

An ERDAS image processing method for retrieving LST and describing urban heat evolution: a case study in the Pearl River Delta Region in South China

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Abstract A spatial-temporal model with Model Maker tool is designed to retrieve Land Surface Temperature (LST) and to describe the changes of urban heat island, as well as urban development. Spectral Radiance, Brightness Temperature, NDVI, and Emissivity are first calculated from TM and ETM+, which are then used to compute LST by using Qin et al.'s mono-window algorithm. The LST is classified based on normalized statistical method, and the normalized heat images are computed between different times. Therefore, the urban heat changes can be shown in the map clearly and directly through an urban heat conversion matrix. Such a model has been applied in this study to obtain the urban heat conversion matrix of South China from 1990 to 2000. The results indicate that the LST increased areas mainly locate along the major roads in the eastern bank of the Pearl River, which is a result of speedy urban expansion and need to be noticed in the future.

Keywords Urban · Thermal · Matrix · Evolution

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Introduction

Urban expansion is attributed to increasing factories, urban population, vehicles and industry, and it may lead to dramatic climate changes from land surface to atmosphere. As one of the most important parameters to investigate the energy interactions and cycles between the atmosphere and ground, Land Surface Temperature (LST) is governed by surface heat fluxes, which are obviously affected by urbanization (Dousset and Gourmelon 2003). Understanding the distribution of LST and its temporal variation will be helpful to decipher its mechanism and find out possible solution.

Although various LST retrieval methods have been developed theoretically (Sobrino et al. 1996; Gillespie et al. 1998; Qin et al. 2001; Jimenez-Munoz and Sobrino 2003), it is still a complicated process to get the LST from original satellite image. A powerful tool with C++ program has been developed (Zhang et al. 2006b), but the inputting file format should be *.raw without geographic information. Moreover, most image-process software needs intricate steps to calculate LST, which limits the application of LST. A direct and systemic model is necessary in order to simplify the operating processes. In this study, we propose an image processing method using the Spatial Model Maker tool of ERDAS Imagine software to obtain the LST directly from Landsat file with *.img format. Such method can also be used to describe urban heat evolution by calculating the differences between two normalized LST images.

LST retrieval methods

Different LST retrieval methods have been developed according to different data sources, such as split-window method (Sobrino et al. 1996), temperature/emissivity

Table 1 Estimation of atmospheric transmittance (Qin et al. 2001)

Profiles	Water vapor (w) (g/cm ²)	Transmittance estimation equation (τ_6)	Squared correlation	Standard error
High air temperature	0.4–1.6	$0.974290 - 0.08007w$	0.99611	0.002368
	1.6–3.0	$1.031412 - 0.11536w$	0.99827	0.002539
Low air temperature	1.4–1.6	$0.982007 - 0.09611w$	0.99463	0.003340
	1.6–3.0	$1.053710 - 0.14142w$	0.99899	0.002375

separation method (Gillespie et al. 1998), mono-window method (Qin et al. 2001), and single-channel method (Jimenez-Munoz and Sobrino 2003). With relative higher resolution, Landsat satellite is one of the longest programs for global change researches and has been applied for agriculture, geology, regional planning and environment. As the thermal infrared (TIR) channel, band 6 records the radiation with spectral range in 10.4–12.5 μm from the surface of the earth. Three LST retrieval methods can be used: mono-window algorithm, single-channel algorithm, and radiative transfer equation. Although all of these methods can provide good results, the radiative transfer equation is not available without parameters in situ atmospheric profile simultaneously when the satellite passes. The mono-window algorithm with radiosounding data can get a better result than the single-channel algorithm with an rms d of 0.9 K (Sobrino et al. 2004).

A mono-window algorithm (Qin et al. 2001) is expressed as Eq. (1). Three variables, emissivity, transmittance and effective mean atmospheric temperature, are required in advance.

$$T_s = \{a(1 - C_6 - D_6) + [b(1 - C_6 - D_6) + C_6 + D_6] \times T_{\text{sensor}} - D_6 T_a\} / C_6 \quad (1)$$

where T_s is the LST in band 6, two constants a , b are 67.355351 and 0.458606, respectively,

$$C_6 = \varepsilon_6 \tau_6 \quad (2)$$

$$D_6 = (1 - \tau_6)(1 + (1 - \varepsilon_6))\tau_6 \quad (3)$$

Where, ε_6 is the emissivity, which can be classified and computed by NDVI, τ_6 is the transmittance given in Table 1, T_{sensor} is the at-sensor brightness temperature in K, T_a represents the effective mean atmospheric temperature given in Table 2.

ERDAS image processing method used to retrieve LST and describe urban heat evolution

Introduction to methodology

Urbanization studies with LST derived from Landsat TM/ETM+ TIR data have been widely conducted (Carnahan and

Table 2 Estimation of mean atmospheric temperature (Qin et al. 2001)

Area	Atmospheric temperature equation (T_a)
For USA 1976	$25.9396 + 0.88045 T_0$
For tropical	$17.9769 + 0.91715 T_0$
For mid-latitude summer	$16.0110 + 0.92621 T_0$
For mid-latitude winter	$19.2704 + 0.91118 T_0$

Where T_0 is the near-surface air temperature in K

Larson 1990; Kim 1992; Nichol 1994; Weng 2001, 2003; Kato and Yamaguchi 2005). All the results indicate that LST are in a great correlation with city evolution. The Spatial Modeler module in ERDAS Imagine software provides a powerful tool to accomplish most image processing functions. Meanwhile, ERDAS is one of the most popular software in the field of satellite image processing. It can be used to observe and analyze the processed results. The ERDAS image processing method with Spatial Model tool is designed as Fig. 1. In this study, the Spatial Modeler module in ERDAS IMAGINE software 9.0 is used to execute the model. The inputting images are rectified radiometrically

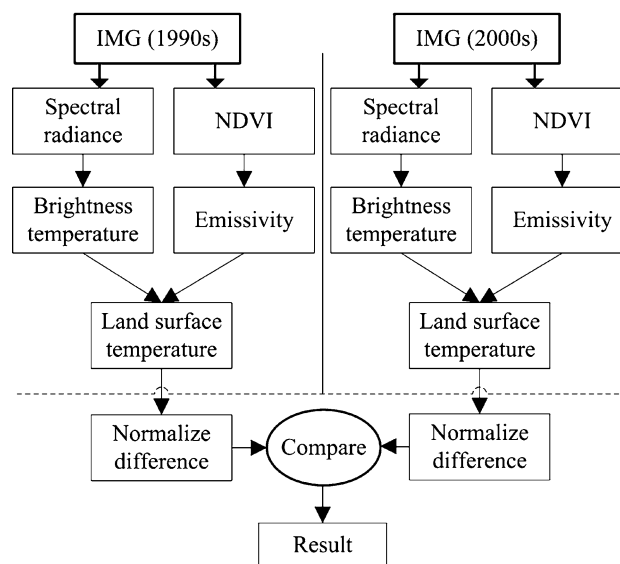
**Fig. 1** Frame of the ERDAS image processing method for urban heat evolution

Table 3 Parameters of spatio-temporal model

Type	Parameters	Purpose
Measured local parameters	Near-surface air temperature	Calculate mean atmospheric temperature and LST
	Near-surface water vapor content	Calculate air transmittance
Constant parameters	$\varepsilon_{\text{water}}, \varepsilon_{\text{urban}}, \varepsilon_{\text{forest}}$	Calculate emissivity of different land type
	a, b	Calculate LST
	K_1, K_2	Calculate brightness temperature
	E_0	Calculate reflectance
Variable parameters in meta file	$L_{\text{max}_\lambda}, L_{\text{min}_\lambda}$	Calculate spectral radiance
	Sun elevation angle	Calculate reflectance

and geometrically to make sure the comparative images have the same size and location. A proper data format is also important for the execution of the model.

In this model, only two measured parameters are required; near-surface air temperature and water vapor content when satellite passes, which can be easily obtained from local weather stations. These two parameters are then converted to air transmittance and effective mean atmospheric temperature. Other required constant values include the emissivity of water, forest and urban land. Other useful values such as L_{max_λ} , L_{min_λ} , and the solar elevation angle can be obtained from the Meta file. The parameters of the model are enumerated in Table 3.

Model built-up

Convert of the digital number into spectral radiance

It is started with creating a new model in ERDAS IMAGINE, designating the names, locations and formats of each file. In order to convert the digital number (DN) of Landsat TM/ETM+ TIR spectrum band into spectral radiance, Eq. (4) is used (Landsat Project Science Office 2001):

$$L = [(L_{\text{max}_\lambda} - L_{\text{min}_\lambda})Q_{\text{calmax}}]Q_{\text{cal}} + L_{\text{min}_\lambda} \quad (4)$$

Where λ is ETM+/TM band number, L is at-sensor radiance, Q_{cal} is the quantized calibrated pixel value in DN, Q_{calmax} is the maximum quantized calibrated pixel value corresponding to L_{max_λ} , L_{max_λ} and L_{min_λ} are the spectral radiance values that are scaled to Q_{calmin} and Q_{calmax} , respectively.

Convert of the spectral radiance to at-sensor brightness temperature

Convert of the spectral radiance to at-sensor brightness temperature is carried out by Eq. (5) (Landsat Project Science Office 2001):

Table 4 TM/ETM+ thermal band calibration constants

Image	K_1 (w/(m ² sr μm))	K_2 (K)
TM (Markham and Barker 1986)	607.76	1260.56
ETM+ (Irish 2000)	666.09	1282.71

Table 5 TM/ETM+ solar spectral irradiances (E_0) (w/(m² $\times$ μm))

Band	1	2	3	4	5	7
TM (Neckel and Labs 1984)	1,957	1,829	1,557	1,047	2,193	7,452
ETM+ (Iqbal 1983)	1,969	1,840	1,551	1,044	225.7	82.07

$$T_{\text{sensor}} = K_2 / \ln(K_1 / L + 1) \quad (5)$$

Where T_{sensor} is at-sensor brightness temperature in K, K_1 is the calibration constant 1 given in Table 4, K_2 is the calibration constant 2 given in Table 4, L is spectral radiance in watts/(m² sr μm).

Precise calculation of NDVI

In this step, enough raster objects and function icons are used in the model so that the NDVI (Eq. (6)) and reflectance can be computed.

$$\text{NDVI} = (\rho_4 - \rho_3) / (\rho_4 + \rho_3) \quad (6)$$

Where ρ_4 is the reflectance measured in the near infrared wave bands and ρ_3 is the reflectance corresponding to the red wave bands (Rouse et al. 1974). In order to get the reflectance of each band, Eq. (7) is used (Landsat Project Science Office 2001).

$$\rho = \pi L D_s D_s / (E_0 \cos \theta) \quad (7)$$

Where L is the spectral radiance from Eq. (4), D_s is Earth–Sun distance in astronomical unit, usually about 1, E_0 is mean exoatmospheric solar irradiance given in Table 5, θ is solar zenith angle in degree, which is provided in the Meta file.

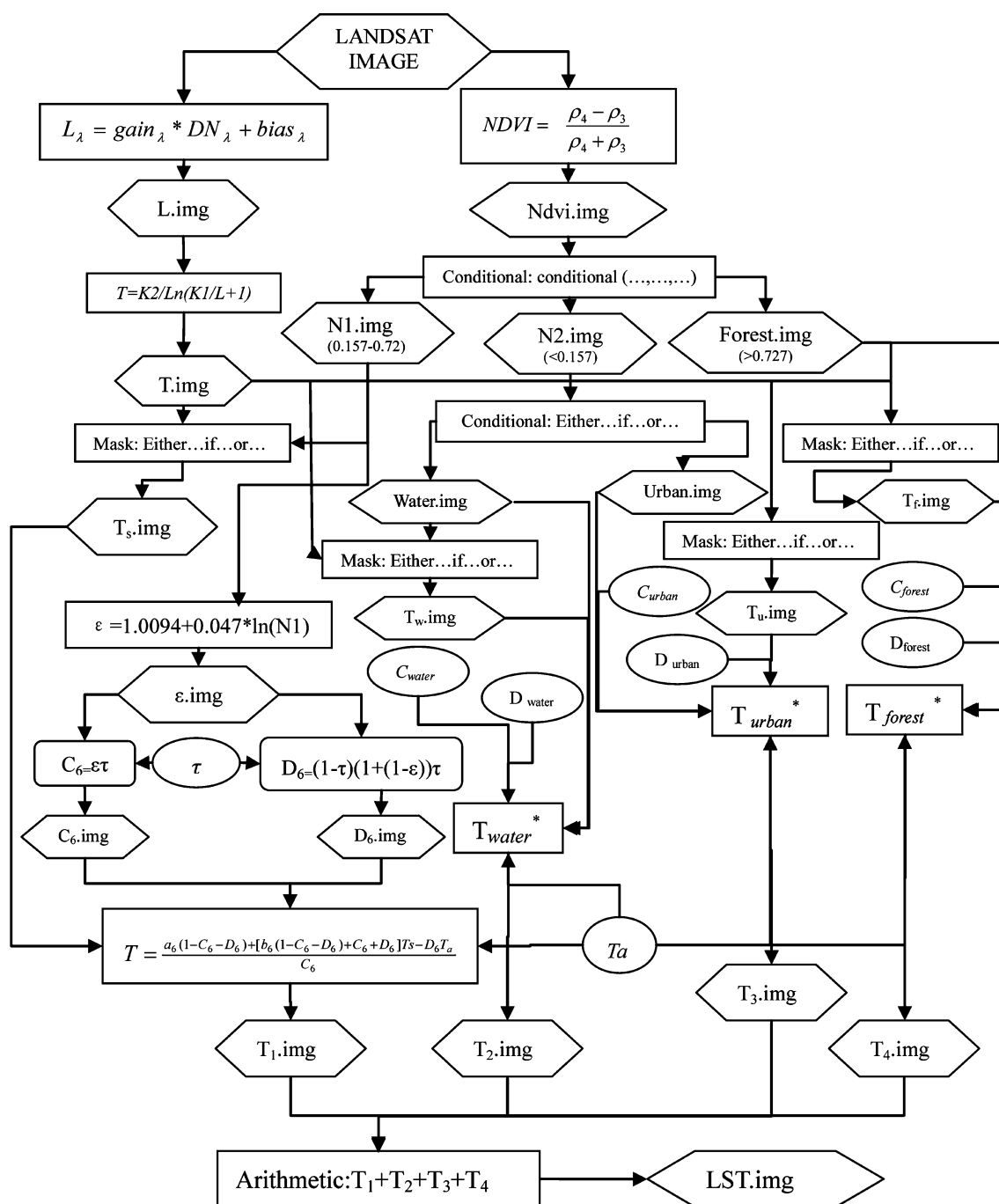


Fig. 2 Flowchart for LST retrieving, where T_{urban}^* , T_{water}^* , T_{forest}^* are the equations like Eq. (1) with corresponding C and D

Calculation of emissivity

Before calculating emissivity, the NDVI values are classified by the conditional function: **CONDITIONAL** {(<test1> <arg1>, (<test2>) <arg2> ...}, where the <test1> and <test2> are the conditions, and <arg1>, <arg2> are the output objects. Various methods can be used to calculate emissivity (Van de Griend and Owe 1993;

Valor and Caselles 1996; Gillespie et al. 1998). When NDVI value ranges from 0.157 to 0.727, Van de Griend and Owe (1993) gave an effective equation (Eq. (8)):

$$\varepsilon = 1.0094 + 0.047 \ln(NDVI) \quad (8)$$

The areas with NDVI values below 0.157 can be classified into water and urban built-up land. According to Eq. (9), if MNDWI is negative, the areas are urban built-up

Table 6 Classification table

Value	Conditions	Description
1	<Mean – Standard Deviation (M – SD)	Low LST Areas (LLA)
2	$\geq M - SD$ and $\leq M + SD$	Normal LST Areas (NLA)
3	>Mean + Standard Deviation (M + SD)	High LST Areas (HLA)

Table 7 Urban heat conversion matrix

1990	2000		
	LLA	NLA	HLA
LLA	1	2	3
NLA	4	5	6
HLA	7	8	9

land with $\varepsilon_{\text{urban}} = 0.970$, else the areas are water with $\varepsilon_{\text{water}} = 0.995$. While NDVI is greater than 0.727, the areas are forest with $\varepsilon_{\text{forest}} = 0.986$. (Qin et al. 2004; Xu 2005)

$$\text{MNDWI} = (\text{Green} - \text{MIR}) / (\text{Green} + \text{MIR}) \quad (9)$$

Where Green means band 2, and MIR means band 5 in TM/ETM+.

Calculation of LST

According to Qin et al.'s mono-window algorithm, LST can be computed directly and quickly in this model. Figure 2 describes the detailed processes to obtain LST.

Normalization of the difference

Another LST image can be obtained in the same way. In order to eliminate the influence of time, a statistical theory is suggested (Zhang 2006a) and the LST images are classified based on Table 6.

In the Spatial Model Maker tool, the functions are as follows,

$\langle \text{image3} \rangle = \text{GLOBAL_MEAN}(\langle \text{image1} \rangle) + \text{GLOBAL_STANDARD_DEVIATION}(\langle \text{image1} \rangle)$,

$\langle \text{image4} \rangle = \text{GLOBAL_MEAN}(\langle \text{image1} \rangle) - \text{GLOBAL_STANDARD_DEVIATION}(\langle \text{image1} \rangle)$,

While the classification function is:

$\text{CONDITIONAL}\{(\langle \text{image1} \rangle < \langle \text{image3} \rangle) \text{ 1, } (\langle \text{image1} \rangle \geq \langle \text{image3} \rangle \text{ and } \langle \text{image1} \rangle \leq \langle \text{image4} \rangle) \text{ 2, } (\langle \text{image1} \rangle > \langle \text{image4} \rangle) \text{ 3}\}$.

Where $\langle \text{image1} \rangle$ stands for the LST image, $\langle \text{image3} \rangle$ and $\langle \text{image4} \rangle$ are urban heat island (UHI) and urban cool island (UCI), respectively.

Retrieval of an urban heat conversion matrix

The temperature difference map can be obtained by comparing the normalized images. According to Leica Geosystems Geospatial Imaging, LLC 2005, the function is as follows,

$\text{EITHER } 0 \text{ IF } ((\langle \text{image1} \rangle \text{ EQ } 0) \text{ OR } (\langle \text{image2} \rangle \text{ EQ } 0)) \text{ OR } ((\langle \text{image1} \rangle - 1) * \text{GLOBAL_MAX}(\langle \text{image2} \rangle)) + \langle \text{image2} \rangle \text{ OTHERWISE}$

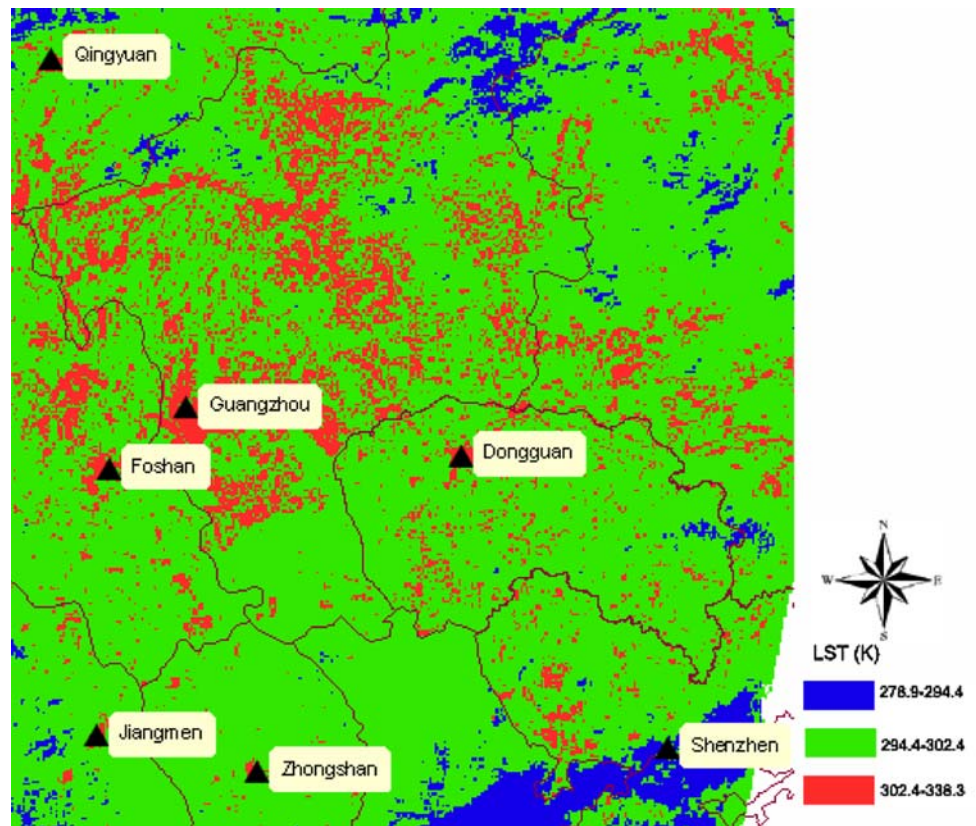
Where $\langle \text{image1} \rangle$, $\langle \text{image2} \rangle$ are the normalized LST images in different years.

The output file has 9 classes, numbered from 1 to 9, which correspond to the elements of the matrix. Each of the classes represents a unique combination of the classes of input files. The conversion matrix is taken to describe the urban heat change map (Table 7). $\langle \text{image1} \rangle$ specifies the columns of the matrix, and $\langle \text{image2} \rangle$ specifies the rows. The values located on the main diagonal are LST non-change areas. Values left to the main diagonal are the LST rising areas. If the pixel value is 3, it means that the change is from Low LST Areas (LLA) to High LST Areas (HLA). Values right to the main diagonal are the LST dropping areas. If the pixel value is 7, it means the change is from HLA to LLA.

Table 8 Parameters used for retrieving LST in the case study

Type	Parameters	For 1990s image	For 2000s image
Variable local parameters	Near-surface air temperature	297.85 K	298.85 K
	Near-surface water vapor content	1.27 g/cm ²	1.27 g/cm ²
Constant parameters	$\varepsilon_{\text{water}}, \varepsilon_{\text{urban}}, \varepsilon_{\text{forest}}$	0.995, 0.970, 0.986	0.995, 0.970, 0.986
	a, b	67.355351, 0.458606	67.355351, 0.458606
	K_1, K_2	607.76, 666.09	1260.56, 1282.71
	E_0	$E_{0 \text{ band3}} = 1,557$	$E_{0 \text{ band3}} = 1,551$
		$E_{0 \text{ band4}} = 1,047$	$E_{0 \text{ band4}} = 1,044$
Various parameters in Meta file	$L_{\text{max}}, L_{\text{min}}$	1.5303, 0.1238	12.650, 3.200
	Solar zenith angle	42°	31°

Fig. 3 Map showing the LST classes in the Pearl River Delta Region for 1990



Application in South China to trace urban heat evolution

Background

The Pearl River Delta has experienced a rapid urban expansion since 1990s. In order to test the ERDAS image processing method, Landsat TM and ETM+ images of 122/44 (Row/Path) on October 13, 1990 and September 14, 2000 were applied in this study. The data acquired date was under the highly clear atmospheric condition, and the images were obtained from the USGS Earth Resource Observation Systems Data Center, which had been subjected to both geometrical and radiometrical correction. The Landsat images were further rectified to a common Universal Transverse Mercator (UTM) coordinate system that is identical to the local feature maps.

Data preparation

According to the recorded data in Wushan weather station of Guangzhou, the actual near-surface air temperature and water vapor content at that time when satellite passed were 297.85 K, 1.27 g/cm² on October 13, 1990, and were 298.85 K, 1.27 g/cm² on September 14, 2000, respectively. The other parameters used in this model are listed in Table 8.

Result and discussion

It is shown in Fig. 3 that:

- (1) In 1990, the LST of water was high relatively, and the difference between the LST of water and the LST of urban was not obvious;
- (2) Most areas of Guangzhou and Foshan were located in HLA, indicating that Guangzhou and Foshan have experienced speedy urban expansions, and urban heat island phenomenon appeared at that time;
- (3) A trend that HLA is distributed along the local main roads indicates that the long-distance transportation was not popular in 1990, whereas the short-distance transportation was developing. Therefore, the local government should find out a way to moderate the thermal environment around main roads.

It is shown in the LST map of 2000 (Fig. 4) that:

- (1) Compared to 1990, the LST of water was lower than that of urban in 2000, which was mainly attributed to global warming. As the density of CO₂ in the earth increased, the temperature of urban land increased quickly, while the temperature of water increases slowly due to its high thermal capacity, so the difference was enlarged (Liu et al. 2006).

Fig. 4 Map showing the LST classes in the Pearl River Delta Region for 2000

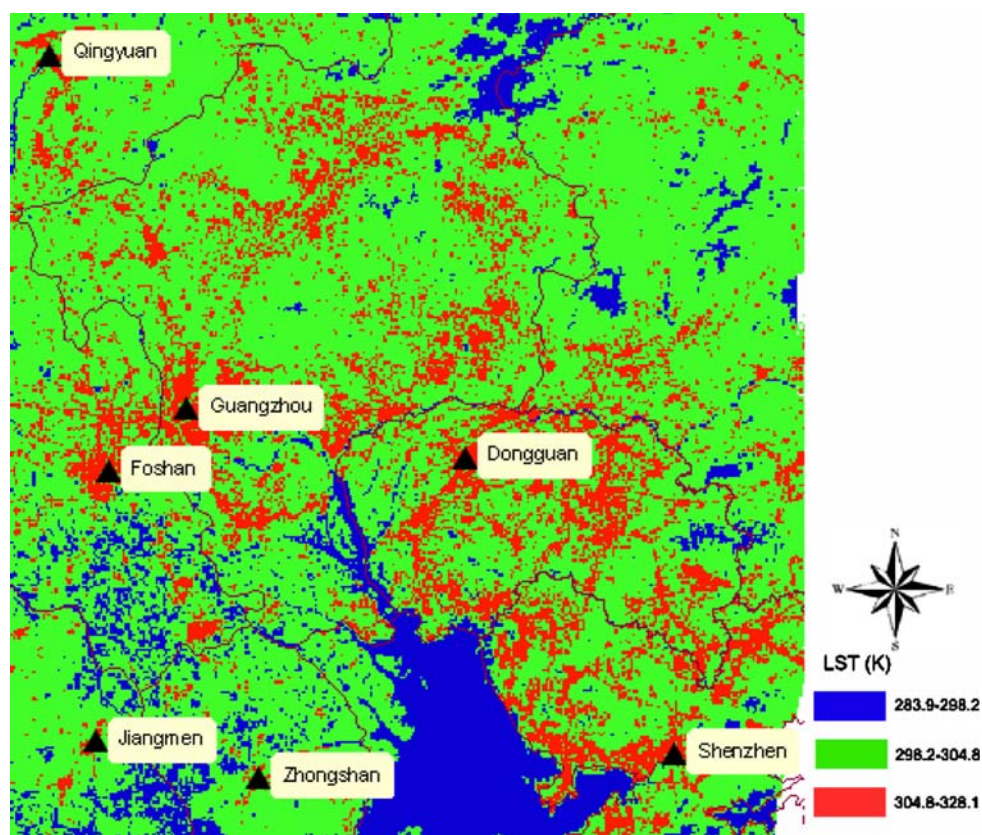
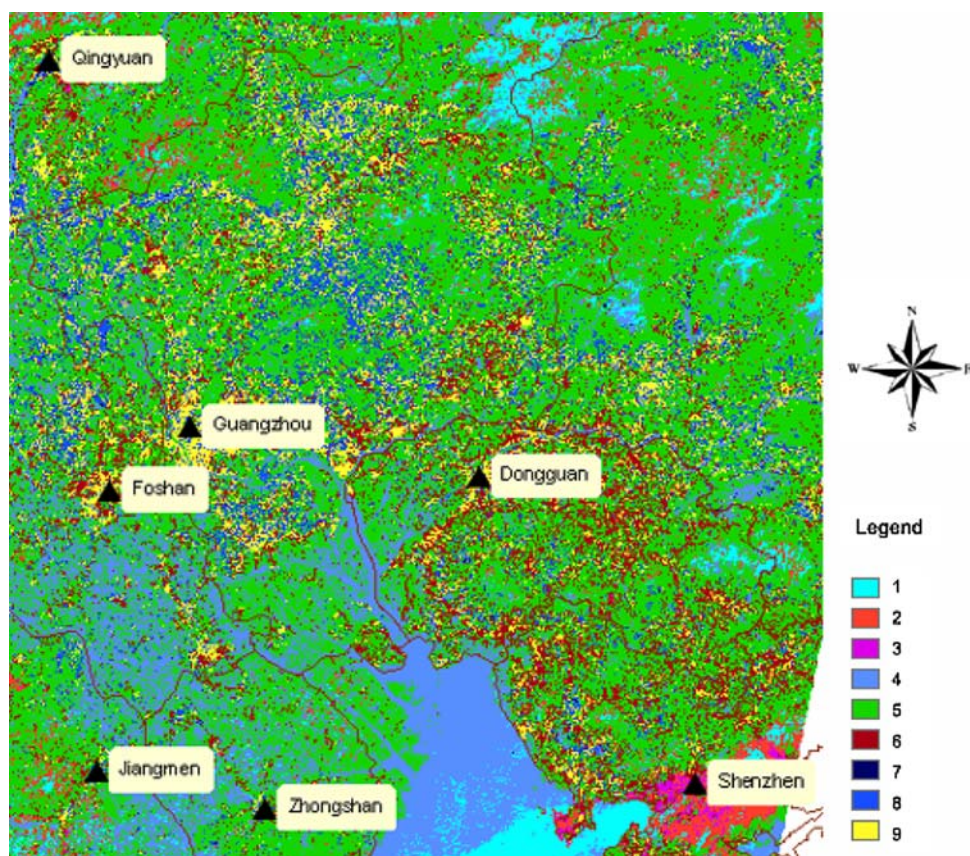


Fig. 5 Map showing the LST evolutions in the Pearl River Delta Region between 1990 and 2000. Where the LST classes with value = 2, 3 and 6 changed from low to high; the LST classes with value = 1, 5 and 9 changed from high to low; and the LST classes with value = 4, 7 and 8 meant no changes during 1990–2000



- (2) There were more and more cities located in HLA, including Foshan, Guangzhou, Dongguan, and Shenzhen. HLA in all of these cities, especially in Dongguan, were increased, which could be attributed to land cover change due to urbanization (Qian and Ding 2005, Liu et al. 2006).
- (3) HLA occurs along the local main roads and the national highway.
- (4) Measures should be taken to moderate the environment of high LST areas.

It is showed that the LST diversion is correlated with urban expansion (Weng 2001, 2002; Dousset and Gourmelon 2003; Qian and Ding 2005). From Fig. 5, we could conclude that a notable city development took place in the Pearl River Delta during 1990–2000, and urban heat was uneven in different parts of this area. Foshan, Guangzhou, Dongguan and Shenzhen cities have experienced a quick and intense city evolution. The urban expansion showed an increase trend near the eastern bank of the Pearl River. The cities of Dongguan and Shenzhen, in particular, contain plenty of HLA dramatically. This was probably caused by the economic development policy of the local government. This result is also in accordance with former studies about urban expansion in the Pearl River Delta (Weng 2001, 2002; Qian and Ding 2005).

Conclusions

Land Surface Temperature is affected by many factors, such as aerosol, land cover and city layout. It therefore deserves to explore convenient and efficient methods to acquire LST and urban heat evolution. This paper provides an ERDAS image processing method to compute LST, and to describe the urban heat evolution. The model can be used to estimate the city development impacts on environment. The application in the Pearl River Delta has demonstrated its ability to provide comprehensive information of urban heat evolution and improved computing efficiency to finish the process in one-step rather than intricate input and output operations. With built-in data set including satellite images and near-surface atmospheric temperature and water vapor content when satellite passes, it will be a powerful tool for scientists and governments to research the locations and dimensions of environment heat changes.

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References

- Carnahan WH, Larson RC (1990) An analysis of an urban heat sink. *Remote Sens Environ* 33:65–71
- Dousset B, Gourmelon F (2003) Satellite multi-sensor data analysis of urban surface temperatures and landcover. *ISPRS J Photogramm* 58:43–54
- Gillespie AR, Rokugawa S, Matsunaga T, Cothorn JS, Hook SJ, Kahle AB (1998) A temperature and emissivity separation algorithm for advanced spaceborne thermal emission and reflection radiometer (ASTER) images. *IEEE Trans Geosci Remote* 36(4):1113–1126
- Iqbal M (1983) An introduction to solar radiation. Academic Press, London, p 390
- Irish RR (2000) Landsat 7 science data user's handbook. National Aeronautics and Space Administration. http://ftpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html. Cited 10 March 2003
- Jimenez-Munoz JC, Sobrino JA (2003) A generalized single-channel method for retrieving land surface temperature from remote sensing data. *J Geophys Res* 108(D22):4688–4694
- Kato S, Yamaguchi Y (2005) Analysis of urban heat-island effect using ASTER and ETM+ data: separation of anthropogenic heat discharge and natural heat radiation from sensible heat flux. *Remote Sens Environ* 99:44–54
- Kim HH (1992) Urban heat island. *Int J Remote Sens* 13:2319–2336
- Landsat Project Science Office (2001) Landsat7 science data user's handbook. Goddard Space Flight Center, NASA, Washington, DC. http://ftpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html. Cited 10 March 2003
- Leica Geosystems Geospatial Imaging, LLC (2005) ERDAS Field Guide. Norcross, Georgia, USA
- Liu Y, Kuang Y, Wu Z, Huang N, Zhou J (2006) Impact of land use on urban land surface temperature—a case study of Dongguan, Guangdong Province. *Sci Geogr Apha Sin* 26(5):597–602 (In Chinese)
- Markham BL, Barker JL (1986) Landsat MSS and TM post-calibration dynamic ranges, exoatmospheric reflectances and at-satellite temperatures. *EOSAT Landsat Tech Notes* 1:3–8
- Neckel H, Labs D (1984) The solar radiation between 3300 and 12500Å. *Solar Phys* 90:205–258
- Nichol JE (1994) A GIS-based approach to microclimate monitoring in Singapore's high-rise housing estates. *Photogramm Eng Rem S* 60:1225–1232
- Qian L, Ding S (2005) Influence of land cover change on land surface in Zhujiang Delta. *Acta Geogr Sin* 60(5):761–770 (In Chinese)
- Qin Z, Karnieli A, Berliner P (2001) A mono-window algorithm for retrieving land surface temperature from Landsat TM data and its application to the Israel-Egypt border region. *Int J Remote Sens* 22(18):3719–3746
- Qin Z, Li W, Xu B, Chen Z, Liu J (2004) The estimation of land surface emissivity for LANDSAT TM6. *Remote Sens Land Resour* 3:28–36 (In Chinese)
- Rouse JW, Haas RH, Schell JA, Deering DW, Harlan JC (1974) Monitoring the vernal advancements and retrogradation (green-wave effect) of natural vegetation. NASA/GSFC Final Report, NASA, Greenbelt, MD, pp 371
- Sobrino JA, Li ZL, Stoll MP, Becker F (1996) Multi-channel and multi-angle algorithms for estimating sea and land surface temperature with ATSR data. *Int J Remote Sens* 17(11):2089–2114
- Sobrino JA, Jimenez-Munoz JC, Paolini L (2004) Land surface temperature retrieval from LANDSAT TM 5. *Remote Sens Environ* 90:434–440

- Valor E, Caselles V (1996) Mapping land surface emissivity from NDVI: application to European, African and South American areas. *Remote Sens Environ* 57:167–184
- Van de Griend AA, Owe M (1993) On the relationship between thermal emissivity and the normalized difference vegetation index for natural surfaces. *Int J Remote Sens* 14(6):1119–1131
- Weng Q (2001) A remote sensing-GIS evaluation of urban expansion and its impact on surface temperature in the Zhujiang Delta, China. *Int J Remote Sens* 22:1999–2014
- Weng Q (2002) Land use change analysis in the Zhujiang Delta of China using satellite remote sensing, GIS and stochastic modeling. *J Environ Manage* 64:273–284
- Weng Q (2003) Fractal analysis of satellite-detected urban heat island effect. *Photogramm Eng Remote Sens* 69:555–566
- Xu H (2005) A study on information extraction of water body with the modified normalized difference water index (MNDWI). *J Remote Sens* 9(5):589–595 (In Chinese)
- Zhang J (2006a) Thermal environment detection in the Pearl River Delta area by remote sensing and analysis of its spatial and temporal evolutions. Dissertation, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (In Chinese)
- Zhang J, Wang Y, Li Y (2006b) A C⁺⁺ program for retrieving land surface temperature from the data of Landsat TM/ETM+ band6. *Comput Geosci* 32(10):1796–1805