MONITORING THE BAY OF BENGAL AS A BALLAST WATER EXCHANGEABLE SEA USING MODIS/AQUA

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ABSTRACT: The study describes the monitoring of the Bay of Bengal as a ballast water exchangeable sea using MODIS/Aqua-derived diffuse attenuation coefficient (K(490)) synchronized with in situ ballast water sampling and analysis along the LNG carrier's route between Japan and Qatar from 2002 to 2005. Based on the relationship between K(490) and corresponding in situ plankton cell densities, the Bay of Bengal is recognized as a ballast water exchangeable sea to meet the regulation of ballast water performance standard of International Maritime Organization (IMO). Furthermore the Bay of Bengal with more than 200m depth and more than 200 nautical mile distance from shore is extracted based on the regulation of ballast water exchange area of IMO. However, an anomalously high K(490) area is found off the coast of Sri Lanka during the northeast monsoon in 2005, which corresponds higher cell densities than the criterion set by the regulation of IMO. The phenomenon of high cell density in the Bay of Bengal seems to be related with the phytoplankton bloom during the northeast monsoon. Seasonal and annual variability of phytoplankton bloom will be investigated to establish an early routing system for avoiding the high cell density area in advance.

KEY WORDS: The Bay of Bengal, Ballast Water Exchangeable Sea, Diffuse Attenuation Coefficient, Phytoplankton Bloom

1. INTRODUCTION

The Bay of Bengal (BoB) is a semi-enclosed coastal sea in the Indian Ocean and hosts a unique system of inter-related oceanographic, biological and sedimentary processes induced by the seasonally reversing monsoon winds and the enormous-but highly variable-supply of freshwater and sediments from Ganges and Brahmaputra and several peninsular Indian rivers (Ittekkot et al., 2003). As far as the biological processes are concerned, BoB is traditionally considered to have low chlorophyll-a concentration ($<0.1 mgm^{-3}$) thus low phytoplankton counts (Madhupratap, et al., 2003). This is one of the reasons why the BoB has been selected as a suitable ballast water exchangeable sea when it is compared with the other coastal sea such as the Arabian Sea (Kozai et al., 2006a). However an anomalously high K(490) area was found off the coast of Sri Lanka during the northeast monsoon in 2005, which corresponds higher cell densities than the criterion set by the regulation of IMO (Kozai et al., 2006b). The phenomenon of high cell density in the Bay of Bengal seems to be related with the phytoplankton bloom during the northeast monsoon (Vinayachandran and Mathew, 2003). The purpose of the study is to investigate the seasonal and annual variability of phytoplankton bloom for establishing an early routing system to avoid the high cell density area in advance.

2. DATA AND METHOD

The ballast water exchange has been recognized as an operational countermeasure to cope with the invasion of non-indigenous species through the ballast water. IMO has adopted the international regulations on ballast water in February, 2004 (IMO, 2004). According to the regulations on the ballast water exchange area (Regulation B-4), the ballast water exchange should be conducted more than 200 nautical miles from the nearest land and in water more than 200 meters in depth described in Table 1. Furthermore the IMO regulation on ballast water performance standard (Regulation D-2) states that ships conducting ballast water management shall discharge less than 10 organisms per cubic meter greater than or equal to 50 μm in minimum dimension and less than 10 organisms per milliliter less than 50 μm and greater than or equal to 10 μm in minimum dimension shown in Table 2.

2.1 Sampling and analysis of ballast water

The ballast water sampling onboard ZEKREET, the LNG carrier of 110000 gross tons have been conducted during the six voyages between Japan and Qatar from April 2002 to February 2005. Tables 3 and 4 show the major specifications of ZEKREET and her six voyages for ballast water sampling, respectively. According to the ship's

record the loading of ballast water was carried out at Chita, Yokkaichi and Sakai, Japan and the exchanges of ballast water were conducted at BoB. The sampling method is described in detail in Kozai et al (2006a). Sampled ballast water was classified for phytoplankton, zooplankton and others and identified in terms of species. Then the number of cell was counted for each species and the cell density was calculated as follows,

Cell density (cells/ml) = Number of plankton cell/ observed volume of sampled water (ml) (1)

Table 1. Ballast water exchange area (Regulation B-4)

Area	Depth	Note
(1) >200 nautical miles offshore	>200m	
(2) >50 nautical miles offshore	>200m	Only if item (1) is unable to conduct.

Table 2. Ballast water performance standard (Regulation D-2)

Size(minimum dimension, d) Criterion		Note
d≧50μm	<10 organisms/m^3	Zooplankton
50μm>d≧10μm	<10 organisms/ml	Phytoplankton

Table 3. Major specifications of LNG carrier ZEKREET

Gross tonnage	110000 tons
Total tank capacity	137000m^3
Ballast water tank capacity	54952m^3
Ballast water exchange	Sequential method

Table 4. Voyage of LNG carrier ZEKREET for ballast water sampling

Source port	Destination port	Period
Chita, Japan	Ras Laffan, Qatar	8/26 – 9/11, 2002
Chita, Japan	Ras Laffan, Qatar	11/28–12/13,2002
Yokkaichi, Japan	Ras Laffan, Qatar	1/31 – 2/15, 2003
Chita, Japan	Ras Laffan, Qatar	4/6 – 4/22, 2003
Yokkaichi, Japan	Ras Laffan, Qatar	7/14 – 7/30, 2003
Sakai, Japan	Ras Laffan, Qatar	1/16 – 2/1, 2005

2.2 MODIS/Aqua image analysis

MODIS (Moderate Resolution Imaging Spectro-Radiometer) onboard Aqua spacecraft launched on May, 2002 by NASA is one of the six sensors dedicated to provide data about land, ocean and atmospheric processes. Diffuse attenuation coefficient for downwelling irradiance at 490nm (K(490)) was chosen among the numerous MODIS- derived products because it represents the total organic and inorganic particles of ballast water including not only phytoplankton and zooplankton but also sediment and others. K(490) is defined as follows (Mueller, 2000).

$$K(490)=0.016+0.15645*X^{-1.5401}$$
where $X=L_{wn}(490)/L_{wn}(555)$ (2)

$L_{wn}(490)$, $L_{wn}(555)$ are normalized water-leaving radiances at 490 and 555nm, respectively. In order to extract the ballast water exchangeable seas from MODIS images IMO's regulation B-4 on the ballast water exchange area (Table 1) is applied to all K(490) products by using ETOPO2, global 2 minutes elevation database published by National Geophysical Data Center (2001).

Based on the match-ups between SeaWiFS-derived K(490) and cell density along the ship' route, Kozai et al (2006a) derived the regression equation with high degree of accuracy as follows,

$$\text{Cell density (cells/ml)}=0.97e^{9.8xK(490)} \quad (3)$$

Since the SeaWiFS and MODIS-derived K(490) products share the same definition expressed as (2) above, it is assumed that the relationship between SeaWiFS-derived K(490) and cell density expressed by (3) above should be applicable to the one between MODIS-derived K(490) and cell density.

3. RESULTS AND DISCUSSION

Fig.1 shows the distribution of the observed mean cell density of loaded ballast water and corresponding MODIS/Aqua-derived K(490) based on the cruise period. According to the results of ballast water analysis,

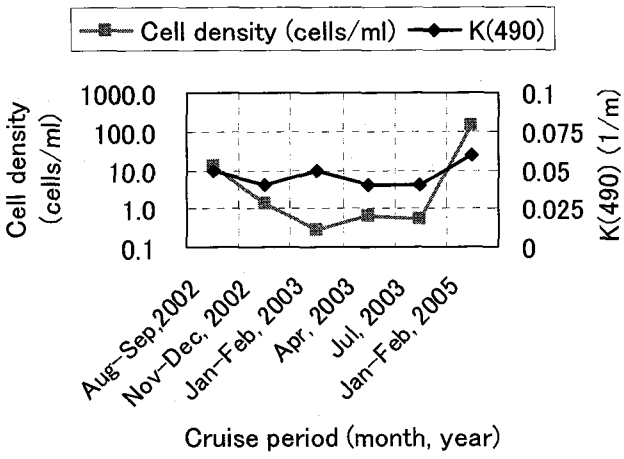

Fig.1 Distribution of the cell density of loaded ballast water and corresponding K(490) based on the cruise period.

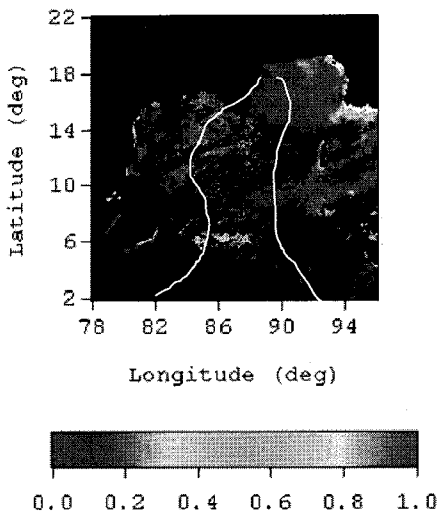

Fig.2 Chlorophyll-a concentration in the Bay of Bengal. (Jan.26, 2005, 07:30 (UT)) (White lines show the 200 nautical miles offshore.)

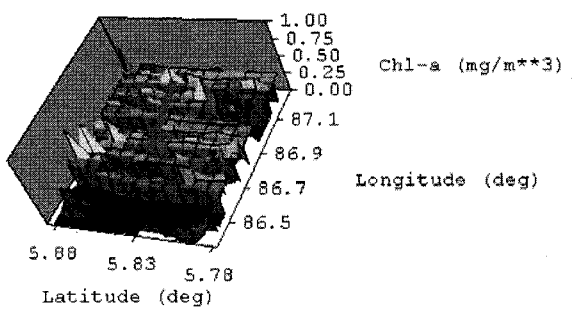

Fig.3 Distribution of chlorophyll-a concentration at the time of ballast water loading. (Red arrow indicates the ship track. Black area represents cloud cover.)

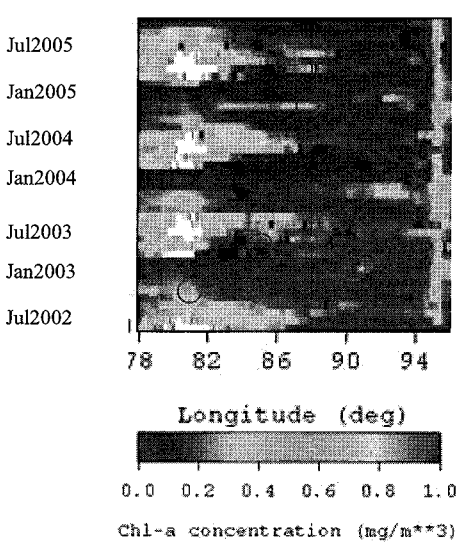

Fig.4 Longitude-time (Hovmoller) diagram of chlorophyll -a concentration based on the monthly mean. (Red circles denote the location and date of ballast water loading.)

the phytoplankton dominates in the most voyages in comparison with zooplankton and others. Furthermore, cell densities are found to be lower than 10 cells/ml which corresponds to the criterion of the ballast water performance standard (Table 2). However, during the voyage of Jan-Feb 2005 high cell density more than 100 cells/ml is recorded. The dominant species was identified as *Pseudo-nitzschia spp.* High cell density may correspond to the high K(490). But the K(490) value of 0.06 (1/m) is not as high as the estimated K(490) of 0.24 which corresponds to 10 cells/ml based on the equation (3) above. The discrepancy between high cell density and low K(490) may be attributable to the phytoplankton bloom at the time and location of ballast water loading on January 26th, 2005 in the Bay of Bengal. According to Vinayachandran and Mathew (2003), chlorophyll-a concentration more than 0.5 mg/m^3 is defined as the phytoplankton bloom. Fig.2 shows the distribution of chlorophyll-a concentration derived from MODIS/Aqua with 200 nautical miles lines from shore. Within the image high concentration area more than 0.3 mg/m^3 is found at 86 degrees East and 6 degrees North. Fig.3 illustrates the enlarged three dimensional distribution of high chlorophyll-a concentration mentioned above. Red arrow within the Figure shows the ship track. Though the mean chlorophyll-a concentration is around 0.3 mg/m^3, areas of high concentration more than 0.5 mg/m^3 are found close to the ship track, which may increase the cell density of loaded ballast water. Fig.4 shows the longitude-time (Hovmoller) diagram of chlorophyll-a concentration based on the monthly mean of 9km spatial resolution with the location and date of ballast water loading as red circles. The concentration between 5 to 6 degrees North is averaged. The major characteristics of chlorophyll-a variability is twofold. One is clear annual maximum more than 1mg/m^3 appeared from June to August in the western half of BoB and annual minimum appeared from December to February. The other is the presence of relatively high concentration during the period from December to February in the central and eastern part of BoB. As far as the Jan-Feb 2005 cruise is concerned, it is found that the location and date of red circle corresponds to the concentration of 0.3 mg/m^3, which is not as high as the ones in every July and at the western half of BoB. Therefore it seems to be safe for ballast water loading during the Jan-Feb 2005 cruise based on this diagram. However it is cautioned that the diagram is based on the monthly mean of 9km spatial resolution. And the concentration between 5 to 6 degrees North is averaged so that it is suspected the maximum concentrations more than 0.5 mg/m^3 corresponding to the phytoplankton bloom at the instantaneous MODIS/Aqua products are suppressed.

4. CONCLUSIONS

The conclusions based on the results and discussion above are summarized as follows.

(1) Clear annual maximums of chlorophyll-a concentration more than 1mg/m^3 are appeared from June to August in the western half of BoB and annual minimums are appeared from December to February.

(2) Relatively high chlorophyll-a concentrations during the period from December to February are seen in the central and eastern part of BoB.
(3) Areas of high concentration more than 0.5 mg/m^3 are found close to the ship track during the 2005 cruise, which may increase the cell density of loaded ballast water.

The discrepancy between high cell density and corresponding low K(490) may be attributable to the phytoplankton bloom, but not resolved yet. Since the sampling depth of loaded ballast water is usually ranging from 9 to 12 meters, it should be questioned how deep the MODIS/Aqua-derived chlorophyll-a concentrations are represented. Taking the relationship between K(490) and transparency into consideration, future works will include the evaluation of depth-integrated chlorophyll-a concentration for BoB which is defined as chlorophyll-a concentration divided by K(490) (Campbell et al., 1995).

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