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Original Article

Visualization of the Distribution of Dissolved Organic Matter in Osaka Bay Using a Satellite Ocean Color Sensor (COMS/GOCI)

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ABSTRACT
A study of the use of a visualization technique for the distributions of dissolved organic matter (DOM) in coastal seas was conducted to assist environmental water management. In this study, the absorption coefficient of colored dissolved organic matter (aCDOM) obtained from a satellite equipped with an ocean color sensor as an index for visualizing the DOM distributions. In 2010, the first geostationary satellite having the sensor (COMS/GOCI) was launched, enabling hourly high-resolution data (~500 m) on aCDOM to be obtained. The spatial and temporal resolutions of the data derived from this satellite are the most appropriate for investigating the water quality in coastal seas, which changes dynamically depending on weather conditions. A surface water sampling was undertaken in 2015 in Osaka Bay, Japan. The concentrations of dissolved organic carbon and nitrogen, the main components of DOM, were highly correlated with field-obtained aCDOM, (R^2 = 0.91, 0.90 (n = 39), respectively). The field-obtained aCDOM was significantly correlated with the satellite-derived aCDOM (R^2 = 0.60, (n = 54)). These results indicate the potential to use satellite ocean color sensors (GOCI) to visualize and assess the distribution of DOM in coastal seas at high temporal resolution.

Keywords: water environment management, semi-enclosed seas, satellite ocean color sensor, dissolved organic carbon and nitrogen

INTRODUCTION

In semi-enclosed marine areas in Japan, including Tokyo Bay, Osaka Bay, and Ise Bay, the loads of organic matter, total nitrogen, and total phosphorous derived from the land have been reduced since the 1970s. However, in Osaka Bay the chemical oxygen demand, which is an indicator of water quality, has remained at the same level since the 1990s [1–3]. In recent years, it has been suggested that refractory dissolved organic matter (DOM) may largely contribute to the values of chemical oxygen demand in aquatic environments [4,5]. Major sources of refractory DOM in coastal areas include water of terrestrial origin [6], and DOM derived from seawater bacteria and phytoplankton [7,8]. Refractory DOM in coastal waters can be transported to adjacent shelf seas, increasing the concentration of DOM in these waters. This may result in an increase in the chemical oxygen demand in coastal waters because of the return flow of shelf sea waters. Thus, studies of the timing and routes of outflow of DOM in coastal waters toward shelf seas are important for coastal environmental water management.

To investigate the outflow of DOM from coastal waters, it is necessary to determine the distribution of DOM at high spatial resolution. Although direct measurement of water samples is the most precise method for determining the concentration of DOM, it is difficult to establish variations in

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outflow from coastal seas based solely on monthly measurements, because frequent changes in the concentration occur, depending on weather conditions. An effective alternative is to use remote sensing satellite data. The movement of low salinity water including terrestrial DOM supplied from large rivers, such as Amazon River, have been assessed using microwave sensor on satellite (e.g. SAC-D/Aquarius) [9]. However, the spatial resolution of the data (approximately 50 km), is inadequate for coastal seas.

The light absorption coefficient of colored dissolved organic matter (aCDOM) obtained from ocean color sensor on satellite has been recently used as a powerful tracer of dissolved organic carbon (DOC), which is the main component of DOM. Colored dissolved organic matter (CDOM) is a part of DOM, which absorbs short wavelength light, derived from rivers and phytoplankton [10]. The estimations of DOC concentration using aCDOM obtained from satellite ocean color sensors such as MODIS and SeaWiFS have recently been conducted in ocean [11,12] and coastal seas [13,14]. The temporal and spatial resolutions of satellite data have been improved and the first geostationary satellite carrying an ocean color sensor (COMS/GOCI) was launched in 2010, enabling hourly high-resolution data (approximately 500 m) on aCDOM to be obtained [15,16].

The data of aCDOM can be obtained from field and satellite. Relationships between satellite-derived aCDOM and field-obtained aCDOM have been reported in previous studies [17–19]. If the relationship between field-obtained aCDOM and the concentration of DOM is elucidated, it may be possible to visualize the distribution of DOM in the region. Dissolved organic matter consists of dissolved organic carbon, nitrogen and phosphorous (DOC, DON, DOP). In this study, we conducted field surveys in Osaka Bay and analyzed the concentrations of DOC, DON, DOP and aCDOM to assess the above relationship. We then investigated the outflow of DOM from coastal waters towards the shelf sea, using the distribution of DOC which was estimated from aCDOM newly obtained from COMS/GOCI.

MATERIALS AND METHODS

Field observation in Osaka Bay

Osaka Bay is a semi-enclosed embayment located in the eastern Seto Inland Sea, and is connected to the adjacent shelf sea (**Fig. 1**). The surface area and mean depth of the bay are 1,450 km^2 and 20 m, respectively. Several rivers flow into the head of the bay; among these, the annual mean discharge of the largest river (Yodo River) is 193 m^3/s, which is approximately an order of magnitude greater than that from the other rivers (data on river discharges were provided by the Ministry of Land, Infrastructure, Transport and Tourism, Japan). Oceanic water from the shelf sea flows into the bay at its mouth.

Surface water was sampled in the bay and the water salinity was measured using a CTD instrument (AAQ1183; JFE-Advantech, Kobe, Japan) several times in August and November 2015. The observation dates, sites, parameters and the research vessels used at each observation are listed in **Table 1**. Water samples were filtered through GF/F 0.45 µm glass fiber filters immediately following sampling, and were stored in glass bottles on board the research vessel. For analysis, each sample was filtered through a 0.2 µm Nucleopore membrane filter, transferred to a 10 cm length circular glass cylinder, and the absorbance was measured in a spectrophotometer (U2900; Hitachi High-Tech Science, Tokyo, Japan) over the wavelength range 300 − 800 nm; aCDOM based on the absorbance at 443 nm was calculated following the method of Mueller *et al*. [20]. The concentration of chlorophyll-a, from cells trapped on the GF/F filter, was quantified using a calibrated fluorometer (Trilogy; Turner Design, San Jose, USA).

Then the concentrations of DOC, DON, DOP which constitute DOM in the GF/F filtrate water for each of the sampling sites in the bay were measured. The concentration of DOC was measured using a total organic carbon analyzer (TOC-L; Shimadzu, Kyoto, Japan). The concentrations of nitrate (NO_3-N), nitrite (NO_2-N), and phosphate (PO_4-P) were also measured using an auto-analyzer (QuAAtro, BL-Tech, Osaka, Japan). The concentrations of total dissolved nitrogen and phosphorous (TDN and TDP, respectively) were also measured using the same auto-analyzer, following oxidative decomposition. The concentration of ammonium (NH_4-N) was measured using a fluorometer (Trilogy; Turner Design, San Jose, USA) with an attached CDOM/NH4 module (Model 7200–041; Turner Design, San Jose, USA), using the ortho-phthaldialdehyde (OPA) method [21]. In this study, dissolved inorganic nitrogen (DIN) was defined as the sum of the concentrations of NO_3-N, NO_2-N and NH_4-N. The concentrations of dissolved organic nitrogen (DON) and dissolved organic phosphorous (DOP) were determined as TDN − DIN and TDP − PO_4-P, respectively.

Data analysis

The geostationary satellite carrying an ocean color sensor (COMS/GOCI), launched in June 2010, provides calibrated ocean reflectance every hour. The GOCI Level-2 products

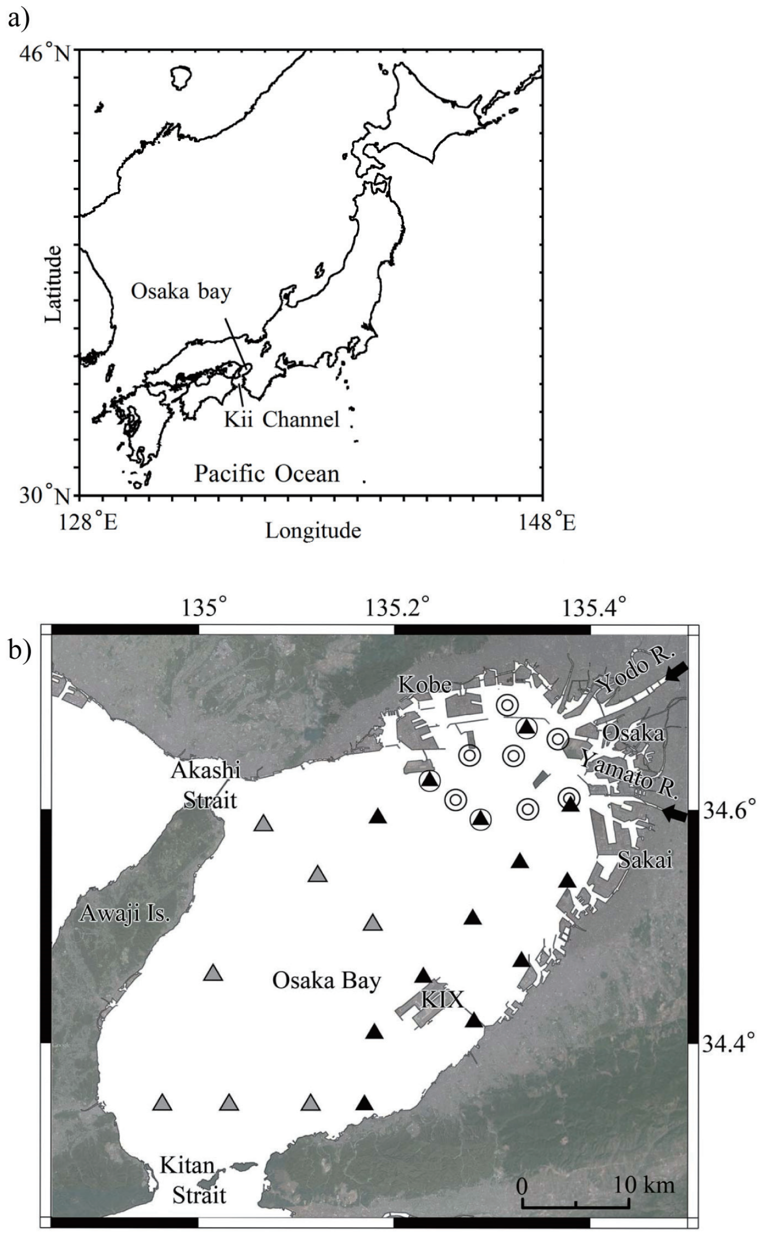

Fig. 1 a) Location of the study area (Osaka Bay, Japan). b) Field measurement and observation sites (triangles, open and double circles). The differences of the marks indicate the differences of the date of observations as shown in **Table 1**.

Table 1 List of field observations in 2015.

Date of observations	Vessel	Observation sites (shown in **Fig. 1b**)	Parameters
3rd August	Osaka	black triangles (13 sites)	aCDOM, DOM
4th August	Osaka	gray triangles (7 sites)	aCDOM, DOM
4th August	Hakuo	open and double circles (10 sites)	aCDOM
2nd November	Osaka	black triangles (13 sites)	aCDOM, DOM
4th November	Osaka	gray triangles (7 sites)	aCDOM, DOM
5th November	Hakuo	double circles (7 sites)	aCDOM

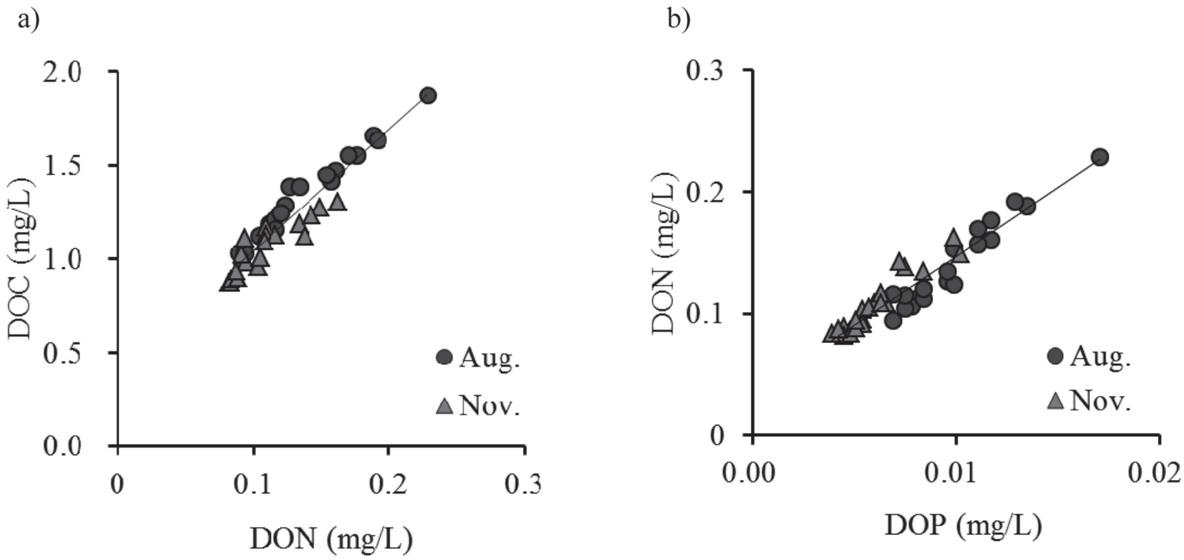

Fig. 2 Relationships between a) DON and DOC, and b) DOP and DON (mg/L).

were obtained from the website of Korea Ocean Satellite Center (KOSC, http://kosc.kiost.ac/eng/p20/kosc_p21.html). The products included aCDOM at 443 nm with a spatial resolution of about 500 m over the Korean and Japanese coastal seas. The pixel data ranging from the latitudes of 34.25 to 34.75 degrees north and the longitudes of 134.85 to 135.50 degrees east were extracted to draw up the figures. The satellite-derived aCDOM for the dates when field samplings were conducted (3 and 4 August, and 2 November 2015) could not be obtained because of cloud cover. Therefore, for the validation process we used the daily averaged satellite data for 5 August (5 − 6 h) and 4 November 2015 (2 − 3 h). The data at noon on 4 November were also used in order to examine the differences between daily averaged data and hourly data.

Data on precipitation in the river watersheds, and the water levels of the major rivers, were obtained from the database of the Japan Meteorological Agency [22] and the Ministry of Land, Infrastructure, Transport and Tourism, Japan [23].

RESULTS AND DISCUSSION

Relationship between DOM and CDOM

The relationships between DOC and DON, and between DON and DOP for August and November are shown in **Figs. 2a and 2b**, respectively. All data were obtained from field observations. The results showed that these parameters were highly correlated, and the slopes and intercepts of the regression curves were not largely different among seasons. The relationships between DOC and DON, and between DON and DOP were:

$$\text{DOC (mg/L)} = 6.52 \times \text{DON (mg/L)} + 0.39\ (R^2 = 0.91,\ n = 40,\ P < 0.01) \quad (1)$$

$$\text{DON (mg/L)} = 11.28 \times \text{DOP (mg/L)} + 0.03\ (R^2 = 0.91,\ n = 40,\ P < 0.01) \quad (2)$$

where R^2, n, and P show the coefficient of determination, number of data, and p-value for the regression coefficients, respectively.

Dissolved organic carbon comprised 90% of the DOM by weight, based on the assumption that DOM composed of DOC, DON and DOP. Thus, the distribution of DOC effectively represented that of DOM.

The relationship between DOC and aCDOM determined by field sampling is shown in **Fig. 3a**, and that between field-obtained aCDOM and satellite-derived aCDOM is shown in **Fig. 3b**. These relationships were:

$$\text{DOC (mg/L)} = 3.60 \times \text{field-obtained aCDOM (/m)} + 0.79\ (R^2 = 0.91,\ n = 39,\ P < 0.01) \quad (3)$$

$$\text{field-obtained aCDOM (/m)} = 1.41 \times \text{satellite-derived aCDOM (/m)} - 0.042\ (R^2 = 0.60,\ n = 54,\ P < 0.01) \quad (4)$$

At the three sites where the concentrations of chlorophyll-*a* were > 20 μg/L in August, field- obtained aCDOM exceeded 0.3, and was substantially different from the satellite-derived aCDOM. We therefore removed the data for these three sites

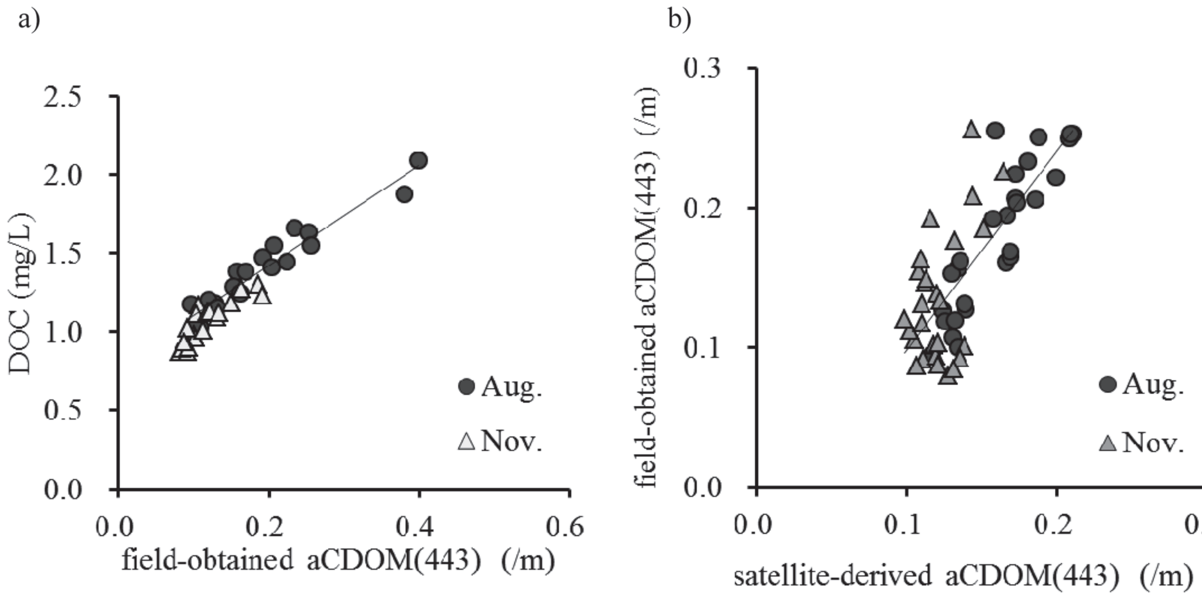

Fig. 3 Relationships between a) DOC (mg/L) and field-obtained aCDOM (/m), and b) field- obtained aCDOM (/m) and satellite-derived aCDOM (/m).

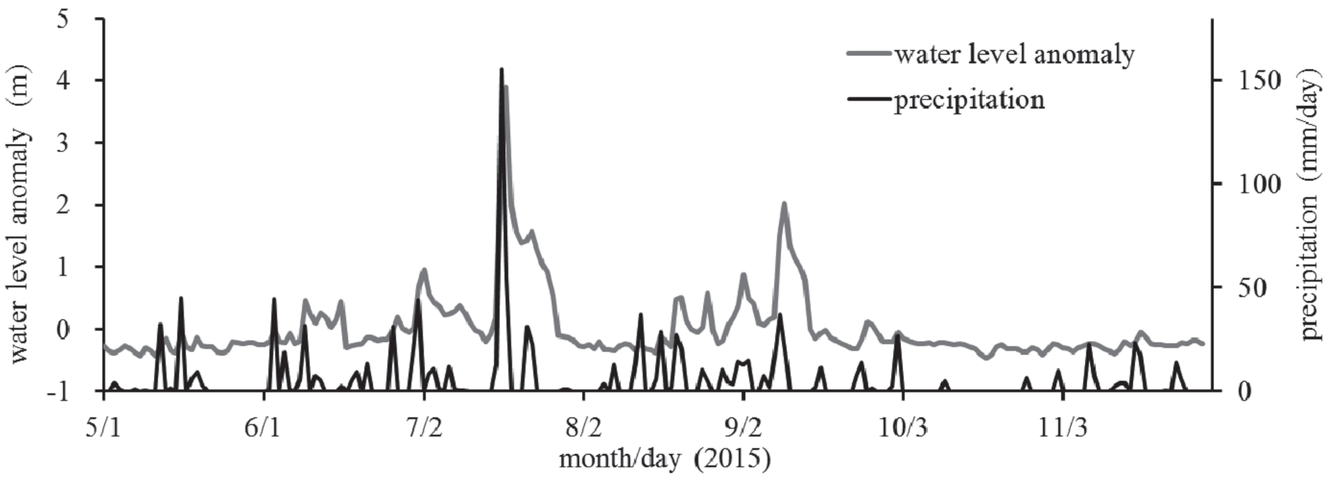

Fig. 4 Temporal variations in precipitation (black line) and water level anomaly in Yodo River (gray line). Water level anomaly was calculated as the difference between daily mean water level and its average from 1st May to 30th November.

from the regression expressions shown by equations (3) and (4). The resulting correlations were both significant, suggesting that it is possible to estimate the concentration of DOC using satellite-derived aCDOM and equations (3) and (4). The root mean squared (RMS) error between the concentration of DOC estimated using satellite-derived aCDOM and the observed concentration of DOC was 0.13 mg/L (n = 39), comparable to those in previous studies [24–27], suggesting that the estimation was sufficiently accurate. The concentrations of DON and field-obtained aCDOM were also significant ($R^2 = 0.90$, n = 39, $P < 0.01$), suggesting DON concentration could also be estimated using satellite-derived aCDOM using equation (4).

Temporal variations of the estimated DOC

Figure 4 shows the temporal variation of daily precipitation measured at a meteorological weather station (Osaka), and the water level measured at an observation point (Hirakata) in the watershed of Yodo River (the main river flowing into the bay). The latter is presented as the differences in

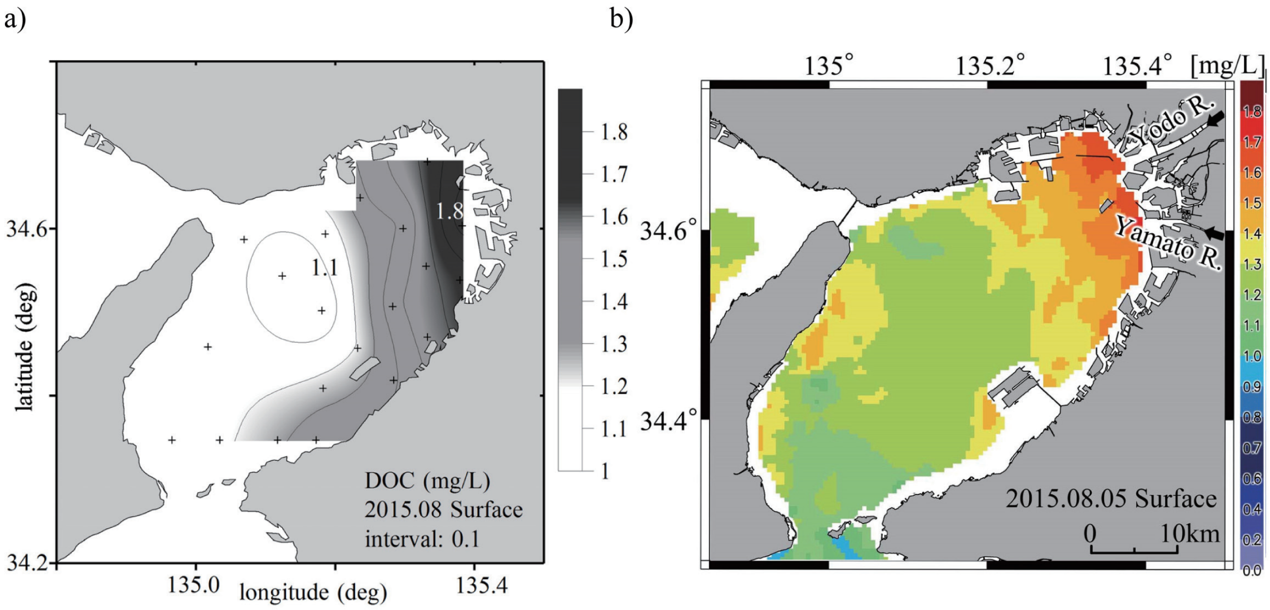

Fig. 5 Distributions of a) field-obtained DOC (mg/L), and b) DOC (mg/L) estimated using satellite-derived aCDOM (/m) for August.

the daily average water levels from the mean value averaged during the period from 1 May to 30 November 2015. The peak water levels were almost invariably evident 1 day following precipitation events, while decreases in the water level following the peaks were more moderate than those of precipitation. The water level in Yodo River increased substantially on 18 July 2015 because of heavy rain, but decreased at the beginning of August, when the first field measurements were conducted. The water levels remained low from the middle of September to November, when the second field measurements were conducted.

The distributions of field-obtained DOC on 3 − 4 August and DOC estimated from the satellite-derived aCDOM obtained on 5 August 2015 using equations (3) and (4) are shown in **Figs. 5a and 5b**, while those measured on 2 and 4 November and estimated on 4 November 2015 are shown in **Figs. 6a and 6b**. The field-obtained DOC concentration (**Figs. 5a and 6a**) and salinity (**Fig. 7**) were interpolated by Kriging method. The estimated distributions of DOC corresponded closely to the measured values in both August and November. The concentrations in November were much lower than those in August, in response to changes in river discharge. The concentration of DOC in August was highest near the river mouth and relatively high along the eastern coast of the bay, suggesting that DOC flowed out to the shelf sea along the coast. The route of the outflow of DOC corresponded to that of low salinity water (**Fig. 7**).

Based on the concentrations of DOC estimated using satellite-derived aCDOM and the equations (3) and (4), the distributions of DOM, which mainly consists of DOC, on a particular date can be visualized without observation. For example, the rapid changes of the distribution of DOC influenced by a meteorological disturbance can be visualized as follows: The water level in Yodo River peaked on 18 July 2015 because of heavy rain on the previous day (**Fig. 4**). The velocity of the density flow associated with estuarine circulation in Osaka Bay has been estimated to be approximately 10 cm/s (approximately 10 km/day) [28], and the residence time of water in the upper layer is estimated to be 7.1 days [29]. The satellite data obtained on 24 − 26 July were within the residence time, and the distribution of DOC estimated using satellite-derived aCDOM data on these dates are shown in **Figs. 8a, 8b, and 8c**. The concentrations were high at the head of the bay on 24 July, and the water mass then moved to the south along the eastern coast of the bay, and generally throughout the bay except for the area along the western coast. These results indicate that the water mass having a high concentration of DOM flowed out of Osaka Bay along the eastern coast toward the shelf sea during the period of moderate flow in the rivers (**Fig. 5**), and throughout the bay after heavy rain (**Fig. 8**).

In this study, we obtained satellite data on the same days in November that field measurements were made only at 7 of the sites, although in total 57 water samples were collected,

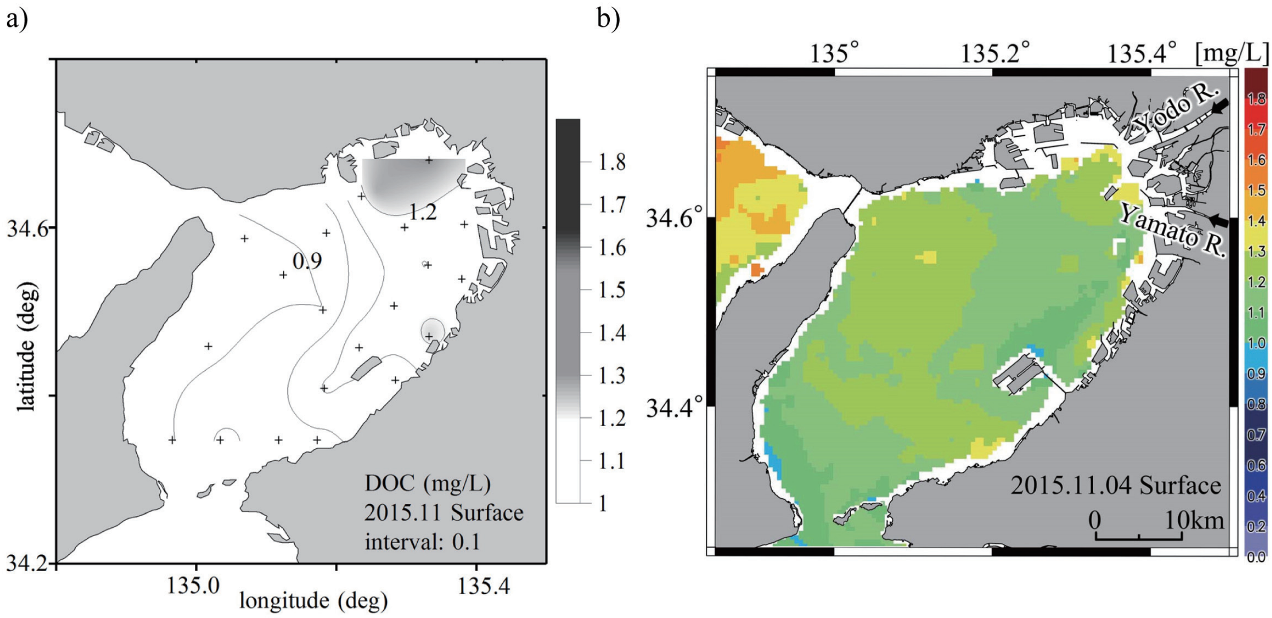

Fig. 6 Distributions of a) field-obtained DOC (mg/L), and b) DOC (mg/L) estimated using satellite-derived aCDOM (/m) for November.

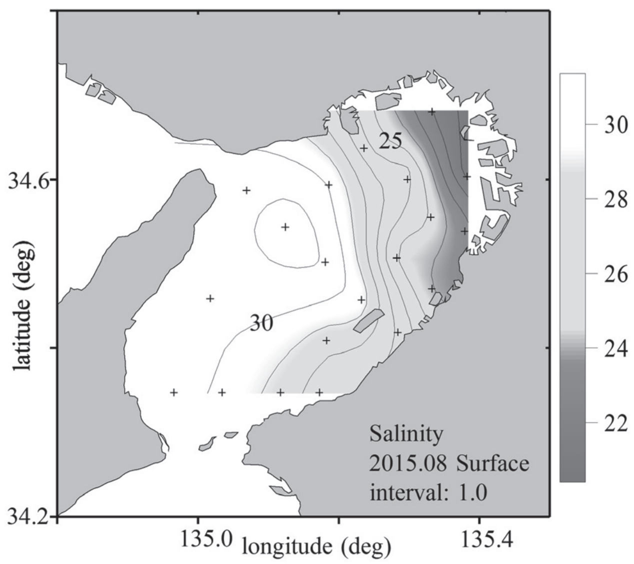

Fig. 7 Distribution of salinity (psu) measured in August.

due to the cloud cover. The correlation coefficient between the field-measured aCDOM and the satellite-derived aCDOM at the 7 sites (shown by gray triangles in **Fig. 1b**) in November was −0.19 when the daily averaged satellite data were used, but was up to 0.58 when satellite data for the same times as the water sampling, noon on 4 November, were used. Thus, the satellite-derived aCDOM changed daily and at different times, indicating that validation needs to be conducted on the same day and at the same time. Hourly aCDOM data obtained from COMS/GOCI makes it possible to conduct matching analysis of satellite-derived aCDOM and field-measured aCDOM as long as the weather is fine on the sampling date. It is still an important finding that the correlations among DOC, the main components of DOM, and satellite-derived aCDOM were significant in both August and November, indicating that determining DOM distributions is possible almost throughout the year. Although more validation data should be used in future studies, the results of this study provide persuasive evidence for the possibility of using visualization of DOM in Osaka Bay, using satellite ocean color sensors.

CONCLUSIONS

In this study we investigated the use of a visualization method for determining the concentration of dissolved organic matter in a semi-enclosed bay (Osaka Bay, Japan), using newly available (2011) data derived from a satellite ocean color sensor. The concentrations of dissolved organic carbon and nitrogen were highly correlated with aCDOM analyzed using a spectrophotometer, and the field-measured aCDOM data was significantly correlated with the satellite-derived aCDOM data. The error in the estimated concentrations of DOC using satellite-derived aCDOM was approximately

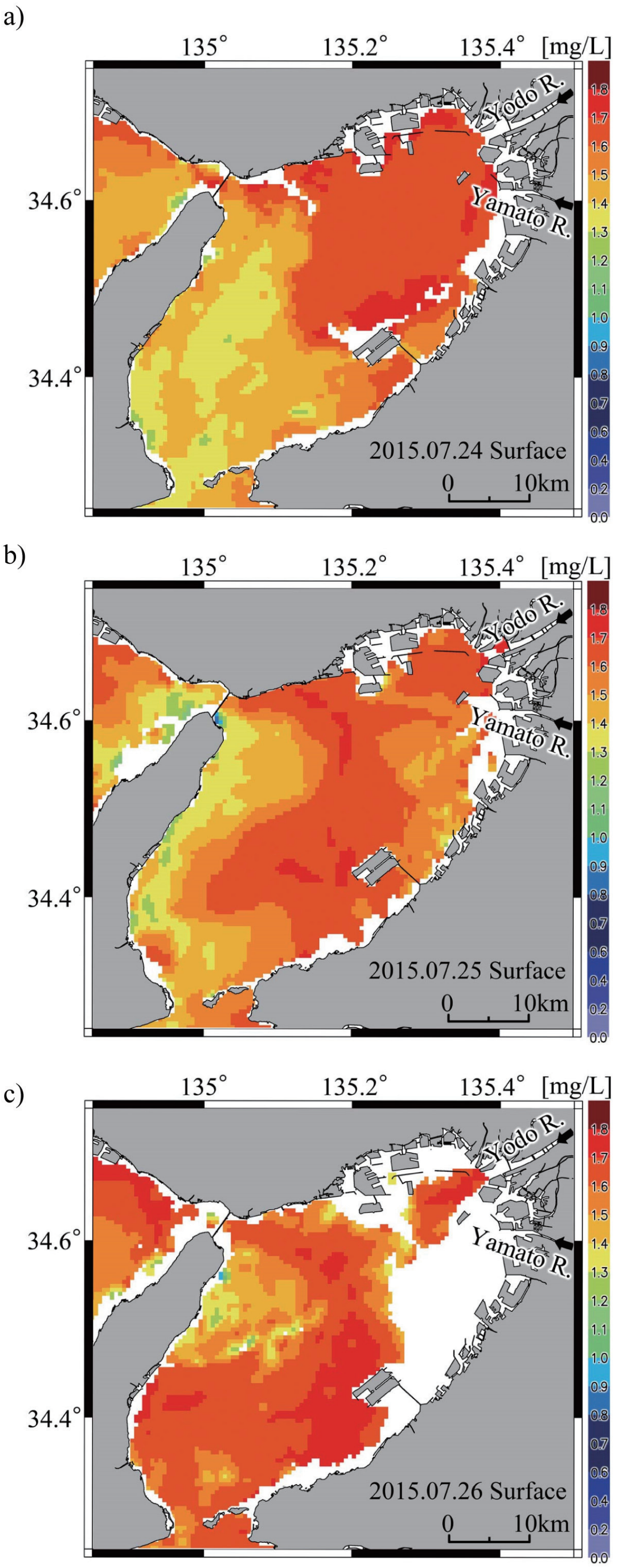

Fig. 8 Distribution of DOC (mg/L) estimated using satellite-derived aCDOM (/m) on a) 24 July, b) 25 July, and c) 26 July, 2015.

10% of the average DOC concentration; this will need to be reduced in future studies by resolving the differences between satellite-derived aCDOM and field-measured aCDOM data. However, the results of this study indicate that it is possible to analyze the route of outflow of DOM from coastal waters toward shelf seas, using a satellite ocean color sensor (COMS/GOCI).

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