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An improved nightlight-based method for modeling urban CO_2 emissions

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ABSTRACT

An accurate modeling of urban CO_2 emissions is important for understanding the dynamics of carbon cycle and for designing low-carbon policies. We develop an improved nightlight-based method to model urban CO_2 emissions and investigate their spatiotemporal patterns. Differing from the previous methods, in processing the pre-modeling data, we bring forward the existing CO_2 inventories from national and provincial levels to city level, and correct the saturation and blooming problems of nightlight. In modeling the correlation between nightlight and statistically accounted CO_2 emissions, we highlight a panel-data regression analysis that considers the spatiotemporal heterogeneity across cities and over time simultaneously. Eleven cities in Yangtze River Delta of China were selected for a case study testing our method. The internal and external validations have proven the predominance of our proposed method for capturing the nightlight-CO_2 correlation, and for describing the spatial distribution and heterogeneity of urban CO_2 emissions.

1. Introduction

Cities are the main contributor to climate change, since they are responsible for more than 70% of the global fossil-fuel-induced carbon emissions, while occupying less than 2% of the earth's land area (Gurney et al., 2015). Their impacts are expected to grow due to continuous urbanization. China has been urbanizing at an unprecedented speed and has become the largest carbon emitter in the world. The proportion of residences qualifying as urban increased from 18% in 1978 to 55% in 2013. The number of prefecture-level cities with population sizes over one million also expanded to 133 (NBS, 2015). Consequently, some Chinese mega cities, such as Shanghai, emitted more greenhouse gases than several countries did, such as Thailand and the Netherlands (World Bank, 2010). Therefore, the reduction in carbon emissions at a city scale becomes increasingly important and urgent.

A long-term monitoring of urban CO_2 emissions is critical for understanding the dynamic patterns and drivers of the carbon cycle and for helping policymakers to design effective policies to mitigate climate change. Based on Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas accounting, a growing number of scholars and research institutes have developed methodologies and tools for quantifying carbon emissions at a city scale, including the International Local Government Greenhouse Gas Emission Analysis Protocol (ICLEI, 2009), the GHG Protocol (WBCSD and WRI, 2004), the Greenhouse Gas Regional Inventory Protocol (Carney et al., 2009), and the Sustainable Energy Action Plan (SEAP) (CoM, 2010). However, despite recent advancements in research aimed at estimating the dynamics of urban carbon emissions, great challenges remain that are largely due to the lack of comprehensive, consistent and comparable statistical data on energy consumption and human activities on a city scale. Furthermore, all of the accounting methods based on energy statistics all treat the city as a homogenous unit but represent the dynamics of the urbanization processes, such as the rapid sprawl of urban built-up areas, poorly (Albert et al., 2015; Edward and Matthew, 2010).

As means of addressing the abovementioned challenges, nighttime light (NTL) has been widely used as a useful proxy for economic output

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(Chen and Nordhaus, 2011), urban extent extraction (Xie and Weng, 2017), population estimation (Sutton et al., 2001), electricity consumption (Cao et al., 2014), and in-use metal stocks (Liang et al., 2014) due to its strong correlation with human activities and its availability at a high spatial resolution for most of the world, beginning in 1992. Recently, this proxy has also been applied to estimate urban CO_2 emissions at different time and space scales. For example, Oda and Maksyutov (2011) downscaled national CO_2 emissions to global 1 km × 1 km grids using nightlight as a proxy and separately allocated the point source emissions based on the global power plant database. Asefi-Najafabady et al. (2014) built upon a previously developed fossil fuel data assimilation system (FFDAS) and expanded the estimated 1 km gridded CO_2 emissions from a single year to multi-years from 1997 to 2010 by combining with nightlight data, gridded population, and global power plant database. Su et al. (2014) analyzed the linear correlation between CO_2 emissions and NTL in provinces and a limited number of cities of China based on a pool-data regression analysis without considering the differences across regions and over time, and predicted the carbon emissions in cities without direct energy data. Meng et al. (2014) and Shi et al. (2016) developed a panel-data regression model that took into account the city-specific coefficient in capturing the relationships between province-level energy-related CO_2 emissions in China with NTL and downscaled the emissions to an urban or 1 km scale. These studies have reached a consensus that the NTL can be used as a valid and useful proxy for downscaling statistically accounted CO_2 emissions to scale of interest (for example, pixel, urban, city, and urban agglomeration). And one can obtain estimates that are much more geographically consistent than energy consumption statistics through bypassing the reliance on statistical energy consumption data.

However, at least three aspects can be substantially improved. First, a suitable carbon accounting method needs to be selected that is compatible with the available energy statistics. The IPCC guidelines are based on detailed energy consumption data by sector and fuel type and are the most preferred and commonly used approach in the existing literature (Oda and Maksyutov, 2011; Meng et al., 2014; Su et al., 2014; Shi et al., 2016). However, detailed energy data are not always available for cities. Taking China as an example, the energy balance table is only available for the whole country, provinces and a limited number of cities, such as Shanghai, Guangzhou, and Shenzhen. In most cities, only certain fragmented information about energy consumption in certain specific sectors (e.g., industrial enterprises and households) can be accessed through the city's statistical yearbook. Thus, the scope and methodological complexity should be taken into account in choosing an appropriate accounting method so a more exact correlation between carbon emissions and NTL can be derived. Second, the intrinsic saturation problem of NTL especially in the city centers needs to be addressed; otherwise it may constrain NTL's further application and estimation accuracy. Internationally, there are a great number of studies focusing on saturation correction. Various methods and indices have been developed generally by combining original NTL with other data sources (such as Normalized Difference Vegetation Index (NDVI), and population density) to increase the variation of NTL in urban cores (Meng et al., 2014; Ma et al., 2017). However, potential improvements still exist in relieving the saturation issue (Bennett and Smith, 2017). Third, the spatiotemporal heterogeneity across cities and over time must be considered. The socioeconomic and geographical conditions usually vary in different cities and at different development stages, even for the same city. These differences may result in significant disparities in both the quantity and change patterns of carbon emissions.

This study aims to address the abovementioned deficiencies so as to better estimate urban CO_2 emissions. In processing the pre-modeling data, we bring forward the existing CO_2 inventories from national and provincial levels to city level, which to some extent breaks through the strong requirement on detailed statistical energy data, and raise the accuracy of pixel-level CO_2 estimation as it is downscaled from city level rather than from country and province. Moreover, we correct the saturation and blooming problems of NTL by integrating time-series NDVI and population density data, which reduces the estimation error in the urban core and rural areas. In modeling the correlation between NTL and statistically accounted CO_2 emissions, we propose a panel-data regression model, which considers the spatiotemporal heterogeneities across cities and over time simultaneously. Eleven cities in the Yangtze River Delta (YRD) of China were selected as a case to test the method. Based on the same dataset, our model was internally validated through a 2-fold cross-validation process and compared with a pool-data regression model and a panel-data regression model that only considers city-specific coefficient. In addition, our model was also externally validated with other studies both at city and pixel level. By doing so, the predominance of our improved method could be seen clearly. Finally, the uncertainties, limitations and potential improvements have also been discussed.

2. Study area and data

2.1. Study area

YRD is China's largest urban cluster, wherein 11 cities were selected for case studies (Fig. 1). There are three reasons for their selection. The first is the important role that the YRD plays in socioeconomic development and carbon emissions. It is one of the most rapidly urbanizing and wealthiest regions in China, with the country's largest urban cluster, covering 2% of the country's territory but contributing 20% and 12% to the total GDP and CO_2 emissions, respectively, in 2005 (Cai and Xie, 2007). The second reason is the relatively lower disparity in societal and natural conditions (e.g., culture, lifestyle, income level and climate) among the cities in the YRD compared to broader areas across China. Choosing a study area with less regional disparity may reduce the disturbance from spatial heterogeneity in correlation analyses between carbon and NTL. The third reason was that the 11 case study cities reflect some generalities of economic structure and transport development of Chinese cities. As shown in Table S1 in the Supplementary Material, some cities in the YRD (for example, Huzhou and Suzhou) have developed the secondary industry as their leading industry, which is consistent with most cities in middle reaches of the Yellow River, the middle reaches of the Yangtze River, and in the northeastern regions. However, there are also cities in the YRD (for example, Shanghai and Hangzhou) whose tertiary industry is the pillar industry. It represents a widely existing situation in the eastern coastal and northern coastal cities in China. For the transport sector, there is a common phenomenon not only in the YRD cities but also across China that the number of civil automobiles has been increasing sharply at a mean annual rate of more than 13% between 2003 and 2013 (NBS, 2015). In summary, owing to the important role, lower disparity and representative generality, we believe that the YRD is a good case study area for both testing our proposed method and increasing our understanding of urban CO_2 emissions in China.

2.2. Description of the data

Table 1 outlines the data used for the analysis, which generally includes two kinds, with a time range from 2003 to 2013. One is the spatial data including NTL produced by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS), land use and land cover data classified based on Landsat Enhanced Thematic Mapper Plus (Landsat ETM+) images, NDVI data based on Moderate-resolution Imaging Spectroradiomet (MODIS) from United State Geographic Survey (http://www.usgs.gov), and population density data. The nighttime light data (version 4) have a spatial resolution of 1 km × 1 km, and its digital number (DN) values of the artificial nighttime light brightness from cities, towns, and other sites ranged from 0 to 63. These data can be accessed online from the National