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RECEIVED 14 August 2025

ACCEPTED 10 October 2025

PUBLISHED 24 October 2025

CITATION

Mao X, Cui W, Zhong H, Yang Y and Zhu Y
(2025) How does marine technology diffuse
across cities? Evidence from China.
Front. Mar. Sci. 12:1685820.
doi: 10.3389/fmars.2025.1685820

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How does marine technology diffuse across cities? Evidence from China

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Marine science and technology have become a new battleground for global marine competition, and the extent of urban marine technology diffusion determines the quality and speed of marine scientific and technological innovation. This study uses marine patents as an entry point, establishes a marine technology classification system, and characterizes marine technology diffusion through the transfer of marine technology patents. By analyzing the spatio-temporal evolution of marine technology diffusion in Chinese cities from 2001 to 2023, it identifies technological hotspots, core participants, and classifies types of urban transformation in marine technology diffusion activities. It also explores the driving mechanisms of inter-city marine technology diffusion. The study finds that: ① from the perspective of temporal evolution, marine biomedical technology and marine high-end equipment technology continue to lead marine technology diffusion in China's technology trading market, with enterprises maintaining their dominant position. Cross-city flow of marine technology has become the norm, and the role of cities has gradually shifted from self-sufficient intra-city flow to open and innovative inter-city exchange. ② Spatially, marine technology diffusion activities reveal an intra-city "II"-shaped pattern formed by the Coastal Economic Belt, Yangtze River Economic Belt, and Longhai-Lanxin Economic Belt. Inter-city marine technology diffusion has formed a diamond-shaped network with Beijing-Tianjin, the Yangtze River Delta, Pearl River Delta, and Sichuan-Chongqing region as hubs. ③ Regarding driving mechanisms, exogenous and endogenous forces shape China's inter-city marine technology diffusion network. Network self-organization, merit-based linkages, and intermediary effects promote the development of the diffusion network. Under multi-dimensional proximity, China's inter-city marine technology diffusion exhibits complementary synergies and symbiotic development characteristics, forming a strong network correlation mechanism.

KEYWORDS

marine patent, marine technology classification, marine technology diffusion, spatio-temporal pattern, driving mechanism

1 Introduction

Marine science and technology have become the new battlefield of global marine competition, and cities have become the important carriers and frontiers of marine technology, and will play an increasingly important role in global marine development (Liu et al., 2021; Dang et al., 2024). The real significance of scientific and technological achievements innovation does not lie in the innovation itself, but in the diffusion of innovation. As the “gateway” between scientific and technological achievements and industrial needs, the transformation of scientific and technological achievements is the “last kilometer” for transforming scientific and technological innovation into economic strength. Technology diffusion is the core part of commercialization and industrialization of scientific and technological achievements (Sawng et al., 2013), and the extent to which the city’s marine technology diffusion function is played determines the quality and speed of marine science and technology innovation (Zou et al., 2023). Diffusion of marine technology promotes marine technological innovation, and the sharing of urban marine knowledge will be the basic premise for the diffusion of marine technology and the transformation of marine scientific and technological achievements. At present, the imbalance between the allocation of marine scientific and technological resources and the transformation of scientific and technological achievements is very prominent in China, and the linkage of marine technology diffusion across multiple regions and cities has become a key path for realizing the synergistic development of knowledge integration and regional economy.

Technology diffusion refers to the systematic migration process of specific technological capability and knowledge structure, with the dual attributes of spatial dimension of conduction effect and cross-organizational boundary penetration of industrial network, which is essentially a kind of knowledge spillover with subjective intention (Zhu et al., 2024). As early as in the 1960s, technology transfer attracted the attention of scholars (Bean, 1961), and the current research on technology diffusion focuses on the following topics: ① Spatial level technology diffusion. There are significant differences in the dominant mechanisms and influencing factors at different scales, and the existing studies on technology diffusion analyze technology transfer from the perspectives of global, transnational, regional and urban (Hameri, 1996; De Marco et al., 2017). ② Industry and emerging technology diffusion. The diffusion of technology transfer in basic industries such as agriculture, manufacturing, finance, (Corradini et al., 2021; Sneddon et al., 2011) and emerging fields such as green, disruptive, and artificial intelligence is widely concerned by academics (Naanaa and Sellaouti, 2017; Zeng et al., 2020; Wang et al., 2024), while the spatial pattern of marine technology diffusion has rarely been discussed. ③ Multi-body technology diffusion. Enterprises, universities, research institutions, government agencies and other important actors involved in technology diffusion, the existing literature on the research perspective of the impact of technology transfer within the enterprise (Jiang et al., 2022), technology diffusion between enterprises in industrial parks, multi-innovation

between the main body of the industry-university-research technology transfer mode (Fuentelsaz et al., 2009), and so on. ④ Expansion of the content of technology diffusion. There are many forms of characterization of technology diffusion, which are often measured by alternative variables such as patent transactions (Dou et al., 2024), human capital migration (Kim and Geum, 2020), collaborative innovation (Trippel, 2013), cross-border trade and capital flows (Ponds et al., 2010), etc. With the deepening of the research, scholars have mainly explored the process of technology diffusion, the driving factors of technology diffusion and countermeasures of technology diffusion in recent years (Aysun, 2024). ⑤ Innovation of technology diffusion methodology. While case-driven measurement model and system simulation model are the mainstream paradigms in technology diffusion methodology research (Bergek, 2020), in recent years, the research on the evolution of intercity technology network and the spatial and temporal evolution of regional diffusion law under the geospatial dimension has begun to become more frequent (Losacker, 2022), and the comparative research on technology diffusion under the cross-country technology field has begun to take off. Nowadays, cities have become the core strategic carriers of knowledge production and technology diffusion (Liu et al., 2017). The innovation spatial network built on the functional nodes of cities is undergoing a profound evolution, and the regional innovation pattern is rapidly transforming from the traditional “core-edge” pattern to the “hub-network” system (Johnston and Huggins, 2016). The interactive flow of cross-regional and cross-city knowledge elements has become a key breakthrough in innovation network analysis and a key research direction in the field of innovation geography (Cheng et al., 2023). Unfortunately, the research on the construction of intercity marine technology diffusion network focusing on the city dimension is still in the academic field. Meanwhile, the innovation measurement system of marine technology diffusion is mostly centered on thesis cooperation and patent partnership, and although many scholars have explored the embodiment of different technological fields in practical application scenarios (Wang et al., 2025; Xu et al., 2025a), the market-driven technology transfer research oriented to the real transaction scenarios is lacking in both breadth and depth.

The global ocean economy has entered a period of rapid growth, and the OECD expects that the contribution of the ocean economy to the global gross value added will exceed 3 trillion U.S. dollars by 2030, but the unevenness of technology diffusion has led to the fact that most of the services in the field of ocean science and technology, such as the development of land and sea-associated space, seawater desalination and comprehensive utilization of seawater, marine renewable energy, etc., have been concentrated in the developed countries. In recent years, the marine economy has become an important pillar of China’s national economy and a new growth pole, and the diffusion and transformation of marine technology has become an important engine for promoting the development of the blue economy and a core support for the strategy of the sea (Wu et al., 2020). However, the achievements of marine science and technology from the laboratory to practical application need to go through multiple links of technology

transfer, transformation and diffusion, the only way to truly enhance the strength of marine science and technology and help the high-quality development of the marine economy is to synchronize the level of scientific research and innovation and the effectiveness of the results of the transformation to accelerate the process of technology diffusion (Zeng, 2020). As a key branch of technology diffusion research, marine technology diffusion shares significant commonalities with other technological fields (such as green technology, biomedicine, and advanced manufacturing) and general technology diffusion in terms of core processes (such as knowledge codification, the construction of dissemination channels, and spillover effects), key influencing factors (such as the policy environment, market demand, and R&D investment intensity), and ultimate goals (promoting innovation and driving economic growth). However, due to the unique attributes of marine technology, including the fluidity of the ocean, the highly corrosive nature of seawater, the extreme fragility of ecosystems, and its strong dependence on specific testing sites and application scenarios (Atmanand, 2019), research on the diffusion of marine technology is particularly important. In particular, it faces severe technical bottlenecks such as the “bottleneck” of deep-sea technology. Then, how does the current Chinese marine technology diffuse? Which subjects in China’s marine technology diffusion practice are the driving force of marine technology application? Is the diffusion of marine technology in China concentrated in a few key technology areas? Which cities have a better foundation of marine technology diffusion transaction system? To answer these questions, we urgently need to carry out empirical research on the diffusion of marine technology in China.

From the actual diffusion process of China’s marine technology, under the strategic leadership of building a strong marine country and the concerted promotion of the whole society, the contribution rate of China’s marine scientific and technological progress has continued to rise, and the system of marine scientific and technological achievements has been gradually perfected, but in the actual advancement of China’s marine technology is still faced with outstanding problems such as insufficient maturity of the technology, poor synergy mechanism between the industry, academia and research institutes, limited channels for market promotion, and the need to improve the policy guarantee system, which has led to the difficulty of effectively applying some of the advanced technologies in the field (Wang et al., 2025). Technology is difficult to effectively land application. In the face of the Western “decoupling and breaking the chain” and “technology blockade”, this technological gap not only exacerbates the difference between the strength and weakness of the development of marine resources, but also restricts the effectiveness of China’s participation in the implementation of global ocean science and technology governance. The premise of participating in global ocean governance is to clarify itself, along with the implementation of the national innovation strategy, the research paradigm in the field of geography focusing on the knowledge migration network, transformation of scientific and technological achievements, and the spatial diffusion of innovation is maturing, but the theoretical construction of the “diffusion of marine science and technology innovation to

support the development of the oceans” is still in a preliminary stage of exploration in the academic community. However, academic research on the theoretical construction of “marine technology innovation diffusion to support marine development” is still in the preliminary stage of exploration, while the research on the diffusion mechanism of marine technology at the geospatial level is still missing. The research, development, and application of marine science patents require the coordinated deployment of multiple processes, promoting innovation in multiple cross-cutting marine technology fields, such as green energy (Sun et al., 2024), port construction (Xu et al., 2025b), shipping optimization (Xu and Chen, 2025), and carbon emission reduction benefits (Xu et al., 2025c). Furthermore, the diffusion and integration of technologies in multiple fields also provides new perspectives for the further development of marine environmental benefits.

Marine science and technology patents are the core carriers of marine innovation diffusion literature (Arnaud-Haond et al., 2011; Wu et al., 2023), and play a key role in promoting economic growth and environmentally sustainable development (Nguyen and Doytch, 2022; Zhou et al., 2023). In view of this, this study takes marine patents as an entry point, establishes a marine technology classification system, and portrays the diffusion of marine technology through the transfer of marine technology patents. By analyzing the spatial and temporal evolution of marine technology diffusion in Chinese cities from 2001 to 2023, the study identifies the technological hotspots, core participants, and types of urban transformations in the diffusion of marine technology in Chinese cities, and discusses in depth the mechanism that drives the diffusion of marine technology between cities. The study not only focuses on expanding the theoretical dimension of “ocean science” and innovation geography, but also aims to provide fundamental support for China to build a marine technology innovation system for the global market.

2 Data and methods

2.1 Acquisition and classification of marine technology patent data

Patent is one of the main output forms of innovation activities, an important indicator of a region’s technological innovation capacity, and the most economically valuable part of regional science and technology assets. Patent transfer, as a characterization tool of regional innovation synergy, not only maps the trajectory of inter-city knowledge synergy network and factor flow, but also constitutes the core conduit of spatial transmission, gradient diffusion and value migration of technological knowledge. (Maggioni et al., 2014) When studying the diffusion of marine technology in Chinese cities, we first classify marine technology specifically, then select the number of marine patents as the evaluation index, and use the Wanfang Data Knowledge Service Platform (<https://www.wanfangdata.com.cn/index.html>), Incopat Global Patent Database (<https://www.incopat.com/>), Qingdao Ocean Industry Patent Database

(<https://www.qingdaoip.cn/>), and Petroleum and Chemical Industry Science and Technology Big Data Wisdom Service Platform (<http://petrochemical.areaip.cn/>) as the data sources, to obtain and construct the 2001–2023 Chinese city The spatio-temporal database of marine patents in China from 2001 to 2023 is acquired and constructed. The specific construction strategy is as follows: ① Multi-source data integration: compare the differences of the five databases, respectively, from the five patent libraries to obtain the details of China's invention patent application and invention authorization data from 2001–2023, a total of 4,338,3522; ② Classification system construction: since there is no specific classification basis for marine technology, this paper draws on the national classification standard for the marine industry and the classification standard for the strategic emerging industries to classify marine technology into 12 items, and based on the classification standard for the strategic emerging industries, it will be classified into 12 items. Marine technology is categorized into 12 items, and according to the keyword search strategy, the corresponding table based on specific word algae is constructed, and the keywords of marine technology are extracted from the existing research, text policy and planning respectively, and Table 1 shows the final keyword-based search of marine technology patents. Under this search strategy, a total of 695,694 Chinese marine invention patents were obtained from 2001 to 2023; ③ All-counts statistics: due to the cross-cutting characteristics of the patent technology fields, an inclusive statistical strategy was adopted to allow the patents to be attributed across technology categories (e.g., there is a cross-cutting relationship between the marine high-end equipment technology and the marine ship technology); ④ Geo-coding: based on the address of the marine patent applicant, the 695,694 marine patents are assigned to the city scale (including prefecture-level cities, autonomous regions, etc., excluding Hong Kong, Macao and Taiwan), and finally form a spatio-temporal database of marine patents in Chinese cities from 2001 to 2023. (Table 1).

This classification system draws on the “National Marine Industry Classification Standard (GB/T 20794)” and the “Strategic Emerging Industries Classification and International Patent Classification Reference Relationship Table (2021) (Trial)”, categorizing marine technologies into 12 classes. Compared with the general International Patent Classification (IPC) system, this classification demonstrates significant advantages and applicability in analyzing marine technology diffusion under China's context. First, this classification system is not based solely on technical functions but is constructed around the strategic priorities and industrial planning of China's marine economic development. Its categories directly correspond to policy language and industrial sectors, enabling research conclusions to provide more direct references for policy formulation and industrial analysis. Second, while the IPC classification aims to achieve global technology retrieval with subcategories typically covering broad generic technologies, the 12 marine technology categories integrated in this study include multiple relevant IPC codes, forming more industry-relevant “technology clusters”. This approach effectively captures comprehensive and systematic technological innovations

in China's marine sector, avoiding potential fragmentation of technology chains caused by the IPC system. To obtain more comprehensive and accurate marine technology patent data, we implemented the following measures: ① Conducted multiple rounds of data screening to continuously optimize the keyword database; ② Conducted manual verification of random samples and adjusted strategies accordingly; ③ Employed broad IPC codes as the foundation to ensure coverage. Additionally, while the hybrid search method combining IPC codes and keywords may introduce some subjectivity and might result in an incomplete marine technology data set, we believe it has effectively captured the core components of most marine technology patent clusters.

2.2 Marine technology diffusion data acquisition and processing

This study follows the standardized method of technology diffusion measurement of the World Intellectual Property Organization (WIPO), and uses marine patent transfer data to characterize the process of technology diffusion. Specific implementation paths: ① Drawing on China's urban marine technology classification framework, retrieve the detailed data of China's marine technology patent transfers from 2001 to 2023 through the Patent Information Service Platform of Intellectual Property Publishing House (<http://search.cnipr.com/>), totaling 57,977; ② analyze the city location of the transferor and transferee based on the information of patent legal status change, excluding Hong Kong, Macao and Taiwan cross-border transfers and addresses. Excluding Hong Kong, Macao and Taiwan cross-border circulation and missing address data, we finally obtained 48,701 pieces of patent transfer data with valid geographic codes. Among them ③ carries out automated cleaning and preliminary localization. For the patent transfers involving cross-border marine technology, we exclude them, and for the records containing only the name of the province/city, we preliminarily locate to the coordinate identification of the province/city and mark the obvious missing information. ④ city-level localization and manual verification. For records whose address information contains at least a valid city name, use the Geode map geocoding API to batch parse and obtain the coordinates of its city-level administrative center. For patent addresses that cannot be recognized, enter the manual verification process. ⑤ Manual verification and correction. Using the name of the “transferor/transferee” unit in the patent, query the registered address or main business premises address of the unit through “TianYanCha” to supplement or check other information of the patent itself (such as the contact person's address and zip code), and other relevant patent address information of the same applicant for corroboration. The data processing results show that the amount of marine technology patent transfers shows an upward and downward trend (with the highest in 2021, accounting for 10.7% of the total transfers). External factors such as standardization of national policies, upgrading of patent management system, and enhancement of standardization awareness of market players, as well as the

TABLE 1 Marine technology patent identification using a keyword search-based classification system.

Marine technology	Technology description	Data keyword search strategy	Coverage of international IPC main classification number
Marine Fishery Technology	Marine aquaculture, marine fishing, seafood processing and other related technologies	More than 200 species of marine fish, 50 species of crustaceans, 100 species of mollusks, and 20 species of marine plants published on the website of the Fisheries and Aquaculture Department of the Food and Agriculture Organization of the United Nations and the China Fisheries Statistical Yearbook 2022	A61K36, A23L1, A61K31, C12N15, C07K14, A23L3, C02F1, A23B4, A61K35, A61K39, A01K61, A23L33, A61K38, A23L7, A01K61, etc.
Marine Ship Technology	Shipbuilding, ship supporting equipment manufacturing and other related technologies	China Association of the Shipbuilding Industry statistics related to ship research (Zou et al., 2025)	B63B35, B63B3, B63B21, B60N2, B63H25, B63B23, C02F1, B63B 21, B63H1, B63B1, B63C9, F16J15, B63H21, B63B27, B63H23, etc.
Marine Biomedical Technology	Marine drug manufacturing, marine functional food manufacturing, Marine Biological Products Manufacturing and Other Related Technologies	Jiao Binghua's Modern Marine Pharmacology and Marine drugs listed on the National Ocean Foundation's Marine Biotechnology website	A61K36, A61K31, A61K8, A61K38, C07K14, A61K35, A01K61, A61K47, A61K9, A23L33, C12N15, A61K39, A61L27, A61F2, C07K16, etc.
Marine Chemical Technologies	Sea salt chemical, marine petrochemical, seaweed chemical and other related technologies	Petroleum and chemical industry science and technology big data wisdom service platform under the National Petroleum and Chemical Intellectual Property Network (NPCIPN)	C08J9, C09K8, B01J27, C08F220, B32B27, B01D53, D01F6, C08J3, D06M15, C08G18, etc.
Marine Renewable Energy Technology	Ocean wind power generation, ocean energy power generation, Other marine energy power generation and other related technologies	Offshore wind power, wave energy, tidal energy, tidal energy, temperature difference energy, salt difference energy, offshore photovoltaic energy (Borthwick, 2016)	F03D9, C02F1, A01K61, B63B35, F16F15, G06F16, G06F18, G06F30, B63B21, F03B13, E02B3, G01N21, G06F17, B66C1, B66C23, etc.
Marine Oil and Gas Technology	Marine oil and natural gas exploitation and other related technologies	Petroleum and chemical industry science and technology big data wisdom service platform under the National Petroleum and Chemical Intellectual Property Network.	C09K8, E21B43, B01D53, E21B47, C02F1, E21B33, C01B3, F16L55, G01N3, B01J23, G01F1, B23K9, E21B17, G01N21, G06Q10, etc
Marine Mineral Technology	Extraction of mineral resources in the coastal zone, Seabed Mineral Resources Extraction and Other Related Technologies	Research on the Status and Prospect of Core Technologies for Mineral Resources Development (Kaikkonen et al., 2018; Du et al., 2024)	E21B43, E21B47, C09K8, E21B33, E21B19, E21B17, E21B7, E21B10, E02D5, E21B21, E21B34, E21B1, E21B25, E21B31, E21B23, etc
Comprehensive Utilization of Seawater Technology	Seawater salt processing, seawater utilization and other related technologies	National Seawater Utilization Report 2023 and China Seawater Utilization Industry Development Research and Trend Forecast Report, 2024-2030	C02F1, B01D53, A01K61, B01D71, C25B11, B08B9, B01D61, B01J20, C25B9, F03B13, A61K8, B01D29, C01F5, C02F3, C01B32, etc.
Marine Ecology Technology	Marine environment testing, marine pollution control, Marine ecological restoration and remediation and other related technologies	Technical Guidelines for Marine Ecological Restoration issued by the Ministry of Natural Resources, Marine Ecological Environmental Protection Plan of the 14th Five-Year Plan, and research on marine ecological technology (Tian et al., 2021)	G01N21, C12Q1, G01N33, G01N27, C02F1, C12N15, G01R31, B01J23, B01D53, B01D71, B01D29, G01N3, A01K61, B01D33, B01J27, etc.
Marine Electronic Information Technology	Marine information collection, marine communication transmission, Marine information sharing and other related technologies	Research on the progress of marine information technology (Xu et al., 2018; You et al., 2020)	H04L12, G06F16, H04B10, H04B1, H01L21, H04N21, G01S19, H04M1, G01N21, H04M3, H04W72, H04B7, H04N5, H04L41, H04L67, etc.
Marine High-end Equipment Manufacturing Technology	Marine engineering equipment manufacturing, deep-sea oil drilling equipment manufacturing, marine environment monitoring and detection equipment manufacturing, and other related technologies.	Classification standards related to "Classification of Strategic Emerging Industries (2018)", "China Marine Emerging Industries Index Report 2021", and research related to marine high-end equipment manufacturing technology (Huang and Zheng, 2020)	G01S19, E21B43, E21B47, B63B21, B63B35, B66C23, B23K26, E21B33, B23K9, B66D1, B63G8, B66C1, B63C9, C09K8, G01B11, etc.

(Continued)

TABLE 1 Continued

Marine technology	Technology description	Data keyword search strategy	Coverage of international IPC main classification number
Marine Material Technology	Marine steel, marine non-ferrous metals, protective materials, concrete, composite materials and functional materials and other related technologies.	China Marine New Materials Market Research Report, Classification of Strategic Emerging Industries (2018), and China Marine Emerging Industries Index Report 2021.	A61K8、G01N21、B01J23、C04B35、G01N3、E04B1、C22C38、B01J20、C01B32、C23C22、A61L27、B01D71、H01R13、C08G18、C08G59, etc.

improvement of data sources and processing methods, have led to a steady increase in the proportion of valid geocoding data of marine technology patents with clear addresses, from about 20% in 2001 to about 90% in 2023., and the obvious improvement in the quality of the data has revealed that a more mature patent layout network has been formed in the field of marine technology, which provides a good basis for the development of the marine technology transaction market. The development of marine technology transaction market provides fundamental support. (Figure 1).

2.3 Classification of marine technology diffusion in cities

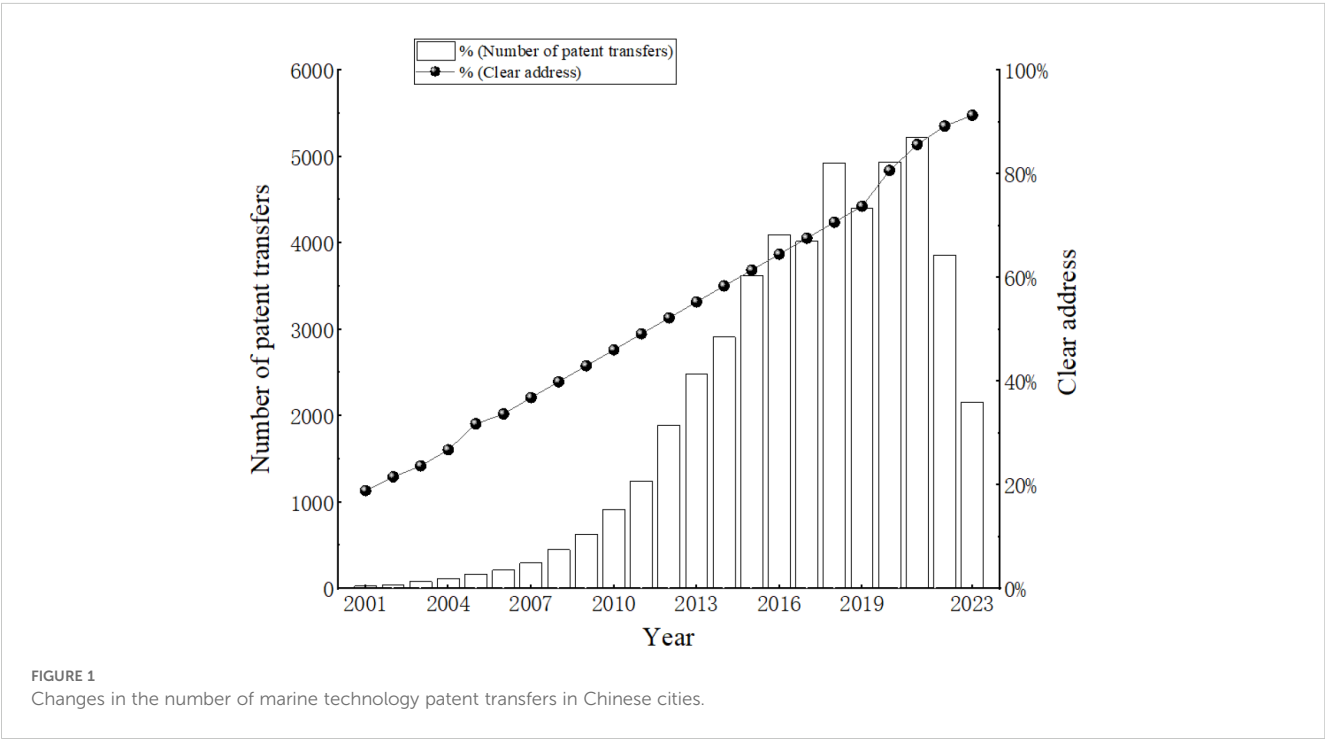
By comparing the difference in the scale of marine technology patent transfers between intra-city and inter-city, the type of urban marine technology diffusion can be classified into 2 modes, the single-dimension type and the multi-dimension type (Table 2): ① The single-dimension type, the technology diffusion activities are strictly limited to within the city’s administrative boundaries, or

there exists only a single external outward marketing or outward source, and according to the degree of its activity, it can be classified into the totally self-sufficient type, the completely exported type, and the completely externally-sourced type. ② Multi-dimensional type, that is, the process of intercity marine technology diffusion is significantly manifested in the form of cross-city spatial conduction, and there are both diffusion and acquisition phenomena, according to the current status of intercity marine technology diffusion, intercity diffusion can be categorized as export-led, exogenous-led, and exported-exogenous type.

2.4 Driving factors of intercity marine technology diffusion

2.4.1 Theoretical modeling

Whether technology flows occur within cities or across cities, the core carrier on which the evolution process relies is still the enterprise, so the driving mechanism of the two types of technology flows is homologous. However, given that the focus of the study is to



reveal the diffusion characteristics of Chinese marine technology at the city scale, this paper focuses on the driving factors and mechanisms of inter-city marine technology flows (Figure 2).

- a. Intracity marine technology flow and intercity marine technology diffusion.
- b. Analysis of driving factors of intercity marine technology diffusion.
- c. Analysis of important subjects of intercity marine technology diffusion.

Inter-city marine technology diffusion reflects the spatial gradient transfer law of regional innovation factors, aiming to reveal the knowledge spillover effect and institutional barriers of different cities in the synergistic development of blue economy. The growth pole theory, the knowledge potential theory and the absorptive capacity theory are good analogies of knowledge as physical potential (Thomas, 1975), and there exists a knowledge potential difference between multiple subjects due to the differences in knowledge reserves and innovation ability. This potential difference is like a natural force that drives the knowledge transfer from high potential subjects to low potential subjects, as well as the effectiveness of external knowledge acquisition among multiple subjects. In terms of intercity marine technology diffusion, the higher the potential of marine technology innovation in a city, the more it represents the leading level of marine technology knowledge reserve and the number of marine technology possession, indicating that its marine technology absorption and

outward diffusion effectiveness is more significant. The technology gap theory also confirms that the technology gap between subjects constitutes the driving factor of technology transfer and diffusion, and the research on technology diffusion shows that technological heterogeneity is the basis for the transfer of different technologies from innovators to recipients, and that if there is no heterogeneity between the technology innovators and recipients, the technology loses the significance of diffusion (Wang and Seidle, 2017). The innovation space theory and the innovation ecosystem theory believe that innovation is a complex ecosystem, which is composed of a variety of subjects such as enterprises, colleges and universities, scientific research institutions, governments, financial institutions and so on interacting with each other and being interdependent (Rutten and Boekema, 2007). Correspondingly, the synergistic effect of innovation is formed between the subjects through knowledge flow, technology transfer and talent exchange. In the diffusion of urban marine technology, there will certainly be a diffusion pattern of mutual interaction between multiple subjects, such as enterprises are often in a dominant position in the process of marine technology diffusion, with which there will be more interacting multi-level subjects; universities and research institutes are also continuing to promote the transformation of marine technology results, and the interaction between the industry, academia and research institutes has also been a hot topic in recent years; and individuals in the diffusion of marine technology also play an indispensable role, and so on.

Multidimensional proximity is not only a factor that affects technology diffusion, but also plays different functions in the process of technology diffusion and constitutes a channel of technology diffusion (Guo et al., 2021). The theoretical framework of multidimensional proximity reveals that geographic, cognitive, institutional, cultural and organizational proximity will form a synergistic driving mechanism for technology diffusion across hierarchical levels by lowering the cost of knowledge transfer and enhancing the mutual trust of the subjects. Cognitive proximity, technological relevance and technological gap between cities can characterize the technological potential difference between the diffusion subject and the receptor, which serves as a threshold condition for the occurrence of transmission and regulates the transmission efficiency of technology diffusion. At the same time, geographical, institutional and economic proximity plays the role of “medium” in the diffusion channel of technological innovation. Without the synergistic intermediary effect of geography, system and economic proximity, it is difficult to build an effective conduction channel between the subject and the receptor of technology diffusion, resulting in the spatial discrete characteristics of the innovation source and the potential receptor, and a significant weakening of the conduction efficiency of technology diffusion.

2.4.2 Modeling

This study applies the multidimensional proximity theoretical framework to construct a multidimensional index system of urban proximity to analyze the driving factors of intercity marine technology diffusion. Given that the model contains time-

TABLE 2 Types classification of city marine technology diffusion.

Mode	Classification	Description of diffusion
Single Dimension	Completely self-sufficient	Only intra-city flow of marine technology
	Completely export-oriented	Only transfer of marine technology to other cities
	Completely exogenous	Only acquisition of marine technology from other cities
Multi Dimension	Export-oriented	Diffusion of marine technology to other cities and acquisition of marine technology from other cities at the same time, but acquisition of marine technology from other cities is dominant
	Exogenous-led	Diffusion of marine technology to other cities and acquisition of marine technology from other cities at the same time, but mainly from other cities
	Multiple Integration Type	Diffusion of marine technology to other cities and acquisition of marine technology from other cities at the same time, and the proportion of the two is basically equal.

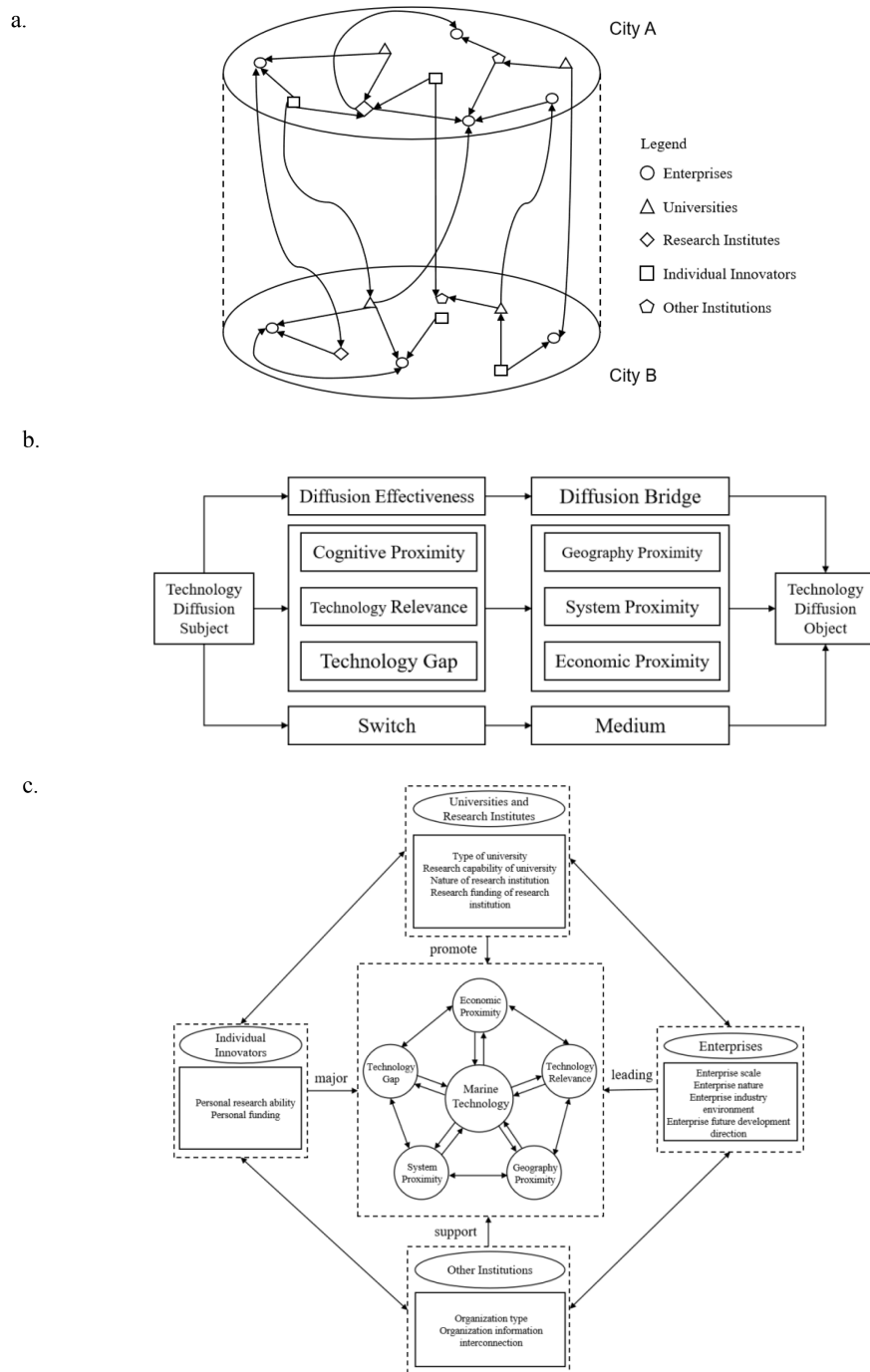


FIGURE 2

Analysis framework of city marine technology diffusion. (a) Intracity marine technology flow and intercity marine technology diffusion. (b) Analysis of driving factors of intercity marine technology diffusion. (c) Analysis of important subjects of intercity marine technology diffusion.

invariant variables such as geographical proximity, fixed effects models cannot effectively estimate coefficients for these variables. Therefore, this study employs mixed negative binomial regression for data from three periods (2001-2008, 2009-2016, 2017-2023). This method allows us to examine the temporal evolution of neighboring factors' influence while obtaining estimated coefficients for all variables. The method of measuring it is shown in Equation 1 and the specific models are as follows (Table 3).

$$\begin{aligned}
 OD_{i \rightarrow j, t}^{city} = & \alpha + \chi_1 Oce_Pat_Apli_{i, t} + \chi_2 Oce_Pat_Apli_{j, t} \\
 & + \chi_3 Tech_Gap_{i, j}^t + \chi_4 Geo_Prox_{i, j} + \chi_5 Eco_Prox_{i, j}^t \\
 & + \chi_6 Inst_Prox_{i, j}^t + \chi_7 Cog_Prox_{i, j}^t + \delta_{i, j}^t \quad (1)
 \end{aligned}$$

where: α is the constant term; χ is the coefficient; $\delta_{i, j}^t$ is the random error term; $Inst_Prox_{i, j}^t$ is the institutional proximity of city i and city j at time t . Referring to the previous research, the

TABLE 3 Definitions and interpretations of variables.

Name of variables		Symbol	Indicator interpretation
Interpreted variable	Diffusion of marine technology	$OD_{i \rightarrow j,t}^{city}$	Amount of marine technology diffused from city i to city j at time t
Explanatory variables	Patents on marine technology	$Oce_Pat_Appli_{i,t}$	Number of marine patent applications in city i at time t
	Number of applications	$Oce_Pat_Appli_{j,t}$	Number of marine patent applications for city j at time t
	Marine Technology Gap	$Tech_Gap_{ij}^t$	Measured as the absolute value of the difference between the number of marine patent applications in two cities at time t.
	Geographical Proximity	Geo_Prox_{ij}	Measured by straight-line geographic distance in latitude and longitude.
	Economic Proximity	$Eco_Prox_{ij}^t$	Ratio of GDP of city i and city j at time t (high GDP city/low GDP city)
	Institutional Proximity	$Inst_Prox_{ij}^t$	$Inst_Prox_{ij}^t = \left[\sum_{n=1}^8 I_{int} I_{jnt} / \left(\sum_{n=1}^8 I_{int}^2 I_{jnt}^2 \right) \right] \times (I_{it} I_{jt} / 2)$
	Cognitive proximity	$Cog_Prox_{ij}^t$	$Cog_Prox_{ij}^t = \frac{\sum_{k=1}^k [(Pat_{i,k} - \overline{Pat_i})(Pat_{j,k} - \overline{Pat_j})]}{\sqrt{\sum_{k=1}^k (Pat_{i,k} - \overline{Pat_i})^2 (Pat_{j,k} - \overline{Pat_j})^2}}$

average level of innovation and entrepreneurship in cities is measured by index, and the similarity of innovation and entrepreneurship structure between cities is calculated, and finally the similarity coefficient is multiplied by the average of innovation and entrepreneurship water to get the institutional proximity of the cities, and the method of measuring it is shown in Equation 2; where: $Cog_Prox_{ij}^t$ is the Cognitive proximity is measured by the marine technology relevance of city i and city j at time t, while the measure of marine technology relevance between cities is borrowed from the industry relevance measure, and the formula is shown in Equation 3.

$$Inst_Prox_{ij}^t = \left[\sum_{n=1}^8 I_{int} I_{jnt} / \left(\sum_{n=1}^8 I_{int}^2 I_{jnt}^2 \right) \right] \times (I_{it} I_{jt} / 2) \quad (2)$$

where: $Inst_Prox_{ij}^t$ is the institutional proximity of city i and city j, I_{int} is the index value of the nth sub-component of city i in year t; I_{jnt} is the index value of the nth sub-component of city j in year t; I_{it} and I_{jt} are the innovation and entrepreneurship indexes of city i and city j in year t, respectively.

$$Cog_Prox_{ij}^t = \frac{\sum_{k=1}^k [(Pat_{i,k} - \overline{Pat_i})(Pat_{j,k} - \overline{Pat_j})]}{\sqrt{\sum_{k=1}^k (Pat_{i,k} - \overline{Pat_i})^2 (Pat_{j,k} - \overline{Pat_j})^2}} \quad (3)$$

where: $Cog_Prox_{ij}^t$ is the relevance of marine technology innovation in city i and city j; $Pat_{i,k}$ is the proportion of applications for k types of marine patents to the total number of applications in city i; $\overline{Pat_i}$ is the mean value of $Pat_{i,k}$; k is the number of types of marine technology patents.

In view of the availability and completeness of the data, some cities with serious missing data of the measurement indicators were excluded such as Sansha City and Dongfang City in Hainan, and some autonomous prefectures in Xinjiang and Tibet, etc., and finally 303 cities above prefecture level were retained. The marine technology patent data and cognitive proximity data come from the statistics of the author's team mentioned above; the economic proximity data come from the Statistical Yearbook of Chinese Cities; the institutional proximity data come from the Regional Innovation and Entrepreneurship Index of China (IRIEC) compiled by Peking University's Big Data Research Center for Enterprises, in which the data of the index for the period of 2021–2023 are filled in according to the trend method; whereas the data of the individual indexes are missing, the interpolation method is used to complete the data. The interpolation method was used to complete them.

3 Time-series dynamics of marine technology diffusion in China

3.1 Marine biomedical technology maintains leadership, high-end manufacturing and emerging marine ecology and materials technology rapidly rises

From 2001 to 2023, China's marine technology trading market will still maintain a leading position in marine biomedical technology, while high-end manufacturing and emerging marine ecology and materials technologies will rise rapidly. Specifically:

Biomedical technology dominates the proliferation of marine technology in China from 2001 to 2023, and the number of patent applications and transfers in this field remain leading. According to the Marine Technology Patent Identification System, a total of 10,682 marine biomedical technologies is involved in technology diffusion from 2001 to 2023, and the peak is reached in 2021 with a total of 1,051 entries.

High-end manufacturing and emerging marine ecological and material technologies have been developing rapidly, and from 2010 to the present, marine biomedical technology, marine high-end equipment manufacturing technology, marine new material technology and marine ecological technology have become the top four in China's marine technology transaction market. And in 2018, the patent diffusion scale of marine high-end equipment manufacturing technology surpassed marine biomedicine technology for the first time, thus forming a persistent marine technology market transaction pattern characterized by the fact that marine biomedicine technology and marine high-end equipment manufacturing technology have become the core technology hotspots of China's marine technology diffusion (with an average annual market share of 24.4% and 16.6%, respectively) and, based on their stable growth trend, have become the two key technologies dominating China's marine technology diffusion process.

With population growth, aging and changes in the disease spectrum, the demand for new types of drugs is increasing. Marine biopharmaceutical technology has unique advantages in anti-tumor, anti-virus and anti-cardiovascular diseases, etc., which can provide new treatment options and sources of drugs to meet the market demand for highly efficient and low-toxicity drugs. Meanwhile, 69.4% of the orders in the global offshore market in marine high-end equipment manufacturing technology are undertaken by China. This market-driven industrial demand has prompted the technology in this field to quickly realize technological realization through patent diffusion, while forcing technological innovation to maintain competitive advantages, and the technical standards and norms in this field are relatively mature, which also facilitates the transfer of technology.

3.2 Enterprises are not only the main exporters of marine technology, but also the main absorbers

According to the categories of innovation subjects and the characteristics of the change of equity subjects in the process of technology transfer, the participating subjects in China's marine technology diffusion network can be divided into four main types: enterprises, higher education institutions and research institutes, individual innovators and other institutions (including institutions, government departments and other social organizations). The data show that the structure of China's marine technology trading market presents three main features: ① enterprises dominate at both ends: the supply side of marine technology contributes about 60% of the technology output, and the demand side absorbs about 90% of the technology trading volume; ② individual innovators are

prominent: the proportion of individual technology output is always greater than 20% during the period of 2001-2023, and it reached 41.16% during the period of 2001-2007; ③ the roles of institutions are differentiated: Universities and research institutes maintain a stable technology output of 20%, while the participation of other institutions in the whole chain of technology flow is lower than the significant level of participating subjects.

From the point of view of diffusion subjects, enterprises, as the main force of technological innovation, play a dual role in technology diffusion. First, through their own technology R&D and innovation, enterprises internally digest and apply part of the marine technology, thus dissipating part of the marine technology to a certain extent. Secondly, enterprises take the initiative to obtain marine technology resources from the outside, extensively absorbing marine technology transferred from universities, research institutes and individuals, so as to enhance their own technical strength and competitiveness (Table 4). This combination of internal and external development mode has enabled enterprises to continuously explore and forge ahead in the field of marine technology, and at the same time has promoted the development of the entire marine technology trading market.

3.3 Transformation of cities from "islands" to "openness", and the flow of marine technology across cities has become a new trend

In the process of development, traditional cities were once in an "island" state. From the perspective of specific data, from 2001 to 2008, China's urban marine technology patents were dominated by intra-city transfer, and the ratio of intra-city technology transfer basically stabilized at more than 70%, of which the proportion of intra-city transfer in 2002 was as high as 80.4%. The administrative regulation system constructed by the local protectionism policy in the early period has led to the spatial transmission of marine technology presenting the characteristics of "closed" technology flow. As the level of openness of the city increases and inter-regional ties increase, the administrative barriers and regional blockades of patent transfer are gradually broken. The unified technology trade market environment creates a favorable policy and cooperation atmosphere for the cross-city flow of marine technology, and ensures the free flow of technological innovation factors. The proportion of China's cross-city flow of marine technology from 2001 to 2023 increased rapidly from the lowest of 19.2% to the highest of 62.3%, especially since 2018, the proportion of inter-city transfer of marine technology exceeded the proportion of intra-city transfer for the first time, and the proportion of intra-city technology transfer will increase in the long term. transfer proportion, and will also show that trend for a long time in the future.

According to the temporal evolution characteristics of marine technology patent transfer, China's marine technology diffusion can be divided into three evolutionary stages: the initial development stage (2001-2008, the total number of patent transfers was 1,388), the accelerated diffusion stage (2009-2016, the transfer scale jumped

TABLE 4 Participation of chinese marine technology enterprises in diffusion analysis.

Stage	Type of participating entities	Output	Absorption by enterprises	Percentage of absorption
2001-2008	Universities/Research Institutions	333	301	90.3%
	Individuals	570	444	77.9%
2009-2016	Universities/Research Institutions	4745	4147	87.4%
	Individuals	5162	4405	85.3%
2017-2023	Universities/Research Institutions	7371	6374	86.5%
	Individuals	8457	7557	89.4%

to 17,789) and the stable growth stage (2017-2023, the total number of transfers reached 29,524). By analyzing the intra-city patent transfer volume and inter-city technology diffusion volume of each marine technology field at different stages, it is found that the 12 types of marine technologies show significant accelerated technology diffusion phenomenon in the three periods, and the inter-city diffusion volume is catching up with or even surpassing the intra-city transfer volume in the evolutionary process. This suggests that InterCitys are actively seeking complementarity of innovation resources, optimizing the allocation of resources and improving the efficiency and quality of innovation through the sharing of patented technologies.

4 Spatial pattern of marine technology diffusion in China

4.1 Intra-city mobility: coastal economic belt - yangtze river economic belt - Longhai-Lanxin economic belt building a "II" pattern

According to China's marine technology transfer data, during the study period (2001-2023), the intra-city flow of China's marine technology patents presents a "II"-shaped structure consisting of three major economic axes: the East Coast Economic Belt (covering coastal cities from the Bohai Sea to the South China Sea), the Yangtze River Economic Belt (with the Yangtze River Delta, the middle reaches of the Yangtze River, and the Chengdu-Chongqing urban agglomeration as the core), the Longhai-Lanxin Economic Belt, and the Longhai-Lanxin Economic Belt. The Longhai-Lanxin Economic Belt (with the Central Plains and Guanzhong City Cluster as the main body), and China's "two horizontal and three vertical" strategic layout of cities and towns with the formation of significant spatial coupling. (Figure 3).

During the period 2001-2008, 1,002 marine technology patent transfers occurred within 101 cities in China, accounting for 72.2% of the total transfers in that period. Although mainly concentrated in coastal cities, cities in the central and western parts of the country have also begun to participate in marine technology flows. Twenty of these cities had more than 10 intra-city marine technology patent transfers, with Beijing (165), Shanghai (110) and Tianjin (63) ranking in the top three. intra-city patent transfers surged to

10,317 during the 2009–2016 period, but their share of total transfers in that period declined to 57.9%. Although the number of cities with intra-city marine technology transfer activities has expanded to 219, only 25 cities have a transfer volume exceeding 100 pieces, of which Beijing (1,720 pieces) and Shanghai (837 pieces) form a significant leading edge, and the volume of intra-city marine technology patent transfers in other cities in the Coastal Economic Belt and the Yangtze River Economic Belt is also growing rapidly, such as Guangzhou (442 pieces), Qingdao (433 pieces), Wuhan (421 pieces), etc.), etc. By 2017-2023, the scale of intra-city patent transfer reaches 12,870 pieces, and the proportion continues to decline to 43.6%, and in the pattern of technology transfer, the volume of inter-city patent transfer realizes for the first time that it exceeds the volume of intra-city transfer. It is worth noting that, in addition to the overall growth shown by the cities in the coastal economic belt, the patent flow of the pivotal cities in the Yangtze River Economic Belt and the Longhai-Lanxin Economic Belt has also significantly accelerated. Specifically, Wuhan (418 cases), Chongqing (249 cases), Chengdu (226 cases), Xi'an (280 cases), Baoji (152 cases) and other inland cities occupy the 8th, 13th, 15th, 11th and 20th rankings respectively.

4.2 Intercity diffusion: shifting from a triangular pattern to a solid rhombic pattern via a "Φ" pattern

From 2001 to 2023, as the scale of participating cities in the intercity marine technology diffusion network continues to expand and the number of marine technology patents grows, China's intercity marine technology diffusion network has evolved from a triangular structure to a "Φ" pattern, and eventually to a diamond-shaped structure. Some core cities in the coastal economic belt and the Yangtze River Economic Belt have become the core nodes of China's intercity marine technology diffusion network by relying on the technology agglomeration effect and strengthening the technology transfer function (Figure 4).

1. The supply-demand effect of intercity marine technology diffusion in Chinese cities has been increasing. from 2001 to 2023, the coverage of the intercity marine technology diffusion network has expanded significantly, with the total number of participating cities increasing from 82 in the first stage to 358

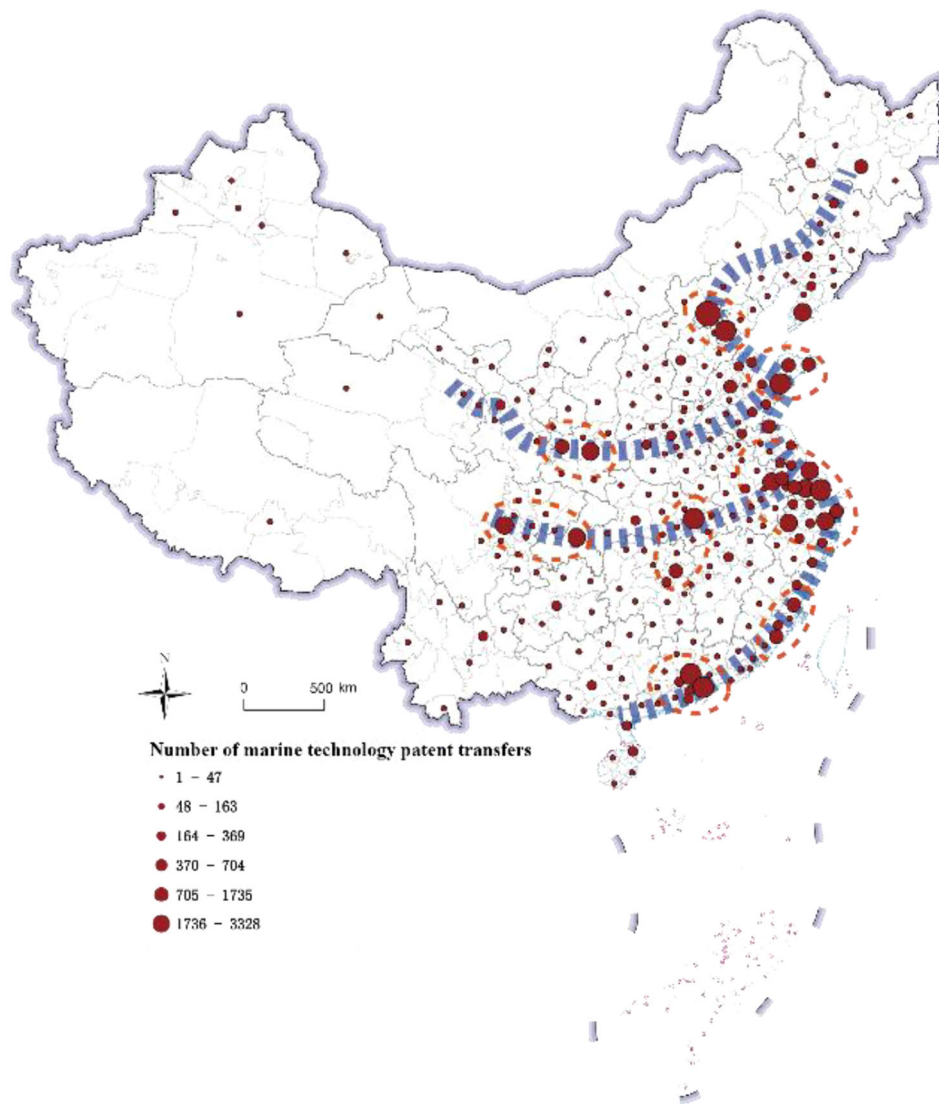


FIGURE 3

Spatial evolution characteristics of China's intra-city marine technology transfer across three phases (2001–2023). This map is based on the standard map of the Map Technical Review Center of the Ministry of Natural Resources (Review No. GS (2023) 2763), and the base map is unaltered, the same below.

in the third stage. Specifically, the cities with technology supply capacity have the most prominent increase, from 48 at the initial stage to 320 at the end; the growth of cities on the demand side of the technology shows a gradual advancement, with the 82 participating cities at the initial stage breaking through to 278 at the second stage, and eventually expanding to 330. It can be seen that, along with the enhancement of the strategic position of the marine economy, more and more cities in China are gradually participating in the supply and demand system of marine technology.

2. The spatial agglomeration effect of intercity diffusion of China's marine technology continues to deepen. 2001–2008, the technology transfer network had a triangular structure, and of the 189 pairs of intercity technology flows, 90 pairs involved

only single-patent transfers, with only 4.8% of the transfers exceeding 5 pairs, and the largest technology outflows were between Beijing and Shanghai. 2009–2016, the network structure evolved into the following. The network structure in 2009–2016 evolved into a “Φ” system, which was built by Beijing-Tianjin, Yangtze River Delta, Pearl River Delta, Sichuan-Chongqing and other important node cities such as Harbin, Hainan and Wuhan, respectively. Among the 2,319 pairs of technology flows in this stage, the proportion of single transfers dropped to 35.3%, while the proportion of transfers of more than five pieces increased to 16.1%. At this stage, marine technology flows frequently between Beijing and Tianjin, the Yangtze River Delta, the Pearl River Delta, the Sichuan and Chongqing regions, and core cities such as

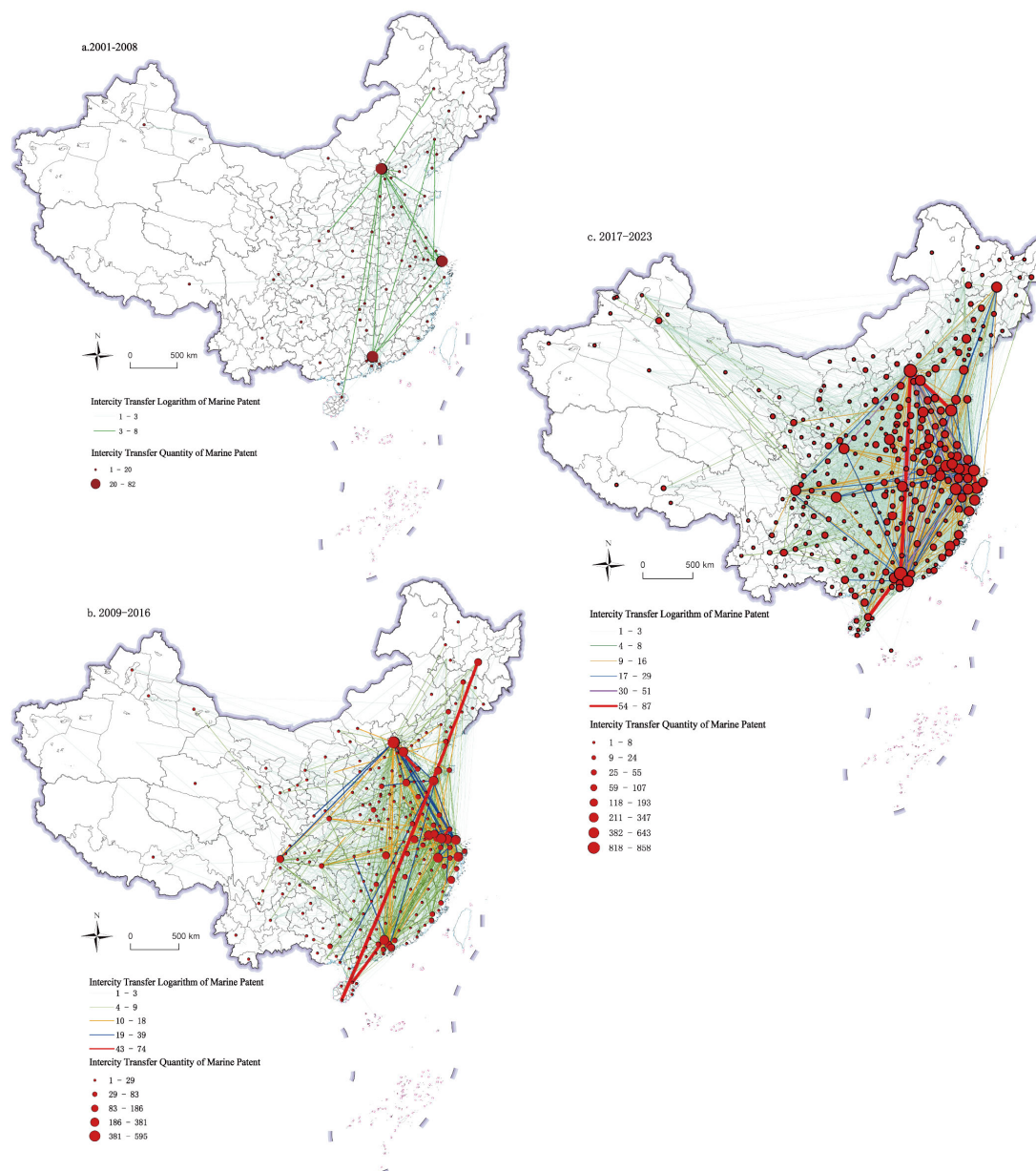


FIGURE 4

Spatial evolution characteristics of China's inter-city marine technology transfer across three phases: (a) 2001-2008, (b) 2009-2016, (c) 2017-2023.

Harbin and Hainan, such as the diffusion of 68 pieces of marine technology patents from Guangzhou to Haikou, 62 pieces of marine technology patents from Beijing to Tianjin, and 52 pieces of marine technology patents from Harbin to Sanya. Direct marine test and application scenarios become the main driving force at this stage, and traditional marine inland R&D cities seeking substantial incubation sites for marine technology gradually diffuse to the South China Sea, coastal cities and other areas with obvious marine characteristics. In 2017-2023, China's intercity diffusion

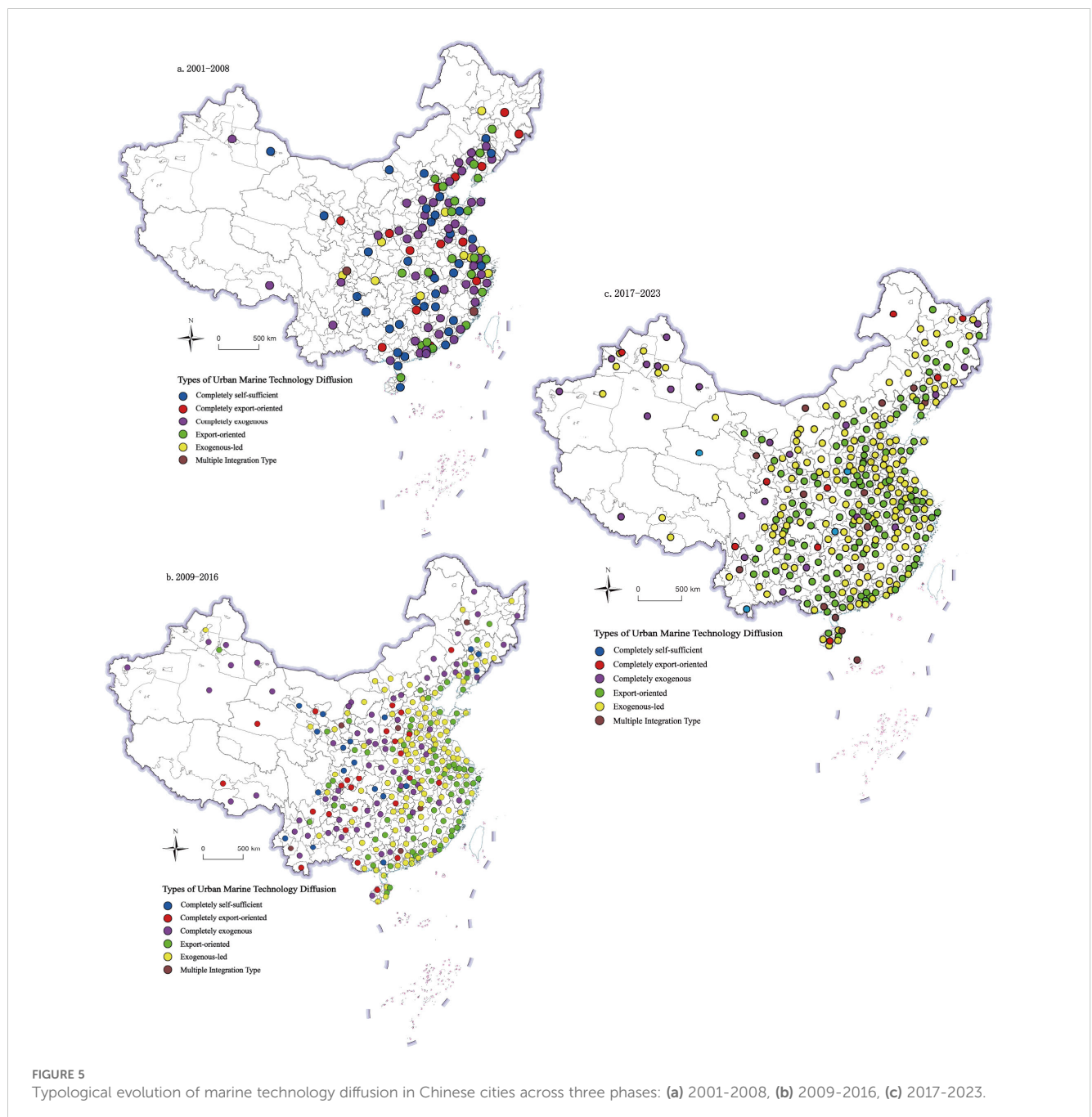
network of marine technology presents the characteristics of structural optimization and continued deepening of spatial agglomeration. The "diamond-shaped" structure with Beijing-Tianjin, Yangtze River Delta, Pearl River Delta, Sichuan-Chongqing as the fulcrum has been stabilized, and among the 5,291 pairs of technology diffusion relationships, there are 642 pairs of inter-city transfers of more than 5 cases, among which the typical diffusion paths are: Beijing-Guangzhou (87 cases), Beijing-Tianjin (62 cases), Guangzhou-Haikou (66 cases), and Ningbo-Shanghai (59 cases). Shanghai (59 cases).

4.3 Urban transformation: open innovation is integrated into urban development, and the marine technology trading market is becoming mature

Based on the classification system of urban marine technology diffusion, we analyze the evolution of urban role transformation in China's inter-city technology network in three phases. (Figure 5).

- (1) The type of cities involved in marine technology diffusion has undergone a major transformation. Cities involved in the diffusion of marine technology have been transformed into “export-led” and “exogenous-led” cities. This

transformation is reflected both in the expansion of technology overflow and in the upgrading of demand capacity: of the 131 cities participating in marine technology transfer in 2001–2008, only 34 cities were of the “export-led” and “exogenous-led” types, accounting for 23.7%; in 2009–2016, the proportion was 23.7%. Of the 318 cities involved in marine technology transfer in 2009–2016, 183 cities are of the “export-led” and “exogenous-led” types, accounting for 57.5%; of the 357 cities involved in marine technology transfer in 2017–2023, only 34 cities are of the “export-led” and “exogenous-led” types, accounting for 57.5%. Of the 357 cities participating in marine technology in 2017–2023, 279 cities are “export-led” and



“exogenous-led”, accounting for 78% of the total, of which 126 cities are “export-led”, accounting for 35.5%. From 2001 to 2008, Beijing topped the list of “export-led” cities with 82 assigned patents; from 2009 to 2016, Nantong topped the list with 523 assigned patents; and from 2009 to 2016, Nantong topped the list of “export-led” cities with 523 assigned patents. From 2009 to 2016, Nantong became the second largest “export-led” city after Beijing with 523 transferred patents; from 2017 to 2023, Hefei became an emerging “export-led” city of marine technology with 609 transferred patents in addition to North, South, Guangzhou and Shenzhen.

2. The flow of marine technology between cities has become more and more frequent. 34 of the 131 cities in China’s marine technology diffusion network from 2001 to 2008 were “completely self-sufficient”, accounting for 25.9% of the total. Cities existed as isolated nodes in the network and did not establish effective connections with neighboring nodes. 2009–2016 analysis of the evolution of the marine technology network shows that the number of cities involved in technology diffusion increased to 318, of which the number of isolated “fully self-sufficient” nodes shrank to 18. By 2017–2023, the number of cities of this type further decreases to 4 (1.1%). In the current topology of the ocean technology diffusion city network structured by 358 city nodes, 354 cities have formed a national technology trading network through technology transfer channels, especially the radiation effect of the four-core hub cities of Beijing, Shanghai, Guangzhou and Shenzhen, which has pushed the market system from regional division to national integration. The data show that the 488 technology transfer pairs established by the four hub cities in 2017–2023 account for 9.2% of the total number of transfer pairs, leading to the flow of 2,819 marine technologies, accounting for 16.9% of the ratio of the volume of inter-city marine technology transfers, which further confirms the strong integration function of the hub cities.

5 Driving mechanisms of marine technology diffusion in chinese

5.1 Driving factors

Due to the discrete and non-negative characteristics of intercity marine technology diffusion and its over-dispersion with variance significantly higher than the mean, this study adopts a negative binomial regression model to analyze the driving mechanism and constructs a three-phase panel data. The test shows that the Alpha value significantly rejects the original hypothesis of “Alpha=0” at the 5% level (the confidence interval does not contain zero), which confirms the applicability of the negative binomial regression, and the collinearity results showed that the variance inflation factor

(VIF) value of all indicators was less than 10. As shown in the regression results in [Table 5](#).

City marine patent application is the core driving element of the evolution of intercity marine technology diffusion network, and the intensity of its role shows a significant incremental trend over time. There is a significant positive correlation between the scale of marine technology diffusion among different cities and the scale of their marine patent applications, which indicates that intercity marine technology diffusion shows the evolutionary characteristics of “complementary advantages and synergistic efficiency”. It is worth noting that the difference in the number of marine technology patent applications between cities is also positively correlated with the scale of knowledge spillover, i.e., the larger the difference in the number of marine technology patent applications between cities, the larger the scale of marine technology diffusion, and the technological potential difference between cities has become an important driving force to promote cross-city technology transfer.

In terms of geographic proximity, the diffusion efficiency of intercity marine technology is increasingly constrained by geographic location spacing, which is specifically manifested in the inverse correlation between the geographic spacing between cities and the number of marine technology diffusion. Every hundred kilometers increase in spatial span; the efficiency of marine technology conduction will have an attenuation effect. regarding the geographical distance constraint, the phenomenon of high-frequency flow of marine patents within the city confirms that administrative barriers and geographic proximity have a constraining effect on the diffusion of marine technology. the empirical data from 2001–2023 shows that the average distance of intercity marine technology diffusion increases from 824.79 km to 941.83 km, while the share of long-distance technology transfers exceeding this mean value decreases from 54.5% to 44.9%. Although the spatial scope of technology cooperation continues to expand, proximity technology collaboration gradually becomes the dominant mode of diffusion.

In terms of economic proximity, this study chooses the city GDP ratio (high/low) as the economic proximity measure, which actually characterizes the reverse action mechanism. The empirical results show that economic proximity is significantly negatively associated with intercity marine technology diffusion from 2001 to 2023, but the direction of transmission is positively facilitated and the strength of the effect continues to increase, which confirms that the diffusion of intercity marine technology in China increasingly tends to be in the direction of cities that match the economic gradient, i.e., it is easier to form technology synergy network in the cities with similar economic levels, and the more consistent the demand for marine technology is, the more likely to promote the diffusion of marine technology. That is, cities with similar economic levels are more likely to form technology synergistic networks, and the more consistent the corresponding marine technology needs are, the more the diffusion of marine technology is promoted.

In terms of institutional proximity, the impact coefficient of city institutional proximity continues to rise, which indicates that intercity innovation and entrepreneurship institutional convergence has a lasting facilitating effect on the diffusion of

TABLE 5 Inter-city marine technology diffusion drivers: results from a negative binomial regression model analysis.

Variables	2001-2008	2009-2016	2017-2023
<i>Oce_Pat_Apli_{it}</i>	0.036*	0.047**	0.059***
<i>Oce_Pat_Apli_{jt}</i>	0.027*	0.031**	0.045***
<i>Tech_Gap_{ij}^t</i>	0.036**	0.059**	0.072**
<i>Geo_Prox_{ij}^t</i>	-0.006*	-0.009**	-0.026***
<i>Eco_Prox_{ij}^t</i>	-0.215*	-0.362**	-2.156***
<i>Inst_Prox_{ij}^t</i>	0.032*	0.063**	0.156***
<i>Cog_Prox_{ij}^t</i>	-0.526*	4.326***	6.158***
Constant	1.965	-2.156	-4.521
Sample size	189	2319	5291

*, **, *** denote significant at 10%, 5% and 1% levels, respectively.

marine technology, the more similar the innovation and entrepreneurship institutional background of the city is more likely to generate marine technology diffusion, when the innovation and entrepreneurship activities between cities have a similarity, they tend to adopt similar policy tools to support innovation, and this similarity can reduce the knowledge exchange and collaborative innovation transaction costs, enhance inter-city trust, and reduce cooperation uncertainty, thus facilitating inter-city marine technology flows.

In terms of cognitive proximity, the coefficient of cognitive proximity of cities is negative in 2001-2008, showing that the smaller the correlation of marine technology innovation between cities, the larger the scale of marine technology diffusion between cities. The main reason is that China's intercity marine technology diffusion system was in its infancy at that stage, with technological innovation activities highly concentrated in the core cities and significant heterogeneity in the field of marine technology among cities. In 2009-2016 and 2017-2023, the parameter of perceived proximity turns from negative to positive and the significance continues to increase, which indicates that the degree of technological relevance has a significant positive correlation with the volume of intercity technology transfer. This evolutionary trend profoundly reflects the transformation of the macro background of China's marine industry development. During 2001-2008, China's marine technology was in a "point breakthrough" phase, with major marine technology network cities focusing on independent R&D in their respective advantageous fields. At this stage, high cognitive proximity may indicate technological homogeneity and resource competition, where knowledge spillover effects are suppressed by intense competitive relationships, even leading to innovation lock-in, thus manifesting as a negative correlation. From 2009-2016 and 2017-2023, with the deepening of the national innovation-driven strategy, China's marine industry began evolving towards "cauterization and systematization." The establishment of platforms such as national laboratories and technological innovation alliances significantly facilitated the formation of cross-regional collaborative innovation networks. In this new

phase, a shared knowledge base no longer serves as a competitive signal but has become a prerequisite for effectively absorbing, understanding, and collaboratively developing complex technologies. It provides a common technical language for innovation entities across cities, lowers cooperation barriers, enables efficient knowledge flow and integration within regional innovation clusters, and collectively addresses systemic technological challenges. Consequently, cognitive proximity has transformed into a powerful positive catalyst, driving technology diffusion from isolated points to a new pattern of networked collaborative diffusion.

5.2 Driving process

Combined with the negative binomial regression results, the driving mechanism of intercity marine technology diffusion in China is summarized (Figure 6). The intercity marine technology diffusion network is formed by driving force, driving effect, driving purpose and performance, and driving result, and the main driving force is categorized as exogenous driving force and endogenous driving force.

At the beginning of the formation of marine technology diffusion network, as marine technology innovation and R&D capabilities are often concentrated in high-level cities, the innovation and entrepreneurship environment and economic volume differences between cities constitute the basic conditions for technology flow. It is found that geographic proximity and cognitive similarity are not necessary conditions for marine technology diffusion, and that cross-city technology transfer stems more from complementary innovation cooperation driven by differentiated technological needs. Similar to the diffusion mechanism in agriculture, green technology and other fields, the self-organization characteristic of networks serves as an important endogenous driving force to promote network growth and evolution through the mechanism of meritocratic connection. As a result, early technology diffusion mainly took place in the three major highly technologically active city clusters, forming a "triangular" spatial layout with a single-core agglomeration pattern.

Along with the advancement of marine technology and the rise of blue economy, multidisciplinary integration and industrialization application have profoundly reconstructed the technology diffusion network. Although network self-organization is still an important driving mechanism, the weight of multi-dimensional proximity has changed significantly. Under the superposition of multiple effects, a large number of edge cities have realized network embedding through establishing technological links with core nodes, accelerating the process of network expansion. The importance of technological intermediary function increases significantly, and cities with similar technological endowments are more likely to form industrial collaboration alliances. It is worth noting that the gradient difference in innovation and entrepreneurship environment and economic development level has an increasingly significant constraining effect on technology diffusion, and nodes that fail to establish effective connections face the risk of

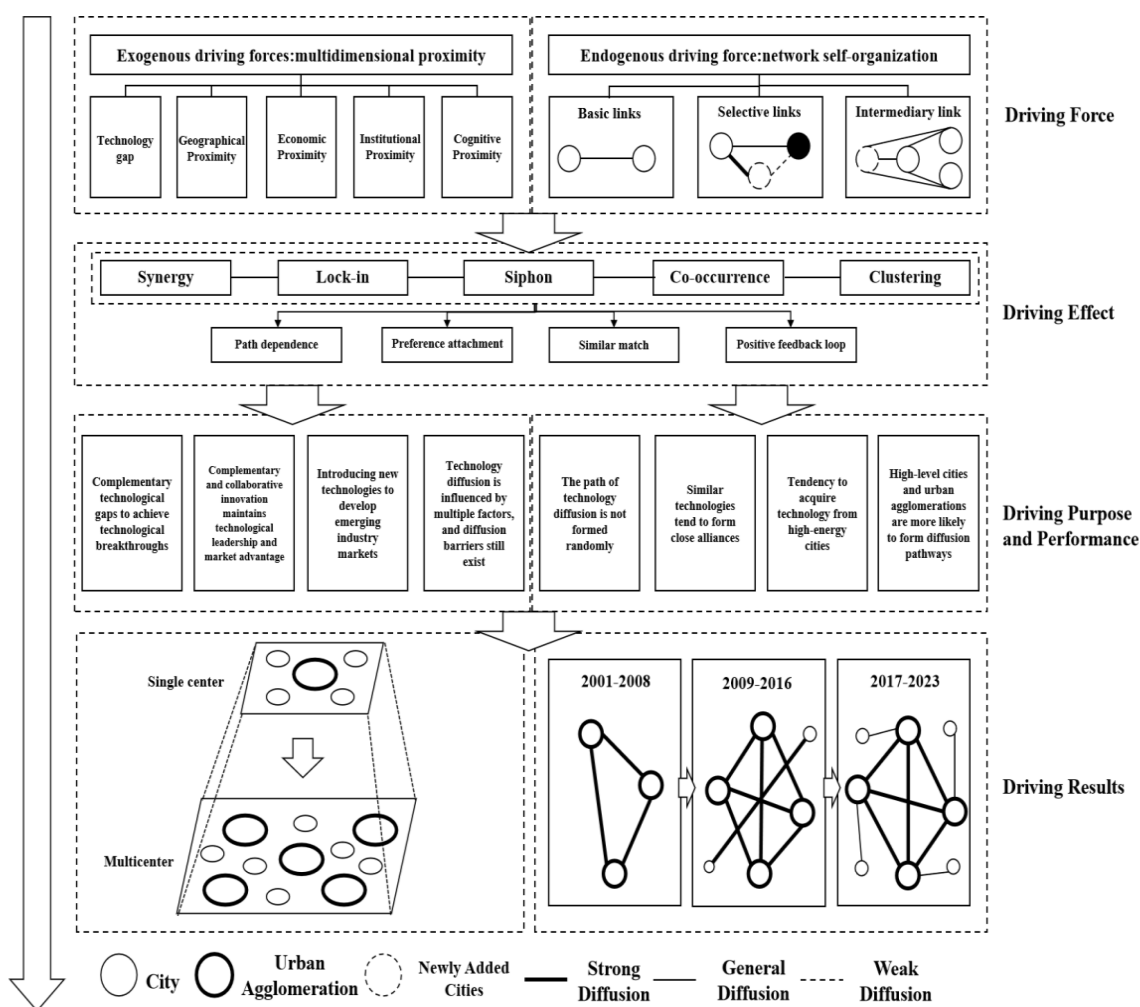


FIGURE 6
Analysis of driving mechanisms for marine technology diffusion in Chinese cities.

marginalization. At the same time, the mode of technological interaction between cities has gradually shifted from being driven by pure technological potential difference to a composite mechanism in which complementary innovation and collaborative innovation coexist, reflecting the structural adjustment brought about by the upgrading of the demand of the marine industry and the evolution of the technological life cycle. Against this background, China's marine technology diffusion network has gone through a transition phase of "Φ" shape, and eventually evolved into a stable "diamond-shaped" structure, showing a new trend of multi-center synergistic development.

5.3 Driving results

5.3.1 Hub dependence: emerging cities' marine technology acquisition path preferring core node cities in innovation networks

In the marine technology diffusion network, the preference of emerging cities for core node cities in technology acquisition is not

an accidental phenomenon, and there are multi-dimensional driving mechanisms behind it. This study analyzes the evolution of China's marine technology diffusion network in stages, and finds that in the later stages of development, about 60% of the new nodes are supplementing the local innovation supply through technology acquisition. It is worthwhile to explore whether the source of these technologies is the highly connected cities in the network or the nodes of the same level. By comparing the second stage (2009–2016) with the first stage (2001–2008) and the third stage (2017–2023) with the second stage (2009–2016) across cycles, the results show that China's marine technology diffusion network exhibits significant meritocratic linkage characteristics. Specifically, Beijing, Shanghai, Guangzhou and Shenzhen participated in nearly 40.8% of technology flows as core hubs in 2001–2008; only 7.3% of the new city nodes in 2009–2016 were closed innovation subjects, and only 13 of the 179 new cities were "fully self-sufficient" cities, while the rest of the city nodes were connected to other cities. In the 179 new cities, only 13 cities belong to the "fully self-sufficient" category, and the rest of the city nodes have cooperated with other cities in marine technology transfer, and

the ratio of technology radiation from core cities has decreased to 19.5%, and the transfer activities of 168 marine patents out of the 862 marine patents transferred have been participated by the four hub cities; in the third stage (2017–2023), the new city nodes have completely realized networked collaboration, and there are no “fully self-sufficient” cities in the new nodes. “Fully self-sufficient” cities, and the participation of core hubs rises back to 27.1%, with new cities participating in the transfer of 70 marine patents, of which 19 marine patents have transfer activities involving 4 hub cities. Network topology analysis confirms that there is a significant core-oriented preference in the technology acquisition path of node cities, which confirms the driving law of “network self-organization”.

5.3.2 Multiple synergies: the structure of marine technology linkages among hub cities (clusters) in the network has become more solid

Under the background of globalization of the ocean economy and deep integration of regions, the network of marine technology links between hub cities is changing from single linear cooperation to complex multiple synergy. Compared with the hub-dependent technology diffusion, the structure of marine technology linkage between hub cities in the network is more solid, and this structure is characterized by a significant “super network”. Under the effect of this structure, the hub cities and city clusters in the network form the network evolution law of “core node interlocking”, and more through the continuous positive feedback mechanism to form path dependence. From the point of view of the current marine technology diffusion system, both coastal areas and inland areas show a major city-region distribution. Refined to the three major economic circles of the ocean and the inland areas of Sichuan, Chongqing and the middle reaches of the Yangtze River, the structure of the diffusion of marine technology shows the core-

marginalized characteristics. It is worth noting that important marine technology diffusion node cities basically have many single-specialty universities (e.g., Ocean University of China, Shanghai Ocean University, etc.) and comprehensive universities (Sun Yat-sen University, Harbin Institute of Technology, etc.) related to marine sciences, and all of them are mega-cities, or even mega-cities, in the country. These universities, as an important part of marine science and technology innovation, provide a strong source of support for technology diffusion. The difference, however with the difference being that the core agglomeration areas of the three major economic circles of the ocean are more centralized, while the core areas of the inland cities are more dispersed (Figure 7). Among the 189 intercity marine technology diffusion pairs in 2001–2008, 8 out of the top 30 pairs (accounting for 35.9% of the whole) in terms of diffusion volume (accounting for 9.9% of the whole) took place between the top 10 cities in terms of marine technology transfer volume, and 7 pairs (accounting for 7.1% of the whole) took place in the core agglomeration area. Of the 2,319 intercity marine technology diffusion relationships in 2009–2016, 11 of the top 30 diffusion pairs (13.3% of the overall) (4.6% of the overall) occurred between the top 10 cities in terms of marine technology transfer volume, and 10 pairs (4.3% of the overall) occurred in core catchment areas. Although the diffusion of Tianjin as a cluster member does not occur among the top 10 cities in terms of marine technology transfer in the intercity marine technology diffusion network for 2017–2023, 16 of the top 30 pairs of diffusion (8.0% of the overall) (4.3% of the overall) occur among the top 10 cities in terms of marine technology transfer, and 18 pairs (5.2% of the overall) occur in the core cluster area. In the multifaceted synergistic network, the transfer links of hub cities are gradually enhanced, and the core agglomeration area (i.e., city cluster) effect also shows an enhancing trend, showing the characteristics of the co-matching network.

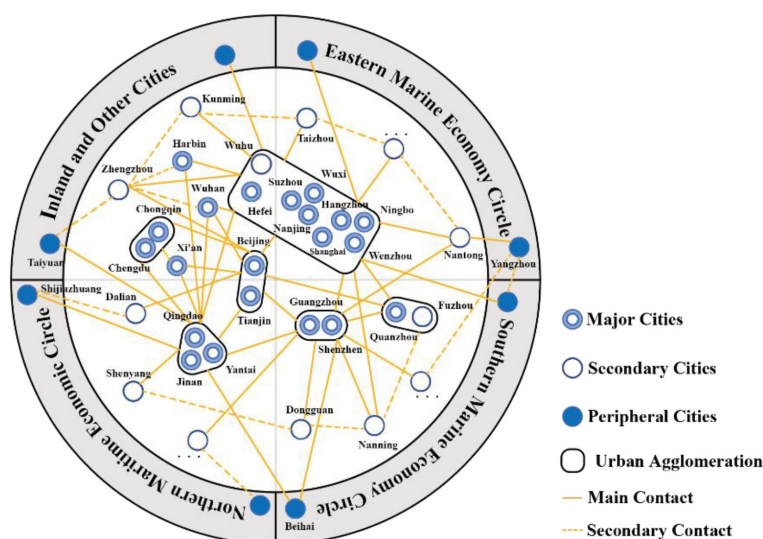


FIGURE 7
Mosaic diagram of key node cities' connectivity structure.

5.3.3 Regional differences: differences in the diffusion radiation of marine technology, and multiple paths between inland and coastal

Intercity marine technology diffusion network shows significant regional differences, and its radiation path and effectiveness are deeply influenced by geographic location, institutional proximity and economic structure, forming a multi-path development pattern that is very different between inland and coastal areas. ① There are significant differences in the radiation patterns of marine technology in core cities. As a national science and technology innovation center, Beijing's technology radiation is more like an enclave mode, with an average diffusion distance of 1,114.6km, while the top 10 cities in terms of the intensity of marine technology diffusion have an average distance of 1,096.1km. Despite the large amount of marine technology patents transferred from Beijing, its technology overflow flows more to economically developed regions such as Guangdong and Shanghai, and to other areas such as the coastal areas. Although Beijing has a large volume of marine technology patent transfer, its technology overflow flows more to economically developed regions such as Guangdong and Shanghai, and its radiation-driven effect on the neighboring Jinbei region is relatively limited, and there is even a certain siphon effect, with its technology overflow covering a wide range of areas, but the radiation intensity is weak; and Shanghai's technological radiation shows a typical "near-neighbor mode", with an average diffusion distance of 933.4km, and the average distance between the top 10 cities in terms of the intensity of marine technology diffusion is 1096.1km. The average distance between the top 10 cities in the intensity ranking is 610.9km, and the strong industrial and capital potential energy is mainly concentrated to the provinces of Jiangsu, Zhejiang and Anhui in the Yangtze River Delta region, forming a close regional synergy, and the diffusion of which is more efficient and direct, with stronger geographical proximity effect. ② At the level of comparison between inland and coastal hubs. The key inland hub, for example, Chengdu, has an average diffusion distance of 1228.5km, and the average distance of the top 10 cities in terms of the intensity of marine technology diffusion is 1,359.8km. Although Chengdu possesses strong scientific and educational resources and the potential to undertake technology transfer, it is far away from the marine practice scenario, and the diffusion of its technology relies on the policy-guided "peer-to-peer" technology transfer and the inland hinterland's technology diffusion. Although Chengdu has strong science and education resources and potential to undertake technology transfer, it is far away from the marine practice scene, its technology diffusion relies more on "point-to-point" technology transfer under the guidance of policy and the cultivation of inland hinterland market, and the path is relatively single, and the localization and industrialization of technology need to be diffused and tested to the coastal areas; on the contrary, in the coastal hubs, Qingdao, for example, has an average diffusion distance of 880.7km, and the average distance of the top 10 cities with the strength of marine technology diffusion is 608.1km. With its advantageous location near the sea and mature marine industry

foundation, technology diffusion shows strong network characteristics, forming a complete closed loop from R&D, incubation to transaction, which can absorb, digest and re-diffuse applicable technologies from the response to technological hotspots and the international market more quickly, forming a self-reinforcing regional innovation cluster.

6 Conclusion and discussion

6.1 Conclusion

Based on the constructed spatio-temporal database of marine patents in Chinese cities from 2001-2023, this paper portrays the diffusion of marine technology by marine patent transfer, and the main findings are as follows:

1. In terms of temporal evolution characteristics, China's marine biomedical technology maintains its leading position from 2001-2023, high-end manufacturing and emerging marine ecological and material technologies are rapidly emerging, and the proportion of inter-city marine technology transfers has exceeded the proportion of intra-city marine technology transfers for the first time since 2018, and it will also show that trend for a long time in the future. Enterprises play an obvious double-end leading role, not only as the main exporter of the supply side of China's marine technology, but also as the integrated absorber of the demand side, widely absorbing marine technology from universities and research institutions, and individual concessions, and more than 80% of the patents of marine technology ultimately flowed to enterprises.
2. In terms of spatial evolution characteristics, the intra-city flow of China's marine technology shows significant spatial agglomeration characteristics, which is mainly distributed in three strategic regions: the coastal economic belt centered on Beijing-Tianjin, the Yangtze River Delta and the Pearl River Delta, the Yangtze River Economic Belt centered on the middle reaches of the Yangtze River and Chengdu-Chongqing and the Longhai Lanxin Economic Belt centered on the axis of Xi'an-Zhengzhou. The structure of the intercity diffusion network has evolved through the "triangle- Φ -rhombus" evolution, forming the four major strategic hubs for the diffusion of China's intercity marine technology, namely Beijing-Tianjin, the Yangtze River Delta, the Pearl River Delta, and Chengdu-Chongqing. With the deepening of market-oriented reform and the demand for open innovation in the marine industry, the function of cities in the technology network has gradually shifted from unidimensional supply to multidimensional composite, and key cities have accelerated the paradigm shift from "inward agglomeration" to "outward radiation".

About 60% of the cities that have newly joined the marine technology diffusion network have supplemented their local innovation resources through inter-city technology synergy in order to pursue the development of new marine-related industries.

3. In terms of driving mechanisms, exogenous and endogenous driving forces reveal the general laws followed in the growth process of China's intercity marine technology diffusion system, and under the driving force of multidimensional proximity, China's intercity marine technology diffusion is characterized by complementary synergistic and symbiotic development, and presents a strong network association mechanism. In addition, intercity economic and geographic proximity and institutional environment convergence have significant positive driving effects on the spatial diffusion of marine technology, while cognitive proximity shows dynamic evolution characteristics, and its mechanism gradually changes from initial inhibition effect to later gain effect.

Based on the above conclusions, the following recommendations are proposed for the development of China's marine technology transfer and transformation market and trading system: ①In view of the fact that Marine technology flows within cities still account for a large proportion in China's current Marine technology, it is suggested to build an "institutional wall-breaking" mechanism, implement a mutual recognition system for market access of technology, and break down institutional obstacles such as inconsistent urban standards and difficulties in mutual recognition of qualifications. ②There is an urgent need to systematically strengthen the core hub role of enterprises in technology transfer and transformation. Support their leadership in forming cross-regional and cross-industry chain technology transfer consortia, and dynamically select a demonstration enterprise cultivation database for marine technology transfer and transformation. ③Enhance the radiating function of core hubs by clarifying the pivotal role of cities like Beijing, Shanghai, Guangzhou, and Qingdao in the national technology diffusion network. Prioritize supporting their establishment of marine technology transfer centers, strengthening technological radiation to surrounding and inland regions through methods such as setting up sub-centers and co-building industrial parks. ④Strengthen cross-regional technology cooperation platforms and supporting mechanisms. To avoid the risk of further marginalization faced by western marine-related R&D cities due to their distance from actual marine technology application scenarios, establish a special marine technology fund to provide targeted funding for eligible western cities, and encourage coastal hub cities to establish long-term cooperation mechanisms with western marine R&D cities. ⑤Implement differentiated promotion strategies for technical categories. For high-end marine equipment manufacturing and other fields with large technology radiation radii, focus on building cross-regional technology trading platforms; for

cognition-dependent fields like marine biomedicine, support the formation of innovation consortia to promote knowledge sharing within clusters. ⑥Promote the transformation of geographical clusters into innovation communities. In regions such as the Guangdong-Hong Kong-Macao Greater Bay Area and the Yangtze River Delta, prioritize the development of cross-administrative marine science and technology resource-sharing platforms to reduce institutional costs for collaborative innovation, thereby converting geographical agglomeration advantages into innovative synergy advantages.

6.2 Discussion

Based on the negative binomial regression model, this paper reveals the spatially independent influence patterns of each potential single driver on urban marine technology diffusion. However, the geographic process and spatial pattern of real marine technology diffusion is often the result of multi-factor coupling and non-linear interaction. The independent effect of a single factor may conceal the complex mechanisms arising from its synergy with other factors. In order to explore the contribution of the interactions among these potential drivers to the spatial divergence of intercity marine technology diffusion, a geodetector approach is introduced to conduct a preliminary exploration of the combined effects of geographic, economic, institutional and cognitive proximity. The unique factor interaction detection module of the geodetector can effectively quantify the strength and direction of the interaction between any two factors, thus revealing a more complex and closer-to-reality spatial differentiation pattern and its driving mechanism under the synergistic effect of multiple factors. The specific results are shown in [Table 6](#).

The results of the geo-detector show that the driving mechanism of marine technology diffusion in China shows a significant structural transformation: the constraining effect of geographic proximity continues to weaken, and the interaction effect of geographic correlation is weakened simultaneously; at the same time, cognitive proximity realizes the leap from the periphery to the core and dominates the late stage of diffusion through the in-depth coupling with the systemic and economic dimension, which confirms the logic of cluster evolution of "the degree of industrial relevance determines technology suitability". This confirms the evolutionary logic of clusterization that "industrial relevance determines technological suitability". Institutional proximity, as a key synergistic link, and its interaction with geographical factors indicate that the breaking down of administrative barriers can partially replace geographical constraints; economic proximity deepens the regional division of labor through gradient matching and supports the shift of the interaction network from a "single core" to a "multiple core".

In addition, this study has constructed a spatio-temporal database of marine patents in Chinese cities based on the national

TABLE 6 Geographic detection results of important drivers of intercity marine technology diffusion.

Stage	Indicator	Geographic proximity	Economic proximity	Institutional proximity	Cognitive proximity
2001-2008	Geographic proximity	0.356989			
	Economic proximity	0.409863	0.168563		
	Institutional proximity	0.254369	0.221589	0.114369	
	Cognitive proximity	0.309658	0.263659	0.105963	0.069636
2009-2016	Geographic proximity	0.245696			
	Economic proximity	0.316936	0.242693		
	Institutional proximity	0.382696	0.478693	0.259853	
	Cognitive proximity	0.286963	0.436314	0.542636	0.343695
2017-2023	Geographic proximity	0.120989			
	Economic proximity	0.232498	0.284767		
	Institutional proximity	0.431567	0.431567	0.332123	
	Cognitive proximity	0.363792	0.632349	0.684792	0.441267

classification standard of marine industries and the classification standard of strategic emerging industries, and based on its classification standard, characterized the process of marine technology diffusion by the amount of marine patent transfer, and conducted a detailed analysis of the technological hotspots, core participating subjects and the type of urban transformation in the diffusion of marine technology in China. However, there are many areas for improvement in the current assessment criteria and the adoption of the urban scale for marine technology diffusion: ① The constructed classification criteria for marine technology are imperfect and subjective. Although the national classification standard is adopted, the coverage of the classification system is still limited and dominated by traditional technologies, while some emerging fields are missing. In the future, how to further refine and improve the classification standard of marine technology, whether it is industry-led or discipline-led is still the next step to overcome the direction. ② While following the internationally accepted paradigm of technology flow characterization and adopting marine patent transfer data to measure the level of marine technology diffusion, its limitations are large, such as failing to explore the quality of marine technology patents and other deep-level information. And there are multimodal paths of marine technology diffusion such as patent transfer, talent migration, equipment trade, etc., while the current data acquisition system overly relies on the patent dimension, resulting in the existence of blind spots for unstructured paths such as technology embedded diffusion and organizational networked diffusion. In addition, future research can be devoted to the construction of a multi-dimensional diffusion measurement framework, by integrating scientists' resume data, technology acquisition data, academic collaborative paper data, etc., to more comprehensively capture the panorama of technology and

knowledge flow across cities, so as to strongly supplement and cross-verify the conclusions of this study.③Based on China's marine technology transaction data from 2001 to 2023, the dynamic evolution characteristics of market hotspots are revealed. In fact, although the hotspots of market patent transactions are identified through the classification of technology fields, the differentiated characteristics of various types of marine technologies in the dimensions of composition of innovation subjects, spatial distribution patterns and time sequence evolution laws are not studied in detail, and in the process of the development of the marine industry, often a single project involves the integration of a number of technologies. In the process of marine industry development, a single project often involves the integration of many technologies. Therefore, how to carry out comparative and linkage analysis of marine technology diffusion across technological fields and even across industries will become a key issue that needs to be broken through in subsequent research.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

XM: Validation, Methodology, Conceptualization, Writing – original draft, Writing – review & editing. WC: Writing – review & editing, Funding acquisition. HZ: Writing – original draft. YY:

Writing – review & editing. YZ: Methodology, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research and/or publication of this article. This research was supported by the Major Program of the National Social Science Foundation of China (Grant No. 22&ZD152).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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