

## NOTES AND CORRESPONDENCE

### Unique Dispersal of the Changjiang-Diluted Water Plume in the East China Sea Revealed from Satellite Monitoring of Colored Dissolved Organic Matter (CDOM)

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#### ABSTRACT

The optical properties of colored dissolved organic matter (CDOM) in the Changjiang (Yangtze River) plume water were investigated during the summer of 2009 and 2010. The absorption coefficient of CDOM at 325 nm ( $a_{CDOM}$ ) increased inversely with decreasing sea-surface salinity (SSS), implying that  $a_{CDOM}$  can be used as a natural tracer of Changjiang-diluted water (CDW). This  $a_{CDOM}$  vs. SSS relationship, however, differed between 2009 and 2010. For mapping the CDW plume, the  $a_{CDOM}$  was retrieved from an ocean-color satellite. Values of SSS were also derived from the satellite-retrieved  $a_{CDOM}$  using field-based SSS vs.  $a_{CDOM}$  relationships. Satellite observations revealed the temporary variable eastward extension of a high  $a_{CDOM}$ , low SSS CDW plume in the central East China Sea (ECS) during the summer. The CDW plume during the summer of 2010 extended southeastward from the mouth of the Changjiang (Yangtze River) to almost 26°N. Moreover, the branch of this southeastward CDW plume was seen to extend northeastward to the eastern ECS where the Kuroshio Current flows northeastward along the shelf break. Subsequently, this branch was distributed around southern Kyushu. Satellite observations revealed this unique dispersal of the CDW plume, which illustrates that the  $a_{CDOM}$  and SSS from ocean-color satellite data are useful for monitoring the dispersal of this river-water plume.

Key words: Ocean-color satellite, CDOM, Salinity, Changjiang-diluted water

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#### 1. INTRODUCTION

Colored dissolved organic matter (CDOM) represents the fraction of the dissolved organic pool that absorbs light in the visible ranges. Because light absorption by CDOM relates directly to ocean color, the CDOM signal can be observed using satellite observations (e.g., Siegel et al. 2002). Processes controlling CDOM distribution and dynamics (sources and sinks) have been reported in various coastal

regions (Blough and Del Vecchio 2002; Coble 2007, and references therein). For regions adjacent to river sources, CDOM tends to behave as a freshwater tracer, decreasing away from the river source with increasing salinity. Plumes of large rivers, such as those from the Amazon and Orinoco Rivers, have been characterized optically in the tropical Atlantic and Caribbean Sea (Del Castillo et al. 1999; Del Vecchio and Subramaniam 2004; Odriozola et al. 2007), and the characteristics of these plumes based on satellite-derived CDOM data have been reported (Hu et al. 2004; Chérubin and Richardson 2007).

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The Changjiang (Yangtze River) is the largest river that discharges into the East China Sea (ECS; Fig. 1a). It is a major source of freshwater on the ECS shelf and supplies about 90% of the total discharge of freshwater from rivers around the ECS and the Yellow Sea (Beardsley et al. 1985; Zhang 1996). Freshwater from the Changjiang discharged into the ECS usually mixes with warm, saline waters (the Taiwan Warm Current and the Kuroshio and its branch currents, which flow northeastward over the outer shelf) to form a low salinity water mass called the Changjiang-diluted water (CDW) (Beardsley et al. 1985; Ichikawa and Beardsley 2002; Lie et al. 2003). The CDW generally has

a sea-surface salinity (SSS) value less than 31 or 32 on the ECS shelf (Chang and Isobe 2003; Chen et al. 2009; Moon et al. 2012). The Asian monsoon, which is southerly during summer, enhances the northeastward flow of the CDW plume. The CDW, the warm currents, and the southerly monsoon are dominant factors affecting the summer circulation in the ECS (e.g., Chao 1991; Chang and Isobe 2003; Liu et al. 2003; Chen et al. 2008). The CDW plume spreads out widely on the ECS shelf, and satellite observations provide a useful method for monitoring its variation.

Prior to the work reported herein, the principal satellite-derived observations of the CDW were based on chlorophyll

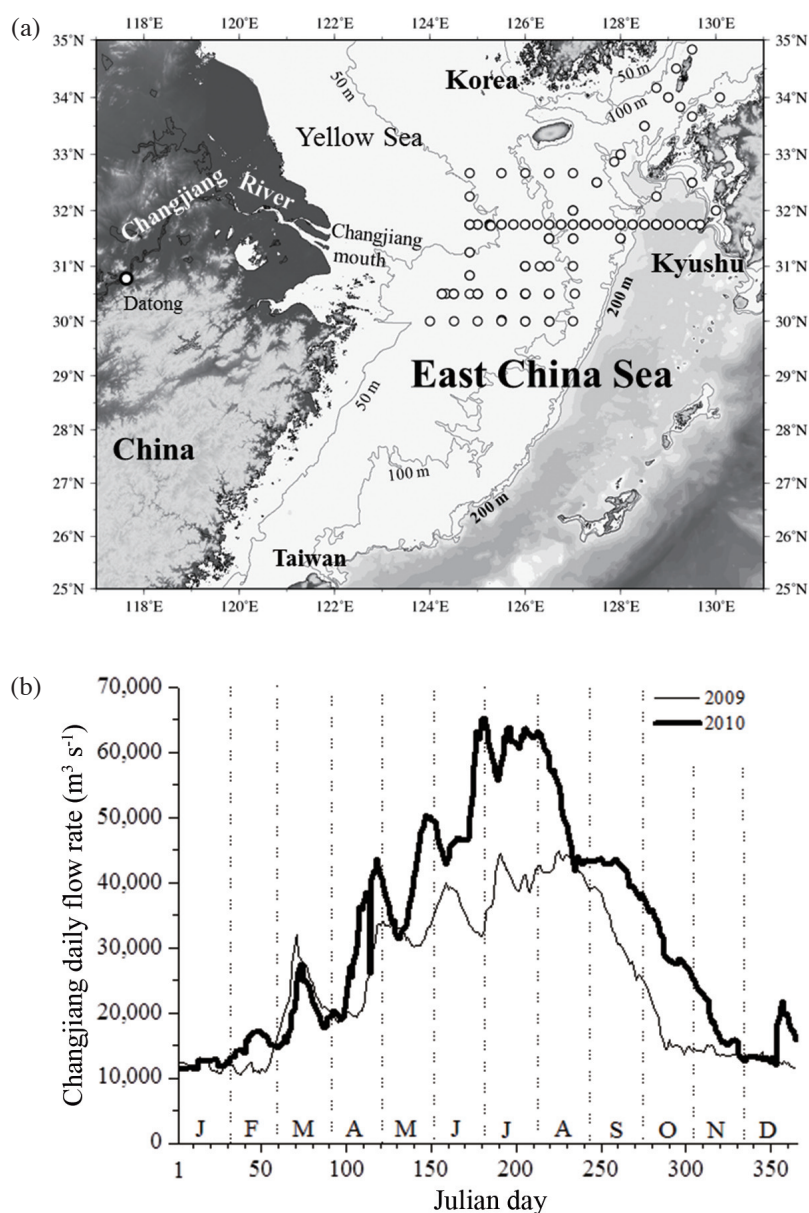


Fig. 1. (a) Location of all sampling stations in the East China Sea (ECS) for all research cruises during the summers of 2009 and 2010 (circles). The 200 m contour marks the shelf break. (b) The Changjiang daily flow rate at the Datong hydrological station along the middle-lower reaches of the Changjiang in 2009 (thin line) and 2010 (thick line) (China Hydrology website; <http://www.hydroinfo.gov.cn>).

concentration (Kiyomoto et al. 2001; Yuan et al. 2005; Gong et al. 2006; Kim et al. 2009; Shi and Wang 2012). These studies showed that the CDW has profound effects on the physical and biological processes that occur on the ECS shelf. Previous field studies also showed that CDOM correlated well with SSS from near the Chinese coast to offshore regions in the ECS (Gong 2004; Guo et al. 2007; Sasaki et al. 2008). Sasaki et al. (2008) suggested the notion of tracking the CDW through satellite-based observations of CDOM.

The objective of the present study was to identify variations in the extent and dispersal patterns of the CDW plume using the CDOM absorption coefficient derived from ocean-color satellite data. The annual Changjiang discharge in 2010 was considerably higher than that in 2009 (Fig. 1b). The spring discharge in late May 2010 was approximately  $50000 \text{ m}^3 \text{ s}^{-1}$  and was higher than the maximum values of the river flow rate during the summer of 2009. Furthermore, the discharge increased remarkably from late June 2010 due to substantial heavy rain. A discharge of over  $60000 \text{ m}^3 \text{ s}^{-1}$  continued until early August 2010. Consequently, we focused on the distribution of the CDW in the summer of 2010 compared with 2009.

## 2. FIELD AND SATELLITE DATA

Field data were collected during four research cruises on board the R/V *Yoko-maru* (Fisheries Research Agency) and *Shoyo-maru* (Fisheries Agency) in the ECS during the summers of 2009 and 2010 (cruise periods: June 19 - 25 and July 15 - 27 for 2009; June 18 - 30 and July 9 - 22 for 2010; Fig. 1a). Surface-water samples were collected with a clean plastic bucket for spectrophotometric analysis. Samples for measuring the absorption coefficient of CDOM were filtered through a nuclepore membrane filter (pore size:  $0.2 \mu\text{m}$ ). Filtrate samples were stored in the refrigerator (about  $4^\circ\text{C}$ ) until laboratory analysis, and scanned using a Shimadzu MPS-2400 double-beam spectrophotometer with 14 cm quartz cells (wavelength  $\lambda$ : 300 - 800 nm, 1-nm intervals). Values of the CDOM absorption coefficient were then calculated using the absorbance data (e.g., Pegau et al. 2002). We selected the CDOM absorption coefficient at 325 nm (hereafter referred to as  $a\text{CDOM}$ ) as an indicator of CDOM abundance. Salinity of the water samples was measured using a Guildline AutoSal 8400B salinometer.

Optical measurements were simultaneously conducted with water sampling during daytime. The optical profiles of spectral irradiance and radiance data were measured using Biospherical Instruments PRR-2600/2610 ( $\lambda$ : 380, 412, 443, 490, 532, 565, and 670 nm) spectroradiometers. Values of remote sensing reflectance ( $R_{\text{RS}\lambda}$ ) were calculated using irradiance and radiance data, and were corrected with a spline function corresponding to wavelengths of satellite bands.

Satellite data were acquired from the MODIS ocean-

color sensor on board the Aqua satellite (EOS PM). Daily and monthly Level-3 mapped MODIS  $R_{\text{RS}\lambda}$  data (412, 443, 488, 531, 547, and 667 nm bands: 4-km resolution) were obtained from the NASA ocean-color website (<http://oceancolor.gsfc.nasa.gov>). An empirical algorithm for  $a\text{CDOM}$  was derived from field  $R_{\text{RS}\lambda}$  and  $a\text{CDOM}$  data and was applied to predict satellite  $a\text{CDOM}$  data for use in the present study. As suggested by Kahru and Mitchell (2001), the ratio of  $R_{\text{RS}\lambda}$  values from two bands at 443 and 531 nm ( $R_{\text{RS}443}/R_{\text{RS}531}$ ) was utilized in the algorithm of the present paper.

## 3. RESULTS AND DISCUSSION

### 3.1 CDOM Absorption Coefficient from Field Data

The magnitude of surface  $a\text{CDOM}$  varied inversely with SSS (salinity: 25.3 - 34.5), which is indicative of the presence of a freshwater source (Fig. 2a). These relationships between  $a\text{CDOM}$  and SSS, however, differed between the summers of 2009 and 2010. A comparison of our results with earlier field studies conducted in the ECS (Gong 2004; Sasaki et al. 2008) revealed that in 2009, high  $a\text{CDOM}$  values corresponded to low SSS ( $> 1.0 \text{ m}^{-1}$  at SSS near 30), whereas the  $a\text{CDOM}$  values in 2010 were low compared to those in 2009 and in previous studies (about  $0.5 \text{ m}^{-1}$  at SSS near 30). A slight non-linear increase of  $a\text{CDOM}$  with decreasing SSS was found for 2009 compared with a linear relationship between  $a\text{CDOM}$  and SSS for 2010 (the coefficient of determination  $r^2$ : 0.77 - 0.78).

Mixing of high  $a\text{CDOM}$  freshwater and low  $a\text{CDOM}$  marine waters is a major factor controlling CDOM distribution and the relationship between  $a\text{CDOM}$  and SSS. The Changjiang significantly influences variability of SSS distribution on the ECS shelf compared to other river outflows. Therefore, the Changjiang water input to the ECS probably acts as a source of surface CDOM to offshore areas of the ECS during summer. This is consistent with the results of earlier field studies conducted at the mouth of the Changjiang and near the Chinese coast (Gong 2004; Guo et al. 2007) and offshore (Sasaki et al. 2008) in the ECS.

River water carries terrestrial CDOM primarily from soils (e.g., Cauwet 2002; Coble 2007). When river discharge increases, it provokes soil leaching and solubilization of organic matter, increasing dissolved material content; however, the process is not that simple because heavy rains add large quantities of water that dilute the leachate (Cauwet 2002). Thus, what is often observed is an increase in dissolved materials at the beginning of a flood and then a decrease, due to dilution, during the later part of the flood. The dilution of CDOM by elevated river discharge might have influenced the  $a\text{CDOM}$  vs. SSS relationship (i.e., low  $a\text{CDOM}$  for a given low SSS; Fig. 2a) in the present study, because there was a rapid increase in the Changjiang discharge during a relatively short time period in 2010. The cause of

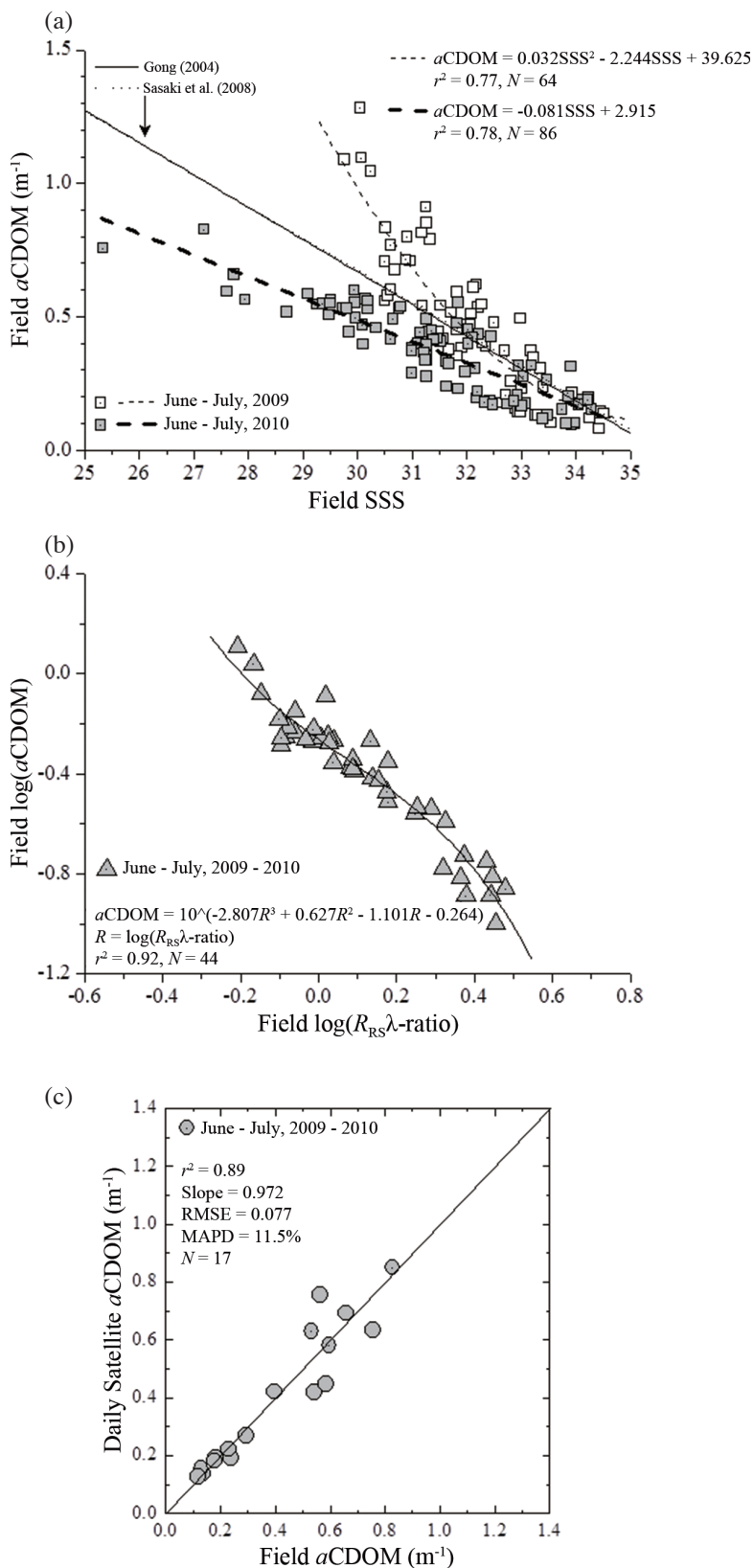


Fig. 2. (a) Variation in field  $a_{CDOM}$  (CDOM absorption coefficient at 325 nm) as a function of field sea-surface salinity (SSS) in the ECS during summers of 2009 (open squares) and 2010 (grey squares). Thin and thick dashed lines are the best fit regression lines for 2009 and 2010, respectively. Solid and dotted lines are the regression lines published by Gong (2004) and reproduced data from Sasaki et al. (2008), respectively. (b) Variation in log-transformed field  $a_{CDOM}$  as a function of field  $R_{RS}\lambda$ -ratio ( $R_{RS443}/R_{RS531}$ ) using all data from 2009 and 2010. Solid line is the best fit to the data. (c) Comparison of field and daily satellite-derived  $a_{CDOM}$  values. MODIS daily data were obtained on the same day as the field observations. Solid line is the 1:1 line.

the non-linear pattern of the relationship between  $a$ CDOM and SSS in 2009 cannot be clearly explained (Fig. 2a) without further work on local sources and sinks of CDOM.

### 3.2 Satellite-Derived $a$ CDOM Data

For field data, the magnitude of  $a$ CDOM correlated with that of the  $R_{RS443}/R_{RS531}$  reflectance ratio in both 2009 and 2010 (Fig. 2b). The best-fit regression line ( $r^2 = 0.92$ ) describes the empirical two-band algorithm that provides the best representation for the majority of data collected in the investigated waters (see the equation of Fig. 2b). Unfortunately, other factors, such as phytoplankton and/or detrital particles, are not necessarily excluded by the simple algorithm utilizing the  $R_{RS}\lambda$ -ratio. The influence of detrital particles on  $R_{RS}\lambda$  data, however, might be negligible for the central ECS during summer, because satellite radiance data indicate that turbid waters were not present in this region during summer (Yuan et al. 2008; Shi and Wang 2012).

Satellite-based  $a$ CDOM data were estimated by substituting the satellite-derived  $R_{RS443}/R_{RS531}$  data into the empirical algorithm as shown in Fig. 2b. Although the number of satellite data points on a given day was sometimes small in comparison with field data because of cloud cover,  $a$ CDOM results still exhibited good agreement between satellite and field values (Fig. 2c). Values of  $r^2$  (0.89) and the slope of the linear regression (0.972) were close to 1.0. To evaluate the performance and uncertainty of our  $a$ CDOM algorithm, in addition to the  $r^2$  and slope values, the root mean square error (RMSE) and mean absolute percentage difference (MAPD) were calculated (see Mannino et al. 2008; Pan et al. 2008). The RMSE and the MAPD values of our satellite-derived estimate of  $a$ CDOM were 0.077 and 11.5%, respectively. These statistical values were reasonable by comparison with typical regional two-band ratio algorithms of CDOM absorption (300 - 380 nm) for other regions: 14.7 - 25.2% MAPD for the Middle Atlantic Bight (Mannino et al. 2008; Pan et al. 2008) and 19.7% RMSE in percent for the California current (Kahru and Mitchell 2001). Our results indicated that the algorithm based on the ratio  $R_{RS443}/R_{RS531}$  is suitable to retrieve  $a$ CDOM in the central ECS with good accuracy. Consequently, we suggest that the optical properties of the CDW can be characterized by CDOM, and thus satellite-derived  $a$ CDOM might be an indicator of the CDW.

Kim et al. (2009) reported that the distribution of satellite-derived high chlorophyll  $a$  (Chl  $a$ ) data approximately corresponded to that of CDW during summer. The CDW likely contains both CDOM and phytoplankton growing on river-supplied nutrients, and both likely contribute to the ocean color that traces the CDW plume in satellite imagery. Our field data also showed that most of the high Chl  $a$  waters in the western part of our research area (124 - 126°E) were found in low salinity waters (not shown). However, the distribution of lower SSS near multiple leading edges

of the CDW plume extension did not always correspond to high Chl  $a$ . In other words, this result (i.e., low Chl  $a$  in the low SSS CDW plume) implies that the presence of terrestrial CDOM within the CDW can lead to overestimation of satellite-derived Chl  $a$  values, as suggested by previous studies (e.g., Gong et al. 2006).

### 3.3 Dispersal of the CDW Plume from Satellite Data

The high  $a$ CDOM plume derived from ocean-color satellite data was distributed along the Chinese coast and extended greatly offshore during the summer (Figs. 3a-1 through a-4). As shown in Figs. 3b-1 through b-4, images of SSS distributions on the ECS shelf were reconstructed using SSS data (hereafter referred to as  $SSS_{\text{satellite-CDOM}}$ ) derived from satellite-retrieved  $a$ CDOM data and the relationships between field SSS and field  $a$ CDOM. Figure 2a shows how these field-based SSS vs.  $a$ CDOM relationships were expressed in terms of two different equations for 2009 and 2010 (see the legend of Fig. 3b). As a result, comparison of  $SSS_{\text{satellite-CDOM}}$  values with field SSS data indicated a reasonably good agreement ( $r^2$ : 0.89, slope of the linear regression: 0.968), although some of  $SSS_{\text{satellite-CDOM}}$  values appeared to be somewhat overestimated (Fig. 3c). The RMSE and the MAPD values of  $SSS_{\text{satellite-CDOM}}$  were 0.942 and 2.7%, respectively.  $SSS_{\text{satellite-CDOM}}$  could be predicted with an error of about 3% (salinity: about  $\pm 1.0$ ), although the predicted values may have errors as a consequence of several uncertainties (e.g., time difference between satellite overpass and field measurement, atmospheric correction errors or the performance of field-based SSS vs.  $a$ CDOM relationship).

The distribution of the CDW plume was revealed from satellite-derived  $a$ CDOM and  $SSS_{\text{satellite-CDOM}}$  images that also showed some interesting oceanographic features, which will be described later. Compared with June 2009 (Figs. 3a-1 and b-1), high  $a$ CDOM and low  $SSS_{\text{satellite-CDOM}}$  values in June 2010 were found further south along the coast (around Taiwan at 25°N) (Figs. 3a-3 and b-3). The distributions of high  $a$ CDOM, low  $SSS_{\text{satellite-CDOM}}$  CDW in July were also more extensive in 2010 (Figs. 3a-4 and b-4) than in 2009 (Figs. 3a-2 and b-2). This was expected, as the extent of the CDW plume extension reflected changes of the Changjiang discharge. The tongue of the CDW plume in the central area on the ECS shelf extended farther southeastward in July 2010 (to around 26°N; Figs. 3a-4 and b-4) than in July 2009 (to around 30°N; Figs. 3a-2 and b-2). This  $SSS_{\text{satellite-CDOM}}$  distribution was verified by Hirate (2010, 2011), who found a water mass of lower salinity in the surface layer in early July 2010 compared with 2009 in his study area (124.8°E, 27.4°N - 127.8°E, 25.3°N). The southerly winds by which the northeastward flow of the CDW plume is promoted were weak near the Chinese coast in June 2010 (Fig. 3d-3) compared with those of other times (Figs. 3d-1, d-2, and d-4). A large portion of the CDW appears to extend southward alongshore as well as eastward

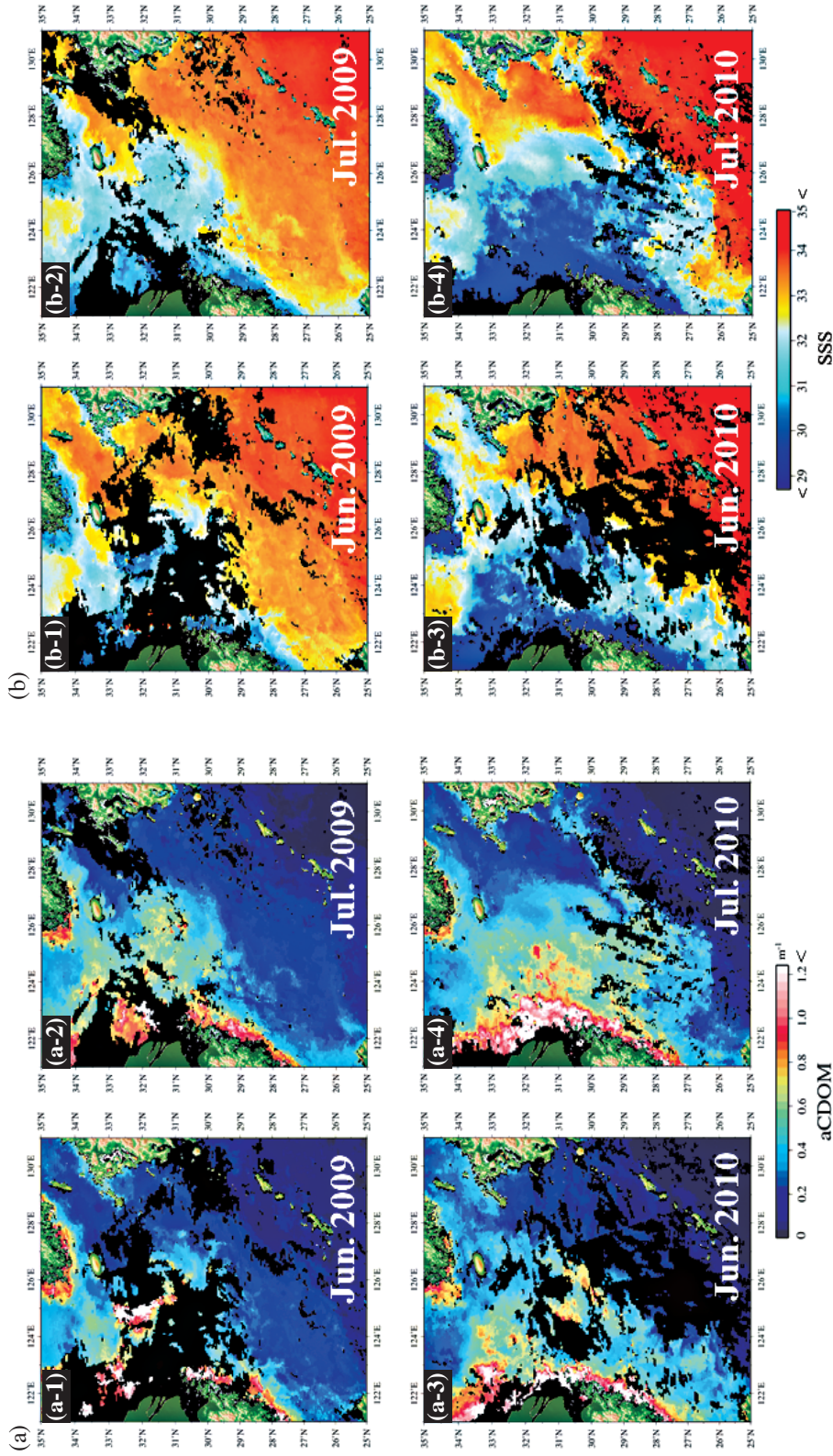


Fig. 3. Monthly-averaged MODIS images of (a)  $a_{CDOM}$  and (b) SSS ( $SSS_{satellite-CDOM}$ ) distributions in June and July of 2009 (upper two panels: 1 and 2) and 2010 (lower two panels: 3 and 4), where values of  $SSS_{satellite-CDOM}$  data were obtained by substituting satellite-retrieved  $a_{CDOM}$  data (Fig. 3a) into field-based relationships between SSS and  $a_{CDOM}$  data set as shown in Fig. 2a. [ $SSS = 2.698 a_{CDOM}^2 - 6.867 a_{CDOM} + 34.523$  for 2009 ( $r^2 = 0.77, N = 64$ ), and  $SSS = -9.652 a_{CDOM} + 35.036$  for 2010 ( $r^2 = 0.78, N = 86$ )]. (c) Comparison of daily  $SSS_{satellite-CDOM}$  and field SSS values on the same day of the satellite overpass. Dotted lines delimit the  $\pm 1.0$  range of agreement with respect to the 1:1 (solid) line. (d) Monthly-averaged sea-wind vectors in June and July of 2009 and 2010. The layout is the same as Figs. 3a and 3b. These data in 2009 and 2010 were obtained from SeaWinds/QuikSCAT and ASCAT/MetOp-A satellites, respectively (NOAA ERDDAP website; <http://coastwatch.pfeg.noaa.gov/erddap>).

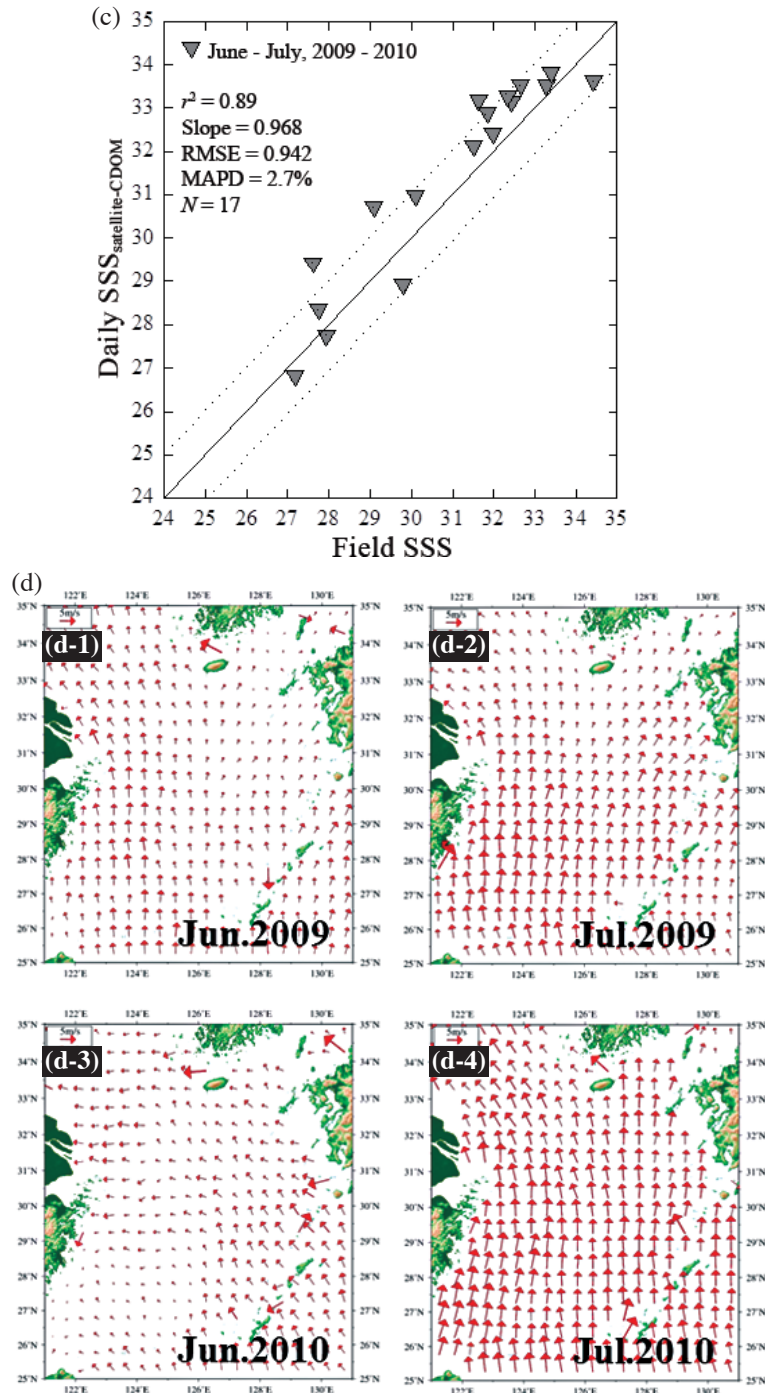


Fig. 3. (Continued)

toward the central ECS in June 2010 (Figs. 3a-3 and b-3). This may have resulted in a greater southern extension of the CDW plume in July 2010 despite stronger southerly winds (Figs. 3a-4, b-4, and d-4). Moreover, during this period, a branch of the low-salinity CDW plume (124 - 126°E, 26 - 28°N) flowed northeastward in the eastern ECS where the high salinity water flows northeastward along the shelf break (Fig. 3b-4). Subsequently, this branch reached southern Kyushu (near 130°E, 31°N). Field observations showed lower SSS values

in 2010 (< 32.5) compared with 2009 (33.3 - 33.9) near southern Kyushu (128 - 130.5°E, 30 - 32°N) in August (Ishida et al. 2010, 2011). Satellite observations revealed that the decrease of SSS around this region was due to the extension of CDW.

In the present study, the satellite  $a$ CDOM and SSS<sub>satellite-CDOM</sub> maps clearly showed the dispersal patterns of the CDW plume in the ECS. The CDW plume extended southeastward from the mouth of the Changjiang, and the dispersal of the plume was observed from the central ECS

to southern Kyushu during the summer of 2010. Although confirmation of the influences of local variability (southerly winds or warm current waters) on the extension of the CDW is necessary, our results suggest that the summer circulation pattern in the ECS may be affected by the temporally variable Changjiang discharge.

Previously, SSS was one of the missing variables in satellite remote sensing studies of the Earth. In recent years, SSS data retrieved from satellite observations have become a major research interest in global water cycle and climate change, and this field of research has just begun. New SSS observations from ESA's SMOS and NASA's Aquarius microwave sensors are being actively investigated (e.g., Grodsky et al. 2012). These satellite-derived SSS techniques measuring microwave brightness temperature in the L-band (frequency of 1.4 GHz) have the advantages of cloud penetration and all-weather capabilities. However, the spatial resolutions of the microwave sensors will be too coarse (about 40 - 150 km) to be useful in the coastal regions. The microwave techniques may be suited for applications that monitor large-scale (global) ocean circulation events. In contrast, ocean-color satellite data are usually collected with a spatial resolution from 0.3 to 1 km [e.g., MODIS Level-2 (1-km resolution) and Level-3 (4- and 9-km resolution) data products]. These regional-scale data are especially useful for processes at scales of coastal and continental shelf regions unless the satellite coverage areas are limited by cloud cover. The strong relationship between  $a$ CDOM and SSS suggests that satellite-derived  $a$ CDOM can be a key tracer for river-water input and then predict  $SSS_{\text{satellite-CDOM}}$  relevant to river waters. An improvement of the performance of  $SSS_{\text{satellite-CDOM}}$  prediction requires further understanding of the behavior of CDOM (i.e., sources and sinks) and variations in the SSS vs.  $a$ CDOM relationship. Currently, the technique described herein for using ocean-color remote sensing of CDOM and  $SSS_{\text{satellite-CDOM}}$  should provide useful information for mapping river-water intrusions in coastal regions.

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