Visualization of riverine water and vortex dynamics around the Naruto Strait based on high-resolution ocean simulation and satellite images

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Abstract. This paper addresses a fusion visualization of vorticity fields and riverine water maps by combining satellite-derived ocean-color images and simulated velocity fields using a high-resolution ocean model. Our visualization successfully described the transportation of low-salinity riverine water from the Yoshino River through the Naruto Strait. The cloudy white riverine water separated from the river plume in Kii Channel and easily passed through the strait owing to the flood current that formed a mushroom vortex. Meanwhile, the high-salinity clear water from the Harima-Nada Sea could horizontally mix in the strong vorticity fields generated by the ebb current after passing the strait. Our fusion visualization is capable of evaluating the transportation and mixing of riverine water through narrow straits.

Keywords: Ocean simulation, river runoff, ocean color satellite images, vorticity, Naruto Strait, stochastic point-based rendering

1. Introduction

River plumes are frequently formed by river runoff in coastal oceans. For example, Fig. 1 shows the river plume forming cloudy white riverine water discharged from the Yoshino River. Additionally, plumes spreading from estuaries can determine the water quality and circulation in coastal oceans, which are essential contributors to the transport of land-derived nutrients \cite{1}. Riverine nutrient fluxes to oceans can be an important rule for land-sea pathways between terrestrial and ocean environments. Riverine material input to regions of freshwater influence (ROFI), which exist between oceans and estuaries \cite{2}, yields primary production associated with fishery resources.
Dynamics of the riverine water in the ROFI are essential to providing information on the ocean environment and ecosystems relevant to coastal fisheries and aquaculture. Sea-surface salinity (SSS) is a direct indicator of riverine water characterized by low salinity water associated with river discharge [3]. Therefore, accurate SSS maps have been improved to detect riverine water in coastal oceans [4]. Coastal oceans often retain complicated terrains such as headlands, inlets, and straits, which can induce large water exchange to provide healthy water quality. However, the fluctuation in the riverine water in space and time can be too large to observe around straits and is not yet fully understood. In particular, the strong flows through a strait can generate many eddies or vortices [5].

This paper addresses fusion visualizations of plume dynamics using high-resolution images derived by ocean color satellites and high-resolution ocean simulations to demonstrate riverine water dynamics in coastal oceans.

Figure 1. True color image derived by the Multispectral Imager (MSI) onboard Sentinel-2 on March 20, 2016, showing the river plume induced by the large runoff (flood) from the Yoshino River into Kii Channel, with atmospherically corrected and contrast (gain=2.2) and luminance (gamma=1.7) toned with the EO browser [20].

2. Methods

2.1. High-resolution ocean simulation

We utilized the prognostic, unstructured grid Finite Volume Community Ocean Model (FVCOM version 3.1.6) [6] and the ocean prediction system DREAMS (Data assimilation Research of the East Asian Marine System) [7, 8] into a single ocean simulation system using the nesting method (Fig. 2). The FVCOM was originally developed by Chen et al. (2003) [6] as a coastal ocean general circulation model. The unstructured triangular grid with a terrain-following, σ-z mixed coordinate in the vertical direction provides flexibility in adjusting the grid resolution and better fits the irregular coastal geometry and bathymetry around estuaries. The
finite-volume approach ensures the conservation of mass, heat, and salt necessary to reproduce the key physical processes under conditions of a dominant halocline in the coastal seas. We employed assimilated ocean products including the tidal signals (water level, temperature, salinity, velocity) as open boundary conditions in the FVCOM from the ocean prediction system DREAMS (Fig. 2).

The initial conditions of water temperature and salinity used in the ocean simulation were produced by inter/extrapolation using a Gaussian function based on long-term averages of the observational data in March obtained from the Marine Information Research Center (MIRC) of the Japan Hydrographic Association from 1963 through 1994. The input bathymetry data used in the simulation were arranged for the model grid in the FVCOM [9]. The numbers of cells and nodes used in the model grid are 6,507 and 12,456, respectively. The number of vertical layers is 26 levels. Reanalysis meteorological Grid Point Value datasets of the Meso-Scale Model (GPV/MSM) produced by the Japan Meteorological Agency were downloaded from the server of the Research Institute for Sustainable Humanosphere [10] and input into the FVCOM to represent the hourly mean air temperature, precipitation, cloud cover, relative humidity, and wind speed. The daily mean river discharges used in the simulation were calculated by the estimated runoff data based on water level observations upstream of the estuaries. Water level data were downloaded from the Water Information System operated by the Ministry of Land, Infrastructure, Transport and Tourism of Japan [11]. The ocean simulations began from an initial state of rest on March 1, 2015, and were conducted for more than 9 months. The simulated results showed the typical features of the ocean environment often observed in Kii Channel, e.g., the river plume from the Yoshino River, and summertime thermocline, as shown in the previous study [12]

2.2. High-resolution satellite images

The Korean geostationary Communication, Ocean and Meteorological Satellite (COMS) carries the world's first geostationary ocean color sensor, the Geostationary Ocean Color Imager (GOCI), to measure radiance from the ocean surface in the visible and near-infrared bands. Observations from GOCI-COMS are available to easily derive high-resolution (~500 m) images, in addition to the higher temporal resolution (eight hours) during the daytime. Images of GOCI-COMS cover approximately 2,500 × 2,500 km² around the Japanese Islands and Korean Peninsula, with a very high signal-to-noise ratio (>1000) [13].

This paper adopted the methodology of producing high-resolution estimated SSS maps in local-scale, coastal oceans based on GOCI products [14]. An advantage of this method is that it can improve the accuracy of SSS estimates using in situ SSS data obtained from an automated observation system, the Observing System for Aquatic Quality at Automated Stations in the Osaka Bay (OSAQAS), operated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) [15]. This approach is advantageous because it captures the plume dynamics around coastal oceans with a high degree of accuracy, unlike approaches using other sensors.

We downloaded Level-1 products from the website of the Korea Ocean Satellite Center (KOSC) [16]. Well-calibrated Level-2 products can be derived from Level-1 data converted with the GOCI Data Processing System (GDPS) developed by the Korea Institute of Ocean Science and Technology [17] (Ryu et al., 2012). Using products of the optical absorption coefficient of colored (or chromophoric) dissolved organic matter (aCDOM) at 443 nm, we estimated the high-resolution SSS maps from aCDOM maps in the study area based on the satellite-derived SSS estimation [14]. The standard products of the total suspended solids (TSS) maps were also produced by the GDPS to compare the simulated velocity fields.
We collected the color images derived by the Multispectral Imager (MSI) onboard Sentinel-2. Sentinel-2A and -2B launched on June 23, 2015, and March 7, 2017, respectively, and provide global coverage of the Earth’s land surface every 5 days via images with high spatial resolution (∼10 m) [18]. The MSI created a great new potential in coastal ocean remote sensing and could allow even sub-mesoscale phenomena in the oceans to be analyzed [19]. However, frequent cloud cover reduces the availability of images, and we cannot often obtain imagery with the rigorous 5-day interval in our study area. As a result, a few high-quality images could be obtained from the Sentinels Scientific Data Hub [20]. Finally, one high-quality Sentinel-2 image around Naruto Strait on March 20, 2016, was derived to compare the simulated velocity fields and the SSS and TSS maps obtained by GOCI-COMS.

2.3. Analysis of the vortex feature

To capture the spatiotemporal pattern in the vortex and flow fields, this study adopted the vortex feature extraction method that uses the neighbor search of a kd-tree [21, 22]. A kd-tree is a data structure that represents an area of a k-dimensional space based on a given point cloud; we simply used three-dimensional space in this study. Centroids of triangular prism cells of the given fluid volume used in the ocean model (FVCOM) are regarded as the point cloud \( P(i) \), which describes the volume of the velocity fields. We assigned the values of the velocity and salinity at the cell to its centroid point and performed principal component analysis for each point using the surrounding \( n = 10 \) points. The eigenvalues of the variance-covariance matrix were calculated to find the vortices statistically. Here, \( V_{jk}(i) \) is the variance-covariance matrix, where \( i \) is the cell index and \( \{ j, k \} \) is the spatial index representing the \( x, y, \) or \( z \) direction. The variance-covariance matrix of the flow velocity is defined as follows:

\[
V_{jk}(i) = \frac{1}{n} \sum_{i=1}^{n} (V_j(i) - \overline{V}_j)(V_k(i) - \overline{V}_k)
\]

We defined a vortex feature value, of which a high value indicates a dominant vortex area, by using the variance-covariance matrix, \( V_{jk}(i) \). Three eigenvalues of \( V_{jk}(i) \) can be calculated \( \lambda_1, \lambda_2, \lambda_3 \). We adopt the sum of the eigenvalues (\( \lambda_{123} = \lambda_1 + \lambda_2 + \lambda_3 \)) as the vortex feature value.

We employed a stochastic point-based rendering (SPBR) approach proposed in previous studies [23]. The SPBR is a method to actualize transparent visualization by incorporating hidden points into a rendering using ensemble average processing. Transfer functions were used to effectively present the simulated data by color and opacity and were defined by mapping tables associated with scalar values. The transfer function used in this study is shown in Fig. 3. We normalized the vortex feature value \( \lambda_{123} \) from 0 to 255. To focus on the large \( \lambda_{123} \) values in the ocean areas, the opacity corresponding to small \( \lambda_{123} \) values was decreased to a small representative value (0.1), while the opacity of large \( \lambda_{123} \) values was set to approximately 0.99. The number of particles used in the SPBR is approximately one million.

The fusion visualization can be expected to follow two qualitative evaluations.
1) The high-resolution satellite images are capable of capturing a distribution of cloudy white riverine water and clear water and a snapshot of their mixing.
2) Their mixing processes can be inferred from the vorticity fields, and the water dynamics can be represented by the flow fields, leading to an understanding of the water transportation and formation processes of river plumes.
Figure 2. Integrated system for ocean simulation using domains (left) in the ocean prediction system with salinity and velocity fields (color and arrows) and (right) in the ocean simulation with bathymetry. Domain resolved with an unstructured grid in the FVCOM. The red square in the left panel indicates our study area. The blue lines and arrows show the data stream from the weather prediction through the ocean prediction to the ocean simulation for the open boundary conditions.

Figure 3. Transfer function used for the vortex feature value to determine the opacity of the fluid volume.
3. Results and Discussions

The river plumes from the Yoshino River are often observed by ocean color satellite sensors in the Kii Channel (Fig. 1) and retain highly turbid, low-salinity water, including a large TSS. For example, Fig. 4 shows that the low-salinity water spreads in the surface layer around the estuary, indicating the river plume from the Yoshino River over the western part of the Kii Channel. A large amount of the riverine water with a low-salinity area was distributed southward along the western coast of the Kii Channel, indicating the typical patterns. The TSS map also suggests the southward migration of the riverine water, while some of the water moved northward and passed through the Naruto Strait. After passing through this area, the riverine water formed an eddy-like pattern on the northern side of the strait, as shown by the black arrow in Fig. 4. A similar pattern is confirmed by the images derived by Sentinel-2 (right panel of Fig. 1). The TSS concentration of the eddy-like water (1.7-2 mg/L) is comparable to that of the water located around the plume boundary (SSS: approximately 33-33.8). On the other hand, the eddy-like pattern in the SSS map is unclear because the riverine water passing through the strait was merged with the inherently low-salinity water (SSS: 31.5-33.5) from the many small rivers facing the Harima-Nada Sea. Thus, the riverine water distributions speculated by the true color images of Sentinel-2 can be quantitatively validated by the TSS maps.

Figure 4. Satellite-derived maps of the surface sea salinity (SSS) distribution (left panel) and total suspended solids (TSS) around the Naruto Strait and estuary of the Yoshino River at 11:00 JST, March 20, 2016. The SSS and TSS data were derived by the GOCI-COMS products. The black arrow indicates cloudy white eddy-like riverine water (Fig. 1). White areas indicate cloud cover.
We examined the relationship between the eddy-like riverine water and the surface velocity and vorticity fields around the Naruto Strait. Figure 5 shows the fusion visualization of a simulated velocity field and true color Sentinel-2 image, indicating the flow pattern around the eddy-like riverine water at the ebb tide. The fusion visualization shows that the southward converging flow toward the Naruto Strait is visible around the eddy-like riverine water on the north side of the strait and that a strong southward current formed in the center of the strait. The converging flow was weak, leading to the small vorticity field around the riverine water.

The black water was advected from the Harima-Nada Sea to the Naruto Strait, as shown by the satellite images in Fig. 5. This suggests that the ebb current transported relatively clear water eastward from the west Harima-Nada Sea along the northwestern coast of the strait. The clear water passed through the strait with the southward strong ebb current. After the ebb current passed, the strong areas of the vorticity field formed around the current. This vorticity field indicates the many vortices generated by the strong current shear, referred to as the famous vortex, the Naruto whirlpools (Naruto no Uzushio), as reported by observational and numerical studies [24, 25, 26, 27]. This passing of the ebb current along with the strong vorticity field could mix the clear water outside of the strait with the cloudy white water discharged from the Yoshino River. It is important to note that the clear water was not mixed in the strait by tidal vertical mixing but was instead mixed by a horizontal mixing process by vortexes such as the Naruto whirlpools.

Figure 5. True color image derived by Sentinel-2 at 10:30 JST, March 20, 2016 (left panel). The right panel exhibits a fusion visualization of the snapshots of surface velocity and vorticity fields at a depth of approximately 1 m superposed on the Sentinel-2 image at the ebb tide in the Naruto Strait. Red shading indicates the strong vorticity filed (vortex feature value, $\lambda_{123}$).
Figure 6. Hourly maps of the simulated velocity and vorticity fields starting from ebb tide in the Naruto Strait (Fig. 5). The left and right panels show the maps at the ebb and flood tides, respectively. Colors and red shading indicate the current speeds and strong vorticity fields (vortex feature value, $\lambda_{123}$), respectively, as in Fig. 5.
Figure 6 shows the temporal variation in the velocity and vorticity fields to examine the relationship between the tidal phases and vorticity distributions based on the ocean simulation results. The southward current (ebb current) with a large and strong vorticity area (+0 h), as shown by Fig. 5, was diminished after three hours (+3 h). In this moment, the southward ebb current impinged on the westward and eastward flows in the south of the strait and formed bands in the strong vorticity field. These bands continue to be dominant in the south of the strait and indicate the southern boundary of the ebb current. After the disappearance of the southward ebb current (+5 h), the northward flood current formed in the north of the strait and the area of the strong vorticity, but the vorticity area in the north of the strait is always smaller than that in the south area of the strait. This indicates that areas of horizontal mixing induced by the northward current can be small. The small areas of strong vorticity can hardly mix the clear water with the cloudy white riverine water, suggesting that the riverine water can easily pass through the strait, transported by the fast flood current.

Thus, the configurations of the areas of strong vorticity formed around the strait are different between the northern and southern sides of the strait. This difference can lead to the northward transportation of riverine water passing through the strait and the mixing of clear water transported from Harima Nada in the south of the strait. This water transportation and mixing can be induced in phase with the tidal period, such as the strength of the velocity fields of the ebb and flood tides.

In creating the figures in this paper, we executed transparent volume rendering by using SPBR. The visualization target is a thin volume on the sea surface. Therefore, similar images can be generated by adopting transparent surface rendering of the sea surface with the polygon-based alpha-blending technique. However, we have adopted volume rendering for more accurate visualization. It should also be mentioned that we did not use the conventional ray-casting method for volume rendering. This is because the target volume is thin, and the visualization result may become inaccurate if the sampling step width is not appropriate. Furthermore, SPBR is advantageous for 3D fusion of multiple data [28, 29]. In this paper, we executed the fusion of the flow field (arrows), vorticity field (volume data), and satellite image (background 2D image).

4. Summary

This paper illustrated an integrated analysis of the vorticity fields and riverine water dynamics by combining satellite-derived ocean-color images and simulated velocity fields using a high-resolution ocean model with an unstructured grid. Based on analyses of the simulated results and satellite-derived images, the two main findings are as follows: 1) cloudy white riverine water from the Yoshino River can be transported by the strong flood current to the Harima-Nada Sea by passing through the Naruto Strait without tidal mixing; on the other hand, 2) clear water from the Harima-Nada Sea with a higher salinity than that from the Yoshino River can be mixed in the strong vorticity fields generated by the strong ebb current after passing through the strait. The TSS of the riverine water corresponds to that of the water on the river plume boundary in the Kii Channel. The ebb current passing through the Naruto Strait can generate a large area of the strong vorticity field representing many vortices, such as Naruto whirlpools. The vortexes can induce horizontal mixing of the clear water and plume water during the ebb tide period when the southward current dominates on the southern sides of the strait. Our fusion visualization approach using satellite images and simulated results is capable of evaluating the transportation and mixing of riverine water induced by tidal currents through narrow straits.
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