EVALUATION LIGHT POLLUTION USING TIME-SERIES OF DMSP/OLS NIGHTTIME SATELLITE DATA DURING THE PAST 21 YEARS IN CHINA

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ABSTRACT: The rapid urbanization process and economy development inevitably brings the light pollution, it has become a widespread attention of the world's environmental issue. In order to reveal the spatiotemporal patterns of light pollution in china, Defense Meteorological Satellite Program Operational Linescan System(DMSL/OLS) imageries from 1992 to 2012 were selected and then these imageries are corrected to ensure the consistency. Furthermore, we employed the slope of the linear regression and nighttime light index methods to demonstrate the china's light pollution characteristic across national, partition and provincial scales respectively. We found that: (1) China's light pollution expanded significantly around provincial capital city during the past 21 years and hot-spots of china light pollution focused in eastern coastal region. Yangtze River Delta, Pearl River Delta and Beijing-Tianjin-Hebei region have formed light pollution stretch regions respectively. In addition, some urban cities in the north of Shanxi, the south of Inner Mongolia and Xinjiang showed the decreasing light pollution significantly.(2) China's light pollution main focused in north china (NC) and east china (EC) and the total nighttime light (TNL)of these two regions accounts for over 50% of the whole country. The fastest growth of light pollution was observed in the northwest china (NWC), followed by the southwest of china (SWC). The growth rate of east china (EC), middle china (MC) and northeast china (NEC) was stable, while that of north china (NC) and south china (SC) declined. (3)Light pollution at provincial scale mainly located in Shandong, Guangdong and Hebei province, and the fastest growth of light pollution was Tibet and Hainan provinces. However, light pollution lever in the developed provinces (Hongkong, Macao, Shanghai and Tianjin) were higher than that of undeveloped provinces. Similarly, the light pollution heterogeneities of Taiwan, Beijing and Shanghai were higher than that of western undeveloped provinces. This conclusion could support government agencies to take effective measures to deal with light pollution environment issue.

1. INTRODUCTION

Light pollution issue has been firstly proposed by astronomers in 1930s [1]. Nowadays, light pollution has become more and more concerned environment issue following the water pollution, air pollution and noise pollution [2]. In 2001, 19% of the global land area exceeds the threshold of light pollution, 21% of the world population living in the light pollution of the environment [3]. At present, with the rapid urbanization and economic development around the world, the light pollution was expanding at an unprecedented speed [2, 4]. Although night lighting facilities can benefit the human activities at night, it will waste energy resource and directly or indirectly effect on animal [5-7] and ecological environment [8-11], human health [12-14] and astronomical observation [1, 15]. Since china government implemented reform and opening policy, unprecedented urbanization have took place across the country with huge electricity energy consumption, thus a large number of "sleepless city" have formed. Due to the lake of policy guidance and law regulation, almost every lager city has been threatened by light pollution. However, the issue of china's light pollution was not widely documented. Therefore, it is important to understand evolvement rules of china's light pollution by for protecting the ecological environment and improving the quality of life of urban resident.

Traditional field survey, with its high cost, low efficiency and cannot obtain historical data. However, earth observation technology has advantage in large range, high frequency and multi-temporal, especially nighttime light remote sensing technology can quickly access region and global nighttime light imagery [16]. Historically, nighttime light remote sensing has been widely used in the field of social and economic parameter estimation [17-22], urbanization monitoring [23-27], important event evaluation [28-30], and environment and health effects [31-33].Moreover, nighttime light remote sensing have been tried to evaluate the light pollution at region and national scale[2,3].

Defense Meteorological Satellite Program Operational Linescan System(DMSL/OLS) is the unique and longest series nighttime light imagery in the world and it was proved to mapping the world atlas of the artificial night sky brightness as early as in 2001[3]. That mapping result showed that about two-thirds of the world population lives in light pollution area and the percent in developed countries was 99% [3]. [2] proposed to analyze contrast trends of light pollution a cross European continent and found that most countries in Europe overall lighting showed a rising trend ,while some country like Novak, Ukraine and Belgium, the nighttime light have falling trend. Time-series nighttime light images were used to explore direct and indirect light pollution level in Athens suburban and the result demonstrated that light pollution increase significantly in study area [34]. Meanwhile, nighttime light imageries also were applied to analyze light pollution in Pakistan. The research result suggested that the area of light pollution rapidly increased and suburban areas were experiencing direct and indirect light pollution of artificial light [35]. The change trend of the china's light pollution was also investigated using multi-temporal DMSP/OLS. The conclusion suggested that light pollution growth mainly located in the eastern coastal cities, while the light pollution falling mainly located in industrial and mineral resource city [36]. In order to investigate the relationship between light pollution and land use type, [37] selected Berlin as study area and confirmed that the road was the main source of light pollution at night. Furthermore, ground investigation from different directions and the high spatial resolution night light remote sensing images were combined to understand the three dimensional of light pollution [38]. As to the research of the impact of light pollution on ecosystems, [39] confirmed the effect of night sky scattered light on biodiversity. Furthermore, [40] evaluated global ecosystem types in exposure to artificial light combing DMSP/OLS images and land cover product and found that Mediterranean-climate ecosystem was affected greatest and global ecosystem have been localized and fragmented by artificially light.

In order to understand china's light pollution during rapid economic and society development period, we investigated time-series DMSP/OLS nighttime light remote sensing imagery from 1992 to 2012 and employed the slope of the linear regression and nighttime light index methods to reveal spatiotemporal patterns of light pollution in china at national, regional and provincial scale repetitively. This study conclusion can assist governance to make decision for light pollution environment issue.

2. STUDY AREA

China is located in the east of Asia, situated in Pacific West Coast and its land area is about 9.6 million square kilometers. Since the economic reform in 1978, China economic has sustained growth almost 40 years and become the world's second-largest economy about GDP in 2014 [41].China also has the largest population over 1.3 billion in 2010 and 54.7% of the total population lived in the urban area by the end of 2014, increased by 26% than 1990. Meanwhile, with the population shifted from rural to urban areas, city has unprecedented development [42].Though China has made the huge achievements during the past years; it faces the serious and plentiful environment pollution issues. Different from other pollution, light pollution in China was far from being concerned. Therefore, it is necessary to explore spatiotemporal patterns of china light pollution. According to natural and socio-economic situation at provincial scale, the study area will be divided into seven partitions (Figure 1).

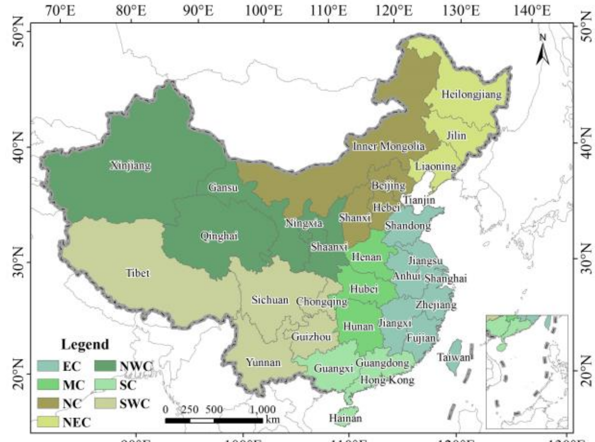

Figure 1. Seven partitions of China geographic. EC= East China; MC= Middle China; NC= North China; NEC= North East China; NWC= North West China; SC=South China; SWC=South West China.

3. DATE PROCESSING

Long term time-series DMSP/OLS nighttime light satellite images from 1992 year to 2012 year are selected as experimental data to study light pollution in China. DMSP/OLS began in 1970s and original purpose design was to obtaining the night cloud distribution information [43], however, scientists found that DMSP/OLS can capture nighttime light of urban area under cloudless conditions. The DMSP/OLS images in this study is version 4 and contains six sensors (Figure 2) which were downloaded from the National Geophysical Data Center (NGDC) website of National Oceanic and Atmospheric Administration (NOAA) (http://ngdc.noaa.gov/eog/dmsp/downloadV4 composites. html, Accessed, 20.10.2015). The annual product of night-time lights contains frequency of cloud-free product, average light product and stable night-time light product respectively. We selected 33 periods global stable night-time light product as study dataset for it has remove background noise like gas flaring, wildlife fire and aurora. Therefore, the brightness in imagery represents the resident night-time light. This imagery was given 30 arc second grids, spanning -180 to 180 degrees longitude and -65 to 75 degrees latitude and data pixel digital number(DN) ranges from 0-63 [44,45].

Because DMSO/OLS nighttime light imagery were acquired by six satellites (F10, F12, F14, F15, and F16) spanning 21 years without on-board calibration, therefore, it necessary to correct nighttime light imagers to improve data comparability and accuracy [43].In order to obtain research dataset for studying, we have made a workflow to process time-series nighttime light imageries (Figure 3), it mainly included three steps: model establishment, image correction and post image processing.

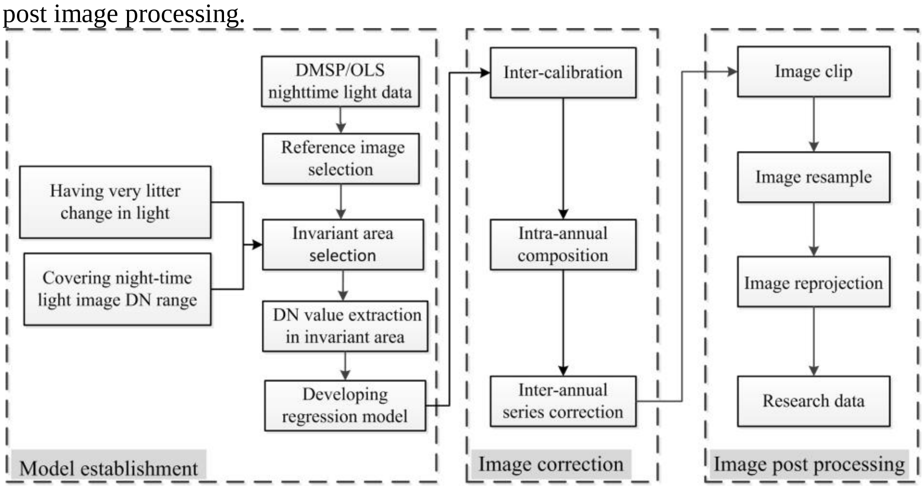

Figure 3. The process flow of DMSP/OLS nighttime light imagery

According to the 1:250 000 administrative boundaries of china, we clipped the study area image from the global image and resampled it in the 1km resolution, then those images were reprojected to the Albers equal area conic projection with1940 Krassovsky ellipsoid and dataset was generated for this research at last.

4. METHOD

4.1. Linear regression trend method

Linear regression trend analysis was used to directly reveal temporal and spatial trends in each pixel with eliminating the DN variation error [46, 47]. The calculation formula is as follows:

$$R = \frac{t \times \sum_{i=1}^{t} i \times DN_i - \sum_{i=1}^{t} i \sum_{i=1}^{t} DN_i}{t \times \sum_{i=1}^{t} i^2 - \left(\sum_{i=1}^{t} i \right)^2}$$

In the formula, R is a slope of the regression trend, DN_i represents DN value in year i. t represents time span (21 year). If R above 0, it shows that the DN value trend is increasing in 21 years and the greater of R value, the increasing trend is more significate. However, If R below 0, it shows that the DN value trend is decreasing in 21 years and the smaller of R value, the decreasing trend is more significate.

4.2. Construction of night-time light index

In order to analyze the spatial and temporal characteristics of light pollution, four nighttime light indexes were constructed, including total night light (TNL), night light mean (NLM), night light standard deviation (NTSD) and proportion of total night light (PTNL). TNL, NLM NTSD index value were extracted using ArcGIS 10. The formula and description of each index are shown in Table 2.

Table2. Nighttime light indexes

Indicator name	Expression	Description
Total night light（TNL）	$TNL = \sum_{i=1}^{63} C_i \times DN_i$	Refers to the total amount level of light pollution in the statistical area. DN_i is the i-th gray level, C_i is the number of pixels responds to gray level.

Night light mean（NTM）	$NTM = (\sum_{i=1}^{63} C_i \times DN_i) / \sum_{i=1}^{63} C_i$	Refers to the average level of light pollution in the statistical area. DN_i is the i-th gray level, C_i is the number of pixels responds to gray level.
Night light standard deviation（NTSD）	$NTSD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(DN_i - NTM)^2}$	Refers to the differentiation level of light pollution in the statistical area. DN_i is the i-th gray level, *NTM* is the night light mean.
Proportion of total night light（PTNL）	$PTNL = TNL / TNL_{all}$	Refers to proportion of TNL in region accounted for TNL of whole region. *T*NL is total night light in region and TNL_{all} is total night light in the whole region.

5. METHOD RESULTS AND ANALYSIS

5.1. Comparison of night light image correction

In order to evaluate the effect of nighttime light images correction, the TNL of china was extracted from different correction method to compare (Figure 4).The TNL of different sensor among original images (Figure 4 (a)) have significant different in the same year, however, after the inter-calibration (Figure 4 (b)), the TNL is more consistent in the cross year, it has showed that the sensor error was effectively eliminated. Furthermore, the inter-annual composition was employed to correct image (Figure 4 (c)), the annual fluctuation of TNL showed increasing trend, but it also has sharply decrease in 2012 year. Thus, inter-annual series correction method was used to correct images and the correction result was showed in Figure 4 (d).After inter-annual series correction, the increasing trend of TNL was more stable, it indicated that the image correction had make good performance and it can be used to analysis the spatial and temporal characteristics of night light pollution in china.

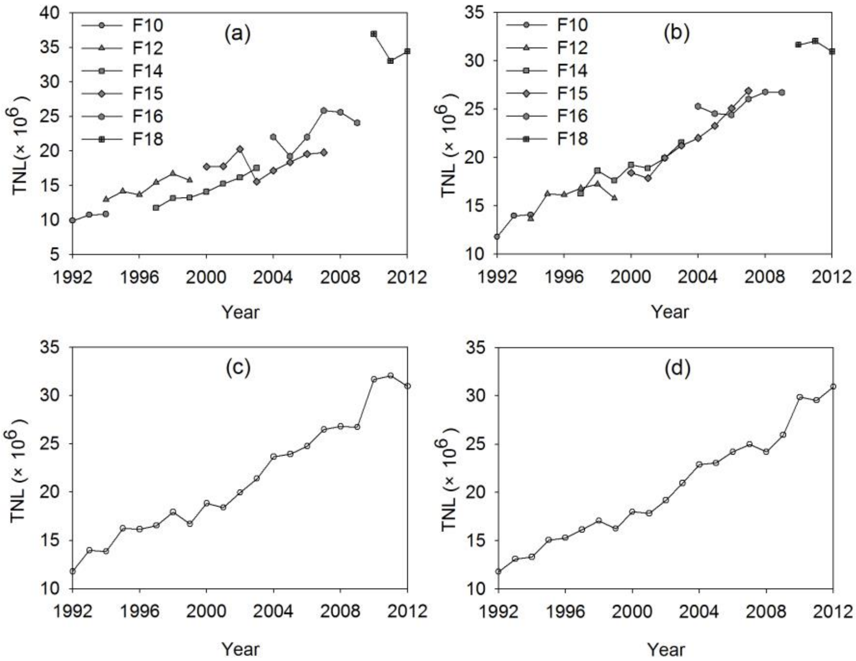

Figure 4. The TNL of nighttime light images before and after correction. (a)original images, (b) inter-calibration, (c)inter-annual composition and(d)inter-annual series correction

5.2. Night light pollution variation characteristic at national sacle

Linear regression trend method was employed to reveal the variation characteristics of light pollution in China from 1992 to 2012, as shown in Figure 5. The figure shows that light pollution has experienced sharply increase trend at national wide during the past year. Light pollution increase area mainly locates around municipalities and provincial capitals, whereas a local area shows the decrease trend, for example, Shanxi and Xinjiang province. Moreover, most of area belongs to stable light area. It can be divided two cases: one case locates in the urban core area and another case is non night light area. The former case is because urban core night light is under saturated from 1992 to 2012, so the night light pollution has significant change. However, the latter case is almost non-residential area and it lacks of the night lighting, thus there is almost no night light pollution. China night light pollution mainly locates in three major urban agglomerations (Beijing-Tianjin-Hebei region, Yangtze River Delta and Pearl River Delta), followed by middle Yangtze, Shandong Peninsula Chengdu-Chongqing and Harbin-Changchun. Moreover, the night light pollution in Inner Mongolia, Shanxi, Shaanxi, Henan and Xinjiang also increase significantly. In addition, some urban cities in the north of Shanxi, the south of Inner Mongolia and Xinjiang showed the decreasing light pollution significantly.

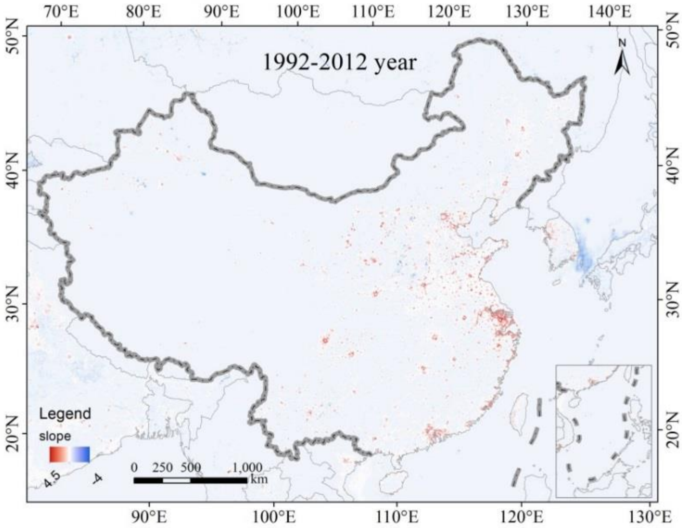

Figure 5. The change trend of nighttime light pollution in China. (Red color represents light pollution increase, blue color represents light pollution decrease and white color represents light pollution stable)

In order to investigate light pollution of three major urban agglomerations (Beijing-Tianjin-Hebei region, Yangtze River Delta and Pearl River Delta), the synthesis map (Figure 6) was generates by using muti-temporal (1992, 2012 and 2012 year) nighttime light imageries. The white color represents stable light pollution from 1992 to 2012, the red color represents extended light pollution and blue color represents decrease light pollution respectively.

Compared to the Pearl River Delta and Beijing-Tianjin-Hebei region , Yangtze River Delta have experienced rapidly and widely light pollution process along the Yangtze River and it has formed about 300km light pollution stretch zone from Shanghai to Nanjing. In addition, Hangzhou and Ningbo urban city light pollution increase significantly. Most of light pollution cities (Guangzhou, Dongguan, Shenzhen, Hongkong, Macao, Zhuhai and Foshan) show white color in Figure 6(c), this result indicates that light pollution in Pearl River Delta is more stable from 1992 to 2012. In addition，light pollution in Hongkong decreased ,which may related to Hongkong hava publish light pollution policy in the recent year.Compared with Yangtze River Delta, Beijing, Tianjin and Hebei urban agglomeration nighttime light pollution mainly located in Beijing and Tianjin stretches area and spatial connectivity of light pollution is less than Yangtze River Delta and Pearl River Delta.

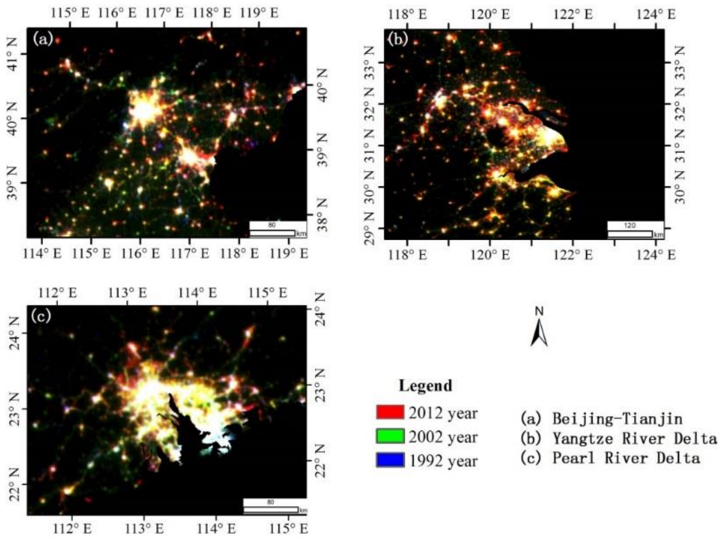

Figure 6. Color composite of nighttime light of three major urban agglomerations (Beijing-Tianjin-Hebei region, Yangtze River Delta and Pearl River Delta) in china.

During the past 21 years, china light pollution has expansion trend(Figure 5),however, light pollution decline area still exist, which are the blue color in Figure 5. In order to analyze the reasons for the decrease of the night light, high resolution satellite images from the Google Earth were selected to validate land cover type, the result showed in Figure 7. Where A and B represent oil mining abandoned facilities ; C、D、E and F represent coal mining abandoned facilities; H and I represent dam construction facilities. It can be found that the main reason of light pollution decrease were abandoned facilities of resource exploitation and the completion of the dam project.

In the process of oil exploration, gas flaring phenomenon will happen. [48] has demonstrated that DMSP/OLS can be used to monitor the gas flaring. In the gas flaring area, the gray value of nightlight imagery was close to the urban core gray value and even saturated. When the oil exploration decrease, the gray value of image corresponding to gas flaring area will decreased significantly and the regression change analysis showed a downward trend. The main reason of light pollution decrease in Shanxi, Shaanxi and Inner Mongolia region was that coal resources exploitation activity weakened or even exhausted and it result that population and economic of city surrounded the mine decrease, so the nighttime light pollution decreased. Nighttime light pollution decline in Yunnan was mainly due to dam construction. During the process of construction project, the high power searchlights would be used to light and it would result strong light pollution. When the project completed, the searchlight can be not used and the nighttime light intensity decreased, so light pollution change trend decreased.

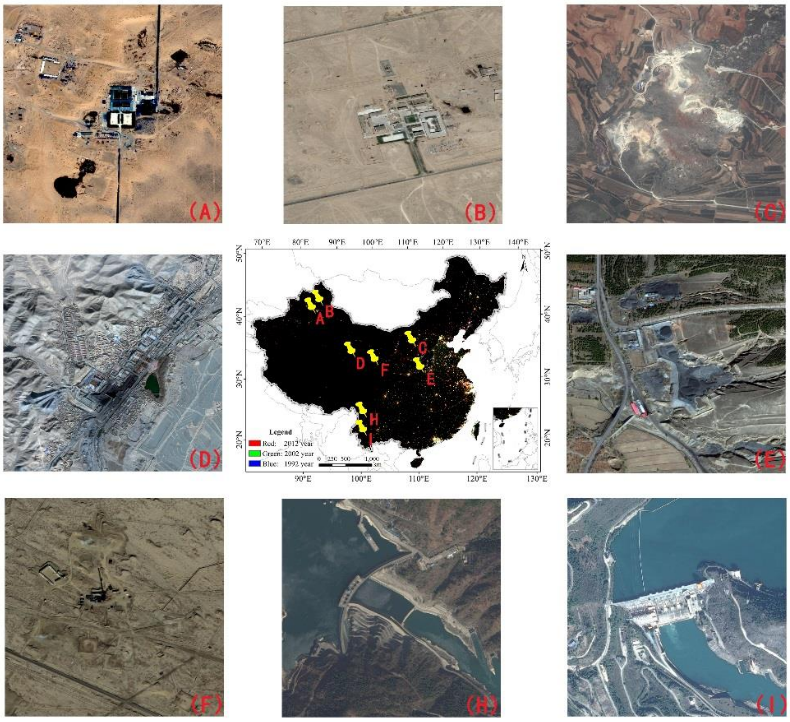

Figure 7. Validation of the nighttime light pollution decline regions（A and B represent oil mining abandoned facilities ; C、D、E and F represent coal mining abandoned facilities; H and I represent dam construction facilities）

5.3. Night light pollution change characteristic at partition scale

In order to understand the change characteristic of light pollution at partition scale in china, the TNL and PTNL index were employed to analysis. The result showed in Figure 8.The TNL among seven partitions showed increase trend from 1992 to 2012. The largest growth range of TNL is East China, followed by North China and the smallest growth range of TNL is the South China. This is because East China includes the five coastal provinces and Shanghai city and economic level of this region was higher than national average. The North China gathered a lager of industry zone and also is the population agglomeration region in China. Overall, the sum of TNL in East China and North China accounts for half of TNL of the whole China. Although the Guangdong province located in South China and its economic level is high, the economic level of Guangxi and Hainan province are lower than national average. The fastest growth rate of TNL is Southwest China, followed by Northwest China. Southwest China increased by 340% and Northwest China increased by 290%. The growth rate of these regions was higher than that of East China and North China. This is understandable because western city have make a rapid development of the since implementation of Western Development Strategy. It also demonstrated that nighttime light pollution will inevitably increase during rapid social and economic development.

As shown in Figure 8, the TNL in East China accounts for about 30% of TNL of the whole country, followed by North China, accounting for about 20% and Southwest China only account for 6% of the whole country. Thus, light pollution has significant spatial imbalanced. Furthermore, the change trends of PTNL of each region are different. According to statistical results of the figure 8, the inter-annual changes trends of PTNL can be divided to three types: increase (Northwest China and Southwest China), decreased (North China and South China), stable (East China, Central China, and Northeast region). The increase pattern shows that the light pollution is in the process of accelerating expand, the growth rate of TNL is higher than that of nationwide. This result demonstrated that light pollution was expanding and intensifying during the past 21 years. Moreover, the decreased pattern indicates that light pollution is in the process of expanding, but the growth rate of TNL is lower than that of nationwide. With the adjustment of industrial structure, especially the iron and steel industry of North China, that directly effect on the economic growth speed, this is one of reason of PTNL decreased in North China. PTNL decreased in South China mainly because that Guangxi and Hainan economic growth speed lower than that of nationwide. The stable pattern shows that light pollution expansion speed relatively consistent with that of nationwide, and there is a fluctuation between the years. The fluctuation of PTNL in East China at is stable over the past year, however, the PTNL in Central China increased firstly and then decreased. In contrast, the PTNL in Northeast China decreased firstly and then increased.

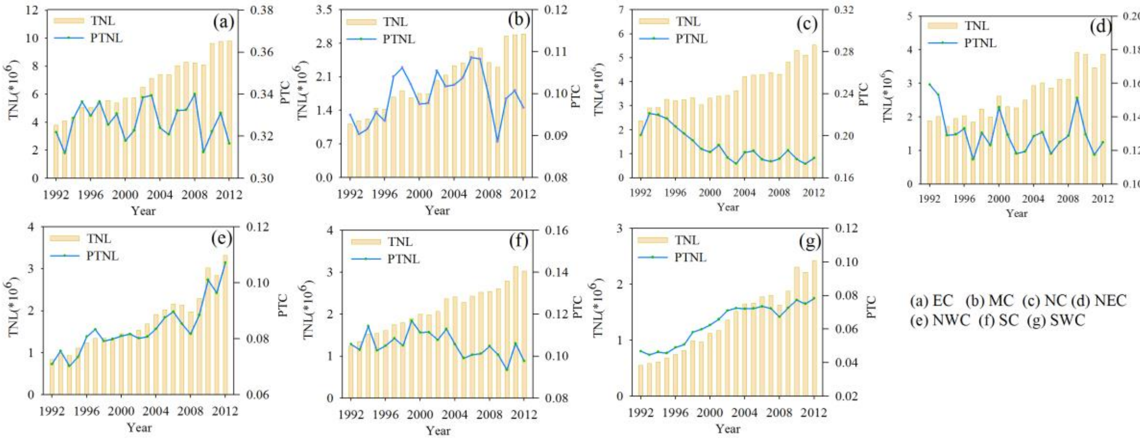

Figure 8. The nighttime light pollution at partition scale in China

5.4. Night light pollution change characteristic at princvical scale

The night light pollution characteristics of 34 provincial administrative regions (including Hong Kong, Macao and Taiwan) in China was analyzed by using the total of night light (TNL), the mean of night light (MNL) and the standard deviation of night light (SDNL). Figure 9 is the statistical results of the total value of night light in each province of China, it can be seen from the figure, for the TNL index, the highest three province are Shandong, Guangdong, Hebei, the lowest three are Hongkong, Tibet and Macao. The result indicates that the TNL is not only related to the level of economic development, but also related to the administrative area. The largest night light pollution is in Shandong, Guangdong, Hebei and other provinces which have higher economic development levels and larger areas . (2) The TNL in Hongkong has declined by 11.1% which related to the government's prevention and controlling measures to light pollution in recent years. The TNL in other provinces showed an upward trend, which indicated that the light pollution in the night showed an increasing trend. Among those provinces, Tibet has the fastest growing rate, which has increased by 768%. Hainan Province has increased by 462%. Beijing and Shanghai, respectively, have increased by 68% and 71%. This result shows that night light pollution growth rapidly in economically undeveloped areas, because those areas have a low TNL in 1992 and keep a rapid pace of development. On the contrary, the growth of TNL is slower in the economically developed areas.

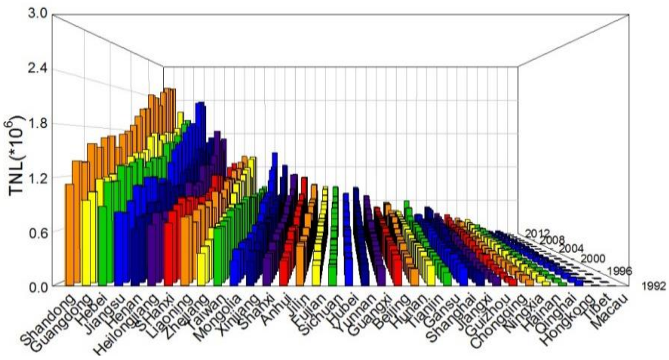

Figure 9. The total nighttime light (TNL) at provincial scale in China

Compared with the TNL, the MNL can eliminate the influence of the administrative area and reflect the regional average night light pollution level. The average statistical results of night lights in each province of China are shown in Figure 10. For the MNL, the top three are Hongkong, Macao and Shanghai, the lowest three are Xinjiang, Qinghai and Tibet. It suggests that the night light pollution level is associated with economic development. Hongkong, Macao and Shanghai are often known as "sleepless city", its MNL digital number range from 20 to 50. Most of the undeveloped provinces belong to the non-luminous areas, their night light pollution degree is low. The fastest growth rate of the MNL is Tibet, followed by Hainan, while the growth rate of economically developed cities is low.

Hongkong has a negative MNL growth, which is consistent with the changing of TNL value. Light pollution increased considerably in Shanghai, Tianjin and Jiangsu, DN has an increase of more than 10. Hong Kong and Macau have smaller increases, because Hong Kong and Macao have a small area and high economic level, thus, their light pollution is serious. In Shanghai, Tianjin and Jiangsu, as the long-term economic development, light pollution has become increasingly serious problem.

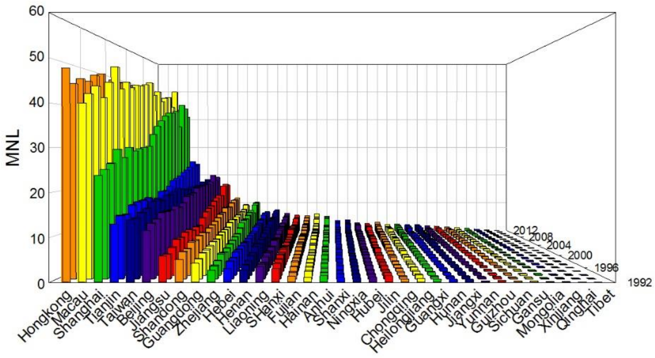

Figure 10. The mean nighttime light (MNL) at provincial scale in China

Standard deviation of night lights(SDNL) can reflect regional heterogeneities. The SDNL in different provinces of China are shown in Figure 11. The SDNL of Taiwan, Beijing and Shanghai are higher, while Xinjiang, Qinghai and Tibet is relatively lower. This result shows that light pollution in the developed area has a greater heterogeneity. It is because MNL in the developed province has a high value but gray value in the suburbs (non-luminous) is 0, resulting in greater heterogeneities within the whole region. For undeveloped provinces, most of the areas have no luminous, the MNL is low, so the night light pollution is less heterogeneities within the whole region. The most provinces SDNL increase during the past year, except for Macao, dropping by 10.3%. SDNL of Tibet has the fastest growth up to 219%, followed by Yunnan, 156%. It shows that the heterogeneities of light pollution among undeveloped provinces were increasing trend.

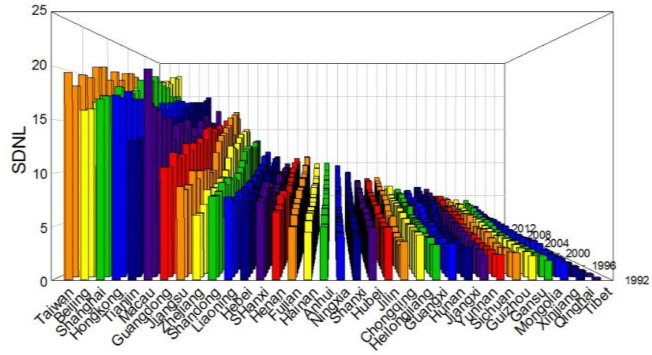

Figure 11. The standard deviation nighttime light (SDNL) at provincial scale in China

6. CONCLUSION

In order to analysis characteristics of the light pollution characteristic of China, this paper proposed process flow to correct the time series DMSP/OLS nighttime light imagery from 1992 to 2012 firstly. Then, linear regression trend method and night light index method were employed to the temporal and spatial characteristics of light pollution at multi-scale. The conclusions of this study are as follows:

(1)After image correction, time series DMSP/OLS nighttime light imagery error can be eliminated efficiently. It improved the consistency of the image and lay foundation for the light pollution analysis furtherly.

(2)Light pollution increase area mainly locates around municipalities and capital cities and formed Yangtze River Delta, Pearl River Delta and Beijing-Tianjin-Hebei region stretch area. Due to resource depletion and dam construction project, local area light pollution decrease in Shanxi, Inner Mongolia, Shaanxi, Xinjiang and Yunnan provinces.

(3) The TNL among seven partitions show increase trend during the past year. The largest growth range of TNL is East China, followed by North China. The fastest growth rate of TNL is Southwest China (increased by 340%), followed by Northwest China (increased by 290%).According to PTNL change trends, Northwest China and Southwest China are increase type, North China and South China are decreased type, and East China, Central China, and Northeast region are stable type.

(4)The greatest of TNL is Shandong at province scale in nationwide, followed by Guangdong province and Hebei. The high level of Light pollution mainly located in the developed provinces (Hongkong, Macao, Shanghai and

Tianjin) and light pollution of Tibet and Hainan growth rapidly.
The light pollution heterogeneities of developed provinces (Taiwan, Beijing and Shanghai) are high, however, that of undeveloped provinces (Xinjiang, Qinghai and Tibet) are low. The growth rate of SDNL of western provinces is higher than east provinces.

In this study, DMSP/OLS nighttime light remote sensing was used to demonstrate he temporal and spatial characteristics of the China light pollution at multi-scale. It is helpful to objectively and accurately understand the light pollution problems during the past rapid urbanization process. Moreover, this conclusion can benefit policy making and light pollution regulation for government. In the next step, we will furtherly carry out the research that night light pollution effect on ecological environment and health risk by integrating multi-source remote sensing data and ground investigation data.

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