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Underwater optical environment in the Upper Gulf of Thailand

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Abstract—Because the composition of coastal water is full of variety by each region, relationship between chlorophyll-*a* (chl.*a*) concentration as a indicator of primary productivity derived by satellite ocean color data and *in situ* data of chl.a may not be same always. Those relations or algorithms should be verified at each coastal water for managing coastal environment. Coastal ocean color algorithms should be built up at each coastal water or at least should be verified by wide range field data for practical application at each region. Intensive research cruises were conducted at the Upper Gulf of Thailand. Optical survey using PRR (Profiling Reflectance Radiometer) showed the character of the Upper Gulf water. Under water optical algorithms for that water were suggested by these survey data. Optical depths in the Gulf of Thailand were also measured to know the compensation depth for primary production. Although the transparency measured by Secchi disk is not so large and surface water looks very turbid, the light energies are reaching to near bottom at almost all stations of the upper Gulf. It suggests that the turbidity of this water were mainly composed of scattering material like as clay mineral rather than absorbing material like as phytoplankton pigment or CDOM.

Key words: coastal water algorithm, PAR, compensation depth, chlorophyll-*a*, CDOM, SS, satellite, remote sensing

Introduction

Ocean color science is making remarkable progress for carbon flux study which is based on primary productivity study in the ocean. CZCS (Coastal Zone Color Scanner) mounted on to NIMBUS-7 satellite was the first sensor which could detect chlorophyll pigment concentration with trustable accuracy (Gordon et al., 1980). After CZCS, many ocean color satellite sensor were lunched and providing many data. Those data are going to be used not only for the global science but also for coastal watching, fisheries information and algal bloom monitoring. Several kinds of algorithms are developed and those are practically trustable level for the oceanic water. Although several approach were done for making case 2 water algorithms, validation data were not collected so widely. Coastal water is important not only for local use but also global science because of its high primary productivity and distributed wide area of the world. The optical surveys for developing coastal ocean color algorithms in the Upper Gulf of Thailand were carried out with the other oceanographic items.

The Gulf of Thailand is located between the South China Sea and Malaysia Peninsula, and the Upper Gulf of Thailand is located in the Northern top of the Gulf. The shape is square of 100 km by 100 km (Fig. 1). Large river named Chaopraya, Maeklong and Bangpakong flow into the northern coastal area of the Upper Gulf of Thailand. The river discharge varies seasonally, from 69 ton/s in April to 1146 ton/s October at Chaopraya. River (Royal Irrigation Department, Thailand 2004), which is the largest one in the upper Gulf. Oceanographic circulation patterns of Gulf water are characterized by monsoon wind and river discharge. Seasonal variations in circulation and salinity distribution are analyzed by a numerical model (Anukul et al. 2002).

One of the purposes of this paper is making clear the seasonal variation of under water optical energy which makes an important roll for primary productivity and the other is to develop regional coastal water algorithms for estimating the concentration of Chlorophyll-*a*, CDOM (Colored Dissolved Organic Materials) and SS (Suspended Substances).

Method

Research Vessel Kasetsart I which belongs to the Faculty of Fisheries, Kasetsart University was used for marine observations. Observing stations are shown in Fig. 1. Six cruises were carried out between October 2003 and July 2005. Those cruise were coded as CU-1, CU-2, CU-3, CU-4, CU-5, and CU-6 for Oct. 2003, Dec. 2003, Jan. 2004, May 2004, Oct. 2004 and Jul. 2005, respectively. Sea surface wind data were collected from the website of PO.DAAC Ocean ESIP Tool (POET) and averaged during three days from the day before the last day to the last day of each cruise. The averaged area was between 12N–14N and 95.5E–101.5E.

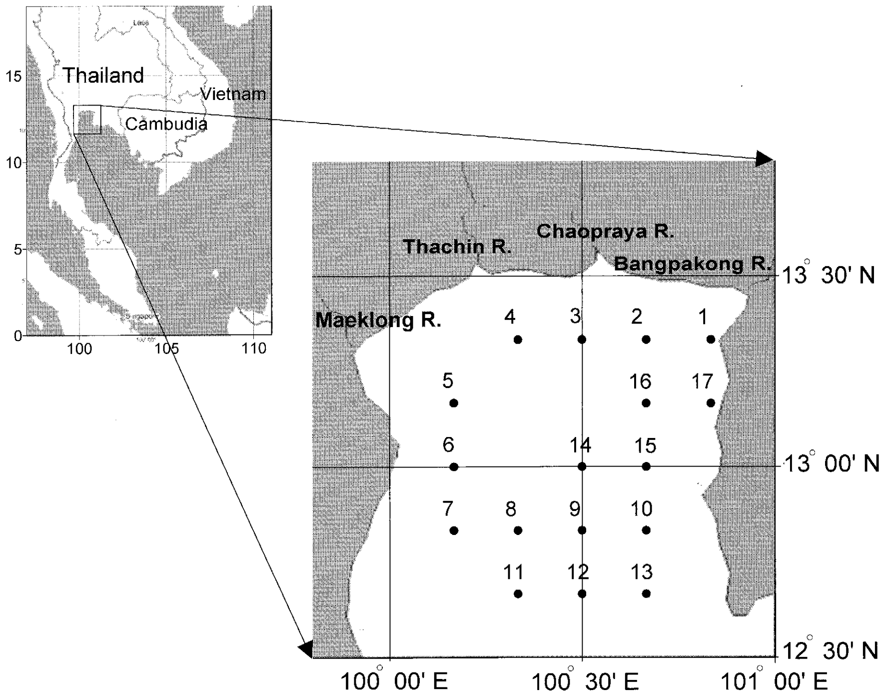

Fig. 1. The Upper Gulf of Thailand and observing stations.

Under water spectrum photometer (PRR-600) and sky spectrum photometer (PRR-610) (Biospherical Instruments Co. Ltd.) were used for measuring under water downward irradiance Ed(λ,z), upward radiance Lu(λ,z), and sky irradiance Es(λ,z). PRR has also sensors for depth, temperature and instrument tilt angle. Getting the optical data at just below the surface is practically impossible because near surface data changed by surface wave and bubble so just below the surface data Ed(0-), Lu(0-) were estimated using by near surface (1–5 m) data. Every Ed and Lu data were standardized by Es data when sky irradiance varied remarkably. Observed wave length λ were 412 nm, 443 nm, 490 nm, 510 nm, 555 nm, 670 nm, 683 nm $\mu W/cm^2/nm$) and PAR (Photosynthetic Available Radiation $\mu E/cm^2/s$). Used PRR were calibrated once in the year. Diffuse attenuation coefficient of downward irradiance Kd was calculated by measured Ed(λ,z). To get general information of oceanography, CTD, and Secchi disk depth were observed.

To cover this observation area, 3–4 days cruise were needed. Sampled waters for chemical analysis were collected by Vandorn sampler. Samples were filtered immediately after sampling and stored in freezer until measurement at laboratory. GF/F filter for Chl-*a*, Millipore filter for SS and CDOM were used respectively. Chl-*a* analyses were done by fluorescence method. CDOM concentrations were measured as light absorption coefficients A(λ)/cm between 300 nm and 700 nm using 10 cm cell on the spectrophotometer. The volumes of SS were measured by weighting of filter. Nutrients (Ammonia, Nitrite, Nitrate, Silicate, and Phosphate) were also measured using Autoanalyzer as background data.

Results and Discussion

The typical distribution patterns of coastal water and oceanic water, which comes from the main Gulf of Thailand, are shown as salinity map in Fig. 2. The average wind direction and speed was also shown with surface salinity map. Low salinity coastal water was piling up in the northwestern edge of the upper Gulf in October 2003 when SE wind blew. On the other hand, when WSW wind blew in May 2004, coastal water was piled up in the western coast of the upper Gulf. Surface chlorophyll-*a* map, SS map, and CDOM map are also shown in the figure. Those patterns show the low salinity coastal water supplied from river has high concentration of CDOM, SS and chl.*a*. The distribution patterns are slightly different each other because of different chemical and biological processes. SS may re-suspend from seabed and CDOM may be reproduced by decomposition of marine biota. Chlorophyll-*a* may be produced by using nutrients supplied from rivers and bottom layer. Transparencies were 2–5 m at coastal water and 5–9 m at oceanic water. The coastal water was easily defined by human's eye observation as turbid water. Although the coastal water has high concentration of Chl-*a*, SS and CDOM as their characters, those cross correlation was not so high. Figure 3 shows the small correlation between SS and Chl-*a* concentrations by all data of CU-1, CU-2 and CU-3 from 0 m to 5 m. Those dispersions might be occurred by the different composition of SS. There seems to be two categories in this figure. One is steep slope relation and the other is gentle slope between chl.*a* and SS. These phenomena might be occurred by the different composition

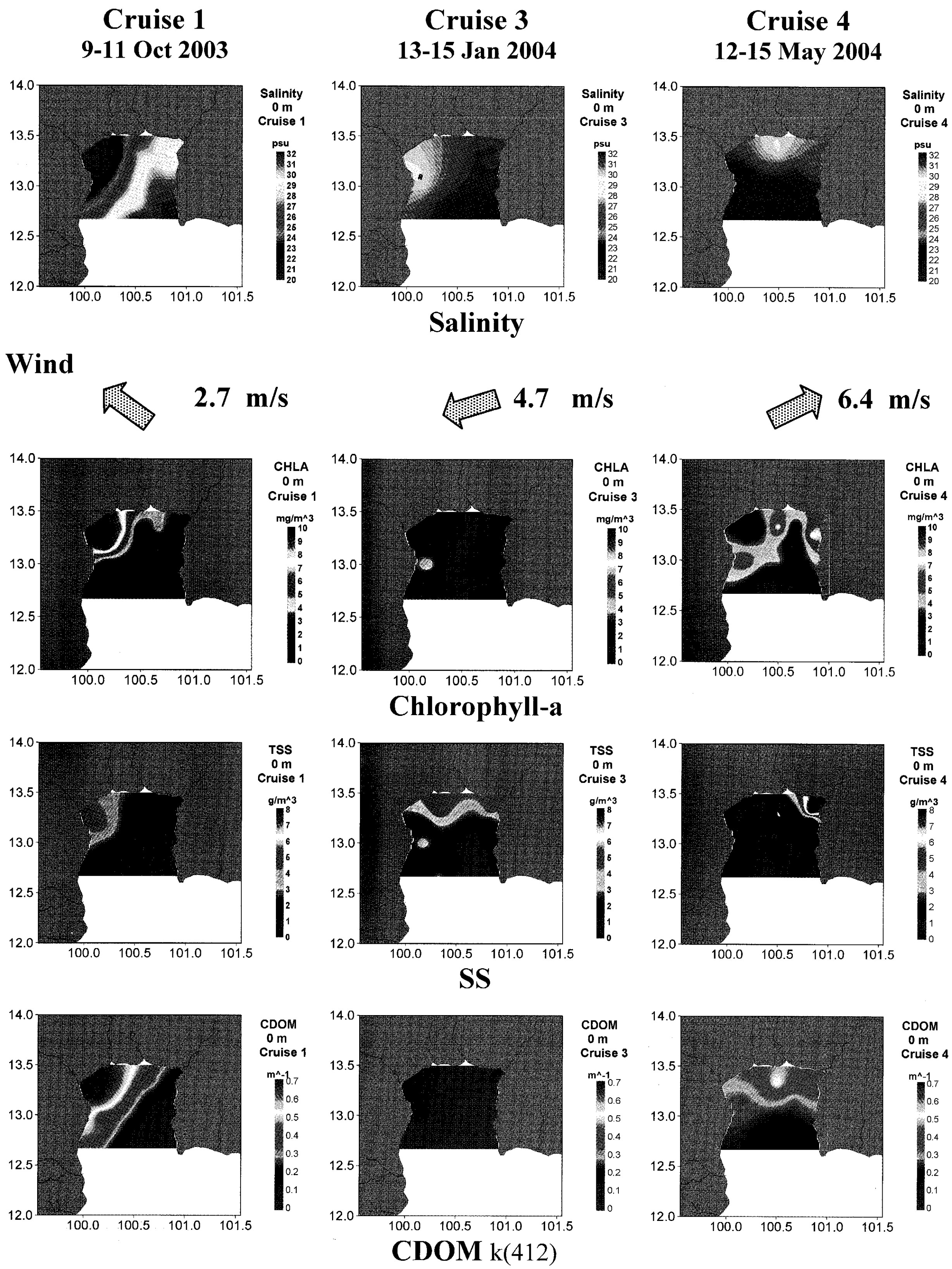

Fig. 2. Surface distributions of coastal water and wind in the Upper Gulf of Thailand.

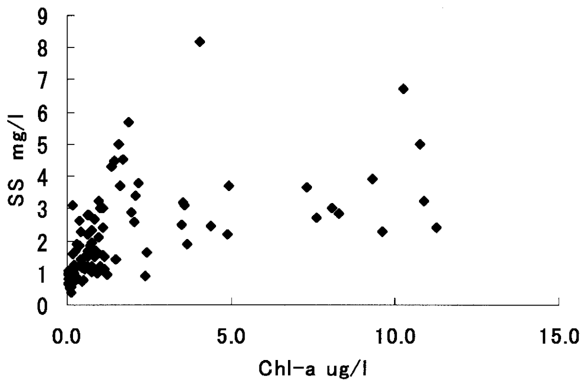

Fig. 3. Correlation between SS and Chlorophyll-*a* concentrations during CU-1, CU-2, CU-3, between surface and 5 m layer.

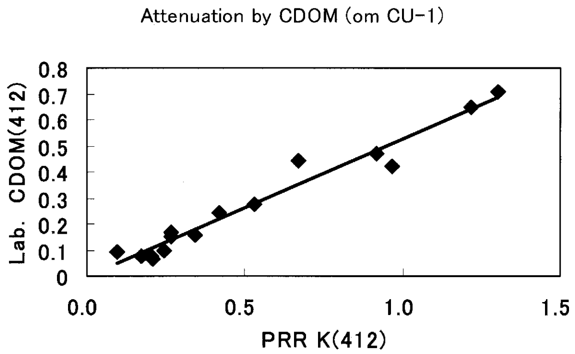

Fig. 4. Correlation between PRR measured K(412) and laboratory analyzed k(412).

ratio of phytoplankton in SS. It can be said that SS can't be the indicator of phytoplankton abundance without further discussion in the Upper Gulf of Thailand.

Downward diffuse light attenuation coefficient K at depth z is defined as

$$K(\lambda, z)=\text{Ln}(Ed(\lambda, z1)/Ed(\lambda, z2))/(z2-z1). \quad (1)$$

This K includes absorption and backward scattering. Laboratory measured CDOM which is defined by light absorption $A(\lambda)$ shows good correlation with field diffuse attenuation coefficient $K(\lambda, z)$ except river mouth (Fig. 4). The water at the river mouth must have the most complicated composition. It must be changed by season or river discharge. So, although CDOM may be estimated by field optical method, the coefficient of the algorithm may have to be determined by season and season.

Under water photosynthetic available radiance (PAR)

Light energy is one of the most important factors for under water biological activity especially for primary productivity. Photosynthetic available radiance (PAR) is the total light energy between wavelength from 400 nm to 700 nm. The unit is usually shown by μE(micro Einsteins)/cm^2/sec. Compensation depth which is balancing point of primary production and consumption is roughly defined as the depth of one percent light energy of surface (Parsons and Takahashi, 1975). The value of light energy at compensation depth is reported as 6.2–7.1 μE/cm^2/sec (Mann and Lazier, 1991). As a simple estimate of compensation depth, tow times of transparency measured by Secchi disk is often used. Coastal water of the upper Gulf contains high concentrations of SS, CDOM and plankton pigment as shown in Fig. 2. SS works as light scattering material. In case where particle (clay mineral for example) is very small as compatible with wavelength, forward scattering light energy is much higher than backward scattering. It means that in spite of turbidity appearance main part of light energy goes downward. On the other hand, in case where CDOM and phytoplankton pigments work as light absorbing material, those materials will avoid light penetration to downward. Observation from sea surface by human's eye is feeling back scattered light. Secchi disk observation is also comparing reflected light by disk and backscattering light from water. So turbidity observation from surface gave us sometimes miss understanding about under water light estimation. In the upper Gulf of Thailand, very turbid waters are often observed by surface observation. However optical measurements show the enough strong PAR existence at under water. Figure 5 shows under water PAR distribution. The bar graph shows vertical distribution of relative PAR by percent to the sea surface PAR. PAR was decreasing to 50% near the surface because longer wavelengths light were immediately absorbed by water molecular in the surface layer. 50–10% of light energy was remained in the middle layer and more than 1% of it reached to near bottom at many stations. White bar in this figure shows Secchi disk depth and it's two times depth. PAR is penetrating deeper than the two times Secchi depth. Sta. 2a, 2b at CU-5 is both side of coastal front. Sta. 2a is coastal water side of the front and the transparency was 4 m. It was looked obviously turbid water. Sta. 2b was oceanic side water and the transparency was 8.5 m. It was clear water. However, 10% depths of surface PAR were not so much different, that is, 8 m and 12 m, respectively. Higher than 1% of surface PAR were existing near the bottom (14 m) at both stations.

Observed maximum sea surface PAR was higher than 2000 μE/cm^2/sec in May 2004 cruise. It means that 1% PAR depth has still enough light energy for primary production. Primary productivity measurements were not done in these cruises. We should verify by field experiment of primary productivity on the next step.

In water algorithms on the Upper Gulf of Thailand

Although Satellite Ocean Color data providers like as NASA or JAXA are preparing several algorithms for estimating Chl-*a*, CDOM, SS etc., there were almost no field validation data in the South Eastern Asian waters. Kendall et al. (2003) developed case 2 water algorithms for MODIS using

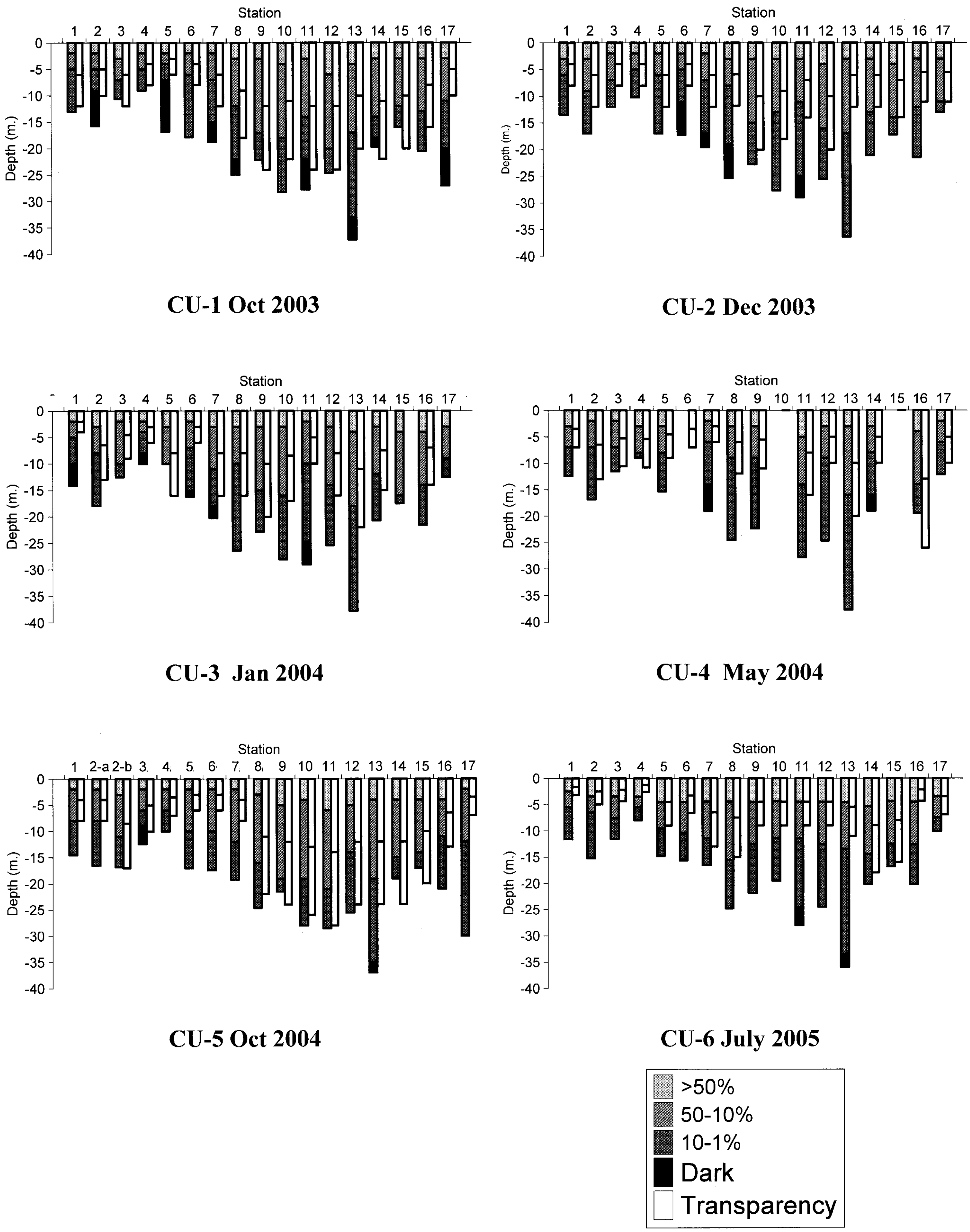

Fig. 5. Vertical distribution of PAR at each cruise. Gray scale bar shows % to the surface PAR. Dark means less than 1%. White bar shows Secchi disk depth and two times of it.

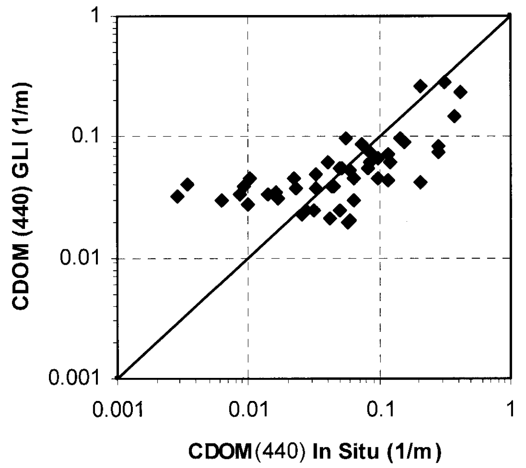

Fig. 6. Validation of ADEOS-2 GLI CDOM algorithms. CDOM(440)GLI was PRR calculated value using by GLI algorithm, In Situ means laboratory analyzed data by sampled water.

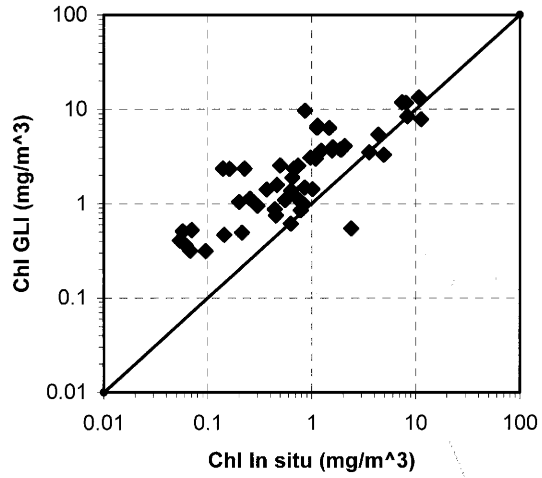

Fig. 7. Validation of ADEOS-2 GLI Chl-*a* algolithms, Chl GLI was PRR calculated value using by GLI algorithm, Chl-in situ were measured by fluorescence method in laboratory.

field data from US and European coastal water. JAXA is also showing several GLI algorithms for detecting those items by website (JAXA 2004). Field validation is essential to use satellite data for regional purpose because the compositions of sea water are different and optical character related to those composition also different by regions. To know the real figure of the Gulf, several kinds of algorithms are discussed with field data and finally new algorithms were suggested.

Remote sensing reflectance Rrs at depth z is defined as

$$\mathrm{Rrs}(\lambda, z) = \mathrm{Lu}(\lambda, z)/\mathrm{Ed}(\lambda, z). \qquad (2)$$

Rrs(λ, 0-) was used for discussion of under water optical algorithms in this paper. Atmospheric correction algorithms were not discussed but only under water process in this work. (0-) means just below the surface. Rrs(λ, 0-) and the several kind of ratio of Rrs(λn, 0-) and Rrs(λm, 0-) were statistically analyzed. As some examples, Fig. 6, Fig.7, and Fig. 8 show the comparison of *in situ* CDOM, Chl-*a*, SS and derived value from GLI algorithms. GLI algorithms value were calculated by PRR data of this work. Very roughly saying, both tendencies are similar, however the error were out of sufficient. The best fit correlations were suggested to estimate those items.

CDOM

CDOM concentration is defined by light absorption coefficient per meter because chemical definitions are so complicated. Although 412 nm band is useful than longer wave length for determine CDOM, GLI algorithms suggesting to use 440 nm. PRR data were used to estimate CDOM by GLI algorithms and compared by field samples. Figure 6 shows those correlation. After the several trials, one best fitting algorithms for CDOM k(412) was suggested. It is named Chula-algorithms as shown in Fig. 8.

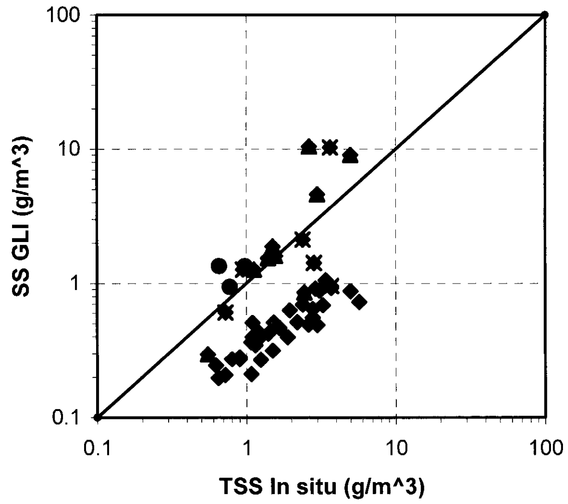

Fig. 8. Validation of ADEOS-2 GLI SS algorithms, SSGLI was PRR calculated value using by GLI algorithm, TSS include both of organic SS and inorganic SS.

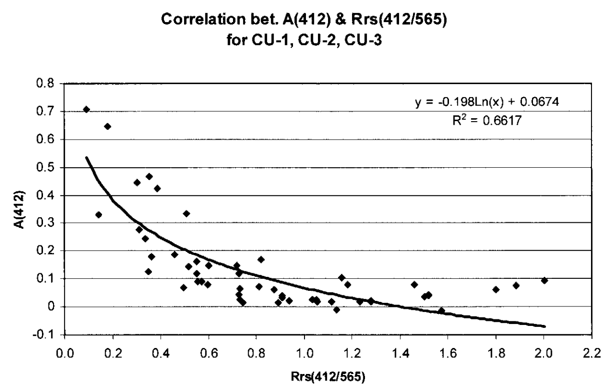

Fig. 9. Correlation between laboratory measured absorption coefficient A(412) and field measured Rrs(412, 0-)/Rrs(565, 0-).

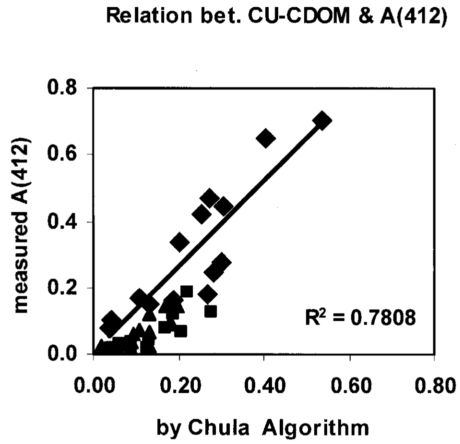

Fig. 10. Validation of Chula-algorithm for CDOM A(412)

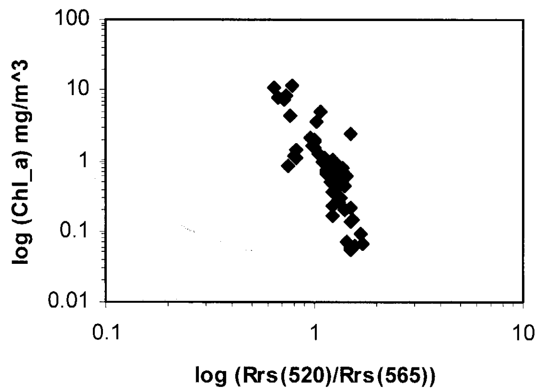

Fig. 11. Correlation between Rrs(520, 0-)/Rrs(565, 0-) and measured Chlorophyll-*a* concentrations.

$$\text{CDOM k(412)} = -0.1981\,\text{Ln(R)} + 0.067, \qquad (3)$$

$$\text{R} = \text{Rrs(412, 0-)/Rrs(565, 0-)}. \qquad (4)$$

Validation of Chula-algorithms for CDOM is shown in Fig. 10.

Chlorophyll-*a*

Chlorophyll-*a* pigment has a maximum light absorbing band around 443 nm and minimum around 565 nm So, the ratio of Rrs(443)/Rrs(565) is usually effective for detecting Chl-*a* on oceanic clear water. However, in case 2 water, the band is so sensitive to measure high concentration and effected high CDOM. Using 520 nm band was chosen as the lowest noise band for coastal water Chl-a survey. Using the ratio of Rrs(520)/Rrs(565) Chula-algorithms for Chl-*a* was suggested as follows.

$$\text{Chl-}a\ (\mu\text{g/l}) = 181.4\exp(-4.74\text{R}), \qquad (5)$$

$$\text{R} = \text{Rrs((520)/Rrs(565))}. \qquad (6)$$

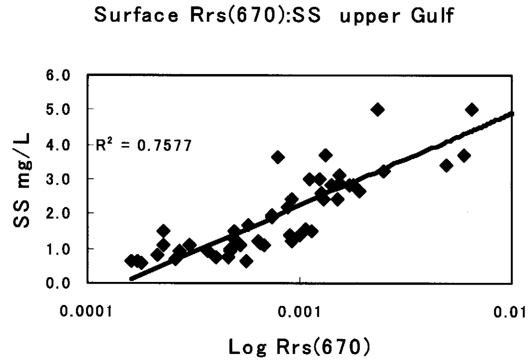

Fig. 12. Correlation between Rrs(670) and SS (mg/l).

SS

As mentioned before, SS in coastal water includes various substances. Some of them work as scattering substances and another as absorbing. For total SS measurement in coastal water, using 670 nm band is suggested. This band has not been used for observation for standard references because of high absorbing by surface water. However, incase there are high density SS, 670 nm light has enough reflected light for detecting SS concentrations. Figure 12 shows the result. Total SS is estimated following the Chula-algorithms as follows.

$$\text{Total SS (mg/l)} = 1.16\,\text{Ln(Rrs(670,0-))} + 10.23. \qquad (7)$$

Summary

General oceanographic patterns in the Upper Gulf of Thailand were shown by field surveys. Although monsoon wind and river discharge affected the coastal water, the coastal water was always piling up in the north or northwestern coast. Relatively clear oceanic water was supplied from the southeast of the Gulf mouth. Enough Light energy for biological activity was approaching to near the bottom.

Gulf of Thailand color algorithms are suggested for estimating CDOM, Chl-*a* and total SS concentrations. Using these basic data, primary productivity algorithms should be developed in the near future.

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