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Seasonal and spring interannual variations in satellite-observed chlorophyll-*a* in the Yellow and East China Seas: New datasets with reduced interference from high concentration of resuspended sediment

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ABSTRACT

Seasonal and spring interannual variations in chlorophyll-*a* (Chl) and total suspended matter (TSM) in the Yellow and East China Seas through a 10-year period were examined by using new datasets from Yellow Sea Large Marine Ecosystem Ocean Color Project (YOC) algorithms. YOC SCHL calculations are based on a combination of the SeaWiFS standard algorithm and a local empirical algorithm for areas of low and high normalized water-leaving radiance 555 nm, respectively. YOC SCHL was lower than the standard SCHL in areas with high concentrations of resuspended sediment, especially along the Chinese and Korean coasts and around the Changjiang Bank from fall to spring. YOC SCHL was high in areas of low TSM in the middle of the Yellow Sea, and offshore of the Changjiang Bank in April, indicating the occurrence of spring blooms. In these areas, TSM was dominated by phytoplankton cells and phytoplankton-related organic particles. Offshore from the Changjiang River mouth and around the Changjiang Bank, YOC SCHL and TSM in March were low and high, respectively, with maximum YOC SCHL values occurring around the Changjiang Bank in May. Spring bloom started with decrease in resuspended sediment concentrations in these areas. During summer, YOC SCHL values were high and TSM concentrations were low; TSM was dominated by organic particles related to phytoplankton activity when Changjiang River diluted water moved from the river mouth to east of the bank. YOC SCHL in spring offshore from the Changjiang River mouth increased significantly during the 10 years, and correspond to an increase in red tide events. In the middle of the Yellow Sea, maximum YOC SCHL in spring increased gradually and significantly during the 10 years. Many of the spatial and temporal variations in YOC SCHL were consistent with a range of earlier *in situ* descriptions. Our results indicate that the satellite ocean data with proper algorithms is a powerful tool to analyze phytoplankton dynamics in moderate-high suspended sediment area.

1. Introduction

The Yellow and East China Seas (hereafter, YECS) are marginal seas surrounded by Japan, China, and Korea. The YECS is connected to the South China Sea, Pacific Ocean, and Sea of Japan by the Taiwan Strait, the strait between Taiwan and the Ryukyu Islands, and the Tsushima Strait, respectively. Most of the YECS consists of shallow continental shelf (<200 m) (Fig. 1). The Changjiang River, one of the world's largest rivers, supplies large amounts of fresh water and sediment to the YECS, especially during summer.

From fall to early spring, turbidity is high in shallow areas of the YECS (<50 m), resulting from strong northeast monsoon activity that causes vertical mixing of the water column and sediment resuspension from the bottom (Xie et al., 2002). The resuspended sediment may dominate total suspended matter (TSM) in this area, although organic particulate matter related to biological activity, such as phytoplankton production, is likely not negligible in some cases.

Phytoplankton is the base of the marine food chain, and chlorophyll-*a* (Chl) is an index of the amount of phytoplankton. Growth of phytoplankton requires nutrients and a favorable light environment for photosynthesis. In coastal area, suspended

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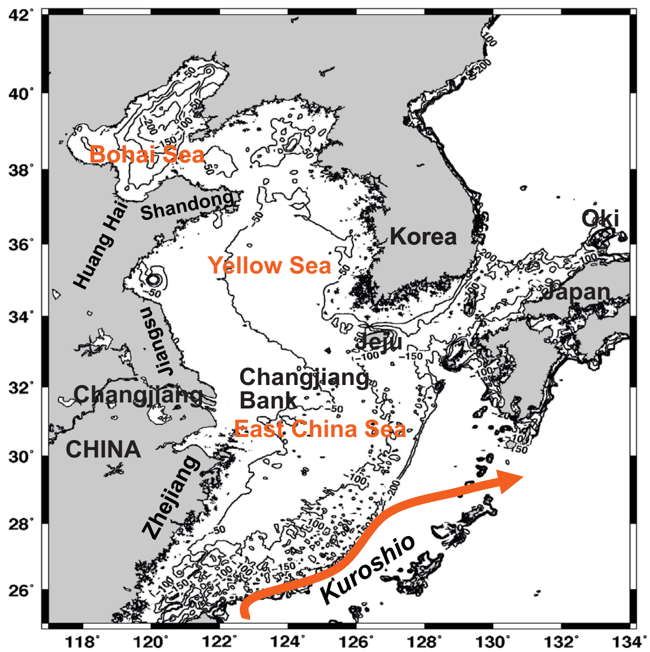

Fig. 1. Map of the study area with bathymetry.

sediment is often one of the major factors for controlling phytoplankton, and it is important to understand the relationship to phytoplankton dynamics (Cloern, 1996).

Ocean color satellite imagery is useful for understanding spatial and temporal variations in Chl. Kim et al. (2009) examined the standard ocean-color product of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and found that the distribution of standard satellite Chl (SCHL) in summer corresponded to Changjiang River Diluted Water (CDW) in the East China Sea. Yamaguchi et al. (2012) also demonstrated that the movement of the summer maximum of standard SeaWiFS SCHL from the Changjiang River mouth to farther offshore corresponded with the extent of CDW.

Spring blooms are important events in the seasonal variation of Chl in temperate coastal ecosystems and are likely also important in the YECS. It has long been hypothesized that initiation of phytoplankton blooms is related to the relationship between the critical depth and the mixed layer depth (Sverdrup, 1953), and it is suggested that it is also important in turbid coastal water (Fichez et al., 1992). Yamaguchi et al. (2012) detected the presence of a spring bloom by using maximum values of standard SCHL and low values of normalized water-leaving radiance (nLw) at 555 nm (nLw555) as an index of suspended sediment. However, variation in the spring bloom throughout the whole YECS was difficult to determine by standard SCHL, which is likely distorted by high concentrations of resuspended sediment in Chinese and Korean coastal areas and around the Changjiang Bank from late fall to early spring.

On longer time scales, Chl may change interannually owing to climate oscillation, climate change, and anthropogenic environmental changes. Increases in red tide events and massive outbreaks of giant jellyfish have recently occurred in the YECS, and eutrophication is suspected as a possible cause (e.g., Kawahara et al., 2006; Siswanto et al., 2008; Zhou et al., 2008). These events suggest that the environment in the YECS may be changing. Yamaguchi et al. (2012) demonstrated that interannual variation in summer standard SCHL is controlled by interannual variation in the Changjiang River discharge into the East China Sea. They also showed that summer standard SCHL has been gradually increasing in the Yellow Sea, where the influence of the variation of discharge was not high. However, both the seasonal SCHL variation and the interannual variation in spring standard SCHL over the whole YECS area are difficult to determine because of interference caused by resuspended sediments.

It is difficult to use ocean color remote sensing for observing Chl in high suspended sediment area because there is no good atmospheric correction algorithm due to accuracy of the aerosol and bio-optical models (Jamet et al., 2011). Siswanto et al. (2011) recently developed new empirical local algorithms for the YECS by using YOC *in situ* Chl and satellite optical data. They optimized the Tassan Chl algorithm for high nLw555 waters. The locally tuned Tassan Chl algorithm is less influenced by high nLw due to suspended sediment than the standard SeaWiFS Chl algorithm (Siswanto et al., 2011). The locally tuned Tassan Chl algorithm is applied to SeaWiFS nLw data processed using standard (case 1) atmospheric correction. Siswanto et al. (2011) recommend combinations of the standard and YOC SCHL algorithms under low and high nLw555 conditions (2 mW cm^{-2} μm^{-1} sr^{-1}), respectively. They also developed an empirical TSM algorithm for this region. However, they demonstrated performance only by fitting the output to *in situ* data and did not explore spatial and temporal variations in the calculated SCHL and TSM.

The objective of our study was to describe spatial and temporal variations in SeaWiFS-based YOC SCHL and TSM using a method that reduces overestimation of SCHL in waters with high resuspended sediment concentrations. In addition, we compared our results with previous field observations to demonstrate consistency. Here, we describe seasonal variations in YOC SCHL and TSM for comparison with standard SCHL estimates. We then describe interannual variations in springtime YOC SCHL and TSM, and the consistency between our estimates and field observations. The ratio of YOC SCHL to TSM was used to estimate the abundances in TSM of resuspended sediment and organic particles derived from phytoplankton.

2. Material and methods

Daily nLw of 412, 443, 490, 555, and 670 nm data from NASA SeaWiFS (Reprocessing 5.1 version) Level 2 Global Area Coverage (GAC) during January 1998 and December 2007 were used to calculate remote-sensing reflectance (R_{rs}). The data had a spatial resolution of 4 km. The OC4v4 algorithm was used to calculate standard SCHL (O'Reilly et al., 2000). For the new local algorithm (YOC SCHL; Siswanto et al., 2011), we used a Tassan-like algorithm and an OC4v4 algorithm for high (>2.5 mW cm^{-2} μm^{-1} sr^{-1}) and low (<1.5 mW cm^{-2} μm^{-1} sr^{-1}) ranges of nLw555, respectively. The Tassan (1994)-like SCHL algorithm is based on computation of three component optical models, which are absorption and backscatter of Chl, TSM and colored dissolved organic matter, referring to Prieur and Sathyendranath (1981).

The algorithm is as follows

$$\mathrm{SCHL} = 10^{\left(-0.166-2.158\ \log_{10}(R)+9.345\ \log_{10}^{2}(R)\right)},$$

where

$$R = \left(\frac{R_{rs_{443}}}{R_{rs_{555}}}\right)\left(\frac{R_{rs_{412}}}{R_{rs_{490}}}\right)^{-0.463}$$

The first term is sensitive to Chl because $R_{rs_{443}}$ and $R_{rs_{555}}$ are close to the Chl absorption maximum and minimum, respectively. The second term consists of $R_{rs_{412}}$ and $R_{rs_{490}}$, shorter and longer wavelength of the Chl absorption maximum, respectively. This is the compensating term, which is the low dependence on Chl and high dependence on absorption of suspended sediments and colored dissolved organic matter (Fig. 1 of Tassan, 1994). Siswanto et al. (2011) suggested that