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Monitoring the trajectory of urban nighttime light hotspots using a Gaussian volume model

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ABSTRACT

Urban nighttime light hotspot is an ideal representation of the spatial heterogeneity of human activities within a city, which is sensitive to regional urban expansion pattern. However, most of previous studies related to nighttime light imageries focused on extracting urban extent, leaving the spatial variation of radiance intensity insufficiently explored. With the help of global radiance calibrated DMSP-OLS datasets (NTL_{grc}), we proposed an innovative framework to explore the spatio-temporal trajectory of polycentric urban nighttime light hotspots. Firstly, NTL_{grc} was inter-annually calibrated to improve the consistency. Secondly, multi-resolution segmentation and region-growing SVM classification were employed to remove blooming effect and to extract potential clusters. At last, the urban hotspots were identified by a Gaussian volume model, and the resulting parameters were used to quantitatively depict hotspot features (i.e., intensity, morphology and centroid dynamics). The result shows that our framework successfully captures hotspots in polycentric urban area, whose ${R_a}^2$ are over 0.9. Meanwhile, the spatio-temporal dynamics of the hotspot features intuitively reveal the impact of the regional urban growth pattern and planning strategies on human activities. Compared to previous studies, our framework is more robust and offers an effective way to describe hotspot pattern. Also, it provides a more comprehensive and spatial-explicit understanding regarding the interaction between urbanization pattern and human activities. Our findings are expected to be beneficial to governors in term of sustainable urban planning and decision making.

1. Introduction

The past three decades have seen unprecedented urbanization worldwide, especially in rapid developing countries such as China. Rapid urbanization has led to intensive urban expansion and population explosion (Liu et al., 2016). A comprehensive understanding of the spatial evolution of urban patterns is vitally important for sustainable development (Zheng et al., 2017).

Nighttime light imagery, which provides a record of luminosity at night, is an intuitive indicator of anthropogenic activities (Guo et al., 2017). Studies on nighttime light imagery have provided fruitful knowledge regarding urban expansion monitoring (Small and Elvidge, 2013; Xie and Weng, 2016; Zhou et al., 2014) and socio-economic statistics estimation (Yu et al., 2015). However, most studies have focused on extracting urban boundaries, yet leaving the inner-city radiance variation insufficiently explored.

Nighttime light hotspot is a region that embraces massive brightly lit pixels, thus making the hotspot an ideal proxy of the area with intensive human activities (Cai et al., 2017). The trajectory of hotspots features, which include luminosity variations, morphology and centroid location, represents the spatio-temporal dynamics of rapid urbanization and reveals the impact of regional urban-planning strategies on human activities.

Few studies have investigated hotspot dynamics from the view of nighttime light imagery. Xiao et al. (2014) calculated the geometric centers of nighttime light and analyzed their migration based on graph theory. Other methods utilized spatial metrics (Zhao et al., 2017), Local Moran's I (Cai et al., 2017) and moving window algorithm (Quan et al.,

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2014) to analyze inner-city variations of nighttime light radiance. Nevertheless, following issues remain unresolved: (1) the temporal variations of hotspots have not yet been fully explored; (2) method for describing hotspot features has not been developed.

Quan et al. (2014) utilized a Gaussian volume model to analyze the hotspot trajectory of urban heat island effect (UHI) in Beijing. Their method probed into the characteristics of the UHI hotspot with regard to its centroid, intensity, and coverage. Since the urban expansion pattern of its study area (Beijing) was monocentric, the study assumed that there was only one urban core. However, subjected to landform features, cities are usually separated into several centers, whilst urban growth and the merging of administrative units transform a monocentric distribution pattern into a polycentric one. Therefore, it might be inappropriate to employ a monocentric model for detecting hotspots in other cities.

In this study, we intend to develop a framework to explore the spatio-temporal dynamics of urban nighttime light hotspots. The overall objectives are to (1) test the feasibility of the proposed method, (2) analyze hotspot trajectory dynamics, and (3) probe into the relationship between hotspot dynamics and regional urban growth.

2. Study area and data

2.1. Study area

Hangzhou, a sub-provincial city and the capital of Zhejiang province, is one of the most prosperous regions in the eastern coast of China. It has an area of 16,596 km^2 and a population of 9.02 million. Rapid urbanization in the last three decades has given rise to a striking increase in urban built-up area and population–up to 252.5% and 54.7%, respectively (Zheng et al., 2017). As illustrated in Fig. 1b, the nighttime light of Hangzhou follows a typical polycentric distribution; thus, Hangzhou is a suitable site for testing our framework.

2.2. Data

The Operational Linescan System of the Defense Meteorological Satellite Program (DMSP-OLS) is the major data source for nighttime light imagery (Zhang et al., 2016). The wide coverage and extended temporal range render DMSP-OLS superiority in long-term studies (Huang et al., 2014). However, because of the low dynamic range (6-bit) the saturation problem restrains the use of ordinary DMSP-OLS data (i.e. stable light data) for extracting hotspots. As shown by the red line in Fig. 2, the saturation effect constraints radiance variations within the urban core, thus drowning out inter-urban radiance heterogeneity. In

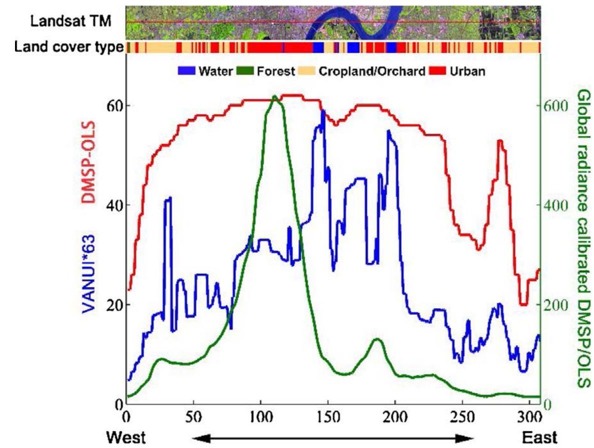

Fig. 2. Latitude transect of stable light DMSP-OLS data (red), VANUI (blue) and the NTL_{grc} data (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

order to resolve the saturation problem, the National Geophysical Data Center (NGDC) released a new type of DMSP-OLS dataset designated as the global radiance-calibrated nighttime light (NTL_{grc}) product, which was a yearly composite data with a spatial resolution of 30 arc seconds. The NTL_{grc} was produced by fixing the gain setting of DMSP-OLS into three stages to record different strength of brightness. The resulting fixed-gain images were further blended with corresponding stable light images (please refer to https://ngdc.noaa.gov/eog/dmsp/radcal_readme.txt, last access on 13 April 2017). In this way, NTL_{grc} imageries can retrieve information with a larger dynamic range. Therefore, NTL_{grc} imageries not only address the saturation problem, but also recover finer details from dimly lit areas, making them more useful in identifying hotspots. The NTL_{grc} imageries were downloaded from the NGDC website (https://ngdc.noaa.gov/eog/download.html, last access on 13 April 2017). Table 1 lists the NTL_{grc} imageries used in this study.

Landsat 5 TM data was applied to calculate NDVI and determine the land-cover type. The dataset was downloaded from the Geospatial Data Cloud (http://www.gscloud.cn/, last access on 14 April 2017). Points of Interest (POI) data are the geographical data provided voluntarily by individuals. It links location-based information or real-world entities into geographical space (Hu et al., 2016). To evaluate land-use types from the functional perspective, POIs from Hangzhou in 2012 were gathered using a web-scraping technique. In sum, a total of 81,644 POIs were used in this study, including four categories relevant to nighttime light emission: road junctions, public infrastructures, human

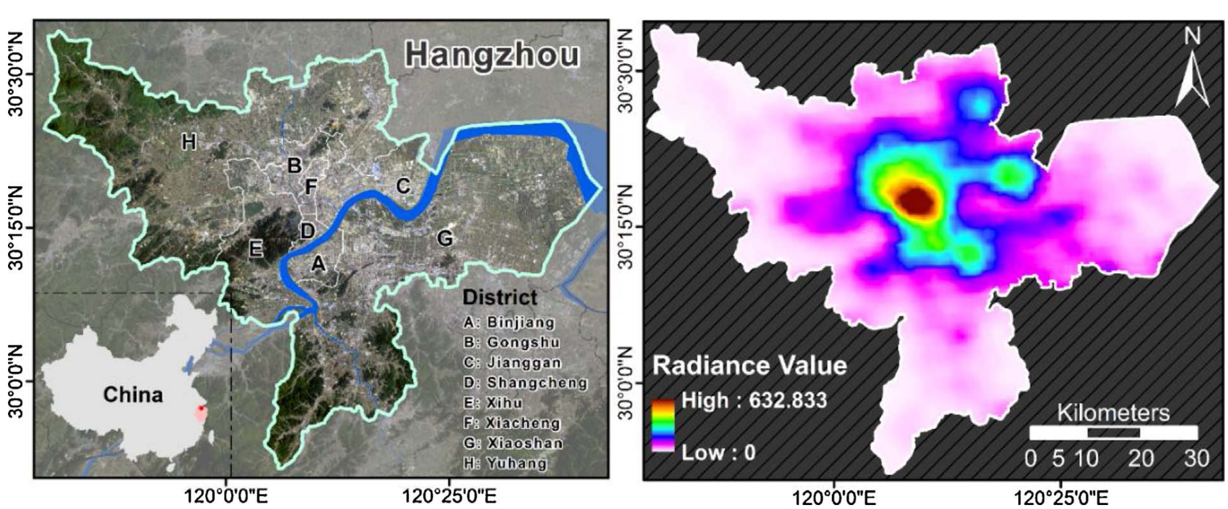

Fig. 1. Location (a) and Nighttime light radiance (b) of Hangzhou.