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Bofeng Cai and Xiuquan Wang contributed equally to this work.

Key Points:

- Spatiotemporal changes of China's carbon emissions are quantified for the first time through reconstruction of a nationwide high-resolution gridded data set
- Hot spots of carbon emissions in China have expanded by 28.5% in the north and shrunk by 18.7% in the south
- China's carbon emissions exhibit a typical spatially intensive high-emission pattern which has undergone a slight relaxation from 2007 to 2012 due to a typical urbanization process

Supporting Information:

- Supporting Information S1

Correspondence to:
X. Wang, G. Huang and J. Wang,
xiuquan.wang@gmail.com;
huang@iseis.org;
wangjn@caep.org.cn

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Spatiotemporal Changes of China's Carbon Emissions

Bofeng Cai[1], Xiuquan Wang[2], Guohe Huang[3,4], Jinnan Wang[1], Dong Cao[5], Brian W. Baetz[6], Lei Liu[7], Hua Zhang[8], Adam Fenech[2], and Zhu Liu[9,10,11]

[1]Center for Climate Change and Environmental Policy, Chinese Academy for Environmental Planning, Beijing, China, [2]School of Climate Change and Adaptation, University of Prince Edward Island, Charlottetown, Prince Edward Island, Canada, [3]Institute for Energy, Environment and Sustainable Communities, University of Regina, Regina, Saskatchewan, Canada, [4]School of Environment, Beijing Normal University, Beijing, China, [5]Center for Environmental Data Analysis and Application, Chinese Academy for Environmental Planning, Beijing, China, [6]Department of Civil Engineering, McMaster University, Hamilton, Ontario, Canada, [7]Department of Civil and Resource Engineering, Dalhousie University, Halifax, Nova Scotia, Canada, [8]School of Engineering and Computing Sciences, Texas A&M University-Corpus Christi, Corpus Christi, TX, USA, [9]Department of Earth System Science, Tsinghua University, Beijing, China, [10]Shanghai Carbon Data Research Center, Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai, China, [11]Tyndall Centre for Climate Change Research and School of International Development, University of East Anglia, Norwich, UK

Abstract Spatiotemporal changes in China's carbon emissions during the 11th and 12th Five-Year Plan periods are quantified for the first time through a reconstructed nationwide high-resolution gridded data set. The hot spots of carbon emissions in China have expanded by 28.5% (toward the west) in the north and shrunk by 18.7% in the south; meanwhile, the emission densities in North and South China have increased by 15.7% and 49.9%, respectively. This suggests a clear transition to a more intensive economic growth model in South China as a result of the energy conservation and emission reduction policies, while the expanded carbon hot spots in North China are mainly dominated by the Grand Western Development Program. The results also show that China's carbon emissions exhibit a typical spatially intensive, high-emission pattern, which has undergone a slight relaxation (up to 3%) from 2007 to 2012 due to a typical urbanization process.

Plain Language Summary Implementation of China's recent climate pledge to the Paris Agreement requires effective carbon reduction policies at various geographical and administrative levels, which will rely on not only accurate estimates of national total emissions but also on a comprehensive understanding of the spatiotemporal changes in carbon emission patterns. The latter is crucial for allocating carbon emission quotas and developing appropriate policies at regional and local scales, yet it remains poorly understood. To this end, we reconstruct the nationwide high-resolution gridded carbon emissions for the first time by compiling the CO_2 emissions from industrial, residential, transportation, and agricultural sectors. This allows us to investigate the spatiotemporal changes in China's carbon emission patterns during the 11th and 12th Five-Year Plan periods when unprecedentedly rapid economic growth, technological development, and environmental change have taken place. Moreover, this enables us to quantify the influences and effectiveness of previous carbon reduction policies (up to 3% relaxation to China's spatially intensive high-emission pattern and 16% reduction in emission intensity). Our findings are of great significance not only for developing evidence-informed climate policies in the current and forthcoming five-year planning periods in China but also for providing scientific references to other countries in support of developing effective climate policies.

1. Introduction

As the biggest emitter of greenhouse gases in the world, China has ratified the Paris Climate Change Agreement and committed to reduce its carbon intensity by 60 to 65% from the 2005 level by 2030 (Jacquet & Jamieson, 2016; Rogelj et al., 2016). Because natural resources and economic activities are unevenly distributed across the country (Luo & Wei, 2009; H. Wang et al., 2015; Yi & Liu, 2015), substantial reduction of carbon emissions in China will require effective and efficient climate mitigation policies at both national and provincial levels. Effective policy-making against climate change relies on not only the accuracy of national total emission estimates (Feng et al., 2013; Guan et al., 2012; Z. Liu et al., 2015; Yu et al., 2014; D. Zhang et al., 2014) but more importantly, also a full and in-depth understanding of the spatiotemporal characteristics of carbon emissions in China (Guan et al., 2014; Gurney, 2015; A. Li & Lin, 2013; Lo, 2016; S. Wang et al., 2014; Y.-J. Zhang et al., 2014). The latter is essential for setting regional allocations of carbon emission quotas in China and developing appropriate policies at regional and local scales (Govindaraju & Tang, 2013; Yu et al., 2014), yet it remains poorly understood due to the insufficient coverage of spatiotemporal variations in CO_2 emissions in national carbon inventories (Hao et al., 2014; J. Wang et al., 2014).

China is now in its 13th Five-Year Plan period (2016–2020) and is undergoing a major structural transformation in its economy toward a new development model focused on better-quality growth (Green & Stern, 2017; J. Zhang & Cai, 2016). Developing evidence-informed climate policies based upon the experiences and lessons learned in previous 5-year planning periods will be of great importance to facilitate its transition to a low-carbon economy (Gu et al., 2016). Particularly, during the 11th and 12th Five-Year Plan periods (2006–2010 and 2011–2015), China has experienced unprecedented economic growth and became the second largest economy in the world; meanwhile, its CO_2 emissions have surpassed the United States and China has become the world's largest emitter. Investigating the spatiotemporal changes in China's carbon emission patterns during these periods can help evaluate the effects of previous carbon reduction policies and will thus provide a scientific basis for developing effective and efficient climate mitigation policies in the current and forthcoming five-year planning periods.

2. Methods

2.1. Reconstruction of China's Carbon Emissions

In order to reconstruct the high-resolution gridded carbon emissions in China, we first collected and surveyed CO_2 emissions in 2007 and 2012 from four major sectors, including industrial, urban residential, transportation, and agricultural sectors. For the industrial sector, we considered emissions from fossil fuel combustions (e.g., thermal power plants) and industrial processes (e.g., cement production, lime production, iron and steel production, glass production, and ammonia production). The emission data for the industrial sector were collected from the China High Resolution Emission Gridded Data, which is based on the First China Pollution Source Census (FCPSC) and subsequent data updates from the latest survey (J. Wang, Cai, et al., 2014; M. Wang & Cai, 2017). The FCPSC is the first nationwide survey of all types of energy consumption complied from the China Energy Statistical Yearbook. The FCPSC data set covers more than 1.58 million officially registered industrial enterprises in China and is more comprehensive than China's national official statistics (which exclude small enterprises with annual revenue less than 5 million CNY). Since the emissions from these industrial enterprises account for over 80% of total CO_2 emissions in China (W. Chen et al., 2017; J. Wang, Cai, et al., 2014; S. Zhou et al., 2013), small mistakes or errors in their geographical coordinates will substantially influence the accuracy of the resulting carbon emission patterns. In order to improve the accuracy, we surveyed the administrative properties (i.e., county or district locations) of all enterprises and verified their geographical coordinates to avoid conflicts. In cases where the recorded coordinate of an enterprise conflicts with its administrative property, its coordinate is replaced by the geometric center of its affiliated county or district. For the urban residential sector, we considered emissions caused by energy use for heating, cooling, and cooking from hotels, restaurants, hospitals, schools, and households at the county/district level. The emission data for the urban residential sector were also collected from the China High Resolution Emission Gridded Data. The emissions from the transportation sector were collected at the provincial level and covered various sources such as roads, railways, rivers, and aviation routes (Cai et al., 2012). For the agricultural sector, we collected the emission data for agricultural activities and rural households from the China Energy Statistical Yearbook published by the National Bureau of Statistics (NBS, 2008, 2013).

We applied a bottom-up aggregation approach (see Figure S1 in the supporting information) to reconstruct China's carbon emissions in 2007 and 2012 with a spatial resolution of 10 km based on the collected emission data from the four major sectors. We interpolated the CO_2 emissions from four sectors into a 10-km grid and generated four separate high-resolution gridded maps, which were then added up to represent the overall carbon emissions. For the point source emissions from the industrial sector, all point sources within the same grid cell were summed up to estimate the total industrial emissions of the grid cell. Assuming EI_i is the total CO_2 emissions from the industrial sector for grid cell i, EI_i can be calculated by

$$EI_i = \sum_{j=1}^{n} \left(\sum_{k=1}^{m} EF_{jk} \times C_k + EP_j \right) \tag{1}$$

where n indicates the total number of point sources within grid cell i, m denotes the total types of fuels combusted by point source j, EF_{jk} is the annual amount of fuel k burned in point source j, C_k is the CO_2 emission factor for fuel k, and EP_j represents emissions from industrial processes for point source j. In this study, we derived the emission factors for different industries from the greenhouse gases inventory of the National Communication on Climate Change of China (http://www.ccchina.gov.cn). The emissions from the urban residential sector were surveyed and collected at the county/district level. We then allocated the CO_2 emissions from the residential sector proportionally to all grid cells according to their population percentages to the affiliated county/district. Similarly, as transportation emissions of a region are closely related to its total population, we interpolated the provincial emissions from the transportation sector proportionally to the 10-km grid cells within each province in accordance with their population percentages. The agricultural emissions were collected at the provincial level and allocated evenly to all grid cells within the province.

The reason that we chose to reconstruct a new data set instead of using the existing data sets (Saikawa et al., 2017) is because that they are all based on a top-down disaggregating approach (as illustrated in Figure S1) to generate gridded carbon emissions. The key idea of this top-down approach is that total emissions at regional levels (e.g., county, city, or province) are proportionally disaggregated to the related grid cells according to the population, development level, etc. Since the emission data at regional levels are usually from government statistics which only provide total emissions without any spatial information (especially for industrial point sources), disaggregating the regional statistics into small grid cells will lead to overly smoothed results because partial emissions from industrial point sources are apportioned to neighboring cells. Apparently, this top-down disaggregation approach cannot reasonably reflect the spatial variations of carbon emissions at local scales. In contrast, we applied a bottom-up aggregation approach to construct the high-resolution gridded emissions data set for China (see Figure S1). In detail, we first collected and verified both the carbon emissions and the geographic locations of all industrial point sources in a region. For each output grid cell covering an industrial point source, the emissions from this industrial point source together with emissions from other sectors (e.g., residential, transport, and agriculture) are aggregated to represent the total carbon emissions from this grid cell; for other grid cells, only emissions from other sectors are aggregated. The advantage of this approach is that the spatial variations of carbon emissions at local scales can be appropriately reflected in the outputted gridded data set (M Wang & Cai, 2017). Here we should note that the focus of this research is not on how the totals of our bottom-up approach are different from the top-down method, as our purpose of introducing the bottom-up approach is to help derive the spatial pattern of China's carbon emissions at a finer resolution. However, we have performed detailed comparisons in both totals and spatial variations of carbon emissions between our method and other data sets (J. Wang, Cai, et al., 2014; M. Wang & Cai, 2017). In general, the totals from our bottom-up approach are slightly higher than other sources and our data set shows a better performance than other data sources in representing the spatial variations of carbon emissions.

2.2. Characterization of Carbon Emission Patterns

We employed a two-step approach to characterize the spatial patterns of China's carbon emissions in 2007 and 2012: (1) the hot spots of gridded carbon emissions in each year were first identified through a geostatistical analysis, and (2) the emission patterns of the identified hot spots were then quantified to represent the spatial characteristics of carbon emissions in each year (refer to the supporting information for more details about this two-step approach). Note that we used the Getis-Ord local statistic to help identify the hot spots of carbon emissions in China. The Getis-Ord statistic is based on the normal z-score and can be used to detect statistically significant spatial clusters of high values (i.e., hot spots) through measuring the z-scores and p-values at all grid cells. Here we used a significance level of 90% (i.e., p-value ≤ 0.10 and z-score ≥ 1.65) as a threshold to identify the hot spots of CO_2 emissions in China. The quantified spatial characteristics of carbon emissions in 2007 and 2012 were then compared with each other to help understand the spatiotemporal changes in China's carbon emission pattern from the 11th Five-Year Plan period (2006–2010) to the 12th Five-Year Plan period (2011–2015). This is to understand the influences and effectiveness of carbon-related policies introduced and implemented during these periods and will be of great importance for guiding the development of new climate mitigation policies toward a low-carbon economy in the Thirteenth Five-Year Plan period (2016–2020) and the forthcoming 5-year planning periods. Here we should note that our study highlights the transition from the 11th Five-Year period to the 12th Five-Year period. In other words, our

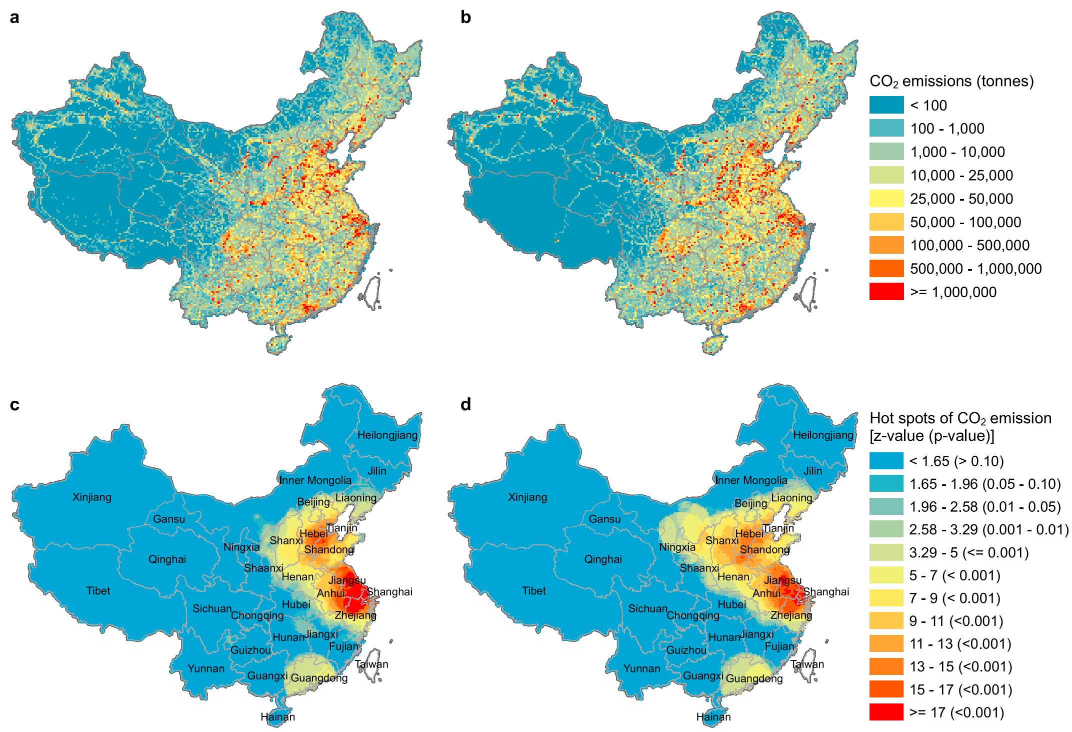

Figure 1. China's carbon emissions and hot spots in 2007 and 2012. (a and b) 10 km × 10 km gridded carbon emissions in 2007 and 2012, respectively; (c and d) hot spots of CO_2 emissions (z-value ≥ 1.65 and p-value ≤ 0.1) in 2007 and 2012, respectively.

analysis emphasizes the policy effects from the beginning of the 11th Five-Year period to its end. In detail, we may assume that there might be a 1-year delay to start seeing the effects of some policy changes, then we can use the carbon emissions data in 2007 to represent the policy effects at the beginning of the 11th Five-Year period (i.e., 2006); similarly, we can use the carbon emissions data in 2012 to represent the policy effects at the end of this period (i.e., 2011). In this sense, our study quantifies the outcomes of carbon mitigation policies from the beginning of the 11th Five-Year period to the beginning of the 12th Five-Year period. A more detailed discussion of the methodology can be found in the supporting information (Getis & Ord, 1992; Mitchel, 2005; Ord & Getis, 1995; Scott & Warmerdam, 2005).

Once the spatial characteristics (hot spots and their spatial patterns) of carbon emissions for 2007 and 2012 were quantified, we further analyzed the changes in geographical location, spatial coverage, and emission patterns of the identified hot spots from 2007 to 2012 to help understand the spatiotemporal changes of China's carbon emissions in recent years. In addition, the gridded carbon emissions were aggregated at the provincial level in association with total area, population, and gross regional product (GRP; Viet, 2010) to help understand the changes in CO_2 emission density and intensity at regional scales. The data for population and GRP at the provincial level were collected from the National Bureau of Statistics of China (http://data.stats.gov.cn). Note that the CO_2 emissions from Taiwan, Hong Kong, and Macao are not included in the gridded carbon emissions data sets and the related analyses.

3. Results

Here we apply a bottom-up aggregation approach to reconstruct China's carbon emissions in 2007 and 2012 with a spatial resolution of 10 km based on the CO_2 emissions from four major sectors, including industrial, urban residential, transportation, and agricultural sectors (see section 2). Hot spot analysis is then applied to the gridded carbon emissions to detect if the CO_2 emissions are significantly clustered. Not surprisingly, the high-emission regions are primarily located in East China where major economic activities are taking place (see Figure 1). Furthermore, these high-emission regions exhibit significant spatially clustered patterns in

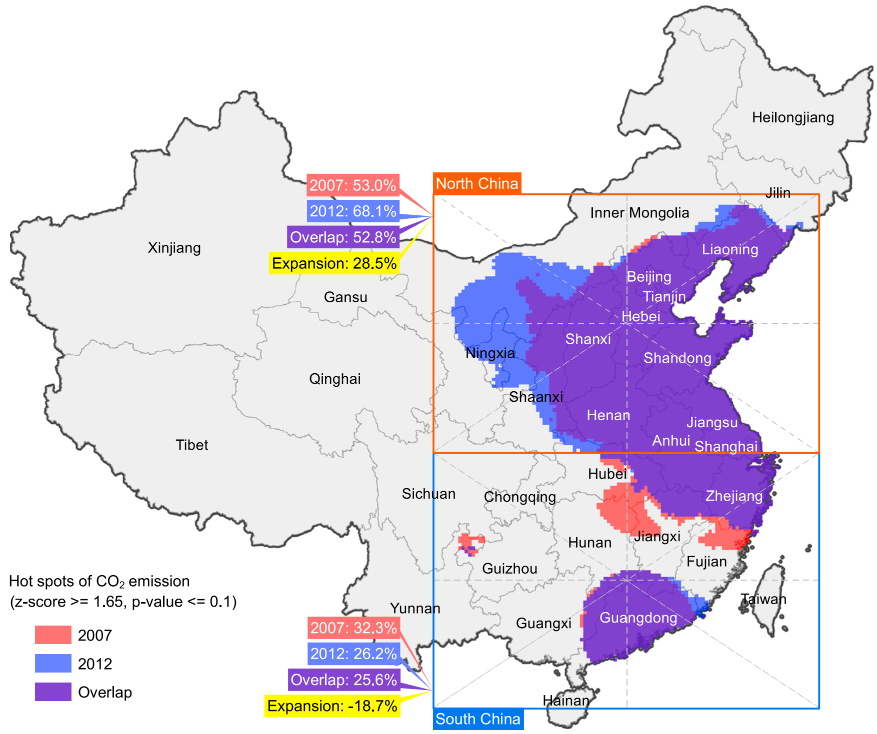

Figure 2. Expansion of hot spots of CO_2 emissions from 2007 to 2012. The two rectangular regions are introduced to help summarize the changes in the spatial coverage of carbon emission hot spots and are labeled as "North China" and "South China," respectively. Note that the boundary between these two rectangular regions is determined using the location of Yangtze River, since the northern part of Yangtze River is usually regarded as North China while the southern part is commonly known as South China. The expanded hot spots in 2012 are calculated as the difference between newly emerged hot spots and vanishing hot spots in 2012 relative to 2007.

the central east (including Beijing, Tianjin, Liaoning, Hebei, Shanxi, Shandong, Henan, Jiangsu, Anhui, Shanghai, and Zhejiang) and the south (mainly in Guangdong), as illustrated by the detected hot spots in Figure 1.

Through comparison of the gridded carbon emissions and their hot spots between 2012 and 2007, we investigate the spatiotemporal changes in China's carbon emission patterns during the two 5-year periods. Although our focus here is on the spatiotemporal changes of carbon emissions, we find the total carbon emissions in China have increased by 33.5% from 2007 to 2012. As the hot spots of carbon emissions account for more than 70% of the total emissions (70.6% in 2007 and 74.0% in 2012, respectively), here we focus on exploring the changes in the spatial coverage and emission patterns of hot spots (see Figure 2 and Table S1 in the supporting information). We find that the hot spots in North China have expanded by 28.5% from 2007 to 2012, while the hot spots in South China have shrunk by 18.7%, leading to an overall expansion of carbon hot spots in China by 12.2%. Such a spatial shift in the coverage of hot spots from south to north is likely to be associated with the Grand Western Development Program (e.g., massive investment to boost economic development in western regions; Lai, 2002; Shenglong et al., 2009) and the energy conservation and emission reduction policies (e.g., shutdown or phase-out of high-emission industries; L. Li et al., 2011; Yuan et al., 2011) implemented in the 11th Five-Year Plan period.

Owing to rapid economic growth, the total emissions in both regions have increased from 2007 to 2012. However, the increasing rate of total carbon emissions in North China (48.7%) is more than three times higher than South China (14.6%), driving the overall increase rate in China to be as high as 39.9%. The emission density of hot spots in North China is generally higher than South China from 2007 to 2012, yet the increasing rate of emission density in South China (40.9%) is approximately 2.5 times higher than North China (15.7%). The shrinkage of carbon hot spots and the increase of emission density in South China suggest a clear transition to a more intensive economic growth model, while the expansion of hot spots to the west

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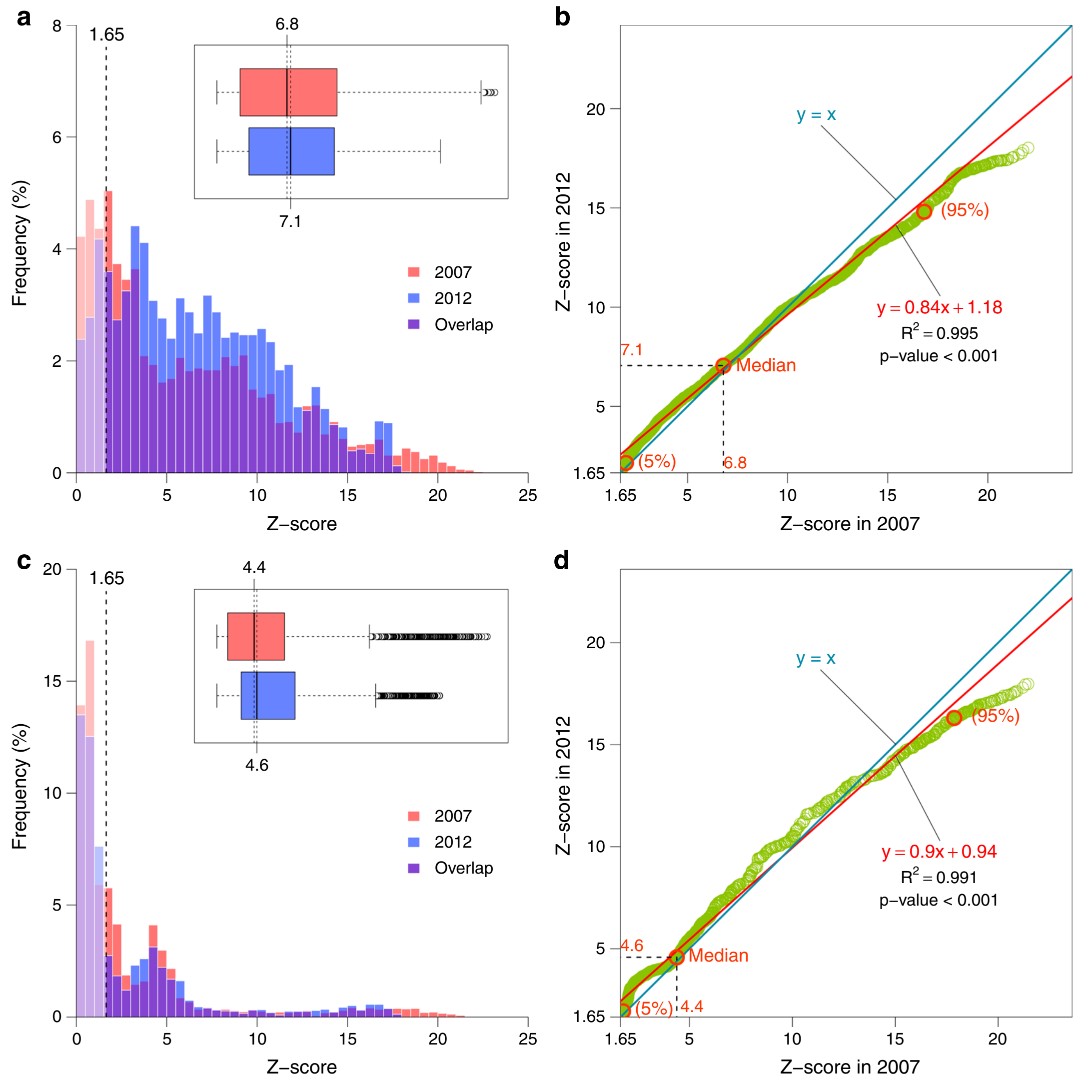

Figure 3. Distributions of the Getis-Ord statistic *z*-scores in North and South China. All grid cells within each region are used to compile the corresponding distributions and scatterplots. Only grid cells with a *z*-score ≥ 1.65 (*p*-value ≤ 0.1) are considered as carbon hot spots. (a) The *z*-score distributions (histogram and boxplot) in 2007 and 2012 and their comparisons in North China. (b) The scatterplot of *z*-scores between 2012 and 2007 and its fitted line for North China. (c and d) Similar to (a) and (b) but for South China.

and the increase of emission density in North China are likely to be dominated by the strategic plans of the Grand Western Development Program.

We further compare the distributions of *z*-scores and CO_2 emissions between 2012 and 2007 to test the statistical significance of changes in the intensiveness of carbon hot spots and the density of CO_2 emissions (shown in Figures 3, S3, and S4). It is noted that the number of grid cells with high *z*-score (≥17.5) has dropped down to zero from 2007 to 2012, while the number of grid cells with medium *z*-score (3 to 17) shows an apparent rise in 2012 (particularly in North China). This is also demonstrated by the fitted lines of *z*-scores between 2012 and 2007, which have coefficients less than 1 (0.84 for North China and 0.9 for South China). However, the medians of *z*-scores in 2012 (7.1 in North China and 4.6 in South China) are still slightly higher than in 2007 (6.8 in North China and 4.4 in South China), suggesting that the hot spots of CO_2 emissions in 2012 are generally more intensive than 2007. This implies there has been a statistically detectable decline (p-value < 0.001) in the intensiveness of carbon emission hot spots (i.e., a shift in *z*-scores from high to medium values) from 2007 to 2012, but such a shift has not substantially changed the intensiveness of hot spots in 2012. The changes in the *z*-scores of the high-emission hot spots (represented by those 95%–100%

percentile grid cells in Figure 3) from 2007 to 2012 are also analyzed (see Figure S3). In general, the *z*-scores for the high-emission hot spots have experienced an average decrease of 2.3 from 2007 to 2012 both in the North and the South, suggesting a relaxation in the intensiveness of those carbon hot spots; meanwhile, the spatial variations in this relaxation in both regions can also be reflected by some slight differences in the shape of the histogram and its maximum and minimum values. In detail, the relaxation in North China manifests higher spatial variability than in South China, implying that the economic development in the North is less homogeneous than in the South. Besides, we find that the emission densities in North and South China have significantly increased from 2007 to 2012 (see Figure S4), which further supports our previous findings about the increase in the emission density of hot spots.

To understand the emission pattern of China's carbon emissions, we break down CO_2 emissions into nine categories and compare the contribution of each category to the total emissions to its percentage of the total area (see Figure 4). The results show that high CO_2 emissions are usually concentrated in very small regions. For example, CO_2 emissions over 10 Mt which account for 29% of the total emissions in 2007 only come from 0.4% of the total area; while in 2012, the contribution of the same category of CO_2 emissions has increased to 37.2% of the total emissions, yet the spatial coverage is still less than 1% of the total area. We further fit the relationships between the contribution to total emissions and the percentage of total area in 2007 and 2012 using the emission data at grid cell scales. This is to quantify the carbon emission patterns and their temporal changes from 2007 to 2012. Although the CO_2 emissions in 2007 and 2012 are both characterized as spatially intensive high-emission patterns, we find a slight relaxation in the overall emission pattern. Particularly, the contributions of extremely intensive high-emission regions (accounting for 1% and 2% of the total area) to the total emissions have declined slightly in 2012 (by 3% and 1.1%, respectively), while the contributions of other high-emission regions have increased accordingly. Such a slight relaxation in the overall emission pattern is also confirmed by the difference maps of carbon emissions at grid scales and relative shares of national total emissions (see Figure S5).

We also compare the CO_2 emissions and the intensiveness (*z*-score) of the overlapped hot spots between 2012 and 2007 (see Figure S6). The emission density and the intensiveness of the overlapped hot spots have slightly decreased from 2007 to 2012, which further supports the slight relaxation in the overall emission pattern. In general, an urbanization process involves building new transportation systems (e.g., roads and highways), relocating heavy industries to suburbs or rural areas, deploying new electricity generation and supply networks, turning agricultural lands and forests into urban surfaces, and so on (Y. Liu et al., 2013). One of the outcomes of such an urbanization process is the increase in the total carbon emissions, while another outcome is apparently the expanding of the spatial coverage of high-emission areas. The latter is usually reflected by the change in the spatial pattern of carbon emissions. As our results show an apparent increase in the total emissions from 2007 to 2012, such a slight relaxation in China's spatially intensive high-emission pattern suggests that the spatial coverage of high-emission areas has slightly expanded from 2007 to 2012, implying a typical urbanization process during the same period. This is very likely associated with the fact that the rapid economic development in major cities has spread widely to other less developed cities and suburbs (Shen & Wu, 2013; Wei, 2015; Y.-J. Zhang et al., 2014). Furthermore, it is worthwhile to mention that some recent studies have presented novel analyses of China's carbon emissions at city levels (Shan et al., 2018; Tong et al., 2018; Zheng et al., 2018); however, these city-level analyses often use a point to represent the geographical location of a city and are incapable of reflecting the spatial variations of carbon emissions (e.g., emissions from transportation networks) within the city's boundary. Thus, they are unable to detect the abovementioned urbanization process.

We aggregate the gridded 10-km carbon emissions at the provincial level to investigate the changes in total CO_2 emissions, emission density (measured by CO_2 emissions per 100 km^2), and emission intensity (measured by CO_2 emissions per capita and CO_2 emissions per 100 million Yuan GRP) from 2007 to 2012 (see Figure S7 and Table S2). Statistically significant increases from 2007 to 2012 are detected in total CO_2 emissions (by 25%), emissions per 100 km^2 (by 11%), and emissions per capita (by 62%) at the provincial level. In the meantime, a significant decrease of 16% is observed in emissions per unit of GRP. Given the slight increase in population (3%) and the significant increase in GRP (98%) from 2007 to 2012 (see Table S2), our analysis suggests a clear transformation in China's economic structure toward a market-oriented and low-carbon economy during this period when its aggregate economy has been almost doubled (S Chen et al.,

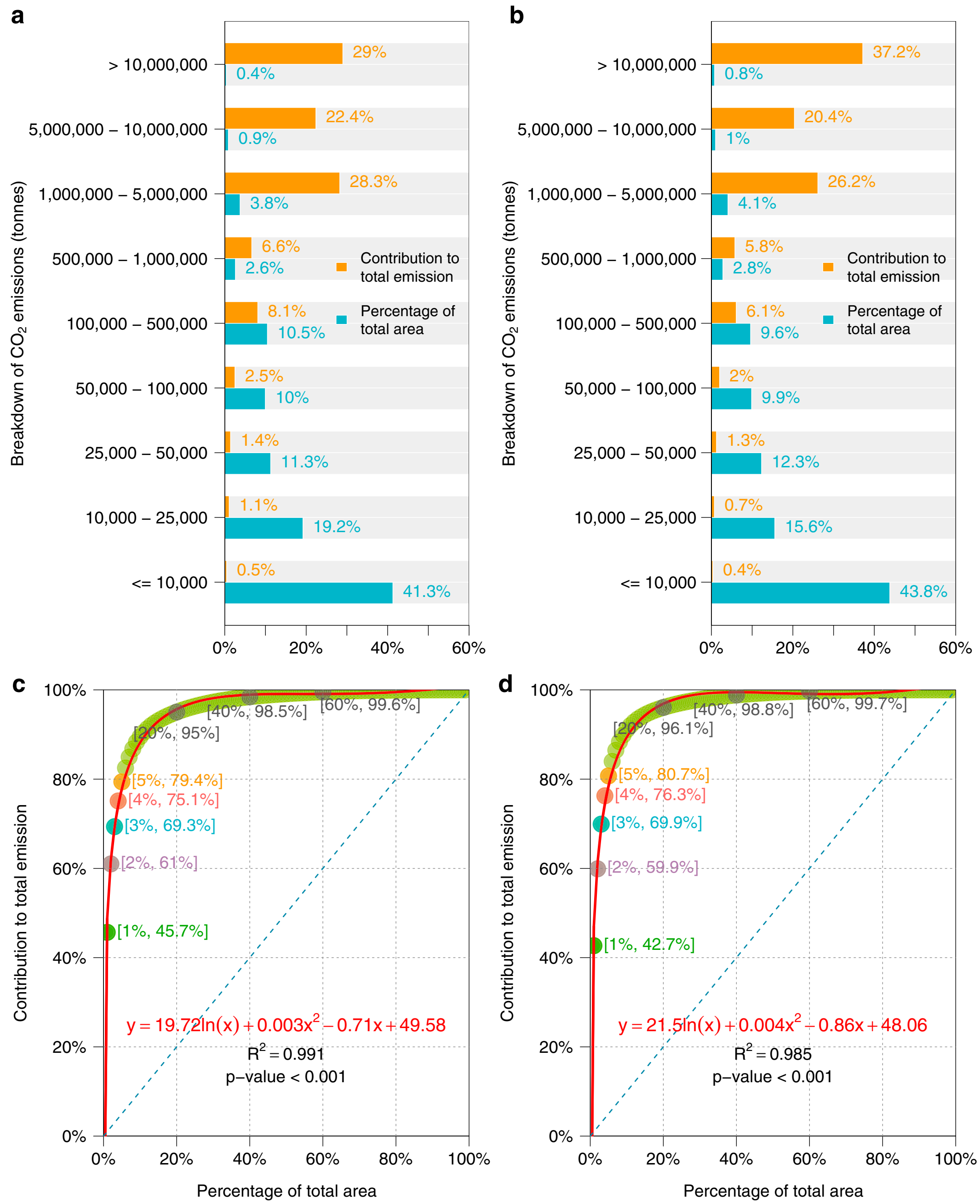

Figure 4. Spatially intensive high-emission patterns of China's carbon emissions. Only grid cells within the detected hot spots of CO_2 emission in Mainland China are considered in the calculation (see section 2). (a and b) The breakdowns of CO_2 emissions and the comparison between their contributions to the total emissions and percentages in the total area in 2007 and 2012. (c and d) The functional relationships between the contribution to total emissions and the percentage of total area in 2007 and 2012, respectively; the mixed logarithm and polynomial functions indicate a typical spatially intensive high-emission pattern of China's carbon emissions (refer to Figure S2).

2011; Dekle & Vandenbroucke, 2012; X. Zhou et al., 2013). Particularly, the population and GRP of Beijing have increased by 23.4% and 81.6% from 2007 to 2012, yet we find concurrent decreases in its total CO_2 emissions (30.4%), emissions per capita (43.6%), and emissions per unit of GRP (61.7%). This demonstrates a successful transition to a low-carbon economy in the City of Beijing as a result of the innovative green development plan (known as "Green Beijing"), which was introduced during the 11th Five-Year Plan period (Hu, 2016; Jiang et al., 2010; Lewis, 2013; Z. Zhang, 2010). Furthermore, we also see an obvious shift in the linear relationship between carbon emissions density and average income from 2007 to 2012 (see Figure S8). In other words, the carbon emissions required for each unit of income increase have decreased from 2007 to 2012. This further confirms the above-mentioned transformation in China's economic structure toward a low-carbon economy.

4. Conclusions

In summary, here we reconstruct the high-resolution gridded carbon emissions of China in 2007 and 2012 by compiling the CO_2 emissions from industrial, urban residential, transportation, and agricultural sectors, which enables us to analyze and quantify the spatiotemporal changes in China's carbon emission patterns during the 11th and 12th Five-Year Plan periods. We find that the hot spots of carbon emissions in China have expanded by 28.5% (toward the west) in the north and shrunk by 18.7% in the south; meanwhile, the emission densities (CO_2 emissions per 100 km^2) in both regions have increased by 15.7% and 49.9%, respectively. The shrinkage of hot spots and the increase of emission density in South China suggest a clear transition to a more intensive economic growth model as a result of the energy conservation and emission reduction policies, while the expansion of hot spots and the increase of emission density in North China are likely to be dominated by the strategic plans of the Grand Western Development Program (e.g., massive investment to boost economic development in western regions).

Our results show that the CO_2 emissions in China exhibit a typical spatially intensive high-emission pattern. Although this pattern has not been changed substantially from 2007 to 2012, we do find a slight relaxation (up to 3%) in its intensiveness. As our results also suggest an increase of 33.5% in total CO_2 emissions during the same period, such a slight relaxation in the emission pattern reflects the effects of a typical urbanization process in China. We also find that there is a statistically significant decrease (16%) in CO_2 emissions per unit of GRP at the provincial level from 2007 to 2012 when an average increase (25%) in provincial total CO_2 emissions is detected. This suggests a transformation in China's economic structure toward a market-oriented and low-carbon economy. As its economy continues to grow, China needs to take further steps to reduce its carbon emissions in order to fulfill its climate commitment to the Paris Agreement (reducing CO_2 emissions per unit of GDP by 60 to 65% from the 2005 level by 2030). Our findings on the spatiotemporal changes in China's carbon emission patterns can reflect the influences and effectiveness of the carbon reduction policies introduced during the 11th and 12th Five-Year Plan periods. The effective policies demonstrated to be successful (e.g., Green Beijing) in previous periods can be of great significance in support of developing new climate policies in the current and forthcoming 5-year planning periods.

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