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ANALYSIS ON THE SPATIAL DISTRIBUTION VARIATION CHARACTERISTIC OF URBAN HEAT ENVIRONMENTAL QUALITY AND ITS MECHANISM
—A Case Study of Hangzhou City

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ABSTRACT: Urban heat environmental quality (UHEQ) is affected by the interacting of weather condition and underlying surface framework of urban area. In the last two decades, many researchers from domestic and overseas have studied many problems at the aspect of urban heat environment such as urban heat islands, urban air temperature and their relation with urban land cover, city population, air pollution etc. In the recent years, Hangzhou, acting as a center city of Zhejiang Province in China, its urbanization quantum and quantity have both changed greatly, in particular, representing as business affairs building, resident real property and all kinds of specialty market having arisen in built-up zone. Based on Landsat TM images data in 1991 and 1999, urban underlying surface temperature value and Normalized Difference Vegetation Index (*NDVI*) were calculated using image interpreting and supervised classification technique by remote sensing software ERDAS image 8. 4. The relation model between urban underlying surface temperature (UUST) and urban air temperature was setup according to the certain correlation pattern. Reference to the relational standard of assessing human comfort and other meteorology data of Hangzhou City in summer, the spatial distribution characteristic and the spatial variation degree of human comfort of heat environmental quality are estimated and mapped on a middle scale, that is, in six districts of Hangzhou City. Then the paper reveals the main characteristic of spatial variation from 1991 to 1999. Lastly, the change mechanism is analyzed and discussed from the viewpoint of city planning, construction and environmental protection.

KEY WORDS: urban heat environmental quality (UHEQ); remote sensing; Geographic Information System (GIS); spatial distribution; variation mechanism

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1 INTRODUCTION

Within many developed countries, the urban heat environment has been extensively studied by taking remote sensing and geographic information system (GIS) as tools for the last two decades (HENRY *et al.*, 1989; ROTH *et al.*, 1989; GASTELOIS *et al.*, 1991; GALLO *et al.*, 1993, 1996; LO *et al.*, 1997; HOYANO *et al.*, 1997; SPRONKEN-SMITH *et al.*, 1998; BEN-DOR and SAARONI, 1997; BEN-DOR *et al.*, 2001). In China, however, only a few studies exist and the data available appear to be rather heterogeneous and the extent of the area considered often limited to the some localization of the city concerned, or only by meteorological methods.

Moreover, research methods often differ between studies, which makes comparison of urban heat environment become difficult in different time and space. Generally, the comparative studies are relatively small. Some papers have nevertheless been published concerning spatial distribution characteristic of urban heat environmental quality (UHEQ), which is available for

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such the assessment of UHEQ of some big Chinese cities like Beijing and Shanghai cities (DENG *et al.*, 2001). The impacts of human activities on UHEQ and its spatial distribution and variation characteristic have been recognized as the most important factor during the last decade years. In the Hangzhou City area, these impacts have exponentially increased from 1990 until now with the building of new dwellings towards the suburbs and the construction of city infrastructure (such as transportation, communications, public utilities, etc.). In general, these impacts have involved in as follows:

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

(2) City green land. Most green lands of the whole city is concentrated on the scene zone of the West Lake. Green lands cover rate of the whole city can attain to 44.6% including the scene zone of the West Lake, but per capita green land area is only 1.03m^2 when excluding a 60 km^2 region of the scene zone of the West Lake (1996). This value is lower than Beijing, Zhengzhou cities etc. whose green vegetation cover rate is already low in China, and even can not attain to 1.20m^2 per capita which is the average green land area per capita of Shanghai (1996).

(3) Living conditions. Radical changes in mentalities and in the life-style of inhabitants equally contribute to the quality modifying of urban heat environment. Among them, we should mention the development of transportation tools and domestic electric appliances which are responsible for the diffusion of artificial heat. For example, the utilization of cars, and the installation of air-conditioning are becoming more and more universal to households in Hangzhou City.

What are the impacts of this urban growth on the quality of urban heat environment and how can it be studied? This paper aims to bring some answers to these questions and represents a contribution to the evaluation of spatial distribution and variation characteristic in UHEQ by the view of city planning and urban construction. It also aims at the promotion of environmental planning and management that preserves special features, while permitting appropriate uses.

2 STDTY AREA

2.1 Overview

Hangzhou, a famous historic cultural and tourism city, is taken as a case in this study. Hangzhou City is situated in the north of Zhejiang Province along the southeast coast of China, on the lower reach of the Qiantang River (Fig. 1a). Its northeast and southeast parts belong to northern Zhejiang Plain, rich in fish and rice production. Some 66% of the total area are hills, 26% plains, and 8% are covered with lakes, rivers and reservoirs. The natural scenery and cultural accumulation of thousands of years contributes to the city. It consists of one county-level city, seven districts and two counties. It covers a total area of 16 596 km^2 including 688km^2 urban area, and has a population of 5.98 million including 1.63 million urban citizens.

2.2 Climate Conditions

Being 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℃, and about 250 frost-free days. It has abundant rainfall and humid air, with annual rainfall of 1500 mm. January is the coldest month of a year with the average temperature of 3.5℃. July is the hottest month with average temperature of 28.6℃.

2.3 Choosing of Sampling Area

We thought that sampling the whole city would entail a huge and unnecessary amount of work, which is instead a question of deciding which districts or zones are the most representative ones.

For this reason, a variable area was sampled within six districts of the city, chosen in such a way as to be representative of the city as a whole. Fig. 1b shows the location and the construction of study sample area.

These six districts include the most densely populated ones (Xiacheng District and Shangcheng District) and also 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 a and b show the overview of the study area and its construction.

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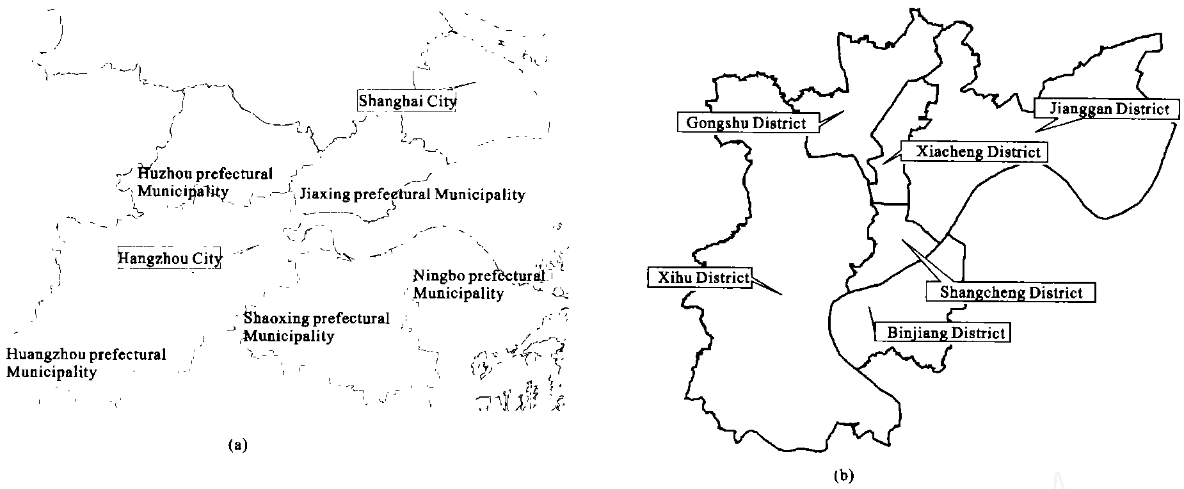

Fig. 1 Location and construction of study area

3 DATA PREPARATION AND ANALYSIS

Many concepts and indicators are introduced in previous research about UHEQ. Human comfort index and 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 paper, some factors are ignored in order to be convenient for research. Air temperature and humidity are the two most important factors being considered.

The brightness temperature and mean radiant temperature can be derived from Landsat TM image, and certain relativity is figured, which exists between brightness temperature and air temperature. So we first prepared the data of land-use type and derived the brightness temperature and mean radiant temperature data from TM images.

3. 1 Landsat TM Image Preprocessing

Landsat TM has three visible bands and three infrared bands with a spatial resolution of 30m and a 120m thermal band (band 6). Two computer compatible tapes (CCT) are obtained from LANDSET to record data acquired on 23 Jul. 1991 and 1 Oct. 1999. The air temperature on that two days respectively ranged from a low of 27. 7℃ to a high of 32. 1℃ and from 21. 3 ℃ to 26. 8℃.

3. 1. 1 Obtaining the image data of the study area

After obtaining the CCT, the image data were extracted using ERDAS 8. 4 on a computer with a Pentium Ⅵ CPU. Hangzhou City mapping is subset from Landsat TM data. Six district's sub-images are obtained as Fig. 1b.

3. 1. 2 Preprocessing

Due to the temperature and vegetation sensitive characteristics of the landsat thermal infrared, near infrared, red channels, the TM data of its 3rd, 4th and 6th channels are chosen for mapping the distribution of NDVI in Hangzhou area and its 6th channels for the study of thermal characteristic, through calibration, positioning, and correction of sun elevation angle and side-darkening, and by bi-linear interpolation magnification.

3. 2 Extraction and Processing of Thermal Characteristics Parameter—Brightness Temperature

3. 2. 1 Calculation of brightness temperature from landsat TM

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

$$L_{TM6} = 0.0056314 DN_{TM6} + 0.124 \quad (1)$$

$$T_B = \frac{k_1}{\ln(k_2/L_{TM6} + 1)} \quad (2)$$

where DN_{TM6} is the value of DN in TM sixth band, T_B is the brightness temperature(K), L_{TM6} is the radiance value after calibration ($mw \cdot cm^{-2} \cdot Sr^{-1} \cdot \mu m^{-1}$), and k_1, k_2 respectively equal to 1260. 56(K) , 60. 766 ($mw \cdot cm^{-2} \cdot Sr^{-1} \cdot \mu m^{-1}$).

3. 2. 3 Display of brightness temperature from landsat TM

At the same time, in order to ease the comprehensive

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analysis, a method of scaling space between gaps of brightness temperatures is used to broaden the image tone sort.

The following formula is for calculation:

$$T_i = K \times (T_{Bi} - C) \qquad (3)$$

set $T_{max} = 240,\ T_{min} = 120$

then $T_{max} = K \times (T_{Bmax} - C),\ T_{min} = K \times (T_{Bmin} - C)$

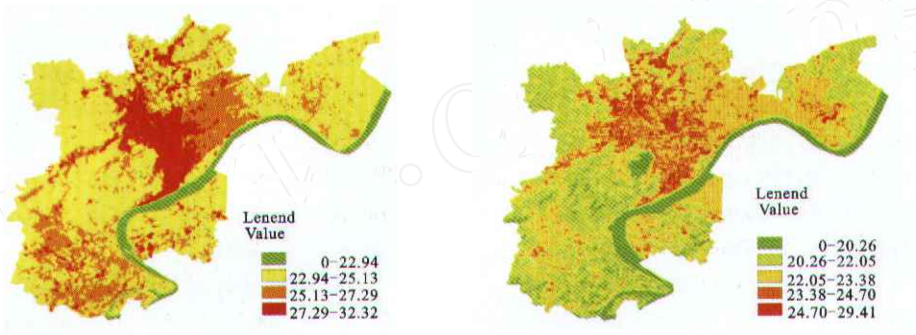
where C and K are unknown constants; T_{Bi} is the brightness temperature at point i; T_i is the brightness temperature after extended calculation. T_{max} is the highest brightness temperature after extended calculation, T_{min} is the lowest brightness temperature after extended calculation. T_{Bmax}, is the highest brightness temperature and T_{Bmin} is the lowest brightness temperature of the image.

In addition, are proper template is used to convolutedly filter the image to get rid of unnecessary noise and burr, and provide the objective continuity of the image. By putting pseudo color on the filtered image, an ideal color image of thermal distribution is obtained. Fig. 2 shows the brightness temperature of Hangzhou City on a day of 1991 and one of 1999 summer after extraction and processing.

3.3 Preparation of Land Use Type Data

3.3.1 Preparation of vector format

In this study, two kinds of data format of land use type are prepared, including vector format data of 1999, and raster format data of 1991 and 1999 data. Preparation of vector format is divided into two phases. That is, the topological relation building of all kinds of land use types and its format transfer.



(a) (b)

Fig. 2 The mapping of the brightness temperature type on a day of 1991(a) and one of 1999(b) summer after extraction and processing

Firstly, by using the digitalization function of ArcGIS 8.1 to input thematic maps with related scale(1:10 000). Secondly, thematic maps of vector format is dealt with by the way of building, cleaning function and the total areas of all kinds of land use type are calculated. Finally, they are transferred to raster format. The last result is showed in Fig. 3.

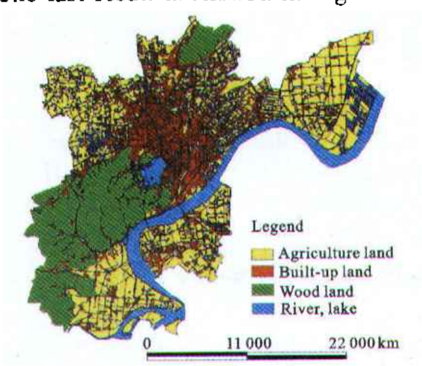


Fig. 3 The mapping of 1999 land-use type in raster format transferring from vector format

3.3.2 Preparation of raster format

To raster format data of land-use type, we obtained them by combining image visual interpret technique and supervised classification technique in ERDAS 8.4. Fig. 4 shows the mapping of urban land use type in 1991 and 1999 from TM image.

4 SPATIAL ANALYSIS MODEL OF URBAN HEAT ENVIRONMENTAL QUALITY

In order to objectively and effectively analyze the distribution and variation characteristics of UHEQ, the methods of GIS logic discriminance 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 UHEQ, 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.

The urban heat environmental quality distribution

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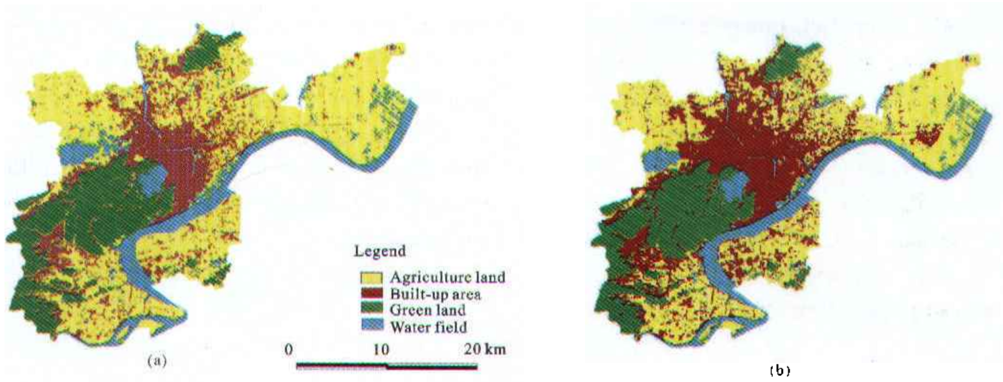

Fig. 4 The mapping of urban land-use type in 1991(a) and 1999(b) from TM image

analytical model is:

$$Q_h = f(N, S, V, W) \quad (4)$$

where Q_h is the analytical result of the urban heat environmental quality in spatial distribution characteristics, which is the function of factors N, S, V, and W. N is the brightness temperature images from landsat TM; S is the thermal map of land-use; V is the vegetation index map of land-use and W is the observed meteorological data.

4.1 Elimination of the Brightness Temperature Deviation Due to the Difference of Weather

As we know, the brightness temperature is decided by the city surface media in the same weather condition. So we sample twenty points in 1991 and 1999 brightness temperature in each kinds of land-use type in order to analysis an approximate value and the brightness temperature deviation due to the difference of weather. Sampling is done by geo-link in ERDAS 8.4. Fig. 5 shows the sampling result of deviation. The average value of the sampling result of deviation is chosen as the last deviation value.

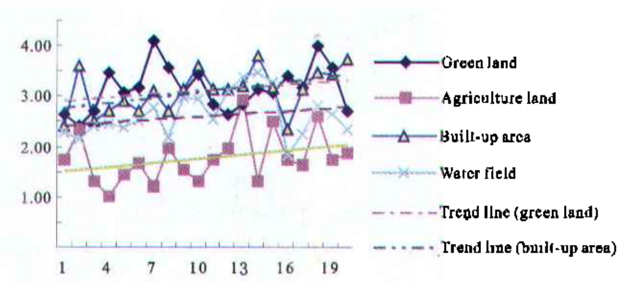

Fig. 5 The sampling result of brightness temperature deviation in each kind of land-use

4.2 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. Thus the mapping of brightness temperature variation is obtained (Fig. 6).

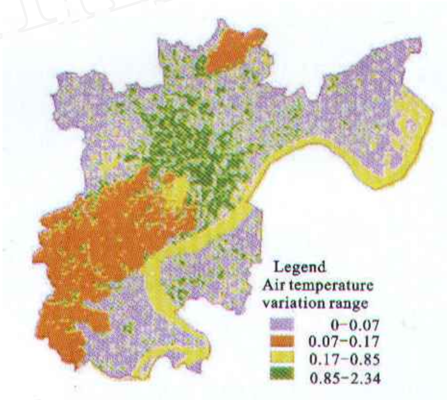

Fig. 6 The mapping of the brightness temperature variation from 1991 to 1999

4.3 Setup of Area with Special Mark (Mask Area) from Different Brightness Temperatures Variation.

For example, we establish a pixel mask area for brightness temperature variation image N with V_{TB} from 1℃ to 3℃.

Maskgrid = select(N, 'value ge 1 and value le 3') (5)

where maskgrid is the mask raster image of certain V_{TB}.

4.4 Fusion and Assimilation Treatment on Remote Sensing Data, Thematic Maps and Meteorological Data of Different Platforms

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

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4.5 Calculating Air Temperature Variation of Different Media of Underlying Surface According to Correlated Pattern of Shanghai City

For locating near Shanghai City, Hangzhou City is thought that its characteristics of the underlying surface media resembles shanghai. According to the relational study (ZHOU *et al.*, 2001) (Table 1), the air temperature of Hangzhou City is calculated and mapped.

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

Type of ground surface	Correlation coefficient	Underlying surface characteristics	Regression equation
Urban built-up area	0.98	Mainly public and residential building	$Y = 11.6 + 0.708X$
Combined area between urban and suburban area	0.99	Wood and crop land	$Y = 35.69 + 0.042X$

Water body is special area, according to relative research about water temperature and air temperature, air temperature is calculated using the follow formula:

$$T_w = [a + b(N - L) + c \cdot h] \cdot T_a + [d + e \cdot (N - L) + f \cdot h] \quad (6)$$

Here, T_w, T_a, N, h, L represents respectively water temperature, air temperature, latitude, altitude and altitude parameter. a, b, c, d, e, f are model parameters. For Hangzhou City, the value of N, h, L and a, b, c, d, e, f are 30, 20, 20, 9.592×10^{-1}, 6.8×10^{-3}, 1.25×10^{-4}, 3.23, 6.5×10^{-1}, 4.01×10^{-3}.

4.6 Calculating Humidity Variation Value in Different Land-use Type Using *NDVI* and the Relative Humidity Variation Value of Hangzhou City in Summer

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 effected by meteorological conditions such as air velocity and vapor pressure etc. and the vapor volume is decided by the degree of green plants evaporation function (ZHANG and FU, 1999). And *NDVI* will be available to further establishing biomes estimate model. *NDVI* were analyzed and calculated as follows,

$$NDVI = \frac{NIR - R}{NIR + R} \quad (7)$$

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

At the same time, it is thought that the last estimated biomes variation is in direct proportion with air relative humidity variation. So the relation between humidity variation value V_h and *NDVI* variation value V_{NDVI} can be exhibited as formula (8),

$$V_h = a + bV_{NDVI} \quad (8)$$

The parameters 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. Results show that air temperature is reduced by 0.7℃ on average 2.3℃ 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. 7 and Fig. 8 respectly shows the mapping of *NDVI* and air relative humidity variation in 1991 and 1999.

4.7 Calculation of the Discomfort Index Tokening UHEQ—Air Temperature and Humidity Index

Air Temperature and Humidity Index (Discomfort Index, *DI*) is used to estimation of urban heat environmental quality.

$$DI = T_d(0.55 - 0.55R)(T_d - 58) \quad (9)$$

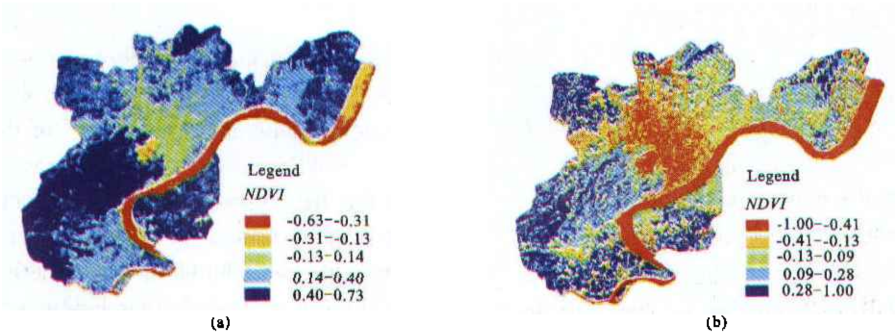

Fig. 7 The mapping of *NDVI* in 1991 (a) and 1999 (b) after extraction and processing

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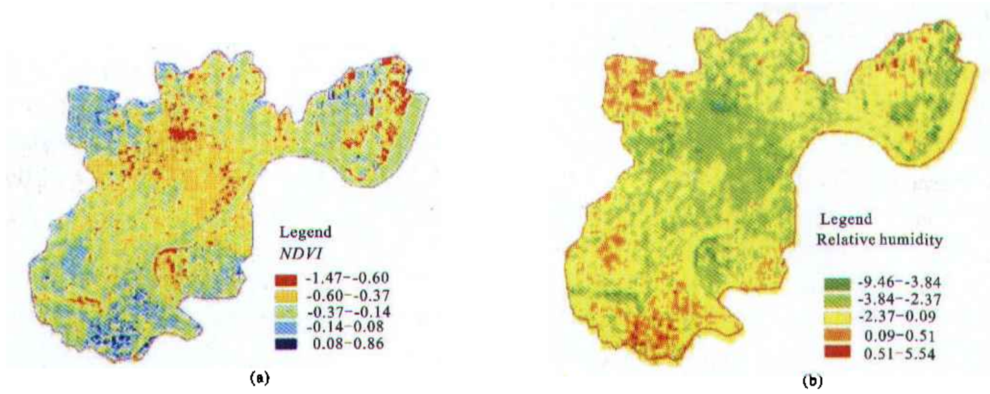

Fig. 8 The distribution characteristic mapping of *NDVI* (a) and the supposed relative humidity (b) in 1991 and 1999

Here *DI* is Discomfort Index, T_d is the temperature of the dry ball, and it is replaced by 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 to 75, almost half of persons will feel discomfortable; when the *DI* value is over 80, most persons will feel discomfortable.

4.8 Spatial Grading of the *DI* Calculation Result According to Comprehensive Analytical Model for Characteristics Variation Distribution of Urban Heat Environmental Quality

In conclusion, the attribution relationship among each stratification factor is established by using attribute coding of land use type and administrative boundary as basic property unit. The multi-factor discrimination is provided by GIS logic analytical method. All of the discriminating factors are as follows: 1) the area ratio of each land-use medium on this brightness temperature area; 2) type of land use (including wood land, waters, agriculture land, building and roads etc.; 3) mean relative humidity of Hangzhou City in summer; 4) the *NDVI* representing green plants biomes.

In above steps, we establish relationships of different elements, line up the related factors according to their importance, and indicate their weights. Finally, the value of impact on the result from different kinds of inside each element could be obtained. That is to be logically discriminated by multi-information and spatially analyzed using the extension module of ArcGIS 8.1 — spatial analysis. Lastly, the calculation results are divided into four variation levels according to the calculation value of *DI*. Fig. 9 shows the spatial distribution of *DI* variation of Hangzhou City from 1991 to 1999.

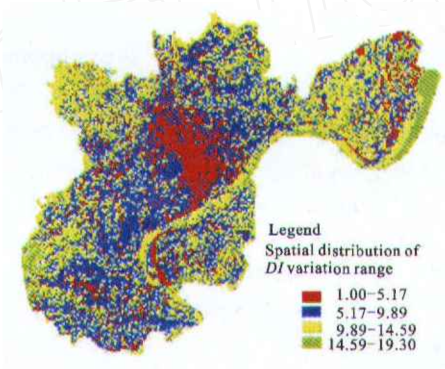

Fig. 9 The spatial distribution of *DI* variation of Hangzhou City from 1991 to 1999

5 ANALYSIS OF THE SPATIAL VARIATION OF UHEQ CHARACTERISTICS AND ITS MECHANISM

The comparison of heat distribution characteristics indicator *DI* in 1991 and 1999 shows the distribution regularity and the spatial variation mechanism of UHEQ characteristics, effect factors as follows:

5.1 Distribution and Variation Regularity of Heat Environmental Quality Characteristics

The UHEQ distribution characteristics of the underlying surface is one of our main research object, the surface brightness temperature and *NDVI* of different time and climate conditions are out of our concern. In fact, for different climate conditions and sampling time, different surface brightness temperatures and air temperatures will be obtained. But, the variation is only for thermal intensity, while the thermal distribution keeps constant, which is determined by the property, structure and area of the ground surface medium.

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From the radiation characteristics of the TM thermal infrared channels and the analytical result by GIS comprehensive analysis, it is clear that the differences of radiance and brightness temperature of surface media are resulted from its texture and spectral reflecting characteristics. In the thermal band, media, such as buildings with cement and tile structure, open squares, residence, bridge surface and road, provide higher brightness temperature, while ground with bare soil and vegetation has lower brightness temperature than that of township. The brightness temperature from water bodies is the lowest. But there is a certain distance between brightness temperature and air temperature water surface. At the same time, it is found that the higher the brightness temperature is, the higher the area ratio of the area with cement and tile in this brightness temperature section is; the lower the brightness temperature is, the higher the area ratio of the area with vegetation is, lower system is, and the lower the ratio for other areas is, such as residence, square and road.

NDVI is an index that represents vegetation biomes. From the analytical result of *NDVI* characteristic distribution, *NDVI* is mainly decided by different vegetation cover type and green biomes. So, the *NDVI* of the garden, school, new settlement developed in recent years is clearly over the ones such as industries, CBDs, transport facilities, wharf etc. The indictors DI tokening UHEQ is the function of the variables air temperature and relative humidity. Air temperature and relative humidity respectively are relative with the brightness temperature and *NDVI*.

It turns out that the UHEQ spatial variation distribution is both effected by brightness temperature and *NDVI* variation. The comparison analysis result of UHEQ spatial variation shows that the UHEQ spatial variation in each city district has a difference degree. Comparing to other districts, UHEQ spatial variation in the center city (mainly Xiacheng District and Shangcheng District) is the smallest, that is, UHEQ has been improved most lightly. In the scenic area of the West Lake and other areas, UHEQ spatial variation is on the second. From the whole of six districts, UHEQ variation degrees in the west of the city and Jianggan District in the east of the city have debased most greatly. UHEQs in Gongshu District and Binjiang District have debased not greatly (Fig. 9).

5.2 Spatial Variation Mechanism of Heat Environmental Quality Characteristics

There are two reasons in the less improvement of the spatial variation range of UHEQ in the city center. First, as everyone knows, 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 help to generate income that can be further utilized for urban development. So in recent years, in Hangzhou City districts the green land are greatly and rapidly developed. The other reason of city green land developing rapidly in Hangzhou is the citizen and governmental consciousness of city environment is becoming more and more strong. On the other hand, the development of old city district revitalization makes the building more and more density and high decrease UHEQ.

Similarly, UHEQs in the west of the city and Jianggan District which is in the east of the city have changed greatly, which is due to two main reasons. One is that, since the 1980s, suburbanization has been in Hangzhou City. In suburban, city development is progression with rural industrialization, rural urbanization and development of real estate (ZHOU, 1997). In this progressing course, city built-up area spreads slowly towards outside, and hundreds of special market arisen for good transport and cheap lent in suburban. In these two districts, open space decreases rapidly, building and construction increases quickly. So UHEQ lets down fast simultaneously.

UHEQ in Gongshu District and Binjiang District has debased slightly. In this two districts, city renewal and suburbanization happen together, but the degree of city renewal is weaker in the city center (mainly Xiacheng District and Shangcheng District), and on the contrary, the degree of suburbanization is stronger in suburbs (mainly in the west and east of Hangzhou City).

6 DISCUSSION AND CONCLUSION

(1) A new way of estimating the spatial change of UHEQ based on remote sensing and GIS that caused by

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the development and reurbanization of city district is introduced. Useful data such as brightness temperature and *NDVI* etc. are derived from landsat TM image using remote sensing technique. Two different UHEQ characteristic maps were setup by the extension module Spatial Analysis of GIS mainstream software ArcGIS 8.1.

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

(3) It is possible to contrast results in the comfort offered by the different urban space, clearly displaying, for example, the difference in performance between zones having or not having gardens, waters and industries, streets having or not having trees. In this paper, only one comfort and well-being index is used, in order to process further study, more human comfort indices should be analyzed and compared, and at last select the most suitable human comfort index.

(4) Green zones are a basic element of ecological engineering affecting city planning. In china, city planning teams consist many of architects, thus many teams are with little ecological knowledge of urban greenery don't know how to use it properly (both the right plant species and the quantity). This matter falls within the sphere of ecological engineering and we feel it is of fundamental importance for environmental guarantees and urban ecology.

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