MEASURING SEA SURFACE SALINITY OF THE JAKARTA BAY USING REMOTELY SENSED OF OCEAN COLOR DATA ACQUIRED BY MODIS SENSOR

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Abstract

Observations on oceanographic parameters using remote sensing techniques intensively have been done for more than 3 decades for estimating and mapping the sea surface temperature (SST) and the abundance of phytoplankton expressed as the concentration of chlorophyll-a and applied them in studying the ocean phenomenon. As a result, the product of these 2 parameters for all over the oceans in the world has been established and available in daily basis. However, on the contrary, there is still limited application for sea surface salinity (SSS) which is also one of the most important oceanographic features. This paper describes a novel method of deriving SSS from remotely sensed ocean color. The method is based on two important observations of optical properties in regions of freshwater influences. The first is the strong effect of Colored Dissolved Organic Matter (CDOM or yellow substance) on ocean color when present in relatively high concentrations. The second is the close relationship between salinity and CDOM originating from fresh water runoff. In this paper, these relationships are demonstrated for the Jakarta Bay, Indonesia. The MODIS sensor in Terra and Aqua satellites imageries and 10 in situ measurements conducted near-simultaneously with the satellites over flight over the bay in 2004 and 2006 were implemented for deriving CDOM and SSS. The empirical relationships demonstrated in this study allow the satisfactory prediction of CDOM and SSS in the Jakarta Bay from remotely sensed ocean color. The root mean square (r.m.s) error difference between the observed and predicted parameters are 0.14 m^{-1} and 0.93 psu for CDOM g_{440} and SSS, respectively, over a range of salinity from 24 to 33 psu. This range is in good agreement with field surveys. Parameters that may influence CDOM, such as Chlorophyll-a (CHL-a) and total suspended material (TSM) concentrations were also analyzed. Results showed that there were no relationship at all between CDOM and CHL-a, and between CDOM and TSM. These indicate that phytoplankton plays a minor role in regulating CDOM abundance, and also suggest that CDOM contribution from sediment and/or from sediment resuspension is negligible. Thus, CDOM sources in the Jakarta Bay are mainly from riverine inputs. SSS maps created from the satellite-retrieved ocean color identify features in the surface salinity distribution such as salinity front of > 32 psu that migrated in and out of the bay according to seasons. Therefore, the ability to obtain synoptic views of SSS such as presented in this paper provides great potential in furthering the understanding of coastal environments.

Keywords: CDOM, SSS, MODIS, Terra and Aqua, algorithm, Jakarta Bay.

INTRODUCTION

The ocean color can be defined as the spectral or wavelength composition of radiance exiting the ocean surface in the visible wavelengths (approximately 0.4~0.7 μm). At any wavelength, this returned radiance is very much dependent upon the absorption and scattering properties of the water as well as dissolved and particulate constituents, such as dissolved organic matter, freefloating photosynthetic organisms (phytoplankton cells),

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suspended mineral particles, etc (Barale, 1986; Holigan *et. al.*, 1989; Kirk, 1994; IOCCG, 2000). All those materials influence optical properties of a water body.

Based on the water optical properties, Sathyendranath and Morel (1983); IOCCG (2000) divided the water body into 2 types, namely case-1, and case-2 water types. In the case-1 waters, phytoplankton and their bio-products play a dominant role in determining the optical properties of the water (ocean). The case-1 waters can be changed into case-2 waters type as soon as at least one of the following substance, resuspended sediments from sea bottom, terrigeneous particulates from river runoff, dissolved organic matter (yellow substance) from land drainage, and dissolved materials from anthropogenic influx is present. In general, the case-1 waters represents the open sea (oceanic waters), while case-2 waters represents the shallow turbid waters (coastal waters).

In case-2 waters, there are two main components of dissolved materials that influenced the ocean color. The first one is inorganic sediment (eg. red clay), and the second is yellow substance or also called as gelbstoff, or gelvin or Colored Dissolved Organic Matter (CDOM). CDOM originates predominantly from humic and fulvic materials of terrestrial origin transported to coastal seas through freshwater runoff from the land (Maul, 1985; Fischer and Kronfeld, 1990; Kirk, 1994; IOCCG, 2000; Binding and Bowers, 2003). Near the rivers, most CDOM typically derives from land drainage, and this resulting in a green or even brown appearance when present in sufficient concentration. Away from continental margin, the effect of river declined, and CDOM is presumably related to primary productivity as a by-product of algal cell degradation and zooplankton grazing (Sathyendranath and Morel, 1983; Binding and Bowers, 2003; Chen *et al*., 2004; Nababan, 2005; Bowers and Brett, 2008; Sasaki *et al*., 2008). However, in sub-tropical bank regions such as the Bahamas that lack fluvial inputs, substrate-related sources, particularly seagrass beds and coral reefs, have been found to be the primary CDOM sources (Boss and Zaneveld, 2003).

Knowledge of the spatial distribution and temporal changes of CDOM is important since the optical properties of CDOM are characterized by strong absorption in the ultraviolet (UV) and the blue end of the visible spectrum, which results in photochemical reactions as well as the protection of aquatic biota (phytoplankton) from damaging UV-B, but reducing light available for phytoplankton photosynthesis (Binding and Bowers, 2003; Kowalczuk, 2003; Kutser *et al*., 2005; Nababan, 2005). Given the importance of CDOM, a method to estimate their amounts in the coastal waters over large geographical regions would be highly desirable. Fortunately, since CDOM is generally in much higher concentrations in coastal and estuary areas and absorbs more UV and blue light than other visible light, then it is easily retrieved from satellite ocean color observation (Bowers and Brett, 2008). So, interpretation of remotely sensed ocean color has largely depended on the ability to establish relationship between the apparent optical properties (remote sensing reflectance) and inherent optical properties (CDOM) (Ahn *et al*., 2008).

Because of CDOM and pollutant transported in river plumes are often diluted in manner consistent with that of salinity, CDOM has been proposed as a proxy to estimate surface salinity (Nababan, 2005). The salinity itself has no direct color signal (Ahn e*t al.,* 2008). However, Monahan and Pybus (1978) showed that CDOM could be related to salinity through ocean color information in water off the west coast of Ireland. Therefore, it is feasible that remotely sensed ocean color from aircraft or satellite could be interpreted in terms of salinity (Binding and Bowers, 2003, Bowers and Brett, 2008). Several studies have documented the relationship between CDOM and surface salinity in many coastal regions in the world, which indicated a strong inverse linear relationship (see Table 1 in Bowers and Brett, 2008) as well as shown by Nababan (2005) in the North-eastern Gulf of Mexico, and Shank *et al*. (2009) in a shallow Texas estuary. Ahn *et al*. (2008) mapped and monitored CDOM and low salinity of the East China Sea (ECS) which was influenced by Yangtze River. Sasaki *et al*. (2008) mapped the low Salinety of Changjiang River using satellite-retrieved CDOM in the ECS during high river flow season. Chen *et al*. (2007) reported the CDOM in estuarine of Tampa Bay, Florida. D'sa *et al*. (2002) estimated the CDOM and surface salinity using Sea-viewing

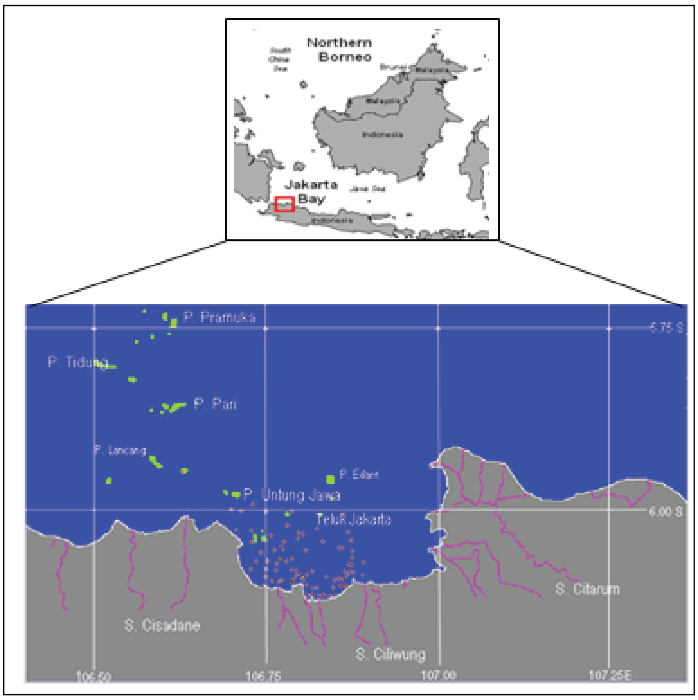

Figure 1. Map of Jakarta Bay with major rivers that influenced its water quality. Black dots are sampling stations, P is Island (green), and S is river (pink color).

Wide Field-of-view-Sensor (Sea-WIFS) in the Florida Bay and Florida Shelf. It seems however, that there is no study on CDOM and the surface salinity has been conducted in Indonesian waters.

As the first step to our study in this topic, the main objective of this paper are two folds: (1) to investigated the temporal and spatial variability of *in situ* CDOM and sea surface salinity (SSS) and their relationship, (2) to explore the potential utility of multi-temporal of MODIS (Moderate Resolution Imaging Spectro-photometer) sensors in Terra and Aqua satellites for accurately estimating and mapping the CDOM and SSS of the Jakarta Bay.

MATERIALS AND METHODS

Study Site

The Jakarta Bay is situated in the north of Jakarta, the capitol of Indonesia. It lies between 106.60-107.10º of East longitudes and 5.90-6.20º of South latitudes (Fig. 1). The border of this bay is between Tanjung Pasir Point (cape) in the west and Tanjung Kerawang Point in the east. The bay covered an area approximately 514 km^2, with 72 km coast lines, and an average depth of 15 m (UNESCO, 2000; Damar, 2001). Environmentally unfriendly rapid land-use development around Jakarta and its big hinterland cities, such as Bogor, Depok, Tanggerang and Bekasi (Jabodetabek regions) with highly dense population (> 20 millions), and the so many small and moderate sized rivers (13 rivers) that discharge their loads into the bay are becoming the main threats to the water quality of the bay. Among the 13 rivers, 3 rivers (Cisadane, Ciliwung and Citarum Rivers) are relatively moderate in size, while 10 others (Kamal, Cengkareng Drain, Angke, Karang, Ancol, Sunter, Cakung, Blencong, Grogol and Pasanggrahan Rivers) are small. Most of those rivers passed big urban areas, as well as many agricultural, industrial, and recreational areas of Jabodetabek.

Any material discharged into the sea causes some changes. Such changes may be great or small, long-lasting or transient, wide spread or extremely localized. If the change can be detected and is regarded as damaging, it constitutes pollution (Perez *at al.*, 2003). Literature reviews on water quality of the Jakarta Bay from 1970's to present indicate that the Jakarta Bay gets continuous pressures due to eutrophication and heavy pollutions (Arifin, 2003; 2005). On the other hand, the Jakarta Bay is economically vital for various stakeholders who use this bay for many purposes (fisheries, tourism and recreation, industry, transportation, research, education and training, conservation area/marine park and many others). Therefore, regarding the importance values of the Jakarta Bay, effort such as long-term commitment to monitor the water quality with effective and efficient method for managing this bay is inevitable.

Sampling Time and Water Quality Parameter Measurements

The water quality samplings were done near-simultaneously with the Landsat-7 ETM+ overflight time over the Jakarta Bay (Path 122; Row: 064) during ± 3 hours before and after the satellite passage at around 9:45 AM local time. In the same date, the Terra (launched in August 1999) and Aqua (launched in 2002) satellites that carrying MODIS sensor also passed over the Jakarta Bay in the morning at 10:15, and in the noon at around 13:05 local time, respectively. Field measurements were made from two boats at 225 stations through the bay (Fig. 1) during 3 sampling periods on June 21, August 24, and September 9 in 2004, and using one boat at 84 stations during 5 sampling periods on May 26, June 11, July 29, August 24, and October 1 in 2006.

At each station, profiles of temperature and salinity were made with a Sea-Bird Electronics (SBE) conductivity-temperature-depth (CTD). However, since only one CTD was available, then measurements for these parameters in 2004 were made only in one boat (boat A), but none for the other boat (boat B). The other parameters, such as the water transparency was measured directly in the field using a secchi disk, while surface water samples were collected for measuring the total suspended material (TSM), chlorophyll-*a*, and CDOM conentrations that will be analyzed further in the laboratory. TSM concentrations were measured gravimetrically on pre-weighted Whatman glass-fibre filters GF/C (47 mm in diameter,

Table 1. Main characteristics of MODIS sensor for land and ocean color channels in the vissible and near-infrared (NIR) spectral regions (adopted from Gao *et al*., 2007 with modification)

Primary use	Band No.	Bandwith (nm)	Ground Resolution (m)	Signal to noise Ratio
Land application channel	1	620-670, Red	250	128
	2	841-876, NIR	250	201
	3	459-479, Blue	500	243
	4	545-565, Green	500	248
	5	1230-1250, Mid-IR	500	74
	6	1628-1652, Mid-IR	500	275
	7	2105-2155, Mid-IR	500	110
Ocean Color Application	8	405-420, Blue	1000	880
	9	438-448, Blue	1000	838
	10	483-493, Blue	1000	802
	11	526-536, Green	1000	754
	12	546-556, Green	1000	750
	13	662-672, Red	1000	910
	14	673-683, Red	1000	1087
	15	743-753, NIR	1000	586
	16	862-877, NIR	1000	516

0.7 μm pore size). Chlorophyll-a concentrations were measured fluoro-metrically after extraction in the acetone for 24 hours following the instruction of Stricland and Parsons (1972). For CDOM concentration, surface water samples were filtered through Whatman glass-fibre filters GF/F (24 mm in diameter, 0.2 μm pore size). Samples were stored for a few hours in the bottles before analysis. CDOM was then measured on the filtrate using a spectrophotometer Shimadzu with a distilated waters as a reference. The absorption coeficient at 440 nm (g_{440}, m^{-1}) was used to represent the concentration of CDOM as calculated from the following equation:

$$g_{440} = 2.3025\ (A_{440} - A_{750})/l \text{ . . . . 1)}$$

where A_{440} *and* A_{750} are the absorbances measured at 440 and 750 nm, respectively. The factor 2.3025 con-verts from base 10 to base e logarithms. The absorbance at 750 nm is subtracted to correct for scattering by particles, l is the cell (cuvette) path length in meters (Binding and Bowers, 2003; Binding *et al*., 2005). Since we used cuvette with 1 cm path length, and the unit of g440 in cm^{-1}, thus domination for the equation 1 is 1.

Satellites used and data processing

A total of 14 images cosnsisted of 8 Terra- and 6 Aqua-MODIS satellites that acquired on June 21, August 24 and September 9 in 2004, and May 26, June 11, July 29, August 24 and October 1, in 2006 were used in this study. MODIS sensor has 36 channels/Bands located in wide spectral range from about 0.4 to 14.3 μm. This sensor was specially designed for remote sensing of land (band 1 to 7), ocean (band 8 to 16) and atmosphere (band 17 to 36). One set of MODIS channels, i.e., at band 8 to 16, in 0.4 to 0.9 μm spectral range is designed mainly for remote sensing of Case-1 waters. Another channels, i.e., at band 1 to 7, in the 0.4 to 2.3 μm region is designed for the remote sensing of land nearly the same of Landsat-5 or-7 satellites, but also has applications for remote sensing of coastal and inland waters (Gao *et al.,* 2007). Table 1 lists the main characteristic of the MODIS chanels. MODIS level-1B data of Tera- and Aqua satelites use in this study for both land and ocean application could be searched and downloaded from the following website: http://ladsweb.nascom. nasa.gov/data/search.html

In this study we used the channels of MODIS for land application, and we chose only 3 bands in the visible regions, namely band 3 (blue), band 4 (green) and band 1 (red), instead of channels for ocean application (band 8 to 14; see Table 1). The reason to choose channels for land application is because the Jakarta Bay is categorized as case-2 waters where the ocean channels are sometimes not appropriate for this study, except for case-1 waters (D'Sa *et al*., 2002). Furthermore, Ocean color channels have much higher signal-to-noise ratios and are sensitive to darker surfaces than the land channels centered in the similar wavelength (Gao *et al.,* 2007). Although land application channels have lower sensivities than the MODIS ocean channels, however, comparison with other sensor such as Landsat-7 ETM+, Hu *et al*. (2004) determined that these channels do provide suffient sensitivity (4-5 times more sensitive than Land-sat-7 ETM+) for water application. Furthermore, the ocean application channels with 1 km spatial resolution (Table 1) will make the observation and mapping the water quality of Jakarta spatial resolution of 500 m.

Because we use multi-temporal images and because the atmospheric path between the space platform (satellite) and the water surface needs to be investigated, remotely sensed data must be ad-equately corrected for the atmospheric influences before their intepretation and use (Maul, 1985; Giardino *et al*., 2001; Thiemann and Kaufmann, 2002). Here, we used a simple atmospheric correc-tion procedure called Dark Pixel or Dark Object Subtraction (DOS) model (Richards, 1986, Ritchie and Cooper, 1987, Brivio *et al*., 2001) to correct for the atmospheric influences. This procedure is based on the assumption that each band of data for a given scene should have some pixel at or close to zero digital number (DN) value, but the atmospheric effect has been added as a constant value to each pixel. Consequently, if the minimum DN value in the image histogram is greater than zero, then the difference between zero and this minimum DN is due to atmospheric condition or sensor noise (USGS, 1984; Richards, 1986; Ritchie and Cooper, 1987). Mathematically, the operation for atmosperic compensation is difined by the simple equation 2 below:

Yij = Xij – Bias . . . . 2)

where Yij=Atmospheric corrected DN value in the image of band i on date j

Xij=Uncorreced DN value in in the image of band i on date j,

Bias=Minimum DN of image histogram.

Employing this equation all 14 images of Terra- and Aqua MODIS were corrected for the atmospheric effects by subtracting the DN of each band in each image with its minimum DN value.

Although Terra and Aqua satellies have the same sensor, i.e., MODIS, the sensor in each satellite does not have the same radiometric (spectral) response. Therefore, it is necessary to convert the DN from both satellite to radiance values, in order for them to have the same physical unit (W cm^{-1} μm cm^{-2} sr^{-1}), and so the data of both satellites are now comparable. Table 2 lists the conversion values for each band (Ouzounov, 2005; Personal communication). Atmosperic corrected radiance of bands 3 (blue), 4 (green) and 1 (red) at each sampling station were extracted. The radiance transformation ratio of blue to green (band 3/ band 4), blue to red (band 3/band 1), and ratio of green to red (band 4/band 1), and the radiance transformation of blue chromaticity or X-Chromaticity = (band 3)/(band 3+band 4+band 1), radiance of green chromaticity or Y-chromaticity = (band 4)/ (band 3+band 4+band 1)], and radiance of red chromaticity or Z chromaticity = [(band 1/(band 3+ band 4+ band1)], where X+Y+Z=1 (Bukata *et al*., 1983) were also computed. The purpose to use transformation of band rationing is for removing sun/shadow and atmospheric effects, while transformation of chromaticity is for enhancing the features in the images through tristimulus color index (Sasmal, 2000). All extracted and computed MODIS radiances data using the above procedure was then correlated with CDOM data measured at the same coordinates in the field through various regression analyses. Regression analysis between CDOM and salinity was also developed. If radiance values data of each band and their transformation in both MODIS (Terra and Aqua) sensors are correlated well with CDOM, and CDOM is strongly correlated to salinity, then it is possible to obtain salinity information from satellite data.

RESULTS AND DISCUSSION

A total of 309 water quality parameter measurements have been conducted in Jakarta Bay during the sampling periods (Table 3), which coincide with a transition from wet to dry season (March to May), dry season (June to August), and a transition from dry to wet season (September to November). Among those total measurements,only 174 data set were used to develop prediction models of CDOM and surface salinity, because the CDOM were not measured on May 24 and September 25, 2004, while *in-situ* salinity measurement were not available for boat B (Table 1) on June 21, August 24, and September 9, 2004.

Table 2. Coefficients for converting the digital number (DN) to radiance (W m^{-2} μm^{-1} sr^{-1}) in the vissible wavelength of Terra- and Aqua MODIS.

Satellite	Band -1 (Red)		Band - 4 (Green)		Band - 3 (Blue)	
	Scale	Offset	Scale	Offset	Scale	Offset
Terra	0.0262678	0	0.0189215	0	0.0216817	0
Aqua	0.0286548	0	0.0188667	0	0.0219852	0

Note: 1). Radiance = DN * Scale + offset

2). Scale and offset coefficients are provided by Dimitrar Ouzounov, Ph.D (2005) from NASA Goddart Space Flight Center (ouzounov@eosdata.gsfc.nasa.gov).

Variation of *in-situ* CDOM and surface salinity

The CDOM absorption generally decreases with increasing salinity (Chen *et al.*, 2007). This study shows similar results, which are indicated by relatively higher values of CDOM at 440 nm (CDOM g_{440}) found during the transition of wet to dry until the early dry seasons (May to June) both in 2004 and 2006, ranging from 0 to 0.168 cm^{-1} and 0 to 0.120 cm^{-1}, respectively with a mean value of 0.037 and 0.007 cm^{-1}, respectively. In dry and transitional dry to wet seasons (July to October), the CDOM g_{440} have lower values ranging from 0 to 0.012 cm^{-1} with a mean value of 0.006 cm^{-1} for 2004, and from 0.001 to 0.012 cm^{-1} with a mean value of 0.005 cm^{-1} in 2006 (Tabel 3).

On the other hand, the surface salinity has a lower mean values (< 32 psu) during the early dry season with a range of 30.9 to 31.8 psu in 2004 and 31.7 to 31.9 psu in 2006 compared to those in mid dry and transition dry to wet seasons (>32 psu) with a range of 32.4 to 33.0 psu in 2004 and 32.6 to 32.7 psu in 2006, respectively, except on July 2006 (< 32 psu) (Table 3). Long hydrographic observation in the Jakarta Bay conducted by Ilahude (1995) showed that the surface salinity ranged between 25.0 and 32.5 psu. Seasonally, low salinity was found during the rainy season (west moonson) from December to February with salinity ranged from 25.0 to < 32.0 psu.

The ranges of surface salinity for transitional wet to dry season (March to May), dry season (June to August), and transitional dry to wet season (September to November) were 28.5 to 32.5, 29.0 to 32.5, and 28.0 to 32.0 psu, respectively. Damar (2001) reported in his study the ranges of salinity from 26.9 to 33.4 psu on April to July 2000, while Razak and Muhtar (2003), found a relative low salinity ranged around 20.3 to32.0 psu with an average of 31.1 psu in their survey conducted on June 2003.

In the early of dry season, a small amount of rainfall that averaged one week before the sampling date were still detected both in 2004 (0.2

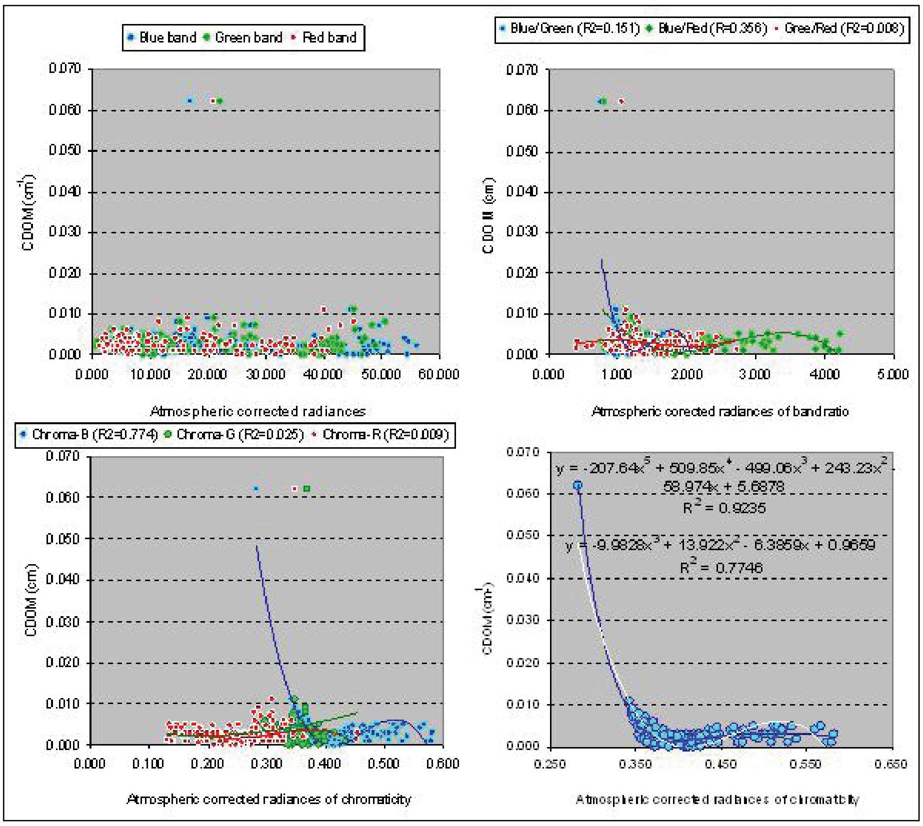

Figure 2. Plot of CDOM g_{440} against radiance of blue, green and red bands of MODIS (upper left), the radiance ratios of bands blue to green, blue to red and green to red (upper right), the radiance of blue, green and red chromaticity, (lower left), and final model for predicting CDOM g_{440} (lower right)

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Table 3. CDOM absorption coefficient at 440nm, surface salinity, chlorophyll-a concentration, total suspended solid (TSS) concentration,and one week averaged rainfall before the sampling date. (CTD casts were made in boat A only).

Date	Boat	N	CDOM absorption (cm^{-1})			Surface Salinity (psu)			Chlorophyll-*a* ($mg\ m^{-3}$)			Total Suspended Matter ($mg\ l^{-1}$)			Rainfall (mm)
			Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	
4-May-04	A	26	---	---	---	30.041	31.478	30.862	0.001	4.760	0.458	33.6	63.4	45.4	1.0
21-Jun-04	A	29	0.005	0.159	0.037	31.402	32.174	31.836	0.298	3.967	0.890	2.0	27.2	8.2	0.2
	B	30	0.000	0.168	0.037	---	---	---	0.104	2.975	0.977	4.6	97.2	31.8	
24-Aug-04	A	32	0.000	0.023	0.007	31.539	32.625	32.362	0.060	2.142	0.552	7.2	31.6	15.3	0
	B	24	0.000	0.018	0.007	---	---	---	0.179	1.369	0.684	9.0	38.6	18.7	
9-Sep-04	A	29	0.000	0.012	0.007	31.964	32.736	32.500	0.000	1.309	0.400	12.0	56.4	25.4	0
	B	28	0.002	0.012	0.006	---	---	---	0.000	1.964	0.562	14.4	39.4	22.6	
25-Sep-04	A	27	---	---	---	32.774	33.162	32.952	0.119	3.392	0.652	45.0	74.2	55.4	0
26-May-06	A	17	0.000	0.021	0.007	31.087	31.855	31.910	0.226	1.810	0.668	20.4	152.8	113.7	3.5
11-Jun-06	A	17	0.002	0.016	0.007	30.643	32.091	31.704	0.453	1.810	1.025	33.6	161.6	119.3	4.8
29-Jul-06	A	15	0.002	0.012	0.004	29.490	31.923	31.572	0.226	2.942	0.966	132.4	161.2	144.1	0
24-Sep-06	A	16	0.001	0.009	0.005	32.225	32.892	32.630	0.582	5.496	1.629	112.8	141.2	127.5	0
1-Oct-06	A	19	0.002	0.008	0.005	32.585	33.054	32.780	0.582	3.298	1.697	116.8	136.4	125.5	0

to1.0 mm) and in 2006 (3.5 to 4.8 mm), while there was no rain at all during the dry and transitional wet to dry seasons (Table 3). Since the CDOM g_{440} concentrations were high in early dry season (June) and lower in the dry and transitional dry to rainy seasons (July-October) and were related to amount of rainfall (Table 3) and also found to be inversely related to salinity, therefore, we hypothesized that CDOM in the estuarine and coastal waters of Jakarta Bay might be mainly of terrestrial origin, so the riverine inputs are the dominant CDOM sources. The findings in this study were consistent with most of other studies which showed that the temporal and spatial variablity of CDOM in many estuaries mostly affected by riverine outflow or amount of rainfall (Table 4), except to those in the Funka Bay, Hokaido, Japan and in the Bahamas Bank (see Table 4 for explanation).

Estimating CDOM g_{440} from remote sensing radiance of MODIS

Figure 2 shows a plot of CDOM absorption at 440 nm (CDOM g440) against corrected atmospheric radiance values of MODIS in the visible bands of blue (Band-3), green (Band-4), and Red (Band-1), transformation the radiances ratio of bands blue to green (Band-3/Band-4), blue to red (Band-3/Band-1), and green to red (Band-4/Band-1), and transformation the radiance of blue (X) chromaticity = Band-3/(Band-3+band-4+Band1), the radiance of green (Y) chromaticity = Band-4/(Band-3+band-4+Band1), and the radiance of red (Z) chromaticity = Band-3/(Band-3+band-4+Band1). This plot is based on 8 Terra- and 6 Aqua-MODIS data acquired in the same date and near-simultaneously with the sampling time. It is very clear from Figure 2 (upper left panel) that there are no correlation at all between all MODIS visible bands and CDOM $g_{440.}$ Similarly, there are also no cerrelation between transformation the radiance ratio of bands blue to green (Band-3/Band-4), and green to red (Band-4/Band-1) (Fig 2 upper right panel), and transformation the radiance of green chromaticity, Band-4/(Band-3 + band-4 + Band1), and the radiance of red chromaticity, Band-3/(Band-3+Band-4+Band1) (Fig 2 lower left panel). Weak relationship was observed between transformation the radiance ratio of blue to red and CDOM g_{440} with the coeficient determination (R^2) = 0.356. The strong correlation was observed for the relationship between transformation the radiances of blue chromaticity and CDOM g_{440} with R^2 = 0.775 by using polynomial regression order three.

However, the strongest relationship was found between transformation the radiance of blue chromaticity and CDOM g_{440} with R^2 = 0.924 by using polynomial regression order five (Fig. 2 lower right panel). Therefore, we use this order five polynomial regression that expressed in the equation 3 as a final model for estimating CDOM g_{440} of the Jakarta Bay.

This equation is expressed as follow:

$$\text{CDOM } g_{440} = -207.64*X^5 + 509.85*X^4 - 499.06*X^3 + 243.23*X^2 - 58.974*X + 5.6878 \quad \text{3)}$$

Where X = Radiance choromaticity of blue = Band-3/(Band-3+band-4+Band1); R^2 = 0.924; N = 174; The root mean square (r.m.s) error between observed and predicted CDOM g_{440} was 0.0014 cm^{-1} or 0.14 m^{-1}.

In developing the model for estimating chlorophyll-a that used to monitor harmful algal blooms (HAB) in the Jakarta Bay by plotting 48 images (30 Terra and 18 Aqua) with total of 873 *in situ* chlorophyll-a measurements in 2004, 2005 and 2006, Wouthuyzen *et al*. (2006) got the similar algorithm, in which Chlorophyll-a concentration was strongly correlated with the radiance of red chromaticity by using also a polynomial regression of order three. However, some research reported that the relationship between CDOM and remote sensing data are in simple linear form. Binding and Bowers (2003) in the Clyde Sea, west coast of Scotland found that CDOM g_{440} was correlated strongly to the ratio of reflectance red to blue bands (R665/R400) of SeaWiFS) with R^2 = 0.94 and the r.m.s. error between observed and predicted g440 was 0.19 m^{-1}, which is nearly the same with our result. Ahn *et al.* (2008) in the East China Sea (ECS) that influenced by Yangtze River also found a simple liniear relatioship between CDOM g440 and the ratio relectance blue to green (R412/R555) of SeaWiFS data with moderately high of R^2 = 0.67. The same of ECS study, but under the influence of Changjian River, Sasaki *et al*. (2008) found a very good fit regression analysis close to

Table 4. Temporal and spatial variability of CDOM observed in various estuaries.

Location	Time	CDOM values (m^{-1})			Sources & Remaks
		Min	Max	Average	
Shallow Texas estuary (g_{305})	Apr. Jul.	8.0 15.0	50.0 77.0	- -	Shank *et al*., 2009. Max. CDOM occurs due to the estuary system was experiencing very high freshwater.
East China Sea (influence of Changian River) (g_{400})	Jul.	0.05	0.20	-	Sasaki *et al.,* 2008 Maximum Changjiang River discharges to the East China Sea in July was considered to be the main origin of CDOM,
Tampa Bay, Florida (g_{400})	Jun. Oct.	0.60 3.39	1.53 16.81	1.11 7.76	Chen *et al*., 2007 The Spatial and temporal distribution of CDOM in Tampa Bay showed that the two largest rivers, the Alafia River (AR) and Hillsborough River (HR) were dominant CDOM sources to most of the bay.
Baltic Sea (g_{375})	Feb.-Mar. Apr - May	1.07 1.41	1.13 1.42	- -	Kowalczuk *et al*., 2006. Maximum CDOM occurs in Apr. to May coinciding with maximum riverine outflow.
Swan River Estuary, South-western, Australia (G_{440})	Aug.	0.09	10.87		Kostoglidis *et al*., 2005. Seasonal gradients of CDOM mainly associated with rainfall
Funka Bay, Hokaido, Japan (g_{440})	Nov - Oct	0.02	0.13	0.07	Sasaki *et al.,* 2005 CDOM in this bay is not significantly influenced by terrestrial material (there is no correlation at all with salinity), but the end of spring bloom increased CDOM absorption, which indicated that CDOM production may be related to microbial activity.
Bahamas Bank (g_{440}) - Banks - Offshores	May-Jun	 0.04 0.01	 0.07 0.06	 0.06 0.03	Otis *et al.,* 2004 CDOM-rich origin found in the shallow banks associated with seagrass beds, coral reefs, and benthic organism, but lower in the deep offshore basin.
South Atlantic Bight (g_{350})	Jun-Aug Jan, Okt-Nov	0.14 0.98	1.13 5.83	0.33 2.67	Kowalczuk *et al*., 2003 High CDOM in Jan, and Okt-Nov., but low in Jun.-Aug were due to the highest and lowest Cape Fear River discharge
Narragansett Bay, Rhode sland (g_{412})	Spring Summer -Winter	0.50 0.20	1.20 0.50	- -	Keith *et al*., 2002 High CDOM in spring correlated with freshwater inflow from watersheds surround the bay, and appears to coincide with episodes of high chlorophyll. During summer–early spring, CDOM rapidly decline to minimum values as the bay respond to intrusions of higher salinity waters from Rhode Island Sound
Jakarta Bay (g_{440})	Jun. Jul-Okt	0.00 0.10	16.80 1.20	3.70 0.70	This study. June is the early dry season, but rain still detected, while July to October is the mid dry season without any rainfall at all.

the 1:1 line between MODIS data and CDOM g_{400} with $R^2 = 0.62$ and r.m.s error = 0.092. Kutser at al., (2005) found strong relationship between CDOM g_{400} and the ratio of green to red bands of Advanced Land Imager (ALI) sensor in lakes ecosystem in Finland and Sweden with R^2=0.73.

It is already well known that phytoplankton absorp light strongly in two regions of the vissible part of spectrum due to availability of chlorophyll-a. The first maximum absorption in the blue regions with its peak in the blue (443 nm), and the second one in the red region with its peak around 680 to 685 nm (Kirk. 1994). Thus, in the blue region, both CDOM and CHL-a almost have the same signal reponse, and these possibly could interfere each other. Since we also measured chlorophyll-a (CHL-a) and total suspended materials (TSM) during the sampling periods (Table 3), then it is possible to check whether those 2 parameters data sets may have any significant effect to the color signal, which possibly interfered the relationship between CDOM and remote sensing data.

Table 3 shows that the CHL-a concentration ranged from 0.001 to 5.5 mg m^{-3}. The highest values of CHL-a concentration are detected on September 24, 2006 (5.50 mg m^{-3}), June 21, 2004 (3.97 mg m^{-3}), September 9, 2004 (3.39 mg m-3), and October 1, 2006 (3.30 mg m^{-3}). However, the mean values of each individual date was relatively low for estuarine areas (< 2 mg m^{-3}), and did not show any significant seasonal distribution pattern.

There were also no relationship at all found between individual data set of CDOM g_{440} and CHL-a in transitional wet to dry and early dry seasons, as well as in dry and transitional dry to wet seasons, except in May 26, 2006 and July 29, 2006 that showed a weak coefficient determination of R^2 (Table 5). These poor correlations between CDOM g_{440} and CHL-a indicate that phytoplankton (expressed as CHL-a) played minor role in regulating CDOM abundance in the Jakarta Bay. Our findings similar with the result of Chen *et al*., (2007) which showed that in the Tampa Bay CDOM g_{400} was not correlated with CHL-a in the dry season, but a moderate correlation was detected in the wet season, and this correlation likely resulted from a coincidence between high concentrations of nutrients (therefore CHL-a) and CDOM, rather than indicating an inherent cause-and effect relationship between CHL-a and CDOM. Nababan (2005) examined the contribution of phytoplankton to *in situ* CDOM formation by analyzing the relationship of CDOM g443 as a function of salinity and as a function of salinity and CHL-a concentration. The results showed that there were no significant increase of R^2 values between CDOM g_{443} vs salinity and vs salinity + CHL-a concentration during fall seasons for most of inshore regions of Northeastern Gulf of Mexico. This suggests that in most coastal regions there were no significant increases in CDOM associated with increase in chlorophyll, and also indicate that the main source of CDOM during fall and winter season was river inflow.

Since Jakarta Bay is influenced by moderate and small size of 13 rivers, it is expected too that high total suspended material (TSM) concentration from river discharges will effect significantly on the color signal at the visible wavelengths (Binding and Bowers, 2003). Therefore, the analysis of temporal and spatial of TSM and their influence to the CDOM in the Jakarta Bay are needed too. The same as CHL-a, TSM concentration was also not showed any significant seasonal pattern, but the concentration remarkably different between 2004 and 2006. The means of TSM concentration of 2006 was 2 to 3 times greater than in 2004. This possibly was due to very active land used development, such as land filling for reclamating areas to build houses in many locations around the coastline of Jakarta Bay. The means of individual date of TSM in 2004 and 2006 ranged between 8.2 to 45.4 mg l^{-1}, and between 113.7 to 141.1 mg l^{-1}, respectively (Table 3). Table 5 displays the determination coefficent of the relationship between CDOM g_{440} and TSM concentration, which indicate a very low values for all data set in all seasons. These poor determination coefficient values suggests that CDOM contribution from sediment and/or from sediment resuspension was also negligible. However, other studies in other coastal and estuarine waters have suggested that CDOM could be derived from bottom sediments (e.g., Boss *et al*., 2001; Burdige *et al*., 2004).

Table 5. Coefficient Determination (R^2) of the relationship between CDOM g_{440} and CHL-a, and between CDOM g_{440} and TSM concentrations.

Date and season	Chl-a (mg/m^{-3})	TSM ($mg\ l^{-1}$)
Transitional wet to dry and early dry seasons		
- Jun. 21, 2004	- <0.001	-0.015
- May 26, 2006	0.281	-0.036
- Jun. 11, 2006	0.001	0.019
- All combined data	<0.001	-0.133
Dry and transitional dry to wet seasons		
- August 24, 2004	0.026	0.026
- September 9, 2004	- < 0.001	-0.003
- July 29, 2006	- 0.242	0.003
- September 2006	0.020	0.015
- October 1, 2006	-0.021	-0.007
- All combined data	-0.044	0.003

Relationship between CDOM g_{440} and sea surface salinity

Since the sea surface salinity (SSS) has no direct color signal (Ahn *et al*., 2008; Del Castillo and Miller, 2008) then it is impossible to generate the direct relationship between SSS and satellite ocean color sensor data. However, as a consequence of its freshwater origin and conservative behavior, CDOM in a number of coastal seas and estuaries has often been observed to be strongly inversely correlated with salinity (Jerlov, 1968; Monahan and Pybus, 1978; Hu *et al*., 2004; Chen *et al*., 2007; see Table 1 in Bowers and Brett, 2008; Shank *et al*., 2009). Therefore, CDOM has been proposed as a proxy to estimate SSS using various satellite ocean color sensors as previously done by D'Sa *et al*. (2002); Hu *et al*. (2003), Binding and Bowers (2003), Nababan (2005); Ahn *et al*. (2008); Sasaki (2008). Although there are many reports indicated the strong relationship between CDOM and SSS as previously discussed above, Sasaki *et al*. (2005) reported in their observations somewhat unexpected result from Funka Bay region, Hokaido, Japan that there was no relationship between salinity and CDOM because salinity in this bay was mostly controlled by the melting ice water merging with Oyashio water, and thus, it may be less affected by river water of terrestrial origin.

In order to generate an algorithm for remote sensing of SSS for the Jakarta Bay, the next step is to identify how CDOM abundance vary with SSS. Figure 3 displays the scatter plot of CDOM g_{440} versus SSS in which shows a strong linear inverse relationship. During developing the empirical model for predicting the SSS, some data were excluded because they showed anomalies eg. high CDOM correspond to high surface salinity. The relationship beteen CDOM and surface salinity is expressed in the equation 4 as follow :

$$SSS = -67.297 * CDOM + 32.891 \quad (N = 45;\ R^2 = 0.88) \ldots\ldots 4)$$

By substituting the equation 3 into the equation 4, then it is possible to map the surface salinity of the Jakarta Bay using MODIS sensor as expressed in the equation 5 below:

$$SSS = -67.297 * \{-207.64 * X^5 + 509.85 * X^4 - 499.06 * X^3 + 243.23 * X^2 - 58.974 * X + 5.6878\} + 32.891 \ldots\ldots 5)$$

where X = Atmospheric corrected radiance of blue choromaticity = Band-3/(Band-3+band-4+Band1).

The root mean square (r.m.s.) error between observed and predicted salinity for each date varied between 0.310 psu for the lowest value (September 24, 2004) and 1.165 psu for the highest value (May 4, 2004), repectively. The overall r.m.s. error for the whole observation dates is 0.93 psu. Binding and Bowers (2003) in their work found a linear relationship between SSS and CDOM as: SSS = 35.6–11.5* CDOM g_{440} with R^2 = 0.93 and that generated the r.m.s error of 1.1 psu for the Clyde Sea, Scotland using SeaWiFS sensor. Nababan (2005) developed a global algorithm for predicting SSS in Northern

Gulf of Mexico using also SeaWiFS data. The predicting model was: SSS=36.59-29.86*CDOM g_{443} (n=8771, R2= 0.86, SSS ranged from 16 to 36 psu, the mean percentage error was 0.82%-2.92%; corresponding to ± 0.29-1.0 psu). His model is good to estimate SST in spring and fall seasons, but introduced higher bias of mean percentage errors of 0.67% to 10.33% corresponding to ± 0.24 to ±3.2 psu in predicting SSS for summer. In the ECS, however, Ahn *et al*. (2008) reported a nonlinear exponential relationship with relatively higher accuracy of ± 1 psu for estimating salinity in the ECS using SeaWiFS data, while Sasaki *et al*. (2008) developed predicting model SSS using MODIS data as: SSS= 35.3-27.3*CDOM g_{400} (n=35, R^2=0.80), for CHL-a <1.3 $mg.m^3$, but for CHL-a ≥ 1.3 $mg.m^3$ the model was: SSS= 33.9-12.2*CDOM g_{400} (n=8, R^2=0.91). Both of these models consistenly could predicted the SSS during high Changian River flow in summer seasons of 2002 to 2007 with an accuracy of about ±1.0 psu. Based on our result and cited results from others scientist in various geographical areas, it seems that detection of SSS by ocean-color satellite to be a feasible methodology for monitoring the coastal environment. A surface salinity map can be created using the equations 5, which express salinity as a function of CDOM.

Implementation to MODIS ocean color imagery

The empirical algorithm expressed in equation 5 was implemented to a series of Terra and Aqua MODIS images to create CDOM and the SSS distribution maps of the Jakarta Bay (Fig. 4). These maps are made not only used Terra and Aqua MODIS that coinsidently with *in situ* available data, but the algorithm is also applied to other images in diffrent months, especially in the wet season (January to early June) in order to get a complete pictures of the SSS in one year (2004). Based on those maps, the surface salinity of Jakarta Bay is seen to range from 24.0-33.5 psu. This range is in good agreement with the past field survey carried out in the Jakarta Bay (Ilahude, 1995; Damar, 2001; Razak and Muchtar, 2003). However, the surface salinity maps produced from Terra MODIS satellited showed a tendency of higher estimated value of 0.5 psu compared to those produced from Aqua MODIS, although the atmosperic influences have been corrected for all data using a simple method (images of May 4, June 21, August 24, September 9 and 25, 2004).

Figure 4 shows that high concentrations of CDOM and hence lower salinities are presents near to coastline, particularly concentrated in

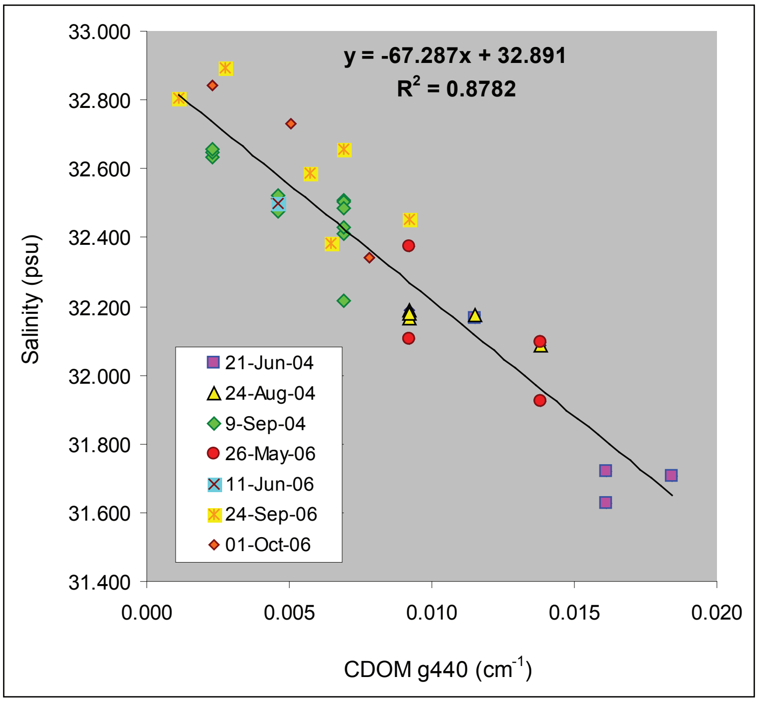

Figure 3. Relationship between CDOM g_{440} and the surface salinity of the Jakarta Bay

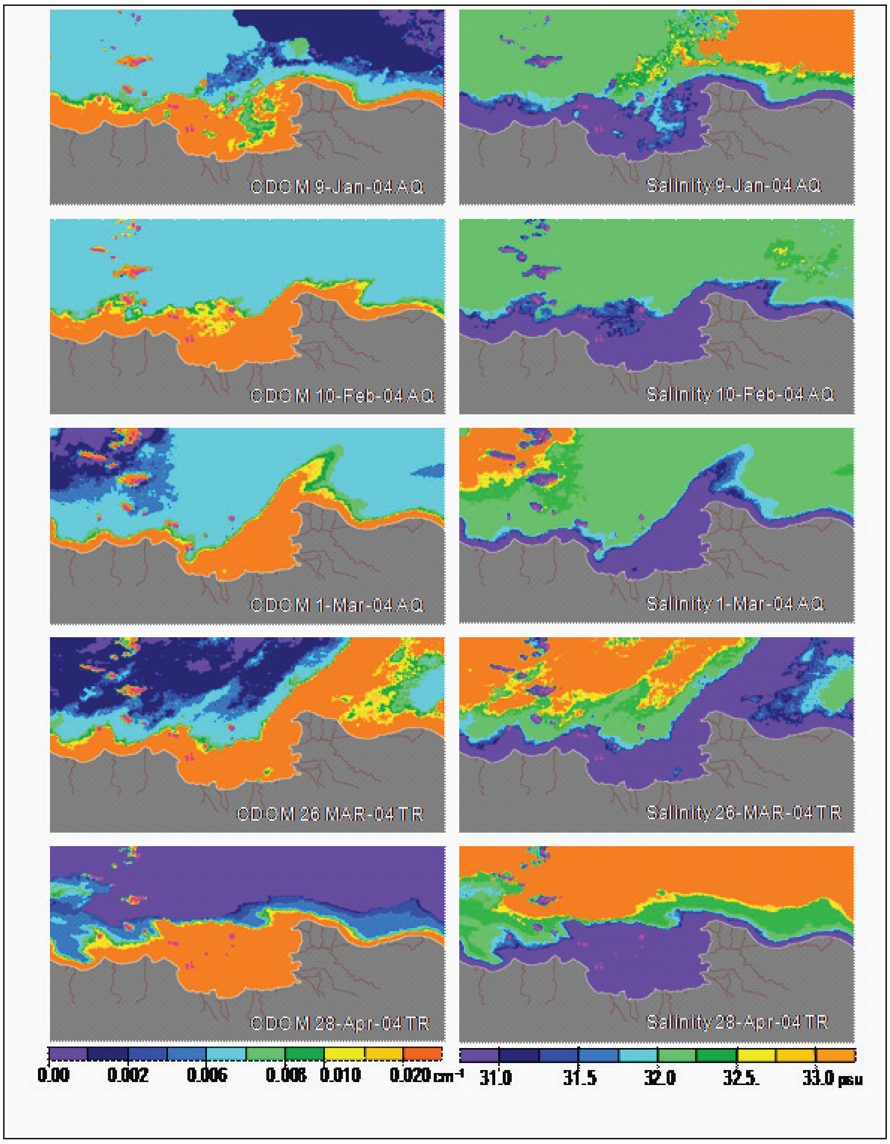

Figure 4(a). Maps of CDOM and surface salinity derived from equation 3 and 5 from January to April 2004 (Tr = Terra; Aq = Aqua satellites)

region of known freshwater runoff through river sources. Strong freshwater influences are detected on the images in the wet season on January to February, and continue to the end of transitional wet to dry season of May 4, 2004, especially around the moderate size rivers mouths, such as Cisadane River in the west part of the bay, and Citarum River in the east part (see Figure 1). The freshwater influences from the rivers decreased rapidly after June, but were still detected as a narrow line a few hundreds meter in front of the coastline until the end of dry season (August). At the beginning of transitional dry to wet season (September), the freshwater discharges from rivers almost completely disappeared in the Jakarta Bay, and all the bay was occupied by waters with higher salinity of > 32 psu. However, the plume of low salinity started to appear again on October 2004, and increased rapidly in November 2004 covering most of the bay.

The surface salinity distribution maps of Figure 4 also revealed some interesting oceanographic features. There is a higher surface salinity front of > 32 psu that migrates in and out of the Jakarta Bay seasonaly. The surface salinity fronts were found during the wet season to transitional wet to dry season (January to May), and remained there until the end of dry season (August, 2004). Entering the

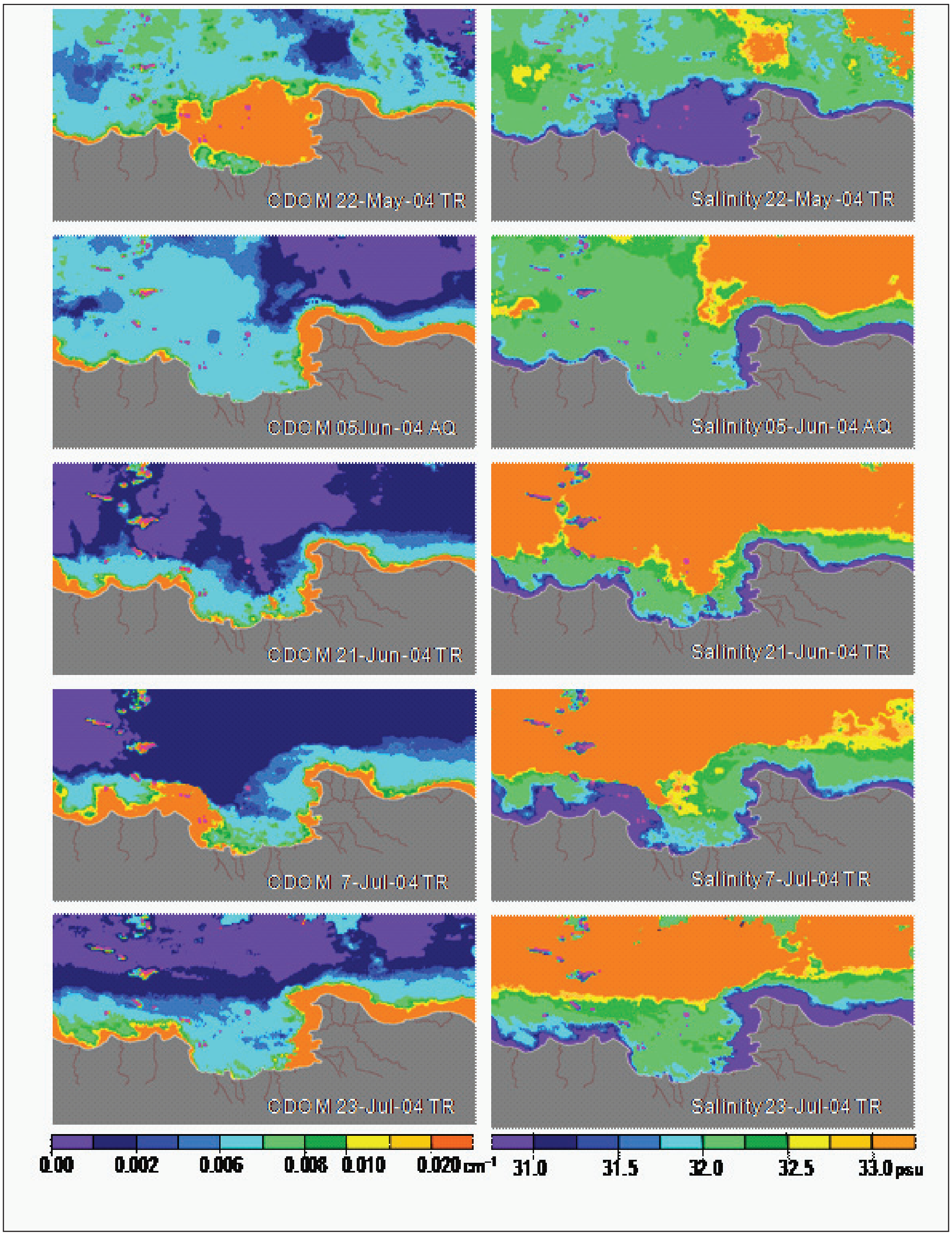

Figure 4(b). Maps of CDOM and surface salinity derived from equation 3 and 5 from May to July 2004 (Tr =Terra; Aq = Aqua satellites)

early transitional dry to wet season (September), the salinity front of >32 psu was pushed to enter the Jakarta Bay and reach close to the coastline and then disappeared again at the end of Sepetember. In this situation, all the bay waters were occupied by salinity > 32 psu until the mid of October. At the end of October, the salinity front formed again and started to move back outside of the Jakarta Bay.

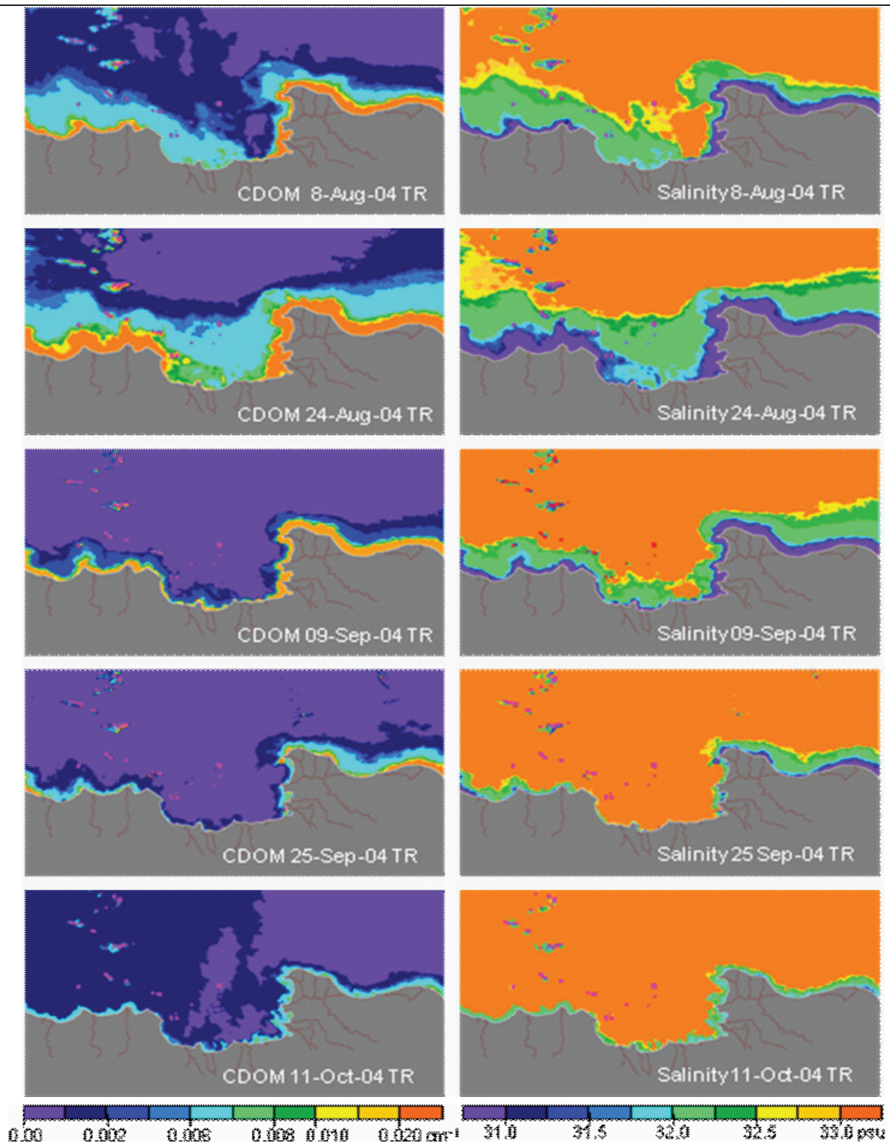

Figure 4(c). Maps of CDOM and surface salinity derived from equation 3 and 5 from August to October 2004 (Tr =Terra; Aq = Aqua satellites)

CONCLUSION

Ten surveys (5 in 2004 and 5 in 2006) have been conducted in the Jakarta Bay to investigate the temporal and spatial variability of *in situ* CDOM and sea surface salinity (SSS) and their relationship, and to explore the potential utility of multi-temporal of MODIS sensors in Terra and Aqua satellites for accurately estimating and mapping the CDOM and SSS of this bay.

The temporal variability of *in situ* CDOM g_{440} abundance is detected to be high in the early of dry season (June) then rapidly decreases in the mid dry season (July-August) to transitional dry to wet season (September-October). On the other hand, the SSS showed an inverse pattern to those of CDOM, with low values in the early dry season then gradually increased in dry to transitional dry to wet seasons. Amount of rainfall is still recorded until early dry seasons, but none after that. From this fact we could conclude that CDOM in the Jakarta Bay is mainly of terrestrial origin, so the riverine inputs are the dominant CDOM source. CDOM was shown to have a strong inverse relationship with SSS. However, there were no relationship at all between CDOM and

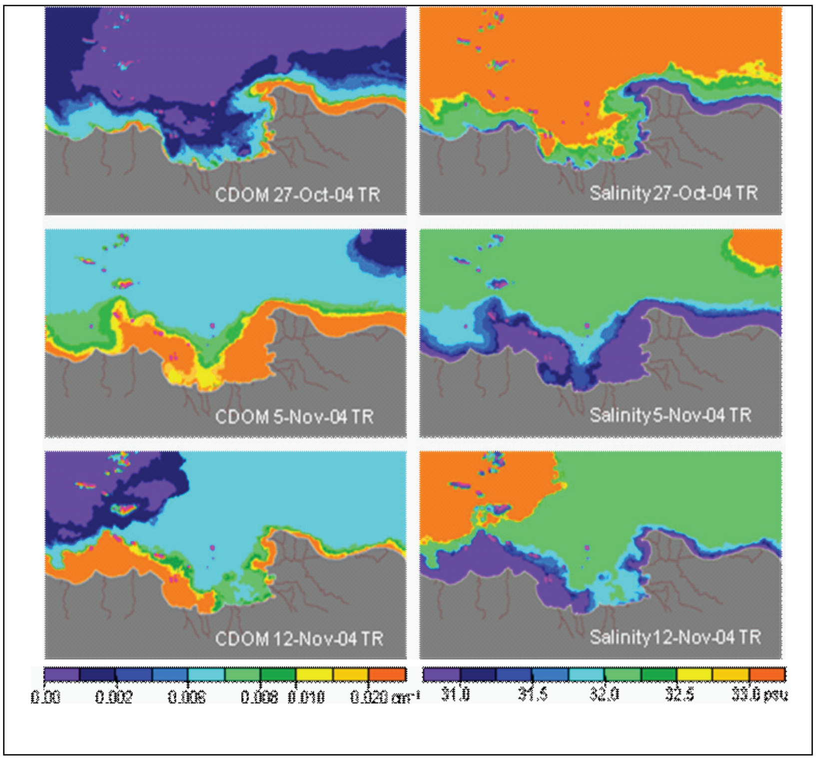

Figure 4(d). Maps of CDOM and surface salinity derived from equation 3 and 5 from October to November 2004 (Tr =Terra; Aq = Aqua satellites)

chlorophyll-a (CHL-a) concentration, and between CDOM and total suspended material (TSM). These indicate that phytoplankton (expressed as CHL-a) played minor role in regulating CDOM abundance, and also suggest that CDOM contribution from sediment and/or from sediment resuspension was also negligible. Again, these results confirm that CDOM sources are mainly from riverine inputs.

CDOM has been proposed as a proxy to estimate SSS from satellite ocean color sensors. Our result shows that CDOM g_{440} is corelated with the radiance transformation of blue chromaticity of MODIS with R^2 = 0.78 by using polynomial regression order three, but the strongest relationship results if polynomial regression order five is applied, resulting in $R^2 = 0.92$. Since CDOM can be estimated accurately enough from MODIS sensor and that there is also a good relationship between CDOM and salinity, therefore, ocean color sensor is demonstrated to be a feasible methodology for detecting, estimating, and mapping the SSS for the Jakarta Bay from space with varying degrees of accuracy, and this could be useful tool for monitoring the coastal environments. SSS map of Jakarta Bay generated using the algorithms developed in this study for the whole month in 2004 showed that SSS ranged from 24.0-33.5 psu. This range is in good agreement with the past field survey carried out in the Jakarta Bay (Ilahude, 1995; Damar, 2001; Razak and Muchtar, 2003). These maps revealed also some interesting oceanographic features. There is a higher surface salinity front of > 32 psu that migrates in and out of the Jakarta Bay seasonally. This kind of oceanographic features can not be easily detected using conventional survey such as by means of CTD cast.

The optical properties of Jakarta Bay are very complex, some other phenomenon that always occur is phytoplankton blooms in a specific month of the year, this sometimes causes massive fish kill. Phytoplankton and their biodegradation after bloom is a source of CDOM. Jakarta Bay is also under the influence of monsoon system, where in the dry season (June-August) relatively strong wind blows from east to west constantly for about 2 months, this will generate wind-induced upwelling or water turbulence that bring sediments as well as nutrients from the bottom of the bay to the surface layer via resuspension process. High concentration of sediment and nutrient that may stimulate pytoplankton blooms (Wouthuyzen, 2007) can also act as CDOM source. Therefore, more intensive sampling is required for a better understanding of the interactions between CDOM and rivers, phytoplankton and sediment.

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