperature, air temperature above water is calculated using the follow formula:

$$T_a = \left( T_w - \left[ d + e(N - L) + fh \right] \right) / \left[ a + b(N - L) + ch \right],$$

where, $T_w$, $T_a$, $N$, $h$, $L$ represent respectively water temperature, air temperature, latitude, altitude and altitude parameter, $a$, $b$, $c$, $d$, $e$, $f$ are model parameter. For Hangzhou, the value of $N$, $h$, $L$ and $a$, $b$, $c$, $d$, $e$, $f$ are 30, 20, 20, 0.9592, 0.0068, 1.25 x 10^-4, 3.23, 0.0065 and 0.0040 respectively.

3.3 Calculating relative humidity variation value in different land use type

In this paper, it is supposed that the city is placed in an ideal status in summer, that is, relative humidity is only related with vegetation biomes and is not affected with meteorological conditions such as air velocity and vapor pressure and so on (Zhang, 1999). The vapor volume is decided by the degree of green plants evaporation function. NDVI will be available to further establishing biomes estimate model. NDVI were analyzed and calculated as follows:

$$NDVI = \frac{NIR - R}{NIR + R}.$$  \hspace{1cm} (5)

Here $NIR$, $R$ represent near infrared band and red band.

Fig.5 shows the mapping of the NDVI value in 1991 and 1999.

At the same time, it is thought that the last estimated biomes variation is in direct proportion with air relative humidity variation. The relation between humidity variation values $V_h$ can be exhibited as Formula (6),

$$V_h = a + bNDVI.$$ \hspace{1cm} (6)

The parameter $a$, $b$ can be obtained using the different NDVI variation value and the monitoring value of relative humidity (including average, min, max value) from 1991 to 1999. According to the relative study (Bao, 2001), the effects of greening on temperature and relative humidity are studied in Hangzhou. Results showed that air temperature is reduced by 0.7°C on average 2.3°C at maximum, and relative humidity increased by 4% on average, 15% at maximum after landscaping and greening in summer. The relative humidity variation appears not clearly, the variation range is about 10. Fig.6 shows the mapping of the relative humidity variation from 1991 to 1999.

3.4 Calculation of the indicator $DI$ (discomfort index) tokening UHTC

Discomfort index is usually used to estimation of urban heat environmental quality. The fellow formula can quantity discomfort index only using air temperature and humidity index(Zhen, 2000):

$$DI = Td - (0.55 - 0.55R)(Td - 58).$$ \hspace{1cm} (7)

Here $DI$ is discomfort index, $Td$ is the temperature of the dry ball, and it is replaced using air temperature that obtained from TM image by calculation, $R$ is the relative
humidity. When the DI value is 60—65, most persons will feel comfortable to heat; when the DI value equals 75, almost half of persons will feel discomfort; when the DI value is over 80, most persons will feel discomfort.

Fig. 7 shows the spatial distribution of DI variation of Hangzhou City from 1991 to 1999.

4 Discussion

Many concepts and indicators are introduced in previous research about UHTC. Human comfort index and human discomfort index are the two most typical examples. A comfort index presents the combined effect of a number of parameters (personal and environmental) on the human thermal sensation and response of the human body to the thermal environment. Human thermal comfort is influenced by the following main six parameters: (1) metabolic rate; (2) clothing thermal resistance; (3) mean radiant temperature; (4) air temperature; (5) air velocity; (6) vapor pressure. In this study, some factors are ignored and only DI (discomfort index) is chosen to convenient for spatial variation research.

The contract analysis of UHTC spatial variation shows that the UHTC spatial variation in each city district has a difference. Comparing to other districts, UHTC spatial variation in the center city (mainly Xiacheng District and Shangcheng District) is the smallest, that is, UHTC has been improved most lightly. In the scenic area of the West Lake and other areas, UHTC spatial variation is in the second. From the whole of six districts, UHTC variation degree in the west of the city and Jianggan District in the east of the city of has debased most greatly. UHTC in Gongshu District and Binjiang District has debased not greatly (Fig. 6). The spatial variation range of UHTC in the city center (mainly including Xiacheng District and Shangcheng District) having improved not greatly has two main reasons. First, China’s reform and open policy has greatly altered the focus of urban planning and management. Since the introduction of market mechanisms to urban management, urban land parcels in different locations have shown different values. This value differentiation has been used as a means to reshape the land use structure. Traditional factories that lack technology content and cause environmental pollution can now be
relocated to suburban areas. High land value of the old site in central city can provide the factory with enough funds for purchasing a new land parcel that is suitable for its expansion, and at the same time, for having leftover funds to improve its capital flow. The removal of factories from the central city has also provided opportunities for urban redevelopment. For the city government, the land and housing markets helped to generate income that can be further utilized for urban development. In recent years, in Hangzhou City districts the green land are rapidly developed. The other reason of city green land developing rapidly in Hangzhou is the citizen and governmental consciousness of city environment is becoming increasingly intense. On the other hand, the development of old city district revitalization making the building more and more density and high decreases UHTC.

UHTC in the west of the city and Jiangnan District in the east of the city having changed greatly has two main reasons. One is that, since 1980s, urbanization has been beginning in Hangzhou City (Zhou, 1997). In suburban, city development is a progression accompanying rural industrialization, rural urbanization and development of real estate. In this progressing course, urban built-up area spreads slowly towards outside, and hundreds of special market arise for good transport and cheap rent in suburban.

In these two districts, open space decreases rapidly, building and construction increases quickly. So UHTC lets down fast simultaneously.

UHTC in Gougu District and Binjiang District has decreased slightly. In these two districts, city renewal and suburbanization happen together, but the degree of city renewal is weaker than in the city center (mainly Xiaocheng District and Shangcheng District), and on the contrary, the degree of suburbanization is weaker than in suburbs (mainly in the west and the east of Hangzhou City).

5 Conclusions

A new way of estimating the spatial change of UHTC based on RS and GIS that caused by the development and reurbanization of city district is introduced. Useful data such as surface temperature and NDVI etc. are derived from landsat TM image using RS. Two different UHTC characteristic maps was setup using GIS software ArcGIS.

Result of spatial distribution of UHTC can be used as a guidance in city planning, construction and environmental protect. It gives us an enlightening that in which segment is the worst in UHTC, what is its form and change mechanism, and what are measures that we should take in the course of building our city.

It is possible to contrast results in the comfort offered by the different urban spaces, clearly displaying, for example, the difference in performance between zones with and without gardens, waters and industries, streets with and without trees. In this study, only one comfort and well-being indices is used, in order to process further study, more human comfort index should be analyzed and compared, and at last select the most suitable human comfort index.

In addition, this paper presents information that is of concern for the urban plan and the authors hope that it will increase awareness of climate variations in urban areas.

References:


(Received for review February 27, 2003. Accepted June 15, 2003)