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Ocean Color Monitoring of Coastal Environments in the Asian Waters

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Satellite remote sensing technology for ocean observation has evolved considerably in these last twenty years. Ocean color is one of the most important parameters of ocean satellite measurements. This paper describes a remote sensing of ocean color data project - Asian I-Lac Project; it also introduces several case studies using satellite images in the Asian waters. The Asian waters are related to about 30 Asian countries, representing about 60% of the world population. The project aims at generating long-term time series images (planned for 10 years from 1996 to 2006) by combining several ocean color satellite data, i.e., ADEOS-I OCTS and SeaWiFS, and some other sensors. Some typical parameters that could be measured include Chlorophyll-*a* (Chl-*a*), Colored Dissolved Organic Matter (CDOM), and Suspended Material (SSM). Reprocessed OCTS images display spatial variation of Chl-*a*, CDOM, and SSM in the Asian waters; a short term variability of phytoplankton blooms was observed in the Gulf of Oman in November 1996 by analyzing OCTS and NOAA sea surface temperature (SST); Chl-*a* concentrations derived from OCTS and SeaWiFS have also been evaluated in coastal areas of the Taiwan Strait, the Gulf of Thailand, the northeast Arabian Sea, and the Japan Sea. The data system provides scientists with capability of testing or developing ocean color algorithms, and transferring images for their research. We have also analyzed availability of OCTS images. The results demonstrate the potential of long-term time series of satellite ocean color data for research in marine biology, and ocean studies. The case studies show multiple applications of satellite images on monitoring of coastal environments in the Asian Waters.

Key words: Ocean color image, Remote sensing, Chl-a, Colored dissolved organic matter (CDOM), Suspended material (SSM), Asian I-Lac Project, Asian waters

INTRODUCTION

The Asian waters are related to about 30 Asian countries, representing about 60% of the world population (Fig. 1). Recent rapid industrialization in Asia has placed very heavy burdens on the coastal environment of the Asian waters. Although there are serious needs of appropriate observation systems for the Asian waters, it is still difficult to monitor these international waters by traditional *in situ* methods. This contribution is aimed at presenting a satellite remote sensing project that combines several satellites data and covers the whole Asian waters.

Over the last twenty years, satellite remote sensing technology for ocean observations has undergone considerable progresses. At the beginning of the eighties, only AVHRR on board of NOAA satellites was available for measuring sea surface temperatures, and a small number of oceanographers became aware of potentialities of the other satellite methods, i.e., the altimeter for geostrophic currents, the microwave scatterometer for surface wind vector, and the ocean color for marine biological parameters, even though the first satellite measurements were delivered by SEASAT and NIMBUS-7 (Tang *et al.*, 1998, 1999; Yoder, 1993). In these last twenty years, satellite remote sensing technology for ocean observation has evolved considerably. Now a greater number of satellite oceanographic sensors are orbiting, and some others will be launched later.

Among the several existing ocean remote sensing methods, ocean color measurements provide us infor-

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mation on the organic and inorganic suspended materials in the surface layer. Chlorophyll-*a* (Chl-*a*), Colored Dissolved Organic Matter (CDOM), and Suspended Material (SSM) are the most important parameters of satellite ocean color measurements; they have been shown to play important roles in ecological and photochemical processes. Impacts of human activities are transferred from land to ocean mainly through rivers and coastal boundaries, which change the ocean color either directly by advection and diffusion, or indirectly by biological and chemical processes. The ocean color sensors have narrow bands in the visible and near-infrared, and provide a discrete spectrum of target water color. Therefore, to investigate the oceanic environment, the ocean color remote sensing is a key technology. It is well recognized that Chl-a concentration can be very well retrieved in clear open oceans from the satellite ocean color measurements, but there are still some technical problems for its retrieval in turbid coastal waters (IOCCG, 2000).

OCEAN COLOR DATA AND ASIAN I-LAC PROJECT

ADEOS-I carrying OCTS was launched in August 1996. OCTS observed both ocean color and sea surface temperature (SST) from October 1996 to June 1997. It provided a valuable 10 months record of 700m spatial resolution data set for oceanographic research (Kawamura and the OCTS team, 1998, Tang and Kawamura, 2000). SeaWiFS was launched in August 1997 aboard the OrbView 2/Sea Star satellite, which is currently providing useful global observations of ocean color. Recently, several new ocean-color sensors have been launched by various countries, all providing excellent coverage of the Asian waters. The Indian OCM, the Korean OSMI, the Taiwanese OCI, NASA's MODIS, MERIS on ENVISAT (ESA EU) are now in space (IOCCG, 1998). Some other new ocean color sensors, such as GLI on ADEOS-II (NASDA Japan), and MODIS on AQUA (NASA US) will also be launched in the near future.

The Asian I-Lac project was designed on the basis of the OCST I-Lac project (Kawamura and the OCTS team, 1998). It has been designed: (i) to establish a long-term series of ocean color images by combining several ocean color satellite data; (ii) to reprocess ADEOS-I OCTS ocean color data with improved algorithms; and (iii) to set up 1-km spatial resolution ocean color database for the Asian waters (Fig. 1).

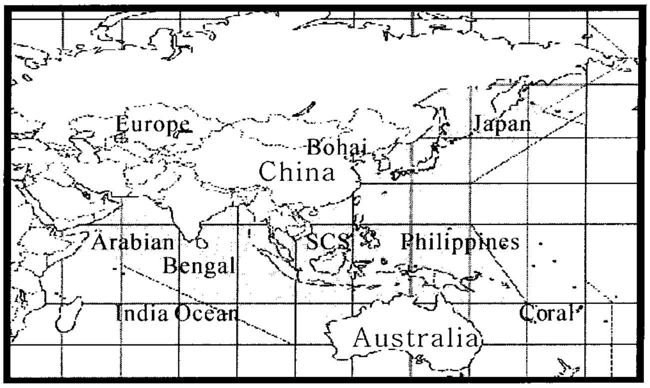


Fig. 1. Aerial coverage of Asian I-Lac region, showing 10 sub-regions.

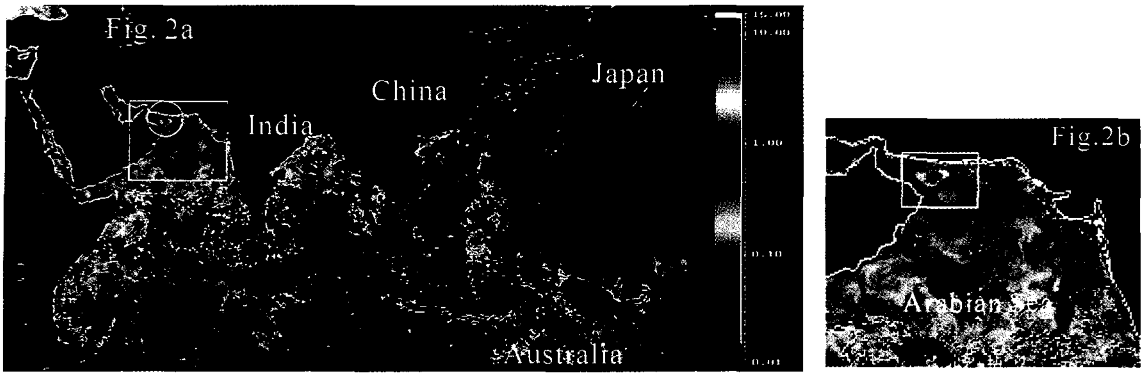
The new ocean color data processing system is now established at the Center for Atmospheric and Oceanic Studies of the Tohoku University in Japan. New algorithms with in-water correction and atmospheric correction are currently under development. Other parameters that are considered include nLws, Chl-a, and K490. An OCTS image browsing system is developed to provide users with the capability of browsing images, selecting data, and transferring images for their research.

RESULTS AND DISCUSSION

Spatial Distribution of Chl-a, CDOM, and SS in the Asian Waters

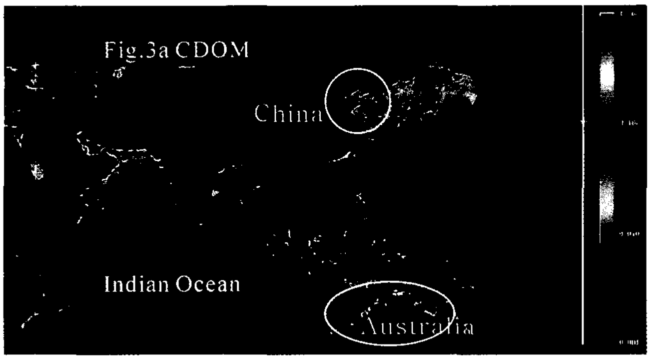
We processed OCTS-derived Chl-*a*, CDOM, and SSM for the Asian waters, and then made monthly composites for the period from November 1996 to June 1997. OCTS Chl-*a* images were processed through SEADAS (Baith *et al.*, 2001) (MSL 1), adopting the in-water algorithm developed by Kishino *et al.* (1998). Fig. 2a illustrates the distribution of Chl-a concentrations in November 1996. This monthly composite image shows a good spatial coverage for the Asian waters. The coastal lines are shown in white color; lands and clouds are in black color. Chlorophyll concentrations were high in the north coastal area of the South China Sea, north coastal areas of the Bay of Bengal, and in the whole northern Arabian Sea, particularly in the mouth of the Gulf of Oman.

Distribution patterns of CDOM and SSM in the Asian waters were also analyzed. Monthly composite images for March 1997 indicate high CDOM and SSM in the Bohai and the coastal area of Australia

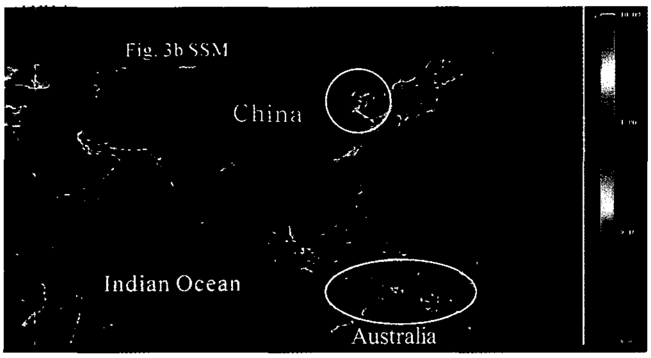


(a) (b)

Fig. 2. (a) Monthly composite OCTS image (Chl-*a*) for November 1996, (b) High Chl-*a* in the Gulf of Oman in Nov 1996.



(a)



(b)

Fig. 3. (a) Monthly composite OCTS-derived CDOM in April, (b) Monthly composite OCTS-derived suspended material (SSM) in April 1997 on the Asian waters.

(Fig. 3a & b). High Chl-a concentrations are related to primary productivity and biomass in the water (Sathyendranath, *et al.*, 1991); CDOM, sometimes called "yellow substances", "gelbstoff", or also "colored, dissolved organic matter", absorbs harmful ultraviolet radiation in an efficient way; it can function as an energy absorption medium during the production of hydrogen peroxide (Moore *et al.*, 1993), and a carbon source for production of inorganic carbon species (Miller and Zepp, 1995). For most regions of the world, the color of ocean is determined primarily by the abundance of phytoplankton and its associated photosynthetic pigments. As the concentration of phytoplankton pigments increases, ocean color shifts from blue to green. The Asian I-Lac project provides comparative studies among Chl-*a*, CDOM and SSM on the Asian waters.

Phytoplankton Blooms and eddies in the Gulf of Oman

The northern Arabian Sea is a semi-enclosed sea. Despite observations made during the International Indian Ocean Expedition (IIOE) in 1990, lager regions of the northern Arabian Sea, including the Persian Gulf and the Gulf of Oman, have remained unknown or only poorly known (Qasim, 1982; Shetye *et al.*, 1994).

While processing OCTS images for the Asian waters, we noticed intensive phytoplankton blooms with high Chl-a values (>6 mg m^{-3}) in the northern Arabian Sea (Fig. 2b) in November 1996. The blooms had a round shape of 100 km in diameter in the Gulf of Oman (60.5°E, 24.°N) (A in Fig. 4a), looking like an anticyclonic eddy feature, and was accompanied by another cyclonic eddy feature of lower chlorophyll values (B in Fig. 4a) in the southwest (61.5°E, 22.5°N). Sea surface temperature (SST) at the same time is shown in Fig. 4b, an AVHRR SST image. It indicates that there was a pair of a cyclonic and an anticyclone eddies around the loca-

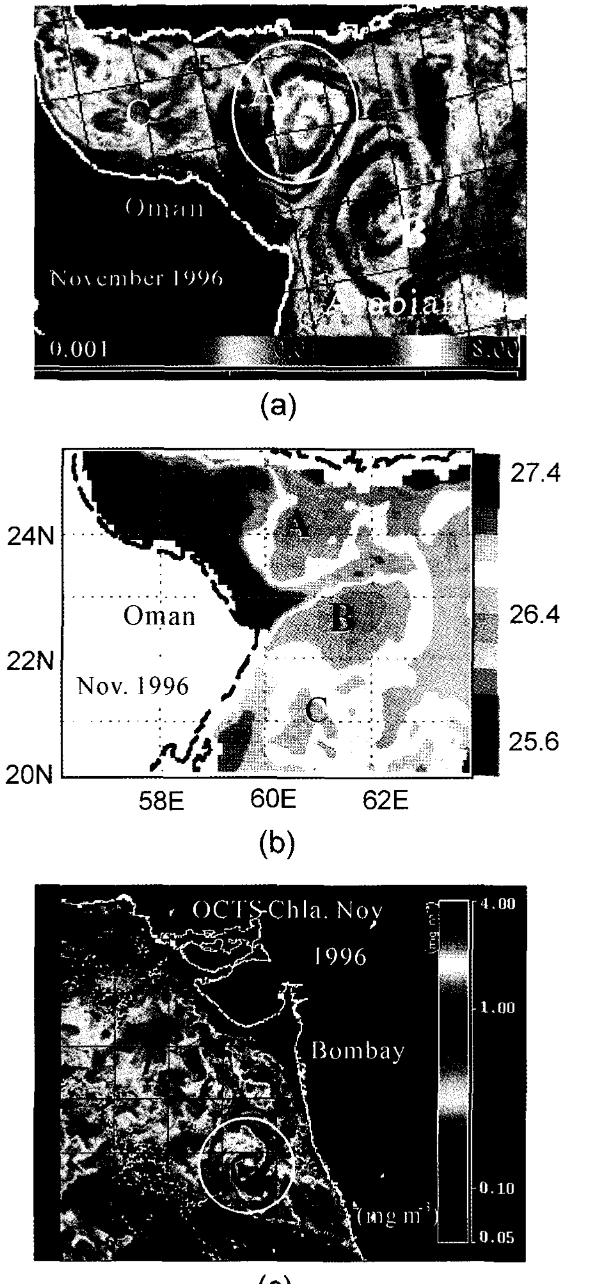


Fig. 4. (a) OCTS-derived Chl-a image in the Gulf of Oman in November 1996. Color bar indicates Chl-a concentration (mg m^{-3}), (b) AVHRR SST image in the Gulf of Oman in November 1996. Color bar indicates SST (°C), (c) OCTS-derived Chl-*a* in the Arabian Sea. Color bar indicates Chl-*a* concentration.

tions of blooming event. We were able to process a series of OCTS images that provided a continuous monitoring of the bloom. AVHRR SST indicated that the bloom was associated with a cold SST eddy. The pair of cyclonic and anticyclonenic eddies can be considered to be influenced by the wind stress associated with the winter monsoon (Tang *et al.*, 2002).

With 700 m spatial resolutions, some other eddies features can also be observed (C in Fig. 4a & b) in the Gulf of Oman and in the coastal area of Bombay (Fig. 4c).

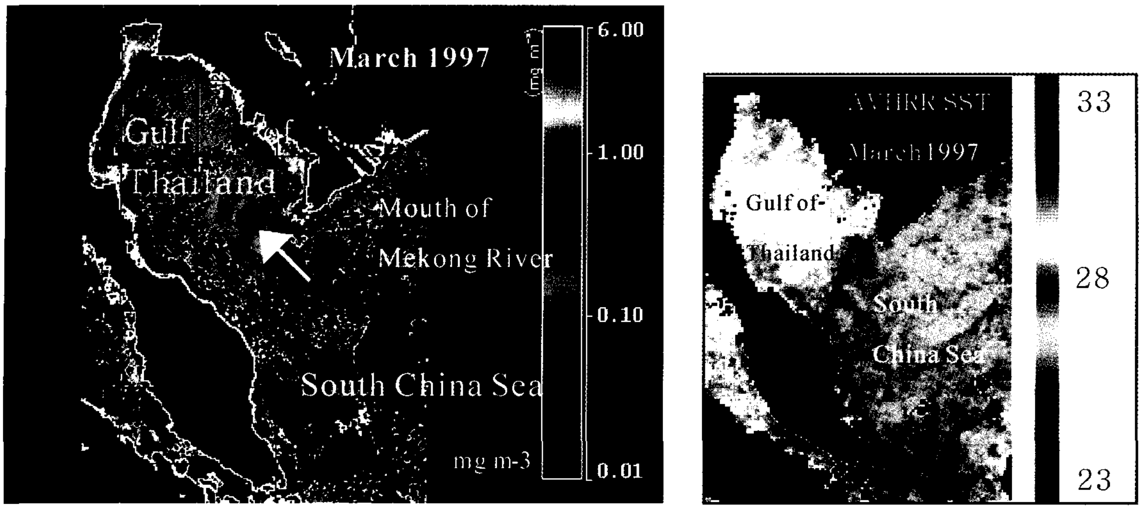
This is the first observation of phytoplankton blooms coinciding with a cold SST eddy in the Gulf of Oman by satellite images, featuring short-term variability. This study further demonstrates the potential of using satellite ocean color and SST images to monitor short-term variability of phytoplankton distributions, and to detect the interaction between phytoplankton blooms and other dynamical oceanic features (Tang *et al.*, 2002).

Monthly Variations of Chl-a and SST in the Gulf of Thailand

The Gulf of Thailand is a semi-enclosed sea connecting with west part of the South China Sea (SCS). It is a major and rapidly developing commercial fishing site, where climate is controlled by the seasonal monsoon winds. We analyzed monthly variation of Chl-*a* and AVHRR SST in the Gulf of Thailand, and the nearby SCS waters. OCTS derived Chl-*a* and other oceanography data were examined for the period from November 1996 to October 1997.

Fig. 5a is an example of OCTS-derived Chl-a images for March 1997 in the Gulf of Thailand and the nearby South China Sea. High Chl-a appeared in the mouth of the Gulf of Thailand (arrow in Fig. 5a). SST image derived from AVHRR is shown in Fig. 5b. More data show monthly variation of Chl-a and SST in the area, and different patterns of Chl-a and SST between the Gulf of Thailand and the SCS. Over a period of one year, Chl-*a* concentrations were higher in November-January than in March-June, particularly in the coastal areas. In the whole area, Chl-a concentrations were also higher in the Gulf of Thailand (0.6 mg m^{-3}) than in the SCS (0.3 mg m^{-3}), particularly in December-January. High Chl-*a* (2 mg m^{-3}) plumes occurred in the mouths of the Mekong and in the mouth of the Gulf of Thailand in November-March. There was an annual SST circle in this area.

These results indicate that the monthly and spatial variations of Chl-*a* are related to monsoon and oceanic condition in this area; Nutrient from river discharges and vertical mixing is a very important factor influencing monthly variation of Chl-*a* distribution.



(a) (b)

Fig. 5. (a) OCTS-derived Chl-a of March 1997 in The Gulf of Thailand and the nearby South China Sea, (b) AVHRR SST image in March 1997 in the Gulf of Thailand. Color bar shows SST (°C).

Availability of OCTS images

For a better analysis of OCTS images availability, we split the whole Asian waters area into 10 super-regions (Fig. 1). These are the Arabian Sea, Bay of Bengal, Indian Ocean, South China Sea (SCS), Philippines Sea, Bohai, Japan waters, Australia waters, Coral Sea and European waters. European waters include the Red Sea, Mediterranean Sea, Black Sea, and Caspian Sea. We then categorized each scene according to its quality into one of five groups designated A (for the best quality) to E (for the worst quality). Factors that were taken into account for this quality judgment included the presence of clouds.

OCTS image coverage and data quality were analyzed for the period of November 1996 to June 1997. Each scene was categorized, according to its quality into one of five groups designated A (for the best quality) to E (for the worst quality). Spatial variation of OCTS images availability for 10 sub-regions (in Fig. 1) is shown in Fig. 6a, and temporal (monthly) variation of OCTS scenes is shown in Fig. 6b. The availability of OCTS images varied from area to area (Fig. 6a), and also varied from month to month (Fig. 6b). There are more images of A-level (best quality, more than 95% coverage) in the Arabian Sea and Bay of Bengal than in the Philippines Sea; there are also more images of E-level (0–25% coverage) in the Australia waters and Philippines waters than in the Arabian Sea. The availability of OCTS images

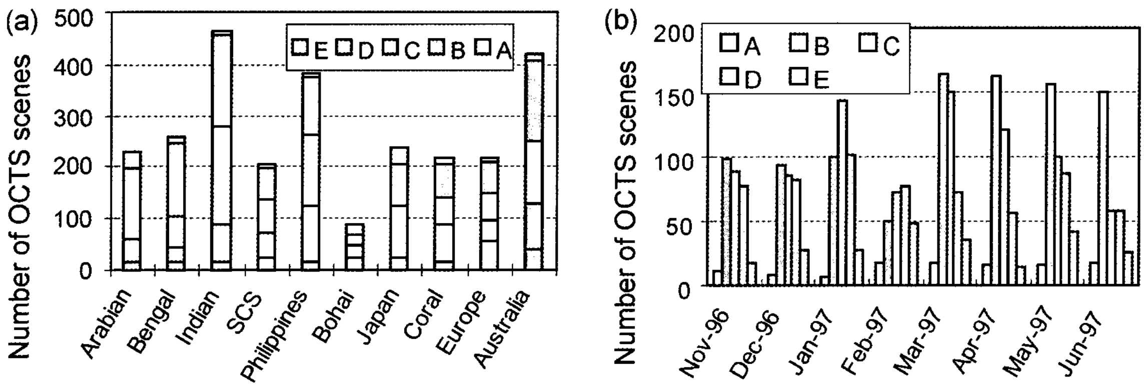


Fig. 6. (a) Spatial variation of OCTS images number (A for the best quality to E for the worst quality) for 10 sub-regions, (b) Temporal variation of OCTD image number (A for the best quality to E for the worst quality) in the Asian waters during November 1996 to June 1997.

is good for the Arabian Sea and the Bay of Bengal, particularly in November and December 1996, which may be attributed to the monsoon season in the Arabian Sea. The image quality for Australia waters is not as good as that of Indian Ocean. Good OCTS images can be observed on the Japanese waters in April 1997. The total number of images for each month increased from November 1996 to March 1997, and then decreased slightly. The percentage of good images (A and B level) increased from March 1997 on (Fig. 6b).

SUMMARY

The Asian I-lac Project is generating a long-term time series of ocean color images with 1-km spatial resolution in the Asian waters. The data system provides ocean color scientists with capability of testing or developing their own algorithm. The spatial distribution patters of Chl-*a*, CDOM and SSM varied from time to time in the Asian waters. In the winter season, Chl-a concentrations were high in the north of Arabian Sea, and along the coasts of China and Australia. Intensive phytoplankton blooms and eddies were observed in the Gulf of Oman in the north of Arabian Sea. OCTS-derived Chl-*a* images are also useful to study monthly variations of Chl-*a* in the Gulf of Thailand and the nearby South China Sea. The availability of OCTS images varied from area to area, and also varied from month to month. OCTS image coverage is good for the northern Arabian Sea during the winter season. The results demonstrate the potential of the wide-ranging ocean color data with 700 m spatial resolution in research on marine biology, environment, and development of ocean color algorithms.

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