Multiple Scatter Plots-based
Multi-Dimensional Transfer Function
and its Application to Ocean Data Visualization

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Abstract. To understand simulation data from the perspective of multivariables is important in numerical simulation study. This study proposes a new multi-dimensional transfer function that enables users to extract and visualize characteristic features with their empirical and intuitive judgment. In the proposed method, data points that represent characteristic features are selected in a couple of 2-dimensional scatter plots. Extracted data in each 2-variable space of multivariate datasets are assigned to different color components such as hue, saturation and/or brightness, respectively, in order to classify and specify the characteristic features. We applied the method to high-resolution ocean simulation data with the advice of oceanographers. As a result of case studies, ocean currents and eddies are intuitively extracted and clearly represented with their physical properties such as current speed, temperature and salinity.

Keywords: Multivariate visualization, Multi-dimensional transfer function, Feature extraction, Ocean simulation

1. Introduction

The ocean, which accounts for 70% of the earth’s surface, stores and transfers heat absorbed from the sun, and plays an important role in global environmental change. These global changes, such as global warming and extreme weather, affect human activities. Recently, due to advances in supercomputing technology, high-resolution, large-scale ocean models have been developed and lots of studies undertaken that aim to elucidate, reproduce and forecast ocean phenomena.

Ocean simulation results contain various types of ocean structures with various types of physical characteristics. For instance, ocean currents have a variety of properties such as current speed, temperature and salinity. However, when visualized as only single physical varia-
For a method to extract features from multivariate data, multivariate analyses such as cluster analysis, which classify similar data, are well known (e.g., [1, 2]). However, these semi-automatic methods have problems about initial parameter setting, ambiguity and validation of analysis results. On the other hand, visual feature extraction methods have been proposed in the visualization and computer graphics community ([3, 4, 5]). These methods are used to visually extract characteristic features in multiple coordinated views. The features are extracted from multivariable data; however, their physical quantities of extracted structures are not represented using these methods. Due to this reason, it is not easy to judge whether the extraction result is valid or not from visualization images using these methods. In order to carry out proper judgement during the process of visual feature extraction, it is necessary to visualize the physical quantities used that feature the extraction process.

We propose a new visualization method, the multiple scatter plots-based multi-dimensional transfer function, which enables both feature extraction from multivariate data and visual representation of their multiple physical quantities. The proposed method, the multiple scatter plots-based multiple transfer function, extracts physical features on a couple of 2-dimensional (2D) scatter plots and assigns data to color components in different 2-variable spaces. The proposed method was presented in AsiaSim 2014 [6]. In the present manuscript, two case studies, which are already reported in [6], are retried to improve the results. Furthermore, an additional case study about visualizing ocean eddies is also performed. All of the case studies have been carried out with advice from physical oceanographers.

2. Related work

2.1. Visual feature extraction from multivariate data

The major method of the feature extraction method is cluster analysis, which is one of the multivariate analysis types such as k-means [7], the hierarchical method [8] and the density-based method [9]. These methods have been applied to extracting ocean currents and vortices. However, for these automatic techniques, the problem remains to be solved with regard to verification of analysis process and validation of analysis results [10]. On the other hand, various kinds of visual feature extraction methods have been proposed in the visualization and computer graphics community. In many visual feature extraction methods, multivariate data is represented in multivariable space such as a scatter plot matrix [11], parallel coordinate plot [12] and these techniques combined [4, 5]. Brushing [13] was firstly introduced by Becker and Cleveland to highlight, label and remove data points, and is used in many linked view systems.

Based on a scatter plot in multivariate space, many works of multi-dimensional transfer functions [14], which assign multiple physical quantities to color and opacity, have been studied. These kinds of transfer functions are applied to boundary detection [15, 16] and feature specification [17, 18]. Visual representation methods of multivariate data have also been proposed for understanding multiple physical quantities and applied to a couple of science and technology fields. Wong et al. [19] proposed a layering method that represents a multiple scalar field and vector field by means of overlapping layers with transparency. Urness et al. [20] presented flow field visualization methods, color weaving and texture stitching, for multi-valued
data based on Line Integral Convolution (LIC) [21]. Multivariate color maps [22], which assign two or more physical variables to independent color components, are applied to visualizing uncertainty data [23], climate data [24] and ocean data [10, 25].

So far, a lot of work about multivariate feature extraction and multivariate representation has been individually studied and applied to many science and technology fields. However, in order to visually extract characteristic features from multivariate data and simultaneously represent these physical properties, it is necessary to satisfy both functions of multivariate feature extraction and multivariate representation. In this study, we propose a method that can extract characteristic features on a couple of scatter plots and represent the meaning of extracted regions based on the multi-dimensional transfer function.

2.2. Ocean simulation

The ocean simulation data used in this study is produced by the OFES [26, 27]. The OFES solves the Navier-Stokes equations, the equation of continuity, the advection diffusion equation and the state equation of sea water discretization using the finite difference method, and calculates the time variation of velocity fields, density, pressure, temperature and salinity. We use two types of model with different computational domains: the quasi-global model from 75°S to 75°N, excluding the Arctic Ocean, and the North Pacific model. The horizontal resolution is 0.1° (about 10 km on the equator) for the quasi-global model and 1/30° (about 3 km on the equator) for the North Pacific model. The number of vertical levels of both models is 54 and the level thickness varies from 5 m for the surface to 330 m for the bottom. A hindcast

![Figure 1: Simulation results of OFES (0.1 degrees)](image-url)
simulation has been performed with NCEP/NCAR reanalysis data [15] for heat flux, salinity flux and wind stress from 1950 to 2004 as a boundary condition on the sea surface. Fig. 1 (a) and (b) depict the simulation result of sea surface temperature (SST) and current speed (velocity magnitude), respectively.

3. Multiple scatter plots-based multi-dimensional transfer function

In this section, we introduce the basic idea and basic functions of the multiple scatter plot-based multi-dimensional transfer function proposed in this study.

3.1. Basic idea

The purpose of the proposed method is to extract characteristic features from multivariate data and to represent their physical quantities. The proposed method uses a 2D scatter plot for intuitive feature extraction. A 2D scatter plot, which is one of the data representation methods, displays 2-variable data with dot points in 2D space and is used to identify the relationship between these data. A conceptual image of the proposed method is shown in Fig. 2. Users select a couple of 2D scatter plots of 2-variables in accordance with target structures. In each 2-variable space, characteristic data regions are extracted and color components are assigned to extracted regions. At this point, color components of hue, saturation and/or brightness, which compose the HSV color model, are used for designing the multi-dimensional transfer function. If the multi-dimensional transfer function is designed on a single 2-variable space, it is the same as a normal 2D transfer function.

Figure 2: A conceptual image of multiple scatter plots-based multi-dimensional transfer function
In the example of Fig. 2, a color component of hue (e.g., yellow, green and blue) is assigned to three groups on the 2D space of variables #1 and #2. In the same way, saturation and brightness is assigned on the 2D space of variables #2 and #3, and variables #1 and #3, respectively. By simultaneously using multiple (in this case, three) 2D transfer functions, feature extraction and representation from multivariate data are realized.

3.2. Basic function

The designing process of the multi-dimensional transfer function and its two main functions, feature classification and feature specification, are explained below. In common with both usage, users firstly choose a single 2D scatter plot that is most relevant to the target structure, and manually extracts data points in 2D space. In the next step, a color component is assigned to extracted data points. Finally, the visualization result is represented using a couple of 2D transfer functions.

In the case of “feature classification”, users manually or automatically select a structure and assign brightness (or saturation) in a 2D scatter plot as shown in Fig. 3 (a) (left). Next, the data points with brightness (or saturation) are mapped to other 2D scatter plots and the user manually assigns hue (e.g., red, green and blue) as shown in Fig. 3 (a) (right). The structure extracted in one 2D scatter plot is classified into several structures in other 2D scatter plots.

“Feature specification” is the second function of the proposed method. The color of the extracted feature is expressed by hue (yellow) as shown in Fig. 3 (b) (left). The data points with hue are mapped to other 2D scatter plots, and the user manually selects colored data points and the assigned remaining color component (e.g., brightness) as shown in Fig. 3 (b) (right). In this example, the extracted structure with a bright color is emphasized, but other structures with dark color are not emphasized.

Figure 3: Basic functions of the proposed method
4. Results

In this section, we perform three kinds of case studies to visualize ocean data using the proposed method. Especially, the multi-dimensional transfer function is designed for visualizing ocean currents and ocean eddies using the function of feature classification and specification.

4.1. Feature classification of ocean currents in global scale

Ocean currents are characterized by not only current speed but also numerous physical aspects such as their temperature, salinity and so on. In this subsection, we attempt to visualize ocean currents and their multiple physical properties in a global scale using the feature classification of the proposed method.

As a first step, the two variables of current speed and temperature are chosen to extract ocean currents. Ocean current is defined not as an absolute value of current speed but a relative value compared with the surrounding area. For example, the fastest data around 27.0 degrees C are about 2.0 m/s; however, the data around 2.0 degrees C are about 1.2 m/s as seen in Fig. 7 (a). For this reason, we manually extracted relatively fast speed regions of each temperature on a 2-variables space of current speed and temperature ($v$-$t$ space). To be more specific, divi-
Binning the temperature range from -3.0 deg. C to 30.0 deg. C into 1,000 histogram bins, 40% of the maximum flow in each range is assigned to a high saturation color (red plots) as shown in Fig. 4 (a). This figure represents a 2D transfer function of saturation (hue is red and brightness is max). By using this 2D transfer function, lots of structures like ocean currents are visualized as shown in Fig. 4 (b). Not only the Kuroshio and Oyashio Currents but also the Antarctic Circumpolar Current, the Gulf Stream and the North Pacific Current can be represented in the high saturation (red) region.

Next step, extracted ocean currents are classified by assigning the 2D transfer function of hue on a 2D scatter plot of temperature and salinity. The mapping result of the extracted region in the uv-t space (Fig. 4 (a)) onto the temperature and salinity space is represented by saturation (hue is red and brightness is max) in Fig. 5 (a). Several clusters of vivid red points are distributed in colored solid lines (magenta, red, orange, yellow, green, cyan, blue and violet). Therefore, in order to distinguish each cluster of fast flow structures, a 2D transfer function of hue is designed in the 2D scatter plot of temperature and salinity. In this 2D transfer function, unique colors of hue are assigned to each cluster of fast flow structures as shown in Fig. 5 (b). A visualization result using only the 2D transfer function of hue is shown in Fig. 5 (c). This transfer function does not include the information of current speed; therefore, ocean structures that have similar temperature and salinity are represented in Fig. 5 (c).
Journal of Advanced Simulation in Science and Engineering

Finally, by using both the 2D transfer function of saturation (Fig. 4 (a)) and 2D transfer function of hue (Fig. 5 (b)), ocean currents in the global scale are classified as shown in Fig. 6. In this result, the Kuroshio Current and the Kuroshio Extension (green), the Oyashio Current (blue), the Antarctic Circumpolar Current (cyan), the Labrador Current (violet), the Gulf Stream (yellow), the Equatorial Countercurrent and the Agulhas Current (magenta) and the South Equatorial Current (red) are represented with different colors. These colors indicate physical properties of temperature and salinity. For example, the Kuroshio Current and the Kuroshio Extension has 12.0 to 22.0 deg. C in temperature and 34.0 to 35.0 psi in salinity. Here, the brightness of each color is fixed to a maximum value.

![Figure 6: Feature classification using two 2D transfer functions (Fig. 4 (a) and Fig. 5 (b))](image)

4.2. Feature specification of ocean currents around Japan

Extracting the distribution of ocean currents is important to understand ocean circulation and its physical roles. As the second case study, feature specification, which is one of the basic functions, is applied for precisely extracting the Kuroshio and Oyashio Currents.

First, we select a 2D scatter plot of current speed and temperature from all combinations of two variables, and manually extract structures with a fast flow region. Because ocean currents are relatively fast flowing as mentioned above, we assigned seven unique colors of hue to fast flow regions in each temperature range to distinguish ocean currents as shown in Fig. 7 (a). Here, the temperature ranges are divided into seven to distinguish ocean currents by trial and error based on the user’s knowledge about typical temperatures of ocean currents. The visualization result using this 2D transfer function is depicted in Fig. 7 (b). The Kuroshio Current (red, orange and yellow) and the Oyashio Current (blue and violet) are roughly represented as the colored region. However, not only ocean currents but also some scrap structures not connected to these currents are also visualized.

In the next step, a 2D transfer function of saturation is designed based on a 2D scatter plot of temperature and salinity (t-s space), so as to specify only ocean currents and remove scrap structures. It is well known that temperature and salinity are two of the primary characteristics to identify ocean water property. Extracted regions in the 2D scatter plot of current speed and temperature are mapped into a 2D scatter plot of temperature and salinity as shown in Fig. 8 (a). A thick structure is distributed from the upper right to the lower left in the figure.
Several scrap structures with color are also located away from the thick structure. Spatially continuous structures like ocean currents must be continuously distributed in any physical spaces. Therefore, a transfer function of saturation is designed in the 2D scatter plot of temperature and salinity, so as to emphasize the thick structure (black solid line) and to shade off those seen in Fig. 8 (a). Fig. 8 (b) shows a transfer function of saturation (hue is temporarily expressed by red, and brightness is max). A vivid color (saturation is high) is assigned to the thick structure and dull color (saturation is low) is assigned to other scrap structures.

By simultaneously using both two 2D transfer functions of hue (Fig. 7 (a)) and saturation (Fig. 8 (b)) together, it is possible to extract correctly and visualize ocean currents. Figure 9 shows a visualization result obtained using two 2D transfer functions. Compared with the visualization result of Fig. 7 (b), the scrap structures are represented as the dull color, but the ocean currents are clearly emphasized. Here, brightness is defined as maximum and the data point that both hue and saturation are not assigned is not displayed.
4.3. Feature specification and classification of ocean eddies in global scale

Ocean eddies, which are swirling ocean streams with relatively high and low heights, are known to transfer heat, salt and kinetic energy and affect weather conditions and marine systems. Understanding ocean eddies is important in the ocean and climate science field. Until recently, many studies about ocean eddies have been carried out using satellite observation and a high-resolution ocean model (e.g., [28, 29]). Extraction methods of eddies have also been investigated to analyze their properties using relative vorticity [30], the Okubo-Weiss parameter [31, 32], sea surface height anomaly [33], and so on. In this study, applying the proposed method to ocean eddy detection, we extract ocean eddies and visualize their multiple physical properties such as temperature and salinity.

Two of the most characteristic features of ocean eddies are that their flow is swirling and the altitude is relatively high or low compared with surrounding areas. Thus, we choose two parameters related to the rotational component of the velocity field and relative value of sea
surface height to identify eddies. As the variable of the swirl flow field, the Okubo-Weiss parameter, which represents the difference between shear strain and vorticity, is employed. The Okubo-Weiss parameter is defined as $Q = s_n^2 + s_s^2 - \omega^2$, where $s_n = \partial u_x / \partial x - \partial u_y / \partial y$, $s_s = \partial u_y / \partial x + \partial u_x / \partial y$, $\omega = \partial u_y / \partial x - \partial u_x / \partial y$ and the velocity field $u = (u_x, u_y)$. The region with a negative Okubo-Weiss parameter indicates ocean eddies. The anomaly value of sea surface height (SSHA) is calculated by subtracting the real value of SSH from its mean value during two decades (so called climatic value). Fig. 10 (a) and (b) show the visualization results of the Okubo-Weiss and SSHA, respectively. Some structures which are not swirl-like ocean currents are depicted as well as fine-grained configurations (~10km), which are not able to be resolved in a numerical model.

![Visualization result of ocean eddies using single variable](image)

Figure 10: Visualization result of ocean eddies using single variable

The 2D transfer function of saturation is set on 2-variables space to extract eddies as shown in Fig. 11 (a). A high saturation color is assigned to the region with a negative Okubo-Weiss parameter, and magnitude of SSHA $\geq 0.1$ m. Fig. 11 (b) shows the visualization result using this 2D color map of saturation (here, hue is red and brightness is max). Small eddies shown in Fig. 10 (a) around the Eastern China Sea and the Sea of Okhotsk are removed in Fig. 11 (b). The configurations over $O$ (100km) with a circular shape, so-called meso-scale eddies, are only detected. The information of sea surface height indicates the size of ocean structures.

The purpose of this case study is to visualize eddies that transfer heat and/or salt. Hence, setting a 2D color map of hue on a 2-variable space of an anomaly of salinity and temperature, extracted eddies are classified by their role whether they transfer heat or salt. These two values are calculated using their snapshot data and climatic data in the same way as SSHA. Fig. 12 (a) is a 2D scatter plot of anomalies of temperature and salinity, and extracted eddies are mapped as the red point. In this 2D space, eddies are classified into nine kinds of property according to the data distribution, in other words, eight colors of hue are assigned to eddies as shown in Fig. 12 (b). For example, the yellow color indicates that eddies have a higher water temperature than climate value. In a similar fashion, the blue color indicates that eddies have a lower temperature and salinity than the climate value. Fig. 12 (c) depicts a visualization result of eddies
Figure 1: Visual feature extraction of eddies on the Okubo-Weiss parameter and SSHA plot and their properties using two of the 2D transfer functions. Fig. 11 (a) and Fig. 12 (b) are used for saturation and hue. Meso-scale eddies and their physical properties are represented in one image, and the role of eddies can be inferred from the image. As for a region with characteristic feature of eddies, for example, a group of red eddies around the Agulhas Current transfer high salinity water (gray dashed line (A)) and violet eddies around a part of the Antarctic Circumpolar Current (B) transfer low temperature. On the contrary, various types of eddies with several colors are mingled around the Kuroshio Current and the Oyashio Current (C), the Gulf Stream (D) and the Mozambique Current (E). In those regions, water mass mixing occurs via eddies with several properties. This result leads to an inter ocean exchange as a result of a vortex pair [34] that occurs around fast flow currents.

5. Summary and discussion
In this study, we proposed a new visualization method that satisfies feature extraction from multivariate data and visual representation of their multiple physical quantities with the aim of
understanding numerical simulation data. Three case studies for visualizing ocean structures were carried out, applying the proposed method to high-resolution ocean simulation data. As a result, ocean structures such as ocean currents and eddies are precisely extracted and effectively represented with their multiple physical properties based on data distribution and user’s domain knowledge. Comments from physical oceanographers who cooperated on the case studies with us are as follows:

- The proposed method might be used for new definition of ocean currents and eddies regions.
- The visualization results and multi-dimensional transfer functions provide us with intuitive understanding of ocean structures and their physical properties.
- The method is able to use high resolution observation data and reanalysis data as well as simulation data.

In the proposed method, all of the visualization process is carried out based on the user’s objective judgement. This point is a special feature of the proposed method (or visual analytics). For that reason, ease of use and validity of the results depend on user’s knowledge and experience. It is noted that the proposed method is not for making a final image but for understanding multivariate data by user’s trial and error. All of the process
is performed manually in the three experiments; however, it is possible to automatically extract characteristic structures using such methods as cluster analysis.

Contrary to this, there are some restrictions to the proposed method. For example, in all case studies, only 2-variable space is used for the transfer function setting; however, users possibly want to design transfer functions using three or more variables. Furthermore, if the transfer functions of saturation and brightness are simultaneously used, the visualization result will become unclear. For this reason, only up to four variables are used in each case study. In such case, in order to treat four or more physical variables, it is possible, in theory, to employ the logical operation [35, 36].

Depending on the extraction region and the choice of physical variables, two or more extracted regions in a 2D scatter plot might overlap with one region in another plot. Moreover, in the case of more high-resolution large-scale data, it is difficult to recognize data distribution in a traditional 2D scatter plot. As future work, novel information representation methods (e.g., [37, 38]) may be required to handle large amounts of data.

This study is mainly focused on 2D data of sea surfaces except for middle-depth and deep oceans. However, as a future prospect, the proposed method is applicable to visualize 3D configurations such as the thermohaline circulation and water mass, which are defined by temperature, salinity and pressure. Furthermore, the notions employed here are applicable for visualizing not only ocean data but also other geoscientific data such as meteorology, climate, and solid earth.

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