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Residential carbon dioxide emissions at the urban scale for county-level cities in China: A comparative study of nighttime light data

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ABSTRACT

Carbon emissions from residential energy consumption in urban areas play a pivotal role in meeting emission targets. It is more beneficial to decomposing the emission reduction target to subnational units. This study aims to map urban residential carbon emissions at a finer spatial resolution to offer reference to disaggregating the carbon-reduction targets down to each sub-unit. With the launch of Suomi National Polar-orbiting Partnership (NPP) satellite, the day-night band of Visible Infrared Imaging Radiometer Suite (VIIRS) onboard represents a major advancement compared with Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) in terms of radiometric accuracy, spatial resolution and geometric quality. Therefore, the useful proxy was utilized to model the spatial distribution of residential carbon emissions at the urban scale for county-level cities in China. Firstly, the dynamic optimal threshold method was used to extract urban built-up areas based on NPP-VIIRS data and the statistical data. Secondly, comparison was conducted between the NPP-VIIRS data and both original and saturation-corrected DMSP-OLS data to explore the performance of NPP-VIIRS data. Finally, the spatial characteristics were analyzed in detail at the regional, provincial and prefectural level, respectively. The results show that the NPP-VIIRS data performed better in both statistic regression and spatial comparison. The spatial patterns indicated that there was an obvious north-south differentiation, especially the carbon emission density (defined as carbon emissions per grid), which was significantly higher in Northeastern China than that of other regions. The climate elements positively contributed to the increase of carbon emissions in residential sector, especially stimulating emissions related to building heating.

1. Introduction

The enormous economic development has been accompanied with a dramatic growth in energy demand in the last two decades in China, which has caused China to surpass the U.S., with nearly one-fifth of total global energy consumption (Nejat et al., 2015). To mitigate the CO_2 emissions, the Chinese government promised to reach the peak of CO_2 emissions no later than 2030 and implement the carbon intensity reduction of 60–65% below 2005 levels by 2030 (CSC, 2015), which indicates that mitigating carbon emissions has become a strategic imperative of China (Zang et al., 2017). As one of the greatest contributors to national CO_2 emissions in China (Fan et al., 2015), residential sector is responsible for over 11% of the country's total energy consumption (Lu and Liu, 2014) and just behind the industrial sector (Zang et al., 2017), having an important effect on energy use and the related environmental problems (Liu et al., 2011). In particular, residential sector has been the fastest-growing sector over the 2001–2012 period in China (Nie et al., 2017), with an annual growth rate of around 8.7% (Fan et al., 2013). Even so, there is still a huge potential for future growth of Chinese residential energy consumption compared with other counties (Fan et al., 2017). Therefore, it is undoubtedly important to pay great attention to the residential sector's role in carbon emissions reduction. Especially, in spite of the fact that urban areas

Keywords abbrevations: DN, Digital number; EANTLI, EVI adjusted nighttime light index; EVI, Enhanced vegetation index; HD, Heating days, representing the number of days when daily temperature is below 18 °C; HDD, Heating degree days, meaning the sum of temperature below 18 °C; HIS, Human settlement index; NDVI, Normalized Difference Vegetation Index; RMSE, Root-mean-square error; VANUI, Vegetation adjusted nighttime light urban index.

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(including county-level cities) account for only 20% of mainland China area (NBSC, 2015), they are home to more than 50% (Zhang et al., 2014) of the total population and share the majority of energy consumption (Zhong et al., 2017). Therefore, energy consumption in urban areas is an important part of strategies on sustainable energy (Crompton and Wu, 2005). With the urban population expected to grow by 20 million per year, the development of urbanization will lead to more household carbon emissions (Li et al., 2015). As a consequence, strategies for carbon emissions reduction are urgently needed in urban areas to meet the national reduction target (Sun et al., 2014).

In the past, many researchers have calculated the residential energy consumption and carbon emissions at the national level, and thus explored their determinants. For example, Pachauri (2004) used survey data for 1993–1994 to analyze the impact of household energy consumption in India. In China, Zha et al. (2010) utilized the data from China's official statistical agencies to estimate the CO_2 emissions from residential carbon emissions divided by urban and rural. Liu et al. (2011) examined the impact of China's increased urban household consumption on carbon emissions. Conclusions were drawn that the use of coal decreased rapidly, while the demand for electricity grew increasingly. Besides, population increase and urbanization drove the change of carbon emissions. Zhao et al. (2012) demonstrated an extensive structure change towards a more energy-intensive household consumption structure as well as an intensive structure change towards high-quality and cleaner energy such as electricity, oil, and natural gas, which reflects a changing lifestyle and consumption mode in pursuit of a higher level of comfort, convenience and environmental protection. Zheng et al. (2014) developed a China Residential Energy Consumption Survey questionnaire and used it in 26 provinces for evaluating China's residential energy conservation policy. Chen et al. (2016) quantified the global energy consumption and pollutant emissions for the residential sector based on temperature-related variables and a series of socioeconomic parameters. Results showed that emissions depend strongly on both temperature and socioeconomic factors. Li et al. (2015) utilized statistical data to calculate the residential CO_2 emissions. They pointed that direct energy consumption was significantly promoted by urbanization. Nie et al. (2017) investigated the driving forces behind the changes in residential energy consumption in China over the 2001–2012 period. The influence of climate effect was confirmed and it works on space heating and cooling activities.

The previous researches had made great contribution to carbon emission reduction by proposing constructive suggestions at the national level. However, in the processes of combating climate change and conserving energy, it is more beneficial to decomposing the emission reduction target to subnational units (Zhou et al., 2018a). Therefore, as a primary task, estimating residential CO_2 emissions in a spatially explicit manner is a big challenge. Nevertheless, the majority of studies estimating emissions from residential energy consumption are usually dependent on statistical data (Yu et al., 2012) or questionnaire. For example, with the survey data and official statistics, Fan et al. (2013, 2015) investigated the carbon emission evolutions in residential sector and driving factors from an end-use perspective at the national level. By means of questionnaire survey, Gu et al. (2013) analyzed the energy consumption of urban households and the influencing factors in Nanjing, China. However, some defects still exist. For example, in terms of macro statistics data, inconsistencies may exist seriously between China's national and provincial data sources (Guan et al., 2012). Moreover, energy consumption at the township level is almost unavailable, and zonal statistics are heavily limited by administrative boundaries (Xie and Weng, 2016). In the aspect of the micro survey, the results are broadly influenced by the respondent samples, and questionnaire survey also costs considerable time and labor (Li et al., 2013b). Therefore, it is difficult to produce a spatially realistic representation of emissions nationwide (Lu and Liu, 2014). To avoid these problems, some scholars try to find a different path to model energy consumption and carbon emissions. Zhu et al. (2013) estimated residential energy consumption using spatial attribute data from meteorological stations, and mapped the spatial distribution at $1^{\circ} \times 1^{\circ}$ resolution. Gridding is a more realistic approach than statistics data acquisition at the level of individual administrative units, and furthermore the results are also easier to integrate with other spatial data in order to carry out interdisciplinary research (Cao et al., 2014). However, although this study provided a significant reference to clarify residential energy consumption pattern, the resolution of $1^{\circ} \times 1^{\circ}$ was too coarse to present more intricate urban inner pattern in mapping carbon emissions. Consequently, it is all the more necessary to introduce high-precision space data sets as a proxy to estimate and analyze urban energy consumption and carbon emissions.

Actually, nighttime light functions as a good proxy for economic activities (Mellander et al., 2015). Due to its capability to remedy the defect of lacking of statistical data at the finer spatial scale, the nighttime light data acquired by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) have been applied to many fields, especially mapping energy consumption and carbon emissions. For instance, Su et al. (2014) assessed China's city-level CO_2 emissions of energy consumptions using DMSP-OLS data and explored major driving forces for proposing feasible mitigation policies. The performance of nighttime light on the estimation of residential carbon emissions also attracts the attention of many scholars. For example, Meng et al. (2014) utilized the DMSP-OLS stable nighttime light and established the relationships between DN (digital number) and carbon emissions from the industrial sector, the transport sector and the residential sector, respectively, and thus found that residential carbon emissions had a satisfactory linear model with lights at the provincial level. However, due to the relatively strong variability of geographical space scale, the relationship at the provincial level may not indicate the same linear correlation at the prefecture level, or at the county level. To further explore the performance of nighttime light at a finer level, Lu and Liu (2014) corrected the DMSP-OLS data by kinds of factors to model residential carbon emissions and concluded that the corrected nighttime light data filled a gap of statistical data to a certain extent. Particularly, with the release of first global Suomi National Polar-orbiting Partnership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) nighttime light composite data, it has been proved that the NPP-VIIRS data have a stronger capacity than the original DMSP-OLS data in simulating the distribution of socioeconomic data (Shi et al., 2014b). However, few research was carried out on modelling residential carbon emissions by utilizing NPP-VIIRS data for China.

Limited by data availability, most studies are conducted at the national or provincial level based on macro-statistics. In order to provide references for the related stakeholders to decompose the targets of emissions reduction, it is crucial to estimate the urban residential carbon emissions at a higher spatial resolution and explore the spatial variations. Given the finer spatial resolution (0.5 km) and wider radiometric detection range than the DMSP-OLS data, there is a need to examine the applicability of NPP-VIIRS data on evaluating urban residential carbon emissions. On top of that, since the ‘cities’ are politico-administrative units that include both urban and rural areas (Miao, 2017), urban areas are not equivalent to cities in China and the scope of urban area is hard to obtain. Hence, few studies focused on the residential carbon emissions at the urban scale for county-level cities. Given that, the NPP-VIIRS data were also used to extract the urban built-up area