Frontiers in Marine Science

TYPE Original Research
PUBLISHED 21 March 2023
DOI 10.3389/fmars.2023.1104045

The impacts of extreme marine weather and marine scientific and technological innovation on marine economic development: Evidence form China's coastal regions

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SPECIALTY SECTION
This article was submitted to Marine Affairs and Policy, a section of the journal Frontiers in Marine Science

RECEIVED 21 November 2022
ACCEPTED 19 January 2023
PUBLISHED 21 March 2023

CITATION
Li C, Jia H, Wan Y, Hu Y, Zeng B, Zhang W, Fan X, Lin T, Shang G and Wang W (2023) The impacts of extreme marine weather and marine scientific and technological innovation on marine economic development: Evidence form China's coastal regions.
Front. Mar. Sci. 10:1104045.
doi: 10.3389/fmars.2023.1104045

The extreme marine weather is a very vital factor and has important implications for of marine economic development. However, there is a lack of systematic and quantitative analyses of its impact on the marine economic development. Here, we study the impacts of extreme marine weather on marine economic development of 11 coastal regions in China, using the dynamic panel model. We found that extreme marine weather exerts a significant negative impact on the marine economic development. The marine scientific and technological innovation promotes marine economic development in a prominent manner. The marine scientific and technological innovation slows down the unfavorable impact of extreme marine weather on the marine economy. After considering different industries for marine economic development and heterogeneity, we found that extreme marine weather and marine scientific and technological innovation have a great impact on marine economic development in the tertiary industry and the areas with high development concerning marine economy level, while deliver a small impact on the marine economic development in the primary industry and the areas low development level. This paper empirically studies the relationship between the two variables of marine extreme weather and marine science and technology innovation and its impact on marine economic development, enriches the research perspective of extreme weather on marine economic development, and provides new method evidence for improving the level of marine scientific and technological innovation and promoting the development of marine economy.

KEYWORDS

extreme marine weather, marine scientific and technological innovation, marine economic development, dynamic panel data model, China's coastal regions

1 Introduction

On a global scale, the marine economic development plays an important role in the national economic system of coastal countries, becoming an important economic growth point and an important support for expanding the space for economic growth and social development. However, the marine economic development is affected by many factors (An and Li, 2020; Ding et al., 2020; Dang, 2021). Among them, extreme marine weather is one of the biggest challenges to marine economic development. Extreme marine weather refers to the extreme climate that occurs in marine areas. The probability of occurrence is usually less than 5%. The extreme weather is classified into extreme high temperature, extreme low temperature, extreme rainfall and extreme wind. Compared with other marine meteorological disasters, the impact of the extreme marine weather on the marine economic development is much larger. Therefore, it is very important to explore and quantify the impact of marine extreme weather on the marine economic development.

A growing body of research has explored the impacts of extreme marine weather on marine economic development. The impacts of extreme marine weather on marine economic development are profound. The extreme marine weather has a huge impact on marine production safety, marine ecosystem, international trade, infrastructure, supply chain, and so on (Olds et al., 2014; Corte et al., 2018; Servino et al., 2018; Marchi et al., 2022). However, there is a lack of systematic and quantitative analyses of the impacts of extreme marine weather on marine economic development and whether marine scientific and technological innovation can reduce the negative impact of marine extreme weather on marine economy and improve the development of marine economy.

To fill the knowledge gap, we perform such analyses associated with marine economic development in China's coastal regions. we use the 22-year data of 11 coastal provinces (municipalities and autonomous regions) in China from 2000 to 2021 to empirically examine the impacts of extreme marine weather and marine scientific and technological innovation on marine economic development[1]. 11 coastal provinces (municipalities and autonomous regions), from north to south, are Liaoning, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan (Figure 1). We construct the static and dynamic panel data models to study the impacts of extreme marine weather on marine economic development, which can help us to quantify the static and dynamic impacts. We adopt the interaction term of extreme marine weather and marine scientific and technological innovation to verify whether the improvement of marine scientific and technological innovation has a positive moderating effect on extreme marine weather. In this way, we can comprehensively explore the influence of extreme marine weather and marine scientific and technological innovation on marine economic development.

China's marine economy is developing steadily. In 2021, the gross output value of China's marine economy was 9.0385 trillion Yuan. At the same time, with the implementation of the maritime power strategy and the 21st Century Maritime Silk Road, the importance of the marine economy has become more and more prominent (Li et al., 2021a; Liu and Li, 2022). China is stepping up efforts to become a strong maritime country, make marine economy perform better, and ensure the stable development of marine economy. Productive activities related to marine economy mainly center on the sea and coastal areas, and the impacts of marine environment and climate on the development of marine economy become critical. Existing studies also reveal that climate change has a profound impact on coastal areas in China, with emphasis on negative and adverse impacts (Ma, 2020; Wang et al., 2021). Unfortunately, China is one of the worst victims of marine disasters. With the rapid development of marine economy, marine disaster risks in coastal areas are becoming increasingly prominent, and the marine disaster prevention and relief situation is pretty serious (Hwang et al., 2020; Xu et al., 2022). Direct economic losses caused by marine disasters in 2021 amounted to 3.07 billion Yuan. However, the marine meteorological disaster is dominant among a wide range of marine disasters. Mitigating the impact of marine meteorological disasters on China's marine economy has become one of the priorities of marine work. It is imperative to shift the marine economy to an innovation-driven and high quality-based development model. Therefore, in the new era, pushing forward marine scientific and technological innovation and having a clear picture of the impact of marine meteorological disasters on the marine economy is conducive to promoting high-quality development of the marine economy and strengthening China's marine development at a faster pace (Guo et al., 2020). Therefore, studying the impact of extreme marine weather on the marine economic development can provide decision-making reference for China and the marine nations to avoid the damage caused by extreme marine weather.

In this article, we address the following questions: (1) How much do extreme marine weather and marine scientific and technological innovation affect the development of marine economy? (2) Whether the marine scientific and technological innovation has a moderating effect on extreme marine weather? (3) Are the impacts different in different China's marine industries, sea areas, marine economic development levels? To answer these questions, we collect the 20-year data of 11 coastal provinces (municipalities and autonomous regions) in China from 2000 to 2021. We construct the static and dynamic panel data model to study the impacts of extreme marine weather on marine economic development, which can help us to quantify the static and dynamic impacts. We explore whether the improvement of marine scientific and technological innovation has a positive moderating effect on extreme marine weather. Furthermore, the heterogeneous effects of extreme marine weather and marine scientific and technological innovation on the three major marine industries are quantitatively analyzed. Also, from the perspective of geographical location and marine economic development, we explore the regional heterogeneity of extreme marine weather and marine technological innovation on China's marine economic development.

This article makes twofold contributions. First, we enrich the research perspective of extreme weather on marine economic development. At present, scholars' research on the marine economy mainly focuses on the upgrading of marine industrial structure, marine scientific and technological innovation, and marine total factor productivity (Zhai, 2020; Zhong et al., 2020). We consider that the marine economy is not only affected by socio-economic

1 For data unavailability, we don't select Hong Kong, Macao and Taiwan as the research samples.

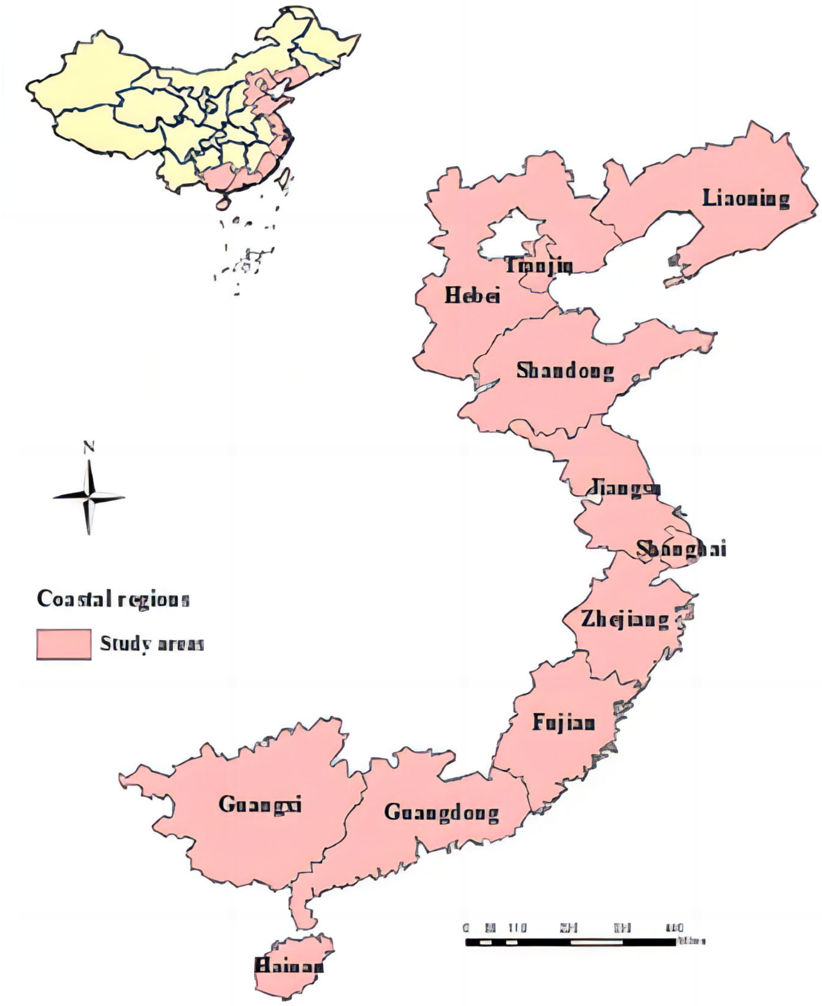

FIGURE 1
Coastal regions in China.

factors, but also largely restricted by natural environment. We provides a new research perspective for the impact factor of marine economy. Second, we provide evidence and methods for boosting marine scientific and technological innovation to promote marine economic development. Currently, the studies mainly center on the impact path of marine scientific and technological innovation, which is attributed to the upgrading of marine industrial structure (Yu and Zou, 2020; Li et al., 2021b; Singh et al., 2021). We find that marine scientific and technological innovation can significantly reduce the negative impact of extreme marine weather on marine economic development, thus fueling marine economic development. We provide new evidence and methods for the relationship between marine scientific and technological innovation and marine economic development.

The rest of the article is organized as follows: Section 2 reviews related literature and proposes research hypotheses. Section 3 introduces the model design, selection of variable definition and data source. Section 4 is the empirical results and analyses. Section 5 tests the robustness of the model and analyzes related results. Section 6 discusses the results. Section 7 is conclusions and policy recommendations.

2 Literature review and research hypotheses

The impact of extreme weather on the social economy has received wide attention. The economic development including agroforestry, animal husbandry, transportation and other industries are largely affected by weather. Many scholars studied the possible impact of extreme weather on the economy and make work arrangements in a reasonable manner. Using the historical data of the weather and economy in Beijing from 2002 to 2013, Sun et al. (2017) found that the construction, wholesale and retail, and financial industries were most susceptible to weather conditions. Liang and Chen (2019) studied the impact of global extreme weather events on the GDP of various countries and found that the extreme weather had the characteristics of “small probability, great loss”, that is, the small occurrence probability of the extreme weather events would greatly impact the GDP. Zhang and Meng (2020) found that China’s agricultural production was geographically decentralized with complex climate change. The same extreme weather had different effects on agricultural production in different regions. Rezaee et al. (2016) studied the impact of extreme weather on fishery in Canada and the Atlantic Ocean. It was concluded that there was a significantly negative interrelation between the number of fishing and the occurrence of extreme weather in Canada by analyzing wind speed, precipitation, air, sea surface temperature, Laplace pressure and ice. Mcintosh and Austin (2019) studied the relationship between economic development and extreme marine weather of ports in the North Atlantic. After examining the changes of 34 evaluation indices in ports affected by extreme weather, it was found that the North Atlantic ports were relatively weak against extreme weather. Based on the above scholars' research, it can be found that extreme weather produces an important impact on social and economic development, and the extreme marine weather serves as an important factor in the development of marine economy. In addition, the extreme marine weather usually leaves a great negative impact on marine economic development. Thus, the following hypothesis is proposed in this paper:

Hypothesis 1: The extreme marine weather has a significantly negative impact on marine economic development.

Over recent years, related research on the impact of scientific and technological innovation on the marine economic development has always been the focus in academia. Innovation-driven development strategy, especially the core technology innovation, was a crucial cornerstone of enhancing the international competitiveness and safeguarding the national security, and a driven force for supporting and leading economic development (Yu and Zhou, 2020). Qin and Shen (2020) pointed out that the improvement of marine technological innovation would significantly promote the improvement of green total factor productivity, and effectively fueled the marine economic development. Ning and Song (2020) applied Panel Vector Autoregressive Model (PVAR) to analyze the dynamic relationship among marine scientific and technological innovation, marine total factor productivity and marine economic development. The research results showed that China's marine scientific and technological innovation and marine total factor productivity had a self-reinforcing mechanism. Han and Xiong (2020) studied the effect of scientific and technological innovation on the industrial structure optimization. The study pointed out that the improvement of scientific and technological innovation significantly promoted the industrial structure optimization, but the industrial structure optimization level was affected by local investments in scientific and technological innovation. Therefore, the scientific and technological innovation is an important safeguard for upgrading the industrial structure. He et al. (2018) pointed out that the improvement of scientific and technological innovation capacity was conducive to promoting the sustained growth of economy. Mele et al. (2019) integrated the economic issues into the marine ecosystem, and showed that the improvement of marine scientific and technological innovation capacity was an important means to conserve marine ecology protection and was conducive to promoting the sustainable development of marine economy. Based on the above studies, the following hypothesis is proposed:

Hypothesis 2: Marine technological innovation has a significant positive impact on marine economic development.

The role of marine scientific and technological innovation in fueling marine economic development involve two aspects: scientific and technological development and model innovation. On the one hand, the improvement of scientific and technological innovation can spur the improvement of fishing efficiency, marine resource extraction capacity, marine cargo transportation capacity and marine natural disaster early warning capacity. Cui (2006) indicated that China's marine resource development and utilization efficiency and the number of marine transportation were significantly tied with the improvement of marine scientific and technological innovation capacity. Zapelloni et al. (2019) studied the sustainable production of marine equipment contributed to the marine circular economy. They pointed out that the technological upgrading of marine equipment could effectively improve the efficiency of the marine circular economic development. Vieira et al. (2019) studied the impact of offshore wind power on the sustainable development of marine economy in Portugal. They pointed out that the improvement of marine scientific and technological capacity could effectively improve the exploitation and utilization efficiency of marine resources and fuel the sustainable development of marine economy. Based on researches of the above scholars, it can be summarized that the development of science and technology has brought about the improvement of production capacity and the ability to resist disasters. On the other hand, the organizational structure innovation, financial technology innovation, and management mechanism innovation have greatly enhanced the efficiency of the marine economic development system and facilitated the development of the marine economy. Shi et al. (2015) studied the transformation mechanism of scientific and technological advances supporting the marine aquaculture industry in Fujian Province. They found that the transformation mechanism of scientific and technological advances with financial support still had major shortcomings. Also, the optimization of financial policy and system held great significance for marine science and technology. Using the development data of *Fisheries Science and Technology Innovation Alliance in China*, Yue et al. (2016) studied the impact of operation mechanism on the fishery economic development. They found that the fishery alliance integrated the regional advantages of various areas in China, promoted the establishment of a sustained and stable fund investment mechanism and improved the institution and system of achievement transformation and application. It also boosted the growth of the fishery economy by advancing fishery scientific and technological innovation. Bhogal and Trivedi (2019) discussed the role of marine insurance in the marine economic development. They pointed out that the marine insurance effectively dispersed the impact of marine accidents on marine economic development and was an important guarantee for marine economic development. Based on the above scholars' research, it can be summarized that the optimization and innovation of the management system has introduced progress in work efficiency, spurred the conversion of science and technology into economic achievements, and enhanced the risk-resistance capacity of marine economy. Therefore, the improvement of marine scientific and technological innovation, on the one hand, can enhance the resistance of marine economic activities to extreme weather; on the other hand, it can disperse the risks brought by extreme weather to the economy. Therefore, the following hypothesis is suggested in the paper:

Hypothesis 3: Marine scientific and technological innovation reduces the negative impact of extreme maritime weather on the marine economy.

3 Models and data

3.1 Models

Therefore, the following three variables are the main focus of this article. Dependent variable: Marine economic development (*GMP*). Core independent variables: Extreme marine weather (*EWI*) and Marine scientific and technological innovation(*INO*).

To investigate the impact of extreme marine weather and marine scientific and technological innovation on the regional marine economy, we construct the following panel data model:

$$lnGMP_{i,t} = \alpha_0 + \alpha_1 lnEWI_{i,t} + \alpha_2 lnINO_{i,t} + \gamma Controls_{i,t} + \sum Year + \sum Province + \epsilon_{i,} \quad (1)$$

$$lnGMP_{i,t} = \alpha_0 + \alpha_1 lnEWI_{i,t} + \alpha_2 lnEWI_{i,t} \times INO_{i,t} + \alpha_3 lnINO_{i,t} + \gamma Controls_{i,t} + \sum Year + \sum Province + \epsilon_{i,} \quad (2)$$

In model (1), $EWI_{i,t}$ and $INO_{i,t}$ are core explanatory variables, representing extreme marine weather index and marine scientific and technological innovation index. $Controls_{i,t}$ represents all the control variable. *Year* is the annual dummy variable. *Province* is the industry dummy variable. ε_i is the stochastic disturbance term. The subscript *i* denotes each coastal area, and the subscript *t* denotes the year.

In model (2), we add the interaction term of extreme marine weather and marine scientific and technological innovation to verify whether the improvement of marine scientific and technological innovation has a positive moderating effect on extreme marine weather. We focus on the interaction term coefficient a_2. If a_2 is significantly positive, it means that marine scientific and technological innovation enable the extreme marine weather to have a positive moderating effect on marine economic development. If a_2 is significantly negative, it means that marine scientific and technological innovation enable the extreme marine weather to have a negative adjustment effect on marine economic development. If a_2 is insignificant, there is no evidence that supporting marine scientific and technological innovation enables extreme maritime weather to have a moderating effect on marine economic development.

Models (1) and (2) are static panel data models. Because of the inertial influence of the marine economy, marine economic development may be affected by economic development in the previous period. Therefore, based on models (1) and (2), we adds the first-order lag term of marine economic development to investigate the dynamic effects (Wu et al., 2016). The dynamic panel data models are as follows.

$$lnGMP_{i,t} = \alpha_0 + \alpha_1 lnGMP_{i,t-1} + \alpha_2 lnEWI_{i,t} + \alpha_3 lnINO + \gamma Controls_{i,t} + \sum Year + \sum Province + \epsilon_{i,} \quad (3)$$

$$lnGMP_{i,t} = \alpha_0 + \alpha_1 lnGMP_{i,t-1} + \alpha_2 lnEWI_{i,t} + \alpha_3 lnEWI_{i,t} \times INO_{i,t} + \alpha_4 lnINO_{i,t} + \gamma Controls_{i,t} + \sum Year + \sum Province + \epsilon_{i,} \quad (4)$$

Where in, $GMP_{i,t\text{-}1}$ represents the first-order lag term of marine economic development. The other variables have the same meanings as the above.

3.2 Variables

3.2.1 Dependent variable

Marine economic development (*GMP*). Marine economic development is generally represented by the total output value of the marine industry. For economic indicators, it is necessary to convert these indicators into comparable prices. There are two methods: price index exchange algorithm and deflator index exchange algorithm. We use the marine GDP price index for comparable price conversion (Song and Shen, 2020). The computing method is as follows:

$$\text{Actual } GMP = (Base \quad GMP \times GMP \text{ price index in 2000})/100 \quad (5)$$

3.2.2 Core independent variables

(1) Extreme marine weather (*EWI*). Combined with the extreme weather indicators recommended by the *World Meteorological Organization* and the definition of extreme weather by *China Meteorological Administration*, this article selects extreme precipitation, extreme wind, extreme high temperature and extreme low temperature to calculate the extreme marine weather. By collecting daily weather data from 2000 to 2021 in the coastal regions, whether the daily weather belong to extreme weather is compared. If any of the extreme weather indicators is met, it will be marked as extreme weather. Then the total number of days with extreme weather per year is summed up. The extreme marine weather is represented by the total number of days. The definition of extreme weather indicators is shown in Table 1.

(2) Marine scientific and technological innovation. Referring to the research of Xu et al. (2022), we select the number of marine technology patent authorization in each region to indicate the regional marine technological innovation level.

3.2.3 Control variables

In order to control the missing variables in the model to ensure the unbiased regression coefficients of the core explanatory variables, this paper adds control variables to the model. In addition to the impact of extreme marine weather and marine scientific and technological innovation, other factors would impact the marine economic development. According to the previous research, the control variables of marine economy include the following variables. (1) Marine capital investment (*INV*). Since China's marine statistical systems are still far from perfect so far, the

TABLE 1 Panel regression analysis results.

	(1)	(2)	(3)	(4)	(5)
L.lnGMP				0.1992** (2.34)	0.1948* (1.83)
lnEWI	-0.0312*** (-2.98)	-0.0307*** (-2.93)	-0.0229* (-1.74)	-0.0175** (-2.15)	-0.0180** (-2.11)
lnINO	0.0236*** (3.62)	0.0263*** (3.66)	0.0259*** (3.26)	0.0181* (1.83)	0.0177* (1.89)
lnINV	0.0905*** (3.82)	0.0808*** (4.82)	0.0928*** (3.50)	0.1903*** (4.85)	0.1891*** (5.12)
lnLAB	0.0394** (2.07)	0.0316* (1.88)	0.0403** (2.04)	0.0213*** (2.97)	0.0222** (2.85)
lnENG	0.5420*** (14.82)	0.5206*** (11.94)	0.5502*** (13.09)	0.3670*** (8.29)	0.3703*** (8.03)
lnPGDP	0.4197*** (6.82)	0.4082*** (4.88)	0.3985*** (5.01)	0.0922 (1.56)	0.0941 (1.62)
lnINF	-0.2295 (-0.28)	-0.2388 (-0.49)	-0.2573 (-0.69)	-0.3827 (-0.82)	-0.3903 (-0.75)
OPEN	0.0823** (1.99)	0.0829* (1.87)	0.0682* (1.79)	0.0502* (1.86)	0.0518* (1.92)
URB	0.0228** (2.05)	0.1184*** (5.34)	0.1245*** (5.56)	1.2955** (1.99)	1.1466** (2.06)
Year & Province	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	-1.4600*** (-2.52)	-1.4605*** (-2.57)	-1.4802*** (-2.77)	-1.2052* (-1.71)	-1.1608 (-1.47)
AR(2)P-Value				0.3941	0.4090
SarganP-Value				0.6702	0.6731
N	242	242	242	220	209

The value in parentheses is t-value. *, **, *** indicate significant at the confidence levels of 1%, 5%, and 10%, respectively. It is the same in the following tables.

statistical data on marine capital is missing. Therefore, we draw on the research of Song and Shen (2020). Based on the year 2000, the perpetual inventory method is used to calculate the capital stock of the coastal regions. The ratio of the total output value of the marine industry (*GMP*) to the gross domestic product (*GDP*) is the marine capital stock of each region. (2) Marine human capital investment (*LAB*). The ratio of the number of employees in the region to the regional gross domestic product is employed to represent the marine human capital investment. (3) Energy input (*ENG*). It is the ratio of regional gross energy consumption to gross regional domestic product. (4) Regional economic development (*PGDP*). It is measured by regional per capita GDP. (5) Inflation rate (*INF*). It is represented by the regional consumer price index. (6) Level of opening-up (*OPEN*). It is the ratio of the total import and export volume to the regional gross domestic product. (7) Urbanization level (*URB*). It is measured by the ratio of the urban population to the total population in the region.

For the robustness test, we use the added value of marine economy industry (MPA) to describe the marine economic development, utilize the number of annual early-warning of marine disasters (*ALT*) to describe the extreme marine weather, and employ the annual number of marine technology patent application ($INO1$) to describe the marine scientific and technological innovation. Furthermore, we consider the average wind (AWI), average temperature (ATM), and average precipitation (AWA) as the latent missing variables.

3.3 Data

In this study, we select 11 coastal provinces (municipalities and autonomous regions) in China from 2000 to 2021. The data including the gross output value of marine economy, the added value of the marine economic industry and the gross output value of the three major marine industries come from the *China Marine Statistical Yearbook*. The weather data comes from meteorological monitoring stations in various regions. Since each region has many meteorological monitoring stations, and this article mainly investigates the impact of extreme marine weather, only the weather data from coastal meteorological stations is selected. The data collected include daily maximum wind speed, average wind speed, daily maximum temperature, minimum temperature, average temperature and daily precipitation. The number of annual early warning of marine meteorological disasters comes from the *Bulletin of China Marine Disaster*. The number of marine scientific and technological patents authorization derives from *China Marine Statistical Yearbook*. The data of other control variables are obtained from the regional statistical yearbooks (See Table 2).

TABLE 2 Moderating effect results.

	(1)	(2)	(3)	(4)	(5)
L.lnGMP				0.1590* (1.70)	0.1585* (1.75)
lnEWI	-0.0084* (-1.82)	-0.0079* (-1.76)	-0.0394*** (-2.92)	-0.0288* (-1.80)	-0.0249** (-2.10)
*lnEWI*lnINO*	-0.0021** (-2.11)	-0.0037*** (-2.34)	-0.0028*** (-4.04)	-0.0018** (-2.03)	-0.0020** (-1.99)
lnINO	0.0176* (1.89)	0.0217*** (2.35)	0.0222*** (2.39)	0.0145* (1.84)	0.0128* (1.79)
lnINV	0.0922*** (3.37)	0.0944*** (3.08)	0.0871*** (3.15)	0.1846*** (3.04)	0.1859*** (5.11)
lnLAB	0.0603** (2.01)	0.0587** (2.08)	0.0405** (1.98)	0.0387* (1.87)	0.0418* (1.82)
lnENG	0.4920*** (10.83)	0.5076*** (11.09)	0.6302*** (12.93)	0.5867*** (9.29)	0.4885*** (8.28)
lnPGDP	0.4401*** (5.22)	0.4028*** (5.78)	0.4820*** (7.02)	0.2829** (1.99)	0.1983** (1.97)
lnINF	-0.3850 (-0.57)	-0.4287 (-0.48)	-0.2927 (-0.66)	-0.3284 (-0.54)	-0.4027 (-0.71)
OPEN	0.0662* (1.86)	0.0685* (1.75)	0.0826* (1.78)	0.0982* (1.88)	0.0586** (2.05)
URB	0.0764 (0.68)	0.1092 (0.73)	0.1036 (0.44)	0.5604* (1.90)	0.7720** (1.99)
Year & Province	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	-1.3380*** (-2.61)	-1.4040*** (-2.38)	-1.6001*** (-2.65)	-1.4827** (-1.97)	- 1.1728* (-1.80)
AR(2)P-Value				0.2921	0.4900
SarganP-Value				1.0000	1.0000
N	242	242	242	220	209

The brackets represent t value, and *, ** and *** respectively represent significant at the confidence level of 1%, 5% and 10%.

4 Results

4.1 Temporal-spatial evolution characteristics

Figures 2A, B show the marine economic aggregates (GMP) in 2000 and 2021. From the two figures, it can be seen that the marine economic aggregates of 11 coastal areas have achieved rapid growth in the past 22 years. Figures 2C, D show the number of marine patents (MTP) which characterize the improvement of marine scientific and technological innovation capacity in 2000 and 2021. The two figures show that marine scientific and technological innovation of 11 coastal areas has increased notably from 2000 to 2021. However, the development of marine innovation capacity in different regions is relatively unbalanced. In 2021, the number of marine patents in Shandong and Guangdong provinces exceeded 1,000, while the number of marine patents in Hebei, Guangxi and Hainan provinces was less than 100. Figures 2E, F show the number of annual extreme marine weather days (WEI) in 2000 and 2021. From the two figures, we can see that the number of annual extreme marine weather days in each region is concentrated in 36-45 days per year. Guangxi has the largest number of extreme marine weather days in 2000, while Guangdong has the largest number of extreme marine weather days in 2021.

4.2 Panel regression results

In the panel regression analysis, we first estimate the static panel model (1), and selects mixed effects regression, fixed effects regression and random effects regression respectively. The regression results are shown in Columns (1), (2) and (3) of Table 1. Then we estimate the dynamic panel model (3). In order to ensure the robustness of the empirical results, we use the System GMM (SYS-GMM) and the Difference GMM (DIFF-GMM) to investigate the dynamic relationship between extreme marine weather and marine technological innovation on the marine economic development. The estimation results are shown in Columns (4) and (5) of Table 1.

The results of panel regression analysis are shown in Table 1. It can be seen from Table 3 that the regression results obtained by the five regression methods are basically the same, indicating that the model is robust. In the static panel model, according to T test and Hausman test, the fixed effect model is the most suitable. In the dynamic panel model, according to the Arellano-Bond sequence correlation test and Sargan test, the test results show that the P value of AR(2) test is greater than 0.1, so there is no second-order autocorrelation in the residual series of the difference equation. The P value of Sargan test is greater than 0.1, indicating that all instrumental variables are valid. Therefore, the

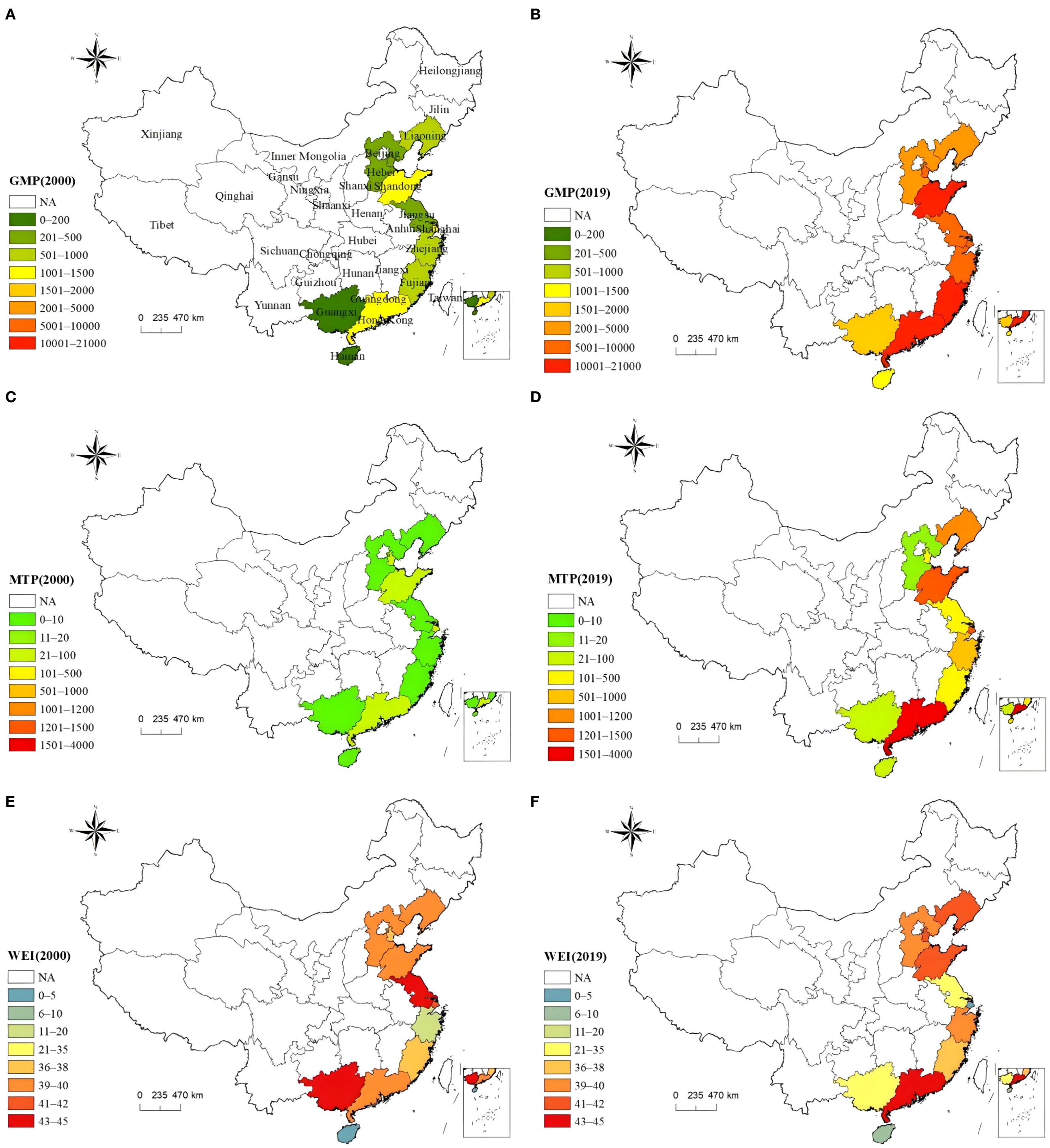

FIGURE 2
Temporal-spatial evolution characteristics. **(A)** GMP value of coastal areas in 2000. **(B)** GMP value of coastal areas in 2021. **(C)** MTP number of coastal areas in 2000. **(D)** MTP number of coastal areas in 2021. **(E)** WEI number of coastal areas in 2000. **(F)** WEI number of coastal areas in 2021.

estimation results of the difference GMM and the system GMM are consistent and effective. Considering that the static panel model may have missing variables and endogenous problems, we use the dynamic panel model for analysis. Compared with the Difference GMM, the system GMM combines the Difference GMM with the Level GMM, and uses the level lag term as the instrumental variable of the Difference GMM. Furthermore, the System GMM estimation efficiency is higher, and the System GMM estimation can significantly reduce the estimation bias in the case of small samples. Therefore, we use the results of System GMM estimation (Column (5) in Table 1) for analysis.

The results of System GMM estimation show that the coefficient of extreme marine weather (*lnEWI*) is negative, while the coefficient of marine scientific and technological innovation (*lnINO*) is positive. They have passed the 10% statistical level significance test. Therefore, the extreme marine weather significantly negatively impact the marine economic development. The improvement of technological innovation

TABLE 3 Heterogeneity analysis of the four sea areas.

	Bohai	Yellow Sea	East China Sea	South China Sea
L.lnGMP	0.4093*** (3.84)	0.3389* (1.72)	0.3172** (1.98)	0.2209* (1.72)
lnEWI	-0.0406** (-2.17)	-0.0502*** (-3.20)	-0.0203* (-1.92)	-0.0293* (-1.88)
lnINO	0.0291* (1.81)	0.0120* (1.94)	0.0117** (2.05)	0.0492*** (3.18)
lnINV	0.0823* (1.77)	0.0932*** (3.43)	0.3048*** (4.55)	0.0220* (1.65)
lnLAB	0.1410*** (3.26)	0.2581*** (5.13)	0.0424* (1.69)	0.0483* (1.73)
lnENG	0.5325*** (7.92)	0.1831* (1.88)	0.3824*** (3.28)	0.5001*** (3.10)
lnPGDP	0.1943* (1.73)	0.1737 (1.38)	0.1402 (0.92)	0.1708 (0.66)
lnINF	0.0225* (1.83)	0.0439* (1.72)	0.0500** (2.14)	0.0299** (2.05)
OPEN	0.3380** (1.97)	0.5050*** (4.40)	0.3843*** (3.83)	0.1259*** (3.77)
URB	1.5039** (2.05)	1.7832*** (3.30)	1.4948*** (3.09)	1.8733*** (2.44)
Year & Province	*Yes*	*Yes*	*Yes*	*Yes*
Constant	-2.9382* (-1.76)	-1.9024*** (-4.92)	-4.0022* (-1.86)	-2.9380* (-1.81)
AR(2)P-Value	0.3983	0.6600	0.4490	0.4029
SarganP-Value	1.0000	1.0000	1.0000	1.0000
N	84	63	84	63

The brackets represent t value, and *, ** and *** respectively represent significant at the confidence level of 1%, 5% and 10%.

capacity will effectively fuel the development of the regional marine economy. For the remaining control variables, except for the consumer price index (*lnINF*) and the per capita GDP (*lnPGDP*), which leave no significant impact on the marine economic development, the other control variables are significant at the 10% level, and are basically consistent with the results of other scholars (Zhang and Chen, 2020). Among them, the marine capital investment, marine human capital investment and energy input significantly advance the development of marine economy. The improvement of the level of opening up and urbanization will further the development of regional marine economy.

4.3 Moderating effect results

The occurrence of extreme marine weather is affected by various comprehensive factors such as environmental periodic changes and air pollution. It is difficult for regional governments to control and reduce the occurrence of extreme marine weather to avoid the negative impact of extreme weather on marine economy. However, with the sustained growth of China's economy, and the improvement of technological innovation capacity, whether the improvement of marine scientific and technological innovation can reduce the negative impact of extreme marine weather on marine economic development? To answer this question, we further estimate Models (2) and (4) study the moderating effect of the marine scientific and technological innovation on the marine economic development.

The empirical results are shown in Table 2. The results of Columns (1), (2), and (3) in Table 2 are mixed effects regression, fixed effects regression and random effects regression, respectively. The results of Columns (4) and (5) are the System GMM and the Difference GMM estimation. It can be seen that the regression results of Columns (1)-(5) are consistent, and the regression results are robust. The extreme marine weather (*lnEWI*) has a significantly negative impact on the marine economic development, and the marine scientific and technological innovation (*lnINO*) has a significantly positive impact on the marine economic development. From the System GMM estimation results (Column (5) in Table 2), the impact of the interaction term of extreme marine weather and marine scientific and technological innovation on the marine economy is significantly negative. It indicates that the marine scientific and technological innovation has a negative moderating effect on the extreme marine weather. The improvement of the marine scientific and technological innovation has alleviated the negative impact of extreme marine weather on the development of marine economic development. It means that the progress made in marine scientific and scientific and technological innovation has enhanced the resilience of marine economic activities to marine extreme weather.

4.4 Further research

4.4.1 Heterogeneous analysis of marine industries

There are three major marine economic industries. The marine primary industry includes marine fishery. The marine secondary industry involves beach placer mining industry, offshore oil and natural gas industry, marine chemical industry, marine biomedicine industry, marine salt industry, marine electric power industry, marine seawater utilization industry, marine engineering architecture industry, and marine shipbuilding industry. The marine tertiary industry consists of coastal tourism, maritime communications and transportation industry, and marine scientific research and management education services. We reclassify the regional marine economic development according to the three marine economic industries. Taking into account the development characteristics of the three marine economic industries, the impacts brought by the extreme marine weather and marine scientific and technological innovation on the three marine industries may be different. Therefore, we conduct heterogeneous analysis of the impacts of the extreme marine weather and marine scientific and technological innovation on the three marine economic industries.

The results are shown in Table 3. We find that the extreme marine weather significantly negatively impacts the three marine economic industries. The impact of extreme marine weather on the marine secondary industry is approximately equal to that on the marine tertiary industry, while is greater than that on the marine primary industry. The marine scientific and technological innovation significantly positively impacts the three marine economic industries. The impact of marine scientific and technological innovation on the marine tertiary industry is largest, while that on the marine tertiary industry is smallest.

4.4.2 Heterogeneity analysis of four sea areas

The total length of China's coastline is approximately 18,400 kilometers. The 11 provinces (municipalities and autonomous regions) located at four marine regions, which are Bohai Sea, Yellow Sea, East China Sea and South China Sea. Considering they differ in the climatic condition and resource reserves, they are redivided to belong to four marine areas (See Table 3). According to the regression analysis of the four sea areas, the results are shown in Table 4. We find that the impacts of extreme marine weather and marine scientific and technological innovation on the marine economic development pass the 10% statistical level significance test. The area with the largest negative impact of marine extreme weather on the marine economic development is the Bohai Sea, with the coefficient of -0.0502. While the area with the smallest negative impact of that is the Yellow Sea, with the coefficient is -0.0063. The area where the marine scientific and

TABLE 4 Heterogeneity analysis of marine industries.

	Primary industry	Secondary industry	Tertiary Industry
L.lnGMP	0.4022*** (3.73)	0.3023*** (3.10)	0.3831* (1.86)
lnEWI	-0.0192*** (-2.60)	-0.0196** (-2.10)	-0.0382* (-1.70)
lnINO	0.0194* (1.73)	0.0207* (1.80)	0.0227* (1.84)
lnINV	0.1384* (1.70)	0.1284** (2.01)	0.2677*** (4.20)
lnLAB	0.0103*** (2.97)	0.5020*** (5.21)	0.2031*** (4.22)
lnENG	0.1039*** (4.04)	0.2886*** (4.02)	0.3395*** (4.11)
lnPGDP	0.0884** (1.99)	0.0221 (0.40)	0.0449** (2.12)
lnINF	-0.0110* (-1.75)	-0.0333 (-0.49)	-0.0282 (-1.51)
OPEN	0.1448* (1.70)	0.0842 (0.92)	0.1298* (1.88)
URB	2.1030* (1.77)	1.5200** (1.99)	0.7720** (2.15)
Year & Province	*Yes*	*Yes*	*Yes*
Constant	2.8845 (1.44)	1.2191*** (2.58)	1.3861* (1.84)
AR(2)P-Value	0.5183	0.4209	0.3902
SarganP-Value	1.000	1.000	1.000
N	220	220	220

The brackets represent t value, and *, ** and *** respectively represent significant at the confidence level of 1%, 5% and 10%.

technological innovation has the greatest positive impact on the marine economic development is the South China Sea, with the coefficient of 0.0492. While the Yellow Sea area with the smallest positive influence coefficient, with a coefficient of 0.0120.

4.4.3 Heterogeneity analysis of marine economic development level

The average of the gross output value of marine economy and the number of marine patents authorization in 11 coastal provinces (municipalities and autonomous regions) from 2000 to 2021 is shown in Table 4. It can be seen that the marine economic development of Guangdong, Shandong, Shanghai and Fujian is relatively advanced. Guangdong, Shandong, Shanghai and Liaoning have the most marine patents authorization, with a high level of marine technological innovation. Therefore, we delineate the top 4 regions as high-level marine economic development areas, the middle 4 regions as medium-level marine economic development areas, and the last three regions as low-level marine economic development areas. According to the regression analysis of the redivided marine economic development level, the results are shown in Table 5. We find that the impact of extreme marine weather and marine scientific and technological innovation on the marine economic development have both passed the 10% level significance test. The extreme marine weather and marine scientific and technological innovation have the greatest impact on the areas with high marine economic development level, with the coefficients of 0.2022 and -0.2902 respectively. The extreme marine weather and marine scientific and technological innovation have the least impact on the areas with low marine economic development level, with the coefficients of 0.0248 and -0.0302 respectively.

5 Robustness test

5.1 Replace dependent variable with the added value of marine economic industries

Both the added value of marine economic industry and the gross output value of marine economy can represent the marine economy development. Therefore, we takes the added value of the marine economic industry as the dependent variable to do re-regression test. The results are shown in Column (1) of Table 6. We find that extreme marine weather is significantly negatively correlated with the added value of marine economic industries, with a coefficient of -0.0472. The marine scientific and technological innovation is still positively correlated with the added value of marine economic industries, with a coefficient of 0.0155. It is in line with the benchmark results of this article.

TABLE 5 Regional heterogeneity analysis of economic development level.

Marine economic development	Low-level area	Mid-level area	High level area
L.lnGMP	0.4583*** (4.02)	0.3390** (1.98)	0.1010* (1.84)
lnEWI	0.0248* (1.78)	0.1920* (1.81)	0.2022* (1.79)
lnINO	-0.0302*** (-3.20)	-0.0281*** (-3.04)	-0.2902*** (-3.44)
lnINV	-0.1922** (2.00)	0.2088*** (3.25)	0.3309** (1.99)
lnLAB	-0.2294*** (3.44)	0.1218** (2.17)	0.2305*** (3.33)
lnENG	0.7029*** (5.82)	0.4280*** (4.28)	0.3392*** (4.02)
lnPGDP	0.4290* (1.84)	0.3393** (2.04)	0.4823*** (3.02)
lnINF	-0.1296* (-1.70)	-0.2280* (-1.73)	-0.3012 (-1.46)
OPEN	0.3302* (1.72)	0.2049** (1.97)	0.2293* (1.80)
URB	0.9921 (1.20)	1.2939*** (4.02)	1.3029** (2.16)
Year & Province	*Yes*	*Yes*	*Yes*
Constant	-0.4822* (-1.77)	-0.5275*** (-2.59)	-2.0302* (-1.73)
AR(2)P-Value	0.4682	0.4250	0.4010
SarganP-Value	1.0000	1.0000	1.0000
N	63	84	84

The brackets represent t value, and *, ** and *** respectively represent significant at the confidence level of 1%, 5% and 10%.

TABLE 6 Robustness test results.

	(1)	(2)	(3)	(4)
L.lnGMP		0.3771*** (3.46)	0.3543*** (3.73)	0.3572* (1.90)
L.lnMPA	0.4042*** (4.01)			
lnEWI	-0.0386* (-1.81)	-0.0485*** (-2.42)		-0.0339* (-1.72)
lnALT			-0.0734* (-1.77)	
lnINO	0.0155* (1.73)		0.0384*** (2.58)	0.0476* (1.88)
lnAPP		0.0759** (1.98)		
lnAWI				-0.0482* (-1.90)
lnATM				0.3380** (1.98)
lnAWA				-0.2837 (-0.93)
lnINV	0.8336*** (2.69)	0.1084*** (4.64)	0.2874* (1.70)	0.2284*** (4.03)
lnLAB	0.1737** (1.98)	0.0298* (1.80)	0.0283*** (3.45)	0.0382* (1.70)
lnENG	1.6921*** (6.66)	0.5620*** (6.88)	0.3229*** (5.29)	0.3782*** (5.28)
lnPGDP	0.3781** (1.99)	0.1731* (1.83)	0.1183* (1.75)	0.1229 (1.52)
lnINF	-0.0468 (-0.37)	-0.3048 (-1.61)	-0.2990 (-0.87)	-0.2176 (-0.43)
OPEN	0.3653 (1.27)	0.2832* (1.79)	0.1285* (1.84)	0.1105* (1.81)
URB	1.4472*** (2.64)	1.4838*** (2.99)	1.3380*** (2.93)	1.2280*** (2.55)
Year & Province	*Yes*	*Yes*	*Yes*	*Yes*
	4.8200* (1.80)	3.9824* (1.85)	2.7470* (1.86)	1.7432* (1.85)
AR(2)P-Value	0.3075	0.1582	0.4733	0.4283
SarganP-Value	1.0000	1.0000	1.0000	1.0000
N	220	220	220	220

The brackets represent t value, and *, ** and *** respectively represent significant at the confidence level of 1%, 5% and 10%.

5.2 Replace the number of patents authorization with the number of patent applications

Both the number of patents authorization and application can represent the innovation vitality and innovation capacity and reflect the innovation level. Therefore, we use the number of patents application to replace the number of patents authorization as the independent variable of marine scientific and technological innovation. The test results are shown in Column (2) of Table 6. The results show that extreme marine weather and marine economic development are still significantly negatively correlated, with a coefficient of -0.0485. There is still a significant positive correlation between the marine scientific and technological innovation and the marine economic development, with a coefficient of 0.0759. It is consistent with the benchmark results of this article.

5.3 Replace the extreme marine weather days with the early-warning number of marine disasters

Both the early-warning number of marine disasters and extreme marine weather days reflect the harsh climate environment faced by marine economic production. Therefore, we utilize the early-warning number of marine disasters issued by the *China Marine Early Warning and Monitoring Department* to replace the extreme marine weather days. We reexamine the impacts of extreme marine weather and marine scientific and technological innovation on marine economic development. The results are shown in Column (3) of Table 6. We find that the marine scientific and technological innovation is significantly positively correlated with marine economic development, while the early-warning number of marine disasters is significantly negatively correlated with the marine economic development in a significant manner. This is consistent with the previous results of this article.

5.4 Missing variables test

Due to the different geographical conditions of each region, the marine economic development may be affected by other factors, such as local temperature, precipitation, and wind conditions. These factors may be the important missing variables. Therefore, the climate variables including average wind, average temperature, and average precipitation, are used as missing variables for re-regression. The results are shown in Column (4) of Table 6. We find that after adding possible missing variables, the impact of extreme marine weather and marine scientific and technological innovation and on marine economy are consistent with the previous results. Therefore, the results of benchmark regression of this article is robust.

6 Discussion

The marine economic development is affected by a complex system with many dynamic factors and their interactions. This paper considers the two possible major system elements of extreme marine weather and marine scientific and technological innovation on marine economic development. On one hand, the extreme marine weather causes great damage to the marine primary industry, marine secondary industry and tertiary industry. So it significantly negatively impact the marine economic development. On the other hand, the marine scientific and technological innovation provides the advanced technologies for marine production activities and improve productivity, and it effectively fuel the marine economic development (Mabon et al., 2020; Li et al., 2021c). Therefore, we should continuously optimize and upgrade of the marine industrial structures, and minimize the impact of extreme marine weather on marine economic development. Also, the government and enterprises should promote the marine scientific and technological innovation and provide the support for the marine economic activities.

The improvement of the marine scientific and technological innovation has alleviated the negative impact of extreme marine weather on the marine economic development. It means that the progress made in marine scientific and technological innovation has enhanced the resilience of marine economic activities to marine extreme weather. The development of marine scientific and technological innovation improves the early-warning capacity of extreme marine weather, promotes the efficiency of marine energy mining and detection, and increases marine carriage capacity and cargo security. The marine scientific and technological innovation enlarges marine transportation radius and extends operation hours at sea, which makes the marine secondary and tertiary industries are more independent on the marine weather (Shao, 2020; Liu et al., 2021). Therefore, it effectively reduces and minimizes the negative impact of extreme marine weather on marine economic development.

The extreme marine weather and marine technological innovation have the greatest impact on the marine tertiary industry and the least impact on the primary industry. The reason may be that compared with the secondary and tertiary industries, the primary industry has a smaller economic scale and relies less on technology. Therefore, an advance in the level of technological innovation has the least impact on the marine primary industry. In addition, there are two periods - fishing season and fishing closed season, which affect the primary industry, especially the marine fishery. The fishing closed season in China is generally from May to September each year. The specific time is adjusted according to local conditions. During the fishing ban, on the one hand, China's fishery resources are protected and restored. On the other hand, it is the months when extreme marine weather occurs frequently. According to statistics, the frequent months of extreme rainfall and typhoons in China are July, August, and September each year. Therefore, extreme weather has relatively little impact on China's marine primary industry. With the continuous upgrading of China's marine industrial structure in recent years, the marine secondary and tertiary industries have played a dominant role in the marine economic development. In 2019, the primary, secondary and tertiary industries of the marine economy accounted for 4.2%, 35.8% and 60%, respectively. The marine tertiary industry relies on marine transportation and marine scientific research, and is closely related to marine technological innovation. Therefore, the level of marine technological innovation has the most tremendous impact on the tertiary industry development. The marine tertiary industry transportation and scientific research are greatly affected by weather, so the industry is most affected by extreme marine weather.

The area with the largest negative impact of marine extreme weather is the Bohai Sea, while the area with the smallest negative impact of that is the Yellow Sea. The South China Sea where the marine scientific and technological innovation has the greatest positive impact, while the Yellow Sea area with the smallest positive influence. The reason responsible for the above results may be that the temperature change of the Bohai Sea is affected by the northern continental climate. When winter begins, except for Qinhuangdao and Huludao, the coast is basically frozen. A large amount of drift ice often occurs during ice melting at the beginning of March. Due to a large amount of fresh water injected from the continental rivers, the salinity in the Bohai Sea is only 30 PSU (Practical salinity unit), which is the lowest in the offshore area of China. Therefore, the impact of extreme weather on marine economy in the Bohai Sea is more severe. On the whole, the current of the Yellow Sea is weak, and the flow velocity is usually only about one tenth of the maximum tidal current. Compared with the Bohai Sea, the Yellow Sea is warm and humid, and the typhoon weather disasters there are much less than those in the East China Sea and the South China Sea. The Yellow Sea is a famous fishing ground in China. The total output value of Shandong's primary industry ranks first in China. The marine primary industry is least affected by extreme marine weather. Therefore, extreme marine weather has a relatively minimal impact on the Yellow Sea area. In the South China Sea, there are many resource exploration and marine transportation activities, which rely on the development of science and technology. Therefore, the improvement of technological innovation has the greatest impact on the marine economy of the South China Sea. By contrast, the Yellow Sea region places more emphasis on the marine primary industry, and the total amount of ocean exploration and marine transportation is slightly lower than other areas. Therefore, the marine scientific and technological innovation has a relatively weak impact on the marine economic development in the Yellow Sea region.

The extreme marine weather and marine scientific and technological innovation have the greatest impact on the areas with high marine economic development level, while have the least impact on the areas with low marine economic development level. The reason may be that regions with a high level of economic development generally take the lead in the number of marine patents authorized, indicating that these regions have a relatively high level of marine technological innovation. Although the number of days of extreme weather is less than that of regions with a medium level of economic development, the regions with a high level of marine economic development are more dependent on the secondary and tertiary industries, so they are more affected by extreme marine weather (Aswathy et al., 2016; Zheng et al., 2020). On the contrary, in areas with lower level of marine economic development, the marine industrial structure is more incomplete, and the marine secondary and tertiary industries are relatively underdeveloped, so they are more likely affected by extreme marine weather.

7 Conclusions and policy recommendations

In this study, we use the data of the marine economic development, marine weather and marine scientific and technological innovation from 2000 to 2021 in 11 coastal provinces (municipalities and autonomous regions) in China, and empirically analyzes the impact of extreme marine weather and marine scientific and technological innovation on the marine economic development. The heterogeneous impact are analyzed in detail.

Our empirical results indicate that (1) the extreme marine weather has a significant negative impact on marine economic development, while the marine scientific and technological innovation has a significant positive impact on the marine economy. The marine scientific and technological innovation has notably reduced the unfavorable impact of extreme marine weather on marine economic development. (2) The impact of extreme marine weather on the marine secondary industry is approximately equal to that on the marine tertiary industry, while is greater than that on the marine primary industry. The impact of marine scientific and technological innovation on the marine tertiary industry is largest, while that on the marine tertiary industry is smallest. (3) The area with the largest negative impact of marine extreme weather is the Bohai Sea, while the area with the smallest negative impact of that is the Yellow Sea. The marine scientific and technological innovation has the greatest impact in the South China Sea, while the smallest positive influence of marine scientific and technological innovation in Yellow Sea. (4) The regions with high marine economic development level are most affected by extreme marine weather and marine scientific and technological innovation, while the regions with low marine economic development level are least impacted.

Based on the above conclusions, the following policy recommendations are drawn:

(1) The marine meteorological monitoring departments strengthen the early warning of extreme marine weather and disperse the risk of extreme marine weather. On the one hand, the marine meteorological monitoring departments in various regions need to further improve the monitoring of extreme weather, and actively introduce satellite monitoring technology, information technology and big data analysis technology to continuously improve the monitoring efficiency of extreme weather. On the other hand, the economic and financial policies should be improved. The relevant financial insurance, financial subsidies and policy support should be optimized. In addition, financial tools should be used to disperse the risks caused by extreme weather so as to reduce the negative impact of extreme marine weather on the marine economy.

(2) The local governments promotes the marine scientific and technological innovation. For all regions, particular in the coastal areas, the attention should be paid to the development of marine scientific and technological innovation. In the process of building China's strength in the science and technology, special attention needs to be paid to the improvement of marine science and technology. Moreover, the universities, enterprises and scientific research departments are encouraged to inspect China's marine economic production on the spot. The policy support and funding support are provided to push forward scientific and technological innovation. These measures could promote the marine scientific and technological innovation and ensure the steady development of the marine economy.

(3) The local governments promote the upgrading of the marine industrial structure. As China's marine economy has entered a new normal of economic development, the government should continuously optimize the structure of marine primary, secondary and tertiary industries and improve the quality of marine industries.

The marine regions develop high value-added industries, green and low-carbon industries, and industries with international competitiveness. In addition, the government should promote the development of the marine tertiary industry and ensure that technological innovation becomes the first driving force for the development of the marine economy. Promoting the development of the marine tertiary industry will effectively boost the scientific and technological innovation and enhance the substitution of science and technology in the development of marine economy.

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

CL (first author): conceptualization, methodology, software, investigation, formal analysis, and writing - original draft; HJ: data curation and writing - original draft; YW: visualization and investigation; BZ: resources and supervision; XF and WZ: software and validation; TL: visualization and writing - review and editing; YH (corresponding author): conceptualization, funding acquisition, resources, supervision, and writing - review and editing. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by Hebei Social Science Fund Project (No.: HB18YJ011), University Level Project of Guizhou University of Finance and Economics in 2020 (No.: 2020XZD01).

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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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1104045/full#supplementary-material

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