Remote Sensing of Environment xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Expansion of major urban areas in the US Great Plains from 2000 to 2009 using satellite scatterometer data

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ARTICLE INFO

Keywords:
Urbanization
QuikSCAT
Dense Sampling Method
Impervious surface
LandScan

ABSTRACT

A consistent dataset delineating and characterizing changes in urban environments will be valuable for socio-economic and environmental research and for sustainable urban development. Remotely sensed data have been long used to map urban extent and infrastructure at various spatial and spectral resolutions. Although many datasets and approaches have been tried, there is not yet a universal way to map urban extents across the world. Here we combined a microwave scatterometer (QuikSCAT) dataset at ~1 km posting with percent impervious surface area (%ISA) data from the National Land Cover Dataset (NLCD) that was generated from Landsat data, and ambient population data from the LandScan product to characterize and quantify growth in nine major urban areas in the US Great Plains from 2000 to 2009. Nonparametric Mann-Kendall trend tests on backscatter time series from urban areas show significant expanding trends in eight of nine urban areas with *p*-values ranging 0.032 to 0.001. The sole exception is Houston, which has a substantial non-urban backscatter at the northeastern edge of the urban core. Strong power law scaling relationships between ambient population and either urban area or backscatter power (r^2 of 0.96 in either model) with sub-linear exponents (β of 0.911 and 0.866, respectively) indicate urban areas become more compact with more vertical built-up structure than lateral expansion to accommodate the increased population. Increases in backscatter and %ISA datasets between 2001 and 2006 show agreement in both magnitude and direction for all urban areas except Minneapolis-St. Paul (MSP), likely due to the presence of many lakes and ponds throughout the MSP metropolitan area. We conclude discussing complexities in the backscatter data caused by large metal structures and rainfall.

1. Introduction

The world's urban population has grown rapidly from 746 million in 1950 to 3.9 billion in 2014, a more than five-fold increase (United Nations, 2014). As the world continues fast urbanization, about 6.4 billion people are predicted to live in cities by 2050, accounting for 66% of the world's population. The worldwide urbanization has transformed economic, social, political settings (Yusuf et al., 2001; Soh, 2012; Fang et al., 2015) and increasingly exerts impacts on climate and ecosystems at multiple scales (Zhou et al., 2004; Kaufmann et al., 2007; Imhoff et al., 2010; Seto et al., 2012; Bounoua et al., 2015). Understanding of urban change becomes critical to urban planners and decision-makers responsible for sustainable urban development (Seto et al., 2014).

For many years, urban extent and infrastructure have been mapped using multiple sources of remotely sensed data, from moderate to high spatial and spectral resolutions. Airborne images captured in visible and infrared spectrum are primary data sources to map urban land uses and land covers (LULC). Moderate-to-low spatial resolution sensors, such as Landsat (Masek et al., 2000; Zha et al., 2003; Yuan et al., 2005), AVHRR (Hansen et al., 2000), MODIS (Schneider et al., 2009, 2010; Friedl et al., 2010; Huang et al., 2016), ASTER (Chen et al., 2007; Pu et al., 2008), and SPOT (Zhang et al., 2003; Ferri et al., 2014; Sertel and Akay, 2015), offer long spans of imagery for the analysis of urban changes. A major limitation of moderate resolution imagery is that an image pixel may contain multiple types of land cover that may have multiple uses. Traditional classification methods that assume only one LULC type exists in an image pixel may therefore fail to produce accurate results with moderate resolution imagery (Small, 2005). Spectral Mixture Analysis (SMA) represents the reflectance in each pixel by a linear combination of spectral endmembers, provided an alternative to quantify reflectance properties of the urban mosaics (Adams et al., 1986; Smith et al., 1990). Although the SMA has proved useful for describing urban composition in subsequent studies (Lu and Weng,

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http://dx.doi.org/10.1016/j.rse.2017.10.004
Received 23 December 2016; Received in revised form 15 September 2017; Accepted 5 October 2017

Please cite this article as: Nguyen, L.H., Remote Sensing of Environment (2017), http://dx.doi.org/10.1016/j.rse.2017.10.004

2004; Pu et al., 2008; Small, 2001; Wu and Murray, 2003), it is usually designed with spectral endmembers specific to a location or research problem. High spatial resolution images from airborne and space-borne platforms are increasingly used for urban mapping to better separate urban features (Herold et al., 2003; Li and Shao, 2014; Lu et al., 2010; Myint et al., 2011). However, these very high spatial resolution (< 2 m) data are typically available only at a high cost over a small area at infrequent intervals.

In modern societies, urban areas are brightly and densely lit at night, in contrast to the sparser lighting in surrounding rural areas. The nighttime lights datasets generated from DMSP-Operational Linescan System (OLS) and, more recently, the Visible Infrared Imaging Radiometer Suite (VIIRS) are used widely to map human settlement and to infer socioeconomic development (Small et al., 2005; Shi et al., 2014; Zhou et al., 2015). Although the night lights datasets have demonstrated a great potential for urban studies, they still have several limitations, such as blooming effects and light saturation in urban cores leading to high commission error, variation in local lighting habit and technologies, seasonality in usage, and, for the OLS data, limited dynamic range (Doll, 2008; Huang et al., 2014; Small et al., 2011; Small and Elvidge, 2013; Zhang and Seto, 2013). Urban structure can be characterized using LiDAR systems (Yan et al., 2015) or high-resolution images processed with photogrammetric methods (Takaku et al., 2014). Although LiDAR or high-resolution image datasets can have very fine spatial resolution (≤ 1 m), they are only available at a high cost for a few locations and with long return intervals, if any.

While spectral data and night lights imagery only show urban changes in the 2-D plane, both 2-D and 3-D urban infrastructure could be characterized using data collected by synthetic aperture radars (SAR) with encouraging results (Henderson and Xia, 1998; Nghiem et al., 2001; Gamba et al., 2002; Soergel et al., 2003; Dell'Acqua and Gamba, 2006; Boehm and Schenkel, 2006; Dell'Acqua, 2009; Taubenbock et al., 2012; Esch et al., 2013; Zhou et al., 2017). SAR data can have high resolution ranging from 10 to 100 m; however, SAR data are noisy with a large sigma-naught equivalent noise floor and fixed azimuth angle from a side-looking antenna, which cause many confounding complications in urban areas (same building can have a very large difference in backscatter at different azimuth angles). More importantly, a key limitation is that many SAR datasets have been collected piecewise at different times over different areas of the world. The Shuttle Radar Topography Mission (SRTM) provided an extensive SAR data collected between 60°S and 60°N in February 2000, which has a potential use for global infrastructure mapping for year 2000 (Nghiem et al., 2001). TanDEM-X SAR also has an extensive coverage in recent years; however, TanDEM-X data are not freely accessible. There has been no consistent collection of global SAR data consistently at frequent repeated time intervals until the advent of Sentinel-1A and 1B SAR, which were launched in 2014 and 2016, respectively.

In June 1999, NASA launched a satellite scatterometer—QuikSCAT—to fill the gap created by the loss of NSCAT in 1997. With a comparably high spatial resolution that is sufficient to address urban scales, studies have demonstrated the capability of scatterometer data to characterize urban growth and development in both horizontal and vertical directions (Nghiem et al., 2009). The DSM concept and formulation rigorously founded on the Rosette Transform (Nghiem et al., 2009) and its utility has been demonstrated and published in the literature where important and useful conclusions were reported. These include: observation of physical and demographic characteristics of the urban environment (Nghiem et al., 2014), environmental impacts of Beijing urbanization (Jacobson et al., 2015), assessment and projection of groundwater vulnerability to nitrate pollution (Stevenazzi et al., 2015; Stevenazzi et al., 2017), urban change and impacts in Italy (Masetti et al., 2015), and global mega urbanization and formation of urban mega agglomeration (Nghiem, 2015).

Our objective is to characterize changes in urban environments using high spatial resolution QuikSCAT dataset generated by the Dense Sampling Method (DSM) (Nghiem et al., 2009). We extend the use of DSM data to test and demonstrate its capability in monitoring annual growth of nine major urban areas in the US Great Plains from 2000 to 2009. To examine the validity of the DSM data for urban monitoring, we coupled it with two other well-known and widely used satellite products, ambient population distribution from LandScan (Bhaduri et al., 2002; Dobson et al., 2000) and the percent impervious surface area (%ISA) from NLCD (Fry et al., 2011; Homer et al., 2007; Xian et al., 2011), which represent patterns of urbanization from independent sources. Based on %ISA and LandScan population datasets both indicating urban development, we hypothesized that there would be strong correlations between DSM backscatter and impervious surface area and population data. Intense rainfall can also modify the backscatter observed by a scatterometer (Hilburn et al., 2006; Tournadre and Quilfen, 2003) due to increased soil moisture on land (Nghiem et al., 2012; Seto and Iguchi, 2007). To have better understanding of those phenomena, we also examine relationship between QuikSCAT backscatter and rainfall data from the National Oceanic and Atmospheric Administration (NOAA).

2. Study area and data

2.1. Study area

Our study region is the US Great Plains, a vast expanse of flatland dominated by prairie, steppe and grasslands, stretching east to west from the Missouri River to the Rocky Mountains and north to south from the coniferous forests of Canada to the Rio Grande. Here we examined urbanization in the nine largest urban areas of the region by 2010 Census population (Fig. 1), including: Dallas-Fort Worth (TX); Houston (TX); Minneapolis-St Paul (MN); Kansas City (KS-MO); Oklahoma City (OK); Tulsa (OK); Omaha (NE) - Council Bluffs (IA); Wichita (KS); and Des Moines (IA). We chose this study region primarily due to the small variation in topography over the entire Great Plains, which minimizes high average backscatter from terrain effects.

2.2. Data

The SeaWinds scatterometer on QuikSCAT satellite collected daily global data covering 90% of the Earth surface with an original footprint of approximately 25 km in azimuth and 37 km in range. Here, we used QuikSCAT data from 2000 to 2009 processed by the Dense Sampling Method (DSM) (Nghiem et al., 2009). The DSM linearly composes a set of multi-azimuths, thin-slice beams to obtain the radar backscatter data posted in a much finer grid with the pixel scale of about 1 km. The DSM also characterizes backscatter fluctuations of the target in each pixel that arise due to azimuth asymmetry, human activities and environmental changes using the index of variability (IV). As a trade-off, the increased spatial resolution results in a reduction in temporal resolution: the near daily temporal resolution of QuikSCAT is reduced to generate an annual higher spatial resolution product. A time series of the annual product is appropriate to identify changes in a growing urban environment. Moreover, the DSM formulation allows the use of data at both vertical (VV) and horizontal (HH) polarizations, and their variability is included in the standard deviation of the product (Nghiem et al., 2009). While backscatter over ocean can have a significant difference between VV and HH data (Nghiem et al., 1997) due to the surface scattering characteristics, VV and HH backscatter data integrated over all azimuth angles are similar over land because of the volume scattering from objects above surface (rocks, trees, buildings, *etc.*), except in flood inundated areas (Brakenridge et al., 2005). Thus, we used both the HH polarization from the inner beam and the VV polarization from the outer beam of QuikSCAT in the data processed by the DSM for this study.

The Multi-resolution Land Characteristics Consortium (MRLC) has generated the National Land Cover Database (NLCD) for the