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Research on the Impact Mechanism of Green Innovation in Marine Science and Technology Enabling Dual Economic Circulations

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Abstract: Currently, accelerating the construction of a new development pattern with dual economic circulations is strategically significant for enhancing the autonomy and sustainability of China's economic development. First of all, this paper, from the perspective of green innovation in marine science and technology, measures its efficiency using the SBM super-efficiency model. Then, a coupling coordination model calculates the coordination degree of dual economic circulations after measuring the domestic and international economic circulations based on the TOPSIS method. Secondly, a two-way fixed effects model is employed to examine the impact of green innovation in marine science and technology on domestic economic circulation, international economic circulation, and dual economic circulations. The study finds that green innovation in marine science and technology effectively promotes domestic economic circulation, international economic circulation, and the dual economic circulations. Additionally, green innovation in marine science and technology mitigates the impact of inter-regional resource misalignment on domestic economic circulation and influences international economic circulation by promoting the high-quality development of the marine economy. Finally, it is discovered that green innovation in marine science and technology exhibits a single-threshold heterogeneous effect on domestic economic circulation and international economic circulation.

Keywords: green innovation in marine science and technology; domestic economic circulation; international economic circulation; dual economic circulations; mechanism

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1. Introduction

The world is undergoing unprecedented change, a situation not seen in the past century. The Political Bureau of the Central Committee of the Communist Party of China (CPC) analyzed the current economic situation and emphasized the construction of a new development pattern with the domestic economic cycle as the principal part, and the dual economic circulations promoting each other. The proposal of the new development pattern to realize the transformation of China's economy from quantitative growth to qualitative improvement, from scale expansion to structural upgrading, and from factor-driven to innovation-driven [1,2], is one of the key initiatives to promote China's high-quality development and realize economic transformation and upgrading, and this strategic initiative is of great strategic significance for China's development. However, many difficulties and challenges need to be overcome to realize this new development pattern.

Innovation is the source of scientific and technological progress and economic growth, and the state plays a key role in promoting innovation, which has become a bottleneck restricting China's ability to build an economic double cycle. In today's increasingly fierce global competition in science and technology, China's economy is gradually moving towards the stage of high-quality development, and the country's need for strategic scientific and technological support is becoming more and more urgent. The CPC Central Committee has paid great attention to science and technology innovation, and has repeatedly emphasized the need to enhance national strategic scientific and technological strength, improve the overall effectiveness of the innovation system, and accelerate the construction of a strong scientific and technological country. In the face of foreign technological thresholds and an insufficient supply of its own science and technology, the country must play a role in organizing and promoting major scientific and technological innovations, take advantage of its own national strengths, narrow the technological gap, and ensure the security and stability of the economic double cycle.

As the cradle of life on earth and the treasure trove of resources, the ocean has gradually become a key area for major countries to gain competitive advantages. Although China's marine industry has realized leapfrog development at the cost of massive resource consumption and environmental pollution [3], the gradual depletion of resources and the continuous deterioration of the ecological environment indicate that this development mode is unsustainable [4]. Green innovation in marine science and technology, as the key to balancing the development of marine economy and the protection of marine ecological resources, can optimize the structure of the marine industry and realize the efficient development of the marine economy, while reducing the consumption of resources and protecting the marine ecology. Looking at the domestic situation, the central government has put forward a higher level of requirements for enhancing green innovation in China's marine science and technology, conquering key core technologies, and strengthening inter-regional ties. From the international standpoint, the global free trade system has been impacted, and China urgently needs to develop new markets and promote an economic double cycle. China's marine science and technology self-reliance and self-improvement is conducive to a comfortable response to the complex changes in the international environment; the key lies in the scientific and rational construction of national marine strategic science and technology forces, and in innovation in and cutting-edge science and technology for deep digging and deep research.

It can be seen that green innovation in marine science and technology is the main driving force to promote the high-quality development of China's marine economy, and it is an important support for the construction of a new pattern of dual-economy circular development. In recent years, China's marine economy has achieved rapid growth, becoming one of the important driving forces of China's economic growth. The role of China's marine economy is becoming more and more prominent under the new situation of the double economic cycle. The Chinese Government has pointed out that "the key to accelerating the development of the oceans and revitalizing the marine economy is science and technology", and that green innovation in marine science and technology is a factor that runs through the whole situation and plays a decisive role. Through green innovation in marine science and technology, it is possible to solve key technical problems on the supply side, promote industrial technological progress, improve industrial efficiency, and facilitate the upgrading and optimization of the industrial structure, thereby realizing the optimal spatial distribution of the marine economy.

In this context, this study's aim—to measure China's marine science and technology green innovative efficiency and ascertain whether green innovation in marine science and technology can empower the dual economic circulations and its impact mechanism—not only helps to review and summarize China's green innovation in marine science and technology experience in the past, but also provides a reference for decision-making departments to carry out the next step of strategic planning and task deployment.

2. Literature Review

2.1. Green Innovation in Marine Science and Technology and Domestic Economic Circulations

Domestic economic circulation mainly refers to the promotion of high-quality economic development through a smooth cycle of domestic production, distribution, circulation, and consumption, with the domestic market as the mainstay of economic development, the core of which lies in giving full play to the potentials and advantages of China's super-large market.

Science and technology is the core driving force for promoting the construction of a maritime power. In this context, the strategies of rejuvenating the sea through science and technology and strengthening the country through the sea have fundamental promoting effects. Under the complex background of global industrial chain restructuring and fierce competition in the field of high technology, collaborative green innovation in marine science and technology has become the key support for coastal areas to realize high-quality domestic economic development [5–7]. In the face of the new round of international competition, the effect of marine science and technology green innovation has gradually appeared, and the accelerated application of the digital intelligence economy in marine science and technology green innovation in coastal areas is conducive to accelerating the construction of a new pattern of division of labor and cooperation in the marine economy [8,9]. In view of the fact that the coastal area is at the core of the land, water, and air multimodal transportation network, and is a key node connecting the domestic economic cycle [10], the construction of a new development pattern requires a shift in four directions, one of which is the shift of market value-added from technology importation to scientific and technological innovation and self-reliance. Green innovation promotes the domestic economic cycle by driving high-quality supply and creating new demand, and stabilizing and strengthening the chain to complement the chain [11,12].

2.2. Green Innovation in Marine Science and Technology and International Economic Circulations

International economic circulation refers to the fact that the chains of the upstream and downstream links of the industrial chain are completely outside the country, and the factors and products are all produced abroad. This circulation model relies mainly on the supply and demand relationship in the international market, and realizes the global allocation of resources and cross-border economic cooperation through international trade and investment activities.

Green innovation promotes the international economic cycle by promoting independent and self-reliant scientific and technological innovation, stabilizing, strengthening, and supplementing the industrial chain [13]. By incorporating cutting-edge science and technology, green innovation in marine science and technology can significantly improve the transaction quality of international trade and promote more efficient economic activities. The expansion of important Chinese enterprises at home and abroad promotes the circular flow of factors of production, and also gives cities, as spatial carriers, a dual role and a division of functions in linking international economic cycles [14,15]. Rapidly rising labor costs have impeded the development of traditional trade, and green innovation in marine science and technology can drive the synergistic development of the region's resource chain, industrial chain, factor chain, governance chain, and communication chain [6,7]. As a key hub connecting coastal and inland areas, coastal provinces are deeply affected by the two-way effect of siphoning and radiation between coastal and inland provinces. This move not only contributes to the innovative construction of China's key industrial chain and the expansion and upgrading of the division of labor, but also has a positive significance in promoting the formation of a unified big market between coastal and inland provinces, as well as in facilitating the mutually reinforcing role of international economic circulations [16].

2.3. Green Innovation in Marine Science and Technology and Dual Economic Circulations

The enhancement of green innovation in marine science and technology capacity has brought about an increasing degree of informatization of the marine industry chain; the high-quality development of the coastal area has a positive role in building a new development pattern of a double-cycle economy [17–19]. Strengthening marine economic cooperation to promote the high-quality development of the marine economy can not only help China stabilize its position in the economic dual circulation, but also set an example for in-depth participation in global marine governance and provide a new model of cooperation and development for the international community [16]. On the one hand, coastal cities have piloted the "unveiling of the list of commanders" system, striving to realize the marine green innovation and scientific and technological mechanism of innovation in parallel, to release the power of marine science and technology. Capital support for marine technology and innovation in related research fields has been strengthened, and the deep integration of the marine value chain, resource chain, and technology chain has been accelerated [20,21]. On the other hand, the ability for independent technological innovation has been further strengthened, and a number of marine innovative technologies have reached the international advanced level [22,23]. The strategy of ocean power is of great significance to the development of China's marine economy, the improvement of the marine environment, the breakthrough of marine science and technology, the maintenance of marine rights and interests, and the innovation of marine governance [17–19].

2.4. Literature Summary

Existing research on green innovation in marine science and technology and domestic and international dual economic circulations has certain shortcomings: (1) Existing studies on green innovation in marine science and technology mainly focus on formulating and optimizing marine technology policies. The construction of efficiency evaluation systems relies heavily on researchers' subjective experiences, needing a more fact-based quantitative scientific evaluation. (2) Regarding the new dual economic circulations pattern, many studies are conceptual and theoretical, needing more systematic quantitative analyses of the current state of dual economic circulations. More in-depth research on theory, empirical data, and calculations needs to be done. (3) Among mainstream research on economic dual economic circulations, only some studies focus on the influencing factors and mechanisms of economic dual economic circulations under the new development pattern, with there especially being a lack of research on the role of marine technology in empowering economic dual economic circulations.

To address these shortcomings, this paper contributes in the following ways: (1) In terms of research scope and perspective, taking green innovation in marine science and technology as an entry point, we construct a multidimensional, multidirectional, and multilevel model of green innovation in marine science and technology empowering dual economic circulations, analyze the relationship between the two from a systemic point of view, clarify the complex linkage mechanism therein, and reveal the intrinsic mechanism of green innovation in marine science and technology empowering dual economic circulations. (2) In terms of research content, a scientific measurement of the efficiency of green innovation in marine science and technology in China's coastal provinces, the domestic economic general cycle, the international economic outer cycle, and the dual economic circulations is conducted to analyze the current development status, development dilemmas, and development needs of China's green innovation in marine science and technology, as well as the quality of the development of the domestic economic inner cycle and the international economic outer cycle, which supplements the relevant research. (3) In terms of research revelations, this study, based on literature research, puts forward countermeasure suggestions targeting the problems faced by the development of the domestic economic macrocycle and the international economic outer cycle, in order to dissolve the breakpoints and blockages in the development of the dual economic circulations, and the conclusions of the study are important for the development of the marine science and technology industry in provinces and cities, increasing the investment in marine science and technology R&D funding by governments at all levels, and constructing a leading system of green innovation in marine science and technology in the context of the dual economic circulations.

3. Hypotheses and Methodology

3.1. Research Hypotheses

Green innovation in marine science and technology is a crucial driver of China's economic growth [24]. Green innovation in marine science and technology promotes domestic economic circulation from both the supply and demand perspectives. On the supply side, it enhances the quality and efficiency of supply, aligns supply with demand, addresses constraints on expanding domestic demand due to insufficient adequate supply, and drives the economy towards domestic market dominance, promoting domestic economic circulation. On the demand side, green innovation in marine science and technology creates new demands, ensuring the regular operation of various processes in the economic system, stimulates consumption potential, and develops new products, technologies, and markets in maritime areas to create new demands, thereby unleashing domestic demand potential, contributing to the expansion of domestic economic circulation.

Resource allocation optimization promotes the large-scale circulation of production factors between regions, facilitating domestic economic circulation at the source. The construction of the new development pattern focuses on "circulation", with reform as a critical factor, aiming to address bottlenecks and obstacles in production, distribution, circulation, and consumption. The goal is to achieve a smooth flow of production factors and optimize resource allocation [25]. Green innovation in marine science and technology standardizes the processes of the marine industry, optimizes regional resource allocation, enhances the circular flow of domestic value chains, increases the degree of product division of labor, improves product-added value, and strengthens the linkage of regional value chains, thereby enhancing regional value chain connections [26]. Based on this, the following hypotheses are proposed:

H1: *Green innovation in marine science and technology promotes domestic economic circulation.*

H2: *Resource mismatch plays a mediating role between green innovation in marine science and technology and domestic economic circulation.*

Green innovation in marine science and technology also serves as a driving force for external economic circulation. Green innovation in marine science and technology not only promotes the domestic economic cycle, but also plays an important role in the external economic cycle. First, at the national level, green innovation in marine science and technology has accelerated the pace of the construction of a strong marine country, helped to resolve the risks of technological decoupling, trade protection, and other uncertainties, maintained the security and stability of the international economic outer cycle, and promoted the development of the international economic outer cycle [27]. Secondly, at the industrial level, the level of innovation is a key factor in determining the position of countries and regions in the global industrial chain and value chain, and the promotion of green innovation in marine science and technology not only contributes to the upgrading and optimization of the industrial chain and value chain, but also significantly improves China's core position in the global industrial division of labor, and further promotes the vigorous development of the international economic outer cycle. Finally, at the enterprise level, enterprises have enhanced their international competitiveness and value creativity through their deep participation in marine technology green innovation. As the discourse power and influence of enterprises in the international market are enhanced, the international economic out-cycle is also further promoted.

Deep involvement in green innovation in marine science and technology enhances a company's competitiveness and value creation in the international arena, strengthening its voice and market influence globally and contributing to the strength and optimization of international economic circulation.

The high-quality development of the marine economy provides a new impetus for China to establish itself in international economic circulation and actively participate in global ocean governance. On the one hand, the increasing localization and regionalization features of the global value chain layout, enhancing the level of the high-quality development of the marine economy and internal dynamics for cooperation, leads coastal areas to open up higher-level cooperative relations in the marine economy. On the other hand, the high-quality development of the marine economy promotes the establishment of a modern marine industry system, optimizes the spatial layout of the industry, fosters high-level international competition, and accelerates the entry of strategic emerging marine industries into the high-end global value chain [28]. The high-quality development of the marine economy is closely related to green innovation in marine science and technology. Scientific and technological innovation is a necessary condition for the sustainable development of the ocean [29]. Current and future marine technologies will promote and accelerate the growth of the marine economy. Technological innovation increases the contribution rate of coastal fisheries to the marine economy [30]. It is a crucial driving force for optimizing and modernizing the marine industry structure. Under the drive of green innovation in marine science and technology, the modern marine industry system is accelerating its construction, promoting the coordinated development of industrial chains, governance chains, resource chains, factor chains, and communication chains of regional green innovation in marine science and technology, integrating new scientific and technological elements in this process [31]. Based on the above analysis, the following hypotheses are proposed:

H3: *Green innovation in marine science and technology promotes international economic circulation.*

H4: *The high-quality development of the marine economy mediates green innovation in marine science and technology and international economic circulation.*

The impact mechanism of green innovation in marine science and technology driving the coupling coordination of dual economic circulations can be studied from macro and micro perspectives. At the macro level, future cooperation in marine economic development will be based on dual economic circulations, focusing on building "hardware" such as interconnected modern marine industry systems and ecological networks for green innovation in marine science and technology. At the micro level, the driving mechanism of green innovation in marine science and technology can effectively change the capital, labor, and resource allocation methods between domestic and international economic circulation. This helps enterprises explore optimal allocation solutions, endowing cities with a dual role as spatial carriers, assisting them in participating in the functional division of domestic and international economic circulation, and incorporating new science and technology into this process. This drives the coordinated development of industrial chains, governance chains, resource chains, factor chains, and communication chains of regional green innovation in marine science and technology [31]. Based on the above analysis, the following hypothesis is proposed:

H5: *Green innovation in marine science and technology promotes the double-cycle economy.*

3.2. Methodology

(1) SBM Super-Efficiency Model

The traditional DEA model does not consider the problem of slack variables in the measurement of inefficiency, and its calculation results usually show the situation that multiple decision units are evaluated to be efficient, and since the maximum value of the efficiency is 1, the efficiency of the efficient decision units is the same, and it is not possible to further differentiate between the efficiency of the efficient decision units. The SBM super-efficiency model not only solves the problem of slack variables, but also allows for further comparisons among the efficient decision units, thus enabling the complete ranking of all decision units and the analysis of the changes in efficiency across periods for comparison, so that the whole decision unit can realize a complete sorting and can be compared across the period to analyze the change in efficiency. Therefore, in this paper, we choose the output-oriented SBM super-efficiency model based on a non-radial non-angle to measure the efficiency of green innovation in marine science and technology (*TEC*) [32,33], and the model is as follows:

$$min\rho = \frac{1+\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1-\frac{1}{q}\sum_{r=1}^{q}\frac{s_r^+}{y_{rk}}}$$
$$s.t.\begin{cases}\sum\limits_{j=1.j\neq k}^{n} x_{ij}\lambda_j - s_i^- \leq x_{ik}\\ \sum\limits_{j=1.j\neq k}^{n} x_{ij}\lambda_j - s_t^+ \geq y_{rk}\\ \lambda_j, s^-, s^+ \geq 0\end{cases} \quad (1)$$

$i = 1, 2, \ldots, m$; r = 1,2,...,q; j = 1,2,...,n$(j \neq k)$. ρ is the efficiency value of the evaluated decision unit, x_{ij} is the ith input data of the jth indicator, y_{rk} is the rth output data of the jth indicator, m is the number of input indicators, q is the number of output indicators, s^-, s^+ are the slack variables of inputs and outputs, λ is the benefit of scale, n is the total amount of the indicator system, and k is the excluded evaluated decision unit in the jth indicator.

(2) Coupling Coordination Model

The coupling coordination model reflects the relationship between systems, encompassing development and coordination. Following the work of Ge Pengfei et al. [34], we first use the entropy-weighted TOPSIS method to calculate domestic economic circulation (*IC*) and international economic circulation (*EC*) separately. Subsequently, a coupling coordination model is established to measure the coupling coordination of dual economic circulations. The method is as follows:

Step 1: Standardization Processing

$$\mathrm{Y_{ij}} = \begin{cases}\frac{X_{ij}-min(X_{ij})}{max(X_{ij})-min(X_{ij})}\mathrm{X}_{ij} \text{ for forward indicators}\\ \frac{maxX_{ij}-X_{ij}}{max(X_{ij})-min(X_{ij})}\mathrm{X}_{ij} \text{ for reverse indicators}\end{cases} \quad (2)$$

where i denotes the province, j denotes the measurement indicator; X_{ij} denotes the initial measurement indicator, Y_{ij} denotes the standardized measurement indicator, $min(X_{ij})$ denotes the minimum value of X_{ij}, $max(X_{ij})$ denotes the maximum value of X_{ij}.

Step 2: Calculate Information Entropy E_j and Weight W_j

$$E_j = ln\frac{1}{n}\sum_{i=1}^{n}\left[\left(\frac{Y_{ij}}{\sum_{i=1}^{n} Y_{ij}}\right)ln\left(\frac{Y_{ij}}{\sum_{i=1}^{n} Y_{ij}}\right)\right] \quad (3)$$

$$W_j = \frac{(1-E_j)}{\sum_{j=1}^{m}(1-E_j)} \quad (4)$$

Step 3: Build Weighted Matrix R

$$R = (r_{ij})_{n\times m} \quad (5)$$

where $r_{ij} = W_j \times Y_{ij}$

Step 4: Determine Optimal Q_j^+ and Pessimal Q_j^- Solutions

$$\begin{cases}Q_j^+ = (maxr_{i1}, maxr_{i2}, \ldots maxr_{im})\\ Q_j^- = (minr_{i1}, minr_{i2}, \ldots minr_{im})\end{cases} \quad (6)$$

Step 5: Calculate Euclidean Distances d_i^+ and d_i^-

$$\begin{cases} d_i^+ = \sqrt{\sum\limits_{j=1}^{m}\left(Q_j^+ - r_{ij}\right)^2} \\ d_i^- = \sqrt{\sum\limits_{j=1}^{m}\left(Q_j^- - r_{ij}\right)^2} \end{cases} \tag{7}$$

Step 6: Calculate Relative Closeness Degree Z_i

$$Z_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{8}$$

where Z_i is between 0 and 1; the larger the value of Z_i indicates that the development level of domestic general circulation and international external circulation in province i is more favorable.

Step 7: Build Coupling Degree Model between Two Systems

$$C_{ab} = 2 \times \left[\frac{Z_a Z_b}{(Z_a + Z_b)^2}\right]^{\frac{1}{2}} \tag{9}$$

where C_{ab} denotes the value of the coupling between the domestic general circulation system and the international external circulation system, taking a value between 0 and 1.

Step 8: Coupling Coordination Model

$$\begin{cases} D_{ab} = \sqrt{C_{ab} \times T_{ab}} \\ T_{ab} = \alpha Z_a + \beta Z_b \end{cases} \tag{10}$$

where D_{ab} denotes the degree of coordination of the coupling between the domestic general circulation and the international external circulation, with values ranging between 0 and 1. α and β are the weight coefficients, the sum of which is 1. α and β are considered to be equal in this system for the two systems of the domestic general circulation and the international external circulation, and each is taken as 0.5.

Based on the actual distribution of values, the degree of coordination of economic double-cycle coupling is uniformly divided in the range of 0 to 1 with reference to the relevant literature, including a number of different levels, as detailed in Table 1.

Table 1. Criteria for classifying the degree of coupling coordination.

Degree of Coupling Coordination	Type	Degree of Coupling Coordination	Type
(0, 0.1]	Extreme disorder	(0.5, 0.6]	Sue for harmonization
(0.1, 0.2]	Severe disorder	(0.6, 0.7]	Primary coordination
(0.2, 0.3]	Moderate disorder	(0.7, 0.8]	Intermediate-level coordination
(0.3, 0.4]	Mild disorder	(0.8, 0.9]	Good coordination
(0.4, 0.5]	On the verge of disorder	(0.9, 1]	Quality coordination

(3) Impact Pathway Model

This study employs a stepwise regression approach to establish a mediation effect model, providing an in-depth analysis of the transmission mechanism between green innovation in marine science and technology and domestic economic circulation. The model discusses the mediation effect of resource mismatch, where *KMIS* represents capital mismatch and *LMIS* represents labor mismatch. The model equations are as follows:

$$IC_{it} = \alpha_1 + \beta_1 TEC_{it} + \varphi_1 Control_{it} + \mu_i + \omega_j + \varepsilon_{it} \tag{11}$$

$$Kmis_{it} = \alpha_2 + \beta_2 TEC_{it} + \varphi_2 Control_{it} + \mu_i + \omega_j + \varepsilon_{it} \quad (12)$$

$$Lmis_{it} = \alpha_3 + \beta_3 TEC_{it} + \varphi_3 Control_{it} + \mu_i + \omega_j + \varepsilon_{it} \quad (13)$$

$$IC_{it} = \alpha_7 + \beta_7 TEC_{it} + \lambda_4 Kmis_{it} + \eta_4 Lmis_{it} + \varphi_4 Control_{it} + \mu_i + \omega_j + \varepsilon_{it} \quad (14)$$

At the same time, a stepwise regression method is used to model the mediating effect of the high-quality development (*MED*) of the marine economy between green innovation in marine science and technology and international out-cycling:

$$EC_{it} = \alpha_5 + \beta_5 TEC_{it} + \varphi_5 Control_{it} + \mu_i + \omega_j + \varepsilon_{it} \quad (15)$$

$$MED_{it} = \alpha_6 + \beta_6 TEC_{it} + \varphi_6 Control_{it} + \mu_i + \omega_j + \varepsilon_{it} \quad (16)$$

$$EC_{it} = \alpha_7 + \beta_7 TEC_{it} + \lambda_7 MED_{it} + \varphi_7 Control_{it} + \mu_i + \omega_j + \varepsilon_{it} \quad (17)$$

(4) Threshold regression model

The threshold effect refers to the phenomenon that when an economic parameter reaches a specific value, it will cause a sudden change in the state of another parameter, and that specific value is called the threshold. This paper draws on the panel threshold regression model proposed by Hansen (1999) to verify the threshold effect of green innovation in marine science and technology (*TEC*) on the domestic general circulation (*IC*) and the threshold effect of green innovation in marine science and technology (*TEC*) on the international external circulation (*EC*). Assuming the existence of a single threshold, the model is as follows:

$$\begin{gathered} IC_{it} = \alpha_8 + \alpha_8 TEC_{it} \cdot 1(TEC_{it} \le \gamma) \\ +\beta_8 TEC_{it} \cdot 1(TEC_{it} \ge \gamma) + \varphi_8 \sum Control_{it} + \mu_i \end{gathered} \quad (18)$$

$$\begin{gathered} EC_{it} = \alpha_9 + \alpha_9 TEC_{it} \cdot 1(TEC_{it} \le \gamma) \\ +\beta_9 TEC_{it} \cdot 1(TEC_{it} \ge \gamma) + \varphi_9 \sum Control_{it} + \mu_i \end{gathered} \quad (19)$$

In this study, green innovation in marine science and technology (*TEC*) was set as the threshold variable, and after determining the critical value γ, the sample interval was divided into two regions and differentiated by the slope values α_8 and β_8, respectively (or α_9 and β_9, respectively). The value $1(\cdot)$ is a schematic function, and the value is determined according to whether the threshold variable is less than or equal to the critical value; if it is true, it takes a value of 1, and the value of the other way around is 0. The sample was repeatedly sampled 200 times using the Bootstrap method with Stata16 statistical software to test the existence of the threshold effect and to determine the number of thresholds. Using the Bootstrap method, 200 repeated samples were taken by the Stata16 statistical software and single-threshold, double-threshold, and triple-threshold tests were conducted to test the existence of the threshold effect and to determine the number of thresholds, and finally, the F-value and p-value of the statistics were obtained.

4. Variable Selection and Data Description

4.1. Variable Selection and Processing

4.1.1. Index System

Based on the theory of social reproduction, the national economic cycle encompasses four stages: production, distribution, circulation, and consumption. Depending on the different application scenarios of the cycle, it can be divided into domestic economic circulation and international economic circulation. The four small cycles in domestic economic circulation occur within the country, while international economic circulation relies on foreign markets to interact with the four small cycles and the foreign market. Drawing on existing research, this study first calculates domestic economic circulation

(*IC*) and international economic circulation (*EC*). Subsequently, a coupling coordination quality model is constructed to calculate the coupling coordination degree of dual economic circulations (*DC*) [35]. Before we can measure the quality of the double cycle and the quality of the coupling, we need to identify the indicators for measuring the two subsystems of the economy, the inner cycle and the outer cycle.

As far as the internal economic cycle is concerned, the key to building a new domestic cycle lies in the formation of a virtuous circle between the demand side and the production side. According to Long Shaobo and others, at present, there are problems of insufficient consumption ability, low consumption willingness, and unreasonable consumption structure on the consumption side, and problems of an insufficiently advanced production structure and low production efficiency on the production side [36]. Based on this, this paper sets the demand-side indicators of the economic inner cycle subsystem as consumption base, consumption willingness, and consumption structure, and the production-side indicators as production scale, production structure, and production efficiency. In terms of the external economic cycle, the key to building a new international economic cycle is to base oneself domestically, fully utilize international resources, and promote the elimination of China's lock-in at the low end of the global value chain. The "bringing in" strategy consists of commodity imports, foreign investment, and technology introduction, while the "going out" strategy consists of commodity exports and domestic capital going global. Based on this, this paper sets the indicators for measuring the external economic circulation subsystem as direct foreign investment, direct outward investment, import trade, export trade, and technology introduction. Table 2 presents the specific definitions of the variables.

Table 2. Domestic economic circulation and international economic circulation.

	Subsystems	Guideline Layer	Indicator Level
Degree of coordination of double-cycle coupling (*DC*)	Domestic Economic Circulation (*IC*)	Consumption Base	Per Capita Disposable Income of Residents (RMB/person)
		Consumption Willingness	Per Capita Consumption Expenditure of Residents (RMB/person)
		Consumption Structure	Proportion of Expenditure on Household Equipment per Capita to Total Consumption Expenditure (%)
		Scale of Production	Growth Rate of Total Fixed Asset Investment in the Whole Society (%)
		Production Structure	Sum of the Proportion of Output in Three Major Industrial Sectors and Labor Productivity
		Production Efficiency	Average Labor Productivity in Three Major Industrial Sectors (%)
	Internal Economic Circulation (*EC*)	Direct Foreign Investment	Growth Rate of Foreign Direct Investment (%)
		Direct Foreign Investment	Growth Rate of Non-Financial Outbound Direct Investment (%)
		Import Trade	Proportion of Import Trade to GDP (%)
		Export Trade	Proportion of Export Trade to GDP (%)
		Technology Introduction	Growth Rate of Technology Introduction Expenditure of Large-scale High-Tech Industrial Enterprises (%)

4.1.2. Calculation of Input and Output Indicators

In order to comprehensively reflect the indicator system of green innovation in marine science and technology efficiency, indicators are selected from both input and output perspectives. The input indicators for green innovation in marine science and technology activities consider three aspects: capital, labor, and material resources. The output indicators for green innovation in marine science and technology reflect aspects such as papers, patents, and research achievements [37]. The input–output indicator system is presented in Table 3.

Table 3. Green innovation in marine science and technology indicator system.

Target Layer	Tier 1 Indicators	Secondary Indicators
Inputs	Capital	Input of funds to marine-related scientific research institutions
	Labor Force	Scientific and technological employees of marine scientific research institutions
	Physical Resources	Marine research institutions
Outputs	Thesis	Number of scientific papers published by marine research institutions
	Patents	Total number of invention patents held by marine research institutions
	Project Results	Number of marine scientific and technological achievements

4.1.3. Mediating Variables

Resource Mismatch: Following the approach of Bai Junhong et al. [38], resource mismatch is divided into the Capital Mismatch Index (*KMIS*) and Labor Mismatch Index (*LMIS*).

Marine Economic Development Level (*MED*): Represented by the proportion of the total marine output to the total regional output [39].

4.1.4. Control Variables

Based on the existing literature, the control variables adopted in this study include Per Capita GDP (*PGDP*), marketization level (*MKT*) represented by a marketization index, Labor Intensity (*EMP*) represented by the total number of employees at the end of the year, and industrialization level (*IND*) represented by the proportion of GDP from the secondary industry.

4.2. Data Sources

For this study, marine economic data from 11 coastal provinces (Liaoning, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Guangdong, Guangxi, Fujian, Hainan) for the years 2005–2019 were selected as the research sample. All data were obtained from sources such as the "Ocean Statistical Yearbook", "China Ocean Economic Statistical Yearbook", "China Statistical Yearbook", "China Regional Economic Statistical Yearbook", "China Trade and Economic Statistical Yearbook", statistical yearbooks of various provinces, China National Knowledge Infrastructure Chinese Patent Database, and China Customs Statistical Database.

5. Empirical Results and Analysis

5.1. Descriptive Statistics

In this paper, the marine economic data of 11 coastal provinces of Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Guangxi, and Hainan from 2005–2019, including green innovation in marine science and technology, domestic economic general circulation, international economic external circulation, economic double circulation coupling and coordination, the high-quality development of the marine economy, GDP per capita, marketization level, labor-intensive, industrialization level, and the level of infrastructure construction are descriptive statistics, and the results are shown in Table 4.

Table 4. Descriptive statistics of the main variables.

VarName	Obs	Mean	SD	Min	Median	Max
TEC	165	0.5575	0.8173	0.0044	0.1554	4.0259
IC	165	0.4414	0.1268	0.1952	0.4347	0.8029
EC	165	0.3606	0.1521	0.0167	0.3408	0.7306
DC	165	0.6157	0.1017	0.2757	0.6142	0.8706
KIMS	165	0.3569	0.7399	−0.3370	0.0968	2.8233
LIMS	165	0.2128	0.4922	−0.3851	0.1795	1.3162
MED	165	0.1794	0.0887	0.0315	0.1717	0.3772
PGDP	165	10.6376	1.7006	−9.7218	10.7879	11.9658
IND	165	3.8189	0.2962	3.1058	3.8795	6.3735
EMP	165	7.7658	0.9326	1.7822	7.9445	8.8749
MKT	165	8.7830	1.6359	1.0730	9.0220	11.4940

5.2. Overall Characterization of the Coupling Degree of the Double Loop

Table 5 demonstrates the changes in the rank of the coupled coordination degree of the dual economic circulations in China's coastal areas from 2005 to 2019, and it can be seen from Table 5 that the changes in the coupled coordination degree of the dual economic circulations in China's coastal areas present the following characteristics: First, the coupled coordination degree of the dual economic circulations shows a stable upward trend. Both the inner and outer circulatory systems have realized quality development, and the degree of coupling coordination of mutual influence and mutual promotion has deepened, which is mainly due to China's economic takeoff in recent years. Secondly, the coupling and coordination degree of China's double-cycle economy is still at a relatively low level, with the coupling and coordination degree rating evolving from mildly dysfunctional in 2005 to primitively coordinated in 2019, which indicates that the coordination relationship between China's domestic and external economic cycles has been handled poorly, with insufficient tapping of domestic demand, an unadvanced production structure, and a long-term embeddedness of the external cycle in the bottom of the global value chain, which has led to the worrisome quality of the double cycle.

Table 5. Degree of coordination of economic double-cycle coupling in China's coastal areas.

Year	Value	Level of Coordination	Year	Value	Level of Coordination
2005	0.286	Moderate disorder	2013	0.562	Sue for harmonization
2006	0.334	Mild disorder	2014	0.531	Sue for harmonization
2007	0.358	Mild disorder	2015	0.533	Sue for harmonization
2008	0.387	Mild disorder	2016	0.574	Sue for harmonization
2009	0.418	On the verge of becoming dysfunctional	2017	0.591	Sue for harmonization
2010	0.448	On the verge of becoming dysfunctional	2018	0.643	Primary coordination
2011	0.469	On the verge of becoming dysfunctional	2019	0.631	Primary coordination
2012	0.515	Sue for harmonization			

5.3. Direct Effect Test

This study employs a double fixed effect model and utilizes Stata16 to test the direct effects of green innovation in marine science and technology on domestic economic circulation, international economic circulation, and the coordination of double circulation. The estimation results are presented in Table 6. In Model (1), the dependent variable is domestic economic circulation, and the results indicate that the estimated coefficient of green innovation in marine science and technology is 0.0256, significantly positive at the 1% level, suggesting a significant promotion effect on domestic economic circulation. In Model (2), the dependent variable is international economic circulation, and the data show that the estimated coefficient of green innovation in marine science and technology is significantly positive at the 1% level (α_2 = 0.0701, $p < 0.01$), indicating a significant promotion effect on the quality of international economic circulation. In Model (3), the dependent variable is the coordination of double circulation, and it can be observed that the estimated coefficient of green innovation in marine science and technology is 0.0279, significantly positive at the 1% level, demonstrating a positive impact on the coordination of double circulation, validating Hypotheses 1, 3, and 6.

Table 6. Direct effect test results.

	(1)	(2)	(3)
	IC	**EC**	**DC**
TEC	0.0256 ***	0.0701 ***	0.0279 ***
	(3.00)	(4.26)	(3.27)
Controls	√	√	√
Constant	0.4592 ***	0.4316 ***	0.6625 ***
	(18.41)	(11.13)	(34.48)
Province fixed effects	√	√	√
Year fixed effects	√	√	√
N	165	165	165
R^2	0.8721	0.6017	0.7184
F	72.7332	14.8132	28.0782

Note 1: *** indicates statistical tests at the 1% significance level. Note 2: √ represents controlled.

5.4. Discussion

The baseline regression results indicate that green innovation in marine science and technology has a positive impact on both domestic economic circulation and international economic circulation. According to the theoretical analysis discussed earlier, green innovation in marine science and technology can facilitate domestic economic circulation by improving resource allocation and, simultaneously, promote international economic circulation by fostering the high-quality development of the marine economy. This, in turn, leads to a new development pattern of dual economic circulations. To test the existence of these paths, this section, drawing on previous research [40], employs a stepwise regression method to examine the mediating effects.

5.4.1. Mediating Effect Test of Resource Mismatch

Table 7 presents the results of the mechanism test with resource mismatch as the mediating variable. Column (1) reports the estimation results of the effect of green innovation in marine science and technology (*TEC*) on domestic economic circulation (*IC*), indicating a significantly positive coefficient at the 1% level, suggesting that green innovation in marine science and technology contributes to the growth of domestic economic circulation. Columns (2) and (3) show the parameter estimation results of green innovation in marine science and technology (*TEC*) on the mediating variables, capital mismatch (*KMIS*), and labor mismatch (*LMIS*). It is evident that the regression coefficients of green innovation in marine science and technology (*TEC*) are significantly negative at the 10% and 5% levels, respectively, indicating that green innovation in marine science and technology effectively mitigates the degree of capital and labor mismatch. Column (4) presents the parameter estimation results when simultaneously incorporating the explanatory variable green innovation in marine science and technology and the mediating variables, capital and labor mismatch. It shows that the impact of green innovation in marine science and technology (*TEC*) on domestic economic circulation (*IC*) remains significantly positive, indicating that the improvement in domestic economic circulation induced by green innovation in marine science and technology is achieved through correcting capital and labor mismatch. Thus, Hypothesis 2 is validated. In terms of factor allocation, green innovation in marine science and technology enhances the specialized production and service capabilities of enterprises, promoting the recycling of resources in domestic economic circulation, reducing waste and pollution, strengthening R&D innovation in dominant products, and upgrading production processes. This, in turn, fosters sustainable development in the marine sector and economic circular development. In terms of factor association, green innovation in marine science and technology facilitates the cross-regional outsourcing of intermediate product production, optimizing resource allocation and driving the large-scale circulation of production factors across regions.

Table 7. Mediating effect of resource mismatch.

	(1)	(2)	(3)	(4)
	IC	**K**	**L**	**IC**
TEC	0.0284 ***	−0.1317 *	−0.1413 **	0.0238 ***
	(3.45)	(−1.81)	(−2.22)	(2.79)
K				−0.0099 *
				(−1.67)
L				−0.0238 **
				(−2.14)
Controls	√	√	√	√
Constant	1.2072 *	−5.9034	−1.6640	1.1092 *
	(1.95)	(−1.00)	(−0.31)	(1.81)
Province fixed effects	√	√	√	√
Year fixed effects	√	√	√	√
N	165	165	165	165
R^2	0.8848	0.5494	0.4544	0.8923

Note1: ***, **, * indicate statistical tests at the 1%, 5%, and 10% significance levels, respectively. Note2: √ represents controlled.

5.4.2. Mediating Effect Test of High-Quality Development of Marine Economy

Table 8 presents the results of the mechanism test with the high-quality development of the marine economy as the mediating variable. Column (1) reports the estimation results of the effect of green innovation in marine science and technology (*TEC*) on international economic circulation (*EC*), indicating a significantly positive coefficient of 0.0665 at the 1% level, suggesting that green innovation in marine science and technology contributes to the growth of international economic circulation. Column (2) shows the parameter estimation results of green innovation in marine science and technology (*TEC*) on the mediating variable, the high-quality development of the marine economy (*MED*), with regression coefficients significantly positive at the 1% level, indicating that green innovation in marine science and technology promotes the high-quality development of the marine economy (*MED*). Column (3) presents the parameter estimation results when simultaneously incorporating the explanatory variable green innovation in marine science and technology (*TEC*) and the mediating variable high-quality development of the marine economy (*MED*). It shows that the impact of green innovation in marine science and technology (*TEC*) on international economic circulation (*EC*) remains significantly positive, indicating that the improvement in international economic circulation induced by green innovation in marine science and technology is achieved through promoting the high-quality development of the marine economy. Thus, Hypothesis 4 is validated.

On the one hand, the development of the marine economy will promote the rational allocation and utilization of deep-sea resources and marine energy, providing more resources and market opportunities for the global economy. This can flow into the global market through trade and international cooperation, meeting the needs of different countries and regions and promoting resource circulation internationally. On the other hand, driven by green innovation in marine science and technology, the development of intelligent shipping technology, port automation technology, ship navigation systems, etc., can improve the efficiency of marine transportation, optimize the marine logistics network, and enhance the efficiency and stability of the global supply chain. Under the impetus of green innovation in marine science and technology, the development of marine information technology provides accurate data support for the marine economy, helping decision-makers formulate scientific marine policies, promoting technological exchange and cooperation between different countries, strengthening international cooperation and win–win situations in the marine sector, and facilitating the sustainable development of the marine economy and international economic circulation.

Table 8. Mediating effect of high-quality development of marine economy.

	(1)	(2)	(3)
	EC	**MED**	**EC**
TEC	0.0665 ***	0.0172 ***	0.0565 **
	(3.71)	(2.78)	(3.20)
MED			0.5794 ***
			(2.43)
Controls	√	√	√
Constant	0.7545	0.7259	0.3339
	(0.46)	(1.19)	(0.21)
Province fixed effects	√	√	√
Year fixed effects	√	√	√
N	165	165	165
R^2	0.6167	0.8974	0.6302

Note1: ***, ** indicate statistical tests at the 1% and 5% significance levels, respectively. Note2: √ represents controlled.

5.4.3. Threshold Effect Existence and Number Test

The Table 9 results indicate that considering green innovation in marine science and technology as the threshold variable and domestic economic circulation as the dependent variable, the single threshold is significant at the 10% level, passing the threshold effect existence test. However, the *p*-values for double and triple thresholds are 0.1900 and 0.5700, respectively, indicating that the threshold existence test does not pass. Therefore, this study concludes that the impact of green innovation in marine science and technology on domestic economic circulation only exhibits a single-threshold effect. Similarly, when considering international economic circulation as the dependent variable, the single threshold is significant at the 1% level, passing the threshold effect existence test. However, the *p*-values for double and triple thresholds do not pass the threshold existence test. Hence, this study suggests that the impact of green innovation in marine science and technology on international economic circulation also only exhibits a single-threshold effect.

Table 9. Threshold effect of green innovation in marine science and technology.

Threshold Variable	Dependent Variables	Number of Thresholds	F-Value	*p*-Value	Threshold Value		
					1%	5%	10%
TEC	IC	Single Threshold	14.42 *	0.0550	18.1828	14.5438	12.4477
		Double threshold	9.90	0.1900	21.1851	14.0953	11.4182
		Triple threshold	8.10	0.5700	28.8464	18.9495	17.0918
	EC	Single threshold	20.32 ***	0.0050	16.0474	11.6059	9.8089
		Double threshold	3.79	0.7400	15.4585	10.9569	9.7703
		Triple threshold	4.88	0.5050	16.5554	12.6552	10.1419

Note1: ***, * indicate statistical tests at the 1% and 10% significance levels, respectively.

After the significance test of the threshold effect, it is necessary to examine the authenticity of the threshold value. Table 10 reports the estimation results and 95% confidence intervals for the single threshold. As shown in the table, the single threshold values for driving domestic economic circulation and international economic circulation growth through green innovation in marine science and technology are 0.6428 and 0.0540, respectively, with 95% confidence intervals of (0.5334, 0.6493) and (0.0445, 0.0540). The confidence interval lengths for the threshold estimates are very short, with 4 and 3 values, respectively, falling within the interval among the 165 observations. This indicates that the threshold estimates are close to the true values, passing the authenticity test of the threshold value.

Table 10. Threshold value estimation for green innovation in marine science and technology.

Threshold Variable—TEC			
Dependent variables	Category	Threshold value	95% confidence interval
IC	Single Threshold	0.6428	(0.5334, 0.6493)
EC	Single Threshold	0.0540	(0.0445, 0.0540)

Using green innovation in marine science and technology (*TEC*) as the threshold variable, Table 11 reports the results of the single-threshold model evaluation. Due to differences in the efficiency of green innovation in marine science and technology in China, its promotion of domestic economic circulation also varies. When green innovation in marine science and technology is at a lower level (TEC < 0.6428), the coefficient indicating its impact on domestic economic circulation is 0.148. At this point, green innovation in marine science and technology has a significant positive effect on domestic economic circulation. When the TEC is at a higher level (TEC > 0.6428), the coefficient indicating its impact on domestic economic circulation is 0.033, reaching a 1% significance level. This suggests that as the level of green innovation in marine science and technology increases, its positive impact on domestic economic circulation gradually weakens after reaching a certain threshold. This phenomenon may be attributed to the strong initial competitive advantage of green innovation in marine science and technology. The introduction and application of new technologies can efficiently and cost-effectively exploit and utilize marine resources, which is crucial for enhancing China's marine economic development and accelerating the domestic economic circulation process. At this stage, the economic growth and environmental benefits brought about by innovation may be significant. However, as green innovation in marine science and technology develops further, it may face technological challenges and difficulties requiring a higher investment and longer research and development cycles for commercial application. Moreover, with the rapid development of innovation, market saturation may increase, and green innovation in marine science and technology may gradually lose its competitive advantage, leading to a diminishing impact on domestic economic circulation.

Table 11. Single-threshold regression results.

	(1)		**(2)**
	IC		**EC**
TEC (TEC < 0.6428)	0.148 ***	TEC (TEC < 0.0540)	−2.500 ***
	(4.30)		(−4.20)
TEC (TEC > 0.6428)	0.033 ***	TEC (TEC > 0.0540)	0.056 ***
	(4.24)		(−3.57)
Controls	√	Controls	√
Constant	0.381 ***	Constant	0.425 ***
	(25.87)		(−13.27)
Province fixed effects	√	Province fixed effects	√
Year fixed effects	√	Year fixed effects	√
N	165	N	165
R^2	0.316	R^2	0.3
F	3.976	F	3.688

Note1: *** indicates statistical tests at the 1% significance level. Note2: √ represents controlled.

When international economic circulation is the dependent variable, and green innovation in marine science and technology is at a lower level (TEC < 0.0540), the coefficient indicating its impact on international economic circulation is −2.500. In this scenario, the impact of green innovation in marine science and technology on international economic circulation is negative. In the early stages, green innovation in marine science and technology may face technological uncertainties and environmental risks. The introduction and application of new technologies may encounter various challenges, including technical feasibility, environmental impact assessment, legal regulations, obstacles to international cooperation, and issues related to intellectual property protection. These risks may result in adverse effects on international economic circulation, such as environmental damage or resource waste. When green innovation in marine science and technology is at a higher level (TEC > 0.0540), the coefficient indicating its impact on the quality of enterprise development is 0.056, reaching a 1% significance level. With the gradual maturity and application of green innovation in marine science and technology, it may bring positive effects to the international economic circulation. The introduction and application of green innovation in marine science and technology can enhance the efficiency of marine resource development, reduce environmental risks, and promote sustainable marine economic development. This will provide more opportunities for international cooperation, stimulate trade, facilitate technological exchange, and foster collaborative projects, ultimately promoting the positive development of international economic circulation.

5.5. Endogeneity Test

The above confirms the positive effect of marine STI on the coupled harmonization degree of the domestic economic general cycle, international economic external cycle, and dual economic circulations, but it is also possible that a higher coupled harmonization degree of the domestic economic general cycle, international economic external cycle, and dual economic circulations may reverse to promote a higher marine STI in coastal provinces. In academic practice, when faced with difficulties in obtaining ideal external instrumental variables (IVs), the lagged terms of endogenous explanatory variables can usually be incorporated into the model as instrumental variables. This practice has been proven to be effective in mitigating the bias and inconsistency problems in parameter estimation, and has also shown better results in solving the problem of weak instrumental variables. Therefore, this paper adopts the research methodology of scholars Jing Guangzheng and Li Ping (2016), choosing one period lag of green innovation in marine science and technology as the instrumental variable, then using two-stage least squares (2SLS) to conduct a regression, and finally conducting a weak instrumental variable test [41]. As can be seen from the estimation results in Table 12, the coefficients of the instrumental variables are all 0.435 with a standard error of 0.129, which is significant at the 1% level. The results of the second-stage regression show that the coefficients of green innovation in marine science and technology (*TEC*) are 0.044, 0.169, and 0.073 with standard errors of 0.017, 0.043, and 0.019 respectively, which are significant at the 1% level.

Table 12. Endogeneity test results.

	IC		**EC**		**DC**	
	OLS	**2SLS**	**OLS**	**2SLS**	**OLS**	**2SLS**
TEC	0.435 *** (0.129)	0.044 ** (0.017)	0.435 *** (0.129)	0.169 *** (0.043)	0.435 *** (0.129)	0.073 *** (0.019)
PGDP	−0.057 (0.075)	0.024 *** (0.008)	−0.057 (0.075)	−0.015 (0.013)	−0.057 (0.075)	0.001 (0.007)
IND	−0.557 ** (0.281)	0.051 (0.032)	−0.557 ** (0.281)	0.046 (0.059)	−0.557 ** (0.281)	0.038 (0.031)
EMP	0.091 (0.058)	−0.056 *** (0.009)	0.091 (0.058)	−0.042 *** (0.012)	0.091 (0.058)	−0.040 *** (0.007)
MARKET	0.082 (0.062)	0.040 *** (0.008)	0.082 (0.061)	0.030 *** (0.012)	0.082 (0.061)	0.034 *** (0.007)

Table 12. *Cont.*

	IC		EC		DC	
	OLS	**2SLS**	**OLS**	**2SLS**	**OLS**	**2SLS**
INFRA	0.299 * (0.167)	0.040 *** (0.014)	0.299 * (0.167)	−0.058 ** (0.028)	0.299 * (0.167)	−0.013 (0.014)
Constant	1.273 (1.121)	−0.006 (0.125)	1.273 (1.121)	0.372 (0.255)	1.273 (1.121)	0.445 *** (0.138)
N	154	154	154	154	154	154
R^2	0.454	0.770	0.454	0.427	0.454	0.600

Note1: ***, **, * indicate statistical tests at the 1%, 5%, and 10% significance levels, respectively.

In testing the validity of instrumental variables, the first step is to verify the correlation of the instrumental variables. If the problem of weak instrumental variables exists in the model, the estimation using two-stage least squares (2SLS) may not only be ineffective in correcting the bias in the ordinary least squares (OLS) estimation, but instead, it may lead to a reduction in the efficiency of the estimation due to the introduction of a larger standard deviation. In order to determine whether the model constructed in this paper faces such a challenge, the results of the first stage were analyzed in depth, and their estimation results are shown in Table 13.

Table 13. Test results for weak instrumental variables.

TEC	IC	EC	DC
	OLS	**OLS**	**OLS**
Bias R^2	0.172	0.172	0.172
F	11.456	11.456	11.456
Minimum eigenvalue statistic	30.538	30.538	30.538
2SLS size of nominal 5% critical value corresponding to 10% in Wald test	16.38	16.38	16.38

The results show that the biased R^2 value is 0.172, which indicates that the instrumental variable still has a fairly strong explanatory strength for the endogenous variables after excluding the effects of other exogenous variables. In addition, the value of the F-statistic is 11.456, which is significantly higher than the commonly considered judgmental threshold of 10, and it can be concluded that the instrumental variable is not a weak instrumental variable. In addition, the critical value corresponding to 10% in all 2SLS size of nominal 5% Wald tests is smaller than the minimum eigenvalue statistic, which further supports the conclusion that there is no weak instrumental variable problem.

In summary, marine STI is an exogenous variable. After considering endogeneity, the impact of green innovation in marine science and technology and innovation on the coupling coordination degree of the domestic economic general cycle, international economic external cycle, and dual economic circulations is still significantly positive, indicating that green innovation in marine science and technology in coastal areas has a stable enhancement effect on the coupling coordination degree of the domestic economic general cycle, international economic external cycle, and dual economic circulations, which can further support the conclusion of this paper.

5.6. Robustness Testing

In order to further verify the robustness of the regression results, this study employs an alternative variable approach to validate the robustness of the regression model, specifically using a new method to measure green innovation in marine science and technology. Drawing on the green innovation in marine science and technology index indicator system created by Liu Dahai et al. in the "National Ocean Innovation Index Report 2019" and employing entropy weighting to objectively assign weights to each indicator [42], a green innovation in marine science and technology index is calculated for 11 provinces. This index is then used to replace the data measured by the DEA method for green innovation in marine science and technology, conducting a robustness test (Table 14). After applying the double fixed effects model for regression, the estimation results remain consistent with the previous findings. There are no significant differences in the core explanatory variable coefficient results compared to the earlier analysis. The significantly positive impact of green innovation in marine science and technology on the domestic economic circulation, international economic circulation, and the coordination degree of double circulation still exists. This indicates that the main conclusions of this study exhibit a good robustness.

Table 14. Robustness test results.

	(1)	(2)	(3)
	IC	**EC**	**DC**
TEC	0.1241 **	0.4076 ***	0.2971 ***
	(2.22)	(3.88)	(5.03)
Controls	√	√	√
Constant	0.4076 ***	0.2618 ***	0.5383 ***
	(11.11)	(4.34)	(17.74)
Province fixed effects	√	√	√
Year fixed effects	√	√	√
N	√	√	√
R^2	0.8671	0.5868	0.7443
F	42.8890	11.6592	28.8752

Note1: ***, ** indicate statistical tests at the 1% and 5% significance levels, respectively. Note2: √ represents controlled.

6. Conclusions and Recommendations

This study utilized panel data from 2005 to 2019 for 11 coastal provinces in China and employed a two-way fixed effects model to empirically investigate the impact of green innovation in marine science and technology on dual economic circulations. The empirical results are summarized as follows: (1) Green innovation in marine science and technology effectively promotes both domestic and international economic circulations. (2) Green innovation in marine science and technology significantly enhances the coupling coordination of domestic and international dual economic circulations. (3) Green innovation in marine science and technology mitigates regional resource misallocation, influencing domestic economic circulation, and simultaneously, the high-quality development of the marine economy acts as an intermediary between green innovation in marine science and technology and the international economic circulation. (4) Green innovation in marine science and technology exhibits a single-threshold effect on both domestic and international economic circulations. Once the threshold for green innovation in marine science and technology is crossed, its promotion of domestic economic circulation gradually weakens, while its impact on international economic circulation shows a negative-then-positive pattern.

Based on these conclusions, the following recommendations are proposed:

1. Strengthen innovation in marine science and technology, and increase investment in marine scientific research. To enhance the ability of marine science and technology innovation and system management, we should strengthen the construction of marine science and technology infrastructure, and optimize the soft environment such as policies, regulations, and related services. This will help to continuously improve the efficiency level of scientific and technological innovation, so as to achieve coordinated development with the scale of investment, strengthen the construction of frontier disciplines, and actively integrate into the global marine science and technology innovation a division of labor system. Relying on major national strategies, increase investment in important coastal areas and emerging marine industries, strengthen

fund management of marine research projects, encourage interdisciplinary integration, and increase R&D capital investment in basic research and applied research.

2. Formulate and implement competitive talent policies. For those areas where the efficiency of marine science and technology innovation and the level of scale investment are relatively weak, efforts should be made from two aspects: On the one hand, strengthen the construction of innovation scale, strive to win the support of national policies, optimize and improve the scale structure of science and technology innovation. On the other hand, the coastal areas should fully tap and make use of the resource advantages of these areas, and actively introduce high-tech and high-level talents in the marine field that match the development of the local marine industry, in order to improve the efficiency of scientific and technological innovation, and then promote the overall improvement of the quality of marine scientific research and innovation in the whole region.
3. Improve the efficiency of marine factor allocation and promote the supporting role of marine scientific and technological innovation in the marine economy. Adhere to innovation-driven approaches, optimize the spatial pattern of maritime areas, enhance the aggregation role of marine factors, improve the efficiency of factor allocation, increase the intensive use of marine resources, and integrate higher levels of scientific and technological innovation into the double cycle of domestic and international economy.
4. Reinforce weak links to achieve the high-quality development of the marine economy. Actively promoting the development of the marine economy will help break through the limitations of resources and environment, broaden the space for survival and development, and generate new driving forces for economic growth. Through the land–sea overall strategy, the spatial layout of the industry should be optimized, guided by land–sea overall planning and regional coordination, and the spatial pattern of the development of the coastal areas should be further improved, so as to build a coastal industrial agglomeration belt with strong competitiveness and thus enhance the radiation capacity of the coastal areas in both the sea and the land. At the same time, the strategy of promoting the sea by science and technology should be thoroughly implemented, and research on cutting-edge leading and subversive technologies in the marine industry should be conducted to occupy the commanding heights of marine science and technology innovation. At the same time, we should actively support and rely on sea-related backbone enterprises to promote their construction of technology research and development centers for major marine industries, so as to achieve sustainable innovation and development in the marine industry.

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