Expansion of Urban Area in the Yellow River Zone, Inner Mongolia Autonomous Region, China, from DMSP OLS Nighttime Lights Data

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Abstract— **Maps from the Version 2 Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) Nighttime Lights Series were used to assess increases in the extents and spatial configurations of urban areas in the vicinity of the Yellow River in Inner Mongolia Autonomous Region, China, over the period 1992 - 2003. Lit area data were extracted and used with population and economic data to examine patterns of urban expansion at the county level. The major trends seen were a dramatic increase in urban areas, metropolization driven by economic expansion, and an important decline in urban population density that reflects increasing prosperity.**

Keywords; urbanization; satellite imaging; metropolization

I. INTRODUCTION

With the rapid development of the Chinese economy in the last two decades, more and more people have relocated to cities and adjacent areas from rural areas and urban areas have expanded relentlessly. As elsewhere in China, the counties of Inner Mongolia Autonomous Region, a major province in Northern China, are also experiencing rapid urbanization, even though the province is in general less developed than other parts of China (e.g., the Special Economic Zones on the east coast). The expansion of urban areas may be tracked using satellite images of nighttime lights – sources of luminosity on the terrestrial surface – and studies using these data have previously been published that examine the growth in area and density of Chinese cities [1-3]. This study focuses on the mid-western area of Inner Mongolia, in the vicinity of the Huanghe (Yellow) River, which has the highest urbanization level in the province, the highest economic development rate, and the fastest urban expansion in Inner Mongolia.

Urbanization is a complex process, involving the economy, society, population, the surrounding region and many other factors (e.g., culture). It is almost always accompanied by expansion in the area in and surrounding cities. There are two types of urban expansion: first, the expansion of the city from interior to exterior as a spatial process with an increase in area; and second, an increase in the intensity of the city: it can thus contain a higher population and have greater economic activity without increasing it's area. The traditional study of city expansion relies on statistical data and on-the-spot surveys but because of delays and uncertainty in the data gathering process, these data have a number of insufficiencies, e.g., in the aspects of comparability, confidence, and timeliness [2]. Since on-the-spot surveys take much time, it is impossible to conduct research on a large scale, such as an entire region. The development of remote sensing technology provides the technical means to address the needs of this research: imaging instruments on orbiting satellites can provide maps of the extent of developed land. The remote sensing technology may be based on detection and measurement of reflected or emitted radiation in a wide range of wavelengths (ultraviolet to radio). Emitted radiation includes the light produced at night in urban areas by street lighting, homes, factories, office buildings, shops, and vehicles.

II. METHOD

A. The DMDP/OLS Sensor

The Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) is a whiskbroom sensor. Its data are 6-bit with values recorded in the range 0 - 63. It has visible-near-infrared and thermal bands. The visible band limits are 0.40 - 1.10 microns, responding to light in the 0.58 - 0.91 microns range at full width half maximum. The OLS is very sensitive, able to detect radiance at levels as low as 10^{-3} $W/cm^2/sr^{-1}$. The OLS is flown on the DMSP series of satellites that have a 101-minute, sun-synchronous, near-polar orbit at an altitude of 830 km. The OLS collects images across a 3000 km swath, providing global coverage twice per day. The National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS) Earth Observation Group provides access to processed OLS data via web-accessible archives [4]. The files are cloud-free composites made using all the available archived DMSP/OLS smooth resolution data for calendar years. The products are 30 arc second grids, spanning -180 to 180 degrees longitude and -65 to 65 degrees latitude. A number of constraints are used by NEDSDIS to select the highest quality data for entry into the composites: data are taken from the center half of the 3000 km wide swaths; sunlit, moonlit, aurora,

and glare-affected data are excluded; and observations with clouds are excluded using the OLS thermal band data and National Centers for Environmental Prediction (NCEP) surface temperature grids. The stable lights product was used here; this is obtained from the average of the visible band 6-bit digital numbers over a calendar year and contains the lights from sites with persistent lighting (cities, towns, and other sites with persistent lighting, including gas flares). Locations with ephemeral events such as fires and background noise were identified and discarded [4].

B. The Study Area

The study area was chosen to encompass the largest cities in the vicinity of the Yellow River in western Inner Mongolia: Huhehaote (also called Hohhot), Baotou, Wuhai, Linhe, and Dongsheng. In the eastern part lie the cities of Huhehaote (2003 population: 1.10 million, of which 75% urban), Dongsheng (2003 population: 0.22 million, of which 70% urban), Jining (2003 population: 0.26 million, of which 90% urban), and Baotou (2003 population: 1.42 million, of which 83% urban). Note that the administrative statistics for these cities correspond to the county area. Huhehaote is the provincial capital and hosts the region's major administrative and educational centers. Baotou's economy is based on steel, aluminum, and the manufacture of heavy machinery, being located close to massive reserves of coal. It is also a center for the extraction of rare earth minerals.

In the western part, the river has provided a viable transportation route in this arid region as well as water for crop irrigation for at least two thousand years. The irrigated area is mostly on the northern side of the river where there is an extensive system of canals that was mostly completed by 1900. It is called the Hetao Irrigation District and some 294 million m^3 of water are diverted annually from the Yellow River. In satellite images of indices of vegetation abundance – such as the Normalized Difference Vegetation Index (NIR+Red/NIR-Red) – an area of irrigated crops of at least 10,000 km^2 appears with much higher values than the surrounding areas. The major cities of Linhe and Wuhai have 2003 populations of 0.52 and 0.42, million, respectively, of which 43%, and 90% are urban, respectively. Smaller but growing population centers in the west of the region include Bayan Gol (Dengkou-Xian county) and Xamba (Hangjin-Hou Qi county).

C. Procedures

Maps of nighttime lights for the years 1992 and 2003 and from the F10 and F15 satellites, respectively, were obtained from National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS) that processes and archives OLS data. The maps were transformed to 250 m grid based on a Lambert Conformal Conic projection from the original 30 arc-second grid. No correction for "blooming" – an expansion of lit areas beyond their known extents resulting from off-nadir viewing and atmospheric scattering – was effected. Calculations of the areas that remained non-urban, remained urban, and changed were made for the eleven-year period, all at the county level. Official total and urban population and GDP figures were obtained for the counties, allowing calculation of rates of change and other statistics. Note that for some counties, the city area is represented by one large center that accounts for the vast majority of the population (e.g., Huhehaote, Baotou). Small towns and villages are excluded from the analysis as the limit for detection is on the order of 4 km on a side [4]. The brightness gradients seen in the OLS imagery towards the centers of the large cities are due at least partly to the increase in the number and luminosity of street lighting. With increasing prosperity, large Chinese towns have installed new, brighter, and elegant fixtures and city retailers and other businesses have increased lighting displays outside their storefronts and restaurants. Note that store and restaurant-front lighting has long been a part of Chinese city life, with considerable areas occupied by strings of lamps extending onto pavement areas. However, these are of much lower luminosity than recent neon and other high-power lighting fixtures.

III. RESULTS AND DISCUSSION

At the county level, all counties showed an increase in lit area (Fig. 1). Especially large increases were seen for counties containing the large cities of Huhehaote and Baotou and in neighboring counties. The proportion of the lit areas within the Huhehaote and Baotou metro zones ("shi shixiaqu") increased from 39% to 67% and from 42% to 76% over the period, and this does not even reflect the additional lit areas contiguous to these cities. For example, the lit area of Tumote-Zuo Qi county to the southwest of Huhehaote increased by over 950 km^2 (to 41%, from just 5% of its total area), while Tumote-You Qi county to the east of Baotou saw an increase of almost 350 km^2 (to 26%, from 11% of its total area). The lit areas of all large centers of population increased importantly in lit area extent over the 11-year period. These include Huhehaote (the capital); Baotou (a major center for the production of steel); Linhe, Wuyuan, and Bayan Gol (all close to the Hetao Irrigation District); Jining, and Dongsheng. This reflects the establishment of new suburban areas with residential, commercial and industrial development, as well as new highways that stretch from former city outskirts to other substantial population centers. This is essentially a process of metropolization, with the most important corridor evident between the capital and the Baotou: by 2003 the area under artificial lighting was continuous, whereas in 1992 the lit areas were completely isolated (Figs. 2 and 3).

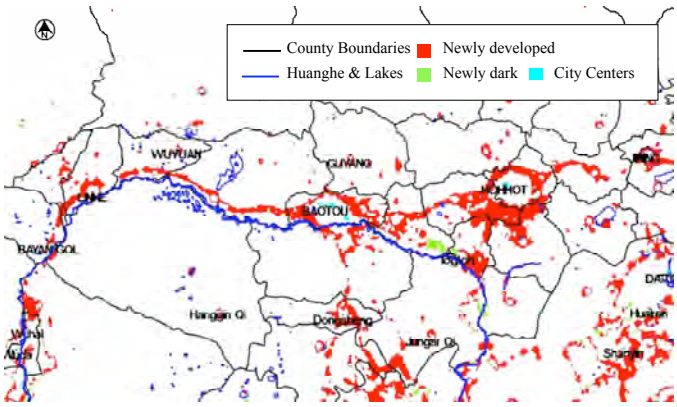

Figure 1. Areas that have undergone urbanization 1992 – 2003

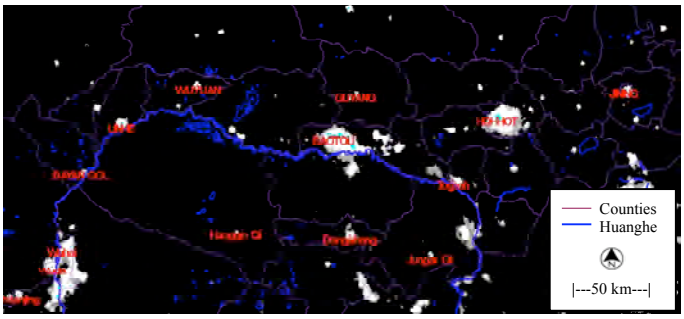

Figure 2. DMSP/OLS map showing lit area extent in 1992

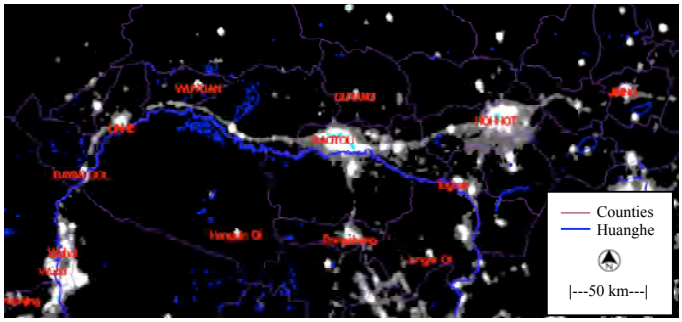

Figure 3. DMSP/OLS map showing lit area extent in 2003

Indeed, apart from the rapid expansion of all large and medium-size cities, metropolization along the Yellow River is the most striking change, and also occurs along new highways that follow other waterways. In the 2003 map there is an almost continuous corridor of developed and lit land that was not apparent in the 1992 map and that stretches from Huhehaote to Bayan Gol: this is some 435 kilometers in length (Figs.1 - 3). This pattern is repeated on a smaller scale along highways leading from Huhehaote to Jining and elsewhere. In 1992, no towns or cities in this region appeared to be connected by contiguous tracts of lit land in this way: all were isolated. A change of this magnitude reflects not only growth but also shifts in population – with migration from the less wealthy agricultural areas to the cities and suburbs – a trend towards larger homes (albeit mostly apartments), a reduced sense of obligation to conserve energy that mirrors the increased ability to pay, and to a lesser extent the massive increase in household ownership of automobiles.

The urban and total populations increased by 31.2% and 11.1%, respectively over the period. However, using lit area from DMSP/OLS as the basis for urban area calculation results in urban population density values that show an important decline in all counties of the region (Table 1). This might seem to imply that suburbanization is taking place, especially with the dramatic increase in automobile ownership over the period that would allow longer commutes to places of employment. However, the astonishing increases in county-level Gross Domestic Product (GDP) – ranging from 384% to 2200% – indicate that it is economic growth that is the driving force behind these patterns: people are moving to live near the new factories and associated centers of employment (i.e., service industries) that are located along the transportation corridors between the major centers.

In previous studies that explore the implications of light intensity as well as stable lights area, an exponential relationship has been seen across the whole of China [3] and on a global basis this holds for lit area without taking intensity into account [5]. In this region, divergent patterns are seen: in 1992 the relationship between lit area and urban population follows this exponential trend (Fig. 4 (a)). However, in 2003 an exponential function does not provide a good fit to the entire data set (Fig. 4 (b)).

TABLE I. CHANGE IN URBAN POPULATION DENSITY, LIT AREA AND GDP, 1992-2003

County	Change in Population Density (people/km^2)	% change 1992-2003		
		Urban Popn.	*Lit Area*	*GDP*
Baotou Shi Shixiaqu	-366	18.2	79.0	648.9
Chaha`er-Youyihou Qi	-1050	17.9	682.7	539.0
Chaha`er-Youyiqian Qi	-693	30.3	888.7	503.5
Chaha`er-Youyizhong Qi	-3689	38.1	478.3	863.6
Dalate Qi	-34	83.3	161.7	1081.1
Dengkou Xian	-1707	29.8	587.1	551.5
Dongsheng Shi	-420	89.3	295.6	1273.3
Fengzhen Shi	-632	27.6	191.4	335.0
Guyang Xian	-451	39.9	335.4	741.0
Hangjin Qi	-416	52.8	338.2	833.3
Hangjin-Hou Qi	-1844	33.5	634.5	507.6
Helinge`er Xian	-517	21.3	1591.2	2199.1
Huhehaote Shi Shixiaqu	-232	25.1	71.9	796.5
Jining Shi	-151	37.0	46.5	707.8
Liangcheng Xian	-848	65.4	833.5	619.4
Linhe Shi	-677	55.6	269.7	413.1
Qingshuihe Xian	-87	31.2	113.9	615.3
Siziwang Qi	-593	31.7	231.1	778.0
Tumote-You Qi	-93	24.2	140.4	447.8
Tumote-Zuo Qi	-186	35.4	654.8	747.2
Tuoketuo Xian	-218	32.9	599.8	871.1
Wuchuan Xian	-1747	39.4	1387.6	725.0
Wuhai Shi Shixiaqu	79	39.7	16.0	629.5
Wulate-Hou Qi	-478	25.3	254.1	448.2
Wulate-Qian Qi	-641	43.7	600.3	384.2
Wulate-Zhong Qi	-438	26.8	228.4	396.1
Wuyuan Xian	-632	45.9	385.0	488.9
Zhunge`er Qi	-27	76.3	135.8	863.8
Zhuozi Xian	-608	22.2	650.8	585.6

Note: Population and GDP statistics from [6] and [7].

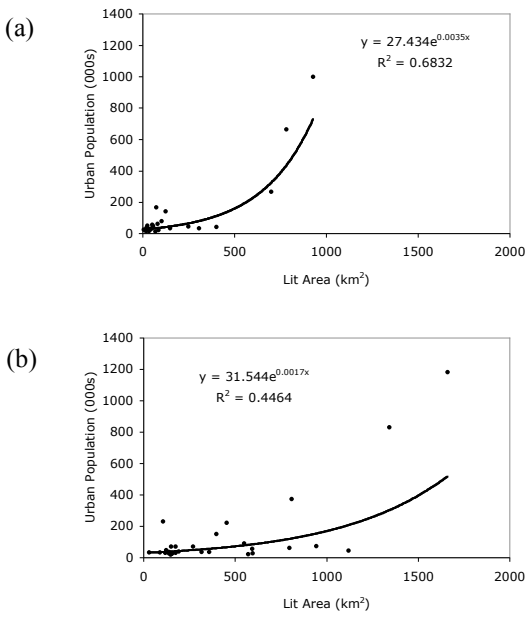

Figure 4. Lit area and urban population in (a) 1992 (b) 2003

Instead, an exponential trend is seen only for the counties with large urban areas. This is because development has been extended mainly by expansion into neighboring counties, so that interpretation of county statistics without reference to adjacent areas is less meaningful. Clearly, current administrative boundaries no longer delineate discrete areas that can be defined in terms of the most important economic and social functions.

IV. CONCLUSIONS

The dramatic increase in the area of nighttime lights in the Yellow River zone of Inner Mongolia and its spatial configuration indicate not only that urbanization is taking place at a very rapid pace but also that the region is becoming increasingly inter-connected, i.e. metropolization has occurred. This is especially evident along the Huhehaote-Baotou transportation corridor that links the two largest cities of the province but has also occurred all along the Yellow River and even at some distance from it (e.g., lit areas are expanding on the northern side of the city Dongsheng towards Baotou and *vice versa*). When combined with urban population data the OLS map data show declining urban population density, indicating that the driving force is rapid economic growth, with the appearance of vastly expanded residential areas following the extensive establishment of new businesses in transportation corridors. This trend is enhanced by the elevated ability of consumers, storekeepers, manufacturers, and municipalities to pay for the higher energy consumption and – to a much lesser extent – vehicle ownership that allows greater freedom of movement. Between 1992 and 2003 the area of newly-developed land in this region increased by 8126 km^2 (8% of the total area up from 3%) with most of this previously under agricultural exploitation, typically vegetable and cereal crops production. This is not a major limiting factor because in value terms agriculture is a less important sector than other industries (e.g., manufacturing, mining, and energy). The trends of expansion, metropolization and decline in urban population density seen here are likely to continue for the foreseeable future. Data such as those from the DMSP/OLS will be extremely useful in assessing the future course of these trends.

ACKNOWLEDGMENT

We thank the NOAA.NESDIS Earth Observation Group. OLS image and Data processing by NOAA's National Geophysical Data Center. DMSP data collected by the US Air Force Weather Agency. We also thank the Center for International Earth Science Information Network (CIESIN) and the Socioeconomic Data and Applications Center (SEDAC) at Columbia University, the Inner Mongolia Normal University School of Geography, and the Bureau of Statistics of Inner Mongolia Autonomous Region.

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