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Urban heat island monitoring and analysis using a non-parametric model: A case study of Indianapolis

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ABSTRACT

A procedure for the monitoring an urban heat island (UHI) was developed and tested over a selected location in the Midwestern United States. Nine counties in central Indiana were selected and their UHI patterns were modeled. Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature (LST) images taken in 2005 were used for the research. The images were sorted based on cloud cover over the study area. The resulting 94 day and night images were used for the modeling. The technique of process convolution was then applied to the images in order to characterize the UHIs. This process helped to characterize the LST data into a continuous surface and the UHI data into a series of Gaussian functions. The diurnal temperature profiles and UHI intensity attributes (minimum, maximum and magnitude) of the characterized images were analyzed for variations. Skin temperatures within any given image varied between 2–15 °C and 2–8 °C for the day and night images, respectively. The magnitude of the UHI varied from 1–5 °C and 1–3 °C over the daytime and nighttime images, respectively. Three dimensional (3-D) models of the day and night images were generated and visually explored for patterns through animation. A strong and clearly evident UHI was identified extending north of Marion County well into Hamilton County. This information coincides with the development and expansion of northern Marion County during the past few years in contrast to the southern part. To further explore these results, an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) 2004 land use land cover (LULC) dataset was analyzed with respect to the characterized UHI. The areas with maximum heat signatures were found to have a strong correlation with impervious surfaces. The entire process of information extraction was automated in order to facilitate the mining of UHI patterns at a global scale. This research has proved to be promising approach for the modeling and mining of UHIs from large amount of remote sensing images. Furthermore, this research also aids in 3-D diachronic analysis.

1. Introduction

It is often observed that air temperatures in densely urbanized areas are higher than those of the surrounding countryside. Among these urban–rural differences, the most notable and well documented is the phenomenon known as the "urban heat island" (UHI) (Kim and Baik, 2005). In spite of the fact that the temperature differences strongly vary at a micro scale, both in rural and urban areas, the thermal characteristics of the urban terrain at a macro scale constitute a basic factor in the creation of an UHI (Chudnovsky et al., 2004).

Over the past few years, studies have been carried out to understand the UHI using both air (Fast et al., 2005; Friedl, 2002; Kim and Baik, 2005; Mihalakakou et al., 2002) and skin surface temperature data (Dash et al., 2002; Golden and Kaloush, 2006; Jin et al., 2005; Jung et al., 2005; Snyder et al., 1998). UHI analysis performed using in-situ data has the advantage of high temporal resolution and a long data record, but lacks spatial resolution (Hung et al., 2006). This spatial discontinuity caused by using air temperature data can be overcome by using skin temperatures. For a large area, skin temperature can be mapped and studied by using satellite remote sensing data in the infrared spectrum (Stathopoulou et al., 2004; Voogt and Oke, 1998). There have been studies that have contributed to the use of remote sensing imagery for understanding the UHI effects. Lo et al. (1997) analyzed the UHI effect by using the Advanced Thermal and Land Application Sensor (ATLAS). Weng (2001, 2003) and Weng et al. (2004) have done several studies to analyze the relationship of the UHI effect with respect to the urban factors such as land cover, vegetation and population. Jung et al. (2005) have tried to model the effect of an UHI on vegetation using hyperspectral remote sensing images. Kato and Yamaguchi (2005) analyzed the effect

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of the UHI using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Enhanced Thematic Mapper (ETM+) images. Hung et al. (2006) have assessed the UHI among selected Asian mega cities using images from Aqua and Terra missions.

There has been a considerable amount of research carried out to model the UHI effect. At a practical level, it becomes difficult to generalize the location and distribution of an UHI due to several reasons. These are attributed mainly to the shape and extent of the city, its layout, the nature and type of the surrounding areas, and the resolution of the imagery used to characterize the phenomenon. These factors not only affect the size and shape of the UHI, but they also affect its magnitude. Another characteristic that proves problematic is the boundary between the urban and rural areas is never crisp. It is an area of transition, which is mostly fuzzy. It is important to incorporate this aspect into the UHI modeling, rather than separately modeling the urban area with one method and the rural area with another.

The main objectives of this research are twofold. First, this paper intends to develop a method for characterizing an UHI as a continuous function that includes both urban and rural surfaces. This helps to visualize the pattern of the UHI over the entire study area. There have been several studies that have used statistical methods such as variograms (Bottyán and Unger, 2003) and non-linear parametric models (Streutker, 2003) to characterize the UHI from remote sensing data sets. Even though these processes are effective for analyzing a single or a small set of images, they prove to be inefficient in modeling an UHI from a large set of images. The reason for this inefficiency is that these processes are image-dependent and require manual interference during the various stages of process execution. In order to overcome these difficulties, in this research, a non-parametric model using fast Fourier transformation (FFT) will be utilized to effectively and efficiently characterize the UHI over space.

The second objective of this research is to analyze the UHI pattern over space and over time. It becomes important to monitor the behavior of the UHI with respect to one location over time. This would aid in developing a better understanding of urban temperature and the contribution of the urban surfaces toward the total energy balance. Theoretically, if land use does not change, the UHI should remain relatively constant with respect to its surrounding rural background. However, this is often not the case. There have been studies which have demonstrated that yearly mean of an UHI is negatively correlated to the rural regions (Streutker, 2002). Therefore, the main goal of this research is the development of a model for an UHI that will expand our current understanding of the phenomenon. Further, as a test for validity of the developed UHI model, the characterized images were analyzed with respect to LULC.

2. Study area and data

2.1. Study area

The main motivation behind this research is to develop a general model for monitoring UHIs using high temporal and low spatial resolution images. As a sample case, metropolitan Indianapolis was selected, both the state capital and the county seat of Marion County, its population is 791,926 according to the 2000 Census, making it Indiana's most populous city and the 12th largest city in the US The 1 July, 2004 federal census estimate for the Consolidated City of Indianapolis is 794,160 with a metropolitan area population of 1595,377. The larger combined statistical area (an agglomeration called the Nine-County Region) has a population approaching 2 million residents (1939,349). Indianapolis is the third largest city in the Midwest after Chicago and Detroit, and is one of only three major cities in the Midwest which had a population growth rate above 5%. As of 2005, Marion County's population is 863,133 (IBRC, 2006). The total area of the nine counties is 7928.7969 km^2. It has a single urban core, and no other large urban areas in the vicinity. The city is located in a flat plain and is relatively symmetrical having the possibility to expand in all directions. Like most American cities, Indianapolis is increasing in population and area (Weng et al., 2004). The results have also shown the presence of multiple UHIs around Marion County (the central part, north, west and east side of the city). This finding would also help in testing our hypothesis of whether our model could effectively characterize multiple UHIs (refer Fig. 1).

Indianapolis experiences a continental climate typical of cities at this latitude that lie far from any significant body of water. It experiences hot summers and cold winters., with high air temperature reaching into 32 °C at times and lows around 16 °C. Spring and fall temperatures create conditions favorable for the development of thunderstorms, which due to the lack of hills or mountains often include tornadoes. The average July high is 30 °C with the average low being 16 °C. January highs average 1 °C, and lows −8 °C. The record high for Indianapolis is 40 °C, on 14 July, 1954. The record low is −33 °C, on 19 January, 1994. Snowfall varies from about 500–760 mm a year (Scheeringa, 2006). Due to the well recognized UHI phenomenon, characterized by a temperature contrast between the city and the surrounding rural area (Chin et al., 2005), we included some of the less populated and less urbanized counties such as Boone, Hamilton, Madison, Hancock, Handricks, Morgan, Johnson and Shelby into our study along with Marion county. The assumption is that including counties that have a greater percentage of rural areas would help the model in characterizing the UHI effectively with respect to its rural background. Only the parts of Clinton, Tipton and Madison Counties present within a single scene were used. The main rationale for not merging two scenes within this research is that we are interested in the UHI effect in the city of Indianapolis (which is located within Marion County). The inclusion of other areas from Clinton, Tipton and Madison Counties would not have impacted the results. Nevertheless, the purpose including these counties (in this case part of three counties and all of five counties) was to create a more comprehensive understanding of the UHI. The UHI phenomenon is most prevalent within urban areas and the effect of the phenomenon could be better understood by contrasting it to its rural surroundings. Theoretically, a portion of area surrounding Marion County composed of parts of eight counties would have been sufficient for such an analysis. However, the complete data for five counties were included as this additional information would not impact the results of the model.

2.2. Data

Land surface temperature and emissivity for large areas (regional and global scales) can only be derived from surface-leaving radiation measured by satellite sensors (Dash et al., 2002). Newer satellite systems such as Moderate Resolution Imaging Spectroradiometer (MODIS) include features to allow for easier calibration and provide surface temperature as a standard product. In this study, land surface temperature (LST) information was utilized, as exemplified by the MODIS (Terra and Aqua satellite missions) sensor. The main rationale for selecting the MODIS imagery was due to its high temporal resolution. The MODIS global daily daytime and nighttime LST are distributed on a daily basis by the land process data archive center (LPDAAC). Therefore, this data would not only aid in understanding the UHI on a spatial scale, but also on the temporal scale. Secondly, the extraction of information from such abundant data source is important (Velickov et al., 2000). MODIS is carried on the National Aeronautics and Space