A comparative 3D visualization tool for observation of mode water

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Abstract

Mode water forms a 3D region of seawater mass, which has similar physical characteristics values. Research and observation of mode water have a long history in physical oceanography because analysis of mode water brings the understanding of various natural phenomena. There have been various definitions of mode water, and comparison of mode water regions extracted with such various definitions is an important issue in this field. This paper presents our study on comparative 3D visualization tool for the comparison of mode water regions. We extract pairs of outer boundaries of mode water regions as isosurfaces and calculates dissimilarity values between the pairs. The tool visualizes the multi-dimensional vectors of the dissimilarity values by Parallel Coordinate Plots (PCP) and provides a user interface to specify particular pairs of mode water regions so that we can comparatively visualize the shapes of the regions. This paper introduces our experiment on a comparison of mode water regions between an observation and a simulation datasets using the presented tool.

Keywords: Comparative visualization, Scientific visualization, Volume dataset, Ocean data, Mode water, 3D shape similarity, PCP, Isosurface.

Index Terms: Human-centered computing—Visualization—Visualization application domains—Scientific visualization Information systems—Information retrieval—Retrieval models and ranking—Similarity measures

1 Introduction

Mode water is defined as particular characteristics of seawater mass. In other words, mode water forms a 3D region which has similar physical characteristics values such as temperature, density, and salinity. Figure 1 shows the distribution of mode water in the world. For example, the northern part of Pacific ocean has central, subtropical, and eastern-subtropical mode water. It is caused by the condition change of air on the seawater surfaces, such as heat transfer and exchange of freshwater. Analysis of mode water brings the understanding of various natural phenomena, such as the flow of seawater and mechanism of climate change. Therefore, research and observation of mode water have a long history in the field of physical oceanography.

A mode water region can be defined as a set of subregions which satisfy pre-defined conditions of physical characteristics. There have been various studies on mode water based on their definitions applying different sets of physical characteristics [4, 7, 9, 11, 15]. Also, various thresholds have been applied to extract mode water regions [2, 10, 16] appropriately. It is therefore important to analyze how different definitions of thresholds might bring similar or different results. These analyses would bring benefits for some scenarios. As an example scenario, let us suppose we have a long time observation of physical characteristics at a particular region of the ocean, and simulation results mimicking the same region with a variety of conditions of physical characteristics. We can compare mode water regions extracted from each timestep of the observation results and each simulation result, and recognize which simulation can reproduce which observation result. This comparison can contribute to collate the observations and simulations.

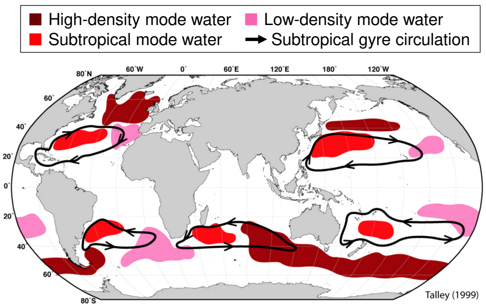

Figure 1: Distribution of mode water in the world [13].

There have been several studies on comparative analysis and visualization of mode water; however, these studies mainly apply 2D scientific or information visualization techniques. We expect 3D visualization techniques would help to understand of difference and similarity on 3D shapes of mode water regions extracted under different conditions.

This paper presents our study on comparative 3D visualization tool for the comparison of mode water regions. This study supposes to compare two volume datasets generated by observation or simulation of the same ocean region. It firstly generates isosurfaces as outer boundaries of mode water regions from both datasets and calculates the similarity of the isosurfaces by applying a 3D shape comparison technique. Applying a variety of conditions of physical characteristics and repeating isosurface generation and 3D shape comparison, we can get a series of similarity values. We visualize the set of similarity values as multi-dimensional data and observe the relationships between similarity values and conditions. This observation helps to select preferable pairs of conditions to appropriately compare two datasets. The tool can also comparatively display a pair of isosurfaces when a user specifies a condition on the multi-dimensional data visualization. This 3D isosurface visualization can help users to understand if the pair of isosurfaces is globally or locally similar.

We tested this tool with real observation and numeric simulation datasets of the northern-pacific ocean and compared various shapes of isosurfaces. This paper introduces this experiment and discusses the usefulness of this tool.

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2 RELATED WORK

2.1 Definition and observation of mode water

Mode water has been defined with various parameters. Table 1 shows examples of references which define mode water applying observation or computer simulation datasets in the northern-pacific ocean. Here, "PV" stands for potential vorticity, and "density" is calculated from temperature, pressure, and salinity [14]. This table suggests that there have been a variety of mathematical definitions of mode water which apply different sets of variables. It may be therefore difficult to compare the studies on mode water conducted based on different definitions.

Table 1: References which define mode water.

Reference	variables
Gao [7]	PV, density
Oka [11]	PV, temperature
Douglass [4]	PV, temperature, density
Yasuda [15]	temperature, gradient of temperature
Matsuzawa [9]	temperature, salinity

A mode water region is defined as a closed 3D region of the ocean where physical characteristics of the seawater satisfy a predefined set of conditions. Table 2 shows the thresholds of variables corresponding to the conditions of mode water regions defined in the past studies. This table suggests that the thresholds of physical variables are different among the past studies even though they observed or simulated the same region (northern-pacific ocean). It is therefore important to analyze how different definitions of thresholds might bring different results. This is the main motivation for us to develop a comparative 3D visualization tool for the observation of mode water regions.

Table 2: References which define mode water.

Reference	data	PV	density
Xu [16]	ARGO	$< 1.5 \times 10^{-10}$	24.9-25.5
Xu [16]	OFES	$< 1.5 \times 10^{-10}$	25.2-25.6
Xu [16]	POPH	$< 1.5 \times 10^{-10}$	24.8-25.3
Xu [16]	POPL	$< 1.5 \times 10^{-10}$	25.3-25.8
Davis [2]	ECCO2	$< 2.0 \times 10^{-10}$	25.0-25.6
Nishikawa [10]	OGCM	$< 2.0 \times 10^{-10}$	24.8-25.3

There have been several studies on visualization of mode water regions. Some of the studies applied "T-S diagram" which assigns temperature and salinity to orthogonal axes and draws scatterplots and iso-contours. It is convenient to understand the distribution of physical characteristics; however, it does not represent any shapes of mode water regions. Other studies applied iso-counters on the cutting planes of the 3D ocean regions [12, 15]. It is convenient to understand the shapes of mode water regions briefly, but it does not represent their 3D shapes.

To summarize, there have been studies of mode water applying scientific and information visualization techniques, but most of the visualizations are 2D-based. Few studies are applying 3D visualization techniques.

2.2 Isosurface-based comparative visualization

Suppose a volume dataset which contains scalar values s_1 to s_N at each grid-point, where N is the number of scalar values. A mode water region can be described as the 3D region surrounding a set of grid-points which satisfies $s_{10} < s_1 < s_{11}$ to $s_{N0} < s_N < s_{N1}$, where s_{i0} and s_{i1} are lower and upper thresholds of the i-th scalar value. Such regions can be perfectly generated as the logical product of interval volumes [6]. Our current implementation just extracts the outer boundary of the mode water region generated by Marching Cubes, but it will be extended by applying interval volumes.

There have been several studies on isosurface-based comparative visualization. Alabi et al. [1] presented an ensemble data visualization technique applying sliced isosurfaces. Demur et al. [3] presented an ensemble of isosurfaces as a set of screen space silhouettes. Hazarika et al. [8] visualized ensemble isosurfaces applying the color-mapping representing distances from the median surface. Our implementation of isosurface-based comparative visualization is close to Hazarika's technique: ours assigns distances from the arbitrary point of an isosurface to the other isosurface to colors of them.

2.3 3D shape comparison

The Recent evolution of 3D object retrieval methods brought a variety of techniques for 3D shape comparison. ElNaghy et al. [5] surveyed 3D object retrieval methods and divided into the following five types:

View-based: Project 3D objects into 2D screens and compare on the 2D spaces.

Graph-based: Generate skeletal graphs of 3D objects and then compare the graphs.

Geometry based: Compare 3D geometric features directly.

Statistics based: Convert 3D geometry into statistic values and then compare them.

General: Compare by other methods.

View-based techniques are especially well applied to various 3D object retrieval studies since there has been a large number of studies and implementation on 2D image retrieval techniques. These techniques are possible to be applied to a 3D object like a mode water region which has been hardly visualized in 3D so far. So, our study presented in this paper also applies a view-based shape comparison technique.

3 TECHNICAL DETAIL OF THE PRESENTED TOOL

3.1 Processing flow

Figure 2 shows the processing flow of the visualization tool presented in this paper. We suppose a set of volume datasets where scalar values s_1 to s_N are assigned to each grid-point. The tool selects a pair of datasets, set conditions to each of them, and extracts outer boundaries of mode water regions as isosurfaces. The tool then compares the 3D shape of these isosurfaces by a view-based method and calculates the similarity.

Here, we suppose multiple isosurfaces can be extracted from a single volume dataset. For example, we can change the conditions of the mode water region and repeat the isosurface generation. we can also extract isosurfaces at multiple time steps if the dataset is time-varying volume. Consequently, we can compare one-to-multiple isosurfaces and treat the similarity values as a multi-dimensional vector. The tool visualizes the multi-dimensional values by Parallel Coordinate Plots (PCP) and provides a user interface to specify particular pairs of isosurface by click operations. Specified pairs of isosurfaces are then displayed applying a comparative 3D visualization window.

3.2 3D outer boundary extraction

The presented tool extract 3D outer boundary of mode water regions as isosurfaces. The tool generates an additional scalar field in a volume dataset: it assigns positive values to the grid-points which satisfies all the conditions while assigning negative values to other grid-points. It then extracts an isosurface as the set of points satisfying that the scalar value is zero, and preserves the outer surface as the 3D outer boundary of a mode water region.

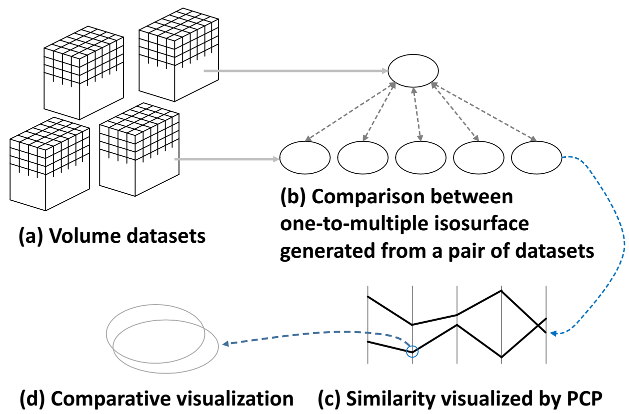

Figure 2: Processing flow.

3.3 Shape comparison

Then, the tool compares a pair of isosurfaces and calculates the similarity values. We implemented a view-based shape comparison method shown in Figure 3. This method firstly generates a polyhedron surrounding an isosurface and treats vertices of the polyhedron as viewpoints. Our current implementation generates a dodecahedron and treats its 20 vertices as viewpoints. Then, it projects the isosurface from each of the viewpoints to a screen and extracts the outer contour of the isosurface. The method calculates the distances and orientation angles of the sample points on the contour and generates a 2D histogram based on these two calculated values. The 2D histogram is normalized with the mean distance and regards frequency as a feature vector. Let $X = \{x_1, x_2, ..., x_{20}\}$ be a set of feature vectors at each viewpoint of shape X. Also let $Y = \{y_1, y_2, ..., y_{20}\}$ be a set of feature vectors at each viewpoint of shape Y. Manhattan distance is calculated between X and Y at each viewpoint by $d(x_i, y_i) = |x_i - y_i|$. Finally, the method calculates the mean distance $\frac{1}{20}\sum_{i=1}^{20} d(x_i, y_i)$ and treat it the similarity $D(X,Y)$ between the shape of two mode water regions.

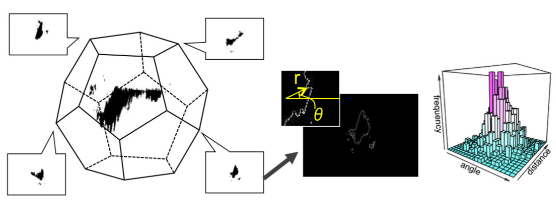

Figure 3: View-based 3D shape comparison.

3.4 Similarity data visualization

We suppose that we can generate multiple isosurfaces from one of the pairs of volume datasets. Consequently, we can calculate multiple similarity values between an isosurface generated from one of the volume dataset and multiple isosurfaces generated from another volume dataset. The tool treats the similarity values as a multi-dimensional vector and visualizes a set of vectors by applying PCP. Our implementation of PCP allows clicking polylines to specify pairs of isosurfaces.

3.5 Comparative visualization

The tool displays a pair of isosurfaces when a user specifies the pair by clicking a particular vertex on the PCP. Users can interactively control the transparency of the isosurfaces. The tool calculates the color of a vertex of an isosurface from the distance from the vertex to the other isosurface. This coloring finely represents which portions of isosurfaces are similar or different each other.

3.6 User Interface

Figure 4 shows a snapshot of the user interface of the presented tool. The center of the window places a drawing area displaying linked views of PCP and comparative isosurfaces as shown in Figure 4 (1)(2). The pair of isosurfaces in Figure 4 (2) is displayed corresponding a vertex on PCP in Figure 4 (1). Similar portions of isosurfaces in Figure 4 (2) show in blue and dissimilar ones show in red. The left and right of the window places user interface widgets for polyline filtering of PCP and visual property adjustment of isosurfaces as shown in Figure 4 (3)(4). Polylines are displayed with similarity values below the user-selected threshold by adjusting PCP filtering in Figure4 (3)left-sided and with the user-selected conditions of mode water regions by adjusting PCP filtering in Figure4 (3)right-sided. The transparency of the isosurfaces can be controlled and a pair of isosurfaces with different conditions of mode water regions is displayed by adjusting PCP filtering in Figure4 (4).

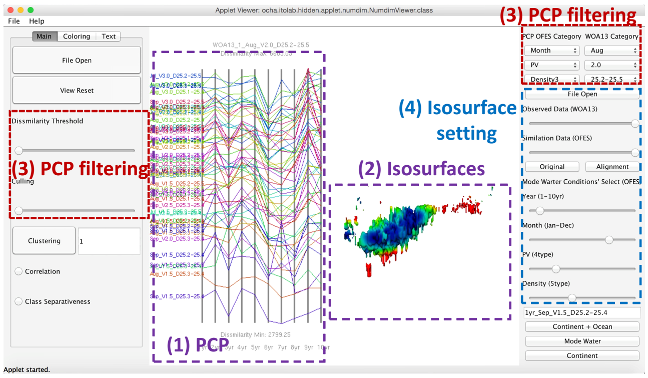

Figure 4: User interface of the tool.

4 Example

We experimented to compare mode water regions of observation and simulation datasets. We downloaded an observation dataset from WOA13 (World Ocean Atlas 2013) [1], and applied a simulation dataset OFES (Ocean general circulation model simulation For Earth Simulator) [2].

Our WOA13 dataset is a regular volume consisting of rectangular elements sized as 0.25-degree latitude/longitude and grid-points which have PV and density values in July, August, and September. Meanwhile, our OFES dataset is also a regular volume consisting of rectangular elements sized as 0.1-degree latitude/longitude and grid-points which have ten years of PV and density values in July, August, and September.

We alternatively set the following conditions to extract mode water regions from the WOA13 and OFES datasets:

- July, August, or September
- $PV < 1.5 \times 10^{-10}$, $PV < 2.0 \times 10^{-10}$, $PV < 2.5 \times 10^{-10}$, or $PV < 3.0 \times 10^{-10}$
- $25.1 \le density \le 25.4$, $25.2 \le density \le 25.4$, $25.2 \le density \le 25.5$, $25.3 \le density \le 25.4$, or $25.3 \le density \le 25.5$

[1] https://www.nodc.noaa.gov/OC5/woa13/
[2] http://www.jamstec.go.jp/esc/research/AtmOcn/product/ofes.html

The combination of above conditions brings 60 patterns of conditions for each of the datasets. This section describes the WOA13 dataset with the i-th pattern of conditions as VW_i, and the OFES dataset with the j-th pattern of conditions as VO_j. In other words, this experiment compared 3,600 pairs of VW_i and VO_j. Here, we calculated similarity values sim_{ijk} between mode water regions extracted from VW_i and the k-th year of VO_j. Then, we treated the similarity values over ten years of the OFES dataset, sim_{ij1} to sim_{ij10}, as 10-dimensional vectors which are used to compare between VW_i and VO_j. This section introduces visualization of 3,600 of 10-dimensional vectors applying PCP.

Figure 5 shows examples of 3,600 of 10-dimensional similarity values visualized by PCP. Colors of polylines in these PCPs are assigned based on conditions of mode water regions. Figure 5 (Upper-left) suggests that observations and simulations in September (drawn in blue) were similar compared with those in July (drawn in red) or August (drawn in green). We also found the useful knowledge on conditions of OFES dataset. Smaller limits of PV values bring better similarity of mode water regions as shown in Figure 5 (Upper-right), where the similarity with the smallest threshold (1.5×10^{-10}) is drawn in red. Narrower ranges of density values bring better similarity of mode water regions as shown in Figure 5 (Lower-left), where the similarity with narrower range (25.3-25.4) are drawn in blue, while wider range (25.1-25.4 and 25.2-25.5) are drawn in red and green respectively. This knowledge will lead us to archive more accurate simulations and reliable reasoning of ocean phenomena. Meanwhile, Figure 5 (Lower-right) shows curious results that larger limits of PV values (3.0 drawn in deep blue, 2.5 drawn in sky blue) bring narrower ranges of similarity, while smaller limits of PV values (1.5 drawn in red, 2.0 drawn in green) bring wider ranges. We would like to explore more detailed results and discuss the reasons for this curious results.

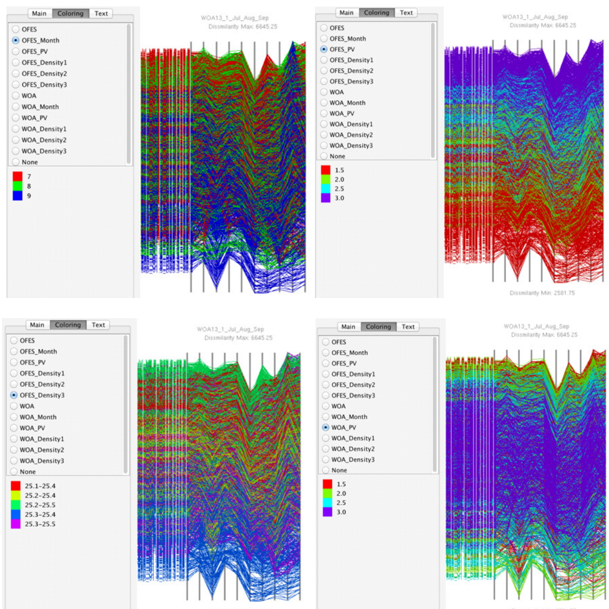

Figure 5: Distribution of 10-dimensional similarlity values visualized by PCP. (Upper-left) Colored based on months of the OFES dataset. (Upper-right) Colored based on PV of the OFES dataset. (Lower-left) Colored based on density of the OFES dataset. (Lower-right) Colored based on PV of the WOA13 dataset.

Figure 6 shows the most similar and dissimilar pairs of mode water regions. The most similar pair was the OFES dataset in September of the sixth year with the conditions $PV < 1.5 \times 10^{-10}$ and $25.3 \leq density \leq 25.4$ with the WOA13 dataset in September with the conditions. $PV < 2.0 \times 10^{-10}$ and $25.1 \leq density \leq 25.4$. Most parts of the isosurfaces are painted in blue which depict small distances. This result suggests that somewhat different conditions for extraction of mode water regions may bring the most similar shapes of the regions. Meanwhile, the most dissimilar pair was the OFES dataset in September of the ninth year with the conditions $PV < 3.0 \times 10^{-10}$ and $25.2 \leq density \leq 25.5$ with the WOA13 dataset in August with the conditions $PV < 1.5 \times 10^{-10}$ and $25.3 \leq density \leq 25.4$. Most parts of the isosurfaces are painted in red or yellow which depict large distances.

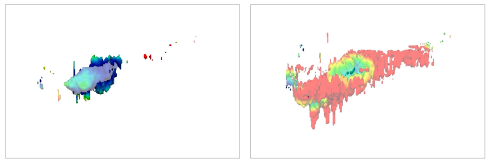

Figure 6: (Left) The most similar pair of mode water regions. (Right) The most dissimilar pair of mode water regions.

Next, we explored mode water regions of the simulation dataset which are similar to a particular mode water region of the observation dataset. As an example, we explored mode water regions of OFES dataset similar to the mode water region of the WOA13 dataset with the conditions $PV < 2.0 \times 10^{-10}$ and $25.3 \leq density \leq 25.5$. Firstly, we filtered the polylines in the PCP based on the conditions of the WOA13 dataset, and then colored the remaining polylines based on the PV values of the OFES dataset. We found the dissimilarity of mode water regions with the condition $PV < 1.5 \times 10^{-10}$, drawn in red, are smaller comparing with larger thresholds of PV values, as shown in Figure 7(a). Then, we filtered the polylines with the above condition and colored the remaining polylines based on the conditions of density. We selected the mode water regions with the condition $25.3 \leq density \leq 25.4$, drawn in blue, as shown in Figure 7(b). Again, we filtered the polylines with this condition, and colored the remaining polylines based on the month of the OFES data, as shown in Figure 7(c). Mode water regions in September, drawn in blue, were obviously better. Finally, we selected a pair of mode water regions, the OFES dataset in September of the sixth year with the conditions $PV < 1.5 \times 10^{-10}$ and $25.3 \leq density \leq 25.4$ with the WOA13 dataset in August with the conditions. $PV < 2.0 \times 10^{-10}$ and $25.3 \leq density \leq 25.5$, as shown in Figure 7(Lower).

5 Conclusion and Future Work

This paper presented a visualization tool for comparison of mode water regions extracted from multiple volume datasets of physical oceanography. The tool calculates multi-dimensional vectors of dissimilarity values from pairs of mode water regions extracted with various conditions and displays the vectors by PCP. The tool also displays pairs of mode water regions by coloring based on their local distances. This paper introduced an experiment with an observation dataset (WOA13) and a simulation dataset (OFES). We demonstrated PCP effectively represented the differences of dissimilarities based on the differences of conditions and provided a user interface to explore the datasets and discover good pairs of mode water regions.

We would like to find more similar/dissimilar pairs of mode water regions and discuss with experts in physical oceanography to archive good reasoning of the results as future work.

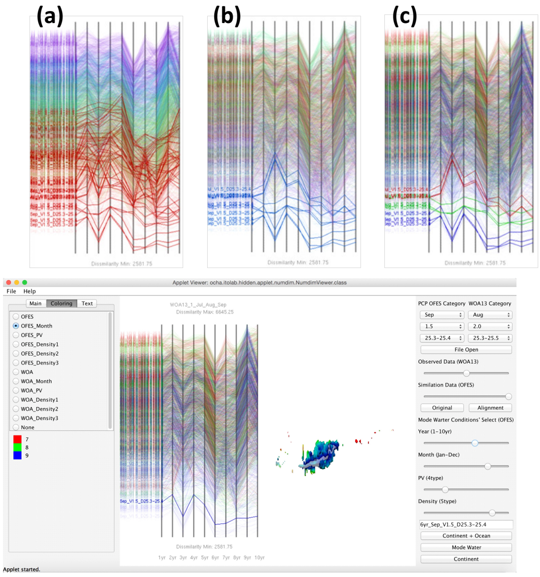

Figure 7: Example of scenario which explores mode water regions of a simulation dataset which are similar to a particular mode water regions of an observation dataset.

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