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Spatio-temporal simulation of energy consumption in China's provinces based on satellite night-time light data

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HIGHLIGHTS

- The satellite remote sensing data is used to estimate energy consumption in China.
- Spatial-temporal geographically-weighted regression models are developed.
- The models simulate accurately the energy consumption of provinces in China.

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ABSTRACT

Delay in publication of energy statistics prevents a timely assessment of progress towards meeting targets for energy saving and emission reduction in China. This makes it difficult to meet the requirements to rapidly monitor and evaluate energy consumption for each province. In this study, an alternative approach is provided to estimate the energy consumption by using satellite remote sensing data. We develop spatio-temporal geographically weighted regression models to simulate energy consumption of provinces in China based on the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) global stable night-time light data. The models simulate China's energy consumption accurately with the goodness of fit higher than 99%. Generally, the national average annual energy consumption is 2.8 billion tonnes of coal equivalent in China between 2000 and 2013, which is close to the actual value with errors smaller than 0.1%. From both temporal and spatial dimensions, the relative errors are smaller than 5.5% at the provincial level. Therefore, the use of satellite night-time light data provides a useful reference in monitoring and assessing provincial energy consumption in China.

1. Introduction

1.1. Context

The ability of China to control its energy consumption and carbon emissions is critical not only for China but indeed for the whole planet. The Chinese government attaches great importance to sustainable development, energy conservation, and emission reduction [1–3]. The "Revolution of Energy Production and Consumption (2016–2030)" issued by the National Development and Reform Commission and the National Energy Administration of the People's Republic of China sets a clear target for energy consumption. By 2020, the total energy consumption in China must be controlled within 5 billion tonnes of coal equivalent; CO_2 emissions intensity of GDP (the ratio of total CO_2 emissions to GDP) should be reduced by 18% compared to those in 2015; and the energy consumption intensity of GDP (the ratio of total energy consumption to GDP) should be reduced by 15% compared to that in 2015. By 2030, the total energy consumption in China must be

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controlled; China's total annual energy consumption should not exceed 6 billion tonnes of coal equivalent; CO_2 emissions intensity of GDP should fall by 60–65% compared with 2005; the peak of CO_2 emissions should be around 2030 and the targets should be achieved as soon as possible. Looking ahead to 2050, the Chinese economy should aim to produce less than half its energy requirements from fossil fuels. Simultaneously, all provinces have included the total energy consumption control target in the "13th Five-Year Plan" energy-development planning goals. Among these provinces Beijing, Inner Mongolia, Hunan and others regard total energy consumption limits as a binding target [4]. This shows that the Chinese government is fully committed to achieve a controlled reduction of its emissions through setting and maintaining achievable targets [5–7]. However, current delays in the production of China's energy statistics prevents a timely assessment of progress in meeting the targets for energy-saving and emission reduction for each province. Typically data used to update the China Energy Statistical Yearbook is one year out of date and that for the Local Statistical Yearbook around 9–10 months [8,9].

With the rapid development of satellite remote sensing technology in China, for example, the successful launch of China's first carbon satellite on December 22, 2016, satellite imagery data is continuing to be enriched. There is now a significant possibility for using satellite remote sensing data for reasonably accurate estimation of energy consumption in China's provinces on a sound scientific basis in response to which further targets for energy-saving and emission-reducing policies can be formulated according to the observed spatio-temporal changes in provincial energy consumption. This is now in need of urgent research given the rapid progress in satellite-based remote-sensing big data. Global night-time light data acquired by the OLS sensor on the US military meteorological satellite DMSP is an ideal data source for monitoring the intensity of human activities to which energy consumption is closely related. The Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) global night-time light data can be used to estimate energy consumption effectively. By considering regional spatial heterogeneity and comprehensively using global night-time light data together with energy consumption, population size, land area and other statistical data, this paper establishes a spatio-temporal geographically weighted regression model of energy consumption in China based on DMSP/OLS night-time light data which can be used to estimate provincial energy consumption and provide a supplementary reference for the use of satellite remote sensing image data for monitoring and assessment of provincial energy consumption.

1.2. Successful applications to date

Sensors to capture global satellite night-time light data are different from sensors by monitoring features of total solar radiation, scattered radiation, direct radiation and reflected radiation, which uses an optical multiplier tube at night with strong photoelectric amplification to effectively detect the low-intensity night-time lights produced by a city's night-time lights and even small-scale residential areas as well as traffic flows. Therefore, the DMSP/OLS night-time light image can be used as a representation of human energy activities and is an ideal data source for monitoring human production and everyday energy use. Since the 1980s, with the gradual improvement of DMSP/OLS global night-time light image data, an increasing number of scholars have applied night-time light data in urbanization monitoring, economic growth assessment, CO_2 emissions spatial distribution analysis and energy/electricity consumption estimation, more and more applied research appears, but there are relatively fewer applied studies on provincial energy consumption estimation in China.

In the field of urbanization monitoring, due to variations in atmospheric conditions and periodic changes in satellite sensors, DMSP/OLS night-time light data obtained in different years cannot be directly compared and this makes it difficult to use the time series DMSP/OLS night-time light data for urbanization monitoring. Some techniques such as normalizing time series DMSP/OLS night-time light data and deriving urban detection threshold using Pseudo Invariant Features [10] and systematically correcting multi-year multi-satellite night-time stable lights data [11] etc have been developed. These have been successfully applied to the following: urban growth analysis at Liaoning region in China [10], revealed urban expansion in China [11], estimation of urban indicators for individual Chinese cities [12], urbanization processes and rural transition synthetic analysis in China [13], mapping of urbanization dynamics at regional and global scales [14], monitoring of urbanization in India [15]. In these cases the techniques proved to be accurate and effective.

In the field of economic growth assessment, it is possible to consider night light as an indicator of personal consumption [16], and DMSP/OLS night-time light satellite imagery was applied to estimate the following: provincial economic development level of China [17], GDP estimation at different spatial scales and regional levels [18], and efficiency as an estimator of economic activity [19]. Results show that the DMSP/OLS night-time light data can well reveal economic development in different levels.

In the field of spatial distribution analysis of CO_2 emissions, integrating the DMSP/OLS night-time stable light (NSL) data with CO_2 emissions data [20], and DMSP/OLS night-time light satellite data was applied to the following: analysis of the spatiotemporal distribution of CO_2 emission in China [20], estimation of the carbon dioxide emissions in China [21], assessment of China's city-level CO_2 emissions arising from energy consumption [22], estimation of CO_2 emissions at urban scales of China [23], estimation of CO_2 emissions in East Asian Region [24], development of a global 1 km × 1 km annual fossil fuel CO_2 emission inventory [25], evaluation of the constraints on the spatial structure of CO_2 emissions from fossil fuels [26], use of imagery as a tool for global mapping of greenhouse gas emissions [27], creation of a global grid of distributed fossil fuel CO_2 emissions [28]. Results show that DMSP/OLS night-time light satellite data with CO_2 emissions data are good agreement, and can be extended to the future using updated data.

In the field of energy/electricity consumption estimation, research at the global and national levels first explored the correlation between night-time light intensity and energy consumption in the major global economies. Based on the determination of the correlation between the two above, regression analysis models were established to estimate the energy consumption. Shi et al. [29] used the calibrated DMSP/OLS Night-time Stabilized Light (NSL) data to characterize the spatio-temporal dynamics of global power consumption. The results indicated that it was relatively appropriate and accurate to estimate the global power consumption by calibrated NSL data. By using the US night-time light data to study 18 cities in the eastern United States, Welch [30] built a regression model of night-time light data together with population, urban area and power consumption variables, which showed that the estimation of electricity consumption performed well using night-time light data at both national and regional scales. Based on DMSP/OLS global night-time light image data, Elvidge et al. [31] conducted a preliminary regression analysis of the relationship between population, economic activity, power consumption and light intensity in 21 countries around the world and found a strong correlation between light intensity and power consumption, which proved that DMSP/OLS night-time light data could be used to estimate power consumption. Chand et al. [32] used DMSP/OLS night-time light data to study the spatio-temporal representation of India's power consumption patterns from 1993 to 2002 and found that night-time light intensity had a significant correlation with power consumption, in which the model's goodness of fit was 0.56. Amaral et al. [33] applied DMSP night-time satellite data to estimate energy consumption in Brazil's Amazon Basin and provided strong evidence for the use of DMSP/OLS night-time satellite sensor images to assess human activities in the Amazon region of Brazil. Letu et al. [34] studied the correlation between DMSP/OLS night-time light intensity and energy consumption in 12 Asian countries including