Study on the Expression of Spatiotemporal Patterns in Marine Ecosystems

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Abstract: The ocean is a three-dimensional ecosystem with a wide range of temporal and spatial scales, thus making the visual expression of marine ecological characteristics extremely challenging. What types of marine ecosystems exist in a region, where are they distributed, what is their current status, and what are their changing trends? These are important questions faced by marine managers and decision makers. Based on the analysis of the relationship between biology and environment, this paper conducts ecological classification and data production for various marine elements. This paper expresses spatiotemporal marine ecological characteristics using a four-level general framework, including sea zone, bathymetry space, water space, seabed space. The bathymetry reflects the relevant marine topographic and landscape characteristics, and the water space and seabed space are composed of water environment, sediment environment and living organisms respectively. The framework’s main functions are the display, description, and statistical analysis of ecological characteristics, and display the spatiotemporal distribution pattern. These methods were combined with the construction of a database and R&D of system functions to fill the gap in this field in China and provide decision support for marine ecosystem management.

Keywords: Ecological characteristics; Spatiotemporal patterns; Characteristics expression; System construction
1. Introduction

Marine ecosystems feature a high degree of complexity; they are a natural whole with interrelation, interaction, and automatic regulation mechanisms formed by the biological and abiotic environment through energy flow and material cycles in a certain time and space. Marine ecosystems have three-dimensional characteristics with a wide range of temporal and spatial scales, thus making the visual expression of marine ecological characteristics extremely challenging.

At present, the mainstream method of visually expressing marine ecological characteristics is habitat mapping on the basis of a general ecological classification system, displaying the mapping results after system integration. In 2012, the United States issued the Coastal and Marine Ecological Classification Standard [1], applying classification mapping in the waters of the Northwest Atlantic [2], the northern Gulf of Mexico [3], and the survey of abyssal benthos in the Northeast Pacific [4], formulating a plan for comprehensive marine and coastal mapping [5]. Australia developed habitat mapping based on CMECS and released Sea Map [6, 7], and the EU released seabed habitats [8] based on the UNIX classification system, which mainly uses survey data such as sediment, benthos, and macroalgae to detail and display habitat types.

In China, this research is in its infancy and there are no similar results, though the country has spent manpower and material resources to carry out marine monitoring and investigation and the construction of a marine information system [9,10] in recent years. The organization and design of the obtained data and products are mainly set according to the nature of the discipline, without taking the ecosystem as a whole into consideration, and with the lack of description of the relationship between biology and environment and its temporal and spatial distribution pattern, it is impossible to have a comprehensive understanding of the marine ecosystem.

The China Sea spans three dimensional zones: temperate zone, subtropical zone and tropical zone, and the water depth gradually increases from the mainland to the sea. In this study, the bathymetry connects the water space and seabed space of the ocean, so as to establish a three-dimensional framework and integrate the regional water body, geological form, sediment and biological data. The study establishes a unified base map reflecting the marine ecological status as a multi-disciplinary, three-dimensional expression. It provides technical support for promoting the unified management of natural resources based on ecosystems.

2. System architecture

The ocean is a three-dimensional, dynamic system composed of marine organisms and their marine environment. The expression of marine ecological characteristics shows the matching characteristics of the physical marine environment and biological distribution. The system architecture for expressing spatiotemporal characteristics in marine ecology includes basic data layers, an ecological characteristics layer, a function layer, and an application layer.
2.1 Basic data layer

Basic marine ecology data refers to biological and environmental data obtained from marine monitoring, observation, and surveys.

(1) Biological data includes structured tabular data on chlorophyll, primary productivity, microorganisms, phytoplankton, zooplankton, benthos, nekton, and other marine life, as well as vector spatial data on biological distribution such as the locations of mangroves, coral reefs, seagrass beds, and oyster reefs.

(2) Environmental data involves many disciplines such as physical oceanography, marine geology, marine geomorphology, and marine chemistry. It includes such measures as water depth, temperature, salinity, flow velocity, flow direction, sediment particle size, sediment quality, dissolved oxygen, and nutrients. The data formats mainly include structured tabular data, vector spatial data, and raster spatial data.
2.2 Data access layer

The existing data resources were sorted, classified, and graded. Considering the spatiotemporal expression needs of marine ecology, a multi-component, multi-dimensional general framework was adopted to build databases for the sea zone, bathymetry, water space (including water environment and aquatic organisms), seabed space (including sediment environment and benthos) based on the unified marine data domain model. Database access and a call interface was developed according to a unified standard.

2.3 Service layer

Since marine ecosystems feature a high degree of complexity, their management should not only be planned step-by-step from the macro level, but also dynamically adjusted by paying close attention to local monitoring. The spatiotemporal expression of marine ecological characteristics provides a basic unified framework to display marine ecological characteristics at different levels in a three-dimensional way. The framework acts as a decision support system that allows comprehensive data utilization, collaboration, and sharing by superimposing various types of data resources. For example, it incorporates data on development, utilization, restoration, the ecological red line, carrying capacity, and protected areas of marine ecosystems.

2.3.1 Describing ecological characteristics

For the defined regional or spatial sites, the description of ecological characteristics was given including the information of each level in the sea zone, bathymetry, water space (including water environment and aquatic organisms), seabed space (including sediment environment and benthos). The information was appropriately increased for surrounding marine protected areas, the ecological red line, typical nearby ecosystems, and other characteristics.

2.3.2 Displaying ecological characteristics

Basic data and ecological data were checked according to the bathymetry, water space, seabed space. Then the ecological types of each group were displayed on a map according to the data extent or predetermined regions (waters under the jurisdiction of the whole country, national nearshore and sea areas, or waters under the jurisdiction of provinces and cities).

2.3.3 Statistical analysis of ecological characteristics and production of a thematic map

The area, quantity, and proportion of each type were counted according to the bathymetry space, water space, seabed space, and the quantities of marine ecological products in the region were counted with each group as the label. The map elements were designed in a standard-sized map sheet and thematic map, including a map name, legend, picture frame, longitude and latitude annotation, and scale to form a base map template. Users can customize the above basic data or ecological characteristics layer, range, proportion, and template type to make thematic maps online.
3. Database construction
The ocean system is a dynamic, continuous, three-dimensional system with a wide range of spatial and temporal scales. The ecological characteristics layer adopts a multi-component, multi-dimensional general framework to integrate and display data related to various ecological processes on large and small scales. The framework includes sea zone, bathymetry, water space and seabed space. Each group shows the spatial distribution of each ecological type, in which spatial data plays the leading role, including vector and raster spatial data.

3.1 Sea Zone
The sea zone provides location and background information for further understanding bathymetry, water space and seabed space characteristics. Assuming a site is located in a certain sea zone, its general ecological characteristics can be inferred. For example, if it is located in the Yangtze River zone in a temperate zone on a continental shelf, the site will be mainly affected by the runoff of the Yangtze River, with relatively low water salinity, high seawater turbidity and medium tidal intensity. Therefore, it can be inferred that the geomorphic type is an estuary delta, which may be affected by upwelling and rich in aquatic resources.

China has four traditional sea areas: the Bohai Sea, the Huanghai Sea, the Donghai Sea and the Nanhai Sea, reflecting the heterogeneity of latitude zones and geographical contours. From the continental coast in the direction of the open sea includes estuarine, nearshore, shallow sea, bathyal regions, and abyssal regions, reflecting the zonal distribution characteristics of of water depth. In addition, typical marine ecosystem types such as estuaries, bays, islands, sandy coasts, muddy coasts, mangroves, coral reefs and seagrass beds are also distributed in different sea area.

3.2 Bathymetry Space
The bathymetry connects the water space and seabed space to establish a three-dimensional framework of marine ecosystem. It refers to the terrain and its related marine landscape characteristics, presenting the physical structure of the environment related to the distribution of biological communities or leading to their differences. The bathymetry space provide structure, controls the transportation of energy and materials, and provides places for organisms to find food and shelter, reproduce, and rest. Different bathymetry space show heterogeneity in material structure, energy structure, and spatial structure, which plays an important role in the formation of biological communities.

The bathymetry space could be divided into four layers showing the spatial distribution data of all ecological types at this level. The first layer shows the tectonic characteristics includes the divergent active continental margin, ocean basin, fault zone, etc.; the second layer shows the physiographic characteristics includes continental seas, coastal geoforms, large open bays, intertidal zones, continental shelves, etc.; and the third layer and fourth layer are divided according to spatial scale, with intersected types, including islands, coves, bedrock coasts, beaches, and shelf plains.
3.3 Water Space

The vast ocean water body provides a wide range of habitats for marine organisms. The “barriers” formed by temperature, salinity, and depth will affect the distribution of organisms. Ocean currents not only affect the ecological environment of marine organisms, but also play an important role in the community structure, distribution, and diffusion of species. The impact of tidal environments on the coastal zone, where only marine organisms with very strong adaptability can survive, is particularly important. The three-dimensional structure of water bodies, high temporal variability, and the extensive spatial scale of water environmental characteristics pose great challenges to the expression of marine ecological characteristics, especially when coupled with the inherent difficulties in the measurement of various parameters.

This paper presents the ecological characteristics of the ocean in terms of vertical level, temperature, salinity, hydrology, and biogeochemistry. The abiotic environmental characteristics in water space is divided into five layers including water layer (surface layer, upper layer, thermocline, lower layer, deep layer, etc.), salinity layer (oligohaline, mesohaline, polyhaline with low salinity, polyhaline with high salinity, euhaline, and high-concentration saline), temperature layer (cold, cool, warm, hot, etc.), Ocean phenomenon layer (ocean current,, water mass ocean front, ocean fluctuation, and biogeochemical characteristics layer (chlorophyll, dissolved oxygen, nutrients, etc.).

The biotic environmental characteristics in water space includes plankton and benthic/attached biota. The former includes phytoplankton, zooplankton, and floating/suspended plants, macroalgae, and microbes. The biotic characteristics shows the spatial distribution of dominant life forms currently observed or monitored. The display object is not all marine organisms, but groups that have been observed, have specific ecological significance, and can be used as research objects and management objectives. For example, algal blooms which is the ecological anomaly formed by the explosive proliferation and aggregation of phytoplankton.

3.4 Seabed Space

The seabed space includes sediments and living benthos. The sediments is the substrate for organisms to survive. Providing living space for benthos and periphyta, it is the most important physical factor affecting the community structure of benthos. Hard bottom sediments include bedrock and reef. Strongly stable, hard, and porous, they are very suitable for the attachment of mollusks and can provide shelter and breeding places for some crustaceans. For example, reef corals must grow on hard substrates such as rock, reef segments, gravel, or dead coral bone. Loose sediments mainly include gravel, sand, and mud, which have relatively poor stability. Gravel provides attachment areas for periphyta. Sandy sediment is suitable for burrowing animals such as crabs, and the nutrient-rich sediment is suitable for the growth of aquatic plants and other epiphytes.

The sediments can be divided into four levels in a nested structure. The layer data of the next level can be processed to produce the data of the previous layer. In addition, there are also biogenic
substrate and anthropogenic substrate in the seabed space, and the distribution data of various types is objectively displayed. The organisms in seabed space mainly includes reef biota, faunal beds, aquatic vegetation beds, emergent wetland, scrub-shrub wetland, forest wetland, microbial communities, moss, and lichen communities. The biotic group establishes 9 layers according to the above biological categories, and the distribution data of corresponding ecological types are displayed in each layer.

4. System development and demonstration

4.1 Visual expression of regional characteristics

The visual expression of marine characteristics in different regions aims to show the sea zone it is located in and the layers of various characteristics types in the bathymetry space, water space, seabed space. Taking the Bohai Sea as an example, we adopted the system architecture mentioned above, collected basic data on organisms and the environment in the Bohai Sea, made maps of various ecological types, and loaded them into the developed system to display their ecological characteristics. The figure below visually expresses the sea zone, the ocean current layer and the layer of phytoplankton algal bloom in the water space, the terrain layer in the bathymetry space and the benthic community in the seabed space, Different types of ecological data can be gradually added to this framework, enriching the content expressed by the system.

Figure 2. Visual expression of marine characteristics in the Bohai Sea

4.2 Description of regional characteristics

Taking the Bohai Sea as an example, according to the structure of the table below to describe the spatiotemporal patterns characteristics. The content can be extracted from the corresponding layer in the system, and the missing data can be added and improved according to the existing basic data and research results.
Table 1 Example description of the spatio-temporal patterns characteristics of the Bohai Sea

| Described region | The Bohai Sea |
|------------------|---------------|
| **Sea zone**     |               |
| Natural sea zone | The Bohai Sea |
| Seaward zone     | Nearshore     |
| Character zone   | The Bohai Bay, Laizhou Bay, Liaodong Bay, Bohai central basin |
| **Bathymetry Space** | Bathymetry characteristics |
| Types            | Level 2: Continental sea |
|                  | Level 3: Cove; estuarine delta; tidal sand ridge group; shelf plain, etc. |
| **Water Space**  | Abiotic component |
| Temperature      | There are great seasonal differences, from frozen water (< 0° C) to very warm water (25°, 30°) |
| Salinity         | Upper polyhaline |
| Hydroform        | Coastal water of Liaodong Bay, coastal water of Bohai Bay and Laizhou Bay, water mass of the Bohai Sea |
| **Seabed Space** | Abiotic component |
| Level 1          | Unconsolidated mineral substrate |
| Level 2          | Fine unconsolidated substrate |
| Level 3          | Sandy mud: mud |
| Level 4          | Sandy silt: silt |
| **Biotic component** | Phytoplankton |
| Plankton         | Diatom phytoplankton |
|                  | Diatom bloom |
|                  | Skeletonema bloom |
| **Benthic/attached biota** | Faunal bed |
|                  | Soft sediment fauna |
|                  | Mobile mollusks on soft sediments |
|                  | Basket whelk community |

The structure of the table describes the characteristics of the region from four aspects: sea zone, bathymetry space, water space, seabed space. Among them, each aspect adopts different architectures and uses the ecological types for feature expression, so that the data from different sources can be unified into the same framework.
5. Summary
The ocean has a wide range of spatial and temporal scales, thus making visual expression of its ecological characteristics extremely challenging. A single ecological characteristic presents the situation of specific ecosystem units at a specific time point. The existing measurement tools can only capture a part of the space-time continuum. Only by integrating large-scale and small-scale components related to geological, biological, water, and sediment processes into a general hierarchical framework can the status and extent of changes in the entire system be presented by comparing a single characteristic at different times. In this paper, the spatiotemporal characteristics of marine ecology are expressed by using the general framework of four levels—the sea zone, bathymetry space, water space, seabed space—through the functions of display, description, and statistical analysis of ecological characteristics. By superimposing management data on marine development, utilization, ecological red line, and protected areas, the framework provides decision support for marine ecosystem management.

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