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China's city-level energy-related CO_2 emissions: Spatiotemporal patterns and driving forces

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HIGHLIGHTS

- We mapped urban CO_2 emissions using DMSP/OLS 'city lights' satellite data in China.
- CO_2 emissions were featured with regional inequalities and spatial agglomeration.
- PCGDP, population, industrial structure, and FDI positively affected CO_2 emissions.
- FDI was found to exert a negative impact on China's city-level CO_2 emissions.
- EKC hypothesis between economic development and CO_2 emissions was confirmed.

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ABSTRACT

Global cities produce more than 70% of the world's CO_2 emissions and thus play an important role in addressing climate change. Few statistics are available with respect to national city-level energy consumption in China—as such, in this study we apply spatiotemporal modeling in order to assess China's city-level CO_2 emission levels using DMSP/OLS nighttime light imagery. We examine the spatiotemporal variations and determinants of CO_2 emissions using a series of distribution dynamic approaches and panel data models for proposing feasible mitigation policies, the results of which show that while per capital CO_2 emissions were characterized by significant regional inequalities and self-reinforcing agglomeration during the study period, regional disparities decreased and spatial agglomeration gradually increased between 1992 and 2013. The results of our estimation further reveal the importance of economic development, population growth, industrial structure, and capital investment as the factors positively affecting China's city-level per capita CO_2 emissions. Conversely, FDI is found to exert a negative impact. Our results also strongly support the existence of an inverted U-shaped relationship between per capita CO_2 emissions and economic development, thereby confirming the EKC hypothesis. The findings obtained in this study could provide important decision-making support in the task of building China's low-carbon cities of the future.

1. Introduction

Climate change is a global issue that is affecting ecosystems across the planet [1–4]. Glaciers are receding and sea levels rise daily as the result of global warming [5]. To many scientists and researchers, it is becoming clear that greenhouse gases (GHGs), especially the carbon dioxide (CO_2) emissions generated as a result of human activities, are the principal cause of global warming [6]. Since the radical development witnessed during Industrial Revolution, human activity has increased the volume of GHGs in the Earth's atmosphere; today, human CO_2 emissions continue to increase, reaching (dangerously high) levels not seen in the last 20 million years [7]. The burning of fossil fuels has been identified as the primary contributor with respect to these emission levels [8]. Facing rising temperatures within the Earth's atmosphere and an increasingly erratic climate, various efforts are now being made by the international community with the aim of lessening the impact of global warming, not least by developing countries. By virtue of the dramatic economic development that followed the "Reform and Opening Up" policy in the late 1970s, China has become the largest developing county in the world [9], however the rapid growth of the Chinese economy has occurred at the cost of a huge consumption of energy resources and the intensive production of CO_2 emissions. The low energy efficiency of China's industrial structure, which is dominated by the country's manufac-

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turing sector, has further contributed to increases in CO_2 emission levels [10]. In 2007, China became the world's largest CO_2 emitter, a status it maintains today. In fact, up to 80% of the increase in CO_2 emissions witnessed since 2008 can be attributed to China [11]. Facing international pressure to curb its CO_2 releases, the Chinese government implemented a bold national strategy to reduce emissions, committing to reduce the country's CO_2 emission intensity (measured as CO_2 per unit of gross domestic product, or GDP) by 17% during its 12th five-year plan (2011–15). In a joint announcement with the United States in 2014, the Chinese government pledged that national CO_2 emissions would peak by 2030, after which reductions would occur [12].

To meet the abovementioned targets, it is important that the spatiotemporal distributions and determinants of CO_2 emissions in China are better understood. Information about the distribution of, and factors behind, historical CO_2 emission levels is critical for predicting future CO_2 emissions and for designing energy-saving and emission reduction policies. In line with such efforts, Wang et al. [13] estimated China's CO_2 emission levels and their spatiotemporal pattern with respect to China's 30 provinces, finding both per capita and total emission levels in provinces in China's eastern region to be significantly higher than those of their counterparts in central and western regions. Similar results were also arrived at by Du et al. [14] and Wang et al. [15]. To estimate the impact of China's CO_2 emissions on climate change, Hao et al. [16] (2016) calculated the number of heating degree days and cooling degree days, as well as the volume of CO_2 emissions, for 29 of China's provinces. Their findings confirmed that the impacts of CO_2 emissions vary across regions. In a recent study, Kang et al. [17] examined the CO_2 environmental Kuznets curve (EKC) hypothesis in relation to China's provinces, finding that economic growth and CO_2 emissions perform an inverted-N curve. The same results were also arrived at by Wang et al. [2]. Using China's 30 provinces as a sample, Liu et al. [12] proposed four different system boundaries for regional carbon accounts, finding that richer areas outsource emissions to other areas and that the reverse is evident in relation to poor areas. In addition, using Guangdong province as an example, Wang et al. [18] examined the impact factors of energy-related CO_2 emissions using the extended STIRPAT model. They found population, economic growth, and the industrial structure to all positively influence CO_2 emissions. Conversely, energy intensity and the energy consumption structure were identified as both negatively influencing CO_2 emission levels. Using Beijing as an example, Wang et al. [19] conducted an empirical study of the influencing factors of CO_2 emissions, finding that urbanization, economic growth, and the industrial structure can cause increases in CO_2 emissions, while energy intensity and R&D output can lead to a decrease in CO_2 emission levels. In addition, in a study of 30 provincial capital cities in China, Fang et al. [20] quantified the impacts of urban form on CO_2 emissions. These scholars found that a compact urban development pattern helps to reduce CO_2 emissions, a conclusion that was also reached by Ou et al. [21]. In a study of the five fastest-growing cities in China (i.e., Beijing, Shanghai, Tianjin, Chongqing and Guangzhou), Wang et al. [22] found that while land-use intensity exerted a positive influence on CO_2 emissions (leading to increases in emission levels), eco-environmental intensity led to reductions in CO_2. Whilst this existing literature has enriched our understanding of the distributions and drivers of CO_2 emissions, it has predominantly focused on the national level, regional level (provincial level) or the level of a few cities, to the exclusion of the national city-level. This is due to the fact that city-level statistics for energy consumptions were simply not available for some decades, especially in underdeveloped regions. As the city constitutes the basic administrative unit for the implementation of CO_2 emissions mitigation policy in China, CO_2 emissions accounting at the city level is crucial if aims to achieve low-carbon development in China are to be met.

Previous studies have demonstrated that satellite remote sensing imagery, especially nighttime light data (NTL) obtained by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS), holds great potential in estimating the value of socioeconomic indicators such as population density [23], GDP [24,25], urban landscape patterns [26], freight traffic [27], and electrical power consumption [28,29]. Because human CO_2 emissions are directly correlated with human activities, it is theoretically feasible to estimate CO_2 emissions using DMSP/OLS nighttime imagery when it is integrated with statistical data on energy consumption. This method for modeling of CO_2 emissions has been demonstrated in a number of existing studies, which have successfully estimated total CO_2 emissions using DMSP-OLS data [30,31]. Like the impact factor studies discussed above, the modeled CO_2 emission levels reported in the DMSP/OLS-based studies also predominantly focused on global, regional, and national levels, excluding the national city level. In addition, we note that most of these studies aimed only to improve the methods used for estimation, thereby failing to further explore the spatiotemporal patterns, driving forces, or potential reduction policies relating to CO_2 emissions.

China implemented a top-down energy statistical system. The government only publishes annually both national and provincial energy statistics. Only part of cities released their statistics, which results in missing data in city-level energy statistics. Responding to the above deficiency and with the aim of furthering contemporary understanding of the spatiotemporal variation of CO_2 emissions, this study first assessed China's national city-level CO_2 emissions from energy consumption between 1992 and 2013, using DMSP/OLS nighttime light imageries and employing conventional inequality indexes and spatial analysis techniques. Using the panel data models, we then quantified the impacts of available socioeconomic factors on CO_2 emissions at the city level. Importantly, we also tested the Environmental Kuznets curve (EKC) hypothesis, which describes the relationship between economic growth and CO_2 emissions, using city-level panel data. This is the first study on analyzing the city-level energy related CO_2 emissions with a coverage of the whole China.

The remainder of this paper is organized as follows. Section 2 focuses on material and methods, presenting a normalized approach for estimating China's national city-level CO_2 emissions, the conventional and spatial analysis methods, and the data used within the study. Section 3 analyzes the spatiotemporal variation and socioeconomic drivers of CO_2 emission dynamics in China's cities. Section 4 sets out our main conclusions and details a series of policy implications that can be drawn from the results of the study.

2. Material and methods

2.1. Estimating China's national city-level CO_2 emissions

Data availability and method reliability constitute two major issues in CO_2 emissions accounting. Due to the lack of city-level energy consumption statistics, the analysis of China's national city-level CO_2 emissions issues is limited. Therefore, the present study aims to employ a normalized approach for assessing China's city-level CO_2 emissions from energy consumption, using DMSP/OLS nighttime light imagery. The steps for CO_2 emissions accounting using city-level data are as follows (see Fig. 1).

First, we calculated the CO_2 emissions of cities with available energy consumption inventories using the unified standard method recommended by the IPCC Guidelines [32]. The energy