The Spatiotemporal Dynamics of Coupling and Coordination between Digital Transformation and the Maritime Economy

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Abstract. In the context of the global wave of digitalization, fostering the deep integration and coordinated advancement of the marine economy with digital technologies has become a strategic necessity. Such integration is essential for unlocking the potential of the blue economy, strengthening the international competitiveness of marine industries, and supporting the long-term objective of building a strong maritime nation. From the perspective of coupling and coordination, this study develops an index framework to assess the interaction between digital economy transformation and the growth of the marine industry. Employing the entropy method and kernel density estimation, it investigates the spatial and temporal dynamics of their coupling coordination in China’ s coastal cities from 2013 to 2022. The results show that the average coordination degree between the two systems was 0.525 during the research period.Significant regional disparities were observed: the Yangtze River Delta emerged as the leading region, followed by the Bohai Rim in a gradient pattern, while the southern coastal area demonstrated a polarized distribution with Guangdong standing out prominently. This research represents the first attempt to enrich the theoretical framework of the coupling-coordination relationship between digitalization and the marine economy, while also providing theoretical guidance and policy insights to advance their coordinated development in China’s coastal regions.

Keywords: Digital economy; marine economy; coordination; kernel density estimation.

1. Introduction

As the digital wave of change ascends once more, the report to the 20th National Congress of the Communist Party of China also emphasized the need to promote the deep integration of the digital economy and the real economyto construct a new development model based on digitalization. At the same time, the marine economy, as a vital pillar of national growth, is entering a critical stage of transformation and upgrading. In 2024, China’s marine economy showed strong momentum, with total output exceeding 10 trillion yuan for the first time, reaching 10.5438 trillion yuan—an increase of 5.9 percent from the previous year [1]. At the 2023 Guangdong–Hong Kong–Macao Marine Cooperation and Development Forum, Academician Ding Dewen of the Chinese Academy of Engineering also emphasized the need to view the coastal ecosystem as a whole and to guide its green and digital transformation under a modern digital framework [2]. Empirical and analytical studies both show that deeply embedding digital technologies into the marine economy is not only crucial for realizing the blue economy’s potential, but also for enhancing the global competitiveness of the maritime industry and fostering a strong maritime nation. In this context, examining the spatiotemporal patterns and drivers of the interrelationship between digitalization and marine economic growth is of significant theoretical and practical importance, as it offers insights into their dynamic interplay and supports the high-quality development of the marine economy.

Currently, scholars both at home and abroad have studied the relationship between the development of the digital economy and the marine economy from various perspectives.Existing studies on their coupling and coordination can be broadly divided into three areas. First, in terms of conceptual definition, digital transformation is regarded as the process through which new digital technologies are embedded across activities to enhance performance [3]. It is generally defined as a comprehensive and profound transformation in which organizations leverage digital technologies and tools to reshape business processes, culture, customer experience, and overall business models [4]. Other studies have further traced the evolution of digitalization as a scholarly concept over the past

century [5]. Correspondingly, in a broad sense, the marine economy is defined as encompassing all economic activities arising from the utilization of marine-related resources and conditions for development and production [6]. Second, regarding the level of integration between the digital economy and the marine economy, some studies have assessed the extent of integration in China's coastal cities, measuring the level of coordination, regional disparity indices, and influencing factors. However, these studies have not addressed the systematic spatiotemporal dynamics of the interaction between the two [7]. Finally, in terms of measurement approaches and regional heterogeneity, studies concerning the high-quality progression of the marine economy have predominantly devoted efforts to constructing index-based evaluation systems and investigating cross-regional imbalances.For example, by building indicators for both the digital economy and the marine economy, some studies have quantified their development in coastal regions and examined the underlying mechanisms [8]. Jiang et al. expanded their research to evaluate the influence of digital economic advancement on the upgrading of marine fisheries, and their findings demonstrate that green technological innovation functions as a mediating channel.These findings once again indicate that the digital economy plays an empowering role in the high-quality development of the marine economy [9].

In short, there is extensive research on the development of the digital and marine economies, both in China and abroad. However, most of these studies focus on the one-way impact of one on the other. Research that treats them as a coupled system and examines their systemic, dynamic, and spatiotemporal relationship remains relatively scarce.Based on this, this paper chooses 11 coastal provinces and municipalities of Tianjin, Hebei and Shandong as the research object from 2013 to 2022. Employing the entropy method together with a coordination degree framework, the paper analyzes the spatial and temporal characteristics of the synergistic relationship between digital innovation in coastal cities and the advancement of the maritime economy.It is hoped that the results can provide a reference for the bidirectional and coordinated development of marine economic development promoted by urban digital transformation and urban digital transformation promoted by marine economic development.

2. Data Sources and Research Methods

2.1. Data Sources

The study focuses on 11 provinces(including municipalities and autonomous regions)along China's coast, such as Tianjin, Hebei, and Shandong, covering the period from 2013 to 2023. To ensure the availability and completeness of the data, the original dataset was primarily drawn from the China Statistical Yearbook(2013–2023), the China Marine Economy Statistical Yearbook(2013–2023), and official websites of provincial statistical bureaus. Missing values were supplemented using the moving average method.

2.2. Entropy Method

The entropy method, originally derived from the field of physics, has been widely applied as an objective weighting technique in various domains such as economic development and sustainable development evaluation [10]. Following the approach of Ye Fang, this study employs the entropy method to construct composite indices for both digital transformation and marine economic development [11]. The calculation involves the following steps:

Step 1: The raw data are standardized using the range method to eliminate dimensional effects. The formula is as follows:

For positive indicators:

$$Y_{ij}=\frac{X_{ij}-\min(X_{ij})}{\max(X_{ij})-\min(X_{ij})} \quad (1)$$

For negative indicators:

$$Y_{ij}=\frac{\max(X_{ij})-X_{ij}}{\max(X_{ij})-\min(X_{ij})} \quad (2)$$

In Equations (1) and (2): X_{ij} represents the raw data of indicator j for individual i,Y_{ij} signifies the standardized value of the indicator, while $\max(X_{ij})$ and $\min(X_{ij})$ correspond to the maximum and minimum values of indicator j for individual i, respectively.

Step 2: Calculate the proportion of indicators:

$$P_{ij}=\frac{Y_{ij}}{\sum_{i=1}^{n} Y_{ij}} \quad (3)$$

Step 3: Calculate entropy:

$$e_j=-\frac{1}{\ln(n)}\sum_{i=1}^{n} P_{ij}\ln P_{ij} \quad (4)$$

Where: $0\leq e_j\leq 1$.

Step 4: Calculate the utility value:

$$D_j=1-e_j \quad (5)$$

Step 5: Calculate indicator weight:

$$W_j=\frac{D_j}{\sum_{i=1}^{n} D_j} \quad (6)$$

Step 6: A combined metric used to evaluate the extent of digital transformation and the advancement of the marine economy simultaneously:

$$S_i=\sum_{i=1}^{n} W_j P_{ij} \quad (7)$$

2.3. Coupling Coordination Degree Model

Building on the work of Zhang et al., this study develops a coordination model to assess the interaction between digital transformation and the growth of the marine economy [12]. The specific calculation formulas are as follows:

First, calculate the coupling degree C.

$$C=2\sqrt{U_1\times U_2/(U_1+U_2)^2} \quad (8)$$

In the formula, U_1 and U_2 are the composite indices of digital transformation and the marine economy. The coupling degree ranges from 0 to 1, with higher values indicating stronger coordination and lower values suggesting disordered development.

Second, the calculation of the coupling coordination degree D.

$$T=\alpha U_1+\beta 2 \quad (9)$$

$$D=\sqrt{C\times T} \quad (10)$$

This part explains how to compute the follow integrated coordination index T for digital transformation and marine economic developmentT is the total coordination index between two systems. α and β are coefficients for the digital transformation level and the marine economic development level, respectively. The study assumes both systems are equally important, so $\alpha = \beta = 0.5$. The value of D (which seems to be the final result of the model) ranges from 0 to 1. A higher D value indicates a stronger and more coordinated relationship between the two systems, while a lower value suggests the opposite. The study categorizes the coupling and coordination status into five stages, as detailed in Table 1.

Table 1. Standards for categorizing coupling–coordination levels

D Value Range	Coordination Stage
(0, 0.2]	Extreme Imbalance
(0.2, 0.4]	low coordination
(0.4, 0.6]	moderate coordination
(0.6, 0.8]	high coordination
(0.8, 1.0]	High-Quality Coordination

2.4. Kernel Density Estimation

Kernel density estimation is employed to investigate the polarization trend, distribution pattern, and distributional extension of the coupling coordination level between digital transformation and the marine economy in coastal provinces (autonomous regions, and municipalities). This approach provides a comprehensive understanding of its dynamic evolution characteristics. The kernel density function used in this study is as follows:

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x_i - \bar{x}}{h}\right) \tag{11}$$

$$K(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \tag{12}$$

In Equations (11) and (12): n represents the number of sample observations, which in this study corresponds to the number of cities observed;x_i represents the coupling coordination degree between digitalization and the marine economy for the cities individually;$\bar{x}$represents the average coupling coordination degree between digitalization and the marine economy for the 11 cities.;h denotes the bandwidth;$K(\bullet)$ refers to the Gaussian kernel function;π represents the mathematical constant π.

3. Selection of Indicators and Data Description

3.1. Digital Transformation

Referring to the studies of Liu Shuchun and Zhang Xueling, this paper constructs an evaluation system for digital economy development from three dimensions: digital infrastructure, digital industry development, and breakthroughs in core technologies [13,14]. The system consists of ten secondary indicators, which are further used to build a city-level evaluation framework for digital transformation, as shown in Table 2.

3.2. Marine Economic Development

From the three dimensions of economic development level, industrial structure, and development potential, this study selects twelve indicators to construct the marine economic development evaluation system, see Table 2. This framework aims to provide a more comprehensive reflection of the development level of coastal cities.

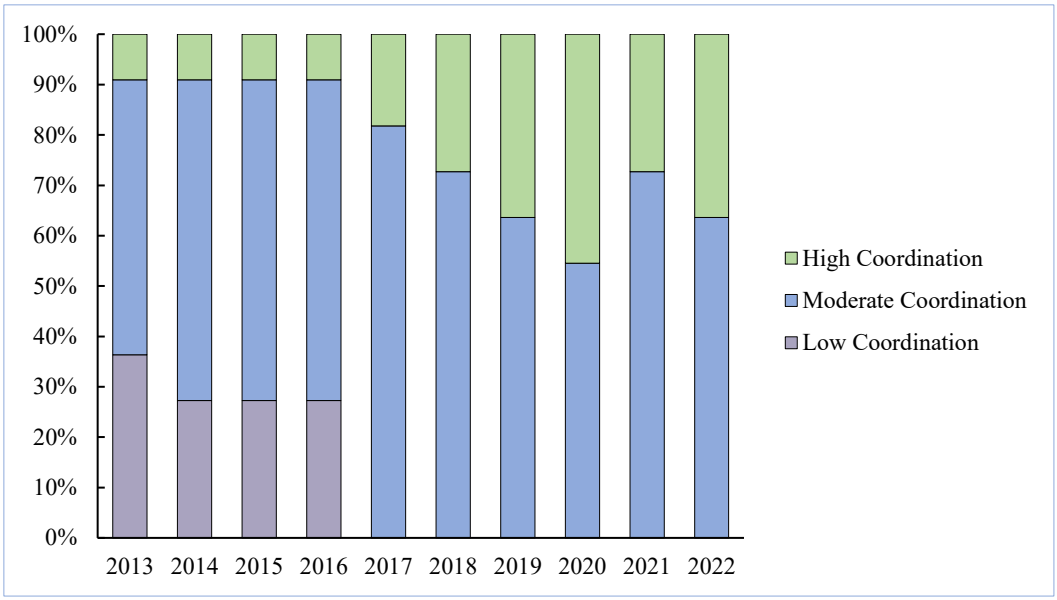


Fig. 1 The evolving composition of coupling coordination types between digitalization and the marine economy in China (2013-2022)(Picture credit: Original)

Table 2. Indicator system for digital transformation and marine economic development

System Level	Dimension Layer	Subsystem	Specific Indicator	Indicator Attribute
Coupling Coordination System between Digital Transformation and Marine Economic Development	Digital Infrastructure	Communication Infrastructure Construction	Long-Haul Fiber Trunk Lines (10,000 km)	Positive
		Communication Base Station Construction	Mobile Telephone Exchange Capacity (10,000 subscribers)	Positive
		Penetration of Mobile Phones	Mobile Phone Penetration Rate (units per 100 people)	Positive
		Ubiquity of the Internet	Number of Internet Broadband Access Ports (10,000 ports per person)	Positive
	Digital Industry Development	Digital Industry Employment	Number of Employees in Information Transmission, Software, and IT Services (10,000 persons)	Positive
		Digital Industry Output	Per Capita Telecom Business Revenue (100 million yuan per person)	Positive
		Digital Industry Revenue	E-Commerce Sales (100 million yuan)	Positive

		Economic Development Level	R&D Expenditure of Industrial Enterprises Above Designated Size (10,000 yuan)	Positive
	Core Technology R&D	Market Scale	Number of Legal Entities in Information Transmission, Software, and IT Services (units)	Positive
		Scientific Research Capability	Number of Patent Applications Granted (items)	Positive
		Economic Development Level	Proportion of Gross Ocean Production to Regional GDP in Coastal Areas (%)	Positive
			Growth Rate of Gross Ocean Production (%)	Positive
			Per Capita Gross Ocean Production (yuan)	Positive
	Marine Economic System	Structural Level	Proportion of Primary Marine Industry (%)	Positive
			Proportion of Secondary Marine Industry (%)	Positive
			Proportion of Tertiary Marine Industry (%)	Positive
		Development Potential	Cargo Throughput of Coastal Ports (10,000 tons)	Positive
			Number of Employees in Marine Research Institutions (persons)	Positive
			Number of Star-Rated Hotels in Coastal Areas (units)	Positive

Table 3. Coupling coordination degree between digitalization and marine economy in 11 Coastal Provinces from 2013 to 2022

Region	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Fujian	0.436	0.451	0.481	0.482	0.507	0.549	0.578	0.592	0.548	0.556
Guangdong	0.615	0.627	0.640	0.653	0.682	0.739	0.753	0.767	0.739	0.749
Guangxi	0.360	0.372	0.385	0.389	0.423	0.468	0.502	0.515	0.456	0.452
Hainan	0.299	0.317	0.353	0.362	0.404	0.472	0.503	0.526	0.434	0.435
Hebei	0.395	0.404	0.412	0.418	0.451	0.475	0.504	0.521	0.491	0.498
Jiangsu	0.512	0.515	0.532	0.533	0.548	0.580	0.592	0.617	0.582	0.592
Liaoning	0.443	0.448	0.483	0.466	0.485	0.501	0.516	0.530	0.483	0.482
Shandong	0.522	0.539	0.556	0.574	0.599	0.619	0.624	0.650	0.640	0.662
Shanghai	0.475	0.495	0.511	0.517	0.544	0.584	0.620	0.626	0.595	0.603
Tianjin	0.351	0.372	0.396	0.384	0.419	0.478	0.533	0.528	0.488	0.492
Zhejiang	0.539	0.549	0.575	0.576	0.602	0.630	0.664	0.688	0.649	0.658

4. Results and Analysis

4.1. Analysis of Coupling Coordination Degree

From 2013 to 2022, the average coupling coordination degree between digital transformation and marine economic development in China's coastal cities was 0.525, which is in the moderate coordination stage. This indicates that digitalization and marine economic development in these cities have formed a relatively positive and mutually reinforcing relationship, although there remains substantial room for further improvement.

Based on Table 3, it can be seen that the coupling coordination degree between digital transformation and marine economic development in China's coastal cities increased overall from 2013 to 2020, reaching the highest in 2020. There was a decrease in 2021, which may be due to the impact of the COVID-19 pandemic, and the growth trend in 2022 recovered. According to Figure 1, the study period can be roughly divided into three stages. From 2013 to 2016, the eleven coastal cities were distributed across three stages—low coordination, moderate coordination, and high coordination—with more than half of the cities falling into the moderate category. During this period, Hebei Province entered the stage of moderate coordination in 2014, while the other seven cities remained at a low level. This may be explained by the fact that China was still in the early stage of development, where the degree of digitalization was relatively low, digital infrastructure was underdeveloped, economic growth relied heavily on extensive expansion, and the integration of digitalization with the marine economy remained superficial. Between 2017 and 2020, all coastal cities that had been in the low coordination stage advanced to moderate coordination, while the proportion of cities reaching high coordination increased year by year. This shift can be attributed to the launch of the 13th Five-Year Plan in 2016, the continued deepening of national strategies, the elevation of the Digital China initiative to a broad societal consensus, as well as the maturing of digital technologies and the nationwide coverage of 4G, and the boom of mobile internet in 2017. In 2021–2022, a temporary setback in the coupling coordination level was observed, likely due to the economic shock caused by the pandemic. However, none of the coastal provinces or cities regressed to the stage of low coordination.

4.2. Kernel Density Estimation Analysis

In this study, the 11 selected cities are divided into three subregions: the Bohai Rim, the Yangtze River Delta core area, and the Southern Coastal region. Using MATLAB software, three-dimensional kernel density distribution curves were generated to depict the overall evolution and level of coupling coordination in these regions. The analysis focuses particularly on four aspects of the kernel density

curves: their positional shifts, overall patterns, distributional extension, and the presence of polarization phenomena.

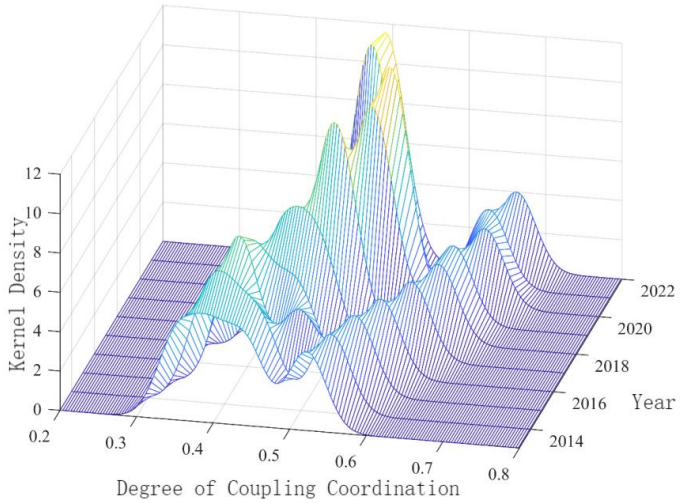


Fig. 2 Kernel density analysis of the coupling coordination degree in the Bohai Rim (2012-2022) (Picture credit: Original)

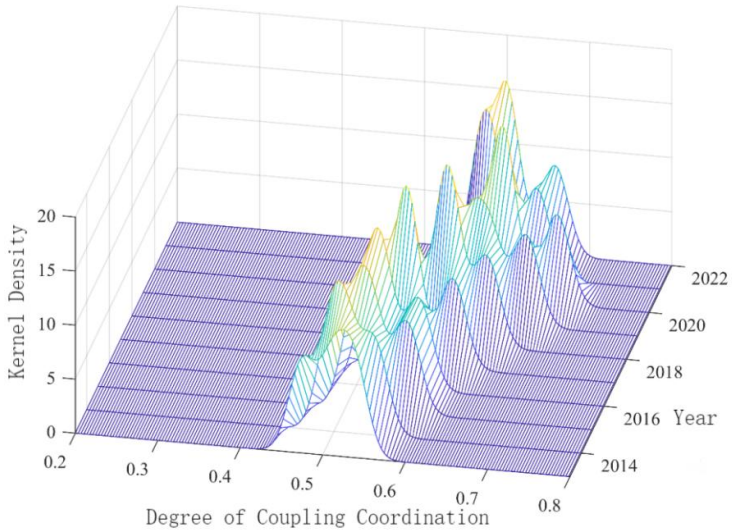


Fig. 3 Temporal evolution of the coupling coordination degree across the Yangtze River delta core area: a kernel density profile (Picture credit: Original)

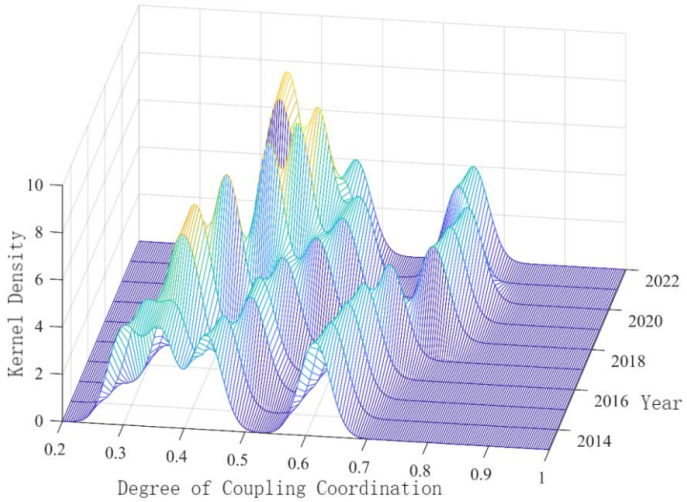


Fig. 4 Distribution dynamics of the coupling coordination degree in the southern coastal region based on kernel density estimation (Picture credit: Original)

4.3. Kernel Density Estimation Analysis

As shown in Figure 2, Figure 3 and Figure 4, the primary peaks of the kernel density curves for overall coordination levels in the three regions consistently shift rightward, indicating a steady improvement in the degree of integration between digital upgrading and the marine economy, with their relationship tending toward a more balanced state.

When it look at the distribution, the main peaks for the Bohai Rim region are in the 0.3–0.5 range, which indicates a generally low-to-medium level of coordination. In contrast, the main peak for the Yangtze River Delta core region is notably shifted to the right, showing that its overall level of coupling and coordination is higher than the Bohai Rim. The main peaks for the Southern Coastal region are also in the 0.3–0.5 range, similar to the Bohai Rim. As for the trend of these distributions, the main peaks for all three regions—the Bohai Rim, the Yangtze River Delta core, and the Southern Coastal region—have consistently risen. This suggests that the overall coupling and coordination levels in these three major regions are becoming more concentrated year by year, and the relative differences in coordination among the provinces within each region are gradually decreasing.

From the perspectives of peak frequency, distributional extension, and polarization, the Bohai Bay region exhibits a distinct multi-peak pattern throughout the study period, with secondary peaks located to the right of the primary peak. This suggests that certain provinces and municipalities consistently maintained higher levels of coupling coordination, significantly above the regional average, and progressed at a faster pace. Overall, however, the majority of provinces demonstrated relatively consistent levels of coupling coordination, with strong alignment in both growth rate and direction. In the Yangtze River Delta, the kernel density curve initially shows a unimodal distribution, but the presence of multiple peaks becomes more evident over time. This indicates that, although the coupling coordination developed at uneven speeds across provinces, the disparities did not fully diverge from the regional trajectory.For the southern coastal region, the kernel density curve reveals a pronounced multi-peak distribution and broader extension during the study period, with secondary peaks appearing to the right of the primary peak. This pattern reflects significant disparities in the development of coupling coordination across provinces, pointing to a severe polarization effect within the region.

5. Conclusion

The main findings are as follows: First, from the temporal perspective, the coupling coordination level between digital transformation and marine economic development in coastal cities has shown a steadily increasing trend over the past decade, with an average annual value of 0.525, indicating a state of moderate coordination. Second, kernel density estimation reveals significant regional heterogeneity. The Yangtze River Delta region has played a leading role, the Bohai Rim has followed with a catch-up trajectory, while the southern coastal region demonstrates strong polarization, with Guangdong standing out as an outlier. Overall, a spatial gradient emerges, decreasing from the eastern to western regions and from the southern to northern areas. Third, the observed initial disparities in 2013 largely stem from historical, geographical, and resource endowments rather than short-term policies. For instance, Guangdong had already reached a high coordination stage by 2013. By 2020, Zhejiang, Jiangsu, and Shanghai in the eastern region also entered the high coordination stage, consolidating their leading positions. Meanwhile, provinces in the northern and some southern regions have continued to make progress, moving steadily toward higher levels of coordination.In sum, these findings are broadly consistent with existing research, which highlights the positive role of the digital economy in promoting marine economic growth. However, by adopting the lens of coupling coordination and spatiotemporal dynamics, this study further identifies regional heterogeneity and developmental stage differences. This provides more nuanced empirical evidence for understanding the integration of digital transformation and marine economic development, and offers practical implications for differentiated regional policies.

Derived from the empirical results above, the following policy recommendations are formulated:The southern coastal region should mitigate the current spatially polarized pattern of Guangdong's predominance. While less developed areas should learn from the advanced experiences of faster-growing regions, they must also preserve their local distinctiveness and adopt context-specific strategies to strengthen digital infrastructure and talent acquisition, thereby narrowing regional development disparities. It is recommended that more developed coastal areas play a leading role, make full use of the policy and resource integration advantages, and promote the application and innovation of digital technology in the marine industry chain. In the future, the influencing factors of digital transformation of coastal cities in China and development of marine economy will be studied further. In addition, the data will be extended to the prefecture level to carry out spatial correlation analysis, so as to provide a more accurate theoretical basis and policy reference for the high-quality development of intelligent marine economy.

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