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The change in temporal trend and spatial distribution of CO_2 emissions of China's public and commercial buildings

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ABSTRACT

The CO_2 emission mitigation of the commercial and public building sector (P&C) is critical for achieving China's carbon peak and carbon neutrality. Analyzing changes in CO_2 emissions and their driving factors from temporal and spatial perspective provides insights for developing equitable and effective decarbonization strategies. This study investigated the change in temporal trend and spatial distribution of CO_2 emissions of China's P&C during period of 2005–2018 according to the Kaya identify and Gravity Center model. Meanwhile, combined with the Logarithmic Mean Divisia Index, this study proposed a decomposed method to identify the driving factor of the movement of the gravity center. The results showed that: 1) in the temporal dimension, China's P&C has still not achieved its CO_2 emissions peak, arriving 820.68 $MtCO_2$. The most positive and negative driving factors were per capita add value of tertiary industry and energy efficiency, respectively; 2) in the spatial dimension, during the 13th Five Year Plan period, the gravity center moved southwestward, and the most positive and negative driving factors were energy consumption unit area and energy efficiency, respectively; Besides, to accelerate the decarbonization of China's P&C, this study reviewed the main decarbonization strategies, divided them into six categories and provided policy implications. In summary, this study provides a completed assessment on CO_2 emission changes of China's P&C, facilitating policy-makers to develop more reasonable implementation plans for emission mitigation.

1. Introduction

As the country with the largest carbon emissions, China accounted for 29.48% of global carbon emissions in 2020, thus the actions taken to reduce carbon emissions in China play an important role in mitigating global warm [1]. In September 2020, the Chinese government reaffirmed its goal of reaching its carbon peak by 2030 and aiming for carbon neutrality by 2060 [2]. Decarbonization of the building sector is regarded as essential to reaching China's carbon emission goals [3,4]. In 2019, China's building sector was responsible for 2.13BtCO_2, accounting for 21.49% of the total energy-related carbon emissions out of China [5]. More specifically, the public and commercial building (P&C) sector has the largest emission potential among all building types [6–8]. In 2019, China's P&C had a collective building floor area of 13.6 billion square meters, produced 846 $MtCO_2$, and encompassed a CO_2 emission unit area of 62.16 kg, which was nearly 2.5 times that of urban residential buildings and four times that of rural residential buildings [5].

The Chinese government has formulated the *Implementation plan for carbon peaking in urban and rural construction* to accelerate the decarbonization of China's P&C [9]. However, in practice, because of the obvious differences in the provincial climate condition, the level of tertiary industry, and the penetration rate of building decarbonization techniques, there is an evident gap in CO_2 emissions trends of provincial P&C and their spatial distribution keeps changing. For example, as the province with developed economic condition and central heating, the CO_2 emission unit area of Beijing (116.42 $kgCO_2/m^2$) was nearly five times that of Yunnan (25.05 $kgCO_2/m^2$), which is not located in China's central heating area and is less economically developed [5]. Therefore, investigating the change in temporal trend and spatial distribution of P&C CO_2 emissions and understanding what drives these changes are urgently required, that may benefit to formulated reasonable decarbonization responsibility and specific decarbonization measure targets of provincial P&C. To solve above problems, this study aims to solve the following three issues regarding the decarbonization of China's P&C.

- **How do CO_2 emissions change at the provincial and national P&C? What drives this change?**

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Abbreviations

Public and commercial building sector	P&C
China Association of Building Energy Efficiency	CABEE
Logarithmic Mean Divisia Index	LMDI
Sever cold area	SC
Cold area	CA
Hot summer and cold winter area	HSCW
Hot summer and warm winter area	HSWW
Warm area	WA
Ministry of Housing and Urban-Rural Development	MOHURD
Building Energy Research Center of Tsinghua University	BERC
International Energy Agency	IEA
Emission factor	*EF*
Energy consumption unit area	*EI*
Economic efficiency	*EE*
Per capita add value of tertiary industry	*PG*
CO_2 emission of public and commercial building sector	*C*
Energy consumption of public and commercial building sector	*E*
Building floor area of public and commercial building sector	*S*
Population	*P*
Add value of tertiary industry	*GDP*
Longitude	*X*
Latitude	*Y*

- **How does the spatial distribution of P&C CO_2 emissions change? What drives this change?**
- **How can decarbonization of China's P&C be accelerated in the future?**

To solve the above issues, this study investigated the changes in historical CO_2 emissions of provincial and national P&C during the period of 2005–2018, and further employed a Logarithmic Mean Divisia Index (LMDI) decomposition method to evaluate the contribution of each driving factor in kaya identity. Meanwhile, the Gravity Center model was introduced to quantify the change in the spatial distribution, and this study developed a decomposition method to identify the major driving factor on the movement of the gravity center. Moreover, this study summarizes the decarbonization measure of China's P&C and proposes some targeted policy implications to seek the best practical path for decarbonization in the future.

This paper is structured as follows: Section 2 reviews the relevant studies on investigating the change in the temporal trend and spatial distribution of CO_2 emissions. Section 3 introduces the calculation process of the LMDI method and gravity central model. Meanwhile, the data source is also represented in this section. Section 4 represents the change in temporal trend of CO_2 emissions of national and provincial P&C during the period of 2005–2015, and analyzes the contribution of each driving factor. Section 5 represents the movement of the gravity center of CO_2 emission of China's P&C and discusses it major driving factors. This section also summarizes the decarbonization measures of China's P&C and proposes some targeted policy implications. Finally, Section 6 describes the main findings of this study, along with recommendations for future research.

2. Literature review

2.1. Research on the temporal trend of CO_2 emissions

Accurate data accounting is a prerequisite when analyzing the temporal trends and spatial distribution of CO_2 emissions [10]. Existing studies have established a time series of energy consumption and carbon emissions in buildings sectors according to bottom-up [7,11,12] and up-bottom methods [4,13]. For the bottom-up, according to the Long-range Energy Alternatives Planning model, the Lawrence Berkeley National Laboratory quantifies the energy consumption of end-user services of China's P&C and residential buildings and includes three layers: building types (L1), end-user services (L2), and equipment (L3) [7]. The China Building Energy Model (CBEM) developed by Tsinghua University also uses a bottom-up approach to calculate the end-use energy. The model includes the building and user number module [11]. Based on macro statistics and micro survey data, Huo et al. established an end-use energy disaggregate model to investigate the energy consumption of five end-use services (i.e. heating, cooling, lighting, water heating, and equipment) in three China's climate areas [8]. Bottom-up methods can facilitate to compare the CO_2 emissions and energy consumption of different regions, but usually need some hypothesis and large-scale survey on building actual energy utilization (e.g. occupant information and behavior, energy efficiency and number of appliance, climate condition and so on) to derive the accurate and reasonable data [13]. There is little authoritative open data for reference in China. By contrast, up-bottom methods have a simpler calculation process and benefit to analyze the trend of macro building CO_2 emissions [13]. Besides, the data source of up-bottom methods is more authoritative and mainly from energy balance sheets, such as the International Energy Agency (IEA) [14], Eurostate [15], and China's Year book [16]. According to splitting the energy balance sheet, the China Association of Building Energy Efficiency [5] has a provincial time-series of energy consumption and carbon emissions, covering urban residential buildings, rural residential buildings, and P&C buildings. This is the data source used in this study.

Referring to the driving factors of changes in the temporal trend. Commoner et al. selected population, scale of the economy, and technological progress as the driving factors, and developed the IPAT model [17]. York et al. extended the IPAT model (STIRPAT), which overcame the deficiency of IPAT that does not allow the driving factors to produce nonmonotonic or nonproportional effects [18]. Hitherto, the STIRPAT model has been widely adopted to carry out regression analysis and to identify the major driving factors of changes in the temporal trends of CO_2 emissions [19–21]. For example, according to the STIRPAT model, Nasit et al. explored the impact of financialization, economic development, and industrialization on the CO_2 emissions of Australia, and the results indicated economic growth and trade openness had an obvious impact on the CO_2 emissions [20]. Cong et al. [21] analyzed the driving factors for China' building sector under different climatic conditions, and pointed out that population had the largest impact on the CO_2 emissions. Factor decomposition methods were also wildly employed to explore the contribution of driving factors, and mainly included Structural decomposition analysis [22] and Index decomposition analysis [23]. Generally, the Index decomposition analysis method is more popular since it is flexible and requires less data. The LMDI method is a branch of Index decomposition analysis, and has been widely used in empirical studies since it has no residual values and can achieve a total decomposition [24]. In building sectors, combing Kaya Identity, Ma, and Cai accessed the driving factors of CO_2 emission unit area of China' P&C at the national level from 2000 to 2005 and pointed out that floor space demand unit of GDP in China's Service Industry was the most important driving factor for the decarbonization in China' P&C [25]. The study of Liang et al. mainly focused on the driving factor of CO_2 emissions from residential buildings in China's megacities, and concluded that housing purchasing power was the most important driving factor for decarbonization [26]. Based on the Generalized Divisia Index Method, Ma et al. investigated the driving factors of CO_2 emission unit area of China megalopolises' P&C [27]. However, there is few studies focusing on the driving factors of CO_2 emissions from China's P&C, especially for the provincial level.

2.2. Research on spatial distribution of CO_2 emissions

Previous studies have investigated the spatial distribution of CO_2 emissions and its' change through different methods. Firstly, studies employing spatial econometric analysis have focused on the factors contributing to CO_2 emissions and have identified spatial autocorrelation features [28]. For example, Wang et al. employed Moran's I index to analyze China's provincial CO_2 emissions and discovered apparent spatial correlation and represented spatial agglomeration characteristics [28]. Yang et al. used data collected between 2000 and 2017 to explore the spatial distribution of residential CO_2, finding that the spatial distribution of the high concentration expanded at first and then contracted [29]. Furthermore, according to convergence analysis, some studies have found that carbon emissions in the different regions of China are converging in the mode of "convergence clubs", while the inter-club gap is growing [30]. Moreover, other studies have employed an inequality index to comprehensively reveal the regional distribution of CO_2. Common inequality indexes include the Theil Index [31], Gini Index [32], coefficient of variation [4,32], Atkinson index [33], and Zenga index [28]. Furthermore, some indexes can be decomposed into different units, groups, and driving factors [34,35]. According to Theil index, Li et al. [36] analyzed the macroeconomic drivers for the regional disparity of per-capita CO_2 emissions in China's building sector. However, there is residual in the decomposition value of the Theil index. To address this shortcoming, Wang et al. [28] combined Kaya identity with the Zenga index to calculate the imbalance of provincial CO_2 and decomposed it into four multiplier factors. The result showed that the imbalance of population was highly correlated with the imbalance of provincial CO_2. Furthermore, some scholars focused on the relationships among different regions to analyze the energy or emission flow in a spatial network, and metrics of the Social network method are common tools used to conduct this analysis [37].

The gravity center method is also widely used in CO_2-emission-related studies since it can directly reflect the spatial distribution and dynamic evolution of regional CO_2 emissions [38,39]. The gravity center is a physical conception that was first utilized to investigate trends in the American population by Hilgard [40]. The gravity center method has been widely applied for analysis of population dynamics [39,41], economics [39,42], technological innovation [43], urbanization [44], environmental pollution [45,46], and energy production and consumption [47]. In this regard, some scholars have explored the dynamic evolution of the gravity center in CO_2 emissions [48,49]. For example, Balsa-Barreiro et al. investigated the movement of the gravity center of global energy-related CO_2 emissions from 1960 to 2016, finding that the gravity center significantly moved southeastward [39]. Song and Zhang reached similar conclusions and even quantified the regional contribution to the movement, indicating that Asia had the largest contribution of emissions southward of the gravity center [50]. Wang and Feng further explored the dynamic evolution of the gravity center of China's regional residential CO_2 emissions [38]. Li et al. found that the gravity center of China's regional industry CO_2 emissions continuously moved south from 2008 to 2017 [51]. Although existing studies have discussed the dynamic movement of the gravity center of CO_2 emissions overall or for different sectors in detail, what and to what extent the driving factors lead to this change remain unclear.

Based on above literature review, this study has two important contributions: 1) Identify the driving factor of operation phase CO_2 emissions of national and provincial P&C; 2) Introduce a gravity center model to quantify the change in spatial distribution of CO_2 emissions of China's P&C. Meanwhile, in combination with kaya identity, this study develops a decomposition method to quantify the contribution of different driving factors to movement of the gravity center.

3. Data and methods

3.1. Kaya identity of CO_2 emissions of China's P&C

The Kaya identity was proposed by Kaya [52] and was used to represent the coupling relationship between carbon emissions and the related factors [27]. Combined with kaya identity, this study tried to quantify the contribution of some factors on the temporal and spatial change of the CO_2 emissions in China's P&C. Associated with the characteristics of public and commercial buildings, Chen et al. [53], Li et al. [54] and Liang et al. [26] have proposed the Kaya identity of China's P&C. Based on these studies, this study developed the Kaya identity of China's P&C and decomposed the CO_2 emission of China's P&C into five factors (Eq. (1)) and their contributions to the gravity center movement.

$$C = \frac{C}{E} \times \frac{E}{S} \times \frac{S}{GDP} \times \frac{GDP}{P} \times P = EF \times EI \times EE \times PV \times P \tag{1}$$

where C represents the CO_2 emission derived from P&C, E represents energy consumption, including primary energy (e.g., coal, natural gas, and oil) and secondary energy (e.g., heating and electricity). S represents the floor area of P&C; GDP and P represent the add value of tertiary industry, and population, respectively. EF, EI, EE, and PV are the abbreviations for energy-related emission factor, energy consumption unit area, economic efficiency, and per capita output value of tertiary industry, respectively.

3.2. LMDI method

The LMDI method was first proposed by Ang [24]. In this study, it was used to directly quantify the contribution of five factors to the temporal change of CO_2 emission of China's P&C. The equation is shown by Eq. (2).

$$\Delta C = C^t - C^0 = \Delta EF + \Delta EI + \Delta EE + \Delta PV + \Delta P \tag{2}$$

where C^t and C^0 represent the CO_2 emissions of China's P&C in t th and benchmark year, respectively. ΔEF, ΔEI, ΔEE, ΔPV and ΔP represent the effect of five factors on the temporal change of CO_2 emissions of China's P&C and are calculated using Eqs. (3)–(7).

$$\Delta EF = \frac{C^t - C^0}{ln(C^t) - ln\left(C^0\right)} ln\left(\frac{EF^t}{EF^0}\right) \tag{3}$$

$$\Delta EI = \frac{C^t - C^0}{ln(C^t) - ln\left(C^0\right)} ln\left(\frac{EI^t}{EI^0}\right) \tag{4}$$

$$\Delta EE = \frac{C^t - C^0}{ln(C^t) - ln\left(C^0\right)} ln\left(\frac{EE^t}{EE^0}\right) \tag{5}$$

$$\Delta PV = \frac{C^t - C^0}{ln(C^t) - ln\left(C^0\right)} ln\left(\frac{PV^t}{PV^0}\right) \tag{6}$$

$$\Delta P = \frac{C^t - C^0}{ln(C^t) - ln\left(C^0\right)} ln\left(\frac{P^t}{P^0}\right) \tag{7}$$

3.3. Gravity center model

The gravity center model is employed to represent the spatial distribution of the CO_2 emissions of China's P&C. The gravity center model has been widely employed to analyze spatial distribution studies such as populations [45,46], energy consumption [47], economic growth [39, 42], and carbon emissions [47–49]. In this study, the gravity center of CO_2 emissions in China's P&C was calculated using Eq. (8) and Eq. (9).

$$X = \frac{\sum_i x_i C_i}{\sum_i C_i} \tag{8}$$

$$Y = \frac{\sum_i y_i C_i}{\sum_i C_i} \tag{9}$$

where x_i and y_i represent longitude and latitude of the given province's capital city i, and C_i represents the CO_2 emission of P&C in province i.

Furthermore, to quantify the contribution of five factors to the change in the spatial distribution of CO_2 emissions of China's P&C, we decomposed the movement of the gravity center. Because the calculation process of latitude and longitude of the gravity center is same, we only used the latitude of gravity center to show the calculation process. First, we defined the change in the latitude of the gravity center of CO_2 emissions in China's P&C using Eq. 10

$$\Delta X = X^1 - X^0 = \frac{\sum_i x_i C_i^1}{\sum_i C_i^1} - \frac{\sum_i x_i C_i^0}{\sum_i C_i^0} = \frac{1}{C^1 C^0}\left(C^0 \sum_i x_i C_i^1 - C^1 \sum_i x_i C_i^0\right) = \frac{1}{C^1 C^0}\left(C^0 \sum_i x_i C_i^1 - C^1 \sum_i x_i C_i^0\right) = \frac{1}{C^1 C^0}\left(\sum_i x_i \left(C^0 C_i^1 - C^1 C_i^0\right)\right) \tag{10}$$

where C^1 and C^0 represent the national CO_2 emissions of China's P&C in target year and base year, respectively; C_i^1 and C_i^0 represent the P&C CO_2 emissions of province i in target year and base year, respectively.

Based on the Kaya identity (Eq. (1)) and LMDI method, we achieved a completed decomposition of the content within the bracket of Eq. (10) into the contributions of the five factors. The full calculation process is showed in the series of Eqs.(11)–(16) as follows:

$$C^0 C_i^1 - C^1 C_i^0 = \frac{C^0 C_i^1 - C^1 C_i^0}{ln\left(C^0 C_i^1 / C^1 C_i^0\right)} \times \left(ln\left(\frac{C^0}{C^1}\right) + ln\left(\frac{C_i^1}{C_i^0}\right)\right) = \frac{C^0 C_i^1 - C^1 C_i^0}{ln\left(C^0 C_i^1 / C^1 C_i^0\right)} \times \left(ln\left(\frac{EF^0 EI^0 EE^0 PV^0 P^0}{EF^1 EI^1 EE^1 PV^1 P^1}\right) + ln\left(\frac{EF_i^1 EI_i^1 EE_i^1 PV_i^1 P_i^1}{EF_i^0 EI_i^0 EE_i^0 PV_i^0 P_i^0}\right)\right) = \Delta EF + \Delta EI + \Delta EE + \Delta PV + \Delta P \tag{11}$$

$$\Delta EF = \frac{C^0 C_i^1 - C^1 C_i^0}{ln\left(C^0 C_i^1 / C^1 C_i^0\right)} \times \left(ln\left(\frac{EF^0}{EF^1}\right) + ln\left(\frac{EF_i^1}{EF_i^0}\right)\right) \tag{12}$$

$$\Delta EI = \frac{C^0 C_i^1 - C^1 C_i^0}{ln\left(C^0 C_i^1 / C^1 C_i^0\right)} \times \left(ln\left(\frac{EI^0}{EI^1}\right) + ln\left(\frac{EI_i^1}{EI_i^0}\right)\right) \tag{13}$$

$$\Delta EE = \frac{C^0 C_i^1 - C^1 C_i^0}{ln\left(C^0 C_i^1 / C^1 C_i^0\right)} \times \left(ln\left(\frac{EE^0}{EE^1}\right) + ln\left(\frac{EE_i^1}{EE_i^0}\right)\right) \tag{14}$$

$$\Delta PV = \frac{C^0 C_i^1 - C^1 C_i^0}{ln\left(C^0 C_i^1 / C^1 C_i^0\right)} \times \left(ln\left(\frac{PV^0}{PV^1}\right) + ln\left(\frac{PV_i^1}{PV_i^0}\right)\right) \tag{15}$$

$$\Delta P = \frac{C^0 C_i^1 - C^1 C_i^0}{ln\left(C^0 C_i^1 / C^1 C_i^0\right)} \times \left(ln\left(\frac{P^0}{P^1}\right) + ln\left(\frac{P_i^1}{P_i^0}\right)\right) \tag{16}$$

Therefore, the contribution of each factor to the gravity center can be represented by the follow equation. Here, we only represent the contribution of population in the longitudinal direction ($MC_{X,P}$, Eq. (17)).

$$MC_{X,P} = \frac{1}{C^1 C^0}\left(\sum_i x_i \left(\frac{C^0 C_i^1 - C^1 C_i^0}{ln\left(C^0 C_i^1 / C^1 C_i^0\right)} \times \left(ln\left(\frac{P^0}{P^1}\right) + ln\left(\frac{P_i^1}{P_i^0}\right)\right)\right)\right) \tag{17}$$

3.4. Data source

In this study, the data covered 30 provinces of the Chinese mainland from 2005 to 2018, except for Tibet. Provincial CO_2 emissions, energy consumption, and the building floor area of public buildings were derived from the Chinese Association of Building Energy Efficiency [5], which splits the Chinese energy balance sheet to get data. Besides, considering the difference between the emission factors of electricity in different regions, this study calculated the emission factors of Chinese six power grids and remanded the CO_2 emission derived from provincial electricity consumption. The Chinese years book provided the popula-

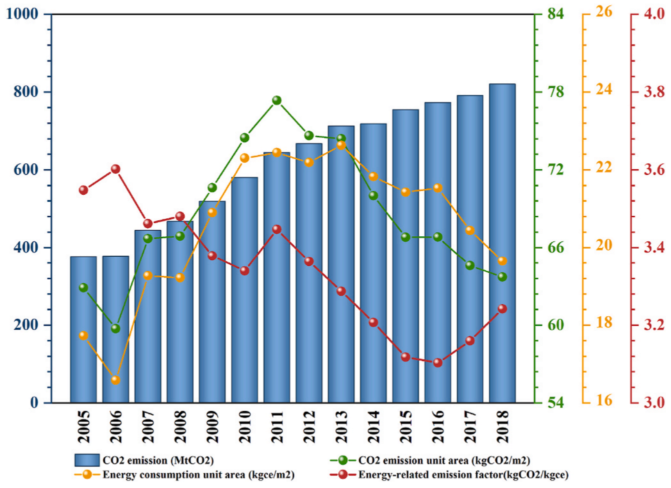

Fig. 1. CO_2 emissions of the Chinese national P&C sector from 2005 to 2018.

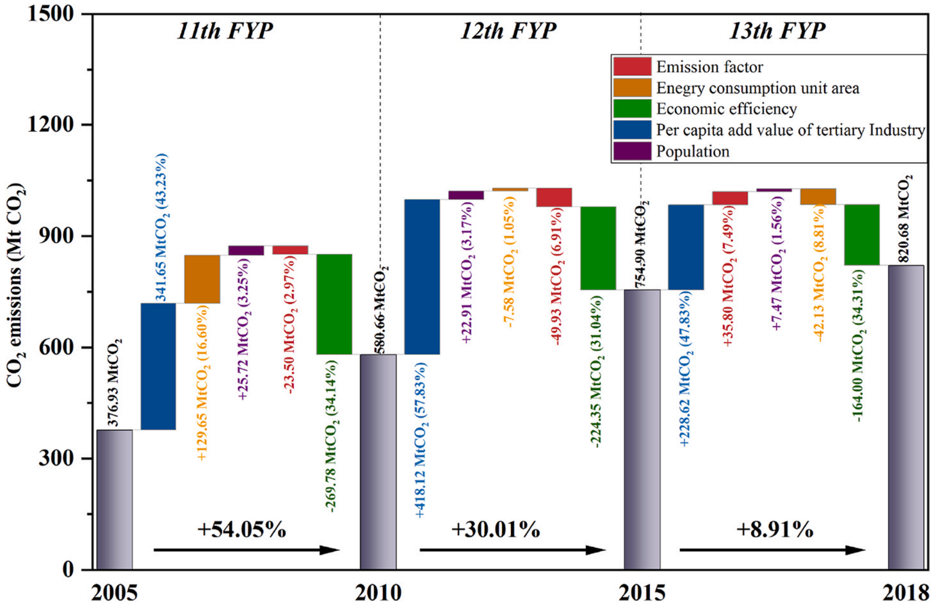

Fig. 2. Driving factors on temporal trend at national level. (Note: 11th, 12th' and 13th FYP represent the period from 2005 to 2010, 2010–2015 and 2015–2018, respectively.)

tion and added value of tertiary industry [55]. The coordinates of each province were collected from a Gaode map.

4. Change in temporal trend of P&C CO_2 emissions

4.1. Temporal trend of P&C CO_2 emission at national level

Fig. 1 represents the CO_2 emissions of China's P&C. CO_2 emissions unit area, energy consumption unit area, and energy-related emission factors represented by an inverted U change trend, and they reached peaks in 2011 (77.36 kgCO$_2$/m^2), 2011 (22.44 kgce/m^2) and 2006 (3.60 kgCO$_2$/kgce), respectively. This can be attributed to a series of energy efficiency and CO_2 emission mitigation policies, such as promoting a higher mandatory building energy efficiency standard (from 30% energy-saving rate to 75% energy-saving rate), establishing the P&C energy consumption monitoring platform, energy renovation for existing P&C buildings, and clean energy production. However, due to the rapid increase in per capita growth, there was a resulting increase in P&C floor area demand (from 4.64 m^2/person in 2005 to 9.21 m^2/person in 2018) that prevented CO_2 emissions of China's P&C from reaching their peak value, and instead, the value increased from 376.93 MtCO$_2$ in 2005 to 820.68 MtCO$_2$ in 2018.

The results of deciphering the temporal change in CO_2 emissions of China' P&C is shown in Fig. 2. It can be observed that economic efficiency was the major contributor for emission mitigation (more than 25%), contributing 269.78 MtCO$_2$ (−34.14%), 224.33 MtCO$_2$ (−31.04%), and 164.00 MtCO$_2$ (−34.31%) in 2005–2010, 2010–2015 and 2015–2018, respectively. The effect of the energy-related emission factor was not fixed. Specifically, the energy-related emission factor hindered and promoted the CO_2 emission of China' P&C before and after 2015, respectively. This may have been caused by the high energy-related emission factor of electricity and quick building electrification process. Specifically, the electrification rate increased from 33.94% in 2015 to 45.84% in 2018, while the energy-related emission factor of electricity (North China Power Grid: 4.58 kgce/kgCO$_2$ in 2018) was higher fossil fuel (i.g Coal, Oil and Natural gas). Therefore, the designing future electrification process of China's P&C should refer to the decarbonization process of electricity generation and energy efficiency of electric appliance. Take Chongqing as an example, the electricity emission factor of Chongqing was 3.05 kgCO$_2$/kgce in 2018, which was nearly twice that of natural gas. The similar energy efficiency ratio (EER) of gas-fired and electric water heater indicates this building electrification process will increase the CO_2 emission of China' P&C. By contrast, duo to the EER of a heating pump (more than 3) is more than triple of gas-fired boiler (less than 1), the heating electrification process can reduce the CO_2 emission of China' P&C.

On the contrary, the per capita add value of tertiary industry was the major contributor for promoting CO_2 emissions of 341.65 MtCO$_2$ (43.23%), 418.12 MtCO$_2$ (57.83%) and 228.62 MtCO$_2$ (47.83%) in 2005–2010, 2010–2015 and 2015–2018, respectively. Meanwhile, after 2010, energy consumption unit area promoted the decarbonization of China's P&C, indicating the improvement of building energy efficiency techniques can effectively offset the growth of P&C end-user services demand. Besides, population has positive impact on the increase in CO_2 emissions, although the impact was smaller and didn't reach 4% during whole period.

4.2. Temporal trend of P&C CO_2 emission at the provincial level

Fig. 3 represents the historical CO_2 emissions trend of provincial P&C and their driving factors. 30 provinces were divided into five climate areas: Severe cold (SC), Cold (CA), Hot summer and cold winter (HSCW), Hot summer and warm winter (HSWW), and Warm areas (WA) [10]. Concerning the trend in CO_2 emissions changes in the 30 provinces from 2005 to 2018, the P&C in most of the provinces still hasn't reach its achieved carbon peak. Because of the decarbonization process of central heating [4], in Chinese central heating areas (sever cold and cold areas), the P&C in some province has achieved its carbon peak, including Beijing (2012, 70.40 MtCO$_2$), Shandong (2012, 72.23 MtCO$_2$), Inner Mongolia (2014, 53.27 MtCO$_2$), Heilongjiang (2016, 60.26 MtCO$_2$), Jilin (2016, 30.35 MtCO$_2$), Hebei (2017, 38.39 MtCO$_2$), etc. Most provinces in other climate areas have still not reached their CO_2 emission peak due to the quick development of the tertiary industry and increasing entertainment demand of residents.

For the driving factors of provincial P&C CO_2 emissions, during the whole study period, per capita added value of tertiary industry was always the most positive contributor for all provinces, contributing more than 30%. Per capita add value of tertiary industry had a higher positive contribution to the provinces in the China's non-central heating area (i. e., Hot summer and cold winter, Hot summer and warm winter, and

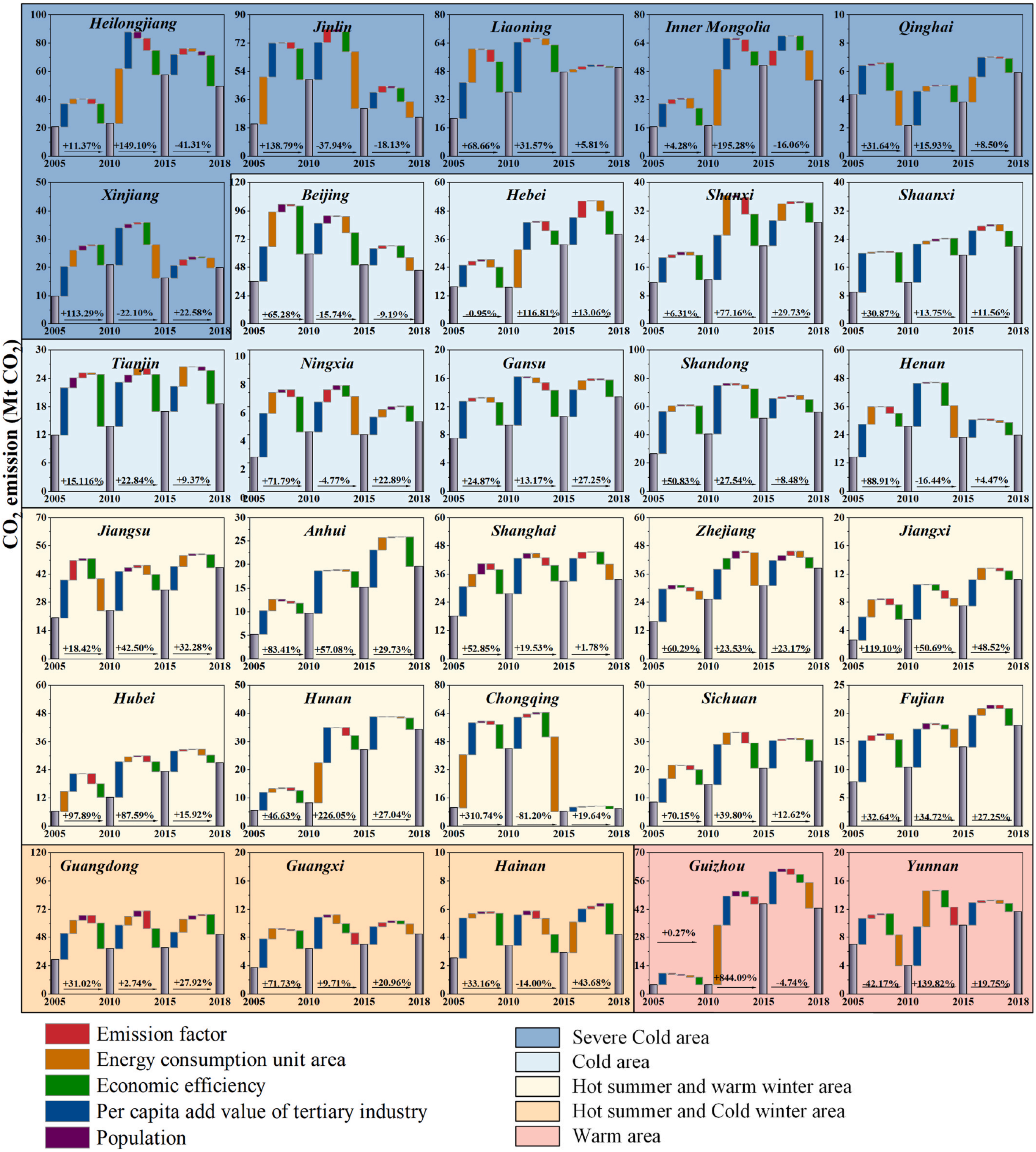

Fig. 3. Driving factors on temporal trend at the Provincial level.

Warm areas) compared with China's central heating area (i.e., Severe cold and Cold area). On the contrary, economic efficiency was most negative contributor for almost all provinces. The average contribution of economic efficiency in each of the five climate areas can be ranked as follows: SA (40.49%)> SC (37.71%) > HSWW (32.01%) > HSCW (29.52%) > WA (18.50%).

The contribution of the energy consumption unit area was not fixed. In the 13th FYP, the energy consumption unit area of more than half provinces has a negative contribution for their P&C CO_2 emissions, such as Xinjiang (−30.44%), Inner Mongolia (−40.91%), Jilin (−29.75%), Shanghai (−27.22%) and Zhejiang (−11.77%), indicating their energy consumption unit area has peaked. While energy consumption unit area has the largest positive contributions in Qinghai (40.92%). Notably, in some provinces (i.e. Anhui, Chongqing, Jiangsu, and Jiangxi) located in China's HSCW climate area, the contribution of energy consumption unit area represented a negative contribution in the 12th FYP and a positive contribution in the 13th FYP, indicating a rebound of energy demand rebound which may be caused by an increasing heating demand and Building Energy Research Center of Tsinghua University (BERC) has pointed out the heating energy consumption of HSCW climate area increased from 2 Mtce to 16.52 Mtce during the period of 2001–2015 [56]. Therefore, to offset this increase, this study suggests improving building insulation performance according to promote better building energy efficiency standards for new buildings and energy retrofit for existing buildings.

The emission factor always had a negative contribution for most provinces during the 12th FYP. In this period. the proportion of renewable energy utilization on a building site increased by 4% [57] and China's air clean plan reduced the energy-related emission factor of heating and electricity production according to eliminating outdated boilers and improving in renewable energy proportion. While, due to the rapid growth of the share of electricity in the energy structure, the emission factors of the provinces rebounded during the 13th FYP. Specifically, emission factor promoted P&C CO_2 emissions for most provinces in China's SC and CA area, especially for Inner Mongolia (20.06%), Liaoning (28.60%) and Hebei (20.49%). That is caused by its' higher emission factor of electricity (5.66 $kgCO_2/kgce$). Notably, the electricity rate of China's SC and CA areas still was lower than other climate areas. Therefore, the decarbonization of energy generation sector should be accelerated.

During the 13th FYP, the population had a less positive or even negative contribution in the provinces of the SC. While, due to the southward migration of the population [41,58] and developed economic condition, the population had the larger positive contributions in Chongqing (5.43%), Guangdong (6.90%), and Zhejiang (9.31%). Considering their better economic condition, this study suggests these provinces improve building insulation performance and building onsite utilization of renewable energy, and establish a great financial support system to accelerate their energy transition.

5. Change in spatial distribution change of P&C CO_2 emissions

5.1. *The movement of the gravity center of China's P&C CO_2 emissions*

Fig. 4 shows the spatial distribution of CO_2 emissions and CO_2 emissions unit area of provincial P&C in 2005 and 2018. Specifically, Shandong had the largest P&C CO_2 emissions contribution (55.98 $MtCO_2$), while Hainan had the smallest contribution (4.22 $MtCO_2$) in 2018. Due to central heating demand, P&C CO_2 emissions unit area of central heating area (i.e SC and CA) (95.99 $kgCO_2/m^2$) was nearly two times that of the other provinces (45.63 $kgCO_2/m^2$) in 2018. Meanwhile, CO_2 emissions unit area of the provinces with developed economic condition were higher than those in the provinces with less developed economic conditions. For example, as shown in Fig. 3, Guangdong, which is adjacent to Guangxi, has three times more P&C CO_2 emissions unit area (61.70 $kgCO_2/m^2$) than Guangxi (24.06 $kgCO_2/m^2$). Besides, P&C CO_2 emissions unit area of Guizhou was lower and higher than other provinces in 2005 and 2018, respectively, which may be caused by the development of the big data industry (e.g., server farms).

Fig. 5 shows the movement of the gravity center of CO_2 emissions in China's P&C, and the provincial contribution is shown in.Table A1 Across all study periods, the longitude and latitude of the gravity center were always greater than the mean longitude (112.74°E) and latitude (33.69°N), respectively, which indicates that the CO_2 emissions of P&C

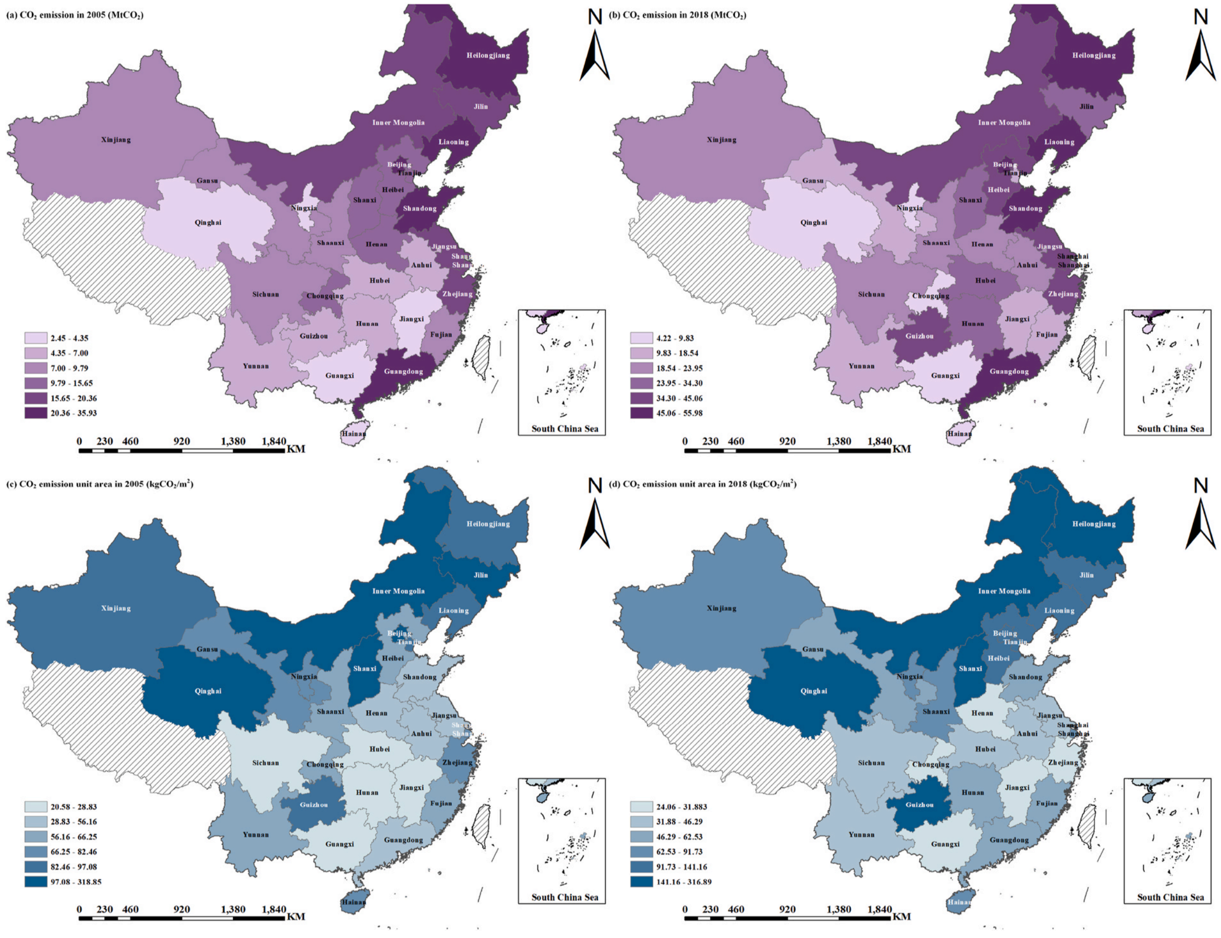

Fig. 4. Spatial distribution of CO_2 emission of provincial P&C in 2005 and 2018.

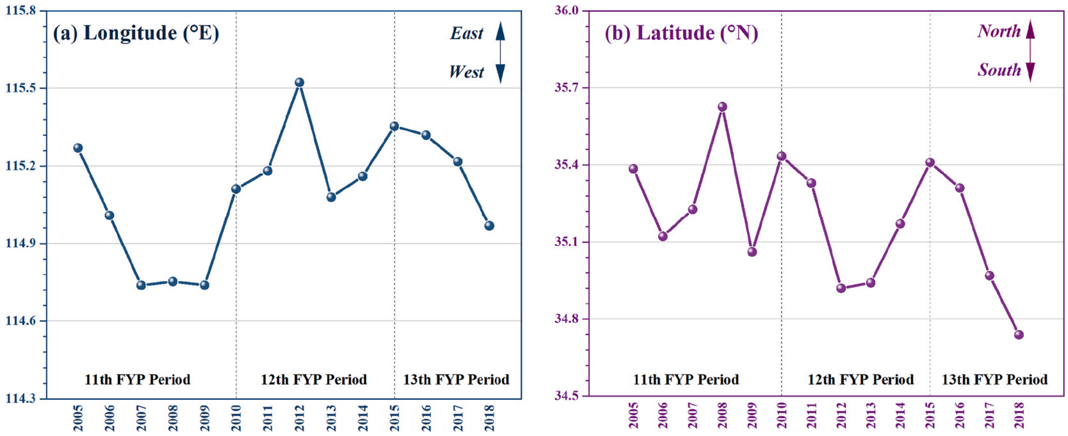

Fig. 5. Movement of the gravity center of CO_2 emissions in China's P&C.

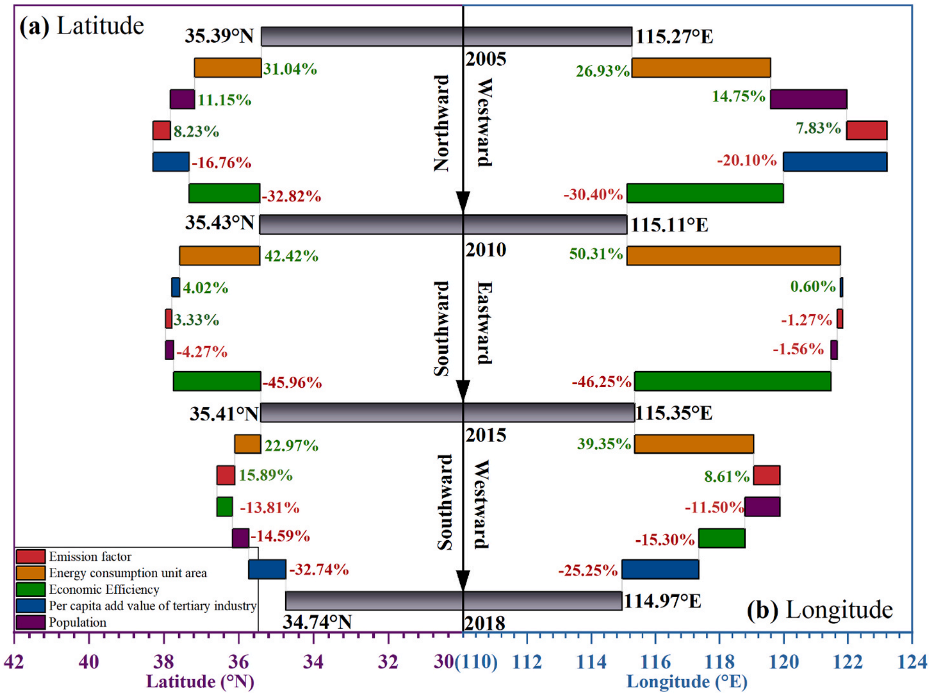

Fig. 6. Contribution of each factor in China's 11th, 12th, and 13th FYP periods. (Note: the values near the bars represent the ratio of different factors' effects to the sum of the absolute value of the combined factors' effect.)

in China's northern and eastern areas were always larger than those of China's southern and western areas, respectively.

Latitudinally, the gravity center showed a fluctuation between 35.90°N and 34.90°N before 2015. After 2015, the gravity center significantly moved south at an increasing speed, as seen in the shift from 0.10 °N/year in 2015 to 0.33 °N/year in 2018. Longitudinally, the movement trend of the gravity center represents an inverted N shape. Specifically, in during the period of 2005–2007, the gravity center moved westward from 115.27°E to 114.75°E. During next four years, the movement orientation of the gravity center shifted back to the east, and the gravity center arrived 115.52°E. In China's 13th FYP Period (2015–2018), the gravity center moved westward at an increased speed, reaching 114.20°E in 2018.

5.2. Driving factors on the movement of the gravity center

Fig. 6 represents the contribution of five factors to the change of spatial distribution of CO_2 emissions in China's P&C and specific values can be seen in Table A1. In Fig. 6 and Table A1, positive values represent promoting the gravity center move eastward and northward in the longitude and latitude orientation, respectively. While negative values represent promoting the gravity move westward and southward in longitude and latitude orientation, respectively.

In the overall study period, energy consumption unit area was the largest contributor for promoting the eastward and northward movement of the gravity center of CO_2 emissions in China's P&C, contributing to more than a quarter of the total absolute contribution latitudinally (31.04% in the 11th FYP, 42.42% in the 12th FYP, and 22.97% in the 13th FYP) and longitudinally (26.93% in the 11th FYP, 50.31% in the 12th FYP, and 39.35% in the 13th FYP), indicating, compared with west and south area of China, the energy consumption unit area increased more quickly in north and east area of China. The provinces in the east area of China usually better residential economic condition, which indicates their residents have higher entertainment demand (i.e end-user services demand) and need to be meet by longer service period and more services appliances. Meanwhile, the central heating demand of provinces in the north area of China was quickly increased, the central heating penetration rate increased from 26.36% in 2005 to 39.16% in 2018. Followed positive contributor is energy-related emission factor, indicating a quicker faster clean-up process of energy structure in south and west area of China, which was mainly caused by quicker decarbonization process of electricity generation. Specifically, the energy-related emission factors of electricity in the north area of China (5.67 $kgCO_2$/kgce) was nearly 1.80 times that of the south area (3.15 $kgCO_2$/kgce), and the provinces in the west area of China usually hydroelectricity potential, especially for Sichuan whose hydroelectricity accounted for more than 85% of its' electricity generation [5]. Population pushed the gravity center southward and westward in the 13th FYP. These shifts were consistent with the movement of population gravity center [41]. Considering the high CO_2 emission unit area in the northern (due to central heating) and eastern area (due to better economic condition), the southward and westward mitigation of the population can have positive impact on the CO_2 emission mitigation of China's P&C sector [59].

Economic efficiency was the largest contributor for promoting westward and southward movement of the gravity center of CO_2 emissions of China's P&C, and its contributions were more than one quarter in both the latitude (−32.82 in the 11th FYP, −45.96% in the 12th FYP, and −13.81% in the 13th FYP) and longitude direction (−30.40% in the 11th FYP, −46.25% in the 12th FYP, and −15.30% in the 13th FYP) during study period. Therefore, the contribution of economic efficiency suggests that the southern and western areas of China showed quicker improvements in tertiary industry efficiency than the northern and eastern areas, respectively. Besides, in the 13th FYP, the per capita add value of tertiary industry. the gravity center moved southward 0.99 °N and westward 2.38°E.

In summary, section 5 investigated the spatial distribution change and it's driving factors addressing the investigation response the second study issue in the Introduction.

6. Decarbonization strategies of China's P&C

To support the development of a reasonable decarbonization pathway and the achievement of a carbon peak and neutrality of China's P&C, this study reviewed relevant decarbonization strategies. Meanwhile, according to factors detailed in the Kaya Identity (Eq. (1)), all measures can be divided into three categories: optimize energy structure (*EF*), improve building energy efficiency (*EI*), and improve economic efficiency (*EE*). Because the population and per capita add value to the tertiary industry belonging to social-economic parameters, these two categories were excluded. Meanwhile, all measures were divided into two categories, onsite (proposed by building sector and implemented directly on buildings) and offsite strategies (proposed by upstream sectors of building sector and finance sectors, such as heating and electricity production, and finance sector), based on sector affiliation, indicating the decarbonization of China's P&C needs collaboration between the building sector and other sectors [60].

6.1. *Optimize energy structure (EF)*

Fig. 7 represents the proportion of final energy and energy-related emission factors of each province. As shown in this figure, the provinces in the northern region China had higher energy-related emission factors due to the high coal sharing and high energy-related emission factors of heating and electricity generation. Therefore, decarbonization of energy structure is more important. To achieve this, for building sector's on-site, P&C should: 1) eliminate the utilization of energy types with the high emission factor (i.e coal), especially for major coal producing provinces in China, such as Heilongjiang, Inner Mongolia, Shandong and Shanxi, coal usually accounted for more proportion in P&C energy structure of these provinces; 2) increase on-site utilization of renewable energy sources, such as ground source heat pumps and photovoltaic rooves, especially for the provinces in SC, SA and HSCW, who have heating demand in winter [61]. For buildings' off-site, the heating and electricity generation sector should accelerate the decarbonization process, including the: 1) elimination of outdated boilers to improve fuel conversion efficiency [62]; 2) increase in on-site utilization of renewable energy sources in heating and electricity generation [63] 3) exploration of the arrangement of carbon capture, utilization, and storage technologies. This study suggests the with high proportion of

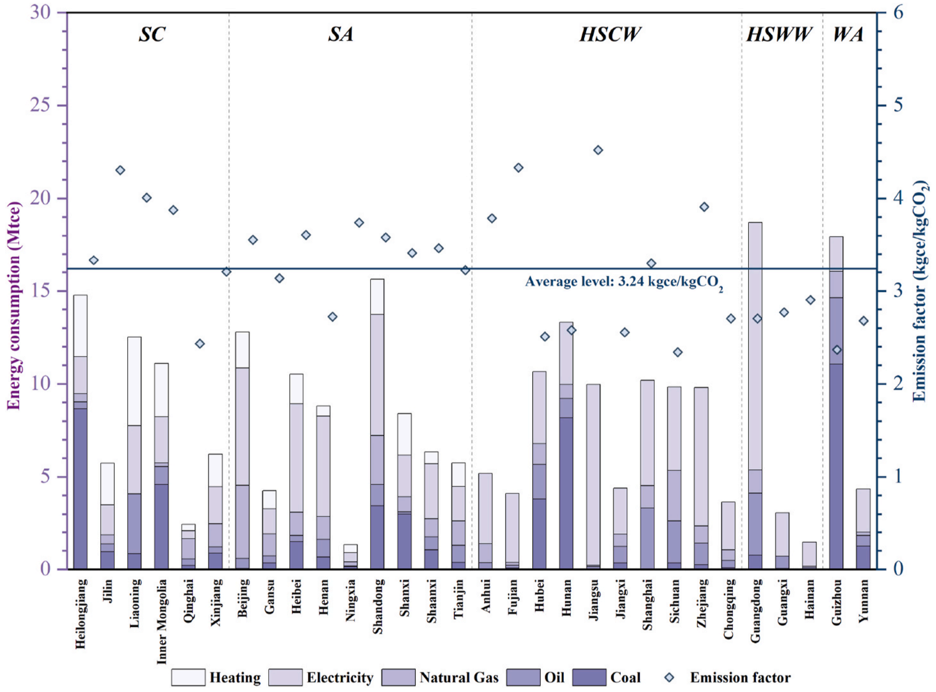

Fig. 7. Energy structure and energy-related emission factor of provincial P&C.

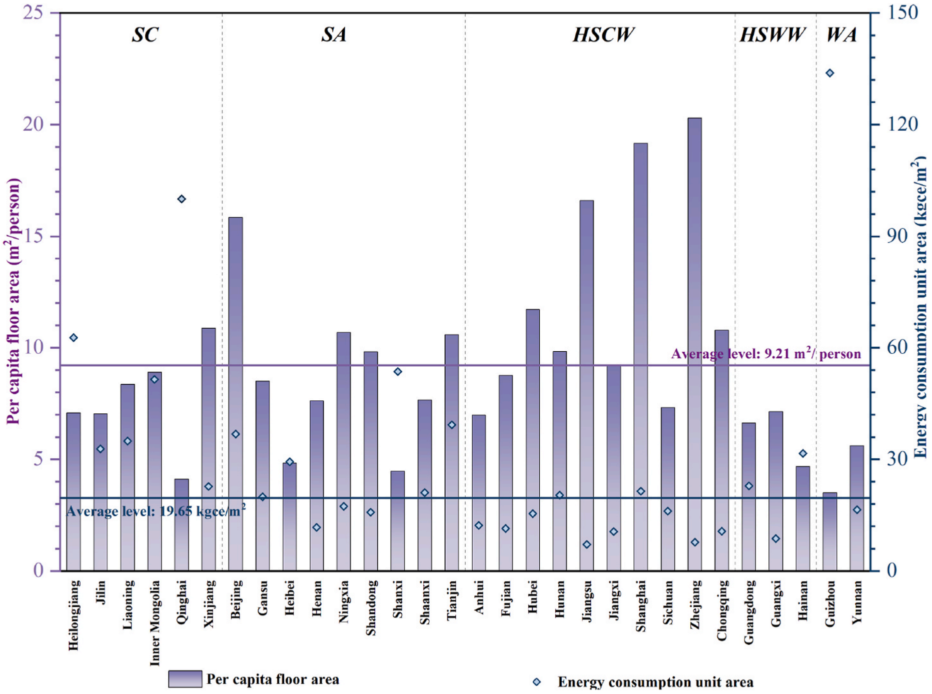

Fig. 8. Energy consumption unit area and Per capita floor area.

secondary energy, such as Jiangsu, Guangdong and Beijing pay more attention on these buildings' off-site decarbonization strategies and accelerated decarbonization of energy system. Besides, considering the high emission factor of electricity and electricity, which is higher than that of coal, natural gas, and oil, the electrification of the P&C building sector should consider the energy efficiency of electric appliances and coordinate with the clean production process of electricity, especially in China's northern region.

6.2. *Improve building energy efficiency (EI)*

Fig. 8 represents the per capita floor area and energy consumption unit area of provincial P&C. For building sector's on-site, China's P&C should 1) optimize new buildings design and promote the building design standard with a higher energy efficiency, such as ultra-low energy, near zero energy, and zero-energy buildings [25,64]; 2) promote energy retrofitting on existing P&C buildings to eliminate the technique

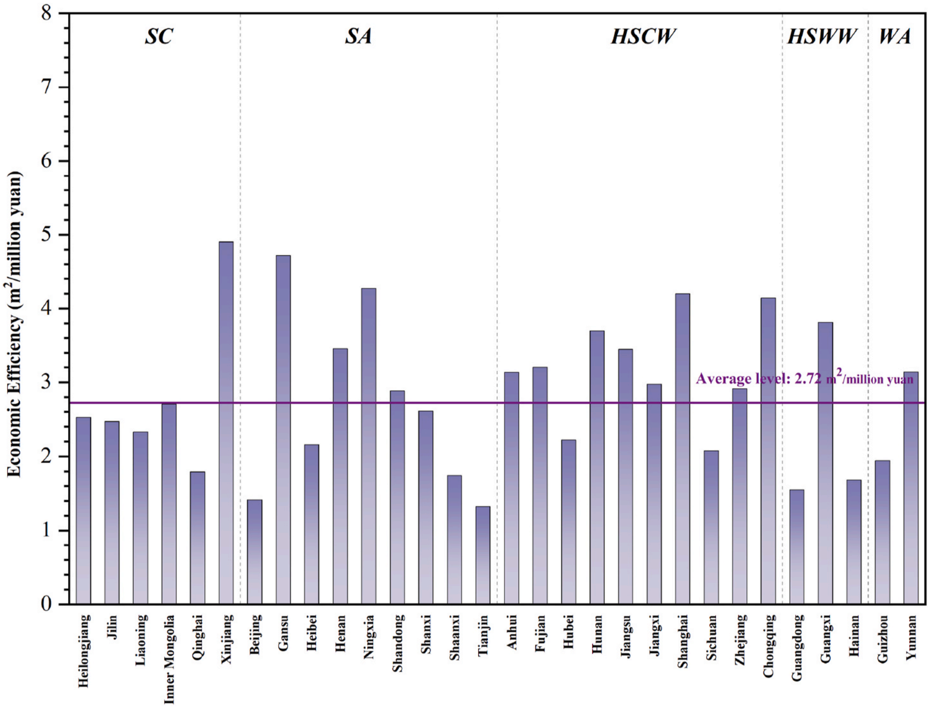

Fig. 9. Economic efficiency of provincial P&C.

lock-in risk [65]; 3) replace the end-user services appliance with higher energy efficiency, including heating, cooling, lighting, and other appliance. Meanwhile, building energy efficiency standard usually is renovated with building metabolism (i.e construction, retrofit and demolition) and has lock-in effect, this study suggests the provinces (e.g Heilongjiang, Qinghai, Hebei and Shaanxi), which have lower per capita floor area and will construct more new building, can promoted building energy efficiency standard with high energy saving rate as soon as possible. While the provinces (e.g Beijing, Zhejiang, Shanghai and Jiangsu), which have larger per capita floor area and will construct less new building, can promote a deeper and broader building energy retrofit. In building sector's off-site, government, and other sectors should adopt a series of financial policies to encourage residents' willingness to save energy, including 1) finance and subsidy, such as subsiding building energy retrofitting, on-site utilization of renewable energy, and project polit of ultra-low energy, near zero energy, and zero-energy buildings [66]; 2) reasonable energy pricing mechanism, such as tiered electricity prices and metering charge for heating [57]; 3) Furthermore, in order to strength this strategy, a carbon trading market of P&C building in national and provincial can be developed.

6.3. Improve economic efficiency

Fig. 9 represents the provincial economic efficiency (floor area/add value of tertiary industry) in 2018. As shown this figure, the unit add value of tertiary industry need less P&C floor area in the provinces with great economic condition, such as Tianjin (132.65 m^2/thousand yuan), Beijing (141.52 m^2/million yuan) and Guangdong (155.18 thousand yuan/m^2), while it needs added unit value of tertiary industry in Xinjiang (490.45 m^2/million yuan), Gansu (472.13 m^2/million yuan) and Ningxia (427.14 m^2/million yuan), which can be achieved by more P&C floor area. Therefore, for those provinces, improving the energy efficiency plays an important role for P&C decarbonization. For building sector 's on-site, those provinces should undergo reasonable urban planning to reduce new P&C construction and the vacancy rate of existing P&C buildings, which will result in the decarbonization of buildings' embodied carbon emissions [67]. For building sector 's off-site, government and other sectors should actively improve industrial production efficiency and promote low-carbon development of the tertiary industry.

In summary, section 6 reviewed major decarbonization measures of P&C and divided them into six categories. Meanwhile, based on the results of this study, section 6 also proposed some targeted policy implications. This section addressed the third aim of the study as detailed in the Introduction.

7. Conclusion and future research orientation

This study investigated the historical CO_2 emission of the national and provincial P&C sector during the period 2005–2018 and identified their driving factors combined with the kaya identity and LMDI method. Meanwhile, this study introduced a gravity center model to quantify the change in spatial distribution of the CO_2 emissions and developed a decomposed method to analyze its' driving factors. Moreover, this study reviewed decarbonization strategies of China's P&C and divided them into six categories based on parameters of kaya identity and whether they belong in the building sector (i.e., on-site and off-site). The main results are as follows:

(1) Regarding the temporal trend, the CO_2 emissions of China's P&C still hasn't reached its carbon peak, increasing from 376.93 $MtCO_2$ in 2005 to 820.68 $MtCO_2$ in 2018. Some provinces in China 's severe cold and cold areas have achieved a peak in their CO_2 emissions (e.g., Heilongjiang, Jilin, Inner Mongolia and so on). The most positive and negative driving factors were per capita added value of tertiary industry (contributions were larger than 40%) and energy efficiency (contributions were larger than 25%).

(2) Regarding the spatial trend, gravity center moved from (115.27°E, 35.39°N) in 2005 to (114.97°E, 34.74°N) in 2018. Movement was southwestward, northeastward, and then southwestward again in the 11th, 12th, and 13th FYP periods, respectively. Economic efficiency (contributions were larger than 25%) and energy consumption unit area (contributions were larger than 25%) were the major obstacles to the southwestward movement, respectively.

Although some meaningful findings were obtained in this study, several gaps can be filled with future endeavors. For the analysis of historic data, the study only focused on the CO_2 emissions of China's P&C. Given the different energy consumption characteristics, the movement of the gravity center, and the driving factors may vary significantly in other building types. Besides, this study didn't consider the end-user services (e.g., heating, cooling, lighting, and other appliances), thus future research on the decarbonization of end-user services is required. Finally, future studies should shift the focus from historical trend analysis to future simulation, developing reasonable decarbonization targets and pathways. This is critical for the achievement of China's carbon peak and neutrality climate goals.

CRediT authorship contribution statement

Kairui You: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yanhui Yu:** Data curation, Formal analysis, Validation, Writing – review & editing. **Weiguang Cai:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Zhengxuan Liu:** Data curation, Formal analysis, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Table A1
Contribution of each factor to the movement

Periods		EF	EI	EE	PV	P	Sum
Latitude	2018–2015	0.48	0.69	−0.42	−0.99	−0.44	−0.67
		15.89%	22.97%	−13.81%	−32.74%	−14.59%	
	2015–2010	0.17	2.14	−2.32	0.20	−0.22	−0.02
		3.33%	42.42%	−45.96%	4.02%	−4.27%	
	2010–2005	0.47	1.79	−1.89	−0.97	0.64	0.05
		8.23%	31.04%	−32.82%	−16.76%	11.15%	
longitude	2018–2015	0.81	3.71	−1.44	−2.38	−1.09	−0.39
		8.61%	39.35%	−15.30%	−25.25%	−11.50%	
	2015–2010	−0.17	6.65	−6.11	0.08	−0.21	0.24
		−1.27%	50.31%	−46.25%	0.60%	−1.56%	
	2010–2005	1.26	4.32	−4.88	−3.23	2.37	−0.16
		7.83%	26.93%	−30.40%	−20.10%	14.75%	

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