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Progress in Digital Climate Governance in China: Statistical Measurement, Regional Differences, and Dynamic Evolution

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Abstract: The capacity for climate governance is crucial for sustainable advancement, with data elements being a pivotal production factor in contemporary governance. This study examines the trajectory and strategy of digital transformation in climate governance, creating a three-dimensional dataset encapsulating 11 primary and 36 secondary indicators to facilitate the assessment of digital climate governance. Employing spatiotemporal analysis and coupling coordination models, this study evaluates the digitalization levels in climate governance across 30 regions in China, examining how to progress digital integration from governmental and market perspectives. Findings reveal a consistent improvement in China's regional digital climate governance, bolstering economic and social progress. Nonetheless, regional disparities and developmental lags persist, with convergence analysis indicating a divergence trend in provincial climate governance capabilities. Moreover, kernel density and Markov chain analyses suggest an ongoing evolution in regional digital climate governance efforts, aiming at achieving a higher development plateau. The study emphasizes the dual role of government and market dynamics in boosting digital governance levels, deducing from two-stage regression that effective government-market interplay is vital for elevating governance quality and fostering new productive forces, recommending an integrated governance mechanism for optimal synergy.

Keywords: digital climate governance; convergence analysis; Markov chain; coupling coordination analysis; China

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1. Introduction

Climate change is a key challenge of the 21st century and has caused significant losses to the global economy and society, requiring measures to respond and adapt to it [1]. Amidst a governance dilemma, the international governance framework is experiencing a critical transitional phase [2]. The deterioration of the climate has precipitated a surge in extreme weather events, disproportionately burdening developing countries with annual losses of USD 35 billion due to meteorological disasters [3]. Consequently, the imperative to address climate change remains a pressing issue for countries around the world for the foreseeable future, demanding a holistic approach that merges technological, environmental, and social strategies to diminish human environmental impact and enhance resilience to climate perturbations [4,5]. As such, climate change response has escalated to a matter of national strategy and international policy concern, emphasizing its criticality to global survival.

Climate governance, a complex and broad concern, entails the collective efforts of governments, businesses, civil societies, and individuals. This universal challenge compels integrated actions from all global nations, evolving into a significant point of international focus, nurturing both cooperative and competitive environments. Varied governmental strategies have been deployed, with the UK setting ambitious targets to decrease emissions by 78% by 2035 and striving for net zero by 2050. Concurrently, China has initiated comprehensive plans for digital integration in environmental governance, focusing on advancing smart and efficient information systems for ecological management. The Intergovernmental Panel on Climate Change has highlighted the critical goal of net zero global carbon emissions by 2050 to control temperature rise within safe thresholds. To reduce the effects of climate change, an innovative overhaul of social and industrial frameworks is essential, pushing for digitization across all facets of governance [6].

Data have emerged as a critical production factor, strongly influencing social governance through extensive digitalization [7]. The exponential growth of digital technology has captured worldwide interest, sparking significant developments in the digital economy and promoting comprehensive integration of digital technologies across different domains [8]. The advent of digital transformation has notably enhanced the operational efficiency of Chinese multinational corporations in their international ventures. With its exceptional efficiency, processing power, and collaborative benefits, digital technology stands out as a crucial enabler for tackling key climate change issues. The World Economic Forum (WEF) has identified digital technology as a key player in reducing the effects of climate-induced secondary disasters and reducing greenhouse gas emissions. COP28 emphasized the strategic role of digital technologies in refining environmental governance mechanisms. The intersection of digitalization, artificial intelligence (AI), and climate change has guided unprecedented opportunities for advancing climate and environmental governance [9]. The fusion and mutual enhancement of digitalization and sustainability are now pivotal themes in global development [10].

Inhabited by over half of humanity, cities generate 80% of the global economic wealth [11], becoming centers of advanced digital infrastructure, robust inter-departmental synergy, and financial stability, which collectively lead to the evolution of the digital economy. The advancement in urban digitization not only drives economic growth but also opens up innovative avenues for tackling climate change. The industrial sector has been revolutionized through the melding of traditional manufacturing with emergent technologies such as computers, IoT, big data, and AI, leading to a model characterized by data-centric operations, intelligent automation, and high interconnectivity. This connection of technology and industry facilitates real-time data management and systemic integration, blurring the lines between the physical and digital worlds. With the advent of digital twins, real-time monitoring and optimization of industrial processes have become feasible, signifying a transition towards Climate 4.0. This transition integrates industrial digitization with climate governance, employing sophisticated analytical tools for environmental monitoring, as demonstrated by a citizen science initiative in Australia that leverages a mobile application for real-time climate data analysis and visualization [12].

The deepening commitment to carbon neutrality across the globe necessitates an effective management of carbon emissions, leading to the development of market-based carbon reduction incentives [13]. This involves establishing carbon-emission trading markets and utilizing carbon finance to advance carbon footprint management [14]. A consensus has emerged internationally on the need for a carbon footprint management system and a functioning carbon market, with countries actively fostering international collaboration to enhance and broaden the carbon market's reach. The success of these markets hinges on the accurate calculation of carbon footprints, where statistical accounting and verification capabilities are essential [15]. The complexity and volume of data involved in carbon footprint calculations emphasize the imperative for a comprehensive digital database. Digital technologies facilitate efficient data collection, accurate data analysis, and improved data security, thereby supporting a dynamic, transparent, and shared platform that is crucial for the effective operation of the carbon financial market [16]. The development of digital carbon footprint databases worldwide plays a critical role in advancing carbon reduction and slowing climate change.

The transformation in climate governance paradigms, especially towards digital integration, has gained significant attention from scholars and professionals. This shift, as Engvall and Leiter have pointed out, facilitates global climate governance through digital advancements [17,18]. However, the transition to digital climate governance (DCG) demands substantial financial and infrastructural support where a city's developmental state heavily influences its digital governance capabilities, thus creating vast regional differences. The absence of concrete measurements to gauge digital climate governance across China's regions highlights a gap in understanding both regional distinctions and governance efficacy. Climate governance, being a systemic undertaking, requires comprehensive enhancements in infrastructural, conceptual, and systemic domains, necessitating cross-regional cooperation to boost governance quality. Analyzing the disparities of digital climate governance contributes to driving targeted improvements, forging inter-regional collaboration, and significantly uplifting global climate governance standards. Furthermore, it intends to contribute to the creation of a robust digital infrastructure for climate governance, including a carbon emissions database, to facilitate global progress toward carbon neutrality and reduction. While digital technologies are playing an increasingly important role in addressing environmental challenges such as climate change, the characteristics and implications of digital environmental governance have not yet been fully conceptualized [19]. The G20 summit has proposed placing climate change and digitalization at the forefront, advocating for comprehensive international collaboration to establish a cohesive framework for digital climate governance to promote future health and well-being [20].

In this study, a comprehensive index system was constructed to measure the digital climate governance capacity of different provinces in China from 2007 to 2021, aiming to identify regional differences and dynamic trends to support the improvement of sustainable development policies. Distinct from existing methodologies, this study adopts a comprehensive approach to assess the progress of China in digital climate governance. It also examines the correlation between climate governance and economic progress, analyzing the coordination of digital climate governance capacity and economic development across regions. Furthermore, this study investigates the factors influencing digital climate governance, considering governmental and market-driven forces. Findings indicate an overall enhancement in China's digital climate governance from 2007 to 2021, although there are still persistent and expanding regional differences. The analysis reveals a general alignment between digital climate governance and economic growth, yet highlights significant regional imbalances in their coordinated development. To address these challenges, the study suggests that both governmental governance and market mechanisms are crucial, recommending enhanced synergy to foster a cohesive governance system.

This study significantly contributes to the field of climate governance across several dimensions. Firstly, it establishes a policy foundation to aid the advancement of digital climate governance systems, systematically evaluating regional capacities and confirming an upward trend in digitization aligned with national policy goals. Secondly, this study employs a variety of analytical methods—including convergence analysis, Gini index, Moran coefficients, and Markov chain analysis—to assess the development of China's digital climate governance. This multifaceted approach allows for a detailed exploration of digital infrastructure, resource supply, monitoring facilities, and environmental governance, providing insights that are critical for sustainable development and policy formulation.

Thirdly, the research addresses regional differences and the evolution of digital climate governance, correlating these dynamics with geographic and natural conditions to clarify the formation mechanisms of climate governance capacities. This analysis fosters an understanding of how climate governance integrates with local environmental factors, advocating for enhanced governance levels. Fourthly, the study assesses the interplay between climate governance capacity and the socio-economic development of regions, offering recommendations for integrating climate governance more effectively into the broader societal framework. This aims to foster the development of both climate governance and economic systems. Lastly, by categorizing influencing factors into governmental and societal domains, the study concentrates on strategies for promoting high-quality digital climate governance. It highlights the importance of synergistic interactions between governmental and market forces in improving the standards of digital climate governance, thus facilitating comprehensive and sustainable development.

The remainder of the paper will be structured as follows: Section 2 provides a literature review, Section 3 describes the research design, Section 4 reports the empirical results of the digital climate governance capacity section and analyzes them, Section 5 analyzes the developmental coherence of the climate governance system and the economic and social development system, Section 6 examines the factors affecting the digital climate governance capacity and analyzes them, and Section 7 summarizes the conclusions of the article and provides policy recommendations.

2. Literature Discussion and Theoretical Analysis

Countries worldwide are striving for high-quality sustainable development, exploring various strategies to effectively address climate change and environmental degradation [21]. The rapid digitalization of the economy has propelled the emergence of innovative technologies that offer digital solutions to pressing global issues [22]. The realm of artificial intelligence (AI) and machine learning (ML) is particularly noteworthy, with sectors striving to leverage these technologies' growing potential. Recent years have witnessed a significant increase in efforts to reduce climate change through digital technologies. Machine learning, a pivotal AI technique, has found applications across diverse sectors, including energy, transportation, agriculture, industry, and geoengineering [23]. Currently, there are articles that have researched the significant role of smart technology in Brazil's climate governance in promoting citizen well-being and climate change adaptation [24]. Some article proposes the establishment of a robust data collection and governance system to assist governments in achieving climate goals, with a focus on Latin America as a case study for analysis [25].

Climate governance is complex, encompassing various subsystems like economy, environment, energy, and society [26]. It involves a multitude of stakeholders, including non-state actors, non-governmental organizations (NGOs), businesses, academia, cities, and international bodies. The structural evolution of climate governance has transitioned from a simplistic to a multifaceted framework, accommodating the growing complications of climate challenges [27]. With the intensification of climate-related issues, the digitization of climate governance has gained forcefulness, enhanced by advancements in infrastructure and the conceptualization of governance. This digital governance model is increasingly being integrated into diverse social governance applications, with the rising practical usage catalyzing the development of digital governance systems [28]. Consequently, the digital climate governance capacity across various regions has significantly improved [29]. However, the adoption of digital climate governance is resource-intensive [30], necessitating substantial capital and human resources. Such requirements have hindered the digitization process in certain regions, leading to significant disparities in digital climate governance capabilities.

As economic and social development accelerates, so too does the recognition of the need to reduce the impacts of climate and environmental changes on this growth [31]. Economic losses and chain reactions triggered by natural climatic events present significant risks to both daily life and the natural environment, especially during escalating global industrialization, urbanization, population growth, and intensifying climate change [32]. Such events, along with secondary disasters, are expected to increasingly and strongly affect economic and social progress [33], thereby elevating governance demands. The Paris Agreement calls for a USD 95 trillion global investment in infrastructure by 2030 to combat climate change, highlighting the critical role of developed countries.

Concurrently, higher economic development lays a solid foundation for digital transformation in governance. Despite the slow growth in private climate change financing [34], there is a notable uptick in investment towards the digital transformation of climate governance. The Green Climate Fund (GCF), a key UNFCCC framework component, has shown effectiveness in engaging the private sector in climate governance investments and securing increased governmental funding for developing countries' climate governance infrastructure [35]. Addressing climate change involves navigating the complex interplay between climate adaptation, economic activities, human development, and energy efficiency. This complexity necessitates a delicate balance and trade-offs among these domains, with a pivotal focus on their coordinated development [36]. Crucially, the alignment between climate governance and economic growth must be such that climate governance efforts do not hinder, but rather support, sustainable economic and social development. The goal is for climate governance capacity to be in harmony with economic development, ensuring that climate initiatives support rather than burden economic and social progress.

Digital climate governance encompasses a multifaceted approach, engaging society, individuals, and businesses [37]. It necessitates a collaborative effort across all societal sectors to elevate governance standards effectively. The Brundtland Report of 1987 pioneered the concept of addressing multiregional environmental issues at the local level, highlighting the pivotal role of local governments in fostering climate governance and sustainable development [38]. Over the past two decades, local governments have emerged as key policymakers and implementers in climate change policy, integrating climate governance measures into many cities' local political agendas. However, the expansive dominion of governments contrasts with their limited institutional size and workforce, posing challenges to the digitalization of climate governance. The development of a carbon trading market and the further integration of market forces into climate governance and energy upgrading open new avenues for enterprise involvement in the low-carbon economy [39]. Despite enterprises' potential in climate governance, governmental guidance often falls short, limiting their contributions and operational scope. This is compounded by fluctuating political support for initiatives like renewable energy [40], which introduces instability and uncertainty for investors. Compared to government-led initiatives, enterprises offer more flexible governance solutions, backed by stronger financial resources and technological capabilities [41]. This dynamism can strengthen digital climate governance. A synergistic collaboration between governments and businesses can leverage their respective strengths, fostering a cohesive governance framework. This partnership is crucial for achieving high-quality digital climate governance swiftly.

3. Data and Methodology

3.1. Construction of the Index System

Developing a system to measure digital climate governance is a pivotal step toward advancing sustainable development. Recognizing the insufficiency of a singular climate governance indicator to encapsulate the full spectrum of governance capacity, there is a pronounced need for a holistic indicator. The paper draws upon the relevant literature in the fields of digital governance and climate governance, aligning with the core principles and objectives of the United Nations' Sustainable Development Goals (SDGs). Additionally, it references climate digital governance initiatives and action plans already implemented in certain regions. By analyzing publicly available online information from Spain, the paper establishes a foundation for selecting indicators for measuring digital governance, thus contributing to the advancement of climate governance frameworks [42]. This indicator must encompass various developmental facets, notably the advancement of digital infrastructure and meteorological monitoring infrastructure (each serving a unique role in shaping digital climate governance). The former establishes a foundational platform for digital initiatives, while the latter underpins the domain of climate monitoring and governance. Additionally, digital resources, representative of a region's developmental trajectory, accumulate over time, making immediate adjustments challenging. Local financial health and investments in climate and environmental initiatives significantly contribute to enhancing climate governance attention and actions, marking a critical path toward sustainable development. Furthermore, the energy sector's enterprises play a vital role in climate governance, necessitating their inclusion in a comprehensive digital climate governance assessment framework. This study's evaluation system, therefore, integrates four dimensions: digital infrastructure, digital resource availability, climate monitoring capability, and climate governance efficacy. Data for this analysis are derived from a range of statistical yearbooks—such as the China Statistical Yearbook, China Energy Statistical

Yearbook, and China Environmental Statistical Yearbook, with additional variables being directly calculated by the researchers. The comprehensive scoring system outlined in Table 1 operationalizes this evaluation approach.

Table 1. The composition of the measuring index of digital climate governance.

First-Level Indicators	Second-Level Indicators	Properties
Digital climate infrastructure	Number of Internet access ports	+
	Optical cable line length	+
	GPS measuring points	+
	Postal and telecommunications business volume	+
Digital infrastructure resources	Employments in the information software industry	+
	Digital transformation index of listed companies	+
	Employments in scientific research industries	+
Climate monitoring facilities	Number of ground observation stations	+
	Number of automatic weather stations	+
	Number of satellite image receiving sites	+
Climate governance	Environmental protection fiscal expenditure	+
	Meteorological affairs expenditure	+
	Investment in ecological construction	+
	Energy industry investment	+

Note: The "+" in the table denotes the indicator is a positive one in the index system.

3.2. Research Methodology

3.2.1. Entropy Weight Method

To enhance the scientific accuracy and objectivity of our comprehensive evaluation, this study employs the entropy weighting method. This approach, widely recognized for its reliability across various fields [43], allows for a precise measurement of each indicator's weight within the comprehensive indicator system. By analyzing correlations and the inherent information within raw data, we ascertain the importance of indicators, thereby refining our assessment of digital climate governance capacity alongside economic and social development. The entropy weight method's calculation steps are as fellow:

In order to avoid the influence of the dimension in the calculation of the indicators, the indicators are first standardized, and after the indicators are classified as positive and negative, they are standardized through Equation (1):

$$\begin{aligned} &\text{Positive } x'_{ij} = \frac{x_{ij} - min\left(x_{1j},\, x_{2j}, \cdots, x_{nj}\right)}{max\left(x_{1j},\, x_{2j}, \cdots, x_{nj}\right) - min\left(x_{1j},\, x_{2j}, \cdots, x_{nj}\right)} \\ &\text{Negative } x'_{ij} = \frac{max\left(x_{1j},\, x_{2j}, \cdots, x_{nj}\right) - x_{ij}}{max\left(x_{1j},\, x_{2j}, \cdots, x_{nj}\right) - min\left(x_{1j},\, x_{2j}, \cdots, x_{nj}\right)} \end{aligned} \tag{1}$$

After calculating the entropy of each dimension, the indicator redundancy is measured and the weights and composite scores are calculated using Equations (2)–(4).

$$E_j = -k\sum_{i=1}^{n} p_{ij} \ln\left(p_{ij}\right) \tag{2}$$

$$p_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{n} x'_{ij}}, i = 1, \ldots, n, j = 1, \ldots, m \;\; k = \frac{1}{\ln(n)} > 0, E_j \geq 0 \tag{3}$$

$$d_j = 1 - E_j,\ w_j = \frac{d_j}{\sum_j d_j},\ s_i = \sum_j w_j x'_{ij} \tag{4}$$

where d_j is the entropy value of the j indicator. The weigh w_j ($0 \leq w_j \leq 1$, $\sum w_j = 1$) is determined by the ratio of redundancy ($1 - E_j$) to total redundancy ($\sum_j^n d_j$).

3.2.2. Decomposition of Regional Differences

The Gini coefficient, a widely recognized measure of inequality, is further refined by the Dagum−Gini coefficient, which offers a modification for analyzing spatial disparities. In our study, we apply the Dagum−Gini coefficient to dissect the spatial variances in digital climate governance across four regions in China. This method, notable for its efficacy in describing regional differences, enables a detailed decomposition of disparities, including intra-region differences, inter-region disparities, and cross-regional overlaps. Such decomposition not only highlights the relative differences more effectively but also enhances the precision of our analysis by handling sub-sample distributions and overlaps. The formula used to calculate the Dagum−Gini coefficient for each province's digital climate governance capacity is seen in Equation (5):

$$G = \frac{\sum_{j=1}^{k} \sum_{h=1}^{k} \sum_{i=1}^{n_j} \sum_{r=1}^{n_h} \left| y_{ji} - y_{hr} \right|}{2n^2 \overline{y}} \tag{5}$$

The overall Gini coefficient (G) consists of three components: within-region variation (G_w), between-region variation (G_{nb}), and cross-region intensity (G_t). The formulas for the three components are shown in Equations (6)–(9)

$$G_w = \sum_{j=1}^{k} G_{jj} p_j s_j \tag{6}$$

$$G_{nb} = \sum_{j=2}^{k} \sum_{h=1}^{j-1} G_{jh} \left(p_j s_h + p_h s_j \right) D_{jh} \tag{7}$$

$$G_t = \sum_{j=2}^{k} \sum_{h=1}^{j-1} G_{jh} \left(p_j s_h + p_h s_j \right) \left(1 - D_{jh} \right) \tag{8}$$

$$G_{jj} = \sum_{i=1}^{n_j} \sum_{r=1}^{n_j} \left| y_{ji} - y_{jr} \right| / 2n_j^2 \overline{y_j} \cdot G_{jh} = \sum_{i=1}^{n_j} \sum_{r=1}^{n_h} \left| y_{ji} - y_{hr} \right| \tag{9}$$

3.2.3. α Convergence

On the basis of studying the difference of digital climate governance capacity in China, this study wants to further explore whether the difference in the average value of the digital climate governance capacity of each region produces changes over time, so this study introduces the α convergence model, and the calculation formula is seen in Equation (10):

$$\sigma_t = \frac{\frac{\sqrt{\left[\sum_j^{n_j} \left(DCG_{jt} - \overline{DCG_t} \right)^2 \right]}}{n_j}}{\overline{DCG_t}} \tag{10}$$

where σ_t is the variance index of digital climate governance capacity, which reflects the overall dispersion of the governance capacity of each province, DCG_{jt} denotes the digital climate governance score of province j in year t, and $\overline{DCG_{jt}}$ represents the average score of all the provinces in year t.

3.2.4. β Convergence

The β convergence studies the trend of changes in digital climate governance scores in different regions, and it contains two methods, absolute β convergence and conditional β convergence, which furthers study the convergence after controlling the influencing factors on the basis of the changes in the level of digital climate governance itself. The convergence model is as Equation (11):

$$ln\left(\frac{DCG_{i,t+1}}{DCG_{i,t}} \right) = \alpha + \beta lnDCG_{i,t} + \gamma Z_{it} + \mu_i + \lambda_t + \mathcal{E}_{it} \tag{11}$$

The left side of the equation shows the growth rate of the digital climate governance level score. μ_i, λ_t and $\mathcal{E}_{\text{it}}$ denote the individual fixed effects, time fixed effects, and random disturbance, respectively. The coefficient of β represents the change in the digital climate governance capacity, and if it is significantly negative, it indicates that the change in the digital climate governance capacity of the provinces exhibits β convergence.

3.2.5. Nuclear Density Estimation

Kernel density estimation is a non-parametric method for studying spatially unbalanced distributions by estimating the probability density function of a random variable by placing kernels around each data point, summing up and estimating the probability density. The continuous smooth density curve of the kernel density estimate represents the location, shape and expansion of the random variable. In this study, the Gaussian function, a widely used kernel density function, is used for estimation. Assuming that the density function of the random variable *x* is *f(x)*, the kernel density is estimated as Equation (12).

$$f(x) = \frac{1}{Nh}\sum_{i=1}^{N} K\left(\frac{X_i - \overline{x}}{h}\right) \tag{12}$$

where K(·) represents the Gaussian kernel density function. $K(x) = \frac{1}{\sqrt{2\pi}}exp\left(-\frac{x^2}{2}\right)$, N is the number of observations in a region, X_i is the number of observations that satisfy an independent and homogeneous distribution, $\overline{x}$ is the mean of the observations, and h is the bandwidth, which determines the accuracy of the estimation and the smoothness of the density profile.

3.2.6. Markov Chain Analysis

In this study, the probability distribution of discrete data is computed through data processing utilizing a Markov chain to reflect the changing characteristics of digital climate governance capabilities. The Markov chain can be defined as $P\{X(t) = j \mid X(t-1) = i\}$ under the assumption that the current state is only related to the state in the previous period, and the Markov chain is characterized by capturing the transfer of the random variable element P_{ij} in the state transfer matrix, which is meant to be the probability of a province's digital climate governance capacity changing from the state *i* in the year *t* to the state j in the next year. P_{ij} = N_{ij}/N_j, N_{ij} is the number of provinces with state *i* in year *t* and state j in the next year, and N_j is the number of provinces with state *i* in the first year. In this study, we categorize the data to form a discrete dataset by the quartiles of the digital climate governance capacity (0.1463, 0.1818, 0.2399).

3.2.7. Coupled Coordination Degree Model

The degree of coupled coordination between digital climate governance capacity and economic and social development is traditionally calculated through Equation (13):

$$C = \left[\frac{\prod_{i=1}^{n} U_i}{\left(\frac{1}{n}\sum_{i=1}^{n} U_i\right)^n}\right]^{\frac{1}{n}} \tag{13}$$

Since the traditional coupling degree C is not a uniform distribution function between [0, 1], the traditional coupling coordination degree model has validity problems, and the coupling degree is no longer in the interval [0, 1]. In order to solve the validity problem, this study modifies the model as Equations (14)–(16):

$$C = \sqrt{\left[1 - \frac{\sum_{i>j,j=1}^{n} \sqrt{\left(U_i - U_j\right)^2}}{\sum_{m=1}^{n-1} m}\right] \times \left(\prod_{i=1}^{n} \frac{U_i}{maxU_i}\right)^{\frac{1}{n-1}}} \tag{14}$$

$$T = \sum_{i=1}^{n} \alpha_i \times U_i, \sum_{i=1}^{n} \alpha_i = 1. \tag{15}$$

$$D = \sqrt{C \times T} \tag{16}$$

where U_i is the normalized value of subsystem i, α_i is the weight of i. C is the degree of coupling between the interaction of digital climate governance and the degree of socio-economic development, and it is a comprehensive evaluation index of the digital governance capacity and the degree of socio-economic development. D is the degree of coupling and coordination of the two systems. The model effectively distributes C in [0, 1] as much as possible, and increases the differentiation of the value of C degree, which greatly improves the validity in the study.

3.2.8. Panel Regression Model

This study uses the following model as Equation (17) for panel regression to explore the influence of both market and government factors in the development of digital climate governance levels:

$$DCG_{it} = \beta_0 + \beta_1\, Market_{\,it} + \beta_2\, Gov_{\,it} + \sum_{k=1}^{n} Controls_{kit}\, \gamma_k + \lambda_i + \mu_t + \varepsilon_{it} \tag{17}$$

where DCG_{it} is the digital climate governance capacity of region i in year t, $Market_{it}$ and Gov_{it} are the core explanatory variables which indicate the role of market and government forces in region i in year t, and Controls represent the series of control variable combinations. Parameters β_1, β_2 and γ_k represent the corresponding regression coefficients. Considering that the trend of digitalization of the society and some potential observed regional heterogeneity may affect the provinces in the digital climate governance, this study adds regional fixed effects λ_i and year effects μ_t to the model. The stages of economic development are dynamic processes of change, and the government plays an important role in infrastructure development and social governance; therefore, as reflected by the coefficients β_1 and β_2, both market forces and governmental factors have impacts on the digital climate governance capacity.

3.2.9. Driscoll and Kraay Standard Errors Model

In order to solve the problems of heteroskedasticity, autocorrelation, and cross-section correlation in regression, this paper uses the Driscoll−Kraay standard error to perform a robustness test. The estimation of fixed effects is implemented in two steps. First, all variables in the model (17) z_{it} will be transformed as follows:

$$\widetilde{z}_{it} = z_{it} - \overline{z}_i + \overline{\overline{z}}\ ,\ \overline{z}_i = T_i^{-1} \sum_{t=t_{i1}}^{T_i} z_{it}\ ,\ \overline{\overline{z}} = \left(\sum T_i\right)^{-1} \sum_i \sum_t z_{it} \tag{18}$$

We simplify the regression model to:

$$y_{it} = \theta x'_{it} + \varepsilon_{it} \tag{19}$$

where the dependent variable is y_{it}, x'_{it} is a vector of independent variables, and θ is a vector of unknown coefficients. Additionally, i denotes the cross-sectional units (“individuals”) and t denotes time. It is common to organize all observations as follows:

$$\mathbf{y} = \left[y_{1t_{11}} \ldots y_{1T_1}\ y_{2t_{21}} \ldots y_{NT_N}\right]' \text{ and } \mathbf{X} = \left[\mathbf{x}_{1t_{11}} \ldots \mathbf{x}_{1T_1}\ \mathbf{x}_{2t_{21}} \ldots \mathbf{x}_{NT_N}\right]' \tag{20}$$

where θ can consistently be estimated by ordinary least squares (OLS) regression, which yields and $\hat{\theta} = \left(\mathbf{X}'\mathbf{X}\right)^{-1}\mathbf{X}'\mathbf{y}$.

4. Discussions of Results

4.1. Digital Climate Governance Index Calculations

Figure 1 illustrates the evolution of digital climate governance scores across four regions (East, Central, West, Northeast) in China from 2007 to 2021. By averaging provincial scores within each region, we ascertain that, while China has made consistent progress in digital climate governance, the overall level remains suboptimal compared to the Eastern region the highest one in nationality and four regions. In 2021, the national overall score stood at 0.4909, with a mean regional score of 0.4465, highlighting significant potential for enhancement. The Eastern region led with a score of 0.5554, indicating the highest level of digital climate governance, followed by the Central (0.4731), Western (0.4010), and Northeastern (0.3564) regions. The capacity was highly related to the social and economic development, while the Eastern region's economy grew the most, featuring the highest score in digital climate governance in regard to constructing and operating the digital governance infrastructure, which has significant costs. These findings validate the robustness of our indicator system and the entropy weight method, suggesting our analysis accurately reflects the state of digital climate governance without overstating the digitalization progress.

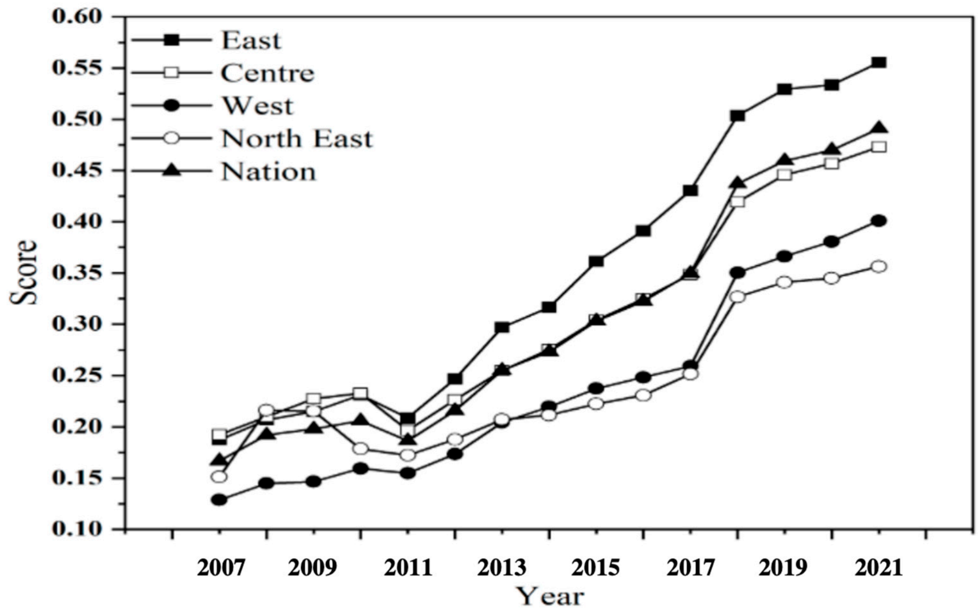

Figure 1. Trend in digital climate governance score.

Significantly, the Eastern region has maintained a leading position in digital climate governance capacity since the onset, with its advantage becoming markedly more pronounced since 2011. This period marked a rapid ascent in digital climate governance across all regions, with the Eastern region not only achieving the fastest growth but also setting the benchmark in climate governance capacity. The digital governance growth in the Eastern region escalated from a modest 0.1874 in 2007 to an impressive 0.5554 in 2021. The average annual growth rate in this region was 0.53% up to 2011, surging to 3.47% thereafter. These findings align with the existing literature, highlighting the Eastern region's superior infrastructure development and digitalization efforts. Interestingly, the Central region exhibited relative advantages until 2011 at 0.1965, possibly due to its resource reserves and industrial base, which facilitated digital infrastructure development by absorbing industrial transfers from the East [44]. Meanwhile, the Northeast region experienced a brief period of dominance around 2008 at 0.2163, but its development pace has slowed significantly since 2010 at 0.1785, trailing behind other regions (0.2312, East; 0.2328, Central).

Figure 2 reveals significant disparities in digital climate governance capabilities across Chinese provinces in 2021. In the Eastern provinces, Guangdong stands out with a score of 0.7469, followed closely by Hebei at 0.6316, both significantly outperforming other provinces in the Eastern region. Jiangsu (0.5835), Zhejiang (0.5771), and Shandong (0.5841) are superior in terms of digital governance. The Western region sees Sichuan (0.6335) and Yunnan (0.4065) leading, with Inner Mongolia (0.4239) and Guangxi (0.4625) also showcasing strong capabilities. In the Central region, Hunan (0.4199) and Hubei (0.4536) are highlighted as notable performers, whereas Heilongjiang (0.3397) emerges as the front-runner in the Northeast. This variation in digital climate governance underscores the impact of diverse resource allocations and industrial bases across the regions, hinting at the necessity for tailored approaches to digital governance transformation.

Figure 2. Digital climate governance scores of provinces in China.

Figure 3 charts the evolution of China's Digital Climate Governance Capability Scores between 2007 and 2018, with subfigures describing provincial scores for each of these years. This period witnessed a general enhancement in carbon neutrality scores across most provinces, with the Eastern region maintaining a distinct lead. Notably, the Guangdong province, which held the highest score in 2007 at 0.2106, impressively advanced to 0.7251 by 2018. Jiangsu, Beijing, and Zhejiang have similarly demonstrated substantial growth potential in digital climate governance. This is closely related to the solid economic development foundation and varying developmental stages across different regions. Provinces along the southeastern coast, such as Guangdong and Zhejiang, were among the first in China to open up to foreign investment. They have achieved high-quality economic development and possess robust industrial foundations. Moreover, they are at the forefront of industrial transformation and have accumulated rich experience in utilizing digital technologies to achieve green development. These factors lay a solid foundation for advanced levels of digital climate governance capabilities [45]. In the Central region, Hubei emerged as the province with the foremost governance capacity. The correlation between these scores and the robust economic and industrial infrastructure of the developed Eastern and Central provinces is stark. A strong economy underpins the deployment of innovative technologies and digital transformation facilities critical for advancing digital climate governance [46]. Meanwhile, Sichuan stands out in the Western region due to its consistently high scores, though other provinces in this area lag. As Sichuan Province serves as the central hub for development in the Western region and a vital gateway for external trade and communication, it holds significant importance in the advancement of digital climate governance. Moreover, the province boasts abundant technical resources, including numerous universities and research institutes. These factors play a pivotal role in enhancing its digital climate governance capabilities [6]. The Northeast, despite its solid industrial foundation, faces challenges in timely industrial structural transformation and upgrading, marking a pivotal phase for its industrial evolution. Consequently, its digital climate governance scores remain comparatively low.

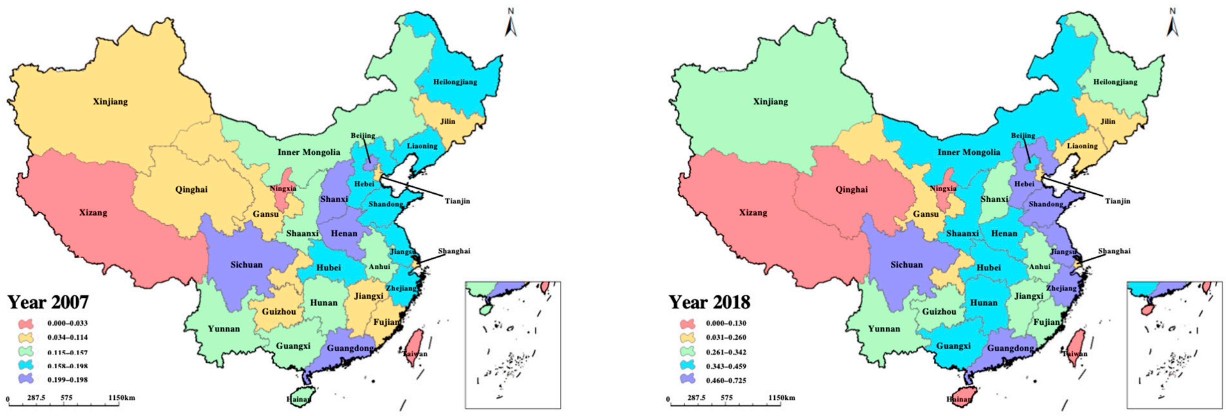

Figure 3. Spatial distribution of digital climate governance in China.

The varied resource endowments, industrial dynamics, and historical contexts across the four regions account for the significant disparities in governance capacity observed. These differences underscore the necessity for region-specific digital transformation strategies in climate governance, emphasizing the importance of formulating development policies along with the localities' unique attributes.

4.2. Decomposition of the Digital Climate Governance Index

This study employs a regional differences decomposition method to dissect the digital climate governance capacity scores by region, as visualized in Figure 4. The decomposition analysis, with the Eastern and Central regions featured in the first row and the Western and Northeastern regions in the second, highlights stark contrasts in their digitalization progress. The Eastern region, with its forefront position in digital infrastructure development, not only continues to bolster its lead but also contributes significantly, accounting for 41% of its digital climate governance capacity in 2021. This finding aligns with expectations and underscores the Eastern region's robust foundation in industrial and digital technology development, propelling it ahead. Achieving commendable strides in digital transformation across various sectors, the Eastern region necessitates further bolstering through policy and market support. Such strategic support is pivotal for sustaining its advantage, paving the way for pioneering advancements in digital climate governance methodologies and technologies and amplifying the national digital climate governance level by setting a precedent for other regions to follow.

The Central region of China distinguishes itself through its advanced climate monitoring facilities, which are underpinned by a robust manufacturing industry base [47]. This combination has been crucial in establishing a high level of climate monitoring, which in turn plays a pivotal role in the region's digital climate governance capabilities. Such facilities, while increasingly utilized in the Western region—with their advantages growing annually—face limitations due to inadequate digital resources and infrastructure. This situation suggests significant untapped potential for enhancing digital climate governance in the Western region. Conversely, the Western and Northeastern regions benefit from a more favourable climate environment and face less pressure in regard to climate governance. However, their digitalization efforts lag, impeding the development of their digital climate governance capacity. This lag not only hinders progress in climate governance but also adversely affects local efforts in climate environment protection. The contrast across regions highlights the importance of tailored strategies to overcome specific challenges, emphasizing the need for investments in digital infrastructure and resources, particularly in the Western and Northeastern regions, to unlock their full potential in digital climate governance.

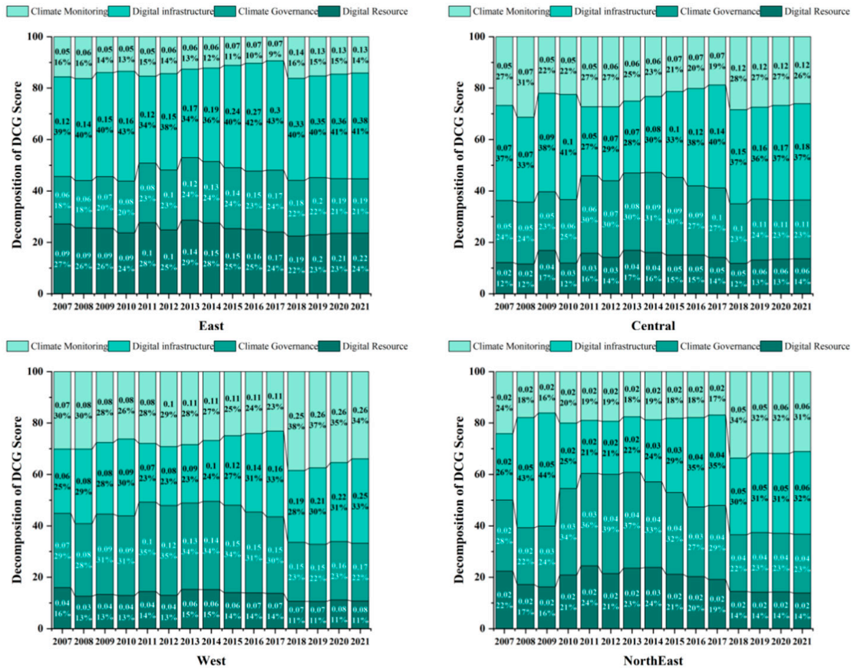

Figure 4. Decomposition of digital climate governance score in the four regions.

4.3. Analysis of Differences in Digital Climate Governance Capacity

Table 2 shows the Gini coefficient's revolution, capturing the fluctuations in digital climate governance capacity disparities from 2007 to 2021. Initially, the overall Gini coefficient stood at 0.221 in 2007, peaked at 0.264 in 2017, and subsequently declined to 0.249 by 2021. Despite a temporary reduction after 2017, the long-term trend indicates a 12.67% increase in the Gini coefficient, suggesting a gradual exacerbation in the imbalance of digital climate governance capacity across regions. The analysis reveals that intra-regional variance aligns with the overall trend and serves as the predominant factor in overall disparities, followed by inter-regional differences. Both the Gini coefficient and intra-regional variance share an "inverted U-shaped" trajectory, implying a peak followed by a decrease, yet with an overall upward shift. Conversely, inter-regional variance indicates a fluctuating yet ascending pattern, signifying a narrowing gap in digital climate governance capacity among regions.

Table 2. Sources of differences in the digital climate governance scores.

Year	G	Between		Overlap		Within	
		G	Contribution	G	Contribution	G	Contribution
2007	0.221	0.094	42.458	0.068	31.024	0.058	26.518
2008	0.229	0.096	41.893	0.073	32.025	0.060	26.083
2009	0.231	0.098	42.642	0.071	30.677	0.062	26.681
2010	0.233	0.089	38.125	0.079	33.788	0.065	28.087
2011	0.232	0.067	28.770	0.098	42.077	0.068	29.153
2012	0.235	0.072	30.759	0.095	40.684	0.067	28.557
2013	0.246	0.073	29.677	0.102	41.530	0.071	28.792
2014	0.246	0.072	29.323	0.103	42.100	0.070	28.577
2015	0.247	0.088	35.594	0.090	36.540	0.069	27.867
2016	0.251	0.099	39.273	0.084	33.365	0.069	27.362
2017	0.264	0.110	41.676	0.083	31.538	0.071	26.786
2018	0.251	0.092	36.512	0.090	35.708	0.070	27.780
2019	0.249	0.092	37.149	0.087	34.944	0.069	27.908
2020	0.249	0.086	34.356	0.093	37.379	0.070	28.265
2021	0.249	0.083	33.542	0.095	38.040	0.071	28.418

The convergence is likely facilitated by the dense economic ties and geographic proximity within provinces, fostering rapid collaboration in digital climate governance. In the Eastern region in particular, where digital resources and technologies are abundant [48], inter-regional exchanges and collaborations with the West and Northeast are instrumental in elevating the governance levels of less-developed areas. Such partnerships, alongside the progress in lagging provinces and the stabilization of cooperative models, are gradually bridging the inter-regional divide. This dynamic serves as a key driver in reducing overall disparities in digital climate governance capacity, indicating a pathway toward more balanced development.

4.4. Convergence Analysis

4.4.1. Sigma Convergence Analysis

The coefficients of the responses in Figure 5 indicate whether there is convergence in the digital climate governance capacities of the regions. Overall, there is no convergence in digital climate governance capacity. The Sigma convergence coefficient increases from 0.1653 in 2007 to 0.4554 in 2021, which indicates a further widening of the overall differences, consistent with the findings above. From the perspective of each region, the Sigma convergence reflects to some extent the findings of the Gini coefficient within the region, with the Sigma coefficient showing an increasing trend of upward fluctuation in the Eastern and Western regions, which have a more dispersed distribution of digital climate governance capacity. In contrast, the Central and Northeastern regions have significantly lower growth rates than the Eastern and Western regions, although the coefficients also show an increasing trend. The above data indicate that the digital climate governance capacity does not meet the conditions of Sigma convergence, and the gap in digital climate governance capacity between regions still exists, which is consistent with the results of the Dagum−Gini coefficient method.

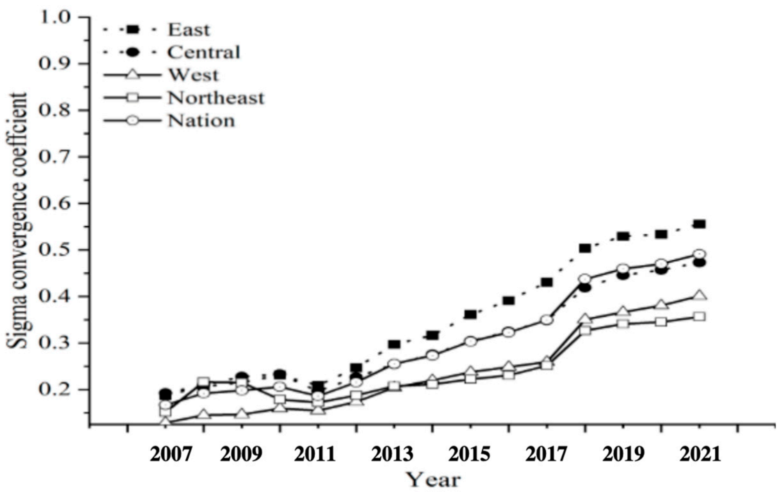

Figure 5. Trends of inter-regional differences in digital climate governance score.

4.4.2. Beta Convergence Analysis

Table 3 illustrates the results of absolute beta convergence. The coefficients of the digital climate governance capability score in columns (1) to (5) are all significantly positive, which indicates that there is no beta convergence in the digital climate governance score, which implies that the degree of digital transformation of climate governance is inconsistent across regions and that the digitization level of the less-developed regions is still lagging behind that of the developed regions. This is perpetuated by the reality that, during past development, developed regions such as the East have been in the leading position in terms of technological innovation and industrial upgrading, and the Eastern region has a first-mover advantage in digital technologies, therefore having a higher degree of competitiveness in the digital transformation of climate governance.

Table 3. Absolute beta convergence regression results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	All	**East**	**Central**	**West**	**Northeast**	**Subsample1**	**Subsample2**
DCG	0.101 *** (−0.019)	0.0799 ** (−0.031)	0.278 *** (−0.0791)	0.134 *** (−0.0326)	0.768 ** (−0.306)	0.439 *** (0.057)	0.067 (0.0508)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	420	140	84	154	42	210	180
R-squared	0.511	0.567	0.612	0.711	0.666	0.498	0.649

Note: Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$.Year FE and Province FE denote the time fixed effect and region fixed effect.

Table 4 presents the findings from a regression analysis focused on conditional beta convergence, accounting for variables such as economic development and industrial structure. Despite these considerations, the coefficient associated with digital climate governance capacity remains significantly positive, suggesting an absence of significant conditional beta convergence in this domain. This outcome implies that disparities in digital climate governance capacity across Chinese provinces are on the rise, pointing to a geographic specificity in the evolution of China's climate governance digitalization. In light of governance capacity's dynamic nature across events, we divided the dataset using 2013 as a pivot, yielding two time-distinct sub-samples. Analysis revealed that, while the core explanatory variables in column (6) show significant positive coefficients, those in column (7) are positive yet not significant. This pattern hints at a stabilization in regional development discrepancies over time, albeit without full convergence, indicating a gradual alignment in digital climate governance capacities.

Table 4. Conditional beta convergence regression results.

Variables	(1)	(2)	(3)	(4)	(5)
	All	**East**	**Central**	**West**	**Northeast**
DCG	0.103 *** (−0.018)	0.0676 ** −0.026	0.232 *** (−0.068)	0.118 *** (−0.0302)	0.393 ** (−0.148)
Year FE	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes
Observations	420	140	84	154	42
R-squared	0.505	0.556	0.569	0.700	0.634

Note: Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$. Year FE and Province FE denote the time fixed effect and region fixed effect.

4.5. Dynamic Evolution of Digital Climate Governance Capabilities

In this study, the kernel density estimation method is used to further explore the time−space evolution characteristics of digital climate governance capacity. As shown in Figure 6, starting from the center of the density curve, the center of the digital climate governance capacity scores moves to the right continuously. Therefore, the digital climate governance capacity of the provinces is increasing and improving. The process of digital climate governance may be closely related to the development of digital technology and the upgrading of infrastructure configuration. However, there is still much room for digital climate governance in China, which means that the process of digitizing climate governance should be further deepened.

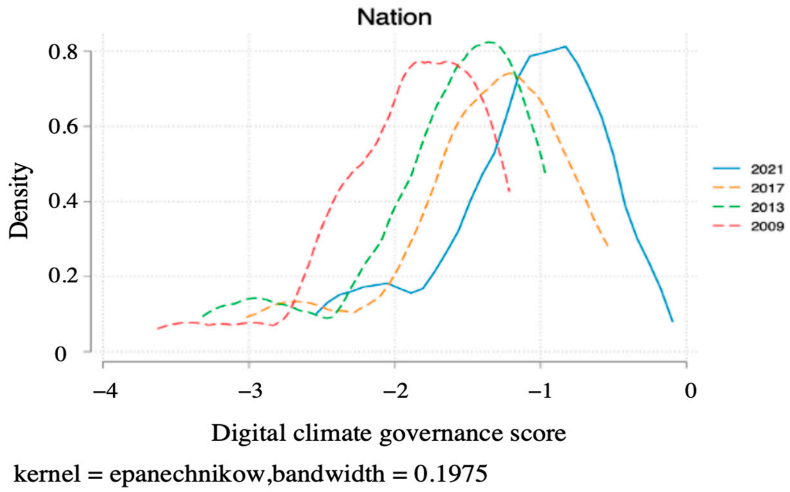

Figure 6. Evolution of the digital climate governance score.

The figure analysis shows that, although the peaks of the graph fluctuate consistently, the range of these fluctuations is getting wider. This suggests that the difference in how provinces in China manage their digital climate governance is growing. Over time, it can be seen that the graph changes from showing one main peak in 2007 to several peaks, indicating that multiple provinces are now leading in digital climate governance. This is corroborated by our data characteristics, with provinces like Guangdong, Zhejiang, and Beijing all featuring notably high digital governance scores. Considering the distinct characteristics and developmental evolutions of various regions, it is evident that each follows a unique dynamic evolutionary pattern. Further analysis of the regional evolution of digital climate governance reveals that these distinct paths reflect the diverse socio-economic and environmental backgrounds across regions. This emphasizes the importance of tailoring digital climate governance strategies to align with each region's specific conditions and developmental needs. Figure 7 illustrates the results of the kernel density estimates for the evolution of the numerical climate governance scores for the four regions. The two pictures in the first row show the results for the Eastern and Central regions, while the second row gives the results for the Western and Northeastern regions. The results of the images show that the dynamical evolution patterns of these four regions vary considerably. The Eastern region shows a significant decrease in the peak and a widening of the change interval as it continues to improve its digital governance score. The absolute differences in the Central region show a trend of widening and then narrowing in the process of increasing digital climate governance, especially between 2017 and 2021. As can be seen from the figure, the change interval shows a wider level at the beginning, and in 2021 the change interval narrows significantly and the peak rises more. As a result, more and more provinces are moving towards a higher level of sustainable development, with the overall level producing a significant catch-up effect.

The evolution of digital climate governance capacity in the Western region shows that the peak and bandwidth intervals show a gradual decline and widening, respectively. As a result, from 2007 to 2021, the absolute divergence of DCG in the Western region has increased, which is consistent with the results of the regional divergence and convergence analyses above. This trend of greater intra-regional divergence has persisted since 2009, becoming more significant over time. This may be related to the fact that the dominant provinces in the region, such as Sichuan and Guangxi, have significantly higher digitization capacities than the other Western provinces. The center of density in the Northeast is moving steadily to the right, and the overall shape is similar to the change in the Central region, while the change in the relative position of the curve reflects that both the left and right ends of the curve are shifting to the right, which suggests that the region's ability of climate governance is improving. Additionally, the peak of the curve is significantly higher in 2021, which suggests that the Northeast region's climate governance capacity is catching up quickly and improving greatly under the collaborative model.

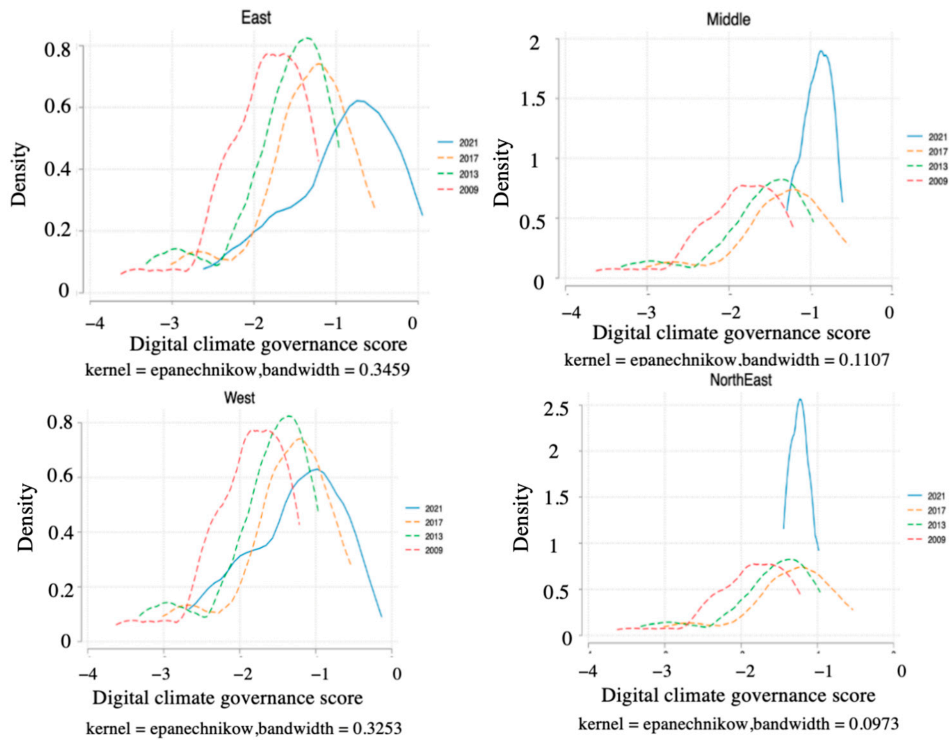

Figure 7. Evolution of the digital climate governance score in the four regions.

4.6. Spatial Distribution of Digital Climate Governance Capacity

In this study, Markov chain analysis is used to further investigate the state transfer changes in governance capacity and make reasonable predictions about future development prospects. The study uses the quartiles of the digital climate governance scores to categorize the states of governance capacity into the following four categories: state one (S1), state two (S2), state three (S3), and state four (S4), with the above states reflecting the development of each region from poor digital climate governance capacity to strong digital climate governance capacity.

Table 5 shows the transfer probability matrix of digital climate governance scores for the whole country and each region. In the whole country, the scores of digital climate governance capacity show a relatively stable trend, and among the four states of S1, S2, S3, and S4, the only one that has shifted to the lower state is S2, in which the probability of 66.7% has shifted to the state of the lower level, while the probability of 33.33% has all shifted to the state of the higher level. All other states are shifted to higher levels or remain at the original state level, which means that the decline of digital governance capacity occurs less often. From the perspective of the development level of each region, the development status of the four regions is similar to the national development trend, and the overall trend of the development level is increasing, which indicates that the overall digital climate governance capacity is improving. However, at the same time, it should be noted that there is a shift from a higher level to a lower level, which indicates that the construction of digital climate governance is not achieved overnight. Additionally, there are fluctuations in the level during the construction process, which means that the construction of digitalized climate governance in China is still facing greater challenges.

Table 5. Markov transition probability of the digital climate governance score.

Regions	State	S1	S2	S3	S4
Nationwide	S1	0.0000	1.0000	0.0000	0.0000
	S2	0.6667	0.0000	0.3333	0.0000
	S3	0.0000	0.0000	0.5000	0.5000
	S4	0.0000	0.0000	0.0000	1.0000
East	S1	0.8857	0.1143	0.0000	0.0000
	S2	0.0000	0.5833	0.4176	0.0000
	S3	0.0286	0.0857	0.6857	0.2000
	S4	0.0556	0.0556	0.0000	0.8889
Central	S1	0.7000	0.3000	0.0000	0.0000
	S2	0.0000	0.6957	0.3043	0.0000
	S3	0.0303	0.0303	0.7879	0.1515
	S4	0.0909	0.0909	0.0455	0.7727
West	S1	0.8621	0.1379	0.0000	0.0000
	S2	0.0000	0.8125	0.1667	0.0208
	S3	0.0385	0.0000	0.7308	0.2308
	S4	0.1935	0.0323	0.0000	0.7742
North East	S1	0.8889	0.1111	0.0000	0.0000
	S2	0.0000	0.7333	0.2667	0.0000
	S3	0.0000	0.1333	0.8000	0.0667
	S4	0.2500	0.0000	0.0000	0.7500

5. Coupled Coordination Analysis

Analysis of the Coupling and Harmonization

The digitalization process of climate governance is highly related to the local economic development and industrial base, and, in the context of the deteriorating climate and ecological environment, it is necessary to maintain a certain level of digital climate governance capacity in order to maintain sustainable and stable economic and social development. In order to study whether the current digital climate governance capacity of the regions is compatible with the local economic development, this study calculates and analyzes the coupling coordination degree of the two systems' development, and the degree of coupling coordination is classified as Table 6.

Table 6. The classification standard of coordination.

Coordination Level	Coordination Degree	Coordination Condition	Coordination Stage
1	(0.0, 0.1]	Extreme Disorder	Decline period
2	(0.1, 0.2]	Severe Disorder	
3	(0.2, 0.3]	Moderate Disorder	Acceptable Disorder Period
4	(0.3, 0.4]	Mildly dysfunctional	
5	(0.4, 0.5]	Nearly dysfunctional	Transition period
6	(0.5, 0.6]	Barely coordinated	
7	(0.6, 0.7]	Elementary coordination	Developmental period
8	(0.7, 0.8]	Intermediate coordination	
9	(0.8, 0.9]	Good coordination	High degree of harmonization
10	(0.9, 1.0]	Quality coordination	

From a temporal perspective, Figure 8 shows that, at the early stage of the development of digital climate governance, the degree of coordination between digital climate governance capacity and economic and social development was low in all regions, and there were large inter-regional differences, with only the provinces of Beijing (0.5967, barely coordinated) and Guangdong (0.4319, on the verge of being dysfunctional) having strong coupling and coordination capacities in 2007. It can be found that, in the process of continuous development, the degree of coordination of the development of climate governance capacity in all regions has increased, and the development between regions has become more balanced with the emergence of some provinces with a higher degree of coordination, such as Shanghai (0.5488, barely coordinated), Shandong (0.5264, barely coordinated) and other provinces, while, at the same time, the original high level of coordination in provinces such as Beijing (0.7520, intermediate level of coordination) further increase in the degree of development coordination.

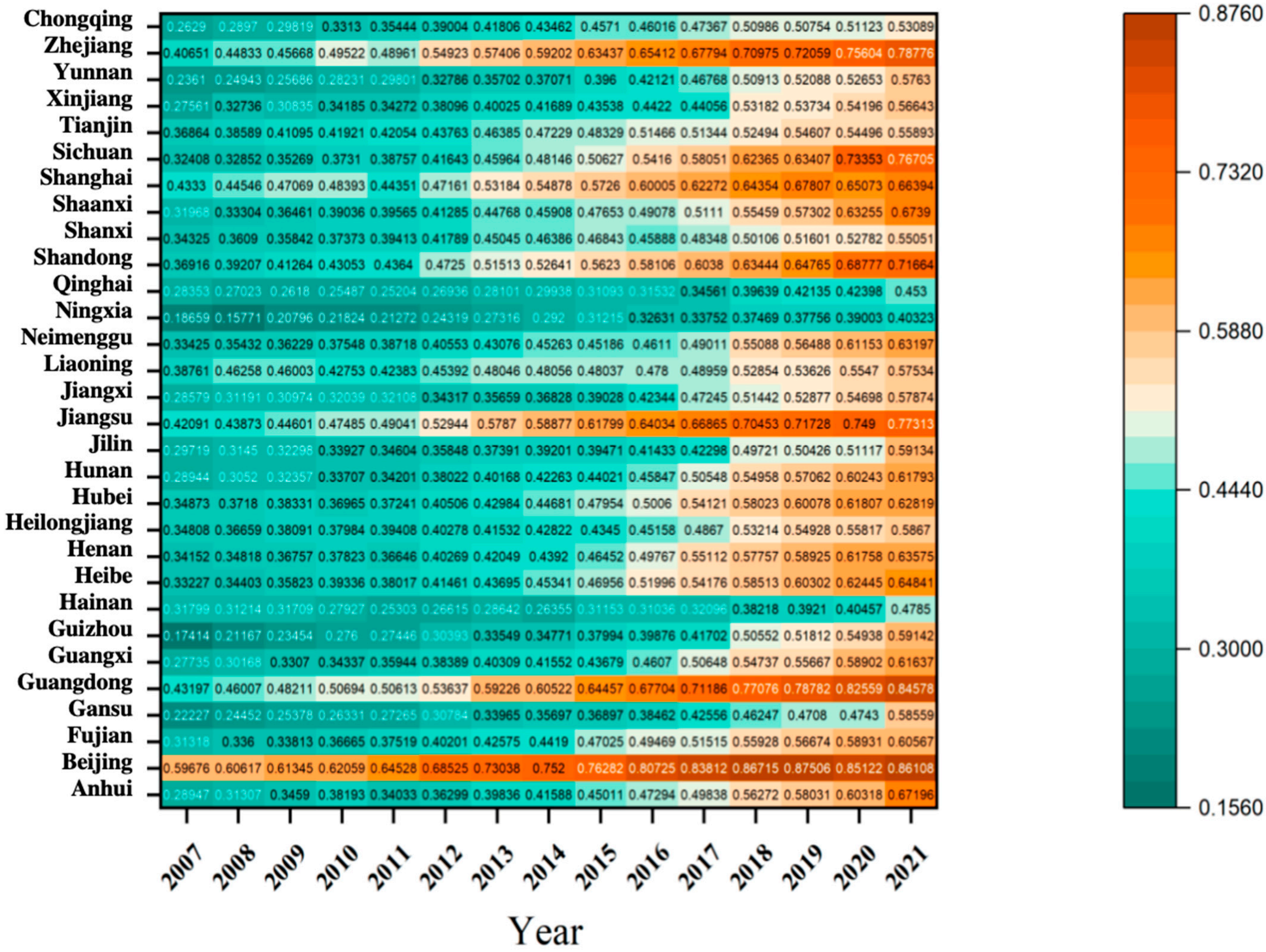

Figure 8. Heat map of coupling coordination degree.

The development coordination in all regions improved greatly in 2021 with the emergence of several high-level provinces, such as Sichuan (0.7671, intermediate coordination), that have achieved catching up, as well as relatively low-level provinces, such as Guizhou (0.5914, barely coordinated) and Gansu (0.5856, barely coordinated), which have also reached an average level of coordinated development. The coordination in provinces with better development bases, such as Beijing (0.8611, well coordinated) and Guangdong (0.8458, well coordinated), has already reached a high level. This is consistent with the conclusion drawn in the previous section that the level of digital climate governance is closely related to local economic development, as well as that a good foundation for industrial and economic development can support the digital reform of climate governance, while the further improvement of the digitalization capacity of climate governance can also better serve the development of the economy and society.

Through the heat map, it can be found that the lower degree of coordination in the Western region mainly exists in two cases, and the environmental development foundation of some regions represented by Xinjiang is better. As a result, the climate governance capacity is stronger; however, the level of economic development is more backward, which leads to the development being uncoordinated. Additionally, other regions' digital climate governance capacity, represented by Qinghai and Ningxia, is poor, and the degree of economic and social development is not coordinated. This reflects the different development characteristics of different regions in China during the development, and, in order to further enhance China's overall climate governance capacity and better serve the economic and social development, each region should be adapted to the implementation of the corresponding policy. In the process of promoting the enhancement of digital capacity, the government should strengthen the vitality of economic development, lay the foundation for digital capacity building, and, at the same time, use digital governance to empower economic and social development.

Figure 9 illustrates the distribution dynamics of the coupled coordination levels of the four regions. First of all, in terms of the distribution position, the center of gravity of the distribution of the four major regions has moved to the right, which indicates that the level of coordination between the digital climate governance capacity and the economic and social development of each region has increased and evolved at a faster pace. Regarding the characteristics of regional peaks, a fluctuating upward trend is observable in all areas except the Eastern region. Notably, the Northeastern region shows a significant rise in peak levels alongside a narrowing of peak widths, transitioning from broad to sharp peaks. This pattern indicates a reduction in the disparity of coordinated development within the region. Conversely, in the Eastern region, the widening of peak widths coupled with a gradual decline in peak values signifies a downturn in coordinated development capacity and an expansion in intra-regional disparities. This trend in the Eastern region may be attributed to its rapid economic growth and swift industrial evolution [49]. Despite advancing digital climate governance, it struggles to match the pace of economic development, contrasting with other regions where economic and digital climate governance capacities develop more harmoniously.

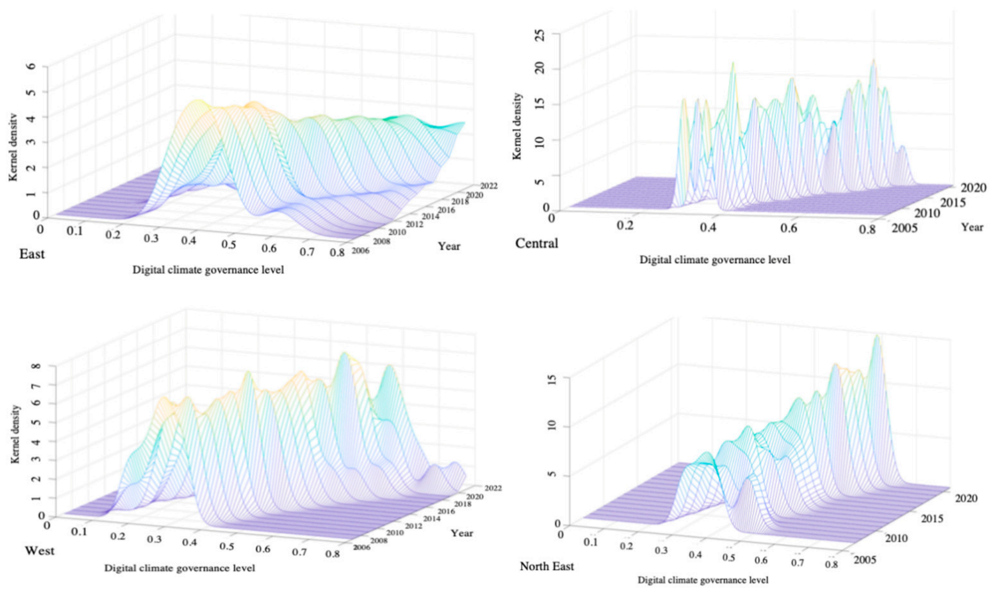

Figure 9. Kernel density distribution of coupled coordination degrees.

On the other hand, in terms of the number of wave peaks, the existence of side peaks in the Central and Eastern regions was more obvious before 2014, and the number of side peaks decreased significantly after 2014, indicating that the uneven development of the degree of coordination within the region has improved. The number of side peaks in the Western region, however, shows signs of increasing over time, which is related to the faster economic social and digital development of Sichuan and other provinces within the Western region [50]. The Western region needs to strengthen the collaboration within the provinces within the region, and the country needs to further strengthen the support for the lagging provinces to further promote the coordinated development of governance and economy. The number of side peaks in the Eastern region has remained stable at a low level, which indicates a more coordinated level of development in the Eastern region. Finally, in terms of the distribution pattern, the Western region has a more significant right-trailing characteristic, which again suggests that there are greater developmental differences within the Western region. The curves in other regions do not have a trailing phenomenon, which indicates a more balanced development in other provinces. To summarize, the coordinated development capacity of all regions has continued to improve, and the speed and quality of development have steadily increased, with some regions suffering from large internal development differences and most others having a more balanced level of coordinated development.

6. Results and Analysis of the Determinants of Digital Climate Governance

Digital climate governance capacity is the result of the coordination of multiple systems and requires the synergistic enhancement of economic and social development, climate governance capacity, and the degree of digitalization in order to effectively promote the digitalization of climate governance [51]. During the process of digital climate governance, the government, as the main body of social governance, is an important driving force for digital climate governance [52]. With the further deepening of marketization of socio-economic development and the further lowering of market access thresholds, the important project of digitalization of climate governance also requires the intervention of market forces, as well as the joint role of active government and effective market, to promote the further deepening of the degree of digitalization of governance.

6.1. Benchmark Results

In order to further investigate the combined impact of government and market on the improvement of digital climate governance capacity, Table 7 illustrates the results of the benchmark regression of the impacts of market and government on digital climate governance capacity, which show that both government and market can contribute to the improvement of digital climate governance. The impact coefficients of government and market in columns (1) to (4) in Table 7 are significantly positive, and the results remain unchanged after controlling for regional fixed effects, while the impact coefficients of government and market in columns (5) to (6) are significantly positive at the 5% and 1% levels, respectively. In the process of transformation and upgrading of China's economic structure, while relying solely on the power of the government to carry out social governance, the introduction of enterprises and other social forces to form a collaborative governance model will form a greater synergy.

Table 7. Baseline Regression Results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
Gov	0.0584 *** (3.66)	0.0670 * (1.99)			0.0618 *** (3.98)	0.0670 ** (2.24)
Market			0.0236 ** (2.40)	0.0377 *** (3.07)	0.0259 *** (2.69)	0.0377 *** (3.21)
Internet	−0.0182 (−0.80)	−0.0435 (−1.61)	0.0221 (0.93)	−0.0212 (−0.74)	−0.0074 (−0.31)	−0.0307 (−1.11)

Table 7. *Cont.*

Variables	(1)	(2)	(3)	(4)	(5)	(6)
Population	0.2189 *** (7.62)	0.4179 (1.39)	0.1300 *** (4.36)	0.2662 (0.93)	0.1857 *** (6.03)	0.3843 (1.32)
PGDP	0.2046 *** (4.71)	0.2394 *** (4.62)	0.1007 ** (2.08)	0.1576 ** (2.55)	0.1475 *** (2.91)	0.1690 *** (2.85)
Industry	0.0560 *** (2.97)	0.0677 (1.53)	0.0592 *** (3.32)	0.0777 ** (2.13)	0.0532 *** (3.14)	0.0522 (1.33)
Enviro	0.1826 ** (2.10)	0.1362 (1.47)	0.2050 ** (2.37)	0.1247 (1.56)	0.1781 ** (2.19)	0.1256 (1.59)
Year FE	No	Yes	No	Yes	No	Yes
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	450	450	450	450	450	450
R-squard	0.677	0.682	0.681	0.693	0.701	0.709

Note: Standard errors are in parenthesis, while *, **, *** denote the significance of the 10%, 5% and 1% levels, respectively. Year FE and Region FE denote the time fixed effect and region fixed effect. The variable definitions are detailed in Appendix A Table A1.

6.2. Empirical Results of Robust Analysis

In order to make the conclusions of this study more reliable, and to further test the robustness of the model used, this study uses three methods to conduct robustness tests, and the test results are shown in the table. Considering the effects of sample characteristics, this study uses the Driscoll−Kraay standard error method to eliminate the effects of heteroskedasticity and autocorrelation, and the results are shown in column (1) of Table 8. Columns (2) through (3) are tested by changing the core explanatory variables, using the level of budgetary expenditures of the provincial treasury to measure the level of government support at the level of social governance. Columns (4) to (5) are re-estimated after centering the core explanatory variables, as well as the control variables, in order to reduce the error caused by potential multicollinearity. The results in Table 4 show that government and market forces can effectively influence the digital climate governance capacity, which is consistent with the results of the benchmark regression, which indicates that the results of the benchmark regression have a certain degree of robustness and support the hypotheses we made in the previous section.

Table 8. Empirical results of robust analysis.

Variables	Driscoll-Kraay Standard Errors	Alternative Explaining Variable		Decentralization	
	(1)	(2)	(3)	(4)	(5)
Gov	0.0670 *** (5.84)			0.0625 *** (3.98)	0.0678 ** (2.24)
Market	0.0377 ** (2.85)			0.0486 *** (2.69)	0.0705 *** (3.21)
Govout		0.0335 *** (2.62)	0.0445 *** (3.00)		
Year FE	Yes	No	Yes	No	Yes
Region FE	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes
Observations	450	450	450	450	450
R-squard	0.709	0.885	0.887	0.701	0.709

Note: Standard errors are in parenthesis while **, *** denote the significance of the 10%, 5% and 1% levels, respectively. Year FE and Region FE denote the time fixed effect and region fixed effect. The variable definitions are detailed in Appendix A Table A1.

7. Conclusions and Policy Recommendations

In the background of escalating climate change challenges, climate governance has become an important issue for governments worldwide, with important implications for sustainable economic and social development. Digital development can overcome future challenges in sustainable development and become a key supporter of sustainability, having the potential to drive climate-friendly development models [53]. Digital technologies are increasingly being utilized to support global governance efforts, addressing common challenges and emerging as a focal point in global governance [54]. Therefore, the use of digital governance technology and the combination of digitalization and climate governance are the main ways to reduce global climate disasters and maintain human well-being. In this study, from the perspective of establishing a digitalized climate governance system, the new progress of China's climate governance development was assessed by establishing a measurement system of 14 indicators in four dimensions. The entropy weighting method was used to calculate the progress of 30 Chinese provinces in regard to digital climate governance from 2007 to 2021. The evolution and spatial characteristics of digital climate governance scores are also discussed. The conclusions drawn from this study are as follows:

First, significant progress in digital climate governance characterizes China's approach to addressing climate change, with a notable improvement to a capacity level of 0.3737 in 2021, which highlights the potential for advancements. The infrastructure for digital climate governance is particularly superior in the Eastern region, yet this area faces challenges in regard to accelerating growth to achieve digital governance. Although relying on current climate and environmental governance strategies may be economical for developed regions, the shift towards a smarter, technology-driven approach is vital for sustainable development in the future. Other countries and regions worldwide should also take note of this issue and proactively establish relevant infrastructures for digital climate governance. By employing methods that are better suited for the future, they can achieve higher-quality sustainable development. Second, there are considerable regional imbalances in digital climate governance in China. Inter-regional differences are the main cause of regional imbalance, followed by intra-regional differences. This situation is closely related to each region's resource endowment, economic development base and industrial structure. However, this does not mean that measures must be taken blindly to eliminate regional imbalances. On the contrary, each region must chart its course for digitizing climate governance, taking into account regional resource endowments, economic strengths, and development contexts. In pursuing the goal of digital governance, regional imbalances are inevitable. Each region should capitalize on its strengths to promote the further development of digital governance capacities. Similarly underdeveloped countries and regions facing circumstances akin to China should also recognize this issue. They should coordinate development resources between regions, exchange successful development experiences, and promote synchronous improvements in development levels across different regions.

Third, various fields are moving towards digitalization, but achieving digitalization with the help of digital technologies remains challenging. There is a growing absolute gap in digital climate governance capacity, as well as a trend towards multipolarity, especially based on having a minor amount of economic base and governance experience. For example, the East and West regions initially show a large gap in economic levels, which leads to a vicious circle of development where poorer governance capacity makes the digital climate governance capacity show a trend of widening absolute differences and polarization. Understanding the dynamic evolution characteristics of each region can help to formulate regional policies aimed at achieving low-carbon sustainable development.

Fourth, the government is the main body of climate governance and plays an irreplaceable role in the process of climate governance. It is also the promoter of the construction of digital climate governance, which plays a decisive role in the process of digitization of climate governance. Since climate governance is a systematic project that requires the coordination of all aspects of social development, this study finds that the social market forces are also an important supporting force in digital climate governance. The government and the market should further build a coordination and communication mechanism to promote the formation of synergistic governance synergy between the active government and the effective market, so as to provide basic governance-level support for the development of productivity.

Based on the above conclusions, this study puts forward the following policy recommendations: first, the government should set different digital climate governance goals for each province in China according to the characteristics of each region. In comprehensively considering factors such as resource endowment, industrial structure, and regional advantages, regions worldwide should formulate appropriate strategies for digital climate governance development based on their unique natural conditions and economic development foundations. For example, the central government should strengthen its leading role in promoting the Eastern region in the application of digital governance development, enhance the level of digital technology frontier development, and explore the path and paradigm shift of digital climate governance. Second, a regional coordination mechanism and international exchange mechanism for the development of digital governance should be established, and central and local governments should be encouraged to carry out inter- and intra-regional assistance coordination activities. It is also encouraged for countries and international organizations to share advanced governance experiences, collectively achieving high-quality digital climate governance. Third, governments should enact digital climate governance development plans tailored to their respective national development contexts while concurrently promoting high-quality economic development. Economic progress can drive advancements in digital technology and provide material support for its development. For economically developed countries, further strengthening of digital technology innovation is crucial, providing a solid financial foundation for innovation in digital technology. For countries with weaker economic foundations, emphasis should be placed on developing specialized industries, further solidifying their industrial and economic infrastructure. Local governments should introduce locally adapted development plans for digital climate governance. Economic development can drive the progress of digital technology and provide a material guarantee for digital climate governance. Developing specialty industries and enhancing economic strength are the primary goals of provinces with weaker economies. Therefore, large economic provinces should strengthen digital technology innovation and actively provide enterprises with financial and tax advantages to participate in digital technology innovation.

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Appendix A

Table A1. Variable definitions.

Variables	Observations
Market	Effective market, calculated by market index
Gov	Efficient government, calculated by proportion of provincial fiscal expenditure
Internet	Digital development, measured by logarithm of the number of Internet users
Population	The logarithm of the number of total population at the end of the year
PGDP	The regional economic development, measured by the logarithm of GDP per capita
Industry	Industrial structure, ratio of the added value of tertiary industry to secondary industry
Enviro	Environmental supervision, measured by the ratio of words related to environmental protection in the local government report

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