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DYNAMIC VISUALIZATION OF SPATIO-TEMPORAL PROCESS MODEL BASED ON NetCDF AND OPTIMAL INTERPOLATION FOR MARINE ENVIRONMENT

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Abstract

The ocean is an indispensable source of materials and energy for the survival of human beings and social development. It is also an essential factor affecting climate change and ecological balance. In view of the dynamic, three-dimensional (3D), and complex marine environment, this study proposes the construction and dynamic visualization of a marine spatio-temporal process model based on Network Common Data Form (NetCDF) and optimal interpolation. The proposed model combines the advantages of NetCDF data models, which store and share high-performance multidimensional data, visualize marine spatio-temporal processes based on optimal interpolation, eliminate the "time crack" of large time resolution data, and ensure continuous, smooth, dynamic visualization. Weekly-averaged survival data of Chinese seas and optimal global interpolation daily-averaged sea surface temperature data of centralized advanced very high-resolution radiometer-only products are selected, and 3D visual expression and analysis of multidimensional, dynamic marine environmental data are realized. Experimental results indicate that the proposed method efficiently and intuitively expresses marine environmental data, thus providing a powerful visualization tool for the expression, change regularity analysis, and trend prediction of complex phenomena.

Keywords: marine environment, multidimensional dynamic visualization, optimal interpolation, process model, spatio-temporal data model

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1. Introduction

About 70% of the Earth's surface is the ocean. The ocean is a paramount part of the earth system and plays an important role in regulating global climate change as well as maintaining ecological balance (Rusu and Măcuţă, 2009; Su et al., 2016; Sul and Costa, 2014). Island and reef are the most biologically diverse of water marine ecosystems but are being degraded worldwide by human activities and climate warming. With mankind's further development and use of the marine. Island, reef and surrounding marine environment and monitoring has become strategic development and research directions. Facing the fierce competition in the ocean, it becomes an important issue for reasonable exploitation and scientific management of ocean. With the rapid development and gradually deepening promotion of "Digital Earth",

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"Digital Ocean" is proposed. "Digital Ocean" is an ocean information system consisting of vast, multi-resolution, multi-time phase, multi-type data and its corresponding algorithm (Zhang et al., 2017; Zahirovic et al., 2019). Many countries have already put "Digital Ocean" into the development programme of marine science and technology as a long-term strategy. As the proceeding of this programme, the task of digitalized management, analysis and expression of marine data has become increasingly pressing.

Marine environmental information is the most important component in "Digital Ocean" (Zhang et al., 2017). Marine environmental information consists of different environmental factors, such as sea atmosphere (cloud, rain, fog, air pressure, air temperature, wind, etc.), sea table (waves, tidal flow, storm surge, etc.), seawater (temperature, salinity, density, internal circulation, thermocline, etc.) and seabed (geology, geomorphology). Marine environmental information has a significant impact on the island protection, development and exploitation (Comăniță et al., 2016). During the long-term marine survey and research, prodigious amounts of complex marine environment information featured as mufti-source, heterogeneous, mufti-dimensional, dynamic in structure and temporal are accumulated. Especially with the development of remote sensing technology, such data has been generated rapidly. Studies on marine environmental information are of great importance in analyzing the spatio-temporal law and influence mechanism of marine phenomena. The marine environment is dynamic, three dimensional, and complex; thus, reliably and quickly expressing the dynamic and multidimensional characteristics of oceans is currently a significant and popular topic in marine surveying and mapping (Bao and Xu, 2012; Böhnke et al., 2013; Su et al., 2016).

Marine environmental data with these characteristics include multiple-sources, heterogeneous, diverse formats, widespread distribution, massive volume, multi-dimensional and dynamic, which make the data processing method of marine data is quite different from the land-based GIS. The data model simulates the spatio-temporal process of specific marine environmental elements. The main model types include a feature-based marine spatio-temporal data model, field-based spatio-temporal snapshot grid model, and process-oriented spatio-temporal data model (e.g., Levican et al., 2015).

Feature-based models take characteristics as the basic unit, and adopt object-oriented technology to design featured space, time, and attributes of space, function, relationship, and association among real examples (Stelzenmüller et al., 2013). ArcMarine defined five general models, which are point, line, surface, grid/grid body, and multimedia data, and established a unified data framework within which users can appropriately modify the model with specific data and applications (Isenor and Spears, 2014; Liu et al., 2014). Liu et al. (2011) expanded the model of ArcMarine by constructing an information database of ocean water body elements, as well as achieved the spatio-temporal dynamic visualization of ocean temperature and ocean current elements. Shaikh et al. (2017) carried out interpolation by linear kriging method of semivariogram model to analyse the sea surface temperature over exclusive economic zone of Pakistan according to statistical spatial homogeneity in the data throughout the surface. Faye et al. (2018) developed a large scale spatio-temporal model of maximum daily river temperature for Scotland that predicts variability in both river temperature and climate sensitivity. The maximum daily river temperature was modelled as a linear function of maximum daily air temperature, with the slope and intercept allowed to vary as a smooth function of day of the year.

Field-based marine spatio-temporal snapshot grid models integrate the spatio-temporal data snapshot model of GIS with that of the marine field. It uses spatial data layers and geographical phenomena from different times to reflect the spatio-temporal evolution of geographical phenomena (Jovanovic and Vukelic, 2015). Su Fenzhen et al. (2014) proposed an angle grid program and an equal-area grid program to solve discrete spatial grid problems, and pointed out that time-discrete segments and attributes must be divided according to specific research objects, actual data, and phenomena. Camila et al. (2016) developed a flexible stochastic spatio-temporal model for daily temperatures in the Pacific Northwest using Bayesian spatial prediction, which is its incorporation of site-specific features of a spatio-temporal field in its spatio-temporal mean. Fablet et al. (2017) extended the analog data assimilation to high-dimensional spatio-temporal fields using a multiscale patch-based decomposition. Field-based spatio-temporal snapshot grid models can facilitate marine data storage. The grid form is simple, intuitive, efficient, and flexible, and has other advantages, but also suffers from data redundancy and spatio-temporal query (Jovanovic and Vukelic, 2015).

Process-oriented spatio-temporal data models focus on process (evolution of geographic entity), use process-oriented data organization and storage to achieve continuous gradation expression of process objects, and are a popular technology in spatio-temporal expression and modeling theory (Isenor and Spears, 2014; Martens and Huntington, 2012; Smith and Cromley, 2012). Reitsma and Albrecht (2005) designed the process-based spatio-temporal data model. Xue and Dong (2012) defined the expression, organization, and storage of continuously graded geographical entities as research objects, proposed a process-oriented spatio-temporal data model, used ocean vortexes as an example, and implemented process organization, dynamic analysis, as well as the visual expression of continuously graded geographical entities. Kuusela and Stein (2018) proposed mapping Argo floats measure seawater temperature and salinity data using locally stationary Gaussian process regression where covariance parameter estimation and spatio-temporal prediction were carried out in a moving-window fashion. Ouala et al. (2018) developed a Neural-Network-based Kalman filter for spatio-temporal interpolation of sea surface dynamics, which could be regarded as an alternative to classical filtering schemes such as the ensemble Kalman filters in data assimilation.

Most of these marine spatio-temporal data models simply expand on land GIS spatio-temporal data models, and as such, their visual expression is limited to two or partial three dimensions, which hardly meet the requirements of dynamic and continuous marine environmental data with fuzzy boundaries. Additionally, these models cannot describe or express complex marine phenomena. In view of the multi-source, mass, multi-dimensional, and dynamic characteristics of marine environmental data, this research proposes a novel spatial-temporal process model to fully utilize the advantages of both NetCDF and optimal interpolation to increase the goodness-of-fit with respect to weekly-averaged survival data of Chinese seas and optimal global interpolation daily-averaged sea surface temperature data. This work constructs a process-oriented marine spatio-temporal data model and introduces NetCDF data model for the integrated organization and management of marine environmental data. It also proposes the construction and dynamic visualization of marine spatio-temporal process model based on optimal interpolation, and achieves three-dimensional (3D) dynamic expression and visualization analysis of marine environmental element data. The integration of the above method not only realized the unified storage and organization of marine environmental data, but also made the marine environment data visualization more clearing, intuitive and vivid.

The remainder of this article is organized as follows: in Section 2 provides a description of the marine spatio-temporal process model based on NetCDF and optimal interpolation and the proposed algorithm flow, in Section 3 we describe our experimental results; and Section 4 summarizes our contributions and outlines future directions for related research.

2. Method

Marine spatio-temporal process objects are abstractions of real marine elements or phenomena. The process-oriented spatio-temporal model includes the data structures of hierarchical process objects and the data structures in, or associated with, process objects (Cavalcanti et al., 2016). The proposed method combines the advantages of NetCDF data models to store and share high-performance multidimensional data, adopts the optimal interpolation method, and achieves continuous, smooth, dynamic visualization of the marine spatio-temporal process.

2.1. Abstract description of marine environment spatio-temporal process model

Marine environmental data is a dynamic, continuous and graduated "process" phenomenon. The process characteristics of marine phenomena are the basis for the storage, organization, and design of marine data. The process is key to the dynamic visualization of marine environmental data.

A process-oriented spatio-temporal data model is a data organization and management technique that takes the process as a spatio-temporal object; it designs and implements spatio-temporal processes, object features, and behaviours (Embling et al., 2012; Leeds et al., 2014). According to the evolving nature of process objects and the hierarchy semantics of the marine spatio-temporal process, this study starts from object-oriented technology and data organization, and then divides marine spatio-temporal process objects into spatio-temporal objects, stage objects, sequence objects, and state objects (Fig. 1). These process objects have the structural characteristics of an inverted pyramid. The internal evolution of the marine spatio-temporal process is the evolution of information energy; it can adopt marine dynamic models, marine event mechanisms, marine spatio-temporal operations, and other formal expressions of mechanisms.

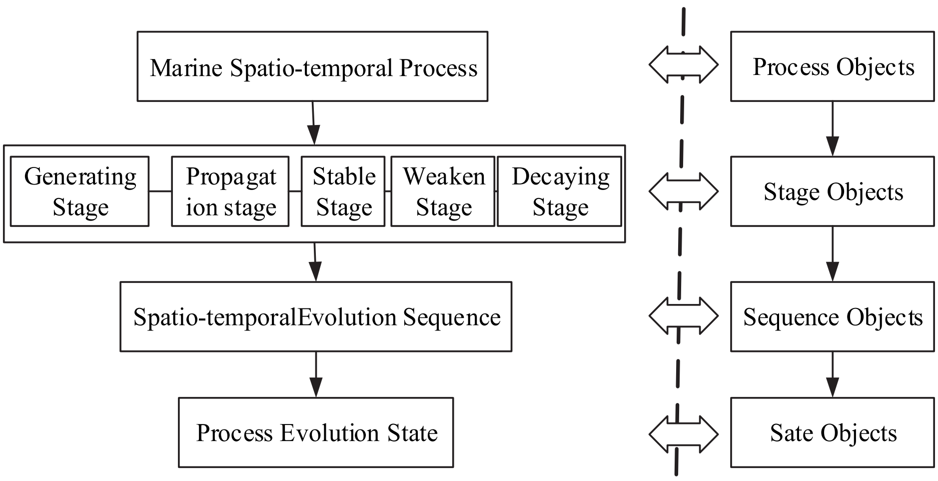


Fig. 1. Hierarchical abstract and relationship description of the marine spatio-temporal process

From the perspective of model building, the evolution mechanism high-resolution into a spatio-temporal function, which is built inside the model. The abstract hierarchical structure of process objects can facilitate their hierarchical storage and analysis, as well as their hierarchical expression.The continuous gradation expression of marine phenomena is vital to marine data model construction, and its implementation relies on hierarchical abstracts, conceptual marine spatio-temporal process objects, and the internal evolution mechanism of the process (Thibaud et al., 2013). The hierarchical abstract and conceptual process objects depict the internal hierarchical structure and sequence relationship between process objects. It is the basis of the process internal dynamics model, event mechanism, and spatio-temporal operational design, and it allows the implementation of a gradation expression mechanism. This model takes the process object as the basic unit, and records marine elements, phenomena, development, and changes. Its state information is comprehensively described by space, time, attributes, and relationships. The model decomposes the spatio-temporal process into an integration of state sets, facilitates the expression of marine elements with different grades or states, and more explicitly describes state changes. Recorded changes in rule information effectively reflect the mechanism of changes. The changes of the spatio-temporal object are reflected by the process; "state" is a series of recorded data, and different sets of states constitute a complete spatio-temporal process.

Process-based marine object organizational structure also includes the association relationships (including sequence relationship) between marine spatio-temporal process objects and their evolution mechanisms. Marine spatio-temporal process objects are expressed by sets of process objects, process stage objects, process sequence objects, and process state objects. Association sets are used to describe association relationships, while function sets describe evolution mechanisms of marine spatio-temporal process objects, and are integrated into the process objects.

2.2. Spatio-temporal process of marine environmental data

Marine environmental data are the most representative marine data and usually refer to the changing information of certain marine elements with time and depth. Marine environmental data may be regarded as a process object (Sajid and Chris, 2012; Thibaud et al., 2013).

Given that the marine environmental data field involves an explicit description of marine elements or phenomena, its hierarchical structure does not separate process objects from different phenomena, and as such, no fuzzy relationship exists between process objects. This field is only necessary to consider how process objects can be graded and to describe the internal relationships among objects in the environmental data field.

Hierarchical descriptions of spatio-temporal processes are conducted as follows. From the bottom layer, spatial distributions and attribute information of process objects at fixed times are recorded. Over time, state changes reflect the spatial distribution and attribute information of processes at particular states. Several states combined in order constitute a stage of the process. The corresponding spatial distribution and attribute information of process objects must be recorded at particular process stages, as these stages constitute the entire process cycle.

2.3. NetCDF-based marine environmental data organization

NetCDF is a universal data access method that can efficiently store, manage, access, and distribute grid data. Its small storage capacity, fast reading speed, and self-descriptive and flexible reading mode have made it a data storage standard in atmospheric science, hydrology, oceanography, and other fields. It became the OGC multidimensional data exchange standard in April 2011.

NetCDF is a type of array-oriented data suitable for network sharing, cross-platform data format description, and coding standards. It is a set of software function libraries (interfaces) and supports the creation, access, sharing, and other operations of multidimensional data (Gaustad et al., 2014).

The NetCDF data model mainly includes classic and enhanced data models. Classic data models consist of three parts: dimension, variable, and attribute. The various parts are interrelated and organically combined, thus describing the meaning of centralized data and the relationship between fields. There is a total of six basic data types for variables and attributes, and only one dimension has unlimited length. The model is easy to understand and use, facilitates the development of common tools, and is suitable for grid data description. However, the data types are limited, and the descriptions of complex, multi-level, nested, multidimensional data are lacking (Castro et al., 2012; Jordi and Wang, 2012).

The enhanced data model increases the group and scalable dimensions, has more basic data types and user-defined data types, and contains a top-level unnamed group. Each group contains one or multiple named sub-groups, user-defined data types, variables, dimensions, and attributes. The model greatly eliminates the limitations of the classical data model and provides nested data structures and recursive data types, which are compatible with existing data, software and conventions. However, the data model is complex, lacks comprehensive and common tools, and is not widely used. Its user-defined types cause difficulties in data sharing, software development, and other aspects. This study adopts the classic data model to organize and manage marine environmental data and achieve unified management.

From a mathematical point of view, the data stored by NetCDF are single valued functions with multiple independent variables (Eq. 1):

$$value = f(x, y, z, \ldots) \quad (1)$$

In the NetCDF, independent variables *x*, *y*, and *z* are the dimensions, the function value is the variable, and the attributes are the properties between independent variables and function values in physics, such as measurement units.

NetCDF file data are stored in an array and, as such, can flexibly and easily store multidimensional data. For instance, the temperature of a certain position at different time periods is stored in the form of a one-dimensional array, while the temperature of a certain region at a specific time period is stored in the form of a two-dimensional (2D) array. Common 3D data (e.g., temperature data of certain sea areas that change with time) and four-dimensional data (4D) (e.g., temperature data of certain sea areas that change with time and altitude) are stored as a series of 2D arrays, whose storage schematic diagrams are shown in Fig. 2. NetCDF can directly store and retrieve data through ID identification without loop traversal, making it much more efficient than traditional multidimensional data storage and retrieval. Thus, it greatly improves storage and retrieval efficiency, as well as helps users understand and accurately manipulate data sets.

2.4. Optimal interpolation of marine environmental data

The dynamic changes of marine elements or phenomena are continuous in space, but actual data are often discrete. Although marine data increase exponentially, collected data are often limited within a specific range of time and space, especially below the ocean surface. This increase is caused by the non-continuous acquisition method (usually a collection is carried out with a specific depth interval) and the particularity of the ocean, which contributes to incomplete data collection. At present, the commonly used spatial interpolation and temporal interpolation methods are often used separately, which makes it difficult to take into account the spatio-temporal correlation between data (Portman, 2014). In the present study, optimal interpolation method is adopted for the spatio-temporal interpolation of marine environmental data, because it integrates effectively with temporal interpolation method and makes interpolation results more reasonable.

Marine environmental data are discrete on the time axis. Hence, when they are used to visualize the dynamic spatio-temporal process, jumping and flashing motion pictures may be obtained, which in turn prevent the expression of continuously graded spatio-temporal evolution from being obtained. Currently, spatio-temporal interpolation effectively solves the spatial and temporal continuity problems of marine environmental data. To achieve continuous gradient dynamic evolution, spatio-temporal interpolation operations for marine environmental data can obtain intermediate state data at different time slices.

Optimal interpolation is a commonly used and fairly simple but powerful method of data assimilation (Cao et al., 2015; Gabriele et al., 2013; Zhang, 2003). Optimal interpolation assumes the marine field is relatively stable, and the covariance equation is known. When *N* marine elements in a known region are selected, the optimal linear estimation of the unknown θ_x is obtained as follows (Eq. 2):

$$\hat{\theta}_x = \sum_{r=1}^{N} C_{xr} \left[\sum_{s=1}^{N} A_{rs}^{-1} (\varphi_s) \right] \quad (2)$$

The confidence interval or error bar of the objective analysis value is (Eq. 3):

$$\left(\theta_x - \hat{\theta}_x \right)^2 = C_{xx} - \sum_{r,s=1}^{N} C_{xr} C_{xs} A_{rs}^{-1} \quad (3)$$

where: $A_{rs} = \overline{\phi_r \phi_s}$ is the covariance matrix of a known marine data value; $C_{xr} = \overline{\theta_x \phi_r}$ is the covariance matrix for the estimated value of marine elements and known marine data, and $r, s = 1, 2, \cdots, N$, N is the number of known marine elements selected from a region.

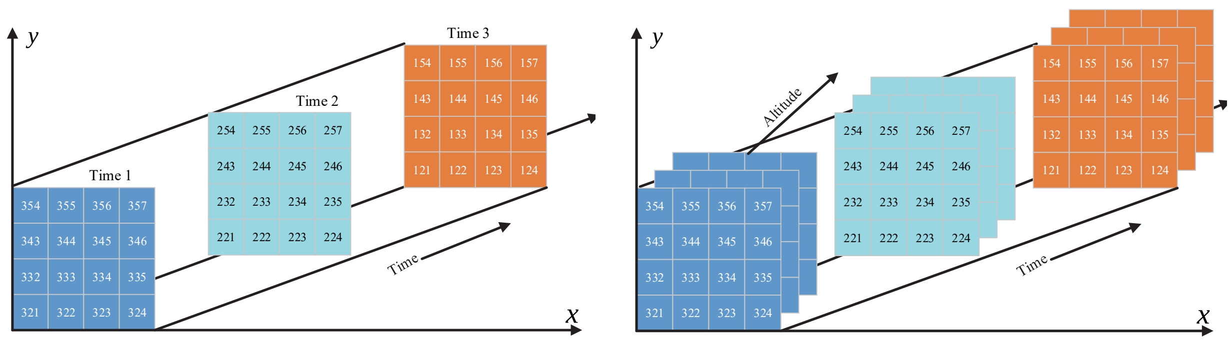


Fig. 2. Multidimensional data storage schematic diagram: (a) three-dimensional data; (b) four-dimensional data

Owing to the irregular distribution of observed data, it is important to select a relevant scale of marine elements. Other studies currently use the following spatial scale of marine elements in China (Eq. 4):

$$Re = \frac{\sqrt{gH}}{f} \tag{4}$$

Optimal interpolation method accounts for the impact of marine data observation time on data analysis, and despite some analytical error, it is easy to adjust and analyze details afterward.

2.5. The proposed method flow

Marine space is the extensive presence of marine materials, energy, information quantity, and process in the ocean. Visualization methods of marine environmental data must express the distribution and variation of marine environmental elements in spatial and temporal dimensions, and thereby represent the spatio-temporal evolution of the marine spatio-temporal process (Shareef, 2014).

The advantage of NetCDF model is that netCDF files are compact, requiring very little overhead to store the ancillary data that makes the datasets self-describing. Optimal interpolation has many attractive characteristics, including quasi-dynamically consistent, multivariate, inhomogeneous and anisotropic covariances. The ensemble for optimal interpolation can be time-invariant. The proposed method combined NetCDF with optimal interpolation constructs marine spatio-temporal process objects, forms a unified field rendering framework, and achieves a 3D dynamic expression of marine environmental data. The proposed method tackles the problem of marine environment data discontinuity and improves the visualization filling the spatio-temporal gaps of the data. The flow of the proposed method is shown in Fig. 3 and is enumerated below.

(1) Data pre-processing. The data stored in different periods or depths are merged to form 3D or 4D independent data that completely express the marine spatio-temporal process.

(2) Marine environmental data are converted and processed according to the NetCDF format, which allows unified storage and management of all relevant data.

(3) Data type and characteristics are used to construct marine spatio-temporal process objects, decompose them into spatial information, and attribute said information and temporal information. All information is managed by the marine spatio-temporal process data model.

(4) The 3D object rendering model that gives consideration to time is built according to the object rendering mechanism.

(5) The temporal interpolation method is adopted to construct time sequence objects according to information from the model and process objects, thus achieving the dynamic expression of marine spatio-temporal process phenomena.

(6) The sphere rendering engine and 3D graphics library allow the adoption of mechanisms of efficient massive data scheduling and dynamic data updating, which combine viewpoint LOD, multi-level caching, and multithreading, as well as achieve multidimensional, dynamic, interactive visualization and query analysis of marine environmental data.

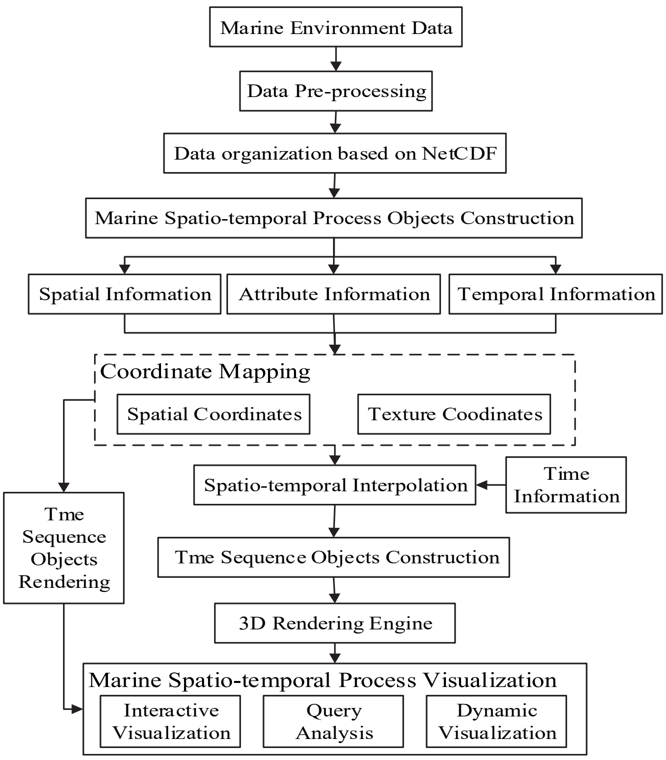


Fig. 3. The flow of the proposed method

3. Experimental

3.1. Experimental data

This study selects the average weekly salinity data of Chinese sea and AVHRR-only products with concentrated global optimal interpolation daily-averaged sea surface temperature data for the experimental analysis. The average weekly salinity data of Chinese sea are available from South China Sea and Adjacent Seas Data Center, National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China (http://ocean.geodata.cn). These data are produced by National Marine Data and Information Service subordinates to the Ministry of Natural Resources of China. These data cover Bohai Sea, Yellow Sea, East China Sea and South China Sea with a spatial resolution of 0.5 degree latitude x 0.5 degree longitude and a time resolution of 7 days from January, 1986 to December, 2008. AVHRR-only products with concentrated global optimal interpolation daily-averaged sea surface temperature data are available on line at https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html.

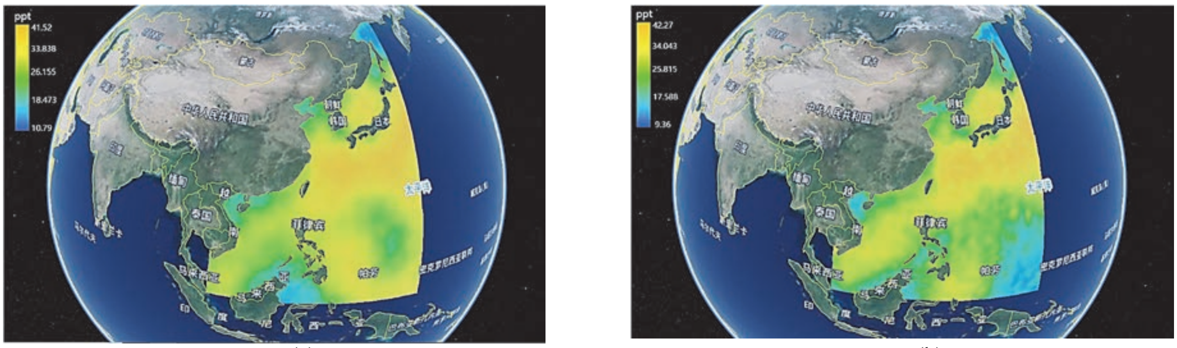
These data are produced by the University of Miami and the NOAA National Oceanographic Data Center. These data are stored in independent files, making it difficult to achieve continuous dynamic visualization and timing analysis of spatio-temporal processes. Hence, the specific application must combine multiple sea surface temperature data into a data set at a specific.

Global optimal interpolation of weekly-averaged sea surface temperature data from December 31, 1989 to July 18, 2012 is processed at a spatial resolution of 1.0 degree latitude x 1.0 degree longitude and a time resolution of 7 days.

3.2. Visualization of ocean salinity field data

The commonly used visualization of ocean salinity data switches according to the time points of data and dynamically updates the scene, thus creating an effect similar to the continuous playback of drawn objects in a time sequence. Sudden changes of time cause jumping or shaking visual scenes, an error more evident with data that have a larger time resolution, which, therefore, cannot smoothly display the spatio-temporal change process of marine elements. The Fig. 4 show the visual effects of weekly-averaged salinity data of Chinese seas, from which one can intuitively reflect changes in data.

This study visualizes the marine spatio-temporal process using optimal interpolation. It uses spatial interpolation for fixed data points and considers the relation between space and time to calculate the temporal interpolation of marine environmental data at adjacent time points. This eliminates the "time crack" and achieves the smooth spatio-temporal process dynamic visualization of marine environmental data. The visualization of the processed mid-point average interpolation (i.e., the mean value of data at adjacent periods) for average salinity data of Chinese seas is shown in Fig. 5. Smoother data transition and dynamic visualization of the spatio-temporal process are obtained.



(a) (b)

Fig. 4. Visualization of salinity data without interpolation: (a) Time steps 1; (b) Time steps 2

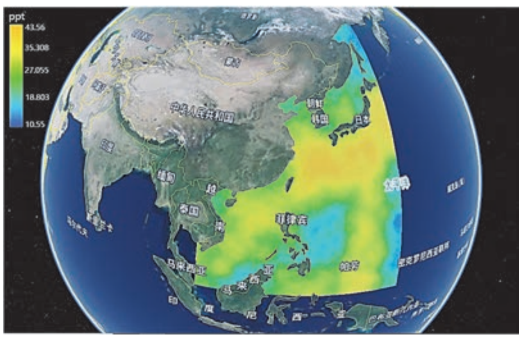


Fig. 5. Visualization of the salinity data interpolation results derived from the proposed method

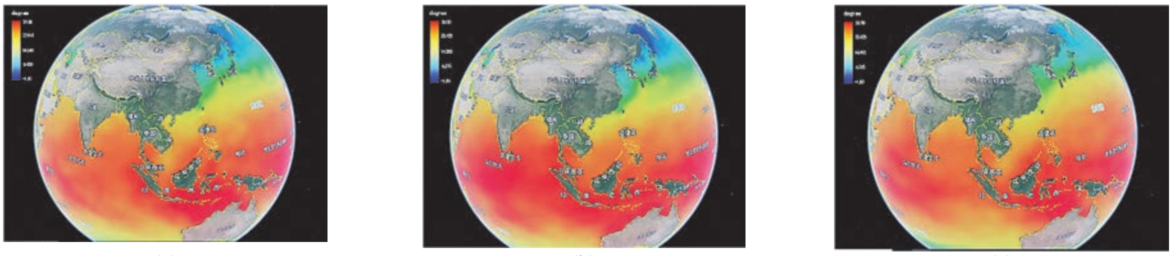
The proposed method uses temporal interpolation to eliminate the "time crack" of large time resolution data, that is, it remains accurate to the original marine environmental data, and achieves a smooth and stable spatio-temporal process dynamic visualization effect.

3.3. Visualization of ocean temperature field data

Seawater temperature is one of the basic elements of marine physical properties and marine hydrological elements. Changes in sea surface temperature can significantly affect the physical condition and nature of oceans and atmosphere. The depth of the ocean can reflect the internal features of the sea, and the ocean thermocline depth and distribution can be determined according to the depth of seawater temperature. The visualization of AVHRR-only products with concentrated global optimal interpolation daily-averaged sea surface temperature data is shown in Fig. 6. Time process visualization can be demonstrated by broadcasting and playback buttons, and it directly and vividly describes the evolution of elements with the passage of time. It supports 3D scenes, and users can view the temperature–time curve (Fig. 7). Marine environmental element data reflect the spatio-temporal changes of marine element value over time and depth. Isosurface, volume rendering, multi-level visualization, and other methods can be adopted for drawing. The annual average sea temperature multi-level data of NODC 1998 World Ocean Map Data from 1990 to 1997 are selected, at a spatial resolution of latitude and longitude $1^{\circ}\times 1^{\circ}$, spatial range of 89.5N-89.5S, 0.5E-359.5E, and depth of 0–5500 m, which is divided into 32 layers. The visual effect of some depth levels is shown in Fig. 8, which supports the dynamic display of the temporal dimension. The profile curve of the "Temperature–Depth" at different points is shown in Fig. 9.

4. Discussion

Through the above comprehensive analysis of the typical marine environmental spatio-temporal data, this study proposes a process-oriented marine spatio-temporal data model, which is the basis for efficient expression of the marine spatio-temporal data. Using the multi-dimensional data organization model NetCDF, the netCDF-based marine environmental data organization and storage method achieves unified description and management, which provides a valuable method for the efficient management and sharing of marine data.



(a) (b) (c)

Fig. 6. Dynamic visualization of sea surface temperature data: (a) Time series 1; (b) Time series 2; (c) Time series 3

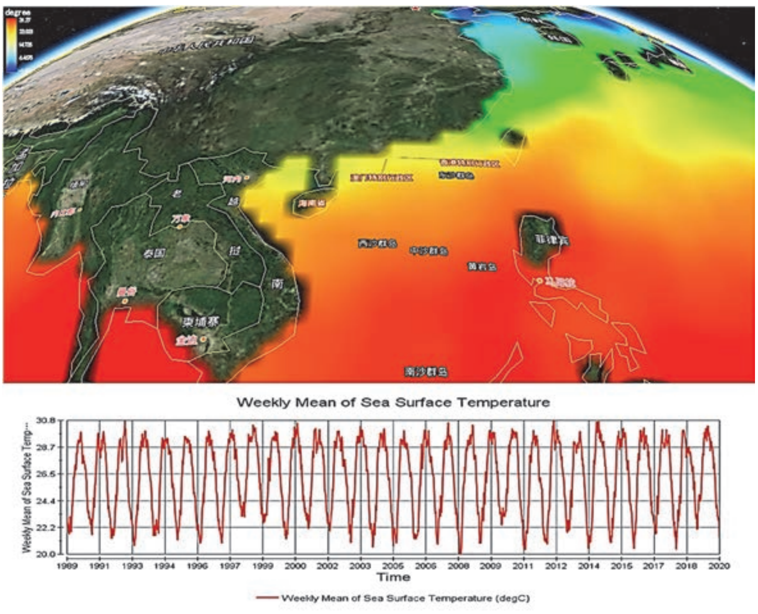


Fig. 7. Time sequence analysis

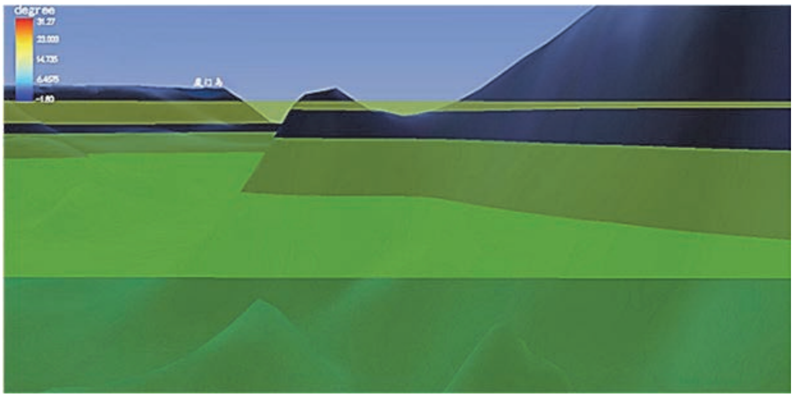


Fig. 8. Visualization of sea temperature depth multi-level data

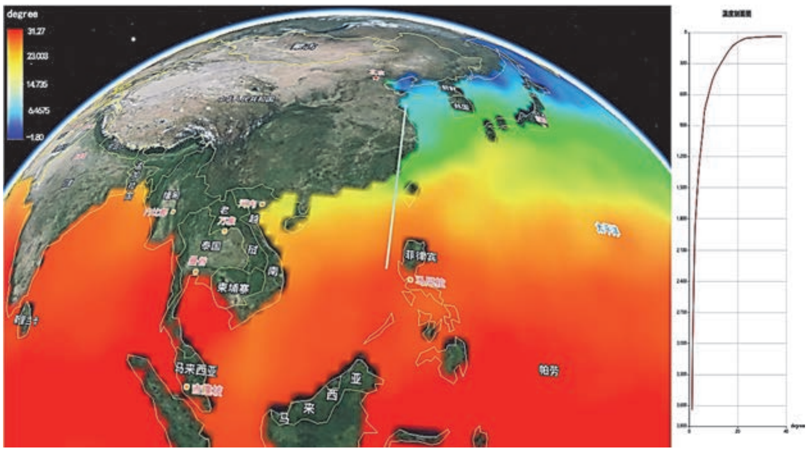


Fig. 9. Depth profile analysis

Based on three-dimensional virtual earth, this paper discusses continuous, smooth visualization in time dimension based on time interpolation, which makes the spatial-temporal distribution characteristic and change trend of marine elements and phenomena visualization more clearing, intuitive, vivid, and provides a visual way to reveal the rules and characteristics of marine phenomena.

The multi-dimensional dynamic visualization of marine environmental data can provide a comprehensive, detailed, and intuitive description of the spatial characteristics and change trends of multidimensional objects. It provides a three-dimensional visualization and analysis tool to intuitively express and reveal marine phenomena in detail. This study comprehensively analyzes marine environmental data and typical marine environment spatio-temporal data models, elaborates the semantics and concepts of the spatio-temporal process of process-oriented marine spatio-temporal data, and introduces the NetCDF multidimensional data organization model. It likewise proposes the construction and dynamic visualization of a marine spatio-temporal process model based on optimal interpolation, achieves the visualization of the marine spatio-temporal process based on temporal interpolation, eliminates the "time crack" of large time resolution data, and ensures the continuous, smooth, and dynamic visualization of marine data over time.

Process-oriented spatio-temporal data models are currently popular. This paper proposes the organization and dynamic visualization of the marine spatio-temporal process based on process modeling and achieves the continuous smooth visualization of marine elements or phenomena in spatial and temporal dimensions. However, the proposed model was done under the assumption of relatively independent time and space. In reality, they are not absolutely independent, but are interrelated and variable. The integration of temporal and spatial dimensions can fully cognize and discover the characteristics and laws of geographic phenomena.

5. Conclusions

Marine spatial-temporal process model plays an important role in the multi-dimensional dynamic visualization of marine environmental data. In this work, marine spatial-temporal process model to integrate NetCDF and optimal interpolation is presented. The proposed model uses NetCDF data models to store and share high-performance multidimensional data, and utilizes marine spatio-temporal processes based on optimal interpolation method to improve the dynamic visualization quality of marine environment data. This paper demonstrates that the proposed model is a more efficient approach for dynamic visualization of weekly-averaged survival data of Chinese seas and optimal global interpolation daily-averaged sea surface temperature data of centralized advanced very high-resolution radiometer-only products.

Some limitations still remain in our study, and further work is required. Therefore, future research will focus on the marine spatio-temporal data model with unified temporal and spatial dimensions and its spatial patterns and should examine the impact of spatial scale on the marine spatio-temporal data model. At any rate, how to elucidate the dynamics of the marine environment data modes is still an open question and more work is needed.

Acknowledgments

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