SATELITE OBSERVATION OF URBAN METABOLISM IN CHINA

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ABSTRACT: Aggregated to an national level DMSP nighttime lights have a linear relationship to population, gross domestic product, total primary energy consumption, and fossil fuel CO_2 emissions. There is no other remote sensing data source that can claim such a positive correlation to the human enterprise. We propose that moderate resolution nighttime lights (<100 m) could be used to develop models of urban metabolism at spatial scales commensurate with the flow of energy and materials upon which cities rely. Such models could be used to design pathways to sustainable cities for the future.

1. INTRODUCTION

The term 'Urban Metabolism' is a conceptual framework for analyzing the flow of energy and materials within cities. The global human society can be viewed as a collection of interconnected organisms, each carrying on a standard set of processes collectively referred to as "urban metabolism" (Burgess, 2008). Global, national, and regional economies are often modeled with a circular flow diagram of households and firms exchanging capital, labor, goods, and services in a circulatory system. However, the human economy is oversimplified when modeled as a circulatory system without a digestive system (Daly and Farber, 2011). As with an organism, there is a digestive system which ingests and consumes resources (food, water, energy, materials) and releases wastes (gases such as CO2, solid and liquid wastes). The digestive system enables the economy, growth in development, and population expansion. The processes are standardized based on society's drive to satisfy the basic requirements for human life plus the enhancements afforded by a common technological base. Through advances in technology, we have been so successful with this metabolism that our numbers have grown from ~300 million in the 1300's to 7 billion in 2011. In 2000, Crutzen and Stoermer (2000) coined the term 'Anthropocene' in recognition that humans had become a driving force in altering the global environment.

There are satellite based systems for monitoring the metabolism of terrestrial ecosystems and near surface aquatic ecosystems. The near infrared versus red "vegetation index" in all its forms has served as a ubiquitous measurement in satellite remote sensing of terrestrial ecosystems since the mid-1970's (Tucker, 1979). Satellite instruments with red and NIR spectral bands are used for tracking spatial and temporal variations in the metabolism of terrestrial ecosystems. These instruments have flown continuously since the 1970's (Landsat, Advanced Very High Resolution Radiometer, MODIS, and others). Similarly, visible band indices have been developed to monitor the metabolism of surface waters via plant pigment concentrations, beginning with the Coastal Zone Color Scanner, SeaWIFS, OCTS and others (O'Reilly et al., 1988).

The success of these systems derives from the fact that they were designed around a unique spectral observable that integrates the spatial distribution and activity levels of photosynthetic organisms, the base of the food chain. Is there a corresponding observable for the human enterprise which could be observed from space? If one could be identified, sensors could be developed and missions could be flown to collect data for modeling "urban metabolism". In this paper we review evidence that satellite observed nighttime lights can be used to map and monitor urban metabolism using China as an example.

2. Results From DMSP

For nearly forty years the U.S. Air Force Defense Meteorological Satellite Program (DMSP) has flown polar orbiting satellites with a visible and thermal cloud imaging sensor known as the Operational Linescan System (OLS). The digital OLS archive begins in 1992 and extends to the present. OLS is unique for its low light imaging capability. Originally designed for the detection of moonlit clouds, the OLS detects lights present at the Earth's surface, including lights from cities and towns, rural development, gas flares, fires and heavily lit fishing boats. With a 3000 km swath and a 2.7 km ground sample distance. NGDC has developed algorithms for processing annual cloud and fire free composites of nighttime lights (Baugh et al., 2010). The 2010 DMSP nighttime of China are shown in Figure 1.

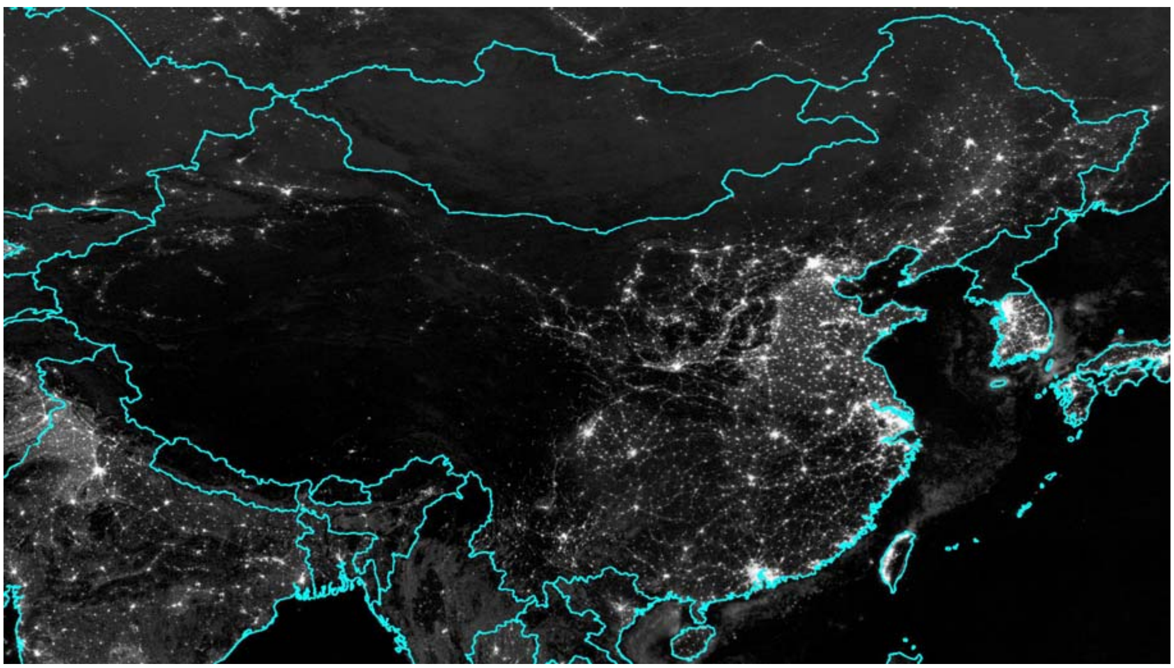

Figure 1. *DMSP nighttime lights of China from 2010.*

For evidence that satellite observed nighttime lights, even at coarse spatial resolution, can serve as a proxy for various aspects of urban metabolism we present results from the version 4 time series of DMSP nighttime lights, spanning 1992 through 2009. For each satellite year, we extracted the sum-of-lights for the countries of the world. The sum of lights, or lights for short, is the sum of the digital numbers associated with each pixel within a countries boundary. This data was then paired with national level annual data on population, gross domestic product, total primary energy consumption, and fossil fuel CO_2 emissions. Figure 2 shows the relationships found for China. There is a logarithmic relationship between lights , and population, a linear relationship with GDP, an exponential relationship with total primary energy consumption and a linear relationship with CO_2 emissions. There is no other satellite remote sensing system with such a clearly demonstrated ability to correlate with these primary variables of urban metabolism. Certainly the DMSP is not making a direct observation of variables such as those shown in Figure 2. The high degree of correlation exists because nocturnal lighting is one expression of urban metabolism and there is a strong tie between all elements of urban metabolism due to the standardization of technologies used in urban areas around the world.

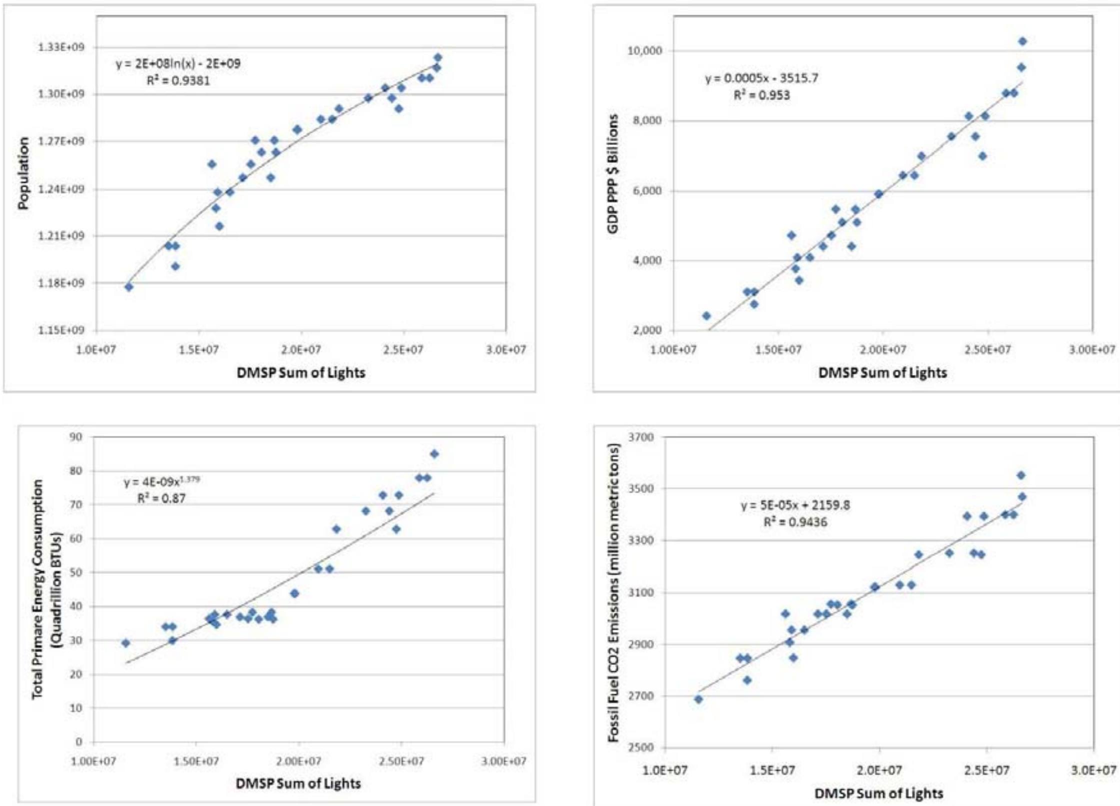

Figure 2. *Aggregate relationship found between the DMSP sum-of-lights index with population, gross domestic product, total primary energy consumption, and fossil fuel CO2 emissions for China from 1992 through 2009. Years generally increase from lower left (1992) to upper right (2009).*

While these results appear impressive, there are substantial shortcomings to DMSP when it comes to the observation of nighttime lights. The coarse spatial resolution (2.7 km ground sample distance (GSD) and 5 km ground instantaneous field of view (GIFOV)) make it impossible to detect the internal structure of urban centers related to the spatial distribution of functional sectors such as residential, commercial, and industrial. The data are recorded with 6 bit resolution. There is no on-board calibration. The low light imaging gain is programmed to track predicted solar and lunar illuminance, but the gain settings are not recorded in the data stream. The system is typically operated at high gain settings, resulting in saturation in urban centers.

The follow-on for the OLS is the visible/infrared imager/radiometer suite (VIIRS), which will fly on the USA's next generation polar-orbiting operational environmental satellite system. The first VIIRS is currently being built and represents an improved, but still imperfect, instrument to measure nocturnal lighting (Lee et al., 2004). The NPOESS VIIRS instrument will provide low-light imaging data with improved spatial resolution (0.742 km), wider dynamic range, higher quantization, on-board calibration, and simultaneous observation with a broader suite of bands for improved cloud and fire discrimination over the OLS. The VIIRS is not, however, designed with the objective of sensing night-time lights. Rather, it has the objective of night-time visible band imaging of moonlit clouds—the same mission objective of the OLS lowlight imaging. While the VIIRS will acquire improved night-time lighting data, it is not optimal for this application. In particular, the VIIRS low-light imaging spatial resolution will be too coarse to permit the observation of key nighttime lighting features within human settlements and the low light imaging is in a single spectral band, offering no ability to distinguish lighting types.

3. ISS Cities at Night Images

Astronauts on the International Space Station have collected substantial numbers of nighttime camera images of cities at night. These images are collected at 20 to 60 meter spatial resolution and record the rich spatial and spectral content that is available from nighttime lights. Nightime data collected at this spatial resolution would enable the development of spatially explicit models of urban metabolism.

Figure 3. Color digital camera image of Beijing acquired April 19, 2011 from the International Space Station. The spatial resolution is approximately 50 meters.

4. CONCLUSION

Using a proxy measure means that when you cannot measure exactly what you want, you measure what you can. This is exactly the case for nighttime lights and urban metabolism. Many scholars and institutions have attempted to develop indices or metrics of sustainability at local, national, and regional scales (Ehrlich and Holdren, 1971; Sutton, 2003; Wackernagel and Rees, 1996). The 'Ecological Footprint' (EF) developed by Mathis Wackernagel is a sophisticated and well regarded index for measuring humanity's demand on nature. The EF includes hundreds of nationally aggregated variables that vary in quality and availability from one nation to the next. The EF measures how much land and water area a human population requires to produce the resources it consumes and to absorb its carbon dioxide emissions. Indices of human impact in the form of 'urban metabolism' derived from Nighttime satellite imagery show strong correlations with metrics such as the EF and they are measured objectively and uniformly across the globe (Sutton et al., 2011).

The suite of satellites in orbit now have focused on the last part of this question: 'How much do we have to use?'. Satellite observed nighttime lights could be used to model 'How much are we using?'. This is an important capability to develop as world's finite resources become further stretched and the global population lurches toward 10 billion people. Satellite observations of nighttime lights at moderate spatial resolution (<100 m) could be used to model the material and energy flow ('urban metabolism') of the human enterprise at a scale commensurate with urban processes. Such models could be used to design pathways to sustainable cities for the future.

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