Spatiotemporal dynamic differences of energy-related CO₂ emissions and the related driven factors in six regions of China during two decades

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Abstract

Carbon neutrality lays out a grand blueprint for carbon emission reduction and climate governance in China. How to reduce energy consumption is the key to achieving this goal. The economic development and energy consumption show a very large gap at the provincial level, and this paper divides China into six regions (North, Northeast, East, Mid-South, Southwest, and Northwest) and analyzes the dynamic changes and reveals the driving factors that have affected CO₂ emission changes from 1997 to 2017. Then, the driving forces including energy intensity, energy structure, energy efficiency, economic activity, and population scale were discussed employing the logarithmic mean Divisia index (LMDI) based on provincial panel data. The results show that CO₂ emissions from energy consumption show an upward trend, from 4145 Mt in 1997 to 13,250 Mt in 2017, with an annual average growth rate of 1.06%; coal consumption is the main source of CO₂ emission. The regions with the highest proportion of CO₂ emissions are the East and North, which account for 50% of total emissions. China's CO₂ emissions from energy consumption, coal consumption, and output have shown significant spatial autocorrelation at the provincial scale. According to coal consumption, energy consumption CO₂ emissions are divided into three stages: phase I (1997–2002), the increase in CO₂ emissions in six regions was attributed to significant and positive impacts of energy intensity, economic activity, and population scale, the effects of which exceeded those of the energy structure and energy efficiency; phase II (2003–2012), the economic activity effect on CO₂ emissions was highest in the East region, followed by the North and Mid-South regions; phase III (2013–2017), the East, Mid-South, and Southwest regions of China were dominated by the positive effects of energy intensity, economic activity, and population scale. The major driver of CO₂ emissions is economic activity; the energy efficiency effect is an important inhibitory factor. Regional economic development and energy consumption in China are unbalanced; we conclude that differentiated emission reduction measures should be of particular concern for policymakers.

Keywords LMDI · Moran's I · Coal consumption · Economic activity · Differentiation · Reduction policy · Carbon neutrality

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Introduction

Climate change has recently become an important research topic and is receiving increasing attention worldwide. Since the global adoption of the Paris Climate Agreement in 2015, the growth of CO₂ emissions has begun to slow down (Le Quere et al. 2021). Although global effort has been devoted to reducing emissions, fossil fuels are still widely used in all parts of the economy, threatening both the environment and people (Lin and Zhang 2016). Anthropogenic activities are expected to lead to a 5 °C increase in the global temperature; however, appropriate and timely interventions could limit this increase to 2 °C (Cansino et al. 2016). The

COVID-19 pandemic is impacting human activities and in turn energy consumption and CO₂ emissions (Le Quere et al. 2020; Liu et al. 2020). Consumption of fossil fuel produced approximately 23.7 billion tons of CO₂ in 2016 throughout the world, accounting for more than two-thirds of the global CO₂ emission (Mei et al. 2020). As the world's second-largest economy and the largest carbon emitter, China is also actively taking responsibility to reduce emissions (Wang et al. 2020a). In 2020, China pledged to achieve a carbon peak by 2030 and strive to achieve carbon neutrality by 2060. In 2030, China's CO₂ emissions per unit of GDP will drop by more than 65% compared to 2005, non-fossil energy will account for about 25% of primary energy consumption, and forest reserves will increase by 6×10^9 m³ compared with 2005. China is currently undergoing rapid economic growth, urbanization, and industrialization, with high levels of energy consumption dominated by coal production. China consumes the most energy worldwide, accounting for 23% of the world's total energy consumption in 2016, and its CO₂ emissions account for 27.3% of the global total (Guo et al. 2018).

The vigorous development of China's economy, especially in manufacturing sectors, has driven rapid growth in energy consumption (Guan et al. 2008). The industrial sector is the main source of energy consumption and CO₂ emissions, and in 2016, the industrial sector accounted for 65.77% of China's total energy consumption in the final sector and 68.44% of China's CO₂ emissions (Wang et al. 2020a). Energy consumption has attracted widespread attention as a major contributor to carbon emissions. Therefore, decreasing CO₂ emissions has been an urgent challenge in China. To promote coordinated economic development in China, the factors affecting CO₂ emissions from energy consumption must be studied concerning regional characteristics, the key factors in different regions of China must be explored, and policy implications to promote carbon emission reduction with following local conditions must be identified. This is an important process in ensuring that China meets the 2030 carbon peak target and achieves coordinated resource, environmental, and economic development. China is able to achieve the 2030 carbon emission intensity target as scheduled, and there are conditions for reaching a peak carbon emission around 2030 (Tollefson 2016). Identifying the driving factors to reduce CO₂ emissions through technological advances and renewable energy use is a topic of great interest in academic research. Prior knowledge of the key driving factors will aid in achieving coordination between economic growth, urbanization, industrialization, and CO₂ emissions (Wang et al. 2014; Chen and Lin 2020; Mei et al. 2020). Climate change is an urgent challenge that requires concerted global action, and understanding the factors that affect CO₂ emissions is conducive to predicting future climate and earth system changes (Raupach et al. 2007).

China's economic development is extremely unbalanced, leading to large differences in regional energy consumption. According to its economic development and geographical location, China is divided into six major regions (Lai et al. 2016). This analyzed the driving factors affecting CO₂ emissions from energy consumption in North, Northeast, East, Mid-South, Southwest, and Northwest China to identify key factors affecting CO₂ emission reduction policies.

There are two main decomposition analysis approaches for carbon emission factors, i.e., structural decomposition analysis (SDA) and index decomposition analysis (IDA) (Sun and Ang 2000; Ang 2005). The SDA and IDA methods have been widely used in identifying the effects of different influencing factors on the overall changes in energy consumption and CO₂ emissions and have been compared by many researchers (Ang and Zhang 2000; Hoekstra and van der Bergh 2003; Peters et al. 2007). SDA is normally combined with input–output data (Xu et al. 2014, Chen et al. 2018); such data are typically issued in China every 5 years; therefore, SDA is unsuitable for in-depth research. IDA uses aggregated departmental data and can readily be applied to period or time-series data (Moutinho et al. 2015). The logarithmic mean Divisia index (LMDI) has relatively low data requirements and can quantitatively decompose CO₂ emissions from energy consumption into several influencing factors. LMDI has recently become the most widely used method of analyzing the decomposition of energy consumption and CO₂ emissions changes (Ang and Liu 2001; Wang et al. 2014; Zhang et al. 2014b; Cansino et al. 2015; Moutinho et al. 2015). The LMDI formula can be easily derived after the IDA identity is specified (Ang 2005). Therefore, the LMDI method was used to decompose the driving factors of CO₂ emissions from energy consumption in China (North, Northeast, East, Mid-South, Southwest, and Northwest).

There is extensive literature addressing the relationship between economic growth, urbanization, energy consumption, and CO₂ emissions. O'Neill et al. (2012), Jones (1991), and Parikh and Shukla (1995) proposed that urbanization is an important factor affecting energy consumption in developing countries. Xu et al. (2014) and Ang et al. (1998) have shown that economic development is the main driving force for CO₂ emissions. Moutinho et al. (2015) followed a similar method to decompose the factors affecting CO₂ emissions in Eastern, Western, Northern, and Southern Europe during 1995–2010 and reported that the CO₂ emissions were related to economic energy consumption. Liu et al. (2007) decompose the CO₂ emission of industrial sectors in China, which revealed that energy intensity is a significant influencing factor of CO₂ emissions change. Hasanbeigi et al. (2012) analyzed the energy intensity of industries in California and reported that the reduction of energy consumption was due to intensity and structural effects. Lee and Oh (2006) studied

CO₂ emissions in APEC countries following index decomposition methods and reported that economic growth and population were the main contributors. Wu et al. (2019) and Wang and Jiang (2019) have shown the relationship between economic growth and carbon emissions in China and decomposed the carbon emission factors into energy structure, energy intensity, economic output, labor input, technology state, and population size. Renewable energy use, economic efficiency, technological development, and energy efficiency improvements can mitigate energy-related CO₂ emissions (Chien and Hu 2007; Menyah and Wolde-Rufael 2010; Yan et al. 2013). However, the economic development of different regions in China is quite different, and few studies have applied provincial panel data to describe the regional differences in CO₂ emissions (Zhang et al. 2011).

The studies referenced above mainly followed the LMDI to research the driving factors of CO₂ emissions. Most previous studies only provided empirical conclusions and ignored regional economic development, and energy consumption in China is unbalanced. Therefore, this study divides China into six regions (North, Northeast, East, Mid-South, Southwest, and Northwest) and focused on analyzing the dynamic changes in the CO₂ emissions in China from 1997 to 2017 by decomposing the CO₂ emissions from energy consumption into energy intensity, energy structure, energy efficiency, economic activity, and population scale following the LMDI method. Additionally, the period was separated into three stages according to coal consumption. Different carbon emission reduction measures were explored based on the empirical results for China's North, Northeast, East, Mid-South, Southwest, and Northwest regions.

Materials and methods

Estimating CO₂ emissions

Based on the IPCC calculation method (IPCC 2007) and China's statistical data, the provincial panel data are used to evaluate CO₂ emissions in China from 1997 to 2017. Nine energy consumptions were analyzed in calculating the CO₂ emissions, including coal, coke, crude, fuel oil, gasoline, kerosene, diesel, natural gas, and electricity. Each energy

consumption is independent, and the conversion between energy is not considered. CO₂ emissions from energy consumption were calculated as follows:

$$E_{CO_2} = \frac{44}{12} \times \sum_{i=1}^9 E_i \times K_i \times SC_i \quad (1)$$

where E_{CO_2} represents the CO₂ emissions of energy consumption, 44/12 represents the conversion coefficient of carbon to CO₂, i denotes the type of energy, E represents the energy consumption, K represents the carbon emission coefficient, and SC represents the conversion coefficient of standard coal (Table 1).

The CO₂ emission intensity was calculated as follows:

$$EI_j = \frac{E_{CO_2j}}{GDP_j} \quad (2)$$

where EI_j is the CO₂ emission intensity of j province.

Spatio-temporal pattern analysis

Exploratory spatial data analysis (ESDA) can be used to identify patterns of spatial association and indicate spatial heterogeneity (Rey and Janikas 2006; Huang and Meng 2013). The ESDA provides measures of global and local spatial autocorrelation to characterize spatial distributions (Ye and Wu 2011). Global and local spatial autocorrelation indices were used to analyze the overall level of spatial autocorrelation and local similarities and variations between neighbors (Zhao et al. 2019).

The global spatial autocorrelation was assessed using Global Moran's I statistics, which can disclose spatial relationships between regions (Getis and Ord 1992). Global Moran's I value ranges from -1 to 1 ; if Global Moran's $I > 0$, the spatial autocorrelation is positive, and the higher the value, the stronger the autocorrelation. When Global Moran's $I < 0$, the spatial autocorrelation is negative, and the closer the value is to -1 , the stronger is the negative autocorrelation (Chuai et al. 2012). This study uses Global Moran's I to analyze the spatial correlation of energy consumption CO₂ emissions at the provincial scale.

Table 1 Carbon emission coefficients

Sources	Coal	Coke	Crude	Fuel oil	Gasoline	Kerosene	Diesel	Natural gas	Electricity
Conversion coefficient of standard coal	0.7143	0.9714	1.4286	1.4286	1.4714	1.4714	1.4571	1.3300	0.3450
Carbon emission coefficient	0.7559	0.8550	0.5857	0.6185	0.5538	0.5714	0.5921	0.4483	0.2720

For local spatial autocorrelation, each local unit is the target item, and the similarity and correlation between the local and adjacent units can be revealed (Anselin 1995). The Moran scatterplot describes four categories based on the spatial correlation results, i.e., HH (high-high), LL (low-low), HL (high-low), and LH (low-high). A positive HH or LL Moran's I cluster refers to a correlation in which units with high or low values are surrounded by other units with similar values. In contrast, when Moran's I is a negative HL or LH cluster, high or low value cells are surrounded by dissimilar cells (Zhao et al. 2019).

With a reliable data source, this study attempted to aggregate CO₂ emissions, coal consumption, and coal output within provinces to reveal regional clustering patterns.

Logarithmic mean Divisia index (LMDI)

In the literature, the output, energy mix, energy intensity, and structural effects are the most common (Moutinho et al. 2015). A country's contribution to one of or several different components of energy-related CO₂ emissions can be identified. Additionally, the driving factors that affected the country's CO₂ emissions change can be analyzed to reveal the energy intensity, energy structure, energy efficiency, economic activity, and population scale effects.

The results of the decomposition analysis are expected to indicate the crucial factors affecting the reduction of CO₂ emissions for China and other countries worldwide. The time-series analyses can decompose the factors of CO₂ emission year by year, to observe its evolution with time.

According to Ang and Liu (2007), LMDI was the preferred method due to its advantages of path independence, ability to handle zero values, and consistency in aggregation (Ang 2004). In this study, the LMDI method was followed to reveal the changes in the driving force of CO₂ emissions from energy consumption in China between 1997 and 2017. It is divided into three stages: 1997–2002, 2003–2012, and 2013–2017 to analyze the contribution of driving forces of six regions in China.

CO₂ emissions from energy consumption are decomposed into the following five effects:

$$E_{CO_2} = \frac{E_{CO_2}}{Q_{coal}} \times \frac{Q_{coal}}{Q} \times \frac{Q}{G} \times \frac{G}{P} \times P = I \times S \times F \times R \times P \quad (3)$$

where E_{CO_2} is CO₂ emissions from energy consumption, Q_{coal} is coal consumption, Q is total energy consumption, G is GDP, P is population, $I = E_{CO_2}/Q_{coal}$ is energy intensity effect, $S = Q_{coal}/Q$ is energy structure effect, $F = Q/G$ is energy efficiency effect, and $R = G/P$ is economic activity effect.

The changes from $E_{CO_2}^0 = \left(\frac{E_{CO_2}}{Q_{coal}}\right)^0 \times \left(\frac{Q_{coal}}{Q}\right)^0 \times \left(\frac{Q}{G}\right)^0 \times \left(\frac{G}{P}\right)^0 \times P^0$ for period 0 to.

$E_{CO_2}^T = \left(\frac{E_{CO_2}}{Q_{coal}}\right)^T \times \left(\frac{Q_{coal}}{Q}\right)^T \times \left(\frac{Q}{G}\right)^T \times \left(\frac{G}{P}\right)^T \times P^T$ for period T are decomposed in the multiplicative decomposition as follows:

$$\Delta D_{tot} = \frac{E_{CO_2}^T}{E_{CO_2}^0} = D_I D_S D_F D_R D_P \quad (4)$$

In additive decomposition is decomposed as follows:

$$\Delta E_{CO_2} = E_{CO_2}^T - E_{CO_2}^0 = \Delta E_I + \Delta E_S + \Delta E_F + \Delta E_R + \Delta E_P \quad (5)$$

According to the LMDI technique (Ang 2005), each effect in the additive decomposition is as follows:

$$\begin{aligned} \Delta E_I &= \sum \frac{E_{CO_2}^T - E_{CO_2}^0}{\ln E_{CO_2}^T - \ln E_{CO_2}^0} \ln \left(\frac{I^T}{I^0} \right) & \Delta E_S &= \sum \frac{E_{CO_2}^T - E_{CO_2}^0}{\ln E_{CO_2}^T - \ln E_{CO_2}^0} \ln \left(\frac{S^T}{S^0} \right) \\ \Delta E_F &= \sum \frac{E_{CO_2}^T - E_{CO_2}^0}{\ln E_{CO_2}^T - \ln E_{CO_2}^0} \ln \left(\frac{F^T}{F^0} \right) & \Delta E_R &= \sum \frac{E_{CO_2}^T - E_{CO_2}^0}{\ln E_{CO_2}^T - \ln E_{CO_2}^0} \ln \left(\frac{R^T}{R^0} \right) \\ \Delta E_P &= \sum \frac{E_{CO_2}^T - E_{CO_2}^0}{\ln E_{CO_2}^T - \ln E_{CO_2}^0} \ln \left(\frac{P^T}{P^0} \right) \end{aligned} \quad (6)$$

Each effect in the multiplicative decomposition is as follows:

$$\begin{aligned} D_I &= \exp \left(\Delta E_I \times \frac{\ln E_{CO_2}^T - \ln E_{CO_2}^0}{E_{CO_2}^T - E_{CO_2}^0} \right) & D_S &= \exp \left(\Delta E_S \times \frac{\ln E_{CO_2}^T - \ln E_{CO_2}^0}{E_{CO_2}^T - E_{CO_2}^0} \right) \\ D_F &= \exp \left(\Delta E_F \times \frac{\ln E_{CO_2}^T - \ln E_{CO_2}^0}{E_{CO_2}^T - E_{CO_2}^0} \right) & D_R &= \exp \left(\Delta E_R \times \frac{\ln E_{CO_2}^T - \ln E_{CO_2}^0}{E_{CO_2}^T - E_{CO_2}^0} \right) \\ D_P &= \exp \left(\Delta E_P \times \frac{\ln E_{CO_2}^T - \ln E_{CO_2}^0}{E_{CO_2}^T - E_{CO_2}^0} \right) \end{aligned} \quad (7)$$

Data sources and geographical distribution

Data sources

Energy consumption data from 1997 to 2017 were selected for analysis as they were the latest available data. The annual time-series data of energy consumption, coal output, GDP, and population scale from 1997 to 2017 used in this study were based on data from the China Statistical Yearbooks, China Energy Statistical Yearbooks, and EPS database. Owing to the lack of relevant data in Tibet, Taiwan, Hong Kong, and Macao, these areas were not included. In this study, China was divided into six regions, i.e., North (Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia), Northeast (Heilongjiang, Jilin, Liaoning), East (Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong), Mid-South (Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan),

Southwest (Chongqing, Sichuan, Guizhou, Yunnan, Tibet), and Northwest (Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang).

Spatial distribution of coal mine

Owing to its rapidly occurring economic development, China is the second most energy consumer worldwide. China's heavy reliance on coal will make it the largest emitter of CO₂ in the world (Guan et al. 2008). Coal plays an important role in meeting China's energy demand (Cheng et al. 2011); ensuring China's energy security, controlling environmental pollution, and achieving sustainable development are inseparable from the basic support of coal (Wang and Li 2016). As shown in Fig. 1, the coal output was highest in the North (1840 MT), followed by the Northwest (891 MT). Shanxi Province and Inner Mongolia in the North and Xinjiang and Shaanxi in the Northwest are the primary coal output bases, producing approximately 70% of China's coal resources. In

2017, the highest coal consumption (East, at 1150 Mt) was 3.4 times the lowest (Southwest, at 341 Mt).

Figure 2 shows that there was a significant increase trend in coal consumption from 1997 to 2017. The total coal consumption has tripled in the past 20 years, from 1.475×10^9 t in 1997 to 4.352×10^9 t in 2017. Coal consumption in China was divided into three phases.

Phase I (1997–2002): slight increase in coal consumption. The Asian financial crisis of 1997 limited coal consumption in China (Wang and Li 2016). Coal use increased from 1.475×10^9 t in 1997 to 1.665×10^9 t in 2002, an increase of 190 million tons over 5 years, and the overall growth process was relatively slow.

Phase II (2003–2012): a sharp increase in coal consumption. Infrastructure construction and economic growth were the main drivers of the rapid growth in coal consumption since 2002 (Liu et al. 2013). This period was the “golden age” of the coal sector. Coal consumption increased from 1.946×10^9 t in 2003 to 4.365×10^9 t in 2012, indicating that coal use became more important.

Fig. 1 Spatial distribution of coal mines in China and coal output and consumption in North, Northeast, East, Mid-South, Southwest, and Northwest in 2017: North (Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia), Northeast (Heilongjiang, Jilin, Liaoning), East (Shang-

hai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong), Mid-South (Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan), Southwest (Chongqing, Sichuan, Guizhou, Yunnan, Tibet), and Northwest (Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang)

Fig. 2 Coal consumption in China, 1997–2017

Phase III (2013–2017): steady state of coal consumption. Energy conservation and emission reduction have limited energy use in China, with coal consumption reaching a steady state, which increased from 4.322×10^9 t in 2013 to 4.352×10^9 t in 2017.

Results

CO₂ emissions from energy consumption in China

CO₂ emissions from energy consumption in China have shown an upward trend, from 4145 Mt in 1997 to 13,250 Mt in 2017, with an annual average growth rate of 1.06%. There were significant differences in the CO₂ emissions at the provincial scale. Table 2 shows provincial-level CO₂ emissions of energy consumption in 1997, 2007, and 2017 and presents the industrial structure in 2017 (the proportion of the primary industry, the secondary industry, and the tertiary industry). However, regional economic development in China is unbalanced; different provinces have varied CO₂ emissions. In 1997, the province with the highest emissions (Shanxi, at 337.89Mt) is 58.6 times the province with the lowest emissions (Hainan, at 5.77Mt). Nevertheless, the highest CO₂ emission (Shandong) was 1462.58 Mt, which was 26 times that of the lowest (Qinghai, 56 Mt) in 2017. Provinces with high CO₂ emissions could be divided into two categories, the first of which included Beijing, Shanghai, and Chongqing which have large economies that the primary industry accounts for less than 5% and the tertiary industry is dominant, while the second is industrially developed regions such as Jiangsu, Hebei, Shandong, and Henan and provinces rich in mineral resources such as Shanxi, Inner Mongolia, and Shaanxi, accompanied by high energy consumption CO₂ emissions, and regional development is dominated by secondary industries. In industrial provinces, especially in economically underdeveloped, energy consumption and inefficient energy use have led to a large amount of CO₂ emissions, which requires investment in timely and effective

elimination of outdated production capacity. Additionally, currently, China has set relatively small emission reduction targets for economically underdeveloped provinces (Liu et al. 2013). Facing the pressure of emission reduction, rich provinces will purchase some raw materials from other provinces, such as the cement and steel produced in Inner Mongolia, which is transported to Beijing and Shanghai (Wang et al. 2014).

CO₂ emissions of six regions

China is one of the largest CO₂ emitters in the world, and CO₂ emissions from energy consumption have increased rapidly in the past two decades (Fig. 3). From 1997 to 2017, the CO₂ emissions of coal consumption in the North, East, Northeast, and Northwest regions showed an increasing trend year by year; the main energy consumption in these regions was coke and crude besides coal. However, in the Mid-South and Southwest, coal consumption and CO₂ emissions showed a trend of first increasing and then decreasing, and both began to decline in 2013. In addition to coal, the Mid-South mainly consumes crude and electricity, and the Southwest mainly consumes coke and diesel. There are differences in the energy consumption structure of six regions in China, but all of them use coal as the main energy. The gap between the rich and the poor in China has led to differences in energy consumption. North, East, and Mid-South regions of China have developed rapidly, with high energy consumption levels and higher CO₂ emissions than the less developed regions in Northeast, Northwest, and Southwest. In recent years, China has proposed a “rural revitalization strategy” and “poverty reduction” aimed at reducing the problem of uneven development between regions. At the same time, in the context of global carbon neutrality, the future use of fossil energy such as coal, crude, and gasoline will gradually be replaced by clean energy. Figure 4 shows that the proportion of CO₂ emissions in the East region was the highest, accounting for 30.22% in 2017, followed by the North, which was approximately 22%. The proportion

Table 2 Provincial-level CO₂ emissions from energy consumption (1997, 2007, 2017) and industrial structure (2017)

Province	CO ₂ emissions (Mt)			Industrial structure (2017)			Province	CO ₂ emissions (Mt)			Industrial structure (2017)			
	1997	2007	2017	Primary industry (%)	Secondary industry (%)	Tertiary industry (%)		1997	2007	2017	Primary industry (%)	Secondary industry (%)	Tertiary industry (%)	
North	Beijing	101.17	128.22	84.49	0.43	19.01	80.56	Henan	193.26	555.21	603.45	9.29	47.37	43.34
	Tianjin	78.31	145.06	179.74	0.91	40.94	58.15	Hubei	172.18	311.88	374.68	9.95	43.52	46.53
	Hebei	292.66	712.52	889.22	9.20	46.58	44.21	Hunan	123.34	278.38	348.38	8.84	41.72	49.43
	Shanxi	337.89	688.08	944.74	4.63	43.65	51.71	Guangdong	201.37	481.73	672.46	4.03	42.37	53.60
	Inner Mongolia	133.24	440.09	865.91	10.25	39.76	49.99	Guangxi	54.05	132.46	252.39	15.54	40.22	44.24
Northeast	Liaoning	323.60	589.54	737.55	8.13	39.30	52.57	Hainan	5.77	41.79	64.96	21.58	22.33	56.10
	Jilin	132.84	201.53	253.49	7.33	46.83	45.84	Chongqing	61.42	124.59	155.46	6.57	44.19	49.24
	Heilongjiang	198.83	291.43	382.32	18.65	25.53	55.82	Sichuan	148.08	277.00	316.54	11.53	38.75	49.73
	Shanghai	158.88	240.38	271.32	0.36	30.46	69.18	Guizhou	113.56	215.29	305.27	15.01	40.09	44.90
East	Jiangsu	233.35	590.67	864.56	4.71	45.02	50.27	Yunnan	83.87	213.59	222.62	14.28	37.89	47.83
	Zhejiang	138.75	394.43	471.50	3.74	42.95	53.32	Shaanxi	97.25	242.43	509.48	7.95	49.70	42.35
	Anhui	132.75	246.98	419.39	9.56	47.52	42.92	Gansu	83.54	158.79	206.82	11.53	34.34	54.13
	Fujian	55.21	174.72	280.58	6.88	47.71	45.41	Qinghai	14.47	36.70	56.00	9.08	44.29	46.63
	Jiangxi	68.62	146.90	234.62	9.17	48.12	42.70	Ningxia	27.09	92.92	264.68	7.28	45.90	46.82
	Shandong	285.86	928.09	1462.58	6.65	45.35	47.99	Xinjiang	94.38	184.42	554.50	14.26	39.80	45.94

Fig. 3 CO₂ emissions in six regions of China between 1997 and 2017. The unbalanced economic development in China has led to large differences in CO₂ emissions from energy consumption

Fig. 4 The proportion of CO₂ emissions in North, Northeast, East, Mid-South, Southwest, and Northwest in 1997, 2007, and 2017

of CO₂ emissions in the Northwest region exhibited an increasing trend, rising from 7.64% in 1997 to 12.01% in 2017. Meanwhile, the proportion of CO₂ emissions in the Northeast and Southwest regions has decreased by 5.44% and 2.27%, respectively. This could be because economic growth and energy consumption have greatly varied across China for a long time, with clear regional differences. The rapid economic growth, industrialization, and urbanization in East, North, and Mid-South China have led to a high degree of energy dependence, which has, in turn, led to a relatively high proportion of CO₂ emissions. However,

economic development in the Northwest, Southwest, and Northeast regions is relatively low, which has led to low land development intensity and CO₂ emissions.

Geographically, provinces with high CO₂ emission intensities were mainly concentrated in Northeast, North, and Northwest China (Fig. 5). Coal-rich provinces and economic development have an intensive concentration of energy consumption industries that showed high CO₂ emission intensities. Owing to their low proportion of the heavy industry, the Southwest, Mid-South, and East provinces of China had low CO₂ emission intensities. Specifically, the CO₂ emission

Fig. 5 Spatial distributions of CO₂ emission intensity and CO₂ emission of energy consumption in six regions, in 2017

intensity varied regionally, which was attributed to China's regional economic development model. To reduce CO₂ emission, more scientific regional environment compensation mechanisms and differentiated development policies need to be formulated as soon as possible. Additionally, regional energy supply and demand need to be balanced.

As shown in Fig. 5, coal is a significant source of CO₂ emissions from energy consumption in China, with the CO₂ emissions of coal consumption accounting for 75% in the North and Northwest, 67% in the Southwest, 60% in the Northeast, and approximately 50% in the East and Mid-South. In the next few decades, China's energy consumption structure dominated by coal resources will remain unchanged (Xu et al. 2014). In 2017, the highest CO₂ emissions from coal (2277 Mt in East) were 3.3 times the lowest (675 Mt in Southwest). The consumption of crude in the Northeast and East is second only to coal, with CO₂ emissions of 308.86 Mt and 749.19 Mt respectively, accounting for about 20% of the total CO₂ emissions of energy consumption in the region. Electricity consumption in the Mid-South region far exceeds that of other regions, generating 651.25 Mt of CO₂ emissions, accounting for 22% in the region. Additionally, CO₂ emissions from the consumption of gasoline, kerosene, diesel, fuel oil, and natural gas were highest in the East, accounting for about 20%, while CO₂ emissions from coke were highest in the North by 13%. The

highest CO₂ emissions from energy consumption were 4044 Mt in the East, and the lowest was 999 Mt in the Southwest. China consumes the most energy worldwide, utilizing almost half of all coal produced (Liu et al. 2013). China is currently committed to clean production to mitigate CO₂ emissions from energy consumption.

Spatial autocorrelation analysis

Global Moran's *I* values of CO₂ emissions from energy consumption between 1997 and 2017 at the provincial level in China were calculated. Figure 6 shows that Moran's *I* > 0 from 1997 to 2017, indicating that China's CO₂ emissions from energy consumption exhibited significant spatial autocorrelation at the provincial scale, indicating that high-emission provinces tended to be adjacent to other high-emission provinces and low-emission provinces tended to be adjacent to other low-emission provinces. Global Moran's *I* values varied from 0.27 to 0.351, with higher values indicating a better agglomeration effect. The value increased with fluctuations from 0.296 in 1997 to 0.351 in 2005, indicating that the agglomeration effect of China's CO₂ emissions from energy consumption has gradually increased. After 2005, the Moran's *I* value decreased with fluctuations and reached the minimum value in 2017 (0.27), indicating that the agglomeration effect gradually weakened.

Fig. 6 The change of Global Moran's I of China's CO₂ emissions from energy consumption (1997–2017). Moran's I passed the significance test of $P=0.05$

Spatial autocorrelation of CO₂ emissions

Figure 7 shows the local spatial autocorrelation of China's CO₂ emissions from energy consumption at the provincial scale in 1997, 2007, and 2017. The CO₂ emissions from energy consumption exhibited clear spatial agglomeration; the agglomeration center of HH did not change but expanded from 1997 to 2017. In 1997, HH clusters included seven provinces and were mainly distributed in the North (Hebei and Shanxi Province), Mid-South (Henan Province), East (Shanghai, Shandong, and Jiangsu Province), and Northeast (Liaoning Province) regions. In 2007, Shanghai changed from the HH to the LH cluster, while Inner Mongolia changed from the LH to the HH cluster; HH aggregation expanded to Shaanxi Province (Northwest) in 2017, and the provinces exhibiting LL agglomeration were mainly centralized in the Northwest and Southwest regions.

CO₂ emissions from industry were dominant in Shanghai, followed by transportation and buildings, and, since 2003, the energy consumption per unit of GDP in Shanghai has decreased significantly (Chen and Zhu 2013). Resource industries were the dominant industrial structures in Shaanxi Province and Inner Mongolia, which are abundant in natural resources, such as coal and oil. These two provinces are facing great pressure to reduce their CO₂ emissions as they are undergoing an important industrialization period. With economic growth and increasing demand for energy consumption, industrial energy utilization should be increased to resolve the “high investment and high consumption” economic growth mode (Zhou et al. 2019; Wang et al. 2020b). The implementation of a set of mitigation measures may achieve economic growth with lower CO₂ emissions (Zhang et al. 2020b).

Spatial autocorrelation of coal output and consumption

Figure 8 shows that the spatial agglomeration of CO₂ emissions from energy consumption in 2017 was consistent with that of coal output (a) and consumption (b). As shown in Fig. 8a, HH clusters were mainly distributed in the North (Shanxi, Inner Mongolia), Mid-South (Henan), and Northwest (Shaanxi). The HL clusters were mainly centered around Shandong, Guizhou, and Xinjiang, which have high coal output, while that in the adjacent areas is low. These regions are important provinces for coal output in China, producing approximately 83% of China's coal resources in 2017. Figure 8b shows that the HH and LL clusters contained nine and twelve provinces, respectively, accounting for 70% of all the provinces, while the HL and LH clusters contained 30% of the clusters, indicating that there was clear regional variation in coal use at the provincial scale. Provinces with abundant coal resources tend to generate more CO₂ emissions than those with fewer coal resources (Lu and Lai 2020). Coal output and consumption have rapidly increased in China since 2002 (Fan et al. 2013). China's rapid urbanization and industrialization inevitably led to the massive consumption of coal resources (Zhang and Lin 2012).

The distinctive features of rapid urbanization and industrialization are high energy consumption and large amounts of CO₂ emissions (Xu et al. 2014). China's energy consumption structure is relatively concentrated; this energy structure dominated by coal resources has not changed in the past 30 years (Wang and Li 2016). Coal-fired power generation is the main source of carbon emissions (Yu et al. 2014). The proportion of coal consumption in China directly determines the energy structure, which is an influencing factor of CO₂ emissions. More coal output and consumption will result in more CO₂ emissions, and industrialization and urbanization will inevitably increase the demand for coal resources. Identifying renewable energy (such as nuclear and renewable energy) that can replace coal is an effective approach to reducing CO₂ emissions (Lin and Zhang 2016).

Driving factors of CO₂ emissions in six regions

The results for the contributions of different factors in the six regions of China are shown in Figs. 9 and 10 in three phases, i.e., phases I (1997–2002), II (2003–2012), and III (2013–2017).

During phase I (1997–2002), the increase in CO₂ emissions across China's six regions (North, Northeast, East, Mid-South, Southwest, Northwest) was attributed to significant and positive impacts of energy intensity, economic activity, and population scale, the effects of which exceeded those of the energy structure and energy efficiency. The economic activity was the predominant contributor to the

Fig. 7 Spatial Moran's I scatter-plots of China's CO₂ emissions from energy consumption in 1997, 2007, and 2017. HH, high-high; HL, high-low; LH, low-high; LL, low-low

Fig. 8 Spatial Moran's I scatterplots: **a** coal output and **b** coal consumption in 2017. HH, high-high; HL, high-low; LH, low-high; LL, low-low

increase in CO₂ emissions (541.91 million tons), which was approximately 169 times that in the Northwest (3.2 million tons).

During phase II (2003–2012), the economic activity effect on CO₂ emissions was highest in the East region, followed by the North and Mid-South regions. The energy efficiency was highest in the North, which played an important role in mitigating CO₂ emissions. The population scale of the North led to an increase in the CO₂ emissions of 247.34 million tons, followed by 164.55 million tons in the East. However, the population scale effect in the Southwest region led to a decrease in

emissions of 2.46 million tons, which could be because the Southwest region is underdeveloped; some people choose to work or settle in other cities, resulting in a decrease in the population scale.

During phase III (2013–2017), the East, Mid-South, and Southwest regions of China were dominated by the positive effects of energy intensity, economic activity, and population scale, which exceeded the negative effects of energy structure and energy efficiency. The decrease in CO₂ emissions in the Northeast (−4.92 million tons) was due to the negative effect of both the energy structure and population scale, which exceeded the positive effects of energy intensity, energy efficiency, and economic activity.

According to Table 3, the CO₂ emissions from energy consumption were lowest in the Northwest region, followed by the Southwest and Northeast. During phase III

Fig. 9 Results of additive decomposition of six regions in China (North, Northeast, East, Mid-South, Southwest, Northwest). CO₂ emissions from energy consumption additive decomposition are divided into three phases: phase I (1997–2002), phase II (2003–2012), and phase III (2013–2017)

Fig. 10 Results of multiplicative decomposition of six regions in China (North, Northeast, East, Mid-South, Southwest, Northwest). CO₂ emissions from energy consumption multiplicative decompo-

sition are divided into three phases: phase I (1997–2002), phase II (2003–2012), and phase III (2013–2017)

Table 3 Results of CO₂ emissions from energy consumption decomposition of six regions in China (North, Northeast, East, Mid-South, Southwest, Northwest)

		North	Northeast	East	Mid-South	Southwest	Northwest
Phase I (1997–2002)	ΔE_{CO_2}	228.7336	33.4350	280.003	152.6795	24.8998	12.2804
	ΔD_{tot}	1.2425	1.0510	1.2609	1.2036	1.0612	1.0388
Phase II (2003–2012)	ΔE_{CO_2}	1575.089	692.2134	2064.468	1332.177	567.8994	839.2
	ΔD_{tot}	2.1723	1.90981	2.320933	2.31244	2.082445	2.9277
Phase III (2013–2017)	ΔE_{CO_2}	54.9956	−4.9202	352.1166	66.8513	−83.0322	213.0957
	ΔD_{tot}	1.0189	0.9964	1.0964	1.0297	0.9233	1.1546

Table 4 Results of CO₂ emissions from energy consumption additive decomposition of China

	ΔE_I	ΔE_S	ΔE_F	ΔE_R	ΔE_P	ΔE_{CO_2}
1997–2002	188.6491	−228.433	−1249.598	1841.1088	180.3041	732.031
2003–2012	42.2086	−33.8994	−5304.15	11,929.95	436.9344	7071.047
2013–2017	509.6506	−676.11	−2979.89	3432.329	313.1239	599.1068
1997–2017	629.0516	−791.8472	−9527.09	17,801.8968	992.1055	9104.116

Table 5 Results of CO₂ emissions from energy consumption multiplicative decomposition of China

	ΔD_I	ΔD_S	ΔD_F	ΔD_R	ΔD_P	ΔD_{tot}
1997–2002	1.0428	0.9505	0.7576	1.5053	1.0409	1.1766
2003–2012	1.0049	0.9961	0.5437	3.9376	1.0515	2.2532
2013–2017	1.0401	0.9491	0.7944	1.3035	1.0245	1.0474
1997–2017	1.0836	0.9039	0.2964	9.6988	1.1350	3.1961

(2013–2017), the CO₂ emissions followed a decreasing trend in the Southwest and Northeast regions, and high CO₂ emissions from energy consumption were observed in the North, East, and Mid-South. The CO₂ emissions increased rapidly in phase II (2003–2012), but the growth trend slowed in phase III (2013–2017), which is because the economic development in the North, East, and Mid-South regions is relatively rapid, while that of the Northwest, Southwest, and Northeast regions is relatively slow. Urbanization and industrialization will be promoted in economically developed regions, resulting in an increase in energy consumption and CO₂ emissions (Zhang and Lin 2012).

Driving factors of CO₂ emissions in China

The results presented in Tables 4 and 5 show that the CO₂ emissions from energy consumption increased by 9104.116 million tons from 1997 to 2017. In phase I (1997–2002), the variations in CO₂ emissions in China increases (732.03 million tons) by approximately 17.6%. During phase II (2003–2012), the CO₂ emissions increased by 7071.047 million tons, which was 2.25 times that in 2003. During phase III (2013–2017), the variation in China's CO₂ emissions (599.11 million tons) increased by 4.6%. The overall effects of energy intensity, economic activity, and population scale on CO₂ emissions were positive, while those of energy structure and energy efficiency were negative. China's economy grew greatly from 1997 to 2017, with the per capita GDP increasing from 6481 to 59,201 Yuan, thereby resulting in the significant increase in the demand for energy products and higher CO₂ emissions (Sharma 2011).

The energy intensity positively affects CO₂ emissions. From 1997 to 2017, the energy intensity effect led to an increase in the CO₂ emissions of 629.05 million tons, 509.65 million tons of which occurred between 2013 and 2017. The accelerated urbanization and industrialization and excessive demand for high-energy products resulted in the rapid and sustained growth of energy consumption, which has increased energy intensity (Zhang and Lin 2012).

From 1997 to 2017, the effect of energy structure on CO₂ emissions was negative, with a decrease of 791.85 million tons. Therefore, the energy structure played an important role in reducing CO₂ emissions in China. Coal consumption decreased from 65.9% in 1997 to 59.6% in 2017, which could be because technological progress and the promulgation of policies and regulations in the industrial sector have promoted energy conservation, emission reduction, and improvements in energy utility efficiency (Xu et al. 2014).

Energy efficiency is used to explain the whole efficiency of energy consumption and economic activities, and the decline in energy efficiency negatively contributes to CO₂ emissions. Energy efficiency has been improved by

energy-saving and emission reduction policies launched by the Chinese government, including the closure of energy and emission-intensive enterprises and the reorganization of the energy market (particularly the coal market) (Xu et al. 2014).

The effect of economic activity on the CO₂ emissions was positive; China's economic growth has directly led to an increase in CO₂ emissions. From 1997 to 2017, economic activities led to an increase in the CO₂ emissions of 17,801.89 million tons, which was an increase of 9.7 times. Energy is the main driver of economic growth, while economic development characterized by industrialization and urbanization leads to increases in energy consumption and CO₂ emissions (Zhang and Lin 2012).

The effect of population scale on CO₂ emissions was positive, and increases in the Chinese population will increase CO₂ emissions. China's population increased from 1.223 billion to 1.388 billion between 1997 and 2017, increasing the CO₂ emissions to 992.1 million tons. One reason for this is that population growth will increase the demand for energy, which will lead to increased energy consumption and CO₂ emissions (Zhang and Lin 2012). Additionally, urbanization in China is increasing with population growth, and the required construction will consume large amounts of energy, resulting in more CO₂ emissions (Wang et al. 2013).

Discussion

Policy implication

China has become one of the largest emitters of “high energy consumption and high carbon dioxide emissions” in the world (Yang et al. 2019), but its per capita emissions are much lower than other developed countries (Hubacek et al. 2007). Per capita GDP growth was the major factor in driving the increase of Chinese CO₂ emissions from energy consumption, while efficiency improvements reduced the emissions only partly (Peters et al. 2007). To date, previous studies have calculated and analyzed the driving factors of CO₂ emissions from China's energy consumption, but have not taken into account the imbalance of economic development. The increasing energy demand and CO₂ emissions pose a severe challenge for energy conservation and emission reduction in China. There were regional differences in economic development, energy structure, energy intensity, energy efficiency, and population scale in North, Northeast, East, Mid-South, Southwest, and Northwest. China was divided into 6 regions in this study. Spatiotemporal dynamic differences of energy-related CO₂ emissions and the related driven factors were analyzed according to the different regions, and the feasible and differentiated emission reduction strategies were marketed when combining with the regional development strategies.

The CO₂ emissions were largest in the East region, followed by the North, which was mainly due to the effects of economic activity, while the energy efficiency was high in the East and North regions. Improving energy efficiency has an inhibitory effect on CO₂ emissions. The East and North regions consume large amounts of coal, and urbanization and industrialization are rapid. The industry serves as a strong driving force for the economic development of the East region, which could accelerate the upgrading of the industrial structure through technological innovation to reduce energy consumption. Inner Mongolia and Shanxi Province in the North are rich in mineral resources with high CO₂ emissions; therefore, mineral resources must be rationally developed to improve energy efficiency. From the perspective of regional development, the East and North regions should fully utilize their geographical advantages and replace coal resources with renewable energy through technological upgrading (Duic et al. 2013). Technological development and the application of renewable energy (such as biomass, wind, and solar energy) can reduce CO₂ emissions from energy consumption (Yan et al. 2013).

Energy consumption in the Mid-South region is dominated by coal, and the CO₂ emissions are mainly affected by economic activity. The energy structure and efficiency in the Mid-South region inhibited CO₂ emissions. Guangdong and Hubei Provinces in the Mid-South are the first low-carbon pilot areas in China. A low-carbon ecological demonstration zone based on production and consumption should be constructed in the Mid-South region; adhere to a production model with low energy consumption, emissions, and pollution; and encourage residents to adopt a low-carbon lifestyle. In Henan Province, as one of the important grain production bases in China, it is necessary to improve the quality of agricultural economic development, establish a low-carbon agriculture awareness, and take the path of sustainable agricultural development. Guangdong and Hainan Provinces in the Mid-South are the pilot areas of China's "reform and opening up" policies (Hainan Free Trade Port, Guangdong-Hong Kong-Macao Greater Bay Area, Pearl River Delta City Clusters). Therefore, integrated economic, energy, and environmental development in Central China must be promoted to balance the pressure of emission reduction in each province. The Mid-South region has advanced manufacturing and modern service industries; therefore, a low-carbon service industry must be vigorously developed, and the manufacturing and service industries must be deeply integrated to meet the inherent demand for low-carbon development.

The proportion of energy consumption CO₂ emissions in Northeast China is following a decreasing trend, which may be due to the slow economic growth. Energy consumption in the Northeast region is dominated by coal, and the energy utilization structure is monotypic. Energy consumption is higher in the Northeast region due to the lower

winter temperatures. Energy efficiency and the proportion of renewable energy should be improved through technological advancement to allow the Northeast region to sustainably develop with low energy consumption, low emissions, and high efficiency. The industrial base in Northeast China should be transformed, and it's the region's unique natural resources that should be utilized to actively develop special industries, such as agriculture and tourism.

The energy utilization efficiency of the Northwest and Southwest regions was relatively low, and the economic development, technology, and management of these regions are lower than those of the others. The land areas and mineral resources in the Northwest and Southwest regions were large and abundant, which should be fully utilized for development. Particularly, extensive attention should be put on energy conservation and emission reduction during the development of coal resources in the Xinjiang and Shaanxi Provinces. Upgrading technology can not only promote economic growth and productivity but also contribute to energy efficiency and reduce CO₂ emissions (Wang et al. 2009; Zhang et al. 2014b).

The economic development, resource endowment, technological development, energy consumption, and carbon emissions of China's regions are highly unbalanced, which has led to differences in the emission reduction pressures between regions. The integrated development of the region should be accelerated, the connection and coordinated development of various regions should be strengthened, and the disparity between the economy, technology, energy, and environment should be reduced. China's industrial structure must be upgraded, and China must urgently achieve carbon emission reduction. The industrial structure is not only determined by economic development, but also closely related to the regional natural resources, possession of highly developed technology, and promulgation of government policies. The upgrading of the industrial structure must consider the comprehensive effects of industrial structure adjustments while achieving carbon emission reduction without affecting economic development while also considering the needs of the people. Energy conservation and emission reduction policies in China should be implemented considering local differences.

In September 2020, China proposed to achieve carbon peaks by 2030 and carbon neutrality by 2060. This goal will boost China's energy transition and technological innovation, and energy consumption with high CO₂ emissions such as coal, fuel oil, and gasoline will be replaced by renewable energy such as wind, nuclear, and solar. Climate change is one of the major challenges facing mankind, and all countries in the world should strengthen cooperation. Developed countries should take the lead on new energy-saving technology developments collaborating with developing countries

as well as accelerate spillovers of low-carbon technologies to developing countries.

Compare with previous research

China, the United States, India, Russia, Japan, Germany, South Korea, Canada, Iran, and the United Kingdom account for two-thirds of global carbon dioxide emissions (Nejat et al. 2015). However, greenhouse gas emissions and energy consumption in developing countries still increase significantly, which is consistent with the result that CO₂ emissions from energy consumption increase year by year in this study. Electricity production, petroleum processing, coking, metal smelting and rolling, chemical manufacturing, and nonmetallic mineral products are the main sources of carbon emissions (Xu et al. 2014). Coal production and consumption are not only the main source of carbon emissions in the world but also the main contributor to China's economic development (Wang et al. 2020a). The coal sector contributes more than 44% of the man-made carbon dioxide emissions from global fuel combustion, and the CO₂ emissions from coal consumption in six regions of North, Northeast, East, Mid-South, Southwest, and Northwest China are all more than 50%. With the rapid development of renewable energy and natural gas systems, the proportion of coal in the energy structure is gradually shrinking.

The western region is expected to peak first, followed by the central region, and then the eastern coastal regions (Zhang et al. 2021). Jiangsu, Shandong, Guangdong, Zhejiang, Henan, Inner Mongolia, Xinjiang, Hebei, Hubei, and Sichuan contribute significantly to total carbon emissions. The emission growth is mainly concentrated in the central region, and the emission growth of provincial capital cities is rapid (Zhao et al. 2019); it is consistent with the CO₂ emissions of energy consumption from 1997 to 2017 calculated in this study. The total amount of CO₂ and per capita emissions in North China are significantly high, which is mainly due to the relatively cold climate and the high level of economic development with multi-demand for energy utilization (Zhang et al. 2014a). This study shows that the North and East account for 50% of energy consumption CO₂ emissions in China. Beijing has obtained a large number of carbon emissions related to electricity through the purchase of Hebei heavy industrial products, indicating that there is a spatial correlation between energy consumption in China; provinces with good economic development can purchase high-emission industrial products from neighboring provinces (Zhang et al. 2020a).

In the next 30 years, under the influence of climate change, China's power demand will increase by about 58.6% (Mei et al. 2020). In order to alleviate climate change and sustainable development, fossil fuels will gradually be replaced by renewable energy. At the same time, China

needs to adjust the current energy supply structure, reduce carbon emissions, and seek a low-carbon development path. GDP and energy utilization technology are related to higher CO₂ emissions (Zhao et al. 2019), which is consistent with the results of this study. China's industrial carbon emission coefficient presents an imbalanced pattern of "low east and high west," mainly due to the slow economic development of the western region (Xu et al. 2014, Wang et al. 2020a). The Northwest and Southeast region lacks the support of advanced energy conservation and emission reduction technologies and pays insufficient attention to strategic emerging industries, resulting in the inefficient utilization of a large amount of energy. The Chinese government should pay attention to the coordination between emission reduction and economic development.

Although there have been many studies on carbon emissions in China, the research in this paper can help enrich this knowledge, especially the analysis of key factors in energy consumption carbon emissions in China's six different regions and differentiated emission reduction measures.

Conclusions

The objective of this study was to divide China into six regions (North, Northeast, East, Mid-South, Northwest, and Southwest) to analyze the spatiotemporal dynamics of CO₂ emissions from energy consumption in 1997–2017 and identify the main driving factors of CO₂ emissions to inform relevant policies for CO₂ mitigation. In 2017, China's CO₂ emissions were extremely spatially uneven, with the highest emissions from a province being 27 times the lowest, and energy consumption was mainly derived from coal. We also analyzed the impact of the spatial distribution of coal mines on CO₂ emissions and illustrated the spatial agglomeration of coal consumption and output in China through Moran's *I* index. The analyses revealed that China's coal consumption and output exhibited a significant spatial autocorrelation at the provincial scale, indicating that regions with high coal consumption and output and low consumption and output were adjacent to other regions with similar consumption and output levels. Coal consumption was highest in the East region, followed by the North and Mid-South regions, and coal output was highest in the North and Northwest regions. Energy consumption was divided into three stages to analyze the driving factors of CO₂ emissions, i.e., phases I (1997–2002), II (2003–2012), and III (2013–2017).

According to the LMDI method, the CO₂ emissions from energy consumption were decomposed into energy intensity, energy structure, energy efficiency, economic activity, and population scale, and the structure of CO₂ emissions in different regions of China was analyzed. Although

decomposition analyses may have been conducted for China, this research helps build a knowledge system in this field, especially in the formulation of regional energy conservation and emission reduction policies. The analysis results show that the main factor causing CO₂ emissions in East and Mid-South China was economic activity, followed by energy intensity and population size, and the main inhibitory factors were energy efficiency and structure. The main driving factors of CO₂ emissions in North China were the economic activity and population scale, while the main inhibitory factor was the energy efficiency, followed by the energy intensity. However, the Northeast, Southwest, and Northwest regions of China are economically underdeveloped, and economic activity has a relatively weak effect on CO₂ emissions in these regions. With rapid scientific and technological development, the CO₂ emissions in the Northeast and Southwest regions followed a decreasing trend, and the energy efficiency effect in the Northwest inhibited CO₂ emissions.

The economic growth mode of China should change to not only consider the quantity of growth, but also the quality, to transform China's economic development model from extensive to intensive. Additionally, rapid industrialization and urbanization are the main sources of carbon emissions in China; it is necessary to speed up the elimination of backward production technologies to encourage technological innovation. Shandong Province (Eastern) should improve energy efficiency, as the region with the highest coal consumption and carbon emissions, and renewable energy should be fully utilized to reduce coal consumption. As major coal output provinces, Inner Mongolia, Shanxi, Xinjiang, and Shaanxi should implement a low-carbon and green mining model to reduce energy consumption. As Heilongjiang and Henan provinces are important grain production bases, it is necessary to improve the quality of agricultural economic development, establish a low-carbon agriculture awareness, increase the use of organic fertilizers, and follow the path of sustainable agricultural development. The economically underdeveloped regions in the Northwest and Southwest have large land areas and low energy efficiency, technology and management levels should be improved, and the development of clean energy should be strengthened in the future.

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Declarations

Competing interests The authors declare no competing interests.

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