Remote Sensing of Environment 193 (2017) 150–164

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

The impact of seasonal changes on observed nighttime brightness from 2014 to 2015 monthly VIIRS DNB composites

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ARTICLE INFO

Article history:
Received 29 March 2016
Received in revised form 27 February 2017
Accepted 4 March 2017
Available online xxxx

Keywords:
Night lights
VIIRS
Seasonality
Urban areas
North America
NDVI
Snow cover
Albedo

ABSTRACT

The VIIRS-DNB sensor launched in 2011 offers the remote sensing community improved capabilities for monitoring and quantifying nighttime brightness. So far, most studies of temporal changes in nighttime lights were focused on examining inter-annual trends or on sudden changes in light emission, related to demographic and economic reasons. Here, the recently released two year (2014–2015) set of monthly cloud-free VIIRS-DNB composites was used to explicitly examine seasonal changes in nighttime lights and their correspondence with seasonality of land cover in Northern and Central America. It was found that monthly changes in nighttime brightness were positively correlated with monthly changes in snow cover and in albedo, and negatively correlated with monthly changes in NDVI. These correlations were strongest in urban areas in the northeast of the USA, where high correlation coefficient values (>0.8) were obtained. Seasonality in nighttime brightness is thus an important factor to consider both when quantifying trends in light emission from annual time series, and in studies examining the adverse consequences of artificial lights on human health and on the environment.

1. Introduction

Artificial night-time lights emitted from human settlements, industrial activities and fishing fleets offer the unique ability to monitor human activity from space from the 1970s onwards (Croft, 1978). The Defense Meteorological Satellite Program – Operational Linescan System (DMSP-OLS) sensor has been widely used for monitoring spatial variability and temporal changes in night lights globally from 1992 onwards (Bennie et al., 2015; Zhang et al., 2015), and it has been shown in a series of studies that the intensity of night lights is related to population density and to economic activity at the global scale (Elvidge et al., 1997a,b, 2001), as well as at the city and locality scale (Small et al., 2005; Levin and Duke, 2012; Levin and Zhang, 2017). Until recent years, most remote sensing studies of night lights were based on the DMSP-OLS sensor, using global annual cloud-free composites which are available from NOAA's National Geophysical Data Center (http://ngdc.noaa.gov/eog/dmsp.html, accessed 26/2/2016). However, the spatial resolution of the DMSP-OLS sensor is coarse (2.7 km), its values are quantized on a 6-bit scale (0–63), are mostly available as non-radiometrically calibrated data, and, the images suffer from overglow around urban areas and are saturated within urban areas (Small et al., 2005; Doll, 2008).

The VIIRS Day/Night Band (DNB) onboard the Suomi National Polar-orbiting Partnership (Suomi NPP, launched on October 2011), offers the remote sensing community enhanced capabilities for monitoring night lights from space (Lee et al., 2006). VIIRS DNB improvements over the DMSP-OLS sensor include higher spatial resolution (750 m), quantitative data which is radiometrically calibrated, and, higher sensitivity to both very low and very high night-time light levels (Elvidge et al., 2013; Miller et al., 2013). Importantly, the VIIRS DNB sensor has been shown to generate better results when mapping urban areas and economic activity from space (Shi et al., 2014a, b). Additionally, DMSP-OLS global cloud-free composites are only available on an annual basis, whereas VIIRS-DNB global cloud-free composites are available on a monthly basis (http://ngdc.noaa.gov/eog/viirs/download_monthly.html, accessed 26/2/2016) and are distributed in radiance vales (in nanoWatts/cm^2/sr) which have undergone a stray-light correction procedure (Mills et al., 2013).

Temporal changes in nighttime lights have been previously studied using different sensors and for a variety of aims. Trends in annual DMSP-derived night lights have been examined to explore urbanization dynamics (Ma et al., 2012) and to map declines in economic activity following the collapse of the Soviet Union (Bennie et al., 2014) as well as after the Syrian crisis (Li and Li, 2014). Monthly composites from the relatively new VIIRS DNB sensor have been used to examine temporal trends such as those related to declines in urban lighting in Iraq (Li et al., 2015) and to examine the consistency of mapping urban areas in Mexico (Aubrecht and León Torres, 2016). At an even finer temporal

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http://dx.doi.org/10.1016/j.rse.2017.03.003

resolution, daily nighttime images have been used to observe changes in total light electricity usage during seasonal festivals such as Christmas and the Ramadan (Román and Stokes, 2015), whereas a ground-based camera has been used to capture night-time images of New York every 10 s to quantify the pulse of the city through its lightscape (Dobler et al., 2015).

Most research on spatial and temporal variability in nighttime lights has focused on anthropogenic factors such as population, economic activity (e.g., Elvidge et al., 1997a, b) and land use type (Levin et al., 2014). However, land surface properties can also affect the observed brightness of nighttime lights as surface albedo determines the amount of light that is reflected upwards (Luginbuhl et al., 2009). The positive effects of surface albedo and the negative effects of vegetation cover on the observed night-time brightness have been recently demonstrated in a study utilizing a fine spatial resolution EROS-B night-time of Jerusalem (Katz and Levin, 2016). Snow cover, due to its high reflectance, has been suggested as an additional factor "contaminating" DMSP and VIIRS DNB night time imagery (Cinzano et al., 2000; Elvidge et al., 2001; Luginbuhl, 2001; Wu et al., 2013a; Román and Stokes, 2015), and was recently shown to affect light pollution within northern high latitude urban areas (Levin and Zhang, 2017).

The availability of a two-year monthly time series of radiometrically calibrated VIIRS DNB cloud-free mosaics enables examination of seasonal changes in the brightness of night lights using time series approaches developed for studying phenological changes in vegetation (e.g., Eastman et al., 2009; Verbesselt et al., 2010). Therefore, the aim of this paper was to explicitly examine seasonal changes in night light intensity, and seasonal land cover factors which may influence observed changes in nighttime brightness. The hypothesis leading this study was that seasonal changes in surface albedo drive changes in observed night-time brightness, and that changes in albedo are caused by seasonal changes in vegetation (for which NDVI was used as a surrogate) and in snow cover. It was expected that seasonal changes in night-time brightness would be greatest within cities and areas of industrial activity because they form major emitting sources of artificial night light which is reflected from the surface upwards and which is then further scattered by the atmosphere.

2. Methods

2.1. Study area

This study focused on Central and Northern America, as a wide variety of environmental and climatic conditions can be found there, including tropical rain forests, Mediterranean Chaparral, arid deserts, temperate forests and taiga (boreal) forests. Some of the analyses were restricted to the 48 conterminous states of the USA, so as to decrease variability in a number of the factors driving night-time lights' brightness, such as differences in countries' gross domestic product.

2.2. Data sets

2.2.1. VIIRS

Twenty-four monthly images (from January 2014 to December 2015) of version 1 of the nighttime VIIRS Day/Night Band cloud-free composites Tile 1 (75N/180W to 0N/60W, covering almost all of Central and Northern America) were downloaded from http://www.ngdc.noaa.gov/eog/viirs/download_monthly.html (accessed March 1st, 2016). These monthly images represent average radiance composite images. The DNB is comprised of a Charge Coupled Device (CCD) accounting for the wide range of reflectance values from nighttime/new moon to daytime conditions (GSFC JPSS CMO, 2014). The dynamic range of the DNB covers approximately 7 orders of magnitude, and its near constant contrast algorithm uses DNB radiances to determine a pseudo-albedo by modeling the lunar and solar radiance for each pixel (GSFC JPSS CMO, 2014). The wavelength range of the DNB channel is between 0.5 and 0.9 μm (GSFC JPSS CMO, 2014). Before averaging, the DNB data was filtered by the Earth Observations Group (EOG) at NOAA/NGDC to exclude the impact of stray light, lightning, lunar illumination, and cloud-cover on the data. DNB data are affected by lunar illumination for about half of the lunar cycle (GSFC JPSS CMO, 2014), and the sensitivity of the DNB is sufficiently low to allow utilization of reflected lunar irradiance for relevant applications (Miller et al., 2013). The "vcmslcfg" option used for this study included data corrected for stray-light (Mills et al., 2013), as this dataset had greater coverage towards the poles. It should be noted that the version 1 series of composites is not filtered to screen out lights from aurora, fires, boats, and other temporal lights. The VIIRS data are distributed in radiance values with units in nanoWatts/cm^2/sr, at a spatial resolution of 15 arc sec. The images used for this study were resampled (by spatial averaging) to a spatial resolution of 0.05° so as to match the spatial resolution of monthly MODIS products described below.

2.2.2. MODIS

Monthly snow data for the months of January 2014–December 2015 were downloaded from Version 5 of the MODIS/Terra Snow Cover Monthly L3 Global 0.05Deg CMG (MOD10CM) collection (Hall et al., 2006; Hall and Riggs, 2007). Snow cover is provided in integer values ranging between 0 and 100%. Monthly NDVI data for the months of January 2014 – December 2015 were downloaded from Version 6 of the MODIS/Terra Vegetation Indices Monthly L3 0.05Deg CMG (MOD13C2) collection (Didan, 2015). Global MOD13C2 data represent cloud-free spatial composites of the gridded 16-day 1-km MOD13A2 product, and are provided to users as a monthly product projected to a 0.05° geographic Climate Modeling Grid (CMG). The NDVI from the MOD13C2 dataset was used for this study, representing vegetation cover and primary productivity. Monthly albedo data for the months of January 2014–December 2015 were based on Version 5 of the MODIS MCD43C3 Climate Modeling Grid (CMG) Albedo Product. Within this study White-Sky Albedo in the visible spectral range was used. As the data is provided at temporal intervals of 8 days (for a moving 16 day input window), it was aggregated into monthly values using the "Aggregate Series" function within Earth Trends Modeler of TerrSet 18.21 (© Clark Labs, 2016). Further missing albedo values (due to cloud cover) were spatially interpolated using the "Intercon" function of TerrSet 18.21 (© Clark Labs, 2016).

2.2.3. Ancillary GIS data

Administrative regions were used to aggregate data beyond the grid cell size, into recognizable and well known areas, such the states of the USA. The boundaries of level 1 administrative regions ($n = 268$) within North and Central American countries were based on Version 2 of Global Administrative Areas, downloaded on February 24th, 2016 from http://www.gadm.org/version2. The boundaries of urban areas within the USA were based on the TIGER/Line Shapefile, 2015, 2010 nation, U.S., 2010 Census Urban Area National (tl_2015_us_uac10.zip, downloaded from ftp://ftp2.census.gov/geo/tiger/TIGER2015/UAC/tl_2015_us_uac10.zip on February 24th, 2016). In this study all urban areas in the USA whose area size was >625 km^2 ($n = 89$) were analyzed. Population data was derived from the global Landscan (Bhaduri et al., 2002) population layer (as of 2012; http://web.ornl.gov/sci/landscan/). Land cover data for the USA was derived from the National Land Cover Database 2011 (NLCD 2011; Homer et al., 2015), representing the most recent national land cover product created by the Multi-Resolution Land Characteristics (MRLC) Consortium for the USA (Homer et al., 2015). NLCD land cover was then used in a stepwise multiple regression analysis to examine the factors explaining seasonal variability in observed night-time brightness.

2.3. Analyses

2.3.1. Quantifying seasonality

Spatial analyses of the datasets were performed at several spatial resolutions and geographical extents. Basic statistics were calculated