Estimation of the Anthropogenic Heat Release Distribution in China from 1992 to 2009

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(Received September 21, 2011; in final form April 23, 2012)

ABSTRACT

Stable light data from Defense Meteorological Satellite Program (DMSP)/Operational Linescan System (OLS) satellites and authoritative energy consumption data distributed by National Bureau of Statistics of China were applied to estimating the distribution of anthropogenic heat release in China from 1992 to 2009. A strong linear relationship was found between DMSP/OLS digital number data and anthropogenic heat flux density (AHFD). The results indicate that anthropogenic heat release in China was geographically concentrated and was fundamentally correlated with economic activities. The anthropogenic heat release in economically developed areas in northern, eastern, and southern China was much larger than other regions, whereas it was very small in northwestern and southwestern China. The mean AHFD in China increased from 0.07 W m^{-2} in 1978 to 0.28 W m^{-2} in 2008. The results indicate that in the anthropogenic heat-concentrated regions of Beijing, the Yangtze River Delta, and the Pearl River Delta, the AHFD levels were much higher than the average. The effect of aggravating anthropogenic heat release on climate change deserves further investigation.

Key words: DMSP/OLS data, estimation, distribution, anthropogenic heat flux, China

Citation: Chen Bing, Shi Guangyu, Wang Biao, et al., 2012: Estimation of the anthropogenic heat release distribution in China from 1992 to 2009. *Acta Meteor. Sinica*, **26**(4), 507–515, doi: 10.1007/s-13351-012-0409-y.

1. Introduction

Energy consumption and greenhouse gases from fossil fuel combustion have increased sharply since the Industrial Revolution. Aerosols, anthropogenic heat, and greenhouse gases, such as CO_2, H_2O, and CH_4, have been released into the atmosphere and exert profound influence on the climate. Changes in the atmosphere's composition, land use, and land cover are considered the main aspects of the climate effect caused by human factors. The impacts of human activities contribute to changes in the composition of the atmosphere and disrupt the energy balance of the earth-atmosphere system, which lead to a warmer and changeable climate. As we know, 'urban heat island' is a common phenomenon partly caused by the release of heat into the environment from energy use of human activities (IPCC, 2007). The economic prosperity of the modern world is based on the vast consumption of various energy resources, which eventually turn into anthropogenic heat released into the atmosphere. Anthropogenic heat is essential for the climate change in urban areas (Block et al., 2004; Fan and Sailor, 2005). Anthropogenic heat may increase turbulent fluxes in sensible and latent heat, which can result in the atmosphere containing more energy (Oke, 1988). The flux of anthropogenic heat caused by human activities can exert a significant influence on the dynamics and thermodynamics of the urban boundary layer (Ichinose et al., 1999; Block et al., 2004; Fan and Sailor, 2005). It

Supported by the National Natural Science Foundation of China (40775008 and 41075015) and Ministry of Science and Technology of China (2010DFA22770).

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can also increase the temperature and height of the boundary layer, especially at night, which affects reaction rates and chemical processing of emitted species (Markar et al., 2006). The climate effect due to anthropogenic heat release is important to climate change. Clearly, the energy balance of the surface can be broken due to anthropogenic heat.

Anthropogenic heat energy forms have been considered as both latent heat and sensible heat emissions in different climate models (Oleson et al., 2011; Block et al., 2004). Estimating the anthropogenic heat flux is essential for determining the effect of anthropogenic heat in climate models. Previous studies generally focused on a single city or a small area (Lee et al., 2009; Hamilton et al., 2009) and did not focus on the continuously changing trends. Contrary to the methods used in urban areas, where anthropogenic heat is considered from all major sources, including buildings, industry, and vehicles (Lee et al., 2009; Hamilton et al., 2009), energy from additional heating resources is ultimately converted into anthropogenic heat. Considering the development of urban agglomeration on a global scale in the near future, the flux of anthropogenic heat release will increase sharply with the development of the world economy. The role that anthropogenic heat is playing in the climate effect of urban agglomerations is essential in global climate change estimation.

Contrary to previous studies, which focused on anthropogenic heat flux in a single area or city (Lee et al., 2009; Hamilton et al., 2009) and its climate effect to a small area (Tong et al., 2004; Block et al., 2004), in this study, the anthropogenic heat flux distribution over entire China from 1992 to 2009 was estimated using DMSP (Defense Meteorological Satellite Program)/OLS (Operational Linescan System) satellite data. This will provide a useful parameterization for climate models and make further research on the climate effect of anthropogenic heat and urban agglomerations in climate models feasible.

The U.S. Air Force DMSP has been in operation since the mid 1960s. The DMSP/OLS is an oscillating scan radiometer with a broad field of view (about 3000-km swath) and captures images at a nominal resolution of 0.56 km. The images are smoothed onboard into 5×5 pixel blocks to 2.8 km to reduce the amount of memory required onboard the satellite. The OLS sensor has two broadband sensors: one is visible/infrared (VNIR; 0.4–1.1 μm) and the other is thermal infrared (TIR; 10.5–12.6 μm), which is able to detect lights from cities and towns and gas flares as well as ephemeral events such as fires or clouds illuminated by moonlight and lightening. The OLS sensor not only detects visible light band sources down to 10^{-9} W cm^{-2} sr^{-1}, but also produces visually consistent imagery of clouds at all scan angles. The sensitivity of the OLS sensor is four orders of magnitude greater than other sensors, such as NOAA-Advanced Very High Resolution Radiometer (AVHRR) or Landsat Thematic Mapper (Elvidge et al., 1997a). This provides the OLS with a unique ability to detect low levels of visible and near-infrared radiance at night. The DMSP/OLS data have been widely applied in many research fields, such as population estimating (Amaral et al., 2006), energy consumption (Husi et al., 2010), economic activity (Elvidge et al., 1997b; Tilottama et al., 2009), human settlement, and urban extension (Small et al., 2005). Additionally, the DMSP/OLS data are applied to analyzing greenhouse gas emissions (Doll et al., 2000) and light pollution (Cinzano et al., 2001). Recent studies (Tilottama et al., 2009; Husi et al., 2010) indicate that the DMSP/OLS satellite data are closely correlated with economic development levels and energy consumption, which provides a good way to estimate these levels. Generally speaking, the areas where the DMSP/OLS data are high are often with developed economies and high energy consumption (Elvidge et al., 1997b; Husi et al., 2010; Tilottama et al., 2009), and therefore, more anthropogenic heat emissions. The world economy is based on the vast consumption of various energy resources, which turn into anthropogenic heat that is eventually released into the atmosphere.

In this paper, a simple model based on DMSP/OLS satellite data provided by the National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA) and the energy consumption statistics published by National Bureau of Statistics of China, is developed to analyze the distribution of anthropogenic heat flux in China, which is closely correlated with economic activity and energy consumption.

2. Data and methods

Assuming that all energy consumption by human beings is eventually converted into heat, the anthropogenic heat flux density (AHFD) (Q_a; unit: J s^{-1} m^{-2}) over a specific area and at a specified time can be approximated by the following equation:

$$Q_\mathrm{a} = \frac{E_\mathrm{c}}{t \cdot A}, \tag{1}$$

where E_c, t, and A represent energy consumption, time, and area, respectively. The effect of anthropogenic heat in different areas and at different scales can be obtained by Eq. (1). Using Eq. (1) along with global energy consumption data for the year 2009 provided by British Petroleum (www.bp.com/statistical-review), we found a mean anthropogenic energy flux density (Q_a) of about 0.10 W m^{-2} for all global land area and 0.28 W m^{-2} for China.

The authoritative statistics come from the *China Statistical Yearbook 2010* and *China Energy Statistical Yearbook 2009*, the latest publications compiled by the National Bureau of Statistics of China (National Bureau of Statistics of China, 2010a, b). The former book contains detailed statistics on all aspects of the society, including the economy, population, energy, and resources in China, separately given by provinces or districts. The latter contains detailed data on energy production and consumption among the provinces.

Stable light data from the DMSP/OLS Nighttime Lights version 4 Time Series were applied to the research. These data are cloud-free composites made using all the available archived DMSP/OLS smooth resolution data by calendar year. The products are 30 arc second grids that span –180 to 180 degrees longitude and –65 to 75 degrees latitude. The stable light data contain the light from cities, towns, and other sites with persistent lighting. Glare, sunlight, and moonlight data, as well as lighting from auroras, have been excluded. Ephemeral events, such as fires, have been discarded. The background noise was identified and replaced with zero values. Each grid of the stable light data from the DMSP/OLS Nighttime Lights version 4 Time Series has a digital number from 0 to 63. The digital number, which is a positive integer assigned to the response of a sensor relative to the intensity of the signal received by the sensor, depends on the number of bits assigned to the quantifying sensor response. For the analysis presented in this work, continuous stable light data from 1992 to 2009 from DMSP satellites were provided by NGDC, including the following four satellites: F10 (1992–1994), F12 (1994–1999), F14 (1997–2003), and F16 (2004–2009).

The mean anthropogenic heat release flux for all of China, as well as some specific areas of China from 1992 to 2008, was obtained from the National Bureau of Statistics of China. The mean digital number for all of China and its districts was obtained by Arc GIS. The relationship between the mean AHFD and the mean digital number was analyzed. The coefficients of determination (R^2) produced by the linear regression between the stable light data from four satellites and the anthropogenic heat flux data were all more than 0.9, which indicates a strong linear correlation (Table 1 and Fig. 1).

Considering the differences among various satellites due to varying instruments and observation conditions, different satellite data obtained in the same year were analyzed by using the *t*-test. Analysis of the satellite data for China obtained by F10 and F12 in 1994 indicates that the correlation coefficient between the two datasets was 0.996, and the *t*-test result shows no significant difference between the two satellites. The same result was obtained with the data for China from F12 and F14 between 1997 and 1999. The correlation coefficient between them was 0.997, whereas the *t*-test result shows that the satellite data were quite similar. It shows that there was no significant difference between the various satellite datasets. It is therefore feasible for the data from different satellites to be applied in this paper.

Table 1. Linear correlation between the anthropogenic heat flux function and the stable light data from four satellites

Satellite	R^2
F10	0.977
F12	0.944
F14	0.949
F16	0.914

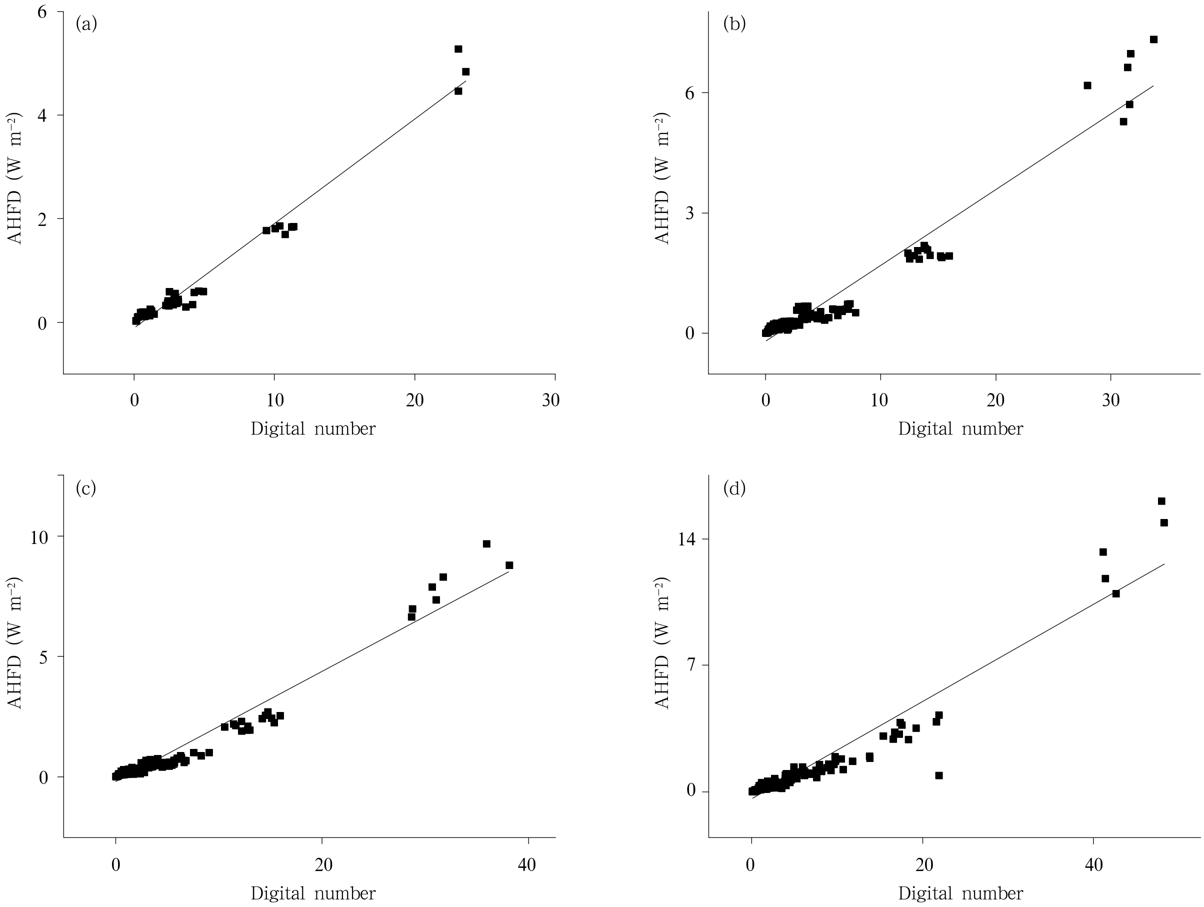

Fig. 1. Relationship between digital number of DMSP/OLS stable light and anthropogenic heat flux density (AHFD) (W m^{-2}) in China. (a) The F10 satellite from 1992 to 1994, (b) the F12 satellite from 1994 to 1999, (c) the F14 satellite from 1997 to 2003, and (d) the F16 satellite from 2004 to 2009.

The curve-fitting model requires the following criteria: (1) when the digital number (DN) of the satellite data is 0, the AHFD should be 0; and (2) when DN becomes large, the AHFD should be at a reasonable level. A curve fit model was used to estimate the AHFD. The AHFD was expected to increase with increasing DN and it would stay at a reasonable level when the DN was at its minimum or maximum. The areas where the DN is 0 are probably desolate areas, such as forests, crop land, ice land, desert areas, and oceans. In these areas, the anthropogenic heat flux is very low (the probable value is 0). For this reason, the DMSP/OLS data are suitable for estimating anthropogenic heat flux in the model. Based on this assumption, different curve-fitting models, including many nonlinear models, were used. Moreover, the statistical hypothesis test was conducted. Based on analysis of different model results, it is indicated that the linear model, $y = kx$, where k is the slope of the linear function, is the best among various models.

3. Statistical analysis of anthropogenic heat release

Energy consumption in China has been recorded from 1978 to 2009 by the National Bureau of Statistics of China (2010a), in which energy consumption data by districts and provinces are available from 1990 to 2008. In the past 30 years, the mean anthropogenic heat release flux in China has increased sharply. The flux was 0.07 W m^{-2} in 1978, whereas it was 0.28 W m^{-2} in 2008, indicating a threefold increase over 30 yr.

As shown in Fig. 3, the distribution of AHFD in

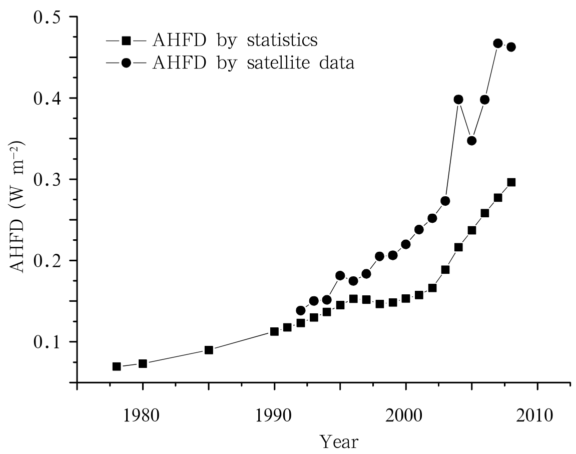

Fig. 2. Mean AHFD (W m^{-2}) in China from 1978 to 2008 by statistics and the estimated result from DMSP/OLS satellite data from 1992 to 2008.

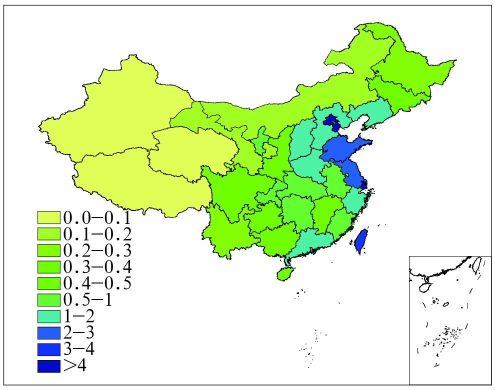

Fig. 3. Distribution of mean anthropogenic heat flux density (W m^{-2}) by statistical data over China in 2008.

China is generally nonuniform, which is consistent with the economic development in different regions of China. The mean AHFD in Beijing is 3.5 W m^{-2}, whereas it is 4.4 W m^{-2} in Tianjin and about 15.0 W m^{-2} in Shanghai. The AHFD is greater than 1.0 W m^{-2} in most areas of China, including most provinces of northern and eastern China, as well as coastal regions. Overall, the anthropogenic heat flux is very low in northwestern China, whereas the levels in northern, central, eastern and southern China are much higher than in other regions. With the development of urban agglomerations and the booming economy, the anthropogenic heat release in northern, eastern and southern China is increasing remarkably and becoming a large atmospheric heat source. Attention should be paid to the possible effects caused by anthropogenic heat on regional climate, which deserve further research.

4. Analysis of the model results based on the satellite data

Estimation of the anthropogenic heat release in China from 1992 to 2009 based on the DMSP/OLS data is shown in Fig. 4. The AHFD distribution in China was obtained for each year from 1992 to 2009. The estimation of anthropogenic heat release by satellite data is consistent with the statistical results. Obviously, the annual evolution of anthropogenic heat release in China is compatible with the development of the economy and urban agglomerations in China. Generally, anthropogenic heat is concentrated in northeastern, northern, and eastern China, as well as the coastal cities of Southeast China, especially in Beijing, the Yangtze River Delta, and the Pearl River Delta areas. The results show that in the AHFD distribution map, the inland cities appear as spots. The AHFD distribution in 1992 suggests that thermal pollution was not serious, except in the economically developed areas. Several years later, the anthropogenic heat release increases on a larger scale over the developed areas. Significant enhancement of anthropogenic heat release in central and southwestern China is shown by satellite data from 2000. A vast area, including northeastern, northern, central, and southern China, appears seriously affected by thermal pollution in 2005. The latest AHFD distribution in China (figure omitted) suggests that the anthropogenic heat emission is still growing. The trend of increasing anthropogenic heat is clearly presented in the satellite data.

The mean AHFD for each grid of China was obtained by the simple linear model. The total AHFD in a region was calculated as the total of the values at all grids within this region using Arc GIS. By using Eq. (1), the total anthropogenic heat emission of an area over one year was obtained. Then, the anthropogenic heat emission was converted into energy consumption unit of 10000 tons of coal equivalents (tce) to assess the model results (1 tce = 29.2 GJ) and compared with

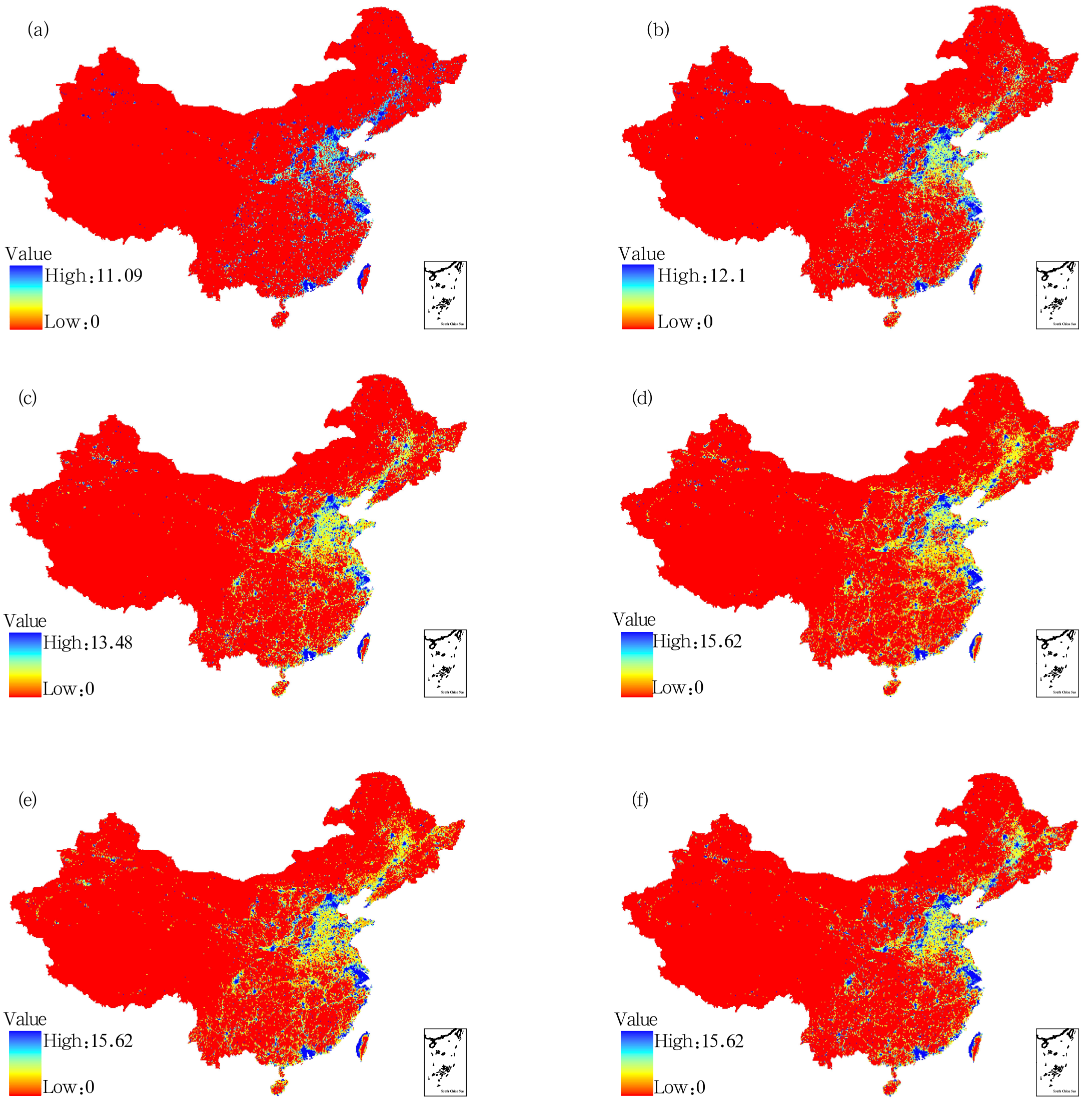

Fig. 4. Estimated AHFD (W m^{-2}) distribution in China from 1992 to 2009 by DMSP/OLS data. (a) F10 in 1992, (b) F12 in 1995, (c) F14 in 2000, (d) F16 in 2005, (e) F16 in 2008, and (f) F16 in 2009.

the official energy consumption statistics. The results are presented in Table 2.

As shown in Table 2, the model results seem generally reasonable in most regions, while significant errors occur in some regions. Errors of the model ranging from 0 to 30% occurred in 14 of the 32 areas, whereas the model showed significant errors for 7 areas of China. Possible explanations for these errors will be addressed in the discussion section. Despite the errors, the DMSP/OLS data still provide useful estimates of the AHFD distribution in China.

The mean AHFD estimated by DMSP/OLS data is shown in Fig. 2. The variation of AHFD is quite similar to the statistical results. An increasing trend AHFD from the DMSP/OLS satellite data is observed. The mean anthropogenic heat flux has increased sharply in the past 20 years. However, the chart shows a low oscillating trend from the late 1990s to the early 2000s. A much more rapid increase in AHFD is shown since the beginning of the 21st century, which is compatible with the data published by the National Bureau of Statistics of China. The possible reason for the oscillation at the end of the 20th century may be the Asian financial crisis, which broke

Table 2. Comparison between official energy consumption statistics and model results

Areas of China	Official energy consumption statistics in 2008 (10000 tce)	Model results (10000 tce)	Residual (percentage)
Beijing	6327.0	7791.2	23
Tianjin	5364.0	6619.7	23
Hebei	24322.0	29997.1	23
Shanxi	15675.0	18877.4	20
Inner Mongolia	14100.0	15381.8	9
Liaoning	17801.0	19218.8	8
Jilin	7221.0	11834.4	64
Heilongjiang	9979.0	23450.6	135
Shanghai	10207.0	8136.9	–20
Jiangsu	22232.0	37827.6	70
Zhejiang	15107.0	24590.2	63
Anhui	8325.0	16498.6	98
Fujian	8254.0	12839.6	56
Jiangxi	5383.0	8074.5	50
Shandong	30570.0	40206.2	32
Henan	18976.0	29819.4	57
Hubei	12845.0	13447.1	5
Hunan	12355.0	10753.4	–13
Guangdong	23476.0	39385.4	68
Guangxi	6497.0	11994.5	85
Hainan	1135.0	3624.7	219
Chongqing	6472.0	4876.2	–25
Sichuan	15145.0	13056.0	–14
Guizhou	7084.0	5360.9	–24
Yunnan	7511.0	13352.9	78
Shaanxi	7417.0	15508.3	109
Gansu	5346.0	7776.0	45
Qinghai	2279.0	2278.0	0
Ningxia	3229.0	4520.6	40
Xinjiang	7069.0	14138.0	100
Hong Kong	641.1	1391.6	117
Taiwan	503.1	509.1	1

in 1997. Obvious effects were imposed by the financial crisis on the global economy that were clearly observed from the satellite data. The satellite data are quite compatible with the statistics. At the beginning of the 1990s, the AHFD obtained by the statistics was very similar to that by the satellite data; however, after this period, the AHFD from the satellite data was generally higher than that from the statistics. The possible reason for this discrepancy could be due to innovations in energy technology in industrial production, which caused a continual decline in energy consumption per unit of GDP. The increase in energy consumption is not proportional to economic development, which results in significant model errors.

5. Conclusions and discussion

The DMSP/OLS stable light data from 1992 to 2009 and the authoritative energy consumption statistics were used to estimate the anthropogenic heat flux distribution in China. Linear regression models were established to obtain the AHFD from the satellite stable light data. Compared with the authoritative statistics, the model results of the anthropogenic heat distribution were generally reasonable. Different fitting models were applied to estimating the anthropogenic heat flux distribution in China. The linear model was adopted because the results of this model resulted in the minimal error. Generally speaking, the DMSP/OLS data are closely correlated with economic activities, such as the GDP and energy consumption, for a given area (Elvidge et al., 1997b). However, significant differences exist with regards to economic development in different areas. For the regions where economic development depends on energy consumption, the model results seem generally credible. Energy consumption increases as the economy grows. However, for the regions where economic development does not depend as much on energy consumption, significant errors occur in the model. For example, the areas for which the model results show an overestimate are usually the areas known for tourism, where fewer energy resources are consumed in the economic development process, such as Hong Kong, Hainan, and Shaanxi. The model underestimates the results for the developing areas where vast energy resources are needed, such as northwestern China. Furthermore, regional differences in energy efficiency for economic development may be a major reason for the model errors. For some regions, energy consumption growth has not been proportional to economic growth due to energy technology innovation. Generally, the anthropogenic heat flux is closely correlated with economic development and energy consumption, but the relationship between energy consumption and economic development is complex.

There are various explanations that may account for the errors produced in the linear model. The model assumes that the DN value is proportional to the radiance in each grid of DMSP/OLS data, but this only occurs when the DN is not very large. When the DN is close to the maximum value, the radiance is no longer proportional. As a result, the assumptions of the model are not correct when the DN is large. Additionally, many factors may contribute to errors in the satellite data, such as the sensor saturation effect and errors produced by the instruments and in the satellite data processing.

Different line functions were applied in the model by different satellites. Furthermore, different satellite data were applied in the estimation of the anthropogenic heat distribution. Slight differences exist among the data from the four satellites used in this paper. There are no significant differences between the model results using data from two different satellites for the same year. Analysis of the model results from the satellite data obtained by F10 and F12 in 1994 indicates that the correlation coefficient between them is more than 0.99, and the t-test result shows that there is no significant difference between them. The same results were obtained from the data for F12 and F14 from 1997 to 1999. The results show that the model results by different satellites in the same year are quite similar. The data differences will not influence the final estimation results on the whole. The data from the four DMSP/OLS satellites were applied separately in four different linear models. There is a slight difference between the data from various satellites, but with the data from one satellite the model results appear credible. Despite errors in the model results, there is an obvious advantage in estimating the anthropogenic heat flux distribution in China by satellite data. The anthropogenic heat release distribution map produced by the satellite data seems much more credible when compared to the statistical map. Moreover, the process of anthropogenic heat development can be clearly retrieved from the DMSP/OLS data.

The DMSP/OLS provides an effective way to estimate the anthropogenic heat flux distribution on a large scale. From the estimation results using DMSP/OLS data, the aggravating trend of AHFD was easily obtained. Additionally, a strong linear relationship was found between AHFD and the satellite data. The regional characteristics of the anthropogenic heat distribution could also be clearly seen, which is much better than the statistical results shown in Fig. 3. The modeling results indicate that the anthropogenic heat release in China was geographically concentrated and fundamentally correlated with economic activities. The heat release in economically developed areas in northern, eastern, and southern China was much larger than other regions, whereas the release in northwestern and southwestern China was very small. A vast area, including Beijing, the Yangtze River Delta, and the Pearl River Delta, in which anthropogenic heat is concentrated, has a AHFD larger than 10 W m^{-2}, which is high enough to affect the local climate. With economic development and sharp increases in the global population, anthropogenic heat pollution will become increasingly serious. With the boom in urban agglomerations on a global scale, large areas where anthropogenic heat flux is serious are bound to turn up in the near future. Anthropogenic heat release is an important aspect of human influence on climate change and should not be ignored in climate change research. Further studies should be focused on the climate effect of anthropogenic heat release in regional and global climate models.

The distribution of anthropogenic heat flux in China from 1992 to 2009 was estimated using DMSP/OLS satellite data in this paper, which provides useful parameterization for further research on climate models. The results indicate that the anthropogenic heat flux is very large in some regions, reaching a level that is high enough to influence the regional climate. This paper focuses on estimating the anthropogenic heat flux distribution in China from 1992 to 2009 using a linear model based on DMSP/OLS stable light data. However, this method is still in the exploratory stage. The initial results suggest that more accurate satellite data and more practical models should be applied in future research for better modeling results. The climate effect caused by anthropogenic heat should be considered in climate models in further research. The climate effect by anthropogenic heat is still considered at the regional scale, but it deserves further research at the global climate change scale.

Acknowledgment. Special thanks go to the Earth Observation Group, National Geophysical Data Center, and National Oceanic and Atmospheric Administration of the United States.

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