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Driving toward sustainable cities: The interplay between Chinese emerging corporate ESG performance and climate finance in achieving low-carbon development

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A R T I C L E I N F O

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A B S T R A C T

Climate finance plays a pivotal role in directing increased capital flow toward climate change mitigation and adaptation activities. Many emerging enterprises have grown rapidly under the influence of climate finance policies, contributing to urban low-carbon transition. Therefore, it is important to explore the interrelationships between climate finance, enterprise low-carbon transformations, and urban carbon emission efficiency. This study delves into the impact of climate finance on urban carbon emission efficiency and its underlying transmission mechanisms, drawing upon comprehensive panel data of 262 Chinese cities and 4125 enterprises from 2009 to 2019. The findings indicate that urban climate finance have significantly positive influences on urban carbon emission efficiency and unveil that enterprise environmental, social and governance (ESG) performance exhibits positive influences on urban carbon emission efficiency, underscoring the critical role of enterprises as the vanguard of climate finance. Moreover, the research presents the mediating effect of enterprise green innovation between the urban climate finance and carbon emission efficiency. The mediating effect manifests distinct threshold effects among different levels of enterprise green innovation. Our results suggest that China should enact tailored climate finance policies for higher urban emission efficiency, including judicious allocation of climate funds and effective guidance on enterprise-driven green technological innovation.

1. Introduction

Climate finance has emerged as a pivotal instrument for addressing the immense challenges posed by climate change to human society and economic development. It plays a significant role in global climate governance and the promotion of low-carbon development. In August 2022, the Ministry of Ecology and Environment in China unveiled the selection of 23 regions as pilot sites for climate finance. The primary objective of these initiatives is to mobilize diverse capital resources within China, enabling a more effective response to the country's climate change mitigation and adaptation strategies while exploring innovative models for climate

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finance development. As an integral component of green finance, climate finance focuses on providing support for climate change mitigation and adaptation efforts. Its initial definition highlights its crucial role as a financial instrument in driving systemic green economic transformation at the global, regional, and national levels. Moreover, climate finance serves as a guiding mechanism that facilitates and encourages increased investments and financing activities in the field of climate change (Buchner et al., 2019; Tozer et al., 2022).

Numerous studies have unequivocally demonstrated the critical role of climate finance in mitigating climate change and adapting to its impacts at the national level (Nakhooda and Norman, 2014; Sjostedt and Povitkina, 2017; Weiler et al., 2016; Klock and Nunn, 2019; Rishikesh et al., 2021; Huang et al., 2023a). Climate finance is considered instrumental in facilitating low-carbon transitions and enhancing the fairness and effectiveness of global climate change responses in developing countries (Pickering et al., 2017; Long et al., 2023). Effective government management is a key factor in assessing the efficacy of climate finance policies, including policy environments, relevant institutions and systems, and the establishment of public fiscal systems. In terms of climate change mitigation, increased financial openness and liberalization have led to technological advancements and increased foreign direct investment, significantly reducing regional carbon dioxide emissions (Tamazian et al., 2009). Well-implemented climate finance aids recipient regions in transitioning toward net-zero emissions, improving local environmental quality, and supporting the innovative development of low-carbon technologies (Scandurra et al., 2019; Carfora and Scandurrab, 2019; Lee et al., 2022). As efforts to address climate change gradually become a focal point of international affairs, the positive impact of climate finance on emission reductions is influenced by the level of political stability in recipient regions (Yang et al., 2022). Furthermore, climate finance has important implications for the social and economic aspects of recipient regions. For instance, it can help unveil bureaucratic challenges in the allocation and transfer of climate funds within individual countries (Calland and Dubosse, 2011). Moreover, it can have leverage effects on the economic development of certain countries (Carfora and Scandurrab, 2019) and it can contribute to social poverty reduction and gender equality, providing support for sustainable development (Atmadja et al., 2021).

Regarding climate finance management models, numerous studies have widely acknowledged that developed countries tend to adopt market mechanisms as a means to drive innovation in climate financial products, and such mechanisms are primarily based on industry. These approaches aim to attract substantial funds and direct them toward low-carbon transition by offering innovative climate financial products (Peng et al., 2018; Sachs et al., 2019; Huang et al., 2023a, 2023b). However, the successful establishment of market mechanisms relies on several essential factors, including a relatively sound policy framework, well-developed legal regulations, strengthened regulatory disclosures, and the attainment of broad social consensus regarding green initiatives. Consequently, an approach led by the government, with market support, appears to be more suitable for advancing low-carbon economic transformation and addressing climate change challenges, particularly in developing countries that have embarked on low-carbon economic transformation at a late stage and possess an imperfect policy framework (Polzin, 2017; Chawla and Ghosh, 2019; Hachaichi, 2022). The current focus of China's climate finance initiatives aligns with this approach.

China has actively been constructing a comprehensive system centered around the principles of "state leadership, local implementation, financial support, and corporate participation". This system emphasizes various aspects, such as infrastructure development, market mechanisms, product services, operational models, supportive policies, and the enhancement of fundamental capabilities. Drawing on China's historical experience of reform and opening-up, the gradual implementation of progressive, and experimental reforms of decentralization has led to the devolution of certain institutional arrangements to local governments, resulting in discernible disparities in institutional setups among different cities. This devolution has indirectly contributed to the increasing trend of decentralization within climate finance systems. Consequently, different cities within the same country have developed climate finance systems tailored to their specific local resource endowments and industrial economic conditions. These localized systems aim to attract climate funds from the public and private sectors. The devolution of power and the adoption of a multicentered structure have provided cities with increased opportunities for direct access to debt financing. As a result, variations in the implementation effects of low-carbon development have emerged among different cities (Bracking and Leffel, 2021; Long et al., 2022).

Furthermore, considering the increased attention from investment institutions on environmental, social, and governance (ESG) concepts, which focus on evaluating company performance based on environmental, social, and corporate governance criteria rather than traditional financial indicators, particularly in terms of the environmental dimension, ESG evaluation can effectively assess a company's performance in addressing climate change. Integrating ESG factors into business strategies and operations can enhance long-term value creation and resilience. By addressing environmental and social risks, companies can mitigate potential adverse impacts on reputation, regulatory compliance, and financial performance. Strong ESG performance enhances corporate transparency, reduces information asymmetry between companies and stakeholders such as creditors, and increases the level of trust and monitoring capacity of creditors, ultimately lowering the cost of corporate debt financing and further motivating companies to implement climate change initiatives (Boubaker et al., 2020; Huang et al., 2023b). Additionally, embedding ESG considerations into decision-making processes can identify new business opportunities, drive innovation, and foster sustainable growth. According to statistics from the International Institute of Green Finance, in 2023, over 1800 listed companies in China independently compiled and disclosed ESG reports, accounting for approximately 40% of listed companies in China. Therefore, corporate ESG performance serves as a crucial foundation for building the climate finance system and evaluating the effectiveness of climate finance implementation. It plays a decisive role in resource allocation and is bound to impact the low-carbon transformation of cities.

Through literature review, we have identified the following research gaps: Firstly, the differential levels of climate-related investment and financing and urban carbon emission efficiency resulting from institutional differences in the Chinese context have not been addressed. Secondly, there is insufficient attention to the contribution and role of enterprises in both climate-related investment and financing and urban low-carbon development. Thirdly, there is a lack of research on the relationship between corporate green technology innovation levels and climate-related investment, as well as urban carbon emission efficiency. Through literature review, when examining the Chinese context, there is a lack of verification regarding the influence of climate finance on different cities in China, thus exhibiting institutional differences.

The paper's main contributions are as follows: Firstly, most of the previous literatures on climate finance focus on the macro level, analyzing how climate finance facilitates green investments, promotes economic structural optimization at the national or regional level. However, at the micro level, research is scarce on how enterprises, as the ultimate carriers of climate funds, follow the government's macrolevel design and harness the positive effects of climate finance to implement low-carbon strategies. This microlevel analysis is crucial for achieving low-carbon urban development and national carbon neutrality targets (Muhammad et al., 2022). Therefore, this paper focuses on corporate level, employing static and dynamic models to analyze relevant data of enterprises, industries, and regions, validating the relationship between micro-level corporate units in driving urban low-carbon development. Secondly, previous literatures have theoretically affirmed the relationship between corporate ESG performance and climate finance. However, there is limited research on whether corporate ESG performance can promote the improvement of urban carbon emission efficiency. This paper focuses on the practical driving force of corporate ESG performance, especially the interaction between corporate ESG performance, climate-related investment and financing, and urban carbon emission efficiency. It validates how corporate ESG performance substantially promotes urban low-carbon development. Finally, this paper also reveals the mediating function of enterprise green technological innovation between the levels of climate finance in cities in terms of its impact on urban carbon emission efficiency. Meanwhile, this paper provide guidance for enterprises in aligning climate finance efforts with strategic management and in serving as a reference for enterprises to participate in driving low-carbon development in cities.

2. Literature review and hypothesis

2.1. Climate finance and carbon emission efficiency

As the cornerstone of economic development, finance assumes a pivotal role in the efficient allocation of funds. Within the context of China, numerous industries and enterprises heavily rely on external financing, thereby emphasizing the criticality of financial resources as a productive factor in facilitating both the high-quality development of cities and the preservation of ecological environments (Sudmant et al., 2017; Long et al., 2021b). In the urban regions of China, carbon emissions account for a substantial 80% of the nation's aggregate emissions, which predominantly originate from various anthropogenic activities encompassing urban economic sectors, urban infrastructures, and urban transportation systems. Consequently, the ramifications of climate finance become significantly consequential regarding curtailing and mitigating carbon emissions within urban environments.

Climate finance plays a pivotal role in steering capital toward low-carbon industries, thereby facilitating the adjustment and upgrading of urban industrial structures to mitigate carbon emissions (Bai et al., 2022). It serves as a catalyst for sustainable economic development by expanding credit access for green and low-carbon enterprises, enabling their expansion and growth, while simultaneously curbing credit availability for high-energy-consuming and high-polluting enterprises, incentivizing emission reduction or transition efforts. Moreover, climate finance generates positive spillover effects that drive continual structural realignment and upgrading, such as promoting the transition toward cleaner energy sources and advancing production modes from traditional to advanced, mechanized, and intelligent systems. Additionally, it functions as a financing mechanism that expedites the development of emerging industries, facilitates the phasing out of outdated sectors, and accelerates the transition toward a low-carbon, high-quality economic growth trajectory, thus curbing carbon emissions (Yan and Tan, 2023). Thus, climate finance, through its resource allocation guidance, facilitates Pareto improvements, propels the reconfiguration and advancement of industrial structures, and ultimately leads to a reduction in urban carbon emissions.

There are varying viewpoints to consider from an economic scale effect perspective. While climate finance can attract additional social capital into the environmental sector, through leveraging mechanisms, thereby fostering the growth of low-carbon and emerging industries, enhancing economic growth potential, expediting the transition toward a green economy, and ultimately aiding in carbon dioxide emission reduction, it is crucial to acknowledge its potential ramifications. Specifically, an overall increase in market demand may occur in the presence of economic scale effects, thus inadvertently leading to escalated energy consumption and a subsequent increase in carbon dioxide emissions (Chen and Chen, 2021; Sun, 2022).

Accordingly, the scale effect of climate finance on urban carbon emissions can be influenced by two distinct dynamics. On the one hand, economic growth induces an expansion in economic scale, amplifying market demand for energy and subsequently escalating energy consumption, thereby resulting in increased carbon dioxide emissions. On the other hand, climate finance can foster high-quality economic growth, driving the adoption of sustainable economic practices to meet the demands of economic transformation, thus curbing carbon emissions and safeguarding the ecological environment. The dominant force between these dynamics in cities at different levels of economic development necessitates rigorous empirical analysis. Based on the current mainstream viewpoint, climate finance plays a positive role in improving urban carbon emission efficiency, the following hypothesis is posited:

H1: The level of climate finance significantly enhances urban carbon emission efficiency.

2.2. ESG and urban carbon emission efficiency

Enterprises, as the microlevel agents within the urban economic system, serve as a conduit for the manifestation of urban economic behaviors while simultaneously influencing the scale and structure of urban economic operations, thereby directly impacting urban low-carbon transformation. In the early stages of government-driven top-level designs for low-carbon transition, numerous enterprises resorted to short-term solutions, such as production output control and production deceleration, to comply with carbon emission limitations. However, it is noteworthy that such measures may not align with the true intentions of government policies. Instead, long-term adjustments serve as the pivotal determinant for achieving carbon neutrality (Li and Fan, 2022; Lin et al., 2023).

The growing prominence of ESG (Environmental, Social, and Governance) rating systems in enterprise-market connections plays a pivotal role by providing an incentive-compatible market-based governance mechanism that facilitates green transformation and development. Rooted in resource dependence theory, enterprises rely on various external resources for their survival and growth (Pfeffer and Salancik, 1978). The assumption of environmental and social responsibilities enables enterprises to access the critical strategic resources controlled by stakeholders, thereby cultivating their competitive advantage. Robust ESG performance signifies enterprises' ability to fulfill their commitments with stakeholders, thereby winning their trust and support and accessing the essential resources and environments necessary for sustainable development. Stakeholder theory suggests that assuming environmental and social responsibilities enables enterprises to transmit reliable signals, reducing transaction costs and enhancing stakeholder involvement in value creation (Freeman and Evan, 1990). Thus, ESG ratings will foster the functioning of market incentives, driving enterprises to proactively engage in green transformation. Particularly, commendable environmental performance by enterprises signifies their ability to improve energy efficiency, reduce carbon emissions, and minimize resource consumption through innovative green technologies. This, in turn, results in cost reduction, enhanced product quality, fulfillment of consumer demands for sustainable development, strengthened corporate brand image and reputation, and heightened market share and competitiveness. In conclusion, strong performance in the environmental dimension of enterprise ESG evaluations has a positive impact on the enterprises and the low-carbon development of the cities in which such enterprises operate. Based on this, the following hypothesis is proposed:

> **H2:** The performance of the environmental dimension in enterprise ESG evaluations is negatively correlated with the carbon emissions of their respective cities.

2.3. The technology intermediation effect

The technology intermediation effect pertains to the phenomenon in which climate-related investments and financing drive the continuous renewal and iteration of green innovation technologies within enterprises. This process fosters enhancements in emission reduction and pollution control technologies, augments production efficiency, and reduces production costs, resulting in increased economic benefits alongside reduced carbon emissions. Consequently, it indirectly raises the carbon emission efficiency of urban areas. Climate finance exhibit a noteworthy promotion effect on green technological innovation within enterprises (Yang et al., 2022). The promotion effects of climate finance on green technology innovation within enterprises are multifaceted. First, they optimize the enterprise financing environment, providing an enabling platform for innovative development. Second, serving as specialized funds from governmental and financial institutions, climate finance diversifies financing channels for enterprises, ensuring capital safeguards for the advancement of green technologies. Third, climate finance contributes to mitigating the innovation risks faced by enterprises, thereby curtailing threats arising from unforeseen events, market fluctuations, and other uncertainties. Enterprises equipped with green innovative technologies demonstrate heightened production efficiency and reduced unit emissions, giving rise to a "crowding-out effect" in the market. As a result, technologically outdated and unscalable enterprises are phased out, reducing the overall societal resource consumption and elevating urban carbon emission efficiency. Based on these observations, the following hypothesis is posited:

> **H3**: Enterprise green technological innovation will act as an intermediary variable in the relationship between the level of urban climate finance and the carbon emission efficiency of cities.

3. Methodology and data

3.1. Model

To investigate whether urban climate finance has an impact on carbon emissions in Chinese cities, a panel model of urban carbon emissions in China is constructed as follows:

$$CEE_{it} = \beta_0 + \beta_1 CFI_{it} + \beta_2 Control_{it} + \mu_i + \varepsilon_{it} \tag{1}$$

The dependent variable CEE_{it} represents the carbon emission efficiency of city i in year t. The key independent variable CFI_{it} represents the level of climate finance development in city i in year t. $Control_{it}$ represents other control variables.μ_i represents the intercept term capturing individual heterogeneity, and ε_{it} represents the stochastic disturbance term.

To investigate whether enterprise ESG performance has an impact on carbon emissions in Chinese cities, a panel model of urban carbon emissions is constructed as follows:

$$CEE_{it} = \beta_0 + \beta_1 ESL_{it} + \beta_2 Control_{it} + \mu_i + \varepsilon_{it} \tag{2}$$

The dependent variable CE_{it} represents the carbon emission efficiency of city i in year t. The key independent variable ESL_{it} represents the performance of the environmental dimension in enterprise i's ESG evaluation in year t. $Control_{it}$ represents other control variables. μ_i denotes the intercept term capturing individual heterogeneity, and ε_{it} represents the stochastic disturbance term.

3.2. Variables and data

3.2.1. Dependent variable: carbon emission efficiency

Carbon emission efficiency is commonly used to reflect the carbon performance of a specific region, thus incorporating the productivity levels of industries at a given carbon emission level (Mukherjee, 2008; Long et al., 2021a). By constructing a data envelopment analysis (DEA) model with super-efficiency stochastic frontier analysis (SBM) that includes undesirable outputs, the carbon emission efficiency of 262 Chinese cities from 2009 to 2019 is estimated. The inputs in the model include energy consumption, fixed capital, and labor, while the desired output is represented by the regional GDP, and the undesired output is represented by the carbon emissions within the region. Fixed capital is estimated using the perpetual inventory method based on the stock in 2005 (Ramanathan, 2006). Labor input is represented by the year-end resident population. Energy input is represented by the annual energy consumption (in 10,000 tons of standard coal). Regional GDP is based on the regional GDP in 2009. Data for capital, labor, and regional GDP are obtained from the National Bureau of Statistics, energy input data are sourced from the "China Energy Statistical Yearbook," and regional carbon emission data are sourced from the China Emission Accounts and Datasets (CEADs) database, with missing data filled using the grey prediction method.

3.2.2. Independent variable: development level of climate finance

The "Guidance on Promoting Climate Change Mitigation and Adaptation Investment and Financing" issued by the Ministry of Ecology and Environment of China emphasizes that climate finance plays a crucial role in guiding and promoting investment and financing activities in the field of climate change, hence it serves as an integral component of green finance. Based on studies by scholars on the development level of green finance (Li and Fan, 2022) and considering the representativeness and data availability of selected indicators, compiling of relevant data pertaining to climate mitigation and adaptation is based on four dimensions: green credit, green securities, green investment, and carbon finance. Subsequently, an evaluation system for the development level of climate finance is constructed, as presented in Table 1. The entropy weighting method aims to ensure that indicators with more informative data receive greater emphasis in the evaluation process, leading to a more robust assessment of climate finance development across different cities over time. The process involves several steps: By employing the entropy weighting method, this study aims to ensure that indicators with more informative data receive greater emphasis in the evaluation process, leading to a more robust assessment of climate finance development across different cities over time. The process involves several steps (a more streamlined introduction has been added to the manuscript):

1. Data Collection: The study gathers data on various indicators related to climate finance development for each city over the period from 2009 to 2019.
2. Normalization: The data for each indicator are normalized to ensure that they are on a comparable scale. This step is important to prevent indicators with larger magnitudes from dominating the weighting process.
3. Calculation of Information Entropy: Information entropy is calculated for each indicator to measure the degree of uncertainty or randomness associated with the data. A lower entropy value indicates that the indicator provides more effective information.
4. Weight Assignment: The weights for each indicator are determined based on their information entropy values. Indicators with lower entropy values, indicating higher information content, are assigned higher weights in the comprehensive evaluation process.
5. Comprehensive Evaluation: Using the assigned weights, the climate finance development level of each city is assessed for the entire period under consideration.

Using these weights and data, the climate finance development level of each city is assessed from 2009 to 2019. The principle of the entropy weighting method lies in assigning weights to each indicator based on the amount of effective information provided by the data. A smaller information entropy indicates a greater amount of effective information, resulting in a larger role and weight in the comprehensive evaluation process.

The data on the proportion of credit scale related to climate change mitigation and adaptation are sourced from the "China Financial Yearbook" and China Stock Market & Accounting Research Database (CSMAR). The data on the proportion of market capitalization of enterprises engaged in climate change mitigation and adaptation are sourced from the CSMAR. The data on the proportion of public expenditure related to climate change mitigation and adaptation are sourced from the "China Environmental Statistics Yearbook." The data on carbon finance are obtained from the website of the China Clean Development Mechanism and the

Table 1
Evaluation system for the development level of climate finance.

Criterion layer	Indicator level	Weight
Green credit	Proportion of credit allocation related to climate change mitigation and adaptation	28.74%
	Proportion of interest expenses in high-energy-consumption industries	10.17%
Green securities	Proportion of enterprise market value in climate change mitigation and adaptation	15.12%
	Proportion of market value in high-energy-consumption industries	3.71%
Green investment	Proportion of public expenditure on climate change mitigation and adaptation	6.95%
	Proportion of green investment	8.40%
Carbon finance	Proportion of China Clean Development Mechanism Project transaction volume	12.22%
	Carbon emission loan intensity	14.69%

National Bureau of Statistics. In cases where data are missing, the grey forecasting method is used to supplement the data.

3.2.3. Independent variable: enterprise performance in addressing climate change

As an increasing number of financial institutions link ESG assessments with investments, an increasing number of Chinese companies have incorporated ESG into their overall business processes and strategic decision-making. The existing ESG criteria and assessments are continuously improving their disclosure requirements and related descriptions of climate information, particularly in the environmental dimension, with a growing emphasis on evaluating climate change mitigation and adaptation efforts. Therefore, this study selects the environmental dimension scores from the ESG assessments of Chinese listed companies from 2009 to 2019 as a proxy variable for their performance in addressing climate change. The data are sourced from the China National Research Data Service (CNRDS) and WIND.

3.2.4. Control variables

To minimize potential estimation biases caused by the selection of limited or inappropriate influencing factors, this study, following the approach of Cong et al. (2022), incorporates several city-level macrolevel control variables into the analysis of the relationship between climate finance and urban carbon emission efficiency. These control variables include the economic development level, industrial structure, environmental regulatory intensity, marketization level, and urbanization level. Additionally, in the study of the relationship between corporate environmental performance and urban carbon emission efficiency, the approach of Wu et al. (2021) is referenced, and firm-level control variables such as asset-liability ratio, firm size, total asset turnover ratio, and return on assets are included.

Considering that the control variables in Model (1) may have an impact on the main effects in Model (2), the $Control_{it}$ variable in Model (2) includes both firm-level control variables and city-level macrolevel control variables.

3.2.5. Data processing

The specific sample processing procedures are as follows: (1) Financial companies and companies with ST, ST*, and PT status in the current year are excluded from the dataset. (2) Samples with severe missing data are removed. (3) To mitigate the influence of extreme values, the winsor2 command in Stata is used to winsorize the continuous variables at the 1st and 99th percentiles. The variable calculations and data sources are provided in Table 2.

3.3. Statistical description of variables

The data used in this study cover the period from 2009 to 2019 and include 262 cities in China (with some missing data, and data from Tibet and the regions of Hong Kong, Macau, and Taiwan are not available). Regarding the missing data points, grey prediction is used for imputation. Some variables undergo logarithmic transformation, and others are adjusted by subtracting a baseline value.

Analyzing the fluctuations in the climate finance level, it is evident that from 2009 to 2019, China's climate finance level experienced a rapid and notably significant increase (Fig. 1). However, the cities displaying a robust development in climate finance are primarily concentrated in the eastern coastal and central regions, with slower progress observed in the western areas. Notably, several exemplary cities have emerged as frontrunners in this domain, including Beijing, Shanghai, Guangzhou, Shenzhen, and others. The rapid development of several cities also indirectly confirms the effectiveness of China's strategy in climate finance development policies, which prioritize selecting pilot projects and gradually promoting nationwide climate finance development from specific areas to a broader scale.

From the urban perspective (Fig. 2), carbon emission efficiency of cities showed a general increase from 2009 to 2019,

Table 2
Variable code, definition and coding rules.

Types	Variables	Definition
Dependent variable	Carbon emission efficiency	Efficiency evaluation considering carbon emissions from undesired outputs
Independent variables	Development level of climate finance	The entropy weight method is used to calculate the data of urban climate mitigation and adaptation investment and financing
	Enterprise performance in addressing climate change	Score for the environment (E) dimension in the ESG score
Control variables for model (1)	Economic development level	GDP
	Proportion of heavy industry	The proportion of the total output value of heavy industry in the total industrial output value
	Environmental regulations	Proportion of environmental words in local government reports
	Marketization level	The marketization level evaluation index comprehensively considers the relationship between the government and the market, the development of non-state-owned economy, the development degree of product market, the development degree of factor market and other sub-items
	Urbanization level	Ratio of non-agricultural population to total population
Added control variables for model (2)	Enterprise asset-liability ratio	Total liabilities at year-end/total assets at year-end
	Enterprise size	The total assets per year
	Turnover of total capital	Operating income/average assets
	Return on assets	Net profit/average balance of total assets

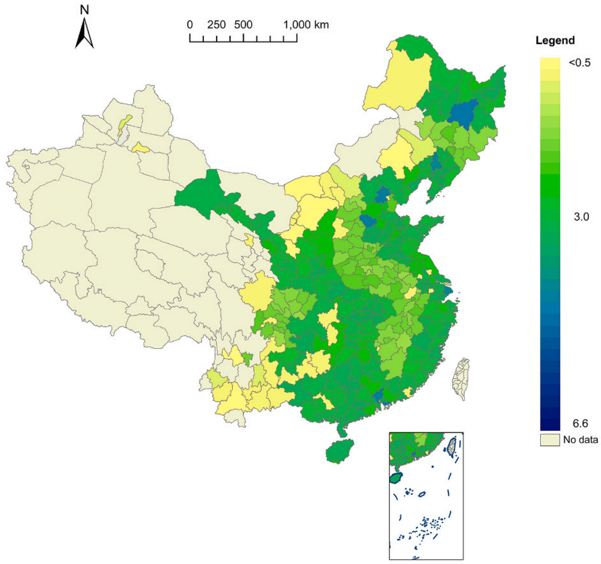

Fig. 1. Climate finance level in China in 2009 and 2019.

accompanied by a significant rise in climate finance levels. The absence of certain city names in the figure does not imply that the data for those cities are not reflected, their data are indeed represented, with only the names being hidden. The red and orange lines represent the climate finance levels of different cities in 2009 and 2019, respectively. It can be observed that the climate finance levels of most cities have significantly improved. The dark blue and light blue lines represent the carbon emission efficiency of different cities in 2009 and 2019, respectively. It can be observed that the carbon emission efficiency of most cities has also significantly improved.

The descriptive statistics for each variable are presented in Table 3. It can be observed that the carbon emission efficiency and climate finance level in Chinese cities during the study period are relatively low as shown by the mean values in Table 3. This suggests that carbon emission management is currently relatively lenient, and there is room for improvement in the level of climate finance. Based on the standard deviations and the range of minimum and maximum values, it can be seen that there is an imbalance among cities in terms of climate finance development and achieving higher carbon emission efficiency. Additionally, there are significant differences among cities in terms of environmental regulations, marketization level, and urbanization level, indicating the presence of notable disparities and asynchronous coordination issues that cannot be ignored.

4. Empirical results

4.1. Baseline regression estimation

To address potential heteroscedasticity issues, a natural logarithm transformation is applied to certain variables. The choice between the random effects model and fixed effects model is determined through a Hausman test. The test results indicate a p-value of 0, showing that the fixed effects model would be the preferred model. Moreover, the descriptive statistics analysis reveals significant differences among individuals, suggesting the presence of substantial heterogeneity. Therefore, a two-way fixed effects model is employed. The results are presented in Table 4.

According to the results in column (1) of Table 4, the estimated coefficient for the climate finance level (CFI) of different cities is statistically significant at the 0.01 level, indicating a positive impact on urban carbon emission efficiency (lnCEE). This suggests that, as the level of climate finance in cities increases, carbon emission efficiency improves. In column (2), the estimated coefficient for the environmental performance in the corporate ESG evaluation (lnESL) is significantly positively correlated with urban carbon emission efficiency at the 0.05 level. This indicates that greater investment in environmental aspects by enterprises has a significant impact on improving the carbon emission efficiency of the respective cities. On the one hand, climate finance increases credit to green innovative companies, promotes energy-saving, low-carbon, and environmentally friendly enterprises, and encourages them to invest more resources in the environmental sector, thus producing green products and reducing emissions. Moreover, it may reduce or cut credit to high-energy-consuming and high-emission enterprises, restraining excessive energy consumption and lowering carbon dioxide emissions, thereby improving urban carbon emission efficiency. On the other hand, climate finance supports green industries and discourages high-emission traditional industries, leading to a transformation and upgrade from high-input, high-emission production methods to low-carbon, green, efficient, and low-emission manufacturing. This promotes industrial optimization and adjustment, achieves a low-carbon economy, and improves carbon emission efficiency.

Furthermore, in column (1), the control variables GDP (lnGDP), marketization level (MARKET), and urbanization level (URBAN) are found to be significantly negatively correlated with carbon emission efficiency at the 0.01 level. This suggests that currently, China

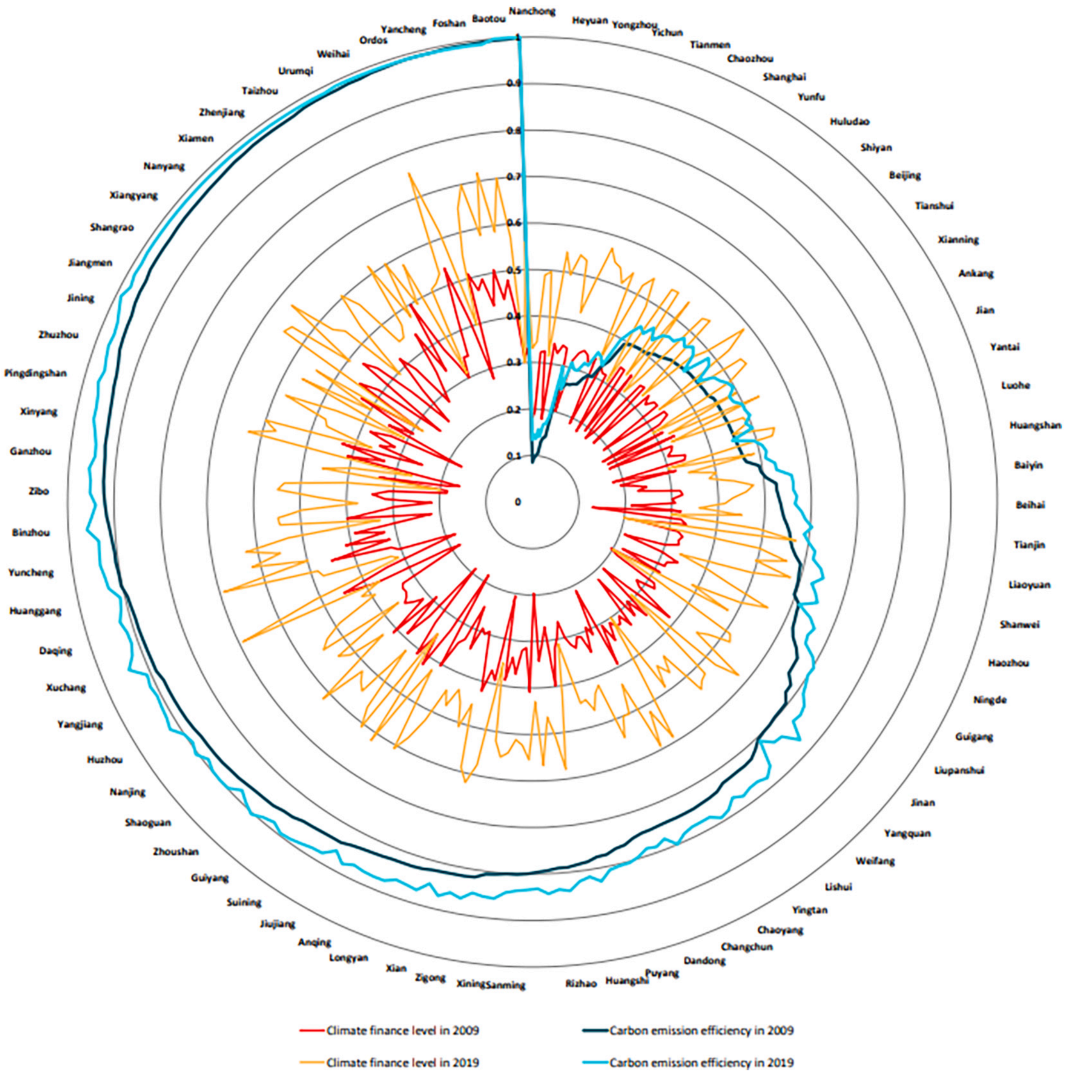

Fig. 2. Climate finance level and carbon emission efficiency by cities in 2009 and 2019.
(Not all city names are displayed in the figure, the absence of certain city names in the figure does not imply that the data for those cities are not reflected, their data are indeed represented, with only the names being hidden.)

Table 3
Statistical description of variables.

Variables		N	Mean	S·D	Min	Max
Carbon emission efficiency	lnCEE	23,295	6.398	1.181	0.693	7.554
Development level of climate finance	CFI	23,295	0.395	0.111	0.064	0.624
Enterprise performance in addressing climate change	lnESL	23,295	4.078	0.126	3.383	4.556
Economic development level	lnGDP	23,295	8.789	1.051	4.97	10.55
Proportion of heavy industry	lnHEAVY	23,295	−1.032	0.43	−2.319	−8.207
Environmental regulations	lnERS	23,295	−5.704	0.396	−8.131	−4.391
Marketization level	MARKET	23,295	12.351	2.544	4.5	19.163
Urbanization level	URBAN	23,295	0.731	0.154	0.223	1
Enterprise asset-liability ratio	LEV	23,295	0.457	0.636	0.195	55.409
Enterprise size	lnSIZE	23,295	22.086	1.36	15.418	28.636
Turnover of total capital	ATO	23,295	0.691	0.569	0.001	9.813
Return on assets	ROA	23,295	0.063	0.199	−6.599	20.786

Table 4
Benchmark regression results.

Variable	(1)	(2)	(3)	(4)
	lnCEE	lnCEE	GER	GER
CFI	5.544*** (15.04)	5.544*** (15.42)	0.018*** (5.71)	0.078* (0.68)
lnGDP	−0.586*** (−4.47)	−0.585*** (−4.74)	−0.008*** (−5.36)	0.548*** (12.29)
lnHEAVY	−0.165 (−1.35)	−0.161 (−1.32)	0.001 (1.56)	−0.084* (−1.8)
lnERS	0.048** (2.40)	0.048** (2.41)	0.001 (0.49)	−0.05 (−0.76)
MARKET	−0.075*** (−3.13)	−0.075*** (−3.11)	0.001 (0.85)	−0.057*** (−5.83)
URBAN	−2.355*** (−5.61)	−2.351*** (−5.73)	0.006 (1.20)	−6.798*** (−4.66)
lnESL		0.21** (2.48)		6.311* (1.51)
LEV		0.002 (0.06)		3.433 (0.93)
lnSIZE		0.015 (0.78)		0.724 (0.61)
ATO		−0.039 (−1.47)		−0.051 (−0.03)
ROA		0.036 (1.32)		8.008** (2.1)
Constant	10.974*** (11.96)	9.809*** (8.99)	0.074*** (8.67)	0.791** (1.88)
N	23,295	23,295	23,295	23,295
R^2	0.354	0.354	0.343	0.414

is still in a stage of rapid economic development driven by industry. Cities with higher levels of economic development, marketization, and urbanization tend to have higher emissions, resulting in lower carbon emission efficiency. The environmental regulation intensity (ERS) in column (1) shows a significant positive correlation with carbon emission efficiency at the 0.5 level, indicating that higher attention from local governments to environmental protection and the implementation of relevant regulatory measures contribute to improving urban carbon emission efficiency.

4.2. Robustness analysis

To ensure the robustness of the research, the reciprocal of carbon intensity, represented by the ratio of urban GDP to its carbon dioxide emissions (GER), was used as the dependent variable in the regression analysis, replacing the original dependent variable. The results are presented in columns (3) and (4) of Table 4. In column (3), while controlling for other variables, it can be observed that the regression coefficient for the climate finance level reaches statistical significance at the 0.01 level, and the direction of the effect remains positive. This indicates that the development of climate finance in cities effectively promotes the improvement of carbon emission efficiency. These results align with the findings of the baseline regression, confirming the robustness of the estimates obtained from Model (1). Similarly, in column (4), while controlling for other variables, it can be observed that the regression coefficient for the environmental performance in corporate ESG evaluations reaches statistical significance at the 0.1 level, with a positive direction of effect. This suggests that good environmental performance of enterprises effectively promotes the improvement of urban carbon emission efficiency. These findings are consistent with the results of the baseline regression, confirming the robustness of the estimates obtained from Model (2).

4.3. Endogeneity discussion

By incorporating multiple factor variables that significantly affect urban carbon emission efficiency, an effort has been made to mitigate the potential endogeneity issue resulting from omitted important variables. Previous studies have highlighted two potential sources of endogeneity. First, there are certain cities that prioritize environmental protection, leading to higher carbon emission efficiency in the region. These cities have a competitive advantage in attracting new technologies, intelligent systems, and environmentally friendly businesses. The presence of companies in such cities fosters increased emphasis from local governments on climate-related investment and financing, thereby establishing a reverse causal relationship and introducing endogeneity in Models (1) and (2). Second, carbon emission efficiency is influenced by input factors, where the current capital, labor, and energy consumption inputs are to a large extent influenced by the previous period's inputs. Hence, regional carbon emission efficiency exhibits inertia over time, with the current efficiency value being subtly influenced by the preceding period's value, contributing to endogeneity. These two reasons may lead to inconsistent estimation results in the models.

To address these issues, two approaches have been adopted. First, instrumental variable (IV) estimation is employed to tackle the endogeneity resulting from the reverse causal relationship. The lagged period of climate investment and financing level is used as an instrumental variable in the two-stage least squares (2SLS) regression. Second, a dynamic panel model is constructed by incorporating the lagged two periods of carbon emission efficiency (L.lnCEE) into Models (1) and (2). The difference generalized method of moments (Diff-GMM) and the system generalized method of moments (Sys-GMM) are applied, using the lagged carbon emission efficiency as an instrumental variable for re-estimation.

Table 5 presents the results for Model (1) in columns (1), (3), and (4), while the results for Model (2) are shown in columns (2), (5), and (6). The Sargan Test indicates that the *p*-values are >0.1, confirming the effectiveness of all instrumental variables. Furthermore, all regression results consistently indicate that urban climate investment and financing level have a significant positive impact on carbon emission efficiency. Similarly, the environmental dimension of the enterprise ESG performance exhibits a significant positive influence on urban carbon emission efficiency.

Therefore, it can be confirmed that there is uncertainty regarding the impact of climate investment and financing level on urban carbon emissions, as stated in Hypothesis 1. Specifically, in the context of China, the findings indicate that urban climate investment and financing level have a significant positive effect on carbon emission efficiency. Furthermore, the validation results demonstrate that the environmental dimension of enterprise ESG performance positively influences the improvement of urban carbon emission efficiency, confirming Hypothesis 2.

5. Mediation effect and threshold effect testing

5.1. Mediation effect testing

Based on the selected variables mentioned above, we introduce a technological innovation variable represented by the annual number of independent applications for green innovation by enterprises (PATENT), sourced from the CSMAR database (https://data.csmar.com/). We first examine the influence of urban climate investment and financing level on carbon emission efficiency. Next, we investigate the impact of climate investment and financing level on enterprise green technological innovation. Finally, we analyze the combined effects of urban climate investment and financing level and enterprise green technological innovation on urban carbon emission efficiency. To address endogeneity concerns, we employ the lagged dependent variable as an instrumental variable and the system GMM estimation method to establish the following stepwise regression test model, aiming to examine the mediating effects:

$$lnCEE_{it} = \beta_0 + \beta_1 lnCEE_{it-1} + \beta_2 Control_{it} + \mu_i + \varepsilon_{it} \tag{3}$$

Table 5
The results of IV estimation, Diff-GMM and Sys-GMM.

Variables	(1)	(2)	(3) Diff-GMM	(4) Sys-GMM	(5) Diff-GMM	(6) Sys-GMM
	lnCEE	lnCEE	lnCEE	lnCEE	lnCEE	lnCEE
L.lnCEE			0.354*** (30.17)	0.736*** (38.36)	0.322*** (24.34)	0.660*** (94.31)
CFI	0.585*** (5.04)	0.427*** (3.82)	0.316* (1.65)	0.684** (2.35)	0.037* (1.83)	0.322* (1.64)
lnGDP	−0.353*** (−18.41)	0.343*** (−18.04)	0.205** (2.23)	−0.171** (−2.41)	0.13 (1.31)	−0.215*** (−8.09)
lnHEAVY	0.625*** (11.25)	0.615*** (11.11)	−0.762*** (−7.56)	−0.094 (−1.22)	−0.683*** (−6.66)	0.025 (0.55)
lnERS	−0.011 (−0.49)	−0.008 (−0.36)	0.211*** (18.98)	0.278*** (13.71)	0.204*** (17.59)	0.141*** (12.16)
MARKET	0.009** (2.11)	0.010** (2.27)	0.065 (3.05)	0.080*** (5.37)	0.077*** (3.53)	0.157*** (16.15)
URBAN	1.473*** (16.04)	1.480*** (16.22)	−0.746*** (−1.44)	0.132 (0.28)	−1.106** (−2.11)	−0.224 (−0.89)
lnESL		0.005** (0.11)			0.16** (2.11)	0.166** (1.97)
LEV		0.042*** (3.49)			0.022 (0.99)	0.183*** (3.07)
lnSIZE		0.023*** (−3.89)			0.087*** (4.69)	0.102*** (4.93)
ATO		0.029** (−2.12)			−0.101*** (−3.95)	−0.12 (−4.13)
ROA		0.046** (2.21)			0.011 (0.36)	−0.063 (−1.42)
Constant	9.443*** (44.70)	9.884*** (27.28)	2.518*** (3.99)	3.46*** (8.67)	2.286*** (2.99)	2.027*** (3.33)
N	19,514	19,514	16,011	16,011	16,011	16,011
R^2	0.236	0.237				
Sargan test *p* value			0.999	0.999	0.999	0.999

$$PATENT_{it} = \beta_0 + \beta_1 PATENT_{it-1} + \beta_2 CFI_{it} + \beta_3 Control_{it} + \mu_i + \varepsilon_{it} \tag{4}$$

$$lnCEE_{it} = \beta_0 + \beta_1 CEE_{it-1} + \beta_2 CFI_{it} + \beta_3 PATENT_{it} + \beta_4 Control_{it} + \mu_i + \varepsilon_{it} \tag{5}$$

The stepwise regression procedure is employed as follows: Building upon the significant positive coefficient of the urban climate investment and financing level in Model (3), we proceed to estimate Models (4) and (5). If the coefficient estimates of the urban climate investment and financing level in Model (4) and the coefficient estimates of enterprise green technological innovation in Model (5) are simultaneously significant and positive, it indicates that urban climate investment and financing development influence urban carbon emission efficiency through the mediating variable of technological innovation, thereby establishing a partial mediating effect of enterprise green technological innovation. Conversely, if the coefficient estimate of the urban climate investment and financing level in Model (5) is insignificant while enterprise green technological innovation remains significant, it suggests a complete mediating effect of enterprise green technological innovation. The estimation results of Models (3)–(5) are presented in Table 6. It is observed that the impact of urban climate investment and financing development on urban carbon emission efficiency is significantly positive in Model (3). Additionally, the influence of urban climate investment and financing development on enterprise green technological innovation is also significant and positive in Model (4). Furthermore, both the urban climate investment and financing level and enterprise green technological innovation demonstrate significant positive effects on urban carbon emission efficiency in Model (5), implying that urban climate investment and financing affect urban carbon emission efficiency through the mediation of enterprise green technological innovation, with the latter exerting a partial mediating effect. The Sobel test is conducted on the model, and the *p*-value is found to be below 0.05, leading to the rejection of the null hypothesis and confirming the statistically significant presence of the mediating effect.

Analyzing the parameter estimates of the three regression equations, we observe that the estimated parameter for the urban climate investment and financing development level in Model (3) is 2.295. Upon introducing the mediating variable of enterprise green technological innovation in Model (5), the parameter estimate decreases to 1.897. This suggests that the inclusion of the mediating variable attenuates the direct impact of urban climate investment and financing development on urban carbon emission efficiency, as a portion of the effect is mediated by the intermediate variable. In Model (4), the estimated parameter for the urban climate investment and financing development level on enterprise green technological innovation is 11.007, indicating that an increase in the level of urban green investment and financing significantly stimulates enterprise green technological innovation. Subsequently, through the parameter estimate of 0.001 in Model (5) representing the influence of enterprise green technological innovation on urban carbon emission efficiency, the desired effect on urban carbon emission efficiency is achieved. Overall, these findings confirm Hypothesis 3, which posits that the development of urban climate investment and financing level facilitates the improvement of urban carbon emission efficiency by means of the mediating role played by enterprise green technological innovation.

5.2. *Threshold effect testing*

To further investigate the uncertainty and specific form of the relationship between climate investments and urban carbon emission efficiency under different green technological innovations, a threshold model is established to verify this uncertainty. Threshold testing is necessary to determine if there are specific levels or thresholds of a certain variable at which the relationship between two other variables changes. In this context, we are interested in understanding if there are particular levels of green technological innovation that affect the relationship between climate investments and urban carbon emission efficiency differently. Green technological innovation is taken as the threshold variable in terms of climate investments impact on urban carbon emission efficiency. The existence of the threshold effect is tested using the LM statistic, but as the LM statistic does not follow a standard distribution, the idea of bootstrapping is adopted to obtain the asymptotic distribution (Hansen, 2000) and subsequently obtain probability values. The results of the threshold effect test are presented in Table 7, where the dual threshold passes the significance test at the 0.05 level, while the triple threshold is not significant.

Based on the results of Table 7, we establish the following dual-threshold model to investigate the relationship between climate investments and urban carbon emission efficiency under different levels of green technological innovation. The adoption of a dual-

Table 6
Mediation effect test results.

Variables	Model(3) lnCEE	Model(4) PATENT	Model(5) lnCEE
CFI	2.295*** (8.59)	11.007** (2.09)	1.897*** (3.69)
PATENT			0.001** (2.20)
Constant	2.361*** (3.84)	−190.789*** (−11.70)	7.416*** (12.43)
Controls	Yes	Yes	Yes
N	5134	5134	5134
Sobel test p value			0.0009

Table 7
Bootstrap threshold test results.

Types	RSS	MSE	F-statistics	p value	Threshold
Single	0.8855	0.0021	51.03	0.0115	31.3422
Double	0.8134	0.0019	40.74	0.0201	2.3857, 33.8865
Triple	0.7984	0.0018	10.24	0.6895	2.3857, 5.8093, 33.8865

threshold model allows for a comprehensive exploration of the intricate interplay among green technological innovation, climate finance, and urban carbon emission efficiency. This modeling approach facilitates a nuanced understanding of the underlying dynamics, their potential implications for policy formulation and the implementation of tailored measures aimed at fostering low-carbon development within urban areas. The dual-threshold model is formulated as follows:

$$\begin{aligned} lnCEE_{it} = {} & \beta_0 + \beta_1 CFI_{it} \times I(PATENT_{it} \le \theta_1) \\ & + \beta_2 CFI_{it} \times I(\theta_1 < PATENT_{it} \le \theta_2) \\ & + \beta_3 CFI_{it} \times I(PATENT_{it} > \theta_2) + \beta_4 Control_{it} + \mu_i + \varepsilon_{it} \end{aligned} \tag{6}$$

Among them, $\theta_1$and θ_2 serve as threshold values for the technological innovation variables, with $I(\cdot)$ denoting the indicator function, where the expression inside the parentheses evaluates to 1 if true and 0 otherwise. The regression results are presented in Table 8.

According to the results of Table 8, when the level of green technological innovation is below 2.3857 in the dual-threshold model (Eq. 6), the fitted coefficient of climate investments on urban carbon emission efficiency is 5.578, and it is significant at the 0.1 level. Hence, the level of green technological innovation within most enterprises in the region is relatively low, and both the region's climate finance is still in a conceptual stage. As a result, the impact of green technological innovation is limited, leading to a relatively small effect of climate investments on regional carbon emission efficiency during this period.

When the level of green technological innovation falls within the range of 2.3857 to 33.8865 in the dual-threshold model (Eq. 6), the impact of climate finance on urban carbon emission efficiency is observed to be negative and statistically insignificant. Several plausible explanations underpin this finding.

First, while climate finance can attract additional social funds into low-carbon industries through leverage effects, leading to a reduction in carbon dioxide emissions, the presence of economies of scale in the market might trigger an overall increase in market demand and subsequent energy consumption. Consequently, enterprises, benefiting from the support of climate finance, may scale up production, leading to a substantial surge in energy consumption by residents, thereby offsetting or even surpassing the emission reduction effects attributed to climate finance.

Second, among enterprises operating at this stage of green technological innovation, a relatively higher proportion belong to the industrial sector (Fig. 3). Such enterprises may primarily focus on production-oriented green technological innovations, where the most pronounced effect is an enhancement in productivity with a slight green attribute. As a result, the marginal cost of product manufacturing decreases, thereby driving productivity gains. Fueled by their self-interests, enterprises may consequently expand their scale to bolster energy inputs, consequently contributing to a considerable increase in carbon emissions and diminishing the emission reduction effect of climate finance.

Figure 3 illustrates the distribution of the number of industrial enterprises across different thresholds from 2009 to 2019 in the research data. Notably, the considerable prevalence of industrial enterprises within threshold 2 (green technological innovation level ranging from 2.3857 to 33.8865) surpasses those within threshold 1 and threshold 3. This indirectly corroborates the notion that Chinese industrial enterprises, supported by climate finance, may exhibit a stronger inclination toward green technological

Table 8
Threshold regression results.

Variables	Model(2) lnCEE	Model(6) lnCEE
CFI	5.544*** (15.42)	
CFI(PATENT≤2.3857)		5.578* (13.48)
CFI(2.3857 < PATENT≤33.8865)		−2.357 (−9.573)
CFI(PATENT>33.8865)		7.149*** (17.622)
Constant	9.809*** (8.99)	8.172*** (10.111)
Controls	Yes	Yes
N	5134	5134
R^2	0.7822	0.8241

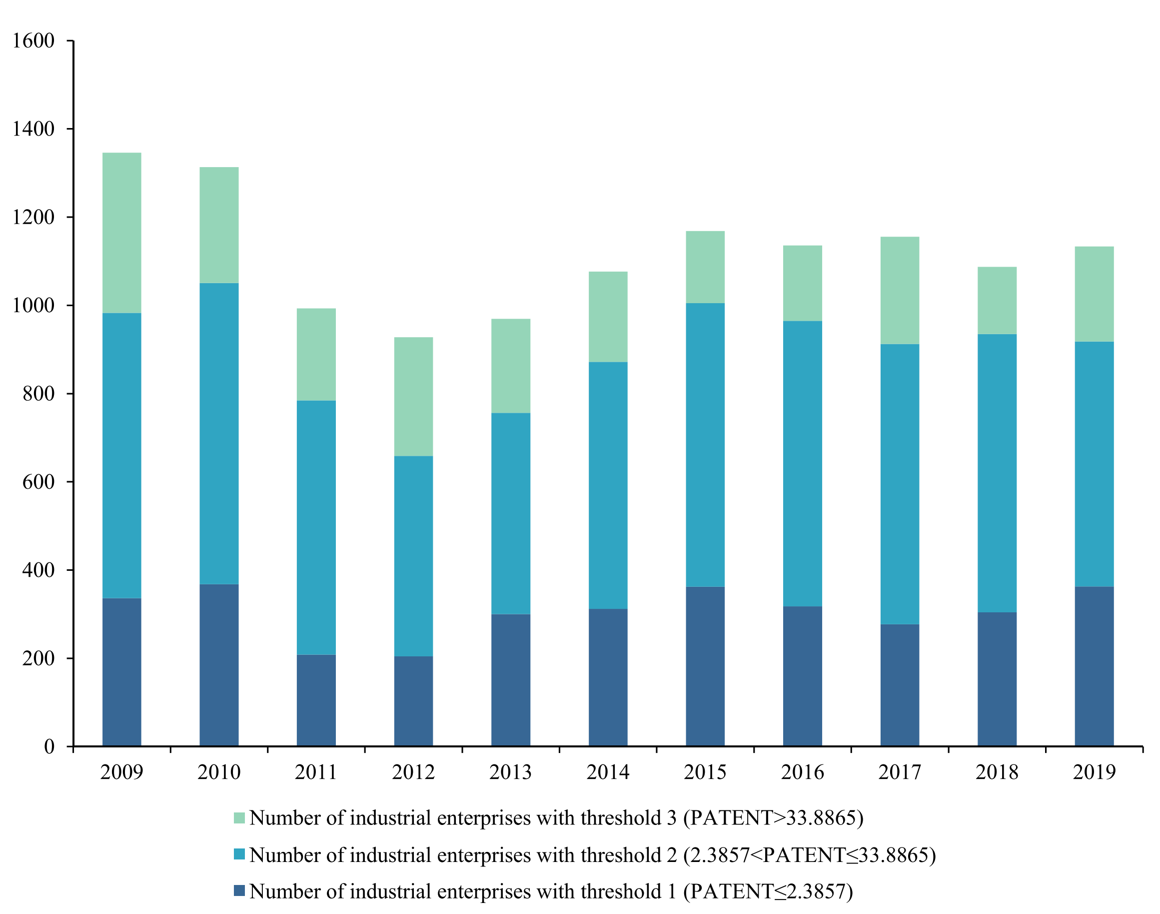

Fig. 3. The number of industrial enterprises within different thresholds.

innovations that yield productivity benefits, ultimately leading to a diminished emission reduction effect associated with climate finance.

When the level of green technological innovation within enterprises reaches a higher level, specifically exceeding 33.8865 in the model (Eq. 6), the influence of climate finance on urban carbon emission efficiency becomes significantly positive, with a substantial effect. For enterprises operating at this stage, their focus lies in genuinely pursuing low-carbon and energy-efficient technological innovations. The results reveals that the effect of climate investments on driving green technological innovation in enterprises is "purer" only when the level of green technological innovation in enterprises exceeds a high threshold (>33.8865). At this level, climate investments can genuinely propel enterprises' green transformation. However, when the threshold is below 33.8865, enterprises tend to focus more on improving production efficiency with the support of climate investments, rather than genuinely transitioning to green practices. In essence, their strategic focus is not on achieving green transformation. The infusion of climate finance encourages these enterprises to actively engage in the development and utilization of low-carbon and environmentally friendly technologies while considering the enhancement of energy utilization efficiency. This approach enables a simultaneous pursuit of production and low-carbon objectives, effectively elevating the carbon emission efficiency within urban areas. Overall, the influence of climate finance on urban carbon emission efficiency in the dual-threshold model follows an "N-shaped" pattern, confirming that climate finance not only act as intermediaries through green technological innovation but also exhibit significant threshold effects. This finding highlights the intricate relationship between climate finance and urban carbon emission efficiency, suggesting that the impact is contingent upon the level of green technological innovation and the specific threshold values involved.

6. Conclusions and policy implications

This paper utilizes a panel dataset of 262 Chinese cities from 2009 to 2019, comprising enterprise-level information, to investigate the influence of climate finance development on urban carbon emission efficiency and its underlying transmission mechanisms. By constructing a comprehensive index system to measure the level of climate finance development and estimate urban carbon emission efficiency, the study aims to explore the dynamics of this relationship. The research findings indicate that the development of climate finance in cities significantly and positively affects urban carbon emission efficiency, and this result is robust across various model specifications. Additionally, the study reveals that the environmental, social, and governance (ESG) performance of enterprises exerts a significant positive impact on urban carbon emission efficiency, highlighting the crucial role of microlevel corporate entities in shaping the low-carbon transformation of cities in the future. Furthermore, the study uncovers that green technological innovation by enterprises serves as a mediating variable, facilitating the transmission of effects between the level of climate finance in cities and urban carbon emission efficiency. Notably, this mediating role demonstrates a significant threshold effect. Under different thresholds of green innovation technology levels, the impact of climate finance on urban carbon emission efficiency exhibits notable variations. This highlights the intricate nature of the relationship between climate finance, urban carbon emission efficiency, and the level of green technological innovation, shedding light on the distinct pathways and effects at various innovation stages.

In summary, the development of climate investment and financing is expected to play a crucial role in achieving China's goals of high-quality economic growth and the "dual-carbon" targets in the future.

At the macro level, it is important to further deepen and improve the climate investment and financing development system and effectively leverage the role of green finance. The central government should set reasonable long-term decarbonization goals, continue to enhance and refine the top-level design of climate investment and financing based on pilot projects, establish sound market incentive mechanisms, and harness the positive externalities of government actions. This will help attract more market funds into climate investment and financing. Local governments should tailor specific policies based on the local conditions of different cities, encouraging commercial banks to increase credit lines for green technologies in their respective cities. They should also increase investment in low-carbon industries while tightening credit for high-energy-consuming and high-emission enterprises. By optimizing capital allocation through the "invisible hand" of the market, the desired outcomes can be achieved. Meanwhile, government should pay more attention to the effectiveness of climate finance and propose supervision and management mechanisms for climate finance. It is essential to focus on whether climate funds are genuinely used for the green and low-carbon transformation of enterprises and to avoid instances where companies engage in "greenwashing" activities, portraying themselves as environmentally friendly while primarily focusing on increasing production capacity.

At the microlevel, the influence of enterprises on urban carbon emission efficiency holds paramount significance. On the one hand, enterprises play a pivotal role in promoting technological innovation by diversifying risks and reducing financing costs, leading to reduced carbon emissions in production sectors. The development of capital markets and climate finance encourages enterprises to adopt energy-saving and emission-reducing measures, bolstering their image and facilitating better financing opportunities. The pursuit of low-carbon, green products and engagement in green technological innovation can potentially grant enterprises additional market share while alleviating external pressures from policies and public expectations. The threshold effect analysis results indicate that in driving the urban low-carbon transformation process through climate finance, green innovation is a crucial factor for enterprises to play a pivotal role. Particularly, industrial enterprises should intensify their focus on green innovation, increase investment in green initiatives, and allocate resources toward talent development in this area. On the other hand, the indirect carbon reduction effects of enterprises are equally noteworthy, as their low-carbon initiatives can trigger positive responses and increased awareness among consumers. The production of low-carbon products holds the potential to drive transformative changes in consumption patterns and lifestyles within urban communities, unlocking substantial emission reduction capacities at the regional level. The transformation of urban lifestyles and consumption behaviors can yield emission reduction potentials that rival the direct emission reductions achieved by enterprises.

In future endeavors, heightened attention should be directed toward understanding the intricate relationship between enterprises, climate finance, and urban carbon emission efficiency. Drawing from the insights regarding threshold effects, it becomes imperative to ensure that climate investment-related funds are judiciously channeled to support green technologies that prioritize both environmental sustainability and energy efficiency enhancements. This approach guards against superficially "green" innovations that may inadvertently lead to heightened production capacities. Consequently, reinforcing the role of climate finance in propelling green technological innovation within enterprises and establishing a comprehensive, market-driven investment mechanism becomes instrumental. Harnessing the risk diversification potential of climate finance can act as a catalyst for the development of green technologies, with climate-driven technological advancements becoming instrumental in elevating carbon emission efficiency.

While this paper examines the relationship between enterprises and climate finance, as well as urban carbon emission efficiency, there are still some research inadequacies. Firstly, corporate strategic management is a complex process, and although ESG largely represents efforts by companies to address climate change, there are still some corporate management actions that have not been incorporated. For example, actions such as entering the green industry through establishment, mergers and acquisitions, alliances, etc., have not been fully considered. Therefore, future research could consider incorporating more representative variables to explore the relationship between enterprises and climate-related investment and financing, as well as urban carbon emission efficiency. Secondly, the sample data at the enterprise level could be further refined, and it is worth investigating the relationship between enterprises in different industries and the levels of climate finance and urban carbon emission efficiency.

CRediT authorship contribution statement

Muxin Liu: Conceptualization, Formal analysis, Methodology, Writing – original draft. **Changyou Xia:** Data curation, Investigation. **Hailin Lan:** Methodology, Validation. **Zhihao Gao:** Data curation, Formal analysis, Validation. **Xiaojie Yu:** Data curation, Validation. **Li Wang:** Supervision, Validation. **Xi Liang:** Supervision, Writing – review & editing. **Yi Wu:** Methodology, Writing – original draft, 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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