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Spatial distribution characteristics of urban thermal conditions: application of GIS and remote sensing

作者: ZHOU Hong-meiet al.

Abstract: The urban thermal distribution characteristics and its variation are dynamically monitored and synthetically analyzed by using GIS technology. The meteorological satellite data serve as main information source, assisted as auxiliary information sources by the landsat satellite TM data, land use thematic maps and meteorological observed data. A correlated pattern on the ground surface brightness temperatures and air temperatures has been studied and established with good performance of application.

Spatial distribution characteristics of urban thermal conditions: application of GIS and remote sensing ZHOU Hong-mei 1, ZHOU Cheng-hu2, GE Wei-qiang1, DING Jin-cai3 (1. Shanghai Meteorological Institute, Shanghai 200030, China; 2. State Key Laboratory of Resources and Environment Information System, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China; 3. Meteorological Center, Shanghai 200030, China) Due to the limitation of site number, manpower and material resources, it is hard to gain a deep understanding of the plane distribution and internal structure of the thermal conditions by routine methods to study the thermal landscape characteristics of the ground surface. Using remote sensing method to study and analyze heat island effect has many advantages, such as high resolution, wide coverage and dense samples. In order to study, in advance and synchronously, the thermal distribution characteristics and its variation, and provide the scientific foundation for environmental monitoring and urban planning, a dynamic monitoring and spatial analytical model is studied and established based mainly on remote sensing monitoring from meteorological and resource satellites, and by using GIS (geographic information system) logic algorithm and comprehensive analytical technology. A comprehensive analysis has been done on the distribution, forming mechanism and the relation with regional structure of the thermal conditions. At the same time, a correlated model on the ground surface brightness temperatures and air temperatures has been established with good performance on its applications. 1 Preprocessing of remote sensing images based on GIS Due to the peculiar geographical location and complex thermal distribution of Shanghai urban area, the thermal distribution characteristics of Shanghai from 1992-1998 has been comprehensively treated and spatially analyzed by GIS spatial analytical method, with NOAA meteorological satellites as main information source, while the landsat satellite TM data, thematic maps of land use, and meteorological data, such as air temperature, wind direction and wind speed, served as auxiliary information sources. 1.1 Preparation and extraction of thermal characteristics from NOAA data 1.1.1 Preprocessing Due to the temperature sensitive characteristics of the NOAA infrared channels, the AVHRR data of its 2nd, 3rd and 4th channels are chosen for Shanghai area mapping, through calibration, positioning, and correction of sun elevation angle and side-darkening, and by bi-linear interpolation magnification. 1.1.2 Extraction and processing of thermal characteristics By using Planck formula, the above mentioned preprocessed NOAA images are retrieved as brightness temperature map to analyze the thermal distribution. At the same time, in order to ease the comprehensive 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: where C and K are unknown constants; TBi is the brightness temperature at point I; YI is the brightness temperature after extended calculation. Ymax is the highest brightness temperature after extended calculation, Ymin is the lowest brightness temperature after extended calculation. TB max is the highest brightness temperature and TB min is the lowest brightness temperature of the image. From Equation 1 the calculated C and K are assigned to 19 and 12 respectively, which could control all the brightness temperatures between Ymin and Ymax . In addition, a proper template is used to convo lutedly 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. 1.2 Preprocessing of TM image In order to put TM image as ground surface medium base map for comprehensive analysis, and improve the accuracy of thermal dynamic analysis from NOAA data, at first, an information interpretation and classification has been done on the TM image. A maximum likelihood method with relatively small classification error has been chosen for training classification on the TM image [1]. The formula of multi-variant normal density function for maximum likelihood classification is: (I = 1, 2, ?, m) where mI is the vector of average value, CI is the matrix covariance, |CI| is the determinant of the matrix. CI-1 is the reverse matrix of Ci. P(x/?I) is the conditional probability function of density, ?I is the type of model, n is the number of dimensions of the model vector, and x is the model for classification. The maximum likelihood discrimination function is: or where the p(?I) is the prior probability. It should be noted that when the number of samples is small, it might not obtain the best result. 1.3 The registration of remote sensing images on different platforms and thermal maps In order to comprehensively analyze with GIS, it is necessary to match remote sensing images with different horizontal resolutions and the thematic maps to a unified scale. 1.3.1 The loading of thematic maps and its format transfer First, by using the digital function of GIS to input thematic maps with related scale, then thematic maps of vector format is transferred to raster format. 1.3.2 The registration of thematic maps and remote sensing images on different platforms (1) The selection of GCP (Cround Control Point) In addition to selecting better mathematical model and resampling method, the selection of GCP is very important for a precise image registration. It is essential to have precise GCPs. Since the resolution of TM images is very high, it is easy to select GCPs. In general, some points with obvious characteristicss, such as river systems, towns and roads, could be selected as GCPs. The resolution of NOAA satellites is low, it would be difficult to select GCP. Since the NOAA spectrum characteristics, that is the reflectivity of town and countryside in infrared band, indicates some differences, an information prominent process could be operated by using multiplication enhancement of near and mid-infrared channels and combination operation method of channels. This is because in the near infrared band (0.725-1.1 um), the reflectivity of soil will increase, as the wave length increases, and will reach its maximum in the mid-infrared wave band (3.55-3.93 um). While in the mid-infrared wave band, it contains reflected radiation of the sun light and the thermal radiation from the ground surface, which results in appreciable surface effect of the town. This paper uses 2-channel multiplication enhancement method that stresses the information of the characteristicsistics points, such as the towns and bridges. Then, the GCPs of NOAA will be easily selected and good performance of application could be obtained. (2) The geometric precise correction and setup for resampling model In order to increase the accuracy of geometric correction, the thrice power polynomial for registration between images and between images and thematic maps is used and also the resampling for image pixels with nearest neighbourhood is used. Through the above-mentioned methods, the registered images will provide an average error less than one pixel. 2 Study and establishment of dynamic analytical model In order to objectively and effectively analyze the characteristics of thermal distribution, the methods of GIS logic discriminance and stratification analysis are used to establish spatial analytical model. The dominant idea is to study and establish dynamic monitoring and spatial analytic model for comprehensively analyzing the thermal spatial distribution and forming mechanism of urban heat island, by using the NOAA brightness temperature as the main factor with other factors, such as land use classified maps and meteorological data, as supplementary factors. The thermal spatial analytical model is: where F is the analytical result of the thermal distribution characteristics, which is the function of factors, N, S, T and W. N is the brightness temperature images from NOAA; S is the thermal map of land use; T is the landsat satellite TM image and W is the observed meteorological data. From the following steps the thermal dynamic analysis by GIS has been done. (1) The calculation of brightness temperature from NOAA The Planck function is used for the brightness temperature calculation, and the Plansk formula is as follows [2]: where TB is the brightness temperature, E is the radiance after calibration, V is the center wave number of the detecting wave band, and C1, C2 are Boltzmann constant. (2) Setup of area with special mark (mask area) from different NOAA brightness temperatures For example, establish a pixel mask area for brightness temperature image N with TB from 35oC to 37oC. Maskgrid=select (N, ¯value ge 35 and value le 37˘) where maskgrid is the mask raster image of certain TB. (3) The amalgamation 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 is solved for the remote sensing and non remote sensing informations of different spatial resolutions. (4) The information extraction and ratio calculation for different media of the ground surface from different NOAA TB mask areas Based on the logic discrimination and information extraction on each of the pixels from the land use and recent TM images, the area ra tio of the ground surfaces with different NOAA TB mask areas to the total area are calculated. The amalgamation result of land use and TM images is as follows: where Wjk is the amalgamation result of land use and TM images, Sjk is the raster image of land use, Tjk is the TM image, j is the classification of medium, and k is the number of pixel. The ratio of ground surface for different media from geometrical area (non-connecting mask area with the same TB) with different TB to the total area is as follows: where Nik is the TB image from NOAA satellite, I is a TB level, j is the kind of medium, k is the number of pixel, n is the number of pixel with the classification of medium j in certain TB mask area, m is the number of pixels in mask area with certain TB level, and Yij is the ratio of mask area to the total area with the classification of medium j and TB level i. (5) Setup of comprehensive analytical model for thermal characteristics distribution The attribution relationship among each stratification factor is established by using attribute coding of administrative (township) boundary as basic property unit. The multi-factor discrimination is provided by GIS logic analytical method. The discriminating factors are as follows: ? Certain brightness temperature (such as 32oC-35oC) of NOAA images ? The area ratio of each land use medium on this brightness temperature area ? Recent scene of TM classified images ? Meteorological condition (including temperature, wind direction, wind speed etc.) First, all the above factors are divided into several levels. Then, we establish relationships between different elements, line up the related factors according to their importance, and indicate their weights. Furthermore, we analyze internally each element, line up different kinds of the elements, and give score to the effect on the result from different elements. Finally, the value of impact on the result from different kinds inside each element could be obtained. Its mathematical model is: where Zp is the final level of combined results at point P, WI is the weight of element number I, QI p is the score by experts on element I at point p, and m is the number of elements. From the classification, logic extraction and comprehensive weight, the resulting image of thermal distribution is finally formed. 3 The analysis on the temporal and spatial variation of thermal characteristics based on GIS In order to objectively analyze the regularity and forming mechanism of the thermal distribution, the calculated thermal results of NOAA satellite, the land use thematic maps, landsat satellite TM data and meteorological data, including air temperature, wind direction and wind speed, are spatially overlaid and comprehensively analysed using GIS[3-5]. That is to be logically discriminated by multi-information and spatially analyzed on the GRID platform of ARC/INFO. The result shows that the forming mechanism and distribution regularity of heat island effect is related with the following factors[6]: 3.1 The thermal distribution is mainly related with the media of underlying surface and the pattern variation of urban area Since our main research object is the thermal distribution characteristics of the underlying surface, the surface brightness temperature of different time and climate conditions is out of our concern. In fact, for different climate conditions and sampling time, different surface brightness temperatures and air temperatures will be obtained[7,8]. 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. From the radiation characteristics of the NOAA 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 infrared 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. 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 are; the lower the brightness temperature is, the higher the area ratio of the area with vegetation and river system is, and the lower the ratio for other areas is, such as residence, square and road (Figure 1). It turns out that the thermal distribution characteristics are mainly related with the media of the underlying surface and the urban pattern variation. There is not much relation with climate change and different seasons. Its thermal intensity has important relations with meteorological and climatological conditions as well as seasonal changes. Figure 1 Underlying surface medium distribution at high temperature season (28-34 oC) in 1998 For example, the high temperature area of Shanghai in 1992 was mainly located in the central district of Puxi and area around Baoshan Iron and Steel Complex. At that time, these areas were urban centers with lots of tall buildings and dense population. After a few years˘ rapid development of urban construction in Shanghai, the inner core of the downtown, and the outer circular core of Pudong, Baoshan, Jiading, Songjiang and part of Nanhui formed a thermal and high temperature area. The inner high temperature and thermal area spread almost all over the districts except the Zhongshan, Xiangyang and Fuxing parks and the Institute of Political Science and Law. The area from Yuyuan to the People˘s Square of Huangpu District has formed a very high temperature area (Figure 2). This densely populated high temperature and thermal area is full of cement and tile structure buildings. Sometimes, the temperature difference between this area and the suburbs, where the thermal intensity is low mainly due to vegetation cover and bare soil would be 6 oC. Thus, the factors related with townships, such as buildings, roads, squares, bridges, and ground being constructed, play a major role in the formation of the high temprature area. In addition, the density and the height of buildings in city proper have a great impact on the thermal diatribution, since the denser the density of the buildings is, the higher the buildings are, the more concentration and the more the thermal effect will be. Figure 2 Remotely sensed urban thermal distribution of NOAA satellite in Shanghai in 1998 3.2 The heat source inside the urban area has some influence on the heat island Apart from the main effect of the underlying surface of the media on the formation of the heat island, the special thermal situation in the urban area could lead to the increase in thermal intensity of some areas, such as the viaducts with lots of traffic, industrial areas with factory buildings, commercial and residential areas with dense population, iron and steel works and power plants, etc. From GIS comprehensive analysis, we found there were three thermal centers in the downtown of Puxi in Shanghai in 1992. The first center, eastern Shanghai industrial district, is located along the north bank of the Huangpu River, where there were power plants, cotton mills, iron and steel works, and soap factories. The second one, Nanshi District, lies along the west bank of the Huangpu River with dense population, high energy consumption, and heat emission. The third one is western Shanghai industrial district, which is along the Suzhou River and with a lot of cotton mills sand weaving factories. When the urban pattern changed with the evacuation of plants, construction of viaducts, so did the heat sources and thermal distribution. For instance, since the circle viaduct along Zhongshan Road was open to traffic, the tail gas from the vehicles has caused a high temprature area, which became a horse hoof like region along the viaduct. At the same time, the western Shanghai industrial district stays high. The center of Hongkou District, where there are concentrated factories and is densely populated, forms a new heat center. Another heat center is an industrial area located at the north circle and Gonghe New Road, along with a heat center at the No.1 Iron and First Steel Works (Figure 3). As to the problem of special heat source from the urban area, it should be noted that the ground surface and air temperatures increase quickly on sunny days of high temperature without wind or with gentle breeze, and the high temperature thermal energy is difficult to send out due to dense tall cement structure, thus the temperature mixing of ground surface and air temprature reduce thermal energy of some sources. In this case, the urban heat sources have little influence on the heat island effect. Figure 3 Remotely sensed urban thermal distribution of NOAA satellite in Shanghai in 1996 3.3 The thermal effects of some meteorological factors, such as weather and climate From the analysis of heat island effect, it is found that sometimes weather and climatological conditions have some effects on thermal distribution and intensity. In fine weather with gentle breeze or without wind, the heat island effect depends on the ground media and structure and has nothing to do with the season. But, during days with strong wind, the heat center sometimes moves with reduced thermal intensity, since the heat energy flows with the wind. The movement is related with wind direction and speed. The higher the wind speed is, the easier the emitting of the thermal energy is. At the same time, the density and height of urban buildings also play roles on the heat island effect, since the cement forest effect in urban area prevents the emitting of thermal energy. Figure 4 shows the GIS synthetic analytical result of the Shanghai urban thermal distribution. 4 Setup of correlated pattern between air and brightness temperatures Since the remote sensing brightness temprature stands for area average brightness temperature (each pixel is 1.1 km2), in order to understand the intensity of thermal distribution, the correlation of brightness temperature and air temprarure should be studied. A synchronous surface observation method and remote sensing is used to study the summer thermal characteristics of Shanghai in 1998, and set up a correlated pattern on brightness temperature and air temperature. The following data are used as basic data for modelling. These are NOAA data of the 4th channel (10.5-11.5 um) on 14 hours, 7 temporal data on July 2, 3, 10, 11, 14, August 10 and 11 in 1998, and real time air temprature data from 30 sites. By using the brightness data from 30 sampling points as independent variables, and the air temperature of the same time phase as dependent ones, the correlated patterns for brightness temperatures and air temperature are established separately. Since there are differences in township structure, density of the buildings, vegetation distribution and river system, the situations of thermal condition are also different. A proper application performance is obtained by using different ground surface media modelling to study the correlated statistical model of satellite brightness temperatures and observed air temperatures. Figure 4 GIS-based synthetically analytical result of thermal distribution in urban Shanghai in 1998 Table 1 The regression equation of different ground media between brightness temperature and air temperature in Shanghai 5 Conclusions The dynamic monitoring and synthetic analysis are proceeded for the urban thermal distribution by using GIS technology. The NOAA/AVHRR data serve as main information sources, assisted by land use thematic maps, landsat satellite TM data and meteorological statistical data. This method is of time saving, cost saving, objective and highly scientific, and provides significant advantages over routine surveying approaches. Reference s

关键词： remote sensing; geographic information system; urban thermal distribution; application and study

