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Variability in annual temperature cycle in the urban areas of the United States as revealed by MODIS imagery

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ABSTRACT

Due to its large spatial coverage and frequent revisit, satellite-derived land surface temperature (LST) has been recently used to explore annual temperature cycle (ATC) variations at regional and global scales. However, variability in seasonality of LSTs has not been examined in detail, particularly in urban areas where elevated temperatures are normally observed. By assuming repetitive temperature cycles, this study aims to reveal differences in ATC parameters between urban and rural areas and the impacts of surface urban heat island (UHI) on the ATC range over the continental United States. To this end, urban areas of larger than 10 km^2 (a total of 1856 urban polygons) in the continental United States were identified from the map of urban extents produced by Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) nighttime light data from 2012. The corresponding rural polygons of the same size were generated by using a buffer method. The ATC parameters were optimized using a sinusoidal function fitted with the 8-day MODIS LST composite data. Results showed that urban and rural areas exhibited a significant difference, with a *p-value* < 0.01, in the ATC parameters, including mean annual surface temperature (MAST), yearly amplitude of surface temperature (YAST), and the revised phase shift parameter. The higher MAST and YAST, but lower phase shift values, were mainly associated with the urban areas. This finding indicated that urban areas contributed to changes in extreme temperatures (the minimum and maximum temperatures) as well as to an overall warming. The regression analysis suggested that surface UHI intensities were positively correlated with the differences in MAST ($R^2 = 0.9$) and YAST ($R^2 = 0.5$) between urban and rural areas, but negatively correlated ($R^2 = 0.2$) with the differences in the revised phase shift parameter. In addition, highest surface UHIs (~3 k) and largest differences in ATC parameters were observed in tropical regions, followed by temperature zones, continental (cold) zones, and arid zones. Overall, this study revealed that urbanization-induced land cover changes could influence urban systems by enhancing temperature variations. However, it should be cautioned that uncertainty in the analysis may arise from the characterization of surface UHIs for the selected ~2000 cities with varying configuration and morphological dimensions.

1. Introduction

The annual temperature cycle (ATC) refers to seasonal temperature variations that are modified by fluctuations in the amount of solar radiation received by the Earth's surface over the course of a year (Thomson, 1995). Traditionally, analysis of annual temperature characteristics depends on sparsely and unevenly distributed air temperature observations or numerical model simulations. Because of its broad spatial coverage and frequent revisits, land surface temperature (LST), derived from satellite thermal infrared sensors, has been recently used to explore ATC variations at regional and global scales. The ATC parameters estimated from LSTs are different in nature from those estimated by air temperatures. LST is directly related to land-atmosphere energy exchange (Bastiaanssen et al., 1998; Friedl, 2002; Oke, 1988) and is subject to surface changes, such as soil moisture (Carlson, 2007; Gillies et al., 1997) and land use/cover composition and configuration (Carlson, 2007; Gillies et al., 1997; Li et al., 2011; Weng et al., 2004). Air temperatures are routine observations collected by an *in-situ* thermometer in a shelter at 1.5–2 m with good thermal contact with the air. Air temperature is correlated to LST but can differ depending on land cover conditions, atmospheric conditions, and the spatial scale at which LST is retrieved (Jin and Dickinson, 2010; Kawashima et al., 2000). For example, differences between air temperatures and LSTs may be large in sparsely vegetated

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areas with most of the net radiation balanced by sensible heat flux (Jin et al., 1997).

The derivation of ATC parameters and analysis of their dynamics requires consistent LST datasets at both high temporal and spatial resolutions. Assessment of subtle changes in temperature cycles dictates that LSTs should be retrieved from satellite thermal sensors with high accuracy and confidence level. Widely used satellite data for large-scale and long-term temperature dynamics include LST products from MODIS (Moderate Resolution Imaging Spectroradiometer) sensors at a spatial resolution of 1 km. Time series of MODIS LSTs have been employed to characterize diurnal temperature cycle (Zhan et al., 2014, Hong et al., 2018), UHI magnitude and extent (Quan et al., 2014; Rajasekar and Weng, 2009), and spatial variations of evapotranspiration (Minacapilli et al., 2016). Although Landsat imagery provides a higher spatial resolution than MODIS data, operational LST maps are still not available. LSTs from AVHRR (Advanced Very High Resolution Radiometer) sensors can date back to the 1980s and have the spatial resolution of ~1 km. Nevertheless, AVHRR LST data are known to be affected by the orbital drift which introduces spurious trends within time series data (Julien and Sobrino, 2012). The availability of MODIS LSTs on a daily basis has enabled the modeling of annual temperature cycles, allowing us to consistently discern possible shifts in annual parameters.

Satellite-derived ATC parameters have been mainly used to characterize landscape thermal behaviors and to study urban climatology. Bechtel (2012) found that ATC parameters could be accurately estimated from 35 Landsat thermal images, and favored the ATC modeling process to extract useful information from time series LST images. Weng and Fu (2014) modeled annual parameters of clear-sky LSTs in Los Angeles, USA, and evaluated the impact of cloud cover on the modeling process. The study showed that the inclusion of cloud-contaminated pixels resulted in lower mean annual surface temperature and higher yearly amplitude of surface temperature. Bechtel (2015) derived annual climatological parameters at the global scale using MODIS LSTs. Moreover, the annual parameters were also employed by Fu and Weng (2016) to understand impacts of urbanization-associated land use and land cover changes on the thermal environment. These studies revealed efforts to better utilize the large amount of freely available thermal images, such as those from Landsat and MODIS. Despite this progress, variability in seasonality of LSTs has not been studied in detail, particularly in urban areas where elevated temperature values are expected in most cases.

At present, the effect of urbanization on ATC variation is not well understood. Urban areas tend to have higher air and surface temperatures than the surrounding rural areas, known as urban heat island (UHI). The UHI effect mainly results from the replacement of vegetative and evaporating surfaces with impervious surfaces that reduce latent heat flux and increase sensible heat flux (Arnfield, 2003; Oke, 1982; Voogt and Oke, 2003). As such, higher temperatures in cities may produce higher amplitude and earlier phase shift in ATC. However, the magnitude of modification on ATC parameters remains unclear, which may differ with cities and with climatic zones. In addition, the effect of UHIs on the ATC variations remains poorly understood. Therefore, the major *scientific questions* addressed in this paper are:

(1) How does urban land cover affect the ATC range?
(2) What is the relationship between the UHI magnitude and the change in the ATC parameters?
(3) How does the relationship in (2) vary across different climatic context?

By selecting approximately 2000 pairs of urban and rural clusters over the continental U.S., this study intends to test the hypotheses (1) that urban land cover can enhance the ATC variation and (2) that a higher surface UHI magnitude can lead to a higher reduction in the ATC range across different climatic zones.

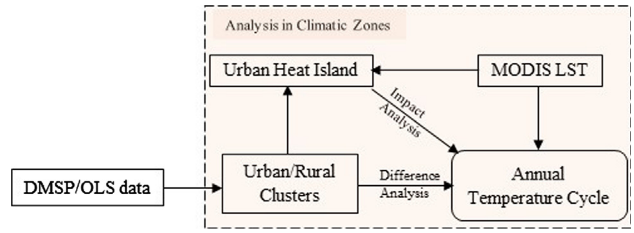

Fig. 1. The overall workflow for data analysis.

2. Data and methods

Fig. 1 illustrates the procedures for data analysis. The analysis steps consist of delineation of urban and rural clusters from the time series Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) nighttime light (NTL) data, annual temperature cycle modeling using a sinusoidal function, and analysis of differences in LSTs and ATC parameters between urban and rural areas. Further analysis was also grouped by the Köppen-Geiger climatic zones.

2.1. Delineation of urban and rural areas

Urban areas were delineated based on the urban extent map derived from DMSP/OLS nighttime light (NTL) data (Xie and Weng, 2017) in 2012. The enhanced time series DMSP/OLS NTL data were produced by implementing a three-step procedure including global inter-calibration, vegetation-based spatial adjustment, and urban archetype-based temporal modification. Final urban extent maps were generated by applying the object-based urban thresholding method to the enhanced time series NTL data. Further details of the algorithm for mapping urban extents over years can be referred to in Xie and Weng (2017). Compared to the USGS NLCD land cover products (Homer et al., 2015; Wickham et al., 2017), the updated NTL urban extents were reasonably accurate, with the city-scale RMSE (root mean square error) of 27 km^2 and Kappa coefficient of 0.65 for CONUS. In this study, to reduce misregistration errors between DMSP/OLS NTL data and MODIS LSTs, only urban clusters larger than 10 km^2 (~3 pixels by 3 pixels) were selected for analysis. Finally, a total of 1856 polygons were generated from the map of urban extent in 2012 and used for further analysis. Although urban areas are selected based on their size in this study, the selected urban polygons may contain one or more cities of varying socio-economic dimensions. For example, the city of Terre Haute, Indiana, was identified as an individual urban polygon with a total area of 71.8 km^2 (estimated from the urban extent map). According to the 2010 census, the city had a total population of 60,785 and its metropolitan area had a population of 170,943. The Washington-Baltimore metropolitan area was also identified as an individual urban polygon with a total area of 2580.67 km^2 (estimated from the urban extent map). According to the Census Bureau's 2012 population estimates, the entire Washington-Baltimore metropolitan area had a population of 9,331,587.

Rural clusters were mapped using a buffer method with the same size area as the corresponding urban clusters. The surface UHIs were calculated as the differences between mean temperatures in urban and rural clusters, and the average ATC range was computed in both urban and rural clusters for comparison. Similar analyses were also performed by grouping urban/rural clusters according to the Koppen-Geiger climate classification map (Fig. 2).

2.2. ATC modeling

The MODIS time series LST data from 01/01/2012 to 12/31/2012 were utilized for characterizing the ATC parameters. Compared to remotely sensed LSTs derived from sensors such as Landsat Therma Infrared Sensor and Geostationary Operational Environmental Satellite