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Mapping Decadal Change in Anthropogenic Night Light

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Abstract

The Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) sensors have imaged emitted light from Earth's surface since the 1970's. Temporal overlap in the missions of 5 OLS sensors allows for intercalibration of the annual composites over the past 19 years [1]. The resulting image time series captures a spatiotemporal signature of human settlement growth and evolution. We use temporal Empirical Orthogonal Function (EOF) analysis to characterize and quantify patterns of temporal change in stable night light brightness and spatial extent since 1992. Temporal EOF analysis provides a statistical basis for representing spatially abundant temporal patterns in the image time series as uncorrelated vectors of brightness as a function of time from 1992 to 2009. The variance partition of the eigenvalue spectrum combined with temporal structure of the EOFs provides a basis for distinguishing between deterministic temporal trends and stochastic year to year variance. The low order EOFs and Principal Components (PC) space together discriminate both earlier (1990s) and later (2000s) increases and decreases in brightness. Inverse transformation of these low order dimensions reduces stochastic variance sufficiently so that tri-temporal composites depict deterministic decadal trends. The most pronounced changes occur in Asia. Throughout Asia a variety of different patterns of brightness increase are visible in tri-temporal brightness composites – as well as some conspicuous areas of apparently decreasing background luminance and, in many places, intermittent light suggesting development of infrastructure rather than persistently lighted development. Vicarious validation using higher resolution imagery reveals multiple phases of urban growth in several cities, numerous instances of highway construction, extensive terracing networks and hydroelectric dam construction [3]. Lights also allow us to quantify the size distribution and connectedness of different intensities of development. Over a wide range of brightnesses, size distributions of spatially contiguous lighted area are well-fit by power laws with exponents near -1 as predicted by Zipf's Law. However, the larger lighted segments are much larger than individual cities; they correspond to vast spatial networks of contiguous development.[2]

Keywords: night light; urban; development; EOF analysis; PCA; Zipf; spatial network; fractal; percolation

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1. Introduction

The Defense Meteorological Satellite Program (DMSP) Operational Linescan System(OLS) has imaged emitted light from Earth's surface since the 1970's. In 1992 a digital archive was established for DMSP-OLS data at the NOAA National Geophysical Data Center. Annual composites of temporally stable night light have been processed and distributed by the NGDC for every year since 1992. Temporal overlap in the missions of multiple OLS sensors allows for intercalibration of the 30 annual composites over the past 19 years. These data offer the opportunity to quantify a unique spatiotemporal signature of human settlement growth and evolution. Here we summarize some initial results of a spatiotemporal analysis of annual change in the extent, distribution and intensity of anthropogenic night light.

2. Mapping night light from space

Since 1994, NGDC has had an active program focused on global mapping of nighttime lights using the data collected by the DMSP-OLS sensors. The basic product is a global annual cloud-free composite, which averages the OLS visible band data for one satellite from the cloud-free segments of individual orbits. Over the years, NGDC has developed automatic algorithms for screening the quality of the nighttime visible band observations to remove areas contaminated by sunlight, moonlight, and the presence of clouds. In the Stable Lights product generation, fires and other ephemeral lights are removed based on their high brightness and short duration. Background noise is removed by setting thresholds based on visible band values found in areas known to be free of detectable lights. In 2010, NGDC released the version 4 time series of Stable Lights, spanning the years 1992-2009. These are available online at <http://www.ngdc.noaa.gov/dmsp/downloadV4composites.html>. Because the OLS visible band has no on-board calibration system, the data from each satellite year should be intercalibration prior to quantitative analysis of the time series. Baugh et al. [4] provides a description of the algorithms used to make the v.4 stable lights products. The intercalibration procedure is described by Elvidge et al. [1].

3. Characterizing Spatio-temporal Change

We use temporal Empirical Orthogonal Function (EOF) analysis to quantify patterns of temporal change in OLS stable night light brightness and spatial extent over the past 19 years. Intercalibrated data are stacked into a spatial time series of images of annual average brightness resulting from both brightly lit cities and from dimmer, less intensively developed areas. Temporal EOF analysis provides a systematic means to represent the time series of brightness of any pixel as a linear combination of uncorrelated temporal vectors. Meaningful combinations of EOFs can be derived from the topology of the Temporal Feature Space. The Temporal Feature Space, defined by the low order Principal Components (PCs), represents the distribution of image pixel time series in terms of the relative contribution of the EOFs. The approach used here is based on EOF analyses commonly used to represent geophysical processes in oceanography and meteorology [5]– but casts the EOFs as temporal rather than spatial modes and uses the topology of the low order PC space to determine which linear combinations of low order EOFs depict physically meaningful temporal patterns [6].

The intercalibration of the annual night light composites considerably reduces spurious interannual variability - but does not eliminate it entirely. Significant year to year variability remains in the intercalibrated image time series. Much of this spurious variance is related to spatial uncertainty in the coregistration of the annual composites. In addition, the phenomenon of low luminance "overglow" results from a combination of limited sensor resolution, atmospheric scattering and subannual spatial coregistration uncertainty in the compositing process. This overglow causes spatial blurring within individual annual composites. Additional temporal blurring results from interannual registration uncertainty. The result is a combination of spurious spatial blurring and temporal variance superimposed on whatever actual changes in brightness may be measured by the sensor. Spatial or temporal filtering has the effect of mixing this spatiotemporal noise with the signal in unknown proportions.

We address the spatial blurring and temporal noise problems by using the information contained in the temporal EOFs and their spatial abundance and distribution. The projections of the low order PCs reveal the relationship among the low order EOFs in terms of the actual temporal EMs that span the space of all temporal patterns present in the image time series. The variance partition of the PC transform makes use of the spatial abundance of different temporal patterns to distinguish the components of the temporal patterns that the greatest number of pixel time series have in common. The two orthogonal projections of the three low order PCs for the night light time series for southeastern Asia are shown in Figure 1 – along with the 3 low order EOFs that represent ~91% of the variance in the image time series. EOF 1 represents the temporal mean brightness of the image time series and accounts for ~87% of the variance. EOFs 2 and 3 represent the decadal trends that explain the next 5% of variance. The remaining 27 modes all represent less than 1% and together less than 9% of the total variance in the image time series.

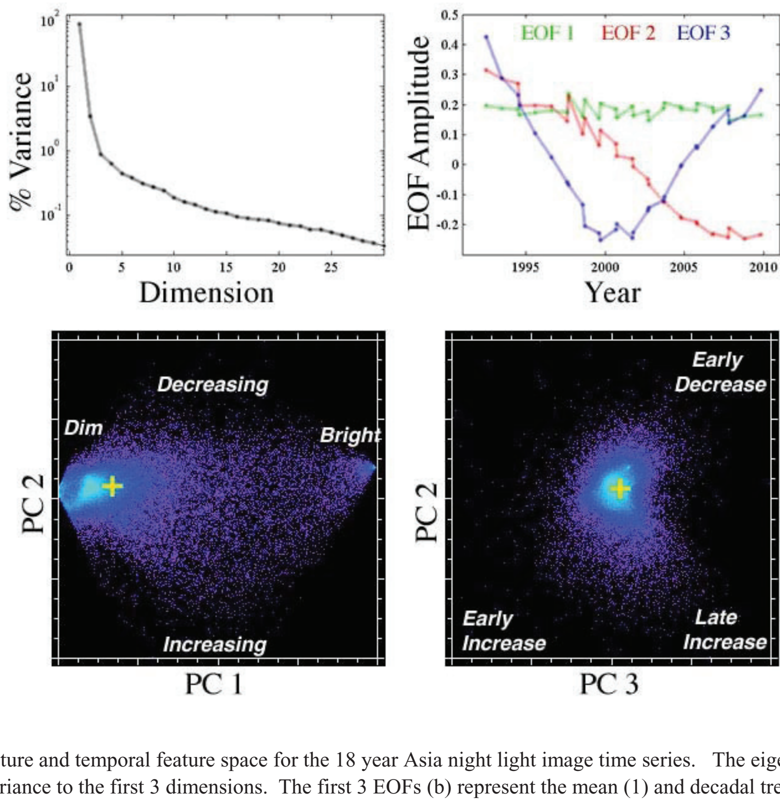

Figure 1 Eigenstructure and temporal feature space for the 18 year Asia night light image time series. The eigenvalue spectrum attributes 96% of variance to the first 3 dimensions. The first 3 EOFs (b) represent the mean (1) and decadal trends (2 & 3) in brightness. Orthogonal projections of PCs 1 to 3 as a density shaded pixel cloud show the temporal feature space of linear combinations of EOFs 1 to 3. The topology of the cloud is dominated by the bimodal distribution of bright and dim lights in thefirst PC. The linear decadal trend of EOF 2 and half cycle of EOF 3 are associated with PC 2 and PC 3 respectively.

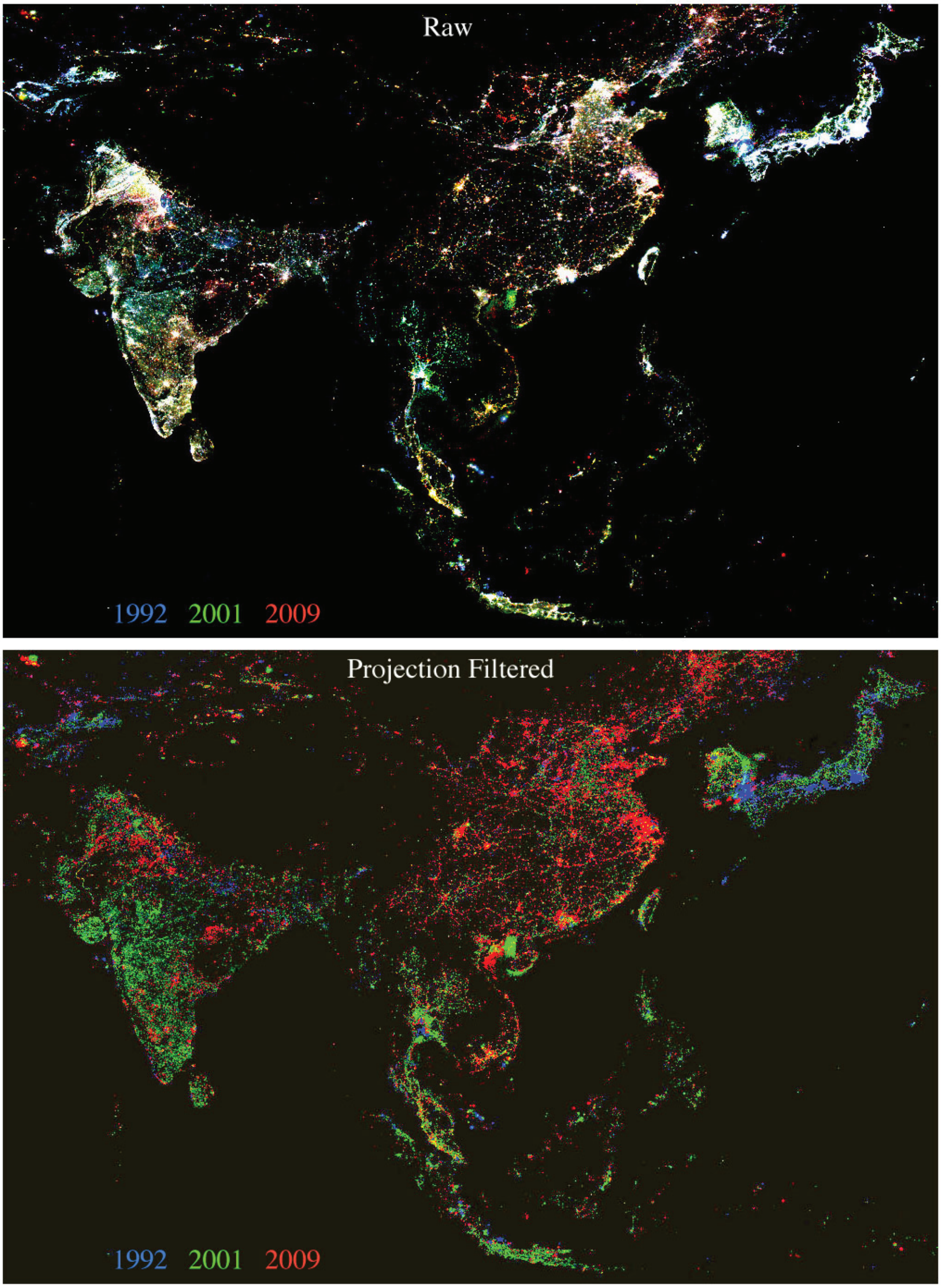

Figure 2. Tri-temporal night light composites for southeastern Asia. Projection filtering emphasizes later brightening in China.

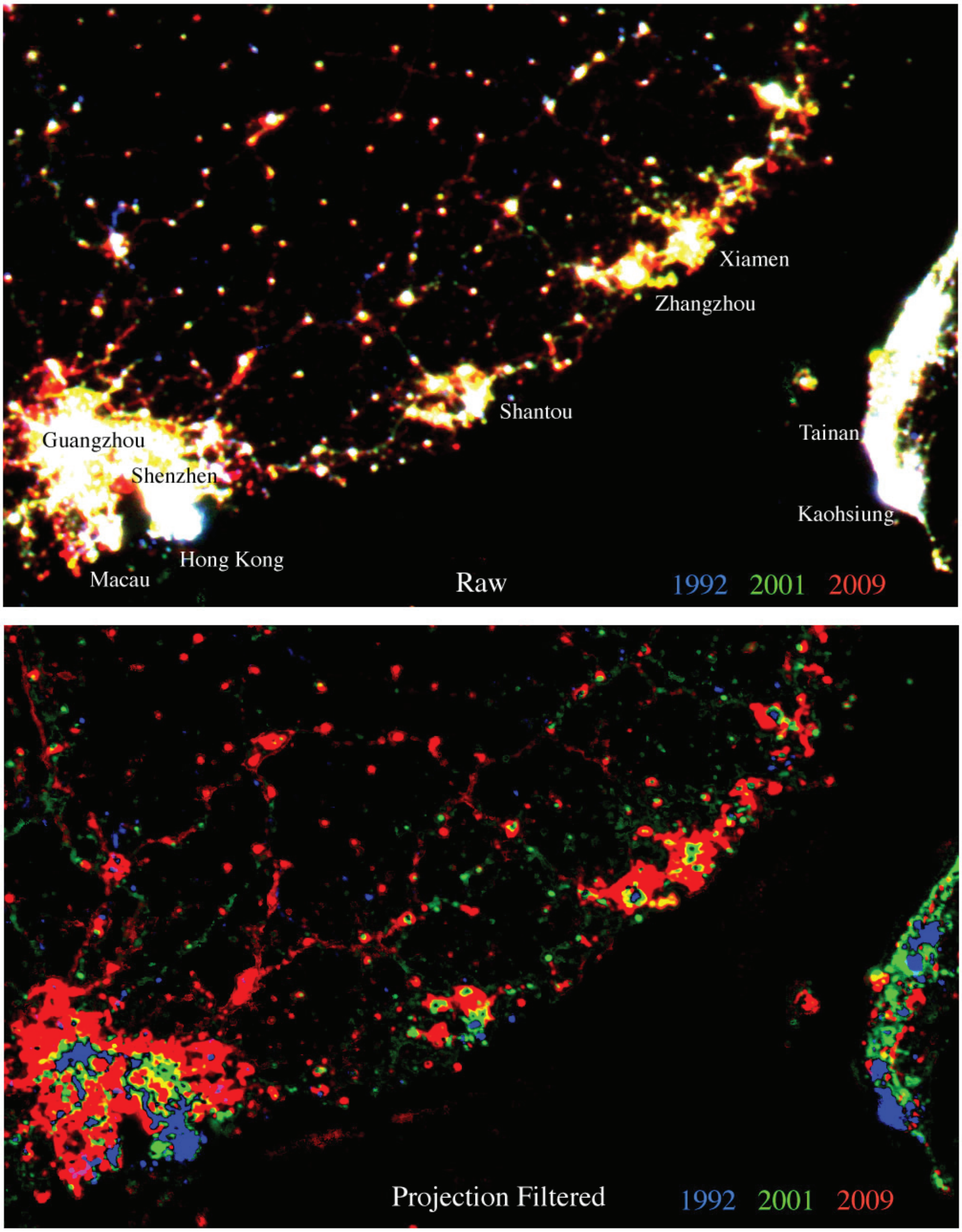

Fig. 3.. Full resolution tri-temporal night light composites. Projection filtering emphasizes later brightening (red) throughout Guandong and Fujian relative to Taiwan (green). More recent development of Shenzhen and the Guangzhou-Hong Kong corridor is also apparent. Thin elongate lights further inland reveal recent develoment of highways and growth of small cities.

The structure of the projection of PCs 2 and 3 highlights the difference between early (1990s) and late (2000s) increases and decreases in the two decade time series. We can simultaneously remove both the spurious variance and the dominant mean brightness from the time series to emphasize only the decadal trends represented by early and late increases and decreases in brightness. This spatially-informed filtering can be accomplished by inverse transforming only dimensions 2 and 3 of the PC transformed image time series. The result is a considerably smoothed time series lacking both the mean brightness and the spurious variance that is not reflected in the low order EOFs depicting the most spatially abundant temporal patterns. This projection filtered image time series does not contain the spurious year-to-year variability and allows the decadal trends of bright and dim lights to be shown simultaneously on the same map.

Projection filtering depicts the decadal patterns of change in night light brightness without the distraction of spurious year-to-year differences in apparent brightness and the ten-fold difference in brightness between the bright, heavily developed urban centers and the much dimmer peripheral areas where development and urban growth begins. The two figures presented here use the same display conventions to compare tri-temporal composites of intercalibratted night light with a projection filtered tri-temporal composite of the same annual composites with only the decadal patterns associated with the 2nd and 3rd dimensions of the PCs and EOFs. The composite pair in Figure 2 shows the regional view of southern and eastern Asia. In both composites warmer colors (red, yellow) indicate brightening over the past 18 years. Cooler colors (blue, cyan) indicate dimming. Green areas show some bightening during the 1990s followed by some dimming in the 2000s; Magenta areas have the opposite pattern. Figure 3 shows a full resolution comparison of the same composites.

Preliminary results of the analysis reveal regional and local differences in timing of development and urban growth. At a regional scale, China shows rapid brightening since 2000 while south and southeast Asia show greater brightening during the 1990s. Larger cities throughout the region show little change at their centers but considerable multi-phase growth at their peripheries. The evolution of city size distributions can be compared with evolution of distributions related to variable threshold of brightness. In a related study we find that size distributions of spatially contiguous lighted area can be well fit with a power law with an exponent near -1 as predicted by Zipf's Law [2].

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