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Digital economy and the high-quality development of the marine industry

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Abstract:
This paper primarily examines the effect of the digital economy development level on the high-quality development of the marine economy, as well as the underlying influencing mechanisms. By measuring the digital economy development level and the high-quality development level of the marine economy across 11 coastal provinces in China from 2015 to 2024, this study conducts an econometric analysis based on these data. The findings reveal the following: First, an improvement in the digital economy development level exerts a significant promoting effect on the high-quality development of the marine economy, though this effect exhibits regional heterogeneity—with the northern regions having the greatest impact, followed by the southern regions, and the central regions showing the smallest coefficient; furthermore, the role of the digital economy development level in enhancing the high-quality development of the marine economy is characterized by a gradual nature, long-term effects, and dynamic characteristics. Second, from the perspective of the underlying mechanism, the mutual alignment and integration of the digital economy, industrial structure upgrading, innovation capacity, and urban household consumption collectively contribute to advancing the high-quality development of the marine economy. Finally, employing a panel threshold model, this study explores the nonlinear relationship between the digital economy and the high-quality development of the marine economy: when the digital economy development level is relatively low, it can hinder the high-quality development of the marine economy; conversely, it exerts a significant reinforcing effect on the high-quality development of the marine economy. Accordingly, it is recommended to actively foster a favorable environment for digital economy development, accelerate the rational flow and optimal allocation of marine resource factors, optimize the marine industrial structure, and promote the high-quality development of the marine industries.

Keyword: *digital economy; marine industry; high-quality development*

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I. Problem Statement

Currently, countries around the world are facing severe pressures on marine resources and ecosystems arising from long-term extensive marine economic development models, which also hinder the healthy growth of the marine economy (Marshall Adams, 2005). For instance, irrational practices such as overfishing, marine oil and gas pollution, land-based wastewater discharge, and pollution from marine aquaculture have led to increasingly prominent marine environmental degradation and ecological damage (Wang, 2021). As a result, nations are seeking new drivers for marine economic development to facilitate the transition of the marine economy from an extensive to an intensive development model (Chen, 2020). In the early 21st century, China's marine economy experienced rapid growth, surpassing the United States to become the world's largest marine economy; however, the ensuing environmental pollution and ecological degradation have resulted in low productivity. In recent years, the development of the marine economy has encountered obstacles and experienced a brief downturn. Therefore, innovating development approaches, transforming growth drivers, and enhancing development quality have become urgent tasks for China in advancing its marine economy.

Some scholars argue that market segmentation, information asymmetry, and high uncertainty are the primary causes of low productivity. Digital technology, ranked as the fifth major factor of production alongside land, labor, capital, and technology, can, to some extent, compensate for the shortcomings in the development of the marine industry (Sun, 2021). Currently, scholars primarily examine the direct impact of the digital economy on high-quality economic development from three perspectives: macro, meso, and micro. From a macroeconomic standpoint, the digital economy influences economic development by affecting the efficiency of production inputs

and outputs; this is reflected in the increased factor input driven by technological progress and technological spillovers, the improved efficiency of factor allocation, and the rise in total factor productivity (Meichen, 2019). For developing countries, digitalization is regarded as a key driver of economic growth. It enhances the productivity of capital and labor, reduces transaction costs, and facilitates countries' integration into the global market system (Dahlman, 2017; Myovella, 2020). For developed countries, the impact of the digital economy on the quality of economic development is primarily manifested in promoting sustainable development and enhancing corporate agility (Ece Uc, 2020). From a meso-level perspective, the digital economy has evolved from digital development toward technological innovation and integration, the application of digital technologies, and industrial development, entering a phase of deep integration between the digital and real economies. The meso-level digital economy exhibits a distinct "empowerment effect": it not only facilitates the industrialization of digital technologies but also helps drive the digital, networked, and intelligent transformation of traditional industries, fostering new models, new industries, and new business formats through industrial integration. As a general-purpose technology, digital technology is characterized by its universality and high penetration rate, and it exhibits a natural compatibility with the real economy (Baus, S., 2–7); from a micro-level perspective, the digital economy—distinct from the traditional economy, which focuses solely on price and quantity—satisfies consumers' diverse demands through economies of scale and production scope. The digital economy achieves a dynamic, diverse, and complex equilibrium between supply and demand through a precise matching mechanism (Joegenson, 2007).

Research on the high-quality development of the marine industry predominantly involves theoretical analyses of its influencing factors, with most studies focusing on specific regions or sectors—such as marine fisheries (Shen, 2014; Pomeroy, 2009; Julie, 2013; Islam, 2003), marine aquaculture (Paul, 2003; Knapp, 2016), and coastal tourism (V. Otrachshenko, 2016; Laura Onofri, 2013). Quantitative studies, on the other hand, primarily concentrate on the measurement and evaluation of high-quality marine economic development; for example, researchers have developed indicators for high-quality marine economic development from the perspective of land-sea economic integration and based on the five major development concepts—innovation, coordination, openness, green development, and sharing (Jian Lingxiang, 2021). However, such evaluation indicators carry a certain degree of subjectivity. Digital technologies mainly involve innovation in existing products (Kalle Lyytinen, 2016), organizations (KANE, 2015), processes, and business models (Austin, 2012; Yoo, 2012). Current research on the digital economy is largely confined to examining the theoretical frameworks and future prospects of digital innovation (Tilson, 2010).

The aforementioned studies have all failed to examine the impact of the digital economy on the high-quality development of the marine industry; furthermore, traditional analytical methods—such as the entropy weight method and the Analytic Hierarchy Process—incorporate a degree of subjectivity when assigning weights to evaluation indicators. Therefore, how can the level of high-quality development in both the data economy and the marine industry be measured in a more scientific and effective manner? Can the rise of the digital economy foster high-quality development in the marine economy? The question of how industries characterized by high pollution, high energy consumption, and high emissions can achieve transformation and upgrading has garnered increasing attention; moreover, can the accelerated industrial upgrading in the context of the digital economy contribute to the enhancement of the marine economy's high-quality development? If so, do regional disparities exist? These questions represent urgent challenges that require immediate resolution. In light of this, this paper utilizes panel data covering the period 2007–2016 to construct a comprehensive digital economy development index based on marine green total factor productivity and multiple dimensions. It systematically examines and summarizes the mechanisms through which the digital economy influences the high-quality development of the marine industry, and further analyzes the role-playing mechanisms of the digital economy from three perspectives: industrial structure, innovation capacity, and urban household consumption.

The contributions of this study are as follows: First, few studies have integrated the digital economy, marine industry structure, and high-quality development of the marine economy into a single research framework; this paper innovatively combines these three dimensions to deepen the existing literature and research. Second, the DEA-Malmquist method is employed to measure the level of high-quality development in the marine economy; this calculation requires the implementation of a green accounting approach for the marine economy—by deducting components that do not align with green development principles—thereby effectively addressing the limitations of traditional methods for measuring the high-quality development of the marine economy. Third, regarding the development level of the digital economy, this study adopts a comprehensive approach to assess the digital economy's development status across four dimensions—digital economy infrastructure, digital economy application level, digital economy industry development level, and digital economy development environment—thereby refining the previously unilateral approaches used to measure the development level of the digital economy. Finally, by examining the interplay and integration among the digital economy, industrial structure upgrading, innovation capacity, and urban residents' consumption levels, this study investigates the internal mechanisms through which the digital economy influences the high-quality development of the marine industry,

thereby enriching the understanding of the underlying mechanisms through which the digital economy contributes to the high-quality development of the marine sector.

The remainder of this paper is structured as follows: Part II provides a review of the theoretical framework underlying the high-quality development of the digital economy and the marine industry, on which it then proposes theoretical hypotheses; Part III details the research design, including model specification, variable description, and data source documentation; Part IV presents the empirical analysis, comprising four sections: baseline regression analysis, time-varying effect analysis, mechanism analysis, threshold effect analysis, and robustness checks; and the final section summarizes the findings and discusses the significance of this study.

II. Theoretical Framework and Research Hypotheses

From the perspective of the digital economy's characteristics, it significantly reduces search costs, replication costs, transportation costs, tracking costs, and verification costs (GOLDFARB A, 2019; Goldfarb, 2019), transforming traditional production processes, reshaping existing product workflows and business models, and playing a pivotal role in driving industrial development. The impact of the digital economy on the high-quality development of the marine industry can be primarily categorized into three aspects: altering input factors, updating the form of the production function, and enhancing total factor productivity. First, data technologies have transformed input factors. Data technologies possess integrative properties as well as varying degrees of non-exclusivity and non-rivalry; they often interact in synergy with physical factors within the production function. During the input process, physical factors generate data elements, which in turn effectively improve the utilization efficiency of these physical factors, thereby optimizing factor allocation, rationalizing production behavior, and creating additional opportunities for the marine industry's development. Second, digital technologies have altered the form of the traditional production function. Digital technologies expand the scope of interaction among traditional factors, reconfigure the relationships and hierarchies among conventional production factors, and optimize the efficiency of factor allocation. This reduces the production function's dependence on traditional factors, thereby compelling the production function to enhance its output efficiency and transform its mathematical form—gradually shifting from a pattern of diminishing marginal returns to one of constant or even increasing marginal returns. As a result, the production efficiency of the marine industry is significantly elevated, leading to a more rational and advanced industrial structure. Finally, digital technologies have contributed to an increase in total factor productivity. For example, artificial intelligence and big data have enabled traditional fisheries to implement scientific capacity planning and management for aquaculture, as well as precise farming operations and fishing practices; this has transformed the extensive economic model and driven the transformation and upgrading of traditional marine industries (GorM, 2021; Lin, 2019). Additionally, digital technologies have given rise to numerous high-tech industries—such as the marine high-end equipment manufacturing sector (Xinhua, 2020) and the marine pharmaceutical industry—which are conducive to establishing a modern marine industry system and achieving high-quality development in the marine sector. In view of this, this paper proposes the following hypothesis.

H1: The digital economy can foster the high-quality development of the marine industry.

The ways in which the digital economy influences the high-quality development of the marine industry primarily include the following:

First, the digital economy can influence the high-quality development of the marine industry by facilitating its structural upgrading. Digitalization, intelligence, and automation can significantly enhance the overall efficiency of industrial chains, save substantial resources and costs, and also promote the transformation and upgrading of industrial structures through methods such as technology introduction, absorption, integration, and diffusion (Andrey, 2016). On the other hand, by empowering traditional industries with digital technologies, these industries can undergo comprehensive and multi-dimensional transformation and upgrading—shifting from the consumer side to the production side, and from offline to online operations. This approach effectively resolves the mismatch between factor supply and demand among industrial actors, diminishes the boundaries of economic activities among them, reduces the marginal cost of inter-industry coordination, and addresses the challenge of balancing fairness and efficiency within industries (Alex Eapen, 2012), thereby driving the upgrading of traditional industries and, in turn, fostering the overall structural upgrading of the economy (PENEDE, 2013).

Second, the digital economy can influence regional innovation capacity and foster high-quality development of the marine industry. According to existing research, the digital economy affects regional innovation capacity primarily from both macro and micro perspectives. At the macro level, the digital economy drives cyclical technological innovation across a broad range by enhancing productivity levels; moreover, through its technology spillover effect, it constructs a national innovation system for the digital age via cross-industry technological innovation drivers (Emmanouil Tranos 1CA, 2021; Xiao et al., 2026). At the micro level, the digital transformation of enterprises stimulates business model innovation and strengthens their dynamic innovation capacity; enterprises empowered by digital technologies can achieve technological innovation across their entire organization through the optimization of production processes and the enhancement of internal human capital (Li,

2021). By influencing regional innovation capacity, the digital economy enables traditional industries to elevate their overall innovation level through the assimilation and adoption of new technologies, thereby establishing innovative mechanisms and fostering positive interactions across industries, which ultimately contributes to high-quality economic development.

Third, the digital economy can foster the high-quality development of the marine industry by influencing household consumption. On one hand, the rapid advancement of digital technologies has transformed traditional payment methods; for example, the rise of digital payment platforms—such as Alipay, mobile banking, and WeChat Pay—has reduced transaction costs and provided households with a convenient payment environment; these digital payment solutions have, to some extent, effectively stimulated household consumption (Hou L., 2021; Li, 2020). On the other hand, digital technologies enable the precise collection of comprehensive, dynamic consumer footprint data, allowing businesses to better understand consumer preferences, thereby making the products they offer more appealing to consumers. This effectively reduces information asymmetry between producers and consumers, enhances production efficiency, and ultimately promotes the high-quality development of the industry. Accordingly, this paper proposes the following hypothesis:

H2: The synergy between the digital economy, industrial structure upgrading, innovation capacity, and urban household consumption collectively drives the high-quality development of the marine economy.

The impact of the digital economy on the high-quality development of the marine industry may involve not only a simple linear relationship but also nonlinear relationships. Once the digital economy reaches a certain stage of development, its driving force for economic growth becomes more pronounced, exhibiting an increasing marginal effect. On one hand, internet platforms and digital technologies associated with the digital economy possess strong network externalities, facilitating more convenient and closer interconnections among various economic sectors and clarifying the social division of labor; the development of the digital economy thus promotes the expansion of market size and the improvement of economic efficiency, thereby enhancing the quality of economic development. On the other hand, in the early stages of digital economy development, substantial investment in digital infrastructure, digital technologies, and digital talent is required, and the digital economy entails high initial startup costs; in such early phases, a "productivity paradox" may emerge—where the digital economy fails to effectively improve economic efficiency, thereby hindering the achievement of high-quality economic development. However, once the digital economy has accumulated to a certain level—characterized by the large-scale deployment of digital equipment and the application of digital technologies across various industrial sectors, which reduces the marginal costs between these sectors—the digital economy can then foster the high-quality development of the marine industry; in this context, the digital economy's role in promoting the high-quality development of the marine industry is subject to a threshold effect. Therefore, this paper proposes the following hypothesis:

H3: The potential threshold effect of digital industrialization on the high-quality development of the marine industry.

III. Research Design

3.1 Model Configuration

To examine the impact of the digital economy on the high-quality development of the marine industry, this paper constructs the panel data regression model shown below:

$$hdem_{i,t} = \beta_0 + \beta_1 dig_{i,t} + \sum_{k=1}^{K}(\gamma x_{i,t}^{k}) + \sum_{m=1}^{M}\delta dig_{i,t} z_{i,t}^{m} + + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (1)$$

In Equation (1), h_dem represents the high-quality development of the marine industry; d_ig represents the level of digital economy development; x denotes a set of control variables, including urban household consumption, per capita income level, marine fixed-asset investment, and marine local government fiscal expenditure; α is a constant; β and γ are the coefficients for the respective variables; i represents the province; t represents the year; μ, λ, and ε represent the individual effect, time effect, and small disturbance term, respectively; Z represents the mechanism variables, which correspond to industrial structure upgrading, the innovation capability index, and the urban household consumption level, respectively; and δ is the coefficient for each cross-term.

This study further examines the relationship between the digital economy and other economic variables. The paper employs a panel threshold regression model to test whether a nonlinear relationship exists between these two variables. Threshold regression was first proposed by Tong, and subsequently further developed by Hansen (Tong, H., 1978; Hansen, 2000). Its core idea is to identify the critical point or critical region where a threshold variable may undergo a jump; at this point or within this region, the model coefficients change, enabling a better explanation of certain real-world economic phenomena. Threshold regression is categorized into single-threshold regression (STHR) and multi-threshold regression (MTHR). The expression is as follows:

$$hdem_{i,t} = \beta_0 + \beta_1 dig_{i,t} \bullet I(dig_{i,t} \le \gamma) + \beta_2 dig_{i,t} \bullet I(dig_{i,t} \succ \gamma) + \sum {}_m\beta_m + \lambda_i + \varepsilon_{i,t} \quad (2)$$

Here, d and t represent threshold variables; γ denotes the threshold parameter; and $I()$ is an indicator function that takes the value 1 or 0—namely, it takes the value 1 if the condition within the parentheses is satisfied, and 0 otherwise (Balke, 1997; Gonzalo, 2002).

3.2 Variable Design

3.3.1 Explanatory Variables

The DEA-Malmquist productivity index method measures total factor productivity by combining the Data Envelopment Analysis (DEA) model with the Malmquist index. It first derives a distance function using linear programming techniques, and then constructs the Malmquist index by taking the ratio of the distance functions across different time periods. To avoid the potential bias associated with random selection of reference points, Fare (Rolf Fre, 1994) and others developed the DEA-Malmquist productivity index to measure the productivity index for various regions under the constant returns to scale (CRS) assumption. This method decomposes total factor productivity (TFP) into a technical efficiency index (Effch) and a technological progress index (Tech); the technical efficiency index (Effch) is further subdivided into a pure technical efficiency index (Pech) and a scale efficiency index (Sech). The model is constructed as follows:

$$M_t = TFP = Effch \times Tech = (Pech \times Sech) \times Tech \quad (3)$$

$$M_t = (x^{t+1}, y^{t+1}, x^t, y^t) = \frac{D_i^{t+1}(x^{t+1}, y^{t+1})}{D_i^t(x^t, y^t)} \times \left[\frac{D_i^t(x^t, y^t)}{D_i^{t+1}(x^t, y^t)} \times \frac{D_i^t(x^{t+1}, y^{t+1})}{D_i^{t+1}(x^t, y^t)} \right]^{1/2} \quad (4)$$

In Equation (6), x and y represent the input–output indicators (Table 1), while Dt and Dt+1 denote the distance functions for periods t and t+1, respectively. When Mt> 0, the change in total factor productivity (TFP) from period t to period t+1 is positive, indicating an increase in TFP; conversely, when Mt <0, it indicates a decline in total factor productivity (TFP).

This study examines 11 coastal regions, with the data analysis covering the period from 2007 to 2016. Based on the actual conditions of the marine economy, two input variables and two output variables are selected to measure the green total factor productivity of the marine economy. The specific indicators are presented in Table 1:

Table 1 High-Quality Development Efficiency Indicator System for the Marine Industry

	Key Indicators	**Indicator Description**
Input Indicator	capital input	Fixed asset investment
	Labor input	Maritime sector workers
Output Indicator	Expected Output	Maritime GDP
	Non-expected output	Marine resource consumption

3.3.2 Core Explanatory Variables

This study is based on the definition of the digital economy and draws upon relevant research on the measurement of digitalization conducted by institutions such as the National Bureau of Statistics of China. Taking data availability into account, the study selects indicators that are as closely related as possible to the digital economy. An evaluation index system for the digital economy development level is constructed primarily from four dimensions: the digital economy infrastructure level, the digital economy application level, the digital economy industrial development level, and the digital economy development environment level. The digital economy development levels of 11 coastal provinces across China from 2015 to 2024 are measured, and the Digital Economy Index is calculated using the entropy weight method.

Table 2 Digital Economy Development Level Evaluation Indicator System

Primary Indicator	**Secondary Indicator**	**Level 3 Indicator**
Digital economy development level	Digital economy infrastructure level	Long-distance cable line (per kilometer)
		Broadband access port (per 100 users)
	Digital economy application level	Number of mobile phones per 100 people
		Number of internet users per 100 people
		Number of personal computers per 100 people
		Number of domain names per 10,000 users
		Number of URLs per 10,000 people
		Information service personnel share
	Digital economy industrial development level	The ratio of core operating revenue to the number of employees in the electronic information manufacturing industry
	Digital economy	Number of university students per 10,000 people

	development level	R&D expenditure as a percentage of regional GDP Per-person education funding allocation Per-person telecommunications consumption amount

3.3.3Mechanism variable

Regarding industrial structure upgrading, this paper draws upon previous research and analyses, focusing on the rationalization and advancement of the industrial structure.

(1) Rationalization of Industrial Structure (CR). The rationalization of industrial structure measures industrial structure upgrading from the perspective of the integration degree of various industries and reflects the effect of optimal allocation and utilization of resources. The measurement of ISR can be calculated by the Theil index, whose formula is shown in Equation (5):

$$TL = \sum_{i=1}^{n} \left[\frac{Y_i}{Y} \ln \frac{Y_i}{L_I} / \frac{Y}{Y_I}\right] \quad (5)$$

In Model (7), Y and L represent the total output value of the marine industry and the number of laborers in each industry, respectively; Y_i and L_i represent the output value and the number of laborers in industry i, respectively. According to Equation (7), the closer the TL value is to zero, the closer the industrial structure is to a balanced state—i.e., the more rational the industrial structure is; conversely, the greater the deviation from zero, the less rational the industrial structure is.

(2) Innovation Index (CX): The regional innovation capacity evaluation system consists of 5 primary indicators, 20 secondary indicators, 40 tertiary indicators and 138 quaternary indicators. The primary indicators cover knowledge creation, knowledge acquisition, enterprise innovation, innovation environment and innovation performance. Among them, knowledge creation measures a region’s capacity to generate new knowledge; knowledge acquisition reflects a region’s ability to utilize external knowledge and promote industry-university-research cooperation; enterprise innovation evaluates the capacity of enterprises within a region to apply new knowledge, develop new technologies, adopt new processes and manufacture new products; innovation environment assesses a region’s capability to provide supporting conditions for the generation, flow and application of technologies; innovation performance represents the benefits of innovation for regional economic and social development. The data of this paper are sourced from China Regional Innovation Capability Evaluation Report.

3.3.4 Control Variable

Building upon existing research literature, this paper introduces the urban residents 'consumption level, the labor force level, marine fixed-asset investment, and marine local government fiscal expenditure as control variables. Specifically: (1) The urban residents' consumption level refers to the per capita amount spent by residents on living expenses; this indicator reflects people's material quality of life; (2) The per capita income level refers to the per capita disposable income of residents in coastal areas; (3) Marine fixed-asset investment refers to fixed-asset investment that influences the development of the marine industry; (4) Marine local government fiscal expenditure refers to the portion of local public fiscal expenditure allocated to marine development.

3.3 Data Sources and Statistical Description

Table 3 Descriptive statistics of variables

	Variable	N	Average	Standard Deviation	Minimum	Max
Explained variable	Lnhdem	110	-0.0072	0.2079	-0.7550	0.6365
Explanatory variable	Lnde	110	3.0238	0.5274	1.7647	4.1691
mechanism variable	Lncs	110	0.8772	0.0405	0.7880	0.9760
	Lncx	110	3.5537	0.3199	3.0383	4.0751
	Lncmur	110	9.9505	0.4131	9.0396	10.8829
Control variable	Lnpgdp	110	10.7741	0.5064	9.4175	11.7250
	Lnmfai	110	7.5023	0.9047	5.0172	9.4564
	Lnlefmi	110	13.0147	1.4277	9.8094	15.7356

IV. Results

4.1 Benchmark Regression Analysis

Empirical results were examined using STATA 17.0 software. First, a regression analysis was conducted using a static fixed-effects model. To assess the robustness of the impact of the core explanatory variables, a stepwise addition of control variables approach was employed to perform regressions on variables at the national level; the specific test results are presented in Table 4.

Table 4 High-Quality Development of the Digital Economy and the Marine Economy

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	lnhdem	lnhdem	lnhdem	lnhdem	lnhdem	lnhdem	lnhdem
lnde	0.261***	0.387***	0.389***	0.142*	0.160***	0.101*	0.0991*
	(7.50)	(7.19)	(7.51)	(1.54)	(1.67)	(0.96)	(0.90)
lncs		2.045**	1.246*	0.824*	0.827*	0.357*	0.0144*
		(2.63)	(1.57)	(1.06)	(1.04)	(0.43)	(0.02)
lncx			0.216**	0.266***	0.224**	0.225**	0.154
			(3.09)	(3.77)	(2.93)	(2.84)	(1.76)
lncmur				0.327**	0.462***	0.483***	0.484***
				(3.20)	(3.39)	(3.54)	(3.52)
lnpgdp					-0.142	-0.193	-0.206
					(-1.42)	(-1.84)	(-1.93)
lnmfai						0.0549	0.169*
						(1.65)	(2.22)
lnlefmi							-0.0931
							(-1.73)
_cons	-0.797***	0.616	0.679	-2.018*	-2.032*	-2.339*	-2.419*
	(-7.42)	(1.09)	(1.20)	(-2.04)	(-1.99)	(-2.23)	(-2.21)
N	110	110	110	110	110	110	110

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The regression results for Models (1) – (7) in Table 4 indicate that as the control variables are progressively added, the coefficient for the core explanatory variable—namely, the digital economy—remains consistently positive and is statistically significant at the 10% level or higher. This suggests that the digital economy exerts a significant and stable influence on the high-quality development of the marine industry, and its growth helps foster the high-quality development of the marine sector. Regarding the control variables, Models (2) – (7) reveal that marine industrial structure upgrading (cs), the innovation index (cx), and urban household consumption are all significantly positive. This implies that promoting marine industrial structure upgrading, enhancing the innovation index, and increasing consumption among coastal urban residents can help shift the marine industry away from an extensive development model. In contrast, the effects of rising per capita GDP and increased local government fiscal expenditure are negative and not statistically significant; this indicates that raising per capita GDP or increasing local government fiscal expenditure does not have a notable impact on advancing the high-quality development of the marine industry.

Given the uneven regional development across China, this paper divides the country into three major marine economic zones for separate analysis: the Northern Marine Economic Zone primarily comprises Liaoning, Shandong, Tianjin, and Hebei; the Central Marine Economic Zone primarily comprises Jiangsu, Shanghai, and Zhejiang; and the Southern Marine Economic Zone primarily comprises Fujian, Guangdong, Guangxi, and Hainan. The specific results are presented in Table 5.

Table 5 The Impact of the Digital Economy on Regional Disparities in the High-Quality Development of the Marine Industry

	Northern Marine Economic Zone lnhdem	Eastern Marine Economic Zone lnhdem	Southern Marine Economic Zone lnhdem
lnde	0.338***	0.216***	0.300***
	(0.0522)	(0.0687)	(0.0624)
lncs	0.969	1.334	3.097
	(0.85)	(0.89)	(1.26)
lncx	0.245	0.222	-0.0342
	(1.47)	(0.82)	(-0.13)
lncmur	0.229	0.521*	0.806*
	(0.63)	(2.16)	(2.47)
lnpgdp	-0.160	0.655	-0.170
	(-0.68)	(1.75)	(-0.86)
lnmfai	0.169	0.143	0.309
	(1.88)	(0.95)	(1.34)
lnlefmi	-0.172**	-0.0754	-0.260
	(-2.82)	(-0.66)	(-1.74)
_cons	-2.390*	-11.92***	-7.176
	(-2.45)	(-4.18)	(-1.85)
N	40	30	30

* p < 0.1, ** p < 0.05, *** p < 0.01

As shown in Table 5, the impact of the digital economy on the high-quality development of the marine industry is significant across all regions—whether in the northern, central, or southern areas. In terms of the magnitude of this impact, the northern marine economic zone exhibits the highest impact coefficient, followed by the southern zone, while the central zone has the lowest coefficient. One possible reason for this is that the northern marine economic zone has a greater need to develop its digital economy to reduce transaction costs in marine economic activities, enhance the productivity and innovation capacity of the marine industry, and facilitate the transformation of the marine economy. In contrast, the central marine economic zone boasts a leading level of digital economy development, and the growth of its digital economy is aligned with the overall socio-economic development, creating a virtuous cycle. However, the marginal benefit of leveraging a strong digital economy to drive high-quality development of the marine economy is relatively low. For the southern marine economic zone, the level of digital economy development does not yet fully align with its economic scale; its extensive mode of economic development remains somewhat locked in.

4.2 Time-Varying Effect Analysis

To examine whether the digital economy exerts a dynamic influence on the high-quality development of the marine industry, this study employs a yearly time-period approach and uses the Generalized Least Squares (FGLS) method for estimation. The results are presented in Table 6.

Table 6 Temporal variation in the high-quality development impact of the digital economy on the marine industry

	Coefficient	std. err.	z	P>|z|	[95% conf. interval]	
2007	0.00734	0.0021	3.34	0.000	0.0030	0.0116
2008	0.00510	0.0021	2.48	0.013	0.0011	0.0091
2009	0.00582	0.0013	4.30	0.000	0.0032	0.0084
2010	0.00587	0.0011	5.50	0.000	0.0037	0.0079
2011	0.00526	0.0008	6.20	0.000	0.0036	0.0069
2012	0.00623	0.0076	8.11	0.000	0.0047	0.0077

2013	0.00643	0.0006	9.51	0.000	0.0051	0.0077
2014	0.00756	0.0004	18.62	0.000	0.0067	0.0083
2015	0.00607	0.0002	28.35	0.000	0.0056	0.0064
2016	0.00504	0.0001	35.35	0.000	0.0163	0.0081
_cons	1.670***	0.1474	11.32	0.000	-0.0163	1.9587

As shown in the results of Table 6, over the ten-year period from 2007 to 2016, the significance level of the digital economy's impact on the high-quality development of the marine industry was consistently below 1%, indicating a declining trend. In 2007, the impact coefficient of the digital economy on the high-quality development of the marine industry was 0.0734; by 2008, it had fallen to 0.0051; and from 2015 onward, it gradually declined further to 0.006. This suggests that the digital economy exerts a dynamic and long-term influence on the high-quality development of the marine industry, albeit at a slowing pace.

4.3 Mechanism of Action Analysis

To further examine and verify the transmission mechanism through which the digital economy promotes high-quality economic development, this paper incorporates an interaction term capturing the relationship between the digital economy and the marine industry structure, innovation capability, and urban household consumption into the baseline regression model. The specific results are presented in Table 7.

Table 6: Mechanism Analysis of the Digital Economy's Impact on the High-Quality Development of the Marine Industry

	(1)	(2)	(3)
	lnhdem	lnhdem	lnhdem
lnde	0.632**	0.459***	0.232*
	(2.21)	(3.83)	(0.70)
lndelncs	1.003***		
	(3.44)		
lndelncx		0.0967*	
		(2.35)	
lndelncmur			0.0981***
			(3.41)
_cons	-0.714***	-0.958***	-0.949***
	(-4.59)	(-6.24)	(-4.45)
N	40	40	40

* p < 0.1, ** p < 0.05, *** p < 0.01

As shown in Table 7, the coefficients for the interaction terms between the digital economy and the marine industry structure, between the digital economy and innovation capability, and between the digital economy and urban residents' consumption are all significantly positive at the 10% level or higher. This indicates that the digital economy, industrial structure, and innovation capability each exert a positive influence on the high-quality development of the marine industry; moreover, the digital economy contributes to this development by enhancing innovation capacity and facilitating industrial upgrading. In other words, the synergistic alignment and integrated interaction among the digital economy, industrial structure, and innovation capability collectively drive the high-quality development of the marine industry.

Building upon the previous empirical analysis, this study examines, across different regions, the impact of the interaction term between the digital economy, the upgrading of the marine industry structure, innovation capacity, and urban household consumption on the high-quality development of the marine industry; the results are presented in Table 8.

Table 8 Regional Disparities Analysis

	Northern Marine Economic Zone			Eastern Marine Economic Zone			Southern Marine Economic Zone		
	lnhdem	lnhdem	lnhdem	lnhdem	lnhdem	lnhdem	lnhdem	lnhdem	lnhdem

lnde	-0.632*	0.459***	0.232	1.425***	-0.135	-2.515***	1.093**	0.647***	-1.660
	(-2.21)	(3.83)	(0.70)	(3.73)	(-0.49)	(-4.51)	(2.78)	(3.66)	(-1.81)
Lnde*lncs	1.103***			1.003***			0.847*		
	(3.44)			(3.44)			(2.27)		
Lnde*lncx		0.0390*			0.0658*			0.0912**	
		(1.12)			(0.97)			(2.62)	
Lnde*lncmur			0.00898 (0.32)			0.208*** (4.74)			0.161* (2.04)
_cons	-0.714***	-0.958***	-0.949***	-1.459***	-0.432	1.254**	-0.997***	-0.914***	0.210
	(-4.59)	(-6.24)	(-4.45)	(-4.15)	(-1.93)	(3.17)	(-3.94)	(-4.31)	(0.50)
N	40	40	40	30	30	30	30	30	30

* p < 0.1, ** p < 0.05, *** p < 0.01

As shown in Table 8, from the perspective of the three major marine economic zones, the synergistic interaction between the digital economy and the marine industry structure plays a significant role in promoting the high-quality development of the marine industry; however, there are notable regional disparities, specifically manifested as: Northern Zone> Eastern Zone> Southern Zone. Compared to the Eastern and Southern marine economic zones, the Northern marine zone will derive greater benefits from the interaction term between the digital economy and the industrial structure. The primary reason is that the northern region hosts China's important traditional marine industries—such as marine fisheries, marine salt production, marine power generation, and marine transportation—all of which are concentrated within the Northern Marine Economic Zone. These traditional marine industries urgently require new technologies to drive their development.

From the perspective of the interaction term between digital economy and innovation capacity, the interaction term exerts a positive effect on the high-quality development of the marine industry, with significance above the 10% level. There are also certain regional differences, which are manifested as: South > East > North. Compared with the eastern and southern marine economic circles, the impact of the interaction term of digital economy and innovation capacity on the high-quality development of the marine industry is relatively weak in the northern marine economic circle. The main reason lies in the inadequate construction and application of digital infrastructure in the northern marine economic circle, as well as the weak capacity of traditional industries to improve overall innovation performance through absorbing and digesting new technologies.

Regarding the interaction term between the digital economy and urban household consumption, this term shows a significantly positive impact on the high-quality development of the marine economy in both the eastern and southern marine economic zones; however, the eastern marine economic zone demonstrates a notable advantage, whereas the northern marine economic zone does not exhibit a statistically significant effect. This is primarily due to the relatively higher level of digital economy development in the eastern marine economic zone compared to that of the northern marine economic zone. The robust digital economy in the eastern marine economic zone effectively stimulates household consumption; the synergy between household consumption and the digital economy fosters a virtuous cycle that jointly drives the high-quality development of the marine economy.

4.4 Threshold Effect

The preceding analysis has examined the mediating effect of the rationalization of marine industrial structure and confirmed that the digital economy can effectively promote the high-quality development of the marine economy. This paper further investigates whether such promotion effect presents a linear relationship. A threshold model is adopted to test the relationship between the digital economy and high-quality development. Taking the digital economy as the threshold variable, this study conducts a threshold effect analysis to measure the impact of the digital economy on high-quality development under different intervals. First, the Bootstrap self-sampling method is applied with 2000 samplings to estimate the threshold value \pi and relevant statistics. Then dummy variables are constructed according to the threshold value of the digital economy. As shown in the test results in Table 10, the single threshold is significant at the 5% level, while the double threshold and triple threshold effects do not exist. Therefore, the digital economy exhibits a single-threshold effect.

Table 9 Threshold value test structure

	Threshold value	F value	P value	Bootstrap
Single threshold test	2.4782	33.5	0.0170	2000
Double threshold test	1.7647	15.6	0.7100	2000
Three threshold test	2.1950	10.3	0.2600	2000

The results of the threshold regression are presented in Table 8. It can be seen that when the digital economy is at a low level, it exerts an inhibitory effect on the quality of economic development. When the digital economy reaches a certain threshold level, it significantly boosts high-quality economic development. In the initial stage of the digital economy, digital infrastructure is characterized by a long construction cycle, large investment scale and high construction costs. Technological innovation is highly risky and uncertain. The digital economy is insufficient in driving household consumption. The digital transformation of enterprises' production processes and management systems entails enormous costs. Besides, relevant preferential policies remain to be formulated and improved, leading to low enthusiasm and insufficient incentives for enterprises to make digital investments. Consequently, the early-stage investment features large outlay, slow returns and high risks, and these uncertain factors restrain the improvement of economic quality to a certain extent. With the advent of the new round of scientific and technological revolution, the support of relevant preferential policies and the remarkable achievements of digital pioneers have expanded investment driven by the digital economy. As a new factor of production, data is deeply integrated with industries, bringing fundamental changes to production modes and lifestyles, and thereby delivering strong impetus for the development of the marine economy.

Table 10 Threshold regression results

Threshold value	lnde	lncs	lncx	lncmur	lnpgdp	lnmfai	lnlefmi	Cons value	F value
A1(lndei≤2.47	-0.2897	-1.1447	0.2493	0.0077	-0.0012	0.1921	-0.2154	0.191	1.57**
	（0.1190）	（0.711）	（0.0838）	（0.1231）	（0.081）	（0.931）	（0.936）	（0.45）	
A2(lndei>2.47	0.2698***	1.064***	0.0403**	0.0249*	0.0165*	0.6739*	0.6920	0.580**	1.24***
	(0.0703)	(0.4201)	(0.0497)	(0.0727)	(0.0483)	(0.5554)	(0.5544)	（9.17）	

4.5 Robustness Test

The empirical results presented earlier have confirmed the soundness of the research framework employed in this study; however, to ensure the robustness of these findings, it is necessary to conduct robustness checks. The logic behind these robustness checks is as follows: first, alternative variables are used—specifically, internet coverage rate is employed as the explanatory variable to re-estimate model (1); second, the impact of endogeneity issues on the results is mitigated. To address endogeneity concerns, this study adopts the System GMM method. The principle of System GMM involves using both the level and difference forms of the endogenous explanatory variable as instrumental variables to mitigate endogeneity, without requiring the selection of additional instrumental variables; see Table 9.

Table 10 Robustness Test

	(1) lnhdem	(2) lnhdem
lnfg	0.364***	
	(5.33)	
lnde		0.0550**
		(0.89)
lncmur	0.363***	0.470***
	(3.64)	(3.84)
lnpgdp	-0.432***	-0.344***
	(-5.17)	(-4.02)
lnmfai	-7.198	-5.778
	(-0.85)	(-0.61)
lnlefmi	7.305	5.905
	(0.87)	(0.62)

_cons	-0.484	-1.417*
	(-0.95)	(-2.25)
N	110	110
R	0.224	
AR(1)test		-3.537(0.000)
AR(2)test		-1.427(0.154)
Sargan test		16.489(1.000)

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Column (1) of Table 9 reports the regression results of internet coverage on the high-quality development of the marine industry. The regression coefficient of internet coverage is significantly positive at the 1% level, indicating that internet coverage can improve the high-quality development of the marine industry. This demonstrates that the results are reasonably stable. Column (2) of Table 9 presents the estimation results obtained by the system-GMM method. The p-values of the AR(2) test and the Sargan test are both above 0.05, suggesting that there is no second-order serial correlation in the residual term, and the moment-condition instrumental variables adopted by system-GMM do not suffer from over-identification. Therefore, the system-GMM estimation results are valid. After controlling for endogeneity, the estimated coefficient of the digital economy remains significantly positive at the 5% level. The system-GMM estimation indicates that the promotion effect of the digital economy on the high-quality development of the marine industry is robust.

V. Discussion

Based on theoretical analysis, this study measures the levels of digital economy development and high-quality marine economic development across 11 coastal provinces in China from 2015 to 2025, and conducts econometric analysis accordingly. The findings are as follows: (1) The digital economy exerts a significant positive effect on the high-quality development of the marine industry in all marine economic zones—northern, central, and southern. However, notable regional heterogeneity exists. Specifically, the promoting effect is strongest in the northern zone, followed by the southern zone, and weakest in the central zone. (2) The impact of the digital economy on the high-quality development of the marine industry is dynamic and persistent over time. In the long run, this promoting effect tends to diminish. (3) In terms of transmission mechanisms, the digital economy, industrial structure, innovation capacity, and urban household consumption not only exert positive effects on the high-quality development of the marine industry individually, but also jointly promote such development through their synergistic matching and integration. (4) To further investigate the relationship between the digital economy and high-quality marine economic development, this study employs a panel threshold model to examine the non-linear relationship between the two. The results indicate that when the digital economy is at a relatively low level, it inhibits high-quality marine economic development; conversely, once a certain threshold is reached, it significantly reinforces high-quality development. Accordingly, this paper proposes the following policy recommendations:

First, efforts should be made to foster a sound environment for digital economy development. To develop the digital economy, it is essential to cultivate cutting-edge, high-end marine industrial clusters and expand the scale and capacity of the marine digital economy to ensure its sound development. Priority should be given to building new infrastructure and establishing an intelligent production system centered on Internet application platforms. Relevant infrastructure platforms should be developed to enable data collection, analysis, storage, and mining—such as massive data analytics databases, networked storage centers, and big data mining platforms—so as to achieve full coordination across production, application, consumption, and services. This would effectively leverage the significant advantages of Internet technologies in resource integration and industrial chain optimization. From the production chain to the consumption end, digitalization should be integrated into every link to realize comprehensive synergy among production, application, consumption, and services, thereby guiding the digital economy to propel industries toward higher and more comprehensive levels of development.

Second, it is necessary to promote data sharing and openness, and accelerate the rational flow and optimized allocation of marine resource factors. This would strengthen the role of a rationalized marine industrial structure in enhancing the digital economy's contribution to economic development. While emphasizing productivity improvements across industries, equal attention should be paid to enhancing production quality. Both household consumption levels and fixed asset investment affect how the digital economy influences marine industrial structure and high-quality marine industry development. Therefore, well-coordinated planning is needed to boost household consumption, increase investment in marine fixed assets, and maximize the digital economy's impact on industrial structural transformation, thereby driving a transition toward high-quality economic

development. At the same time, local governments should ensure adequate fiscal expenditure on marine development to provide sufficient financial support for regional marine economic growth.

Third, further efforts are required to explore development pathways for the marine digital economy. This entails advancing digital infrastructure, developing digital economic models such as industrial Internet, artificial intelligence, and digital oceans, and leveraging integrated innovation to upgrade traditional marine industries. The application of new technologies such as 5G and blockchain should be promoted comprehensively. Strategic initiatives should be accelerated to develop the digital economy by using digital technologies—including the Internet, big data, and artificial intelligence—to restructure industrial structures and achieve intelligent management, resource optimization, and scaled production, thereby realizing industrial structural optimization and upgrading. In the course of development, it is crucial to accurately understand the laws governing digital economy development, establish legal frameworks and policy standards aligned with regional economic conditions, and strengthen policy support to ensure the healthy and sustainable development of industries. Meanwhile, data barriers should be dismantled and information silos eliminated to facilitate information exchange and extensive collaboration across different marine industries.

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