

## *Retraction*

# **Retracted: Measurement of Coordinated and Coupled Development and Evaluation of Sustainable Development for Marine Economic-Ecological Complex System**

### **Discrete Dynamics in Nature and Society**

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This article has been retracted by Hindawi following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of one or more of the following indicators of systematic manipulation of the publication process:

- (1) Discrepancies in scope
- (2) Discrepancies in the description of the research reported
- (3) Discrepancies between the availability of data and the research described
- (4) Inappropriate citations
- (5) Incoherent, meaningless and/or irrelevant content included in the article
- (6) Peer-review manipulation

The presence of these indicators undermines our confidence in the integrity of the article's content and we cannot, therefore, vouch for its reliability. Please note that this notice is intended solely to alert readers that the content of this article is unreliable. We have not investigated whether authors were aware of or involved in the systematic manipulation of the publication process.

Wiley and Hindawi regrets that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our own Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

### **References**

- [1] M. Wen, C. Liu, K. A. Mamonov, and J. Du, "Measurement of Coordinated and Coupled Development and Evaluation of Sustainable Development for Marine Economic-Ecological Complex System," *Discrete Dynamics in Nature and Society*, vol. 2021, Article ID 2043635, 12 pages, 2021.

## Research Article

# Measurement of Coordinated and Coupled Development and Evaluation of Sustainable Development for Marine Economic-Ecological Complex System

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The development of marine economy has stimulated the need for marine natural products and services, as well as the demand and utilization intensity of marine resources. As a result, the coastal regions start to discharge more and more pollutants, posing a serious threat to marine ecoenvironment. Because of the interactions between marine economy and marine ecology, it is of practical significance to study the marine economic-ecological complex system (MEECS). However, the relevant studies have several common defects: the incomplete data statistics system, the limited attention on development law or action mechanism, and the lack of long-term quantitative and empirical analysis. To overcome these defects, this paper tries to measure the coordinated and coupled development (CCD) and evaluate the sustainable development of MEECS. Specifically, an ecology-dominated coordinated development model was proposed for the complex system, and a differential equation model was established to describe the dynamic coordinated development of the complex system. Through data envelopment analysis (DEA), the sustainable development of the complex system was evaluated based on its input-output efficiency. Through experiments, the outputs of decision-making units (DMUs) of our model were obtained, and the development of the subsystems in MEECS was evaluated comprehensively to verify the effectiveness of our algorithm.

## 1. Introduction

The ocean provides humans with an abundance of food and rich chemical, power, and mineral resources. It is an important link in global ecological balance [1–4]. In recent years, there is a growing demand of natural products/services and resources and a rise in the utilization intensity of natural resources. As a result, the coastal regions in China discharge more and more pollutants, which seriously threaten the marine ecoenvironment. Therefore, it is of practical significance to measure the coordinated and coupled development (CCD) and evaluate the sustainable development of the marine economic-ecological complex system (MEECS) [5–10].

The coordinated development of marine economy and ecoenvironment is critical to the national strategies for ocean and regional coordinated development [11–14]. Broszeit et al. [15] empirically analyzed the coordinated development level of the regional MEECS, constructed a coordination measurement model for the complex system based on core influencing factors, and carried out principal component analysis (PCA) and regression fitting, producing the trend map for the coordination level of the MEECS in 2015–2020. Paoli et al. [16] probed deep into the relationship between the ecoenvironment and the three industries of regional marine economy, created an entropy-based coordination measurement model that combines the merits of various econometric models, and performed feature analysis and

simulation of different stages of development, namely, uncoordinated recession, coordinated development, and transition. Beaumont et al. [17] examined the problems in the industrial structure of marine economy and the surrounding environment, analyzed the environmental evolution and the coordination of the MEECS, using artificial neural network (ANN) and variable fuzzy evaluation, and plotted the ecological and economic outcomes of the complex system.

The destruction of the marine ecoenvironment will seriously restrict the development of major marine economic industries, such as marine fisheries, marine tourism, and marine biomedical industry [18–20]. Woods et al. [21] treated marine economy, society, and ecoenvironment as three dimensions of the same complex system, analyzed the system features such as action, penetration, and dependence, and constructed a nonradial, nonangular slack-based measure (SBM) model for the complex system with a ring structure. Jacob and Rao [22] set up a marine ecological service database covering coastal city development index, marine ecology-economy investment, and labor input of marine environmental protection, carried out phased analysis on the development efficiency of the MEECS, and measured the development level and overall efficiency of the complex system in each stage, with the aid of data envelopment analysis (DEA). Bicho and Haws [23] combined the improved entropy method with DEA into a second-order relative evaluation model for the subject effort of coastal provinces in China for high-quality economic development and compared the measured SBM superefficiencies of eight coastal cities.

So far, researchers engaging in marine development have analyzed several problems in marine ecology, resources, and economy from the perspectives of different disciplines and industries. However, the relevant studies have several common defects: the incomplete data statistics system, the limited attention on development law or action mechanism, and the lack of long-term quantitative and empirical analysis. To overcome these defects, this paper tries to measure the CCD and evaluate the sustainable development of MEECS. Section 2 proposes an ecology-dominated coordinated development model for the MEECS and establishes a differential equation model that describes the dynamic coordinated development of the complex system. Section 3 carries out DEA to evaluate the sustainable development of the complex system based on its input-output efficiency. Section 4 conducts several experiments to determine the output of the decision-making units (DUs) in our model and the composite development level of each subsystem in the complex system.

This paper attaches equal importance to marine ecological development and marine economic growth and treats the MEECS as an organic whole. The coordinated development of the complex system was discussed in detail from the perspective of each subsystem. In addition, DEA was introduced to enhance the pertinence and timeliness of the research.

## 2. Complex System CCD Analysis

Figure 1 illustrates the ecology-dominated coordinated development model for the complex system. As shown in Figure 1, marine economy cannot grow properly and the ocean cannot realize sustainable development, which features resource conservation, balance, orderliness, and co-existence, unless the resources are developed properly and the environmental policies are implemented reasonably. To adopt the model, the coastal provinces must first clarify the objectives of the MEECS, stop putting consumerism above anything else, and seek regulation and institutional guarantee that conform to the law of sustainable development.

This paper constructs a differential equation model to describe the dynamic coordinated development of the MEECS. Let  $EC_1$  and  $EC_2$  be the development state of marine economy and the damage state of marine ecoenvironment, respectively,  $\beta_1$  and  $\beta_2$  be the growth rates of marine economy and ecoenvironmental damage, respectively, and  $\alpha_{12}$  and  $\alpha_{21}$  be the degree of impact from marine ecoenvironment on marine economy and that from marine economy on marine ecoenvironment, respectively. Then, the coordination  $\sigma$  between the development of the two subsystems of the MEECS and the coordination of subsystem development can be established based on the above parameters:

$$\left\{ \begin{array}{l} \sigma = \frac{(\alpha_{12} \times \alpha_{21})^{1/4}}{\sqrt{2}}, \\ EC_i(\tau + 1) = \frac{\alpha_i EC_i(\tau)}{1 + \sum_{j=1}^2 \alpha_{ij} EC_j(\tau)}. \end{array} \right. \quad (1)$$

Figure 2 provides the coordination indices of subsystem development in the complex system. Let  $v_i$  and  $u_{ij}$  be the growth rate and inhibition effect of the  $i$ -th factor affecting system development, respectively,  $u_{ij}$  be the competitive rate reflecting the proportion of the  $i$ -th factor affected by the  $j$ -th factor, and  $i=1$  and  $j=2$  are the development levels of marine economy subsystem and marine ecology subsystem, respectively. Then, model (1) can be written in the differential form:

$$\left\{ \begin{array}{l} \frac{da_1}{d\tau} = v_1 EC_1 - u_{11} EC_1^2 - u_{12} EC_1 EC_2, \\ \frac{da_2}{d\tau} = v_2 EC_2 - u_{22} EC_2^2 - u_{21} EC_1 EC_2. \end{array} \right. \quad (2)$$

Formula 2 can be further simplified as

$$\frac{d(EC_i)}{d\tau} = EC_i(v_i - u_{ii} EC_i) - \sum u_{ij} EC_i EC_j, \quad (3)$$

where whether  $u_{ij}$  and  $u_{ji}$  are greater than zero determines the type of competition between subsystems. (1) If both  $u_{ij}$  and  $u_{ji}$  are greater than zero, then the  $i$ -th and  $j$ -th factors are pure competitors. The development of one factor is

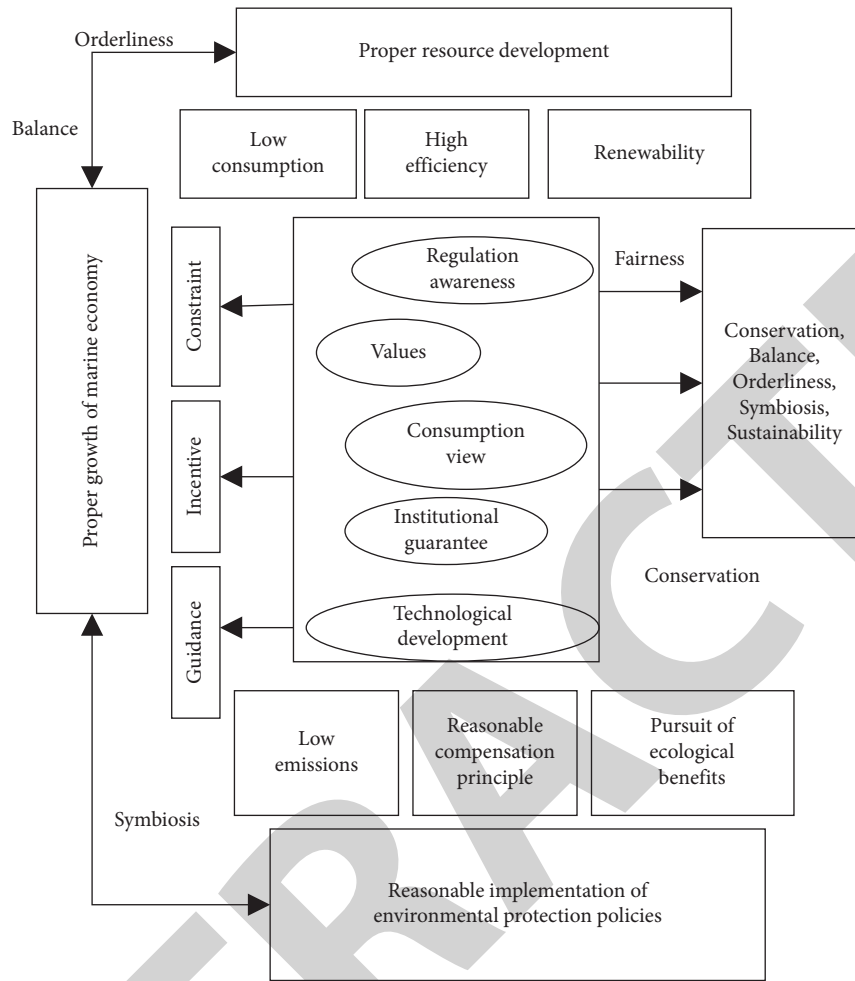


FIGURE 1: Ecology-dominated coordinated development model for the complex system.

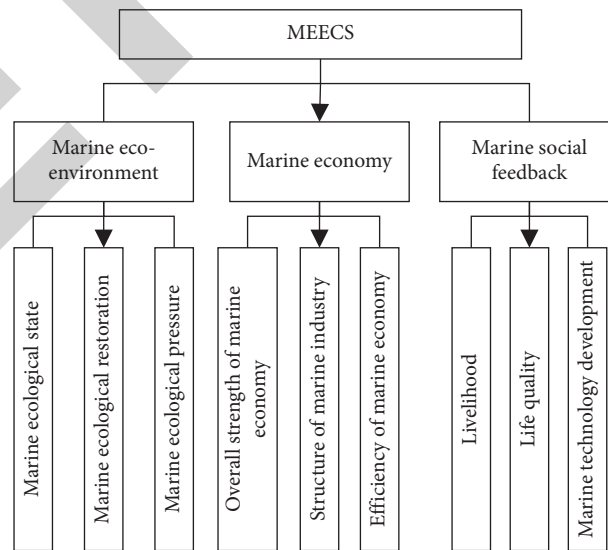


FIGURE 2: Coordination indices of subsystem development in the complex system.

constrained by the development of the other. (2) If both  $u_{ij}$  and  $u_{ji}$  are smaller than zero, then the two factors promote each other. (3) If both  $u_{ij}$  and  $u_{ji}$  are zero, the two factors do

not affect each other. (4) If  $u_{ij} > 0$  and  $u_{ji} < 0$ , the  $i$ -th factor suppresses the development of the  $j$ -th factor, while the  $j$ -th factor hinders the development of the  $i$ -th factor, creating a

supplier-receiver relationship. (5) If  $u_{ij} > 0$  and  $u_{ji} = 0$ , there is an amensalism between the two factors: the former suppresses the development of the latter, but the latter does not affect the development of the former. (6) If  $u_{ij} < 0$  and  $u_{ji} = 0$ , there is a symbiosis between the two factors: the latter promotes the development of the former, but the former does not affect the development of the latter.

To facilitate the calculation of parameters for subsequent simulation, the simplified model (3) can be written as a discrete model with piecewise continuous derivative solutions:

$$\frac{dEC_i(\tau)}{d\tau} = v(\tau)EC_i(\tau) - u(\tau)EC_i(\tau)^2. \quad (4)$$

According to the properties of the solutions to the discrete model, the solutions of formula 4 are not absolutely differentiable when  $v$  and  $u$  change continuously. If  $i = 1$  or  $2$ , the parameters can be rounded:

$$\frac{dEC_i(\tau)}{d\tau} = v(\tau)EC_i(\tau) - u(\tau)EC_i(\tau)^2, \quad m < \tau < m + 1, \quad (5)$$

where  $m$  is a positive integer. Transposing the terms, we obtain

$$-\frac{dEC_i(\tau)}{d\tau} + v(\tau)EC_i(\tau) = -u(\tau)EC_i(\tau)^2, \quad m < \tau < m + 1. \quad (6)$$

Multiplying both sides with  $1/a^2$ , we obtain

$$-\frac{EC_i(\tau)'}{d\tau} + v(\tau)\frac{1}{EC_i(\tau)} = u(m), \quad m < \tau < m + 1. \quad (7)$$

Multiplying both sides with  $e^{v(m)\tau}$ , we obtain

$$\frac{EC_i(\tau)'}{EC_i(\tau)^2}e^{v(m)\tau} + \frac{v(m)e^{v(m)\tau}}{EC_i(\tau)} = e^{v(m)\tau}u(m), \quad m < \tau < m + 1. \quad (8)$$

Formula 8 is equivalent to

$$\frac{d(e^{v(m)\tau}/EC_i(\tau))}{d\tau} = e^{v(m)\tau}u(m), \quad m < \tau < m + 1. \quad (9)$$

Integrating with respect to formula 9, we obtain

$$\frac{1}{EC_i(\tau)}e^{v(m)\tau} - \frac{1}{EC_i(m)}e^{v(m)m} = \frac{u(m)(e^{v(m)\tau} - e^{v(m)m})}{v(m)}. \quad (10)$$

Transposing the terms, we obtain

$$\frac{1}{EC_i(\tau)}e^{v(m)\tau} = \frac{e^{v(m)m}}{EC_i(m)} + \frac{u(m)(e^{v(m)\tau} - e^{v(m)m})}{v(m)}. \quad (11)$$

By arranging formula 11, we obtain

$$\frac{e^{v(m)\tau}}{EC_i(\tau)} = \frac{v(m)e^{v(m)m} + EC_i(m)u(m)(e^{v(m)\tau} - e^{v(m)m})}{v(m)EC_i(m)}. \quad (12)$$

Taking the reciprocal of formula 12, we obtain

$$\frac{EC_i(\tau)}{e^{v(m)\tau}} = \frac{v(m)EC_i(m)}{v(m)e^{v(m)m} + EC_i(m)u(m)(e^{v(m)\tau} - e^{v(m)m})}. \quad (13)$$

Multiplying both sides with  $e^{v(m)\tau}$ , we obtain

$$EC_i(\tau) = \frac{v(m)EC_i(m)e^{v(m)\tau}}{v(m)e^{v(m)m} + EC_i(m)u(m)(e^{v(m)\tau} - e^{v(m)m})}. \quad (14)$$

If  $\tau$  approximates  $m + 1$ , formula 14 becomes

$$\begin{aligned} EC_i(m+1) &= \frac{v(m)EC_i(m)e^{v(m)m}e^{v(m)}}{v(m)e^{v(m)m} + EC_i(m)u(m)(e^{v(m)}e^{v(m)m} - e^{v(m)m})} \\ &= \frac{v(m)EC_i(m)e^{v(m)m}e^{v(m)}}{v(m)e^{v(m)m} + v(m)e^{v(m)m}(u(m)EC_i(m)/v(m))(e^{v(m)\tau} - 1)} \\ &= \frac{EC_i(m)e^{v(m)}}{1 + (u(m)EC_i(m)/v(m))(e^{v(m)} - 1)} \\ &= \frac{EC_i(m)e^{v(m)}}{1 + ((e^{v(m)\tau} - 1)/v(m))u(m)EC_i(m)}. \end{aligned} \quad (15)$$

Making  $e^{\beta i} = \beta_i$  and  $((e^{\beta i - 1})/\beta_i) u_{ij} = \alpha_{ij}$ , the continuous-time model that characterizes the development and changes

of the MEECS subsystems can be converted into the following discrete-time model:

$$EC_i(\tau + 1) = \frac{\beta_i EC_i(m)}{1 + \sum_{j=1}^2 \alpha_{ij} EC_j(\tau)} \quad (16)$$

MEECS services are mainly produced by marine resource components, nonresource components, and system functions. With society and people as the main service objects, the relevant services are mostly realized through the two subsystems: marine economy and ecoenvironment. The connotations of the MEECS in Figure 3 reflect the potential services, produced services, and realized services of each subsystem. It can be inferred that the marine economy subsystem  $EC_1$  consists of three parts: the total output  $EC_{11}$  of the primary industry, the total output  $EC_{12}$  of the secondary industry, and the total output  $EC_{13}$  of the tertiary industry; the marine ecoenvironment subsystem  $EC_2$  also consists of three parts: degree of environmental pollution  $EC_{21}$ , resource reserves  $EC_{22}$ , and degree of environmental protection  $EC_{23}$ .

### 3. Sustainability Development Evaluation

Under the effects of the development indices of economic and ecoenvironment subsystems and external development indices, the MEECS converts various resources and non-resources into economic outputs and delivers the outputs to the marine and costal land ecosystems. Figure 4 presents the input-output energy flows of the complex system. It can be seen that based on the basic economic inputs, the economic and ecoenvironment subsystems provide feedback to the complex system through their respective economic activities, such as production, operation, and consumption. The waste generated is discharged back to the marine and costal land ecosystems.

Suppose the MEECS is composed of  $w$  parts. Then, there are  $w$  comparable DUs, each of which has  $q$  inputs and  $t$  outputs. This paper treats the ocean as a complex system that receives marine ecoenvironment development indices and outputs marine economic development indices. The sustainable development of the complex system was evaluated by analyzing its input-output efficiency through DEA. Figure 5 describes the input-output of DEA.

Let  $a_{ij}$  be the economic input of the  $j$ -th DU,  $DU_j$ , on the  $i$ -th input;  $b_{lj}$  be the economic output of  $DU_j$  on the  $l$ -th output;  $o_i$  be the weight of the  $i$ -th input; and  $p_l$  be the weight of the  $l$ -th output. Then, the corresponding sets can be denoted as follows:  $A_j = (a_{1j}, a_{2j}, \dots, a_{qj})^T$ ,  $B_j = (b_{1j}, b_{2j}, \dots, b_{tj})^T$ ,  $o = (o_1, o_2, \dots, o_q)^T$ , and  $p = (p_1, p_2, \dots, p_t)^T$ . The data of  $A_j$  and  $B_j$  can be obtained from historical statistics.

For weight vectors  $o = (o_1, o_2, \dots, o_q)^T$  and  $p = (p_1, p_2, \dots, p_t)^T$ , the efficiency index  $\xi_j$  of  $DU_j$  can be calculated by

$$\xi_j = \frac{p^T B_j}{o^T A_j}, \quad j = 1, \dots, w. \quad (17)$$

Formula 17 shows that  $\xi_j$  is the ratio of input  $o^T A_j$  to output  $p^T B_j$ . The weights  $o$  and  $p$  can be adjusted to make  $\xi_j \leq 1$ . For DEA, the  $C^2R$  model has a clear modeling path, a simple form, and a solid theoretical basis. Suppose  $\xi_j^*$  is the efficiency index of the DU to be evaluated,  $DU_j^*$ . Then, a

fractional programming model  $C^2R$  can be established with  $\xi_j^*$  as the objective and the efficiency indices of all DUs as the constraints

$$P_{C^2R} = \begin{cases} \max \frac{p^T b^*}{o^T a^*} = \xi^*, \\ \frac{p^T b_j}{o^T a_j} \leq 1, \quad j = 1, 2, \dots, w, \\ p \geq 0, o \geq 0, p \neq 0, o \neq 0. \end{cases} \quad (18)$$

Let  $h = 1/o^T a^* > 0$ ,  $\theta = ho$ , and  $\lambda = hp$ , and formula 18 can be converted into a linear programming model:

$$LP = \begin{cases} \max \lambda^T b^* = \xi^*, \\ \theta^T a_j - \lambda^T b_j \geq 0, \quad j = 1, 2, \dots, w, \\ \theta^T a^* = 1, \\ \theta \geq 0, \lambda \geq 0. \end{cases} \quad (19)$$

The dual programming model of formula 19 can be described as

$$DP = \begin{cases} \min \phi, \\ \sum_{j=1}^w a_j \mu_j \leq \phi a^*, \\ \sum_{j=1}^w b_j \mu_j \geq b^*, \\ \mu_j \geq 0, \quad j = 1, 2, \dots, w. \end{cases} \quad (20)$$

The linear programming model (19) is DEA effective, provided that both parameters  $\theta^*$  and  $\lambda^*$  are greater than zero and the optimal objective value  $O_{C^2R}$ , i.e.,  $\lambda^{*T} B^*$ , equals 1. Hence, it is difficult to judge if the model is DEA effective.

The dual programming model can be rewritten as

$$DP = \begin{cases} \min \phi, \\ \sum_{j=1}^w a_j \mu_j + H_I \leq \phi a^*, \\ \sum_{j=1}^w b_j \mu_j - H_P \geq b^*, \\ \mu_j \geq 0, \quad j = 1, 2, \dots, w, \\ H_I \geq 0, H_P \geq 0. \end{cases} \quad (21)$$

The dual programming model is DEA effective, provided that all the optimal solutions  $\mu^* = (\mu_1^*, \dots, \mu_w^*)^T$ ,  $H_I^*$ ,  $H_P^*$ , and  $\phi^*$  are known,  $H_I^*$  and  $H_P^*$  are both zero, and  $\phi^*$  equals 1. It is also rather difficult to directly judge if the model is DEA effective.

To overcome the above difficulties, this paper proposes a  $C^2R$  model with non-Archimedean infinitesimals to determine whether the DEA of the target DU  $DU_j^*$  is effective:

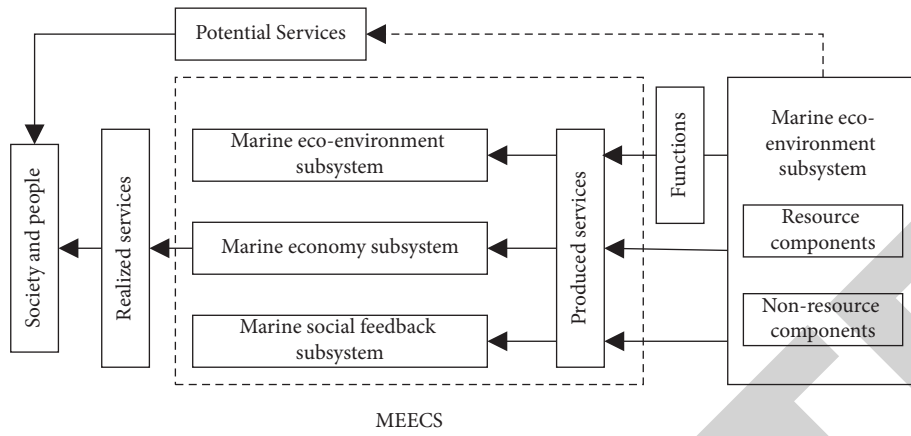


FIGURE 3: Connotations of the complex system.

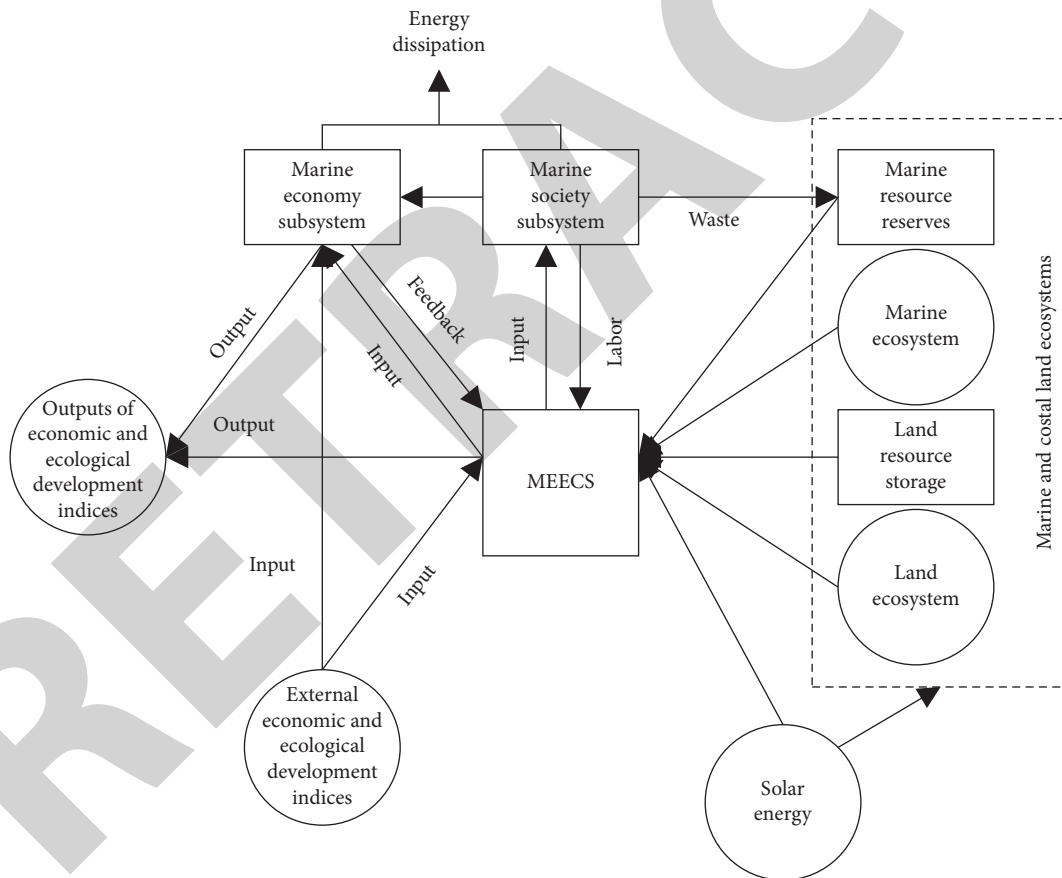


FIGURE 4: Input-output energy flows of the complex system.

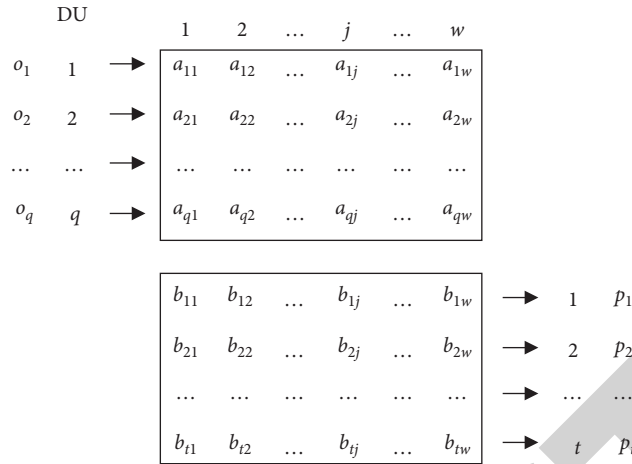


FIGURE 5: Input-output of DEA.

$$\text{NAI} = \begin{cases} \max \lambda^T b^*, \\ \theta^T a_j - \lambda^T b_j \geq 0, \quad j = 1, 2, \dots, w, \\ \theta^T a^* = 1, \\ \theta \geq \rho g', \lambda \geq \rho g. \end{cases} \quad (22)$$

The dual programming model of NAI can be expressed as

$$(\text{NAI}_{\text{DP}}) \begin{cases} \min [\phi - \rho(g'^T H_I + g^T H_P)], \\ \sum_{j=1}^w a_j \mu_j \geq \phi a^*, \\ \sum_{j=1}^m b_j \mu_j \geq b^*, \\ \mu_j \geq 0, \quad j = 1, 2, \dots, w, \\ H_I \geq 0, H_P \geq 0. \end{cases} \quad (23)$$

Let  $\delta = \varphi^*$  be the efficiency index of the target DU  $DU_j^*$  and  $\gamma = g'^T H_P^* + g^T H_I^*$  be the sum of redundant economic input  $g'^T H_P^*$  and insufficient economic input  $g^T H_I^*$ . Then,

the weak effectiveness and effectiveness of the DEA on  $DU_j^*$  can be judged by the following criteria:

- (1) If  $\varphi^* < 1$ , then the DEA on  $DU_j^*$  is not weakly effective
- (2) If  $\varphi^* = 1$  and  $\gamma > 0$ , i.e., at least one of  $H_P^*$  and  $H_I^*$  is positive, then the DEA on  $DU_j^*$  is weakly effective
- (3) If  $\varphi^* = 1$  and  $\gamma = 0$ , i.e., the sum of  $H_P^*$  and  $H_I^*$  is zero, then the DEA on  $DU_j^*$  is effective

Suppose  $A^*$  and  $B^*$  belong to the possible production set (PPS) of all probable marine production activities. Then, the input-oriented  $C^2R$  dual programming model can be established as

$$\text{DP} = \begin{cases} \min \phi, \\ \sum_{j=1}^w A_j \mu_j \leq \phi A^*, \\ \sum_{j=1}^w B_j \mu_j \geq B^*, \\ \mu_j \geq 0, \quad j = 1, 2, \dots, w. \end{cases} \quad (24)$$

The PPS can be established as

$$\text{PPS} = \left\{ (A, B) \mid \sum_{j=1}^w A_j \mu_j \leq A, \sum_{j=1}^w B_j \mu_j \leq B, \mu_j \geq 0, \quad j = 1, 2, \dots, w \right\}. \quad (25)$$

In the PPS, the input  $A^*$  should be minimized without changing the output  $B^*$ . If  $A_0$  is minimized, then the optimal value  $\varphi^*$  of the dual programming equals 1. In this case, the DEA on  $DU_j^*$  is effective.

#### 4. Analysis of Experiments and Results

This paper sets up a database of Chinese coastal regions through a survey on marine economy and marine ecology in

the research period and uses the database for analysis of experiments and results. Table 1 shows the outputs of the DUs in our MEECS. The radial and relaxation motions refer to the gap from the DEA efficient frontier and the correction needed to reach the frontier. Estimated value stands for the corrected value, i.e., the sum of original value, radial motion, and relaxation motion.

Calculations show that nitrate content and ammonia content had the largest relaxation motions in the sample



TABLE 1: Outputs of DUs.

	Variable	Original value	Radial motion	Relaxation motion	Estimated value
Marine fishery output	Output 1	42,500.000	0.001	0.001	42,500.000
Coastal tourism output	Output 2	27,652.000	0.001	712.035	27,812.085
Marine transport output	Output 3	12,687.000	0.001	453.472	13,251.251
Offshore oil and gas output	Output 4	963.371	0.001	78.953	1,159.563
Ocean shipbuilding output	Output 5	836.682	0.001	0.001	1,574.320
Sea salt output	Output 6	761.225	0.001	0.475	1,624.789
Dissolved oxygen content	Input 1	6.296	-0.684	0.001	5.975
Sea water pH	Input 6	7.859	-0.829	-0.261	6.632
Sea water salinity	Input 7	35.851	-3.674	-0.945	27.435
Ammonia content	Input 3	7.581	-0.758	-2.752	3.934
Nitrite content	Input 5	3.572	-0.357	-1.356	1.821
Chemical oxygen demand	Input 8	1.765	-0.128	-0.498	1.324
Inorganic phosphate content	Input 2	0.023	-0.002	0.001	0.029
Nitrate content	Input 4	19.394	-2.271	-7.651	10.316

period, suggesting that marine ecological and economic development is mainly constrained by the excessive discharge of nitrogenous pollutants. Among the outputs, coastal tourism output, marine transport output, and offshore oil and gas output were far from the zero value. Hence, the three industries have a good development potential and should receive more economic inputs.

Figure 6 presents the double exponential curves of the interaction between the subsystems in the research period, which reflect the evolution of suppression/inhibition effects between the subsystems. It can be learned that the marine ecoenvironment exerted a high stress on marine economy; in return, marine economy acted as a strong constraint on marine ecoenvironment.

The proposed model was applied to measure the coordination between MEECS subsystems of China's coastal provinces in the sample period. On this basis, the phase and type of the coordinated development between the subsystems were derived for each province in the period. As shown in Table 2, the synchronous development between marine economy and ecoenvironment proceeded under clear mutual constraints. Before 2018, the coordination between subsystems remained in the antagonistic state. To this day, the coordination between subsystems is still ecologically vulnerable. In recent years, with the advancement of marine science and technology, the adjustment of the marine industry structure, the rising quality of residents in coastal cities, and the effective implementation of marine environmental protection policies, the coordination of the complex system has been improved to a certain extent, and the coordination has gradually shifted from synchronized development to comprehensive and coordinated development.

Figure 7 presents the composite score of subsystem development in the MEECS. From 2010 to 2020, the score of the MEECS in China increased from 0.353 to 0.421. The system coordination quickly increased from the initial antagonism to synchronous coordination. Meanwhile, the social feedback system score rose from 0.211 to 0.635, and the system level improved from the initial microfeedback to early feedback, a sign of good development state.

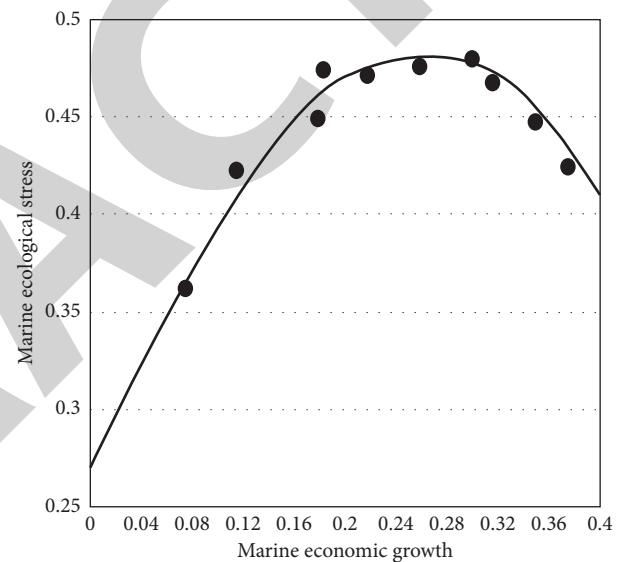


FIGURE 6: Double exponential curves of the interaction between the subsystems.

Figures 8 and 9, respectively, show the score of each state layer in the ecoenvironment system and the economy system. It can be seen that the scores of marine ecoenvironment condition and marine ecoenvironment pressure in China decreased year by year, indicating that the human and natural factors faced by the ecoenvironment system are increasing step by step. The scores of marine economy scale and marine economy vitality continued to increase, and the marine economy developed with vigor and vitality. However, the marine economy structure score fluctuated greatly and dropped despite the growing proportion of the tertiary industry. Therefore, the marine economy is heavily reliant on marine resources, although the marine industries are increasingly diverse.

The coastal provinces might differ significantly in MEECS development state, owing to factors such as ecoenvironment conditions, resource reserves, and economic foundation. Figures 10 and 11 display the composite scores of the complex system and the economy subsystem of

TABLE 2: Coordinated development of the complex system.

Year	2015	2016	2017	2018	2019	2020
$EC_1$	-0.01	-0.02	-0.03	0.00	0.00	0.02
$EC_2$	0.00	0.00	0.01	0.02	0.02	0.02
$u_{12}$	-0.76	-0.45	-0.12	-0.12	0.32	0.89
$u_{21}$	-0.33	-0.16	-0.02	0.08	0.09	0.15
Input	-18.32	-9.32	-8.71	-1.79	4.86	9.42
Output	24.75	21.58	18.46	15.37	15.61	11.53
Coordination phase (ecology vs. economy)	Antagonism	Antagonism	Antagonism	Antagonism	Synchronous coordination	Synchronous coordination
Coordination phase (economy vs. ecology)	Synchronous coordination	Synchronous coordination	Synchronous coordination	Synchronous coordination	Synchronous coordination	Synchronous coordination
Type of coordination	Ecologically vulnerable	Ecologically vulnerable	Ecologically vulnerable	Ecologically vulnerable	Ecologically vulnerable	Ecologically vulnerable

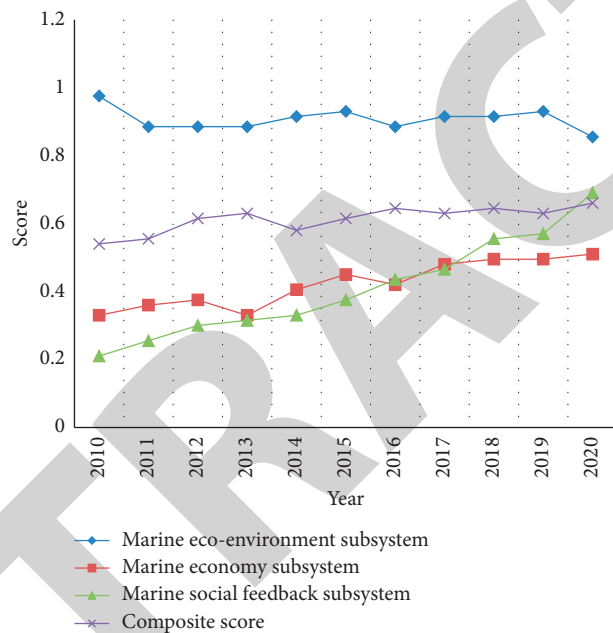


FIGURE 7: Composite score of subsystem development.

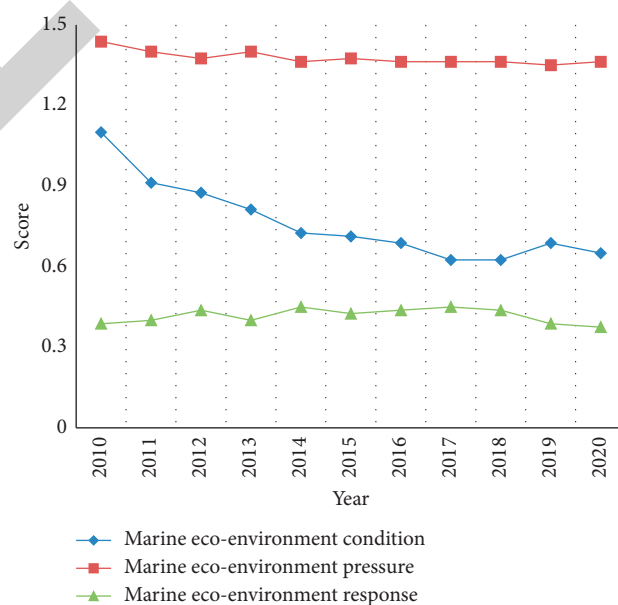


FIGURE 8: Score of each state layer in the ecoenvironment subsystem.

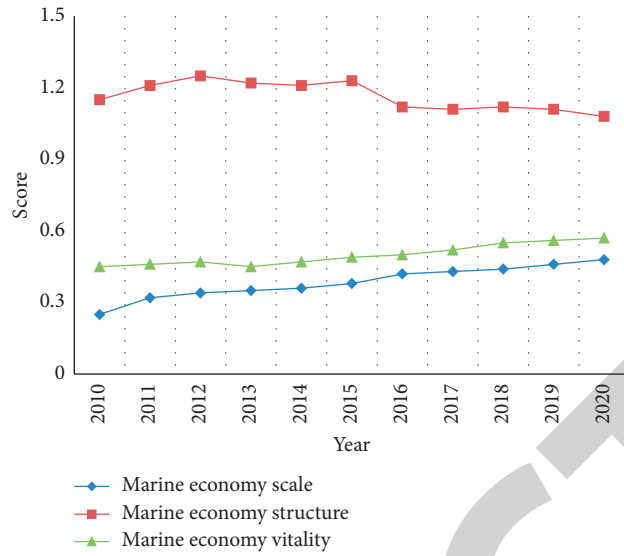


FIGURE 9: Score of each state layer in the economy subsystem.

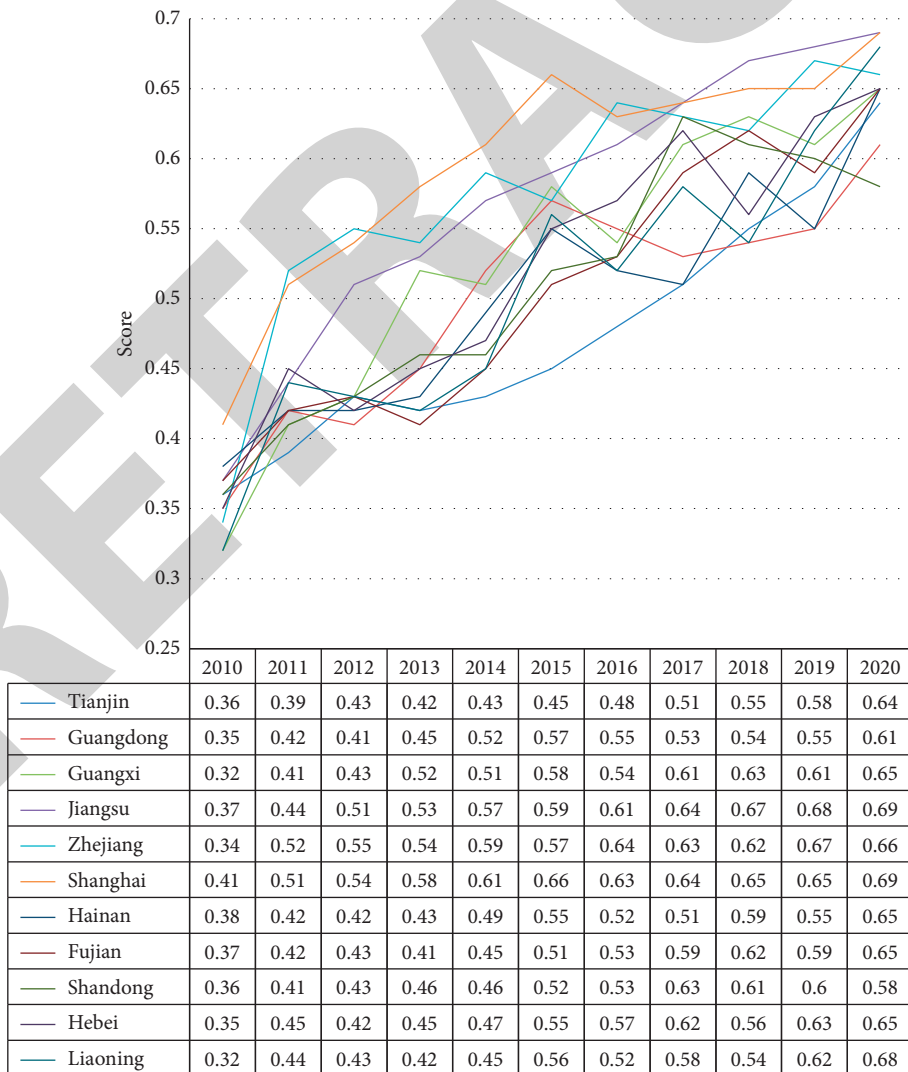


FIGURE 10: Composite scores of the complex system of coastal provinces in 2010–2020.

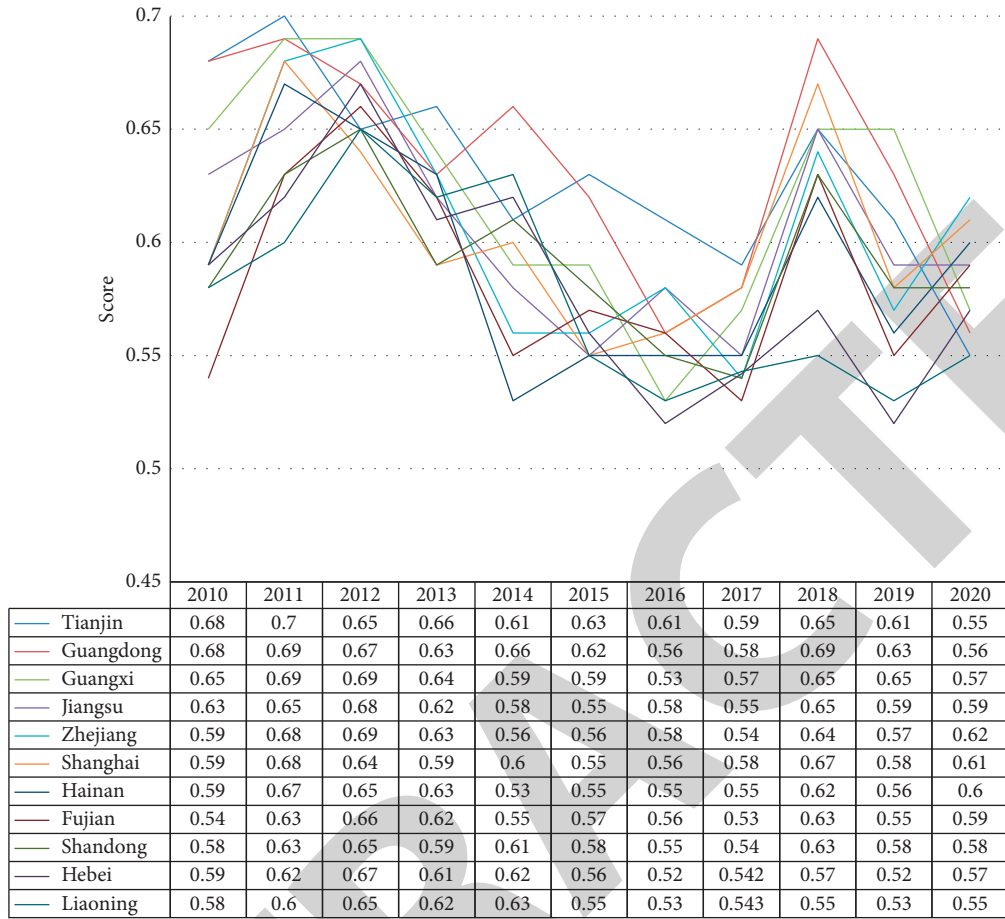


FIGURE 11: Composite scores of economy subsystem of coastal provinces in 2010–2020.

coastal provinces in 2010–2020, respectively. It can be seen that the composite scores of the complex system in all coastal provinces increased to different degrees, exhibiting an overall upward trend. Shanghai, Zhejiang, and Jiangsu have gradually evolved into the core growth provinces of MEECS in China. The evolution trend of other provinces was similar. As for the development trend of the ecoenvironment subsystem, the ecoenvironment deteriorated in all coastal provinces by varied degrees. However, some provinces, namely, Shanghai, made an increasingly strong marine ecological response, stepped up their efforts in environmental protection, and achieved positive results on marine ecological protection and restoration. On the contrary, some provinces failed to make up for the ecological losses with ecological responses. Hence, the ecoenvironment subsystem developed poorly in these provinces, causing a continued growth in ecological stress. Furthermore, although the ecoenvironment subsystem in most provinces belonged to the level of synchronized coordination, their scores were poised to decrease, an evidence of weak sustainable development ability.

### 5. Conclusions

This paper mainly discusses the CCD measurement of the MEECS and the sustainable development evaluation of

the complex system. First, the authors constructed an ecology-dominated coordinated development model for the MEECS and derived a differential equation model to describe the dynamic coordinated development of the complex system. Next, DEA was implemented to analyze the input-output efficiency of the MEECS and evaluate the sustainable development of the complex system. Through experiments, the outputs of each DU in our model were obtained and the development of each subsystem in the MEECS was evaluated comprehensively. The results show a certain development potential in coastal tourism output, marine transport output, and offshore oil and gas output. In addition, the double exponential curves of the interaction between the subsystems in the sample period were presented, which reflect the basic evolution of the promotion and inhibition between the subsystems. Finally, the composite scores of the MEECS, the subsystems, and the complex system of each coastal province were displayed and used to analyze the significant regional difference in the development state of the complex system.

### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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