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Seasonal and summer interannual variations of SeaWiFS chlorophyll *a* in the Yellow Sea and East China Sea

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ABSTRACT

Seasonal variability in satellite chlorophyll *a* concentrations (SCHL) in the Yellow Sea and the East China Sea (YECS) was investigated using 10-year averages of monthly data collected between September 1997 and October 2006. Interannual variations were also assessed to help clarify the influence of Changjiang River discharge (CRD) during summer. The YECS was represented by 12 areas each with different seasonal variability in SCHL. SCHL were overestimated during winter due to re-suspension of sediment near the Changjiang Bank and near coastal areas. Increases of SCHL were observed over large areas of the YECS during spring, as would be expected with the occurrence of spring blooms. The spatial distribution of the summer maximum of SCHL shifted from the Changjiang River mouth to just east of Jeju Island from July to September. An eastward shift of the high SCHL water coincided with the movement of the Changjiang diluted water (CDW), taking approximately 2 months to move from Changjiang River mouth to Jeju Island. Summer SCHL between 1998 and 2006 in this region were positively correlated with CRD with a time lag of 0–2 months, suggesting that the interannual variation of SCHL was controlled by the interannual variation of CRD. SCHL during summer in the Yellow Sea gradually increased over the 10 years, indicating possible eutrophication.

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1. Introduction

The Yellow Sea and East China Sea (YECS) are marginal seas surrounded by Kyushu and the Ryukyu Islands of Japan, Taiwan Island, mainland China, and the Korean Peninsula. They are connected to the South China Sea, Pacific Ocean, and the Sea of Japan by the Taiwan Strait, by the strait between Taiwan and the Ryukyu Islands, and by the Tsushima Strait, respectively. Most of the YECS consists of shallow continental shelf (<200 m) (Fig. 1).

Numerous rivers flow into the YECS from mainland China, including the Changjiang River, which accounts for 90% of the discharge to the YECS. Freshwater discharge from the Changjiang River forms the Changjiang diluted water (CDW) in the East China Sea which mixes with the surrounding high salinity waters (Su and Weang, 1994). Numerical simulations by Chang and Isobe (2003) indicated that during summer when the southerly monsoon predominates, CDW extends offshore and moves northeastward near Jeju Island to the Tsushima Strait, and about 70% of the Changjiang River discharge (CRD) flows through the Tsushima Strait.

The summer CRD supplies large amounts of nutrients to the East China Sea, and an increase of chlorophyll *a* (chl-*a*), an index of primary production, is expected in the CDW (Ning et al., 1998; Gong et al., 2003). Siswanto et al. (2008) suggested that the increase in dissolved inorganic nitrogen (DIN) in the middle of the East China Sea from 1971 to 2001 was caused by increases in both CRD and nitrogen fertilizer use in China. Recently, the world largest dam, the Three Gorges Dam, was constructed in the Changjiang River. Water storage by the dam was almost complete in June 2006 and full operation began in 2009. Gong et al. (2006) and Jiao et al. (2007) suggested a decrease in nutrient load associated with freshwater discharge and a reduction in primary productivity during summer following the first phase of water storage in June 2003.

The YECS is a temperate coastal area, and spring blooms may be important for primary production. Hyun and Kim (2003) observed that a spring bloom occurred in the middle of the Yellow Sea in April. Furuya et al. (2003) also reported sporadic increases in chl-*a* in April between the 50-m and 150-m isobaths along the PN

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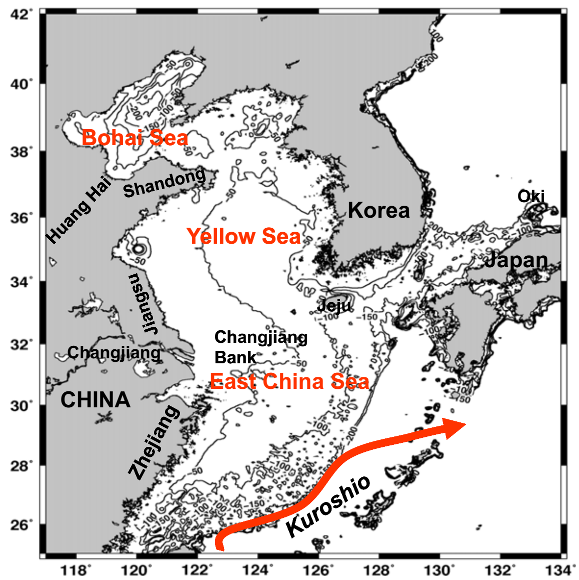

Fig. 1. Map of the study area with bathymetry.

observation line. However, there is no detailed information about spring blooms in the East China Sea (Gong et al., 2003).

Satellite ocean color data are expected to be useful for detecting the temporal and spatial variability and magnitude of chl-*a* increases caused by the spring bloom and summer CDW. Ning et al. (1998) examined Coastal Zone Color Scanner (CZCS) data from 1978 to 1986 and found that these data were useful for distinguishing the character of physicobiological regions. Kiyomoto et al. (2001), using CZCS and Ocean Color and Temperature Scanner (OCTS) data, suggested that spring blooms may occur over a large area of the East China Sea. However, they also reported that these ocean color satellite data overestimated chl-*a* concentrations near the coast because of high concentrations of re-suspended sediment. Gong (2004) also suggested that high levels of colored dissolved organic matter (CDOM) from the Changjiang River may have resulted in an overestimation of satellite chl-*a* concentrations (SCHL). Despite the uncertainties surrounding the concentration data, SCHL should provide important information for this region. For example, Kim et al. (2009b) used Sea-Viewing Wide Field-of-view Sensor (SeaWiFS) data to detect interannual variability in the CDW distribution in the East China Sea.

In this study, we investigated the distribution of seasonal variations in SCHL in the YECS caused by spring bloom and summer CDW as well as possible overestimations of SCHL due to re-suspension of sediment in winter (in the region 25–42°N, 117–134°E, Fig. 1). We also examined the summer interannual variation in SCHL as affected by CDW due to variations in CRD, including variations influenced by the Three Gorges Dam.

2. Materials and methods

Daily SCHL and normalized water-leaving radiances at 555 nm (nLw555) data from September 1997 to October 2006 from NASA SeaWiFS Reprocessing 5.1 Level 2 Global Area Coverage (GAC) were used. The nLw555 data can serve as an index of suspended sediment (Ahn et al., 2001). Both the SCHL and nLw555 data sets had spatial resolution of 4 km. The monthly composites for each year and the 10-year averages were calculated from daily geometrically corrected SCHL and nLw555 data using Windows Image Manager (WIM) software (http://www.wimsoft.com/).

In this study, spring, summer, fall, and winter were defined loosely as March to May, June to August, September to November, and December to February, respectively. To understand the spatial differences in the seasonal changes in SCHL due to suspended sediment in winter, the spring bloom and CDW in summer, the distribution of the maximum 10-year averages of monthly SCHL, and the months corresponding to maxima from March to May and June to September were derived. The maximum months were filtered by a median filter over the neighboring 9×9 pixels. In addition, 12 representative areas for examination of seasonal and interannual variations in SCHL and nLw555 were chosen based on the distribution of the maximum months from March to May and June to September. Even if the maximum month was the same, geographically separated regions were identified as different areas.

The monthly CRD data from September 1997 to August 2006 at the Datong station were used to explain SCHL variations during summer (Zhu, personal communication).

3. Results

3.1. Spatial variability in SCHL and nLw555

Nine-year averages of SCHL were higher (0.3–2.5 mg m^{-3}) on the continental shelf than in the shallower Kuroshio area (0.02–0.3 mg m^{-3}); SCHL in the Changjiang River mouth and Bohai Sea was particularly high (3.0–25 mg m^{-3}) (Fig. 2). During winter, the high SCHL tongue-shaped structure near the Changjiang Bank extended toward the southeast along the 50-m isobath. During April, SCHL was high (1.3–20 mg m^{-3}) over the eastern East China Sea, Yellow Sea, and Bohai Sea, and the tongue-shaped structure became unclear due to the increase of SCHL in the surrounding areas. During summer, the tongue-shaped structure on the Changjiang Bank became more clearly defined again and extended toward the northeast and reached around Jeju Island in August. During September, the high SCHL tongue-shaped structure changed direction from northeastward to southeastward.

The 10-year averages of nLw555 were also high (0.5–7.0 mW cm^{-2} um^{-1} sr^{-1}) in the coastal regions and similar to SCHL, especially near the Yellow River (Huang He) mouth, the Changjiang River mouth, and the coast of Jiangsu in all seasons (Fig. 3). During winter, a high nLw555 tongue-shaped structure on the Changjiang Bank extended to the southeast over the area shallower than the 50-m isobath. The shape of the high nLw555 area was very similar to the tongue-shaped structure of the high SCHL described previously (Fig. 2), and SCHL in this region was expected to be overestimated because of the presence of large amounts of suspended sediment re-suspended from the bottom, as suggested by Kiyomoto et al. (2001). During February, the tongue-shaped structure spread widely and connected to the area of high nLw555 around the Korean coast. The high nLw555 tongue-shaped structure was observed until May and disappeared during summer. The distribution was quite different from that of SCHL; high SCHL were observed over the YECS in April and a high SCHL tongue-shaped structure extended during summer. The area of high SCHL with low nLw555 that occurred during April–August was not expected to be strongly affected by suspended sediment.

3.2. Spatial distributions of maximum months of SCHL during spring and summer

SCHL maxima were found in April during spring (March–May) in large areas of the middle YECS (Fig. 4A) and in March in a large area of the Bohai Sea, along the coast of the Yellow Sea, and on the Changjiang Bank. Maximum values of SCHL were also seen in March outside the Kuroshio area and in May from the Changjiang River mouth to the Zhejiang coast.

Maximum SCHL was seen in June during summer (June–September) in the middle of the Yellow Sea, near and offshore the

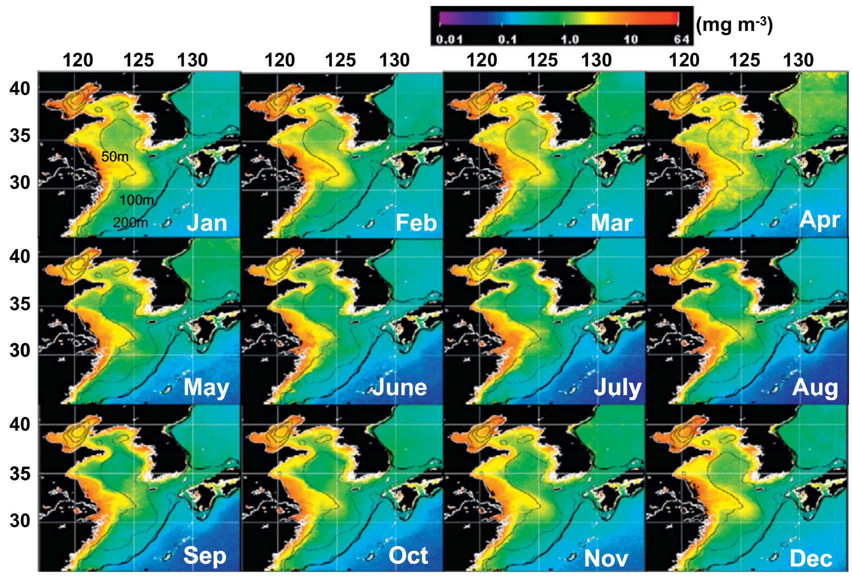

Fig. 2. Distribution of 10-year average of monthly SCHL with bathymetry.

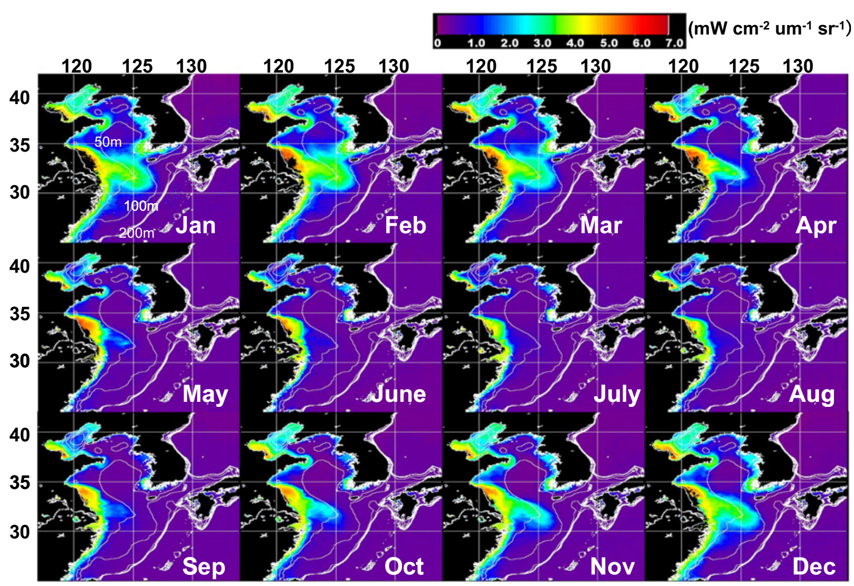

Fig. 3. Distribution of 10-year average of monthly nLw555 with bathymetry.

Zhejiang coast, and from the Ryukyu Islands to the western coast of Kyushu (Fig. 4B). SCHL maxima were also detected in areas between the Changjiang River mouth and the shelf break of the East China Sea, around the Changjiang Bank, and from east of Jeju Island to the southwestern Sea of Japan during July, August, and September, respectively. In September, maximum SCHL was observed off the Korean and Chinese coasts, in the southeastern Yellow Sea, and between the shelf break of the East China Sea and the Kuroshio region.

3.3. Areal difference in seasonal variation of SCHL and nLw555

A spring maximum in SCHL was seen in April (0.61–2.32 mg m^{-3}), whereas nLw555 were lower than in winter (0.37–1.09 mW cm^{-2} um^{-1} sr^{-1}) in the middle of Yellow Sea, southwest of the Korean coast, east of Jeju Island, southeast of the Changjiang River mouth, east of the Changjiang Bank area, offshore from the Zhejiang coast, and in the shelf break area (Areas 2, 4, 6, 8, 9, 10, and 11) (Fig. 5). Since these high SCHL were not caused by high contents of suspended sediment, these spring maxima could be the results of spring blooms.

A summer maximum in SCHL was observed offshore from the Zhejiang coast (Area 10) and Jiangsu coast, near and southeast of the Changjiang River mouth and at the shelf break area (Areas 5, 7, 8, and 11), and east of the Changjiang Bank area (Area 9) in June, July, and August, respectively (Fig. 5). These distributions indicate the eastward movement of the summer maximum SCHL area and show that the maximum decreased with distance from the Changjiang River mouth (8.3 mg m^{-3}) eastward in those areas (1.34 mg m^{-3}). Additionally, in these areas, nLw555 during summer were smaller than those during winter; nLw555 were less than 2 mW cm^{-2} um^{-1} sr^{-1}.

Maximum SCHL (0.70–0.95 mg m^{-3}) and low nLw555 (<1 mW cm^{-2} um^{-1} sr^{-1}) were observed in the fall southwest of

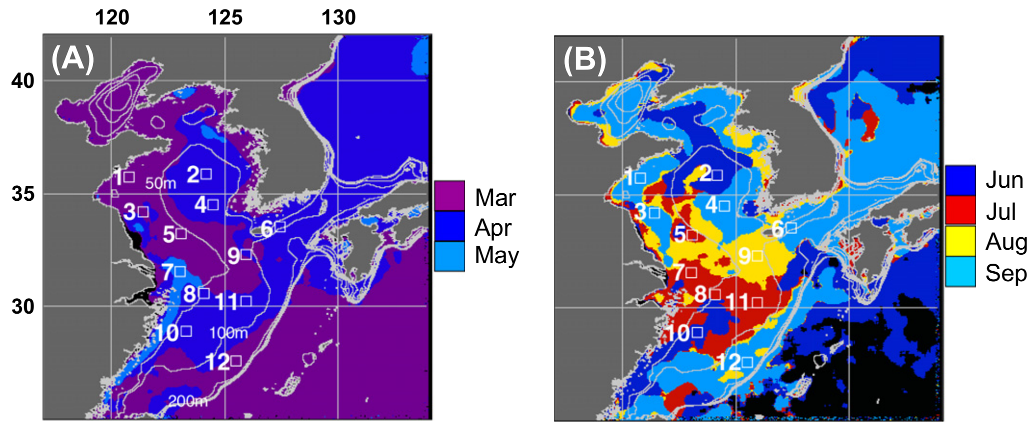

Fig. 4. Distribution of maximum month of 10-year average of SCHL during spring (March–May) (A) and summer (June–September) (B). White squares indicate the representative areas based on the distributions of maximum month of 10-year average of SCHL during spring and summer (Table 1). Light gray lines indicate the coastline and bathymetry.

the Korean coast and east of Jeju Island in September (Areas 4 and 6) (Fig. 5).

High SCHL (1.1–6.3 mg m^{-3}) and high nLw555 (1.9–4.5 mW cm^{-2} um^{-1} sr^{-1}) were observed during winter to early

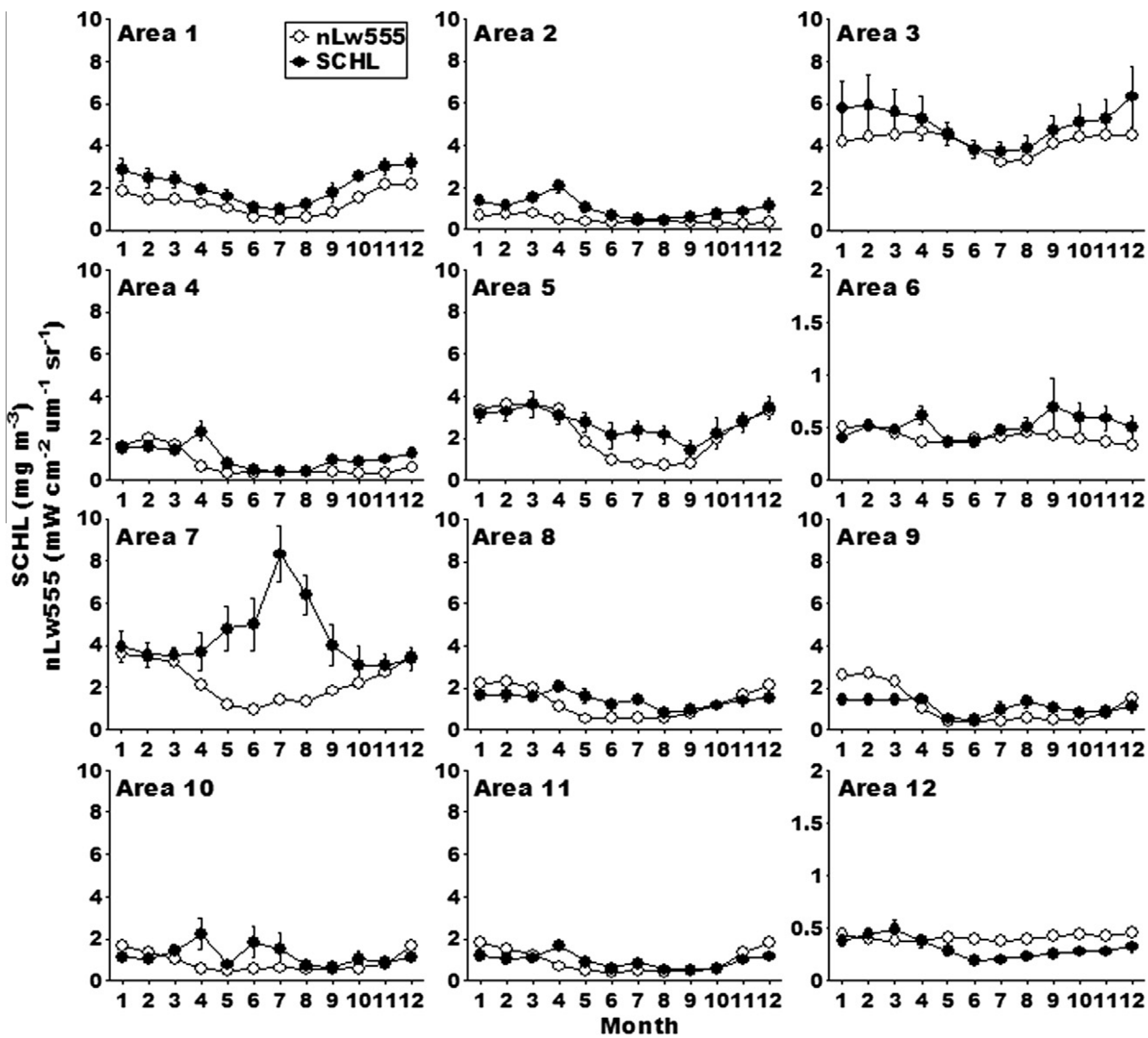

Fig. 5. Seasonal variations in the 10-year average of SCHL (closed) and nLw555 (open) in each area (see Fig. 4 and Table 1). The bars of SCHL indicate spatial standard deviation in each area.

Table 1
Location and season of the SCHL maximum in each area.

Area	Location	Seasonal SCHL maximum
1	Near Shandong coast	Winter
2	Middle of Yellow Sea	April
3	Near Jiangsu coast	Winter
4	Southwest of the Korean coast	April, September
5	Offshore of the Jiangsu coast	July, Winter
6	East of Jeju Island	April, September
7	Changjiang River mouth	July
8	Southeast of the Changjiang River Mouth	April, July
9	East of the Changjiang Bank area	April, August
10	Offshore of the Zhejiang coast	April, June
11	Shelf break area	April, July
12	Kuroshio region	March

spring (December–March) in coastal areas of the YECS and around the Changjiang Bank (Areas 1, 3, 4, 5, 7, 8, and 9). In particular, SCHL were higher than in other seasons at the Shandong coast and near and offshore of the Jiangsu coast (Areas 1, 3, and 5) (Table 1, Fig. 5). Because changes in both parameters in those areas during winter to early spring were very similar, it is possible that the high SCHL may be a result of overestimation caused by high turbidity.

3.4. Summer interannual variation of SCHL and CRD

As described in 3.3, the summer maximum of the 10-year average of SCHL extended from southeast of the Changjiang River mouth to east of Jeju Island (Areas 8, 9, and 6) (Fig. 5). In those areas, the magnitude of the SCHL maximum was high in years when the CRD maximum was high, with a time lag of a few months between the maxima (Fig. 6). The areas in which SCHL and CRD were positively correlated ($r > 0.50$, $p < 0.005$) with time lags of 0, 1, and 2 months clearly corresponded with the areas around the Changjiang River mouth (Fig. 7A), around the Changjiang Bank (Fig. 7B), and from Jeju Island to the Tsushima Strait (Fig. 7C), respectively. The maxima of CRD and SCHL from June to September in each year showed positive correlation southeast of the Changjiang River mouth (Area 8) (Fig. 8A, $r = 0.73$, $p < 0.05$) and in the area east of Jeju Island (Area 6) (Fig. 8C, $r = 0.83$, $p < 0.01$). The maxima were also weakly correlated east of the Changjiang Bank, although the significance of this correlation was not strong (Fig. 8B, $r = 0.26$, $p > 0.1$). However, the correlation was more significant if the data of 2004, when SCHL in this area were abnormally high for an unknown reason, were excluded ($r = 0.66$, $p < 0.1$).

SCHL in the area near the Shandong coast and the middle of the Yellow Sea (Areas 1 and 2) increased over the 10 years in summer with no corresponding change in nLw555 (Fig. 6). SCHL and CRD were also negatively correlated with time lags of 1 and 2 months ($r < -0.50$, $p < 0.005$) in the middle to north Yellow Sea (Fig. 7B). The negative correlation indicates a coincidence of an increase in SCHL and a decrease in CRD.

4. Discussion

4.1. Seasonal variability of SCHL

The distribution of areas with high SCHL corresponded well with the distribution of areas with high nLw555 for areas shallower than 50 m in the YECS during winter (Figs. 2 and 3); as a result, SCHL was thought to have been overestimated by the presence of high suspended sediment, as suggested by Kiyomoto et al. (2001). Siswanto et al. (2011) found a similar overestimation of SCHL in the YECS coinciding with areas where nLw555 > 1–3 mW cm^{-2} um^{-1} sr^{-1}. The areas with the highest nLw555 in the Bohai Sea, Changjiang Bank, and Changjiang River mouth corresponded to areas with fine grained bottom sediment (Zhu and Chang, 2000); re-suspension of the sediment can occur due to vertical mixing caused by a strong northeast monsoon (Xie et al., 2002). Furthermore, cross-shelf circulation has been suggested to transport coastal sediment to the middle of the East China Sea (Yuan et al., 2008). The development of a better case-II algorithm (i.e., an algorithm for waters where optical properties are mainly controlled by non-phytoplankton-derived material) is required for further analysis of chl-*a* variability in those areas during winter.

An area with SCHL maxima coinciding with low nLw555 was observed over a large part of the YECS shelf (Areas 2, 4, 6, 8, 9, 10, and 11) in April (Fig. 5). Higher chl-*a* concentrations from the Changjiang River mouth to the Okinawa islands were observed in April 1996 (0.4–2 mg m^{-3}) than in summer 1994 (0.4 mg m^{-3}) and were suggested to be related to the spring bloom along the PN observation line (Furuya et al., 2003; Kanda et al., 2003).

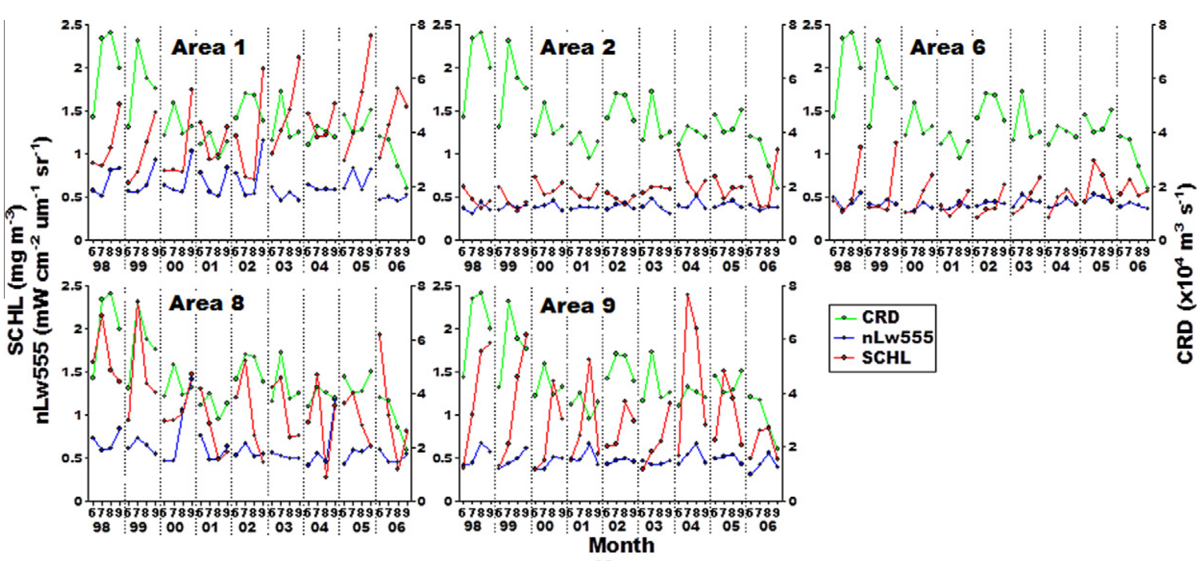

Fig. 6. Interannual variations in SCHL (red), nLw555 (blue), and CRD (green) from June to September in each area. Vertical dashed lines denote the border of each year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

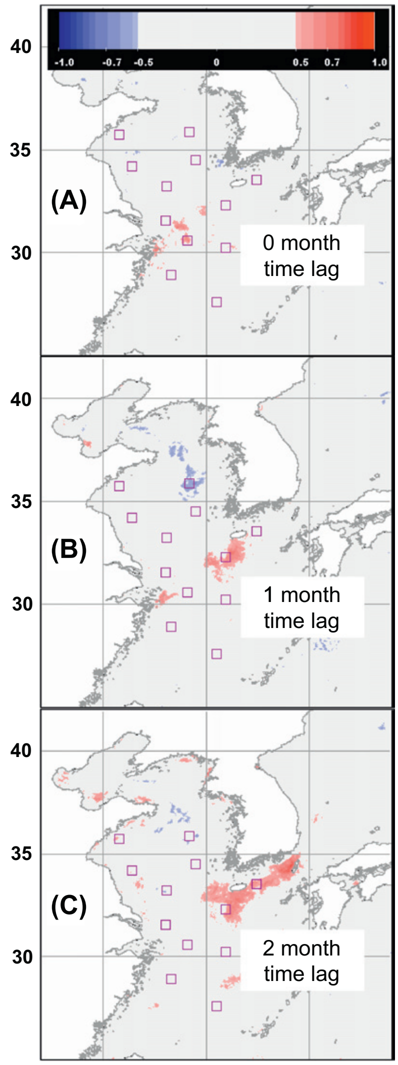

Fig. 7. Correlation between SCHL and CRD from June to September with a time lag of 0 (A), 1 (B), and 2 (C) months over the study area. The color bar indicates the correlation coefficient (*r*). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Meanwhile, high chl-*a* concentrations were not observed (<0.6 mg m^{-3}) on the shelf of the southern East China Sea in March 1998 (Gong et al., 2003). It is assumed that the correspondence of high SCHL and low nLw555 in large areas of the YECS in April related to the spring bloom and that the bloom continued until May (although SCHL in May were lower than in April in most of the area). Maxima of the 10-year average of SCHL, and of the low nLw555, were seen in January-March outside the Kuroshio (Area 12) (Fig. 5), indicating that phytoplankton biomass was high during winter in this area.

During summer, the 10-year average of SCHL shifted west toward the northeast from the Changjiang River mouth to east of Jeju Island (Areas 8, 9, and 6) for a period of 2 months (Fig. 6). Kim et al. (2009b) established criteria (>0.48 mg m^{-3}) for classifying the distribution of high SCHL in summer using K-means clustering and reported that the extension of high SCHL areas corresponded to the spread of the low salinity CDW. Our results showed not only the extension of the distribution of high SCHL areas (Fig. 4) but also a shift in the seasonal maximum of SCHL from the Changjiang River mouth to the east of Jeju Island (Fig. 5). This eastward shift in the summer seasonal SCHL maximum corresponds to the movement of the CDW which is influenced by a maximum discharge in July. These results are consistent with those from a numerical modeling study that also indicated that CDW extended northeastward to the Tsushima Strait during the summer within 0 to 2 months (Chang and Isobe, 2003).

Although the 10-year average of summer nLw555 was lower than the spring average (Fig. 3), a large amount of CDOM with fresh water flows through the Changjiang River into the East China Sea. Gong (2004) and Gong et al. (2007) suggested overestimation of SCHL due to CDOM around the Changjiang River mouth during summer. However, Kiyomoto et al. (2001) reported that SCHL and *in situ* chl-*a* were not very different in the eastern East China Sea. Siswanto et al. (2011) also found that overestimation was prevalent in reported high nLw555. The extension and magnitude of SCHL shown in this study were similar to those for ship-observed chl-*a* south of Jeju Island, as reported by Kim et al. (2009a). These results indicated that the CDOM influence might not be great in the middle to eastern parts of the East China Sea and that water with higher chl-*a* concentrations extended from Jeju to the Tsushima Strait. Fairly long (1–2 months) traceability of high SCHL in CDW may be related to the high regeneration rate reported in the East China Sea (Kanda et al., 2003; Chen and Chen, 2003) and to nutrient replenishment from incursion of the Kuroshio across the shelf break (Zhang et al., 2007b).

During fall, maxima of the 10-year SCHL average coinciding with low nLw555 were observed along the southwestern Korean coast and east of Jeju Island in September (Areas 4 and 6) (Fig. 5). Over a large area of the Sea of Japan, the fall bloom appeared between early October and early December (Yamada et al., 2004). Our results indicate that the fall bloom might occur in the southwestern part of the Korean coast and east of Jeju Island; however, it is difficult to identify the fall bloom clearly in the eastern East China Sea because CDW may also affect chl-*a* in this region during September.

4.2. Interannual variability of SCHL and CRD in summer

In summer, interannual variations in SCHL from offshore of the Changjiang River mouth to east of Jeju Island (Areas 8, 9, and 6) were well correlated with interannual variations in CRD with lags of 0–2 months; time lags were longer in areas far from the Changjiang mouth (Fig. 7A–C). Furthermore, interannual variations in the summer maximum of CRD corresponded with maximum SCHL southeast of the Changjiang River mouth and east of Jeju Island (Areas 8 and 6) (Fig. 8A and C). Those results suggested that the area of CDW does indeed relate to CRD as reported by Lie et al. (2003). Kim et al. (2009b) showed that low salinity CDW corresponded to higher SCHL (>0.48 mg m^{-3}) water and that the interannual variations in the area of high SCHL were well correlated with CRD with time lags of 1–2 months. Our results also showed that the magnitudes of SCHL (>0.48 mg m^{-3}) in these areas were mainly controlled by the amount of CRD including the nutrients and indicated that the main pathway for CDW in summer was from offshore of the Changjiang River mouth to the east of Jeju Island. In general, the distribution was consistent with the results of the numerical model of Chang and Isobe (2003). Isobe and Matsuno (2008) suggested possible differences between a low salinity area and high SCHL area and used a numerical model to explain the difference; however, the difference may be due to interannual variability of the CDW distribution caused by wind and other factors, and their assumption of light limitation in the middle of the East China Sea was probably not valid because turbidity (suspended sediment) indicated by nLw555 was not high in CDW during summer (cf. Fig. 3).

Gong et al. (2006) suggested that primary production in the Changjiang estuary during summer in 2003 was low because of the influence of the Three Gorges Dam. However, our results show large temporal and spatial variability of SCHL in the area;

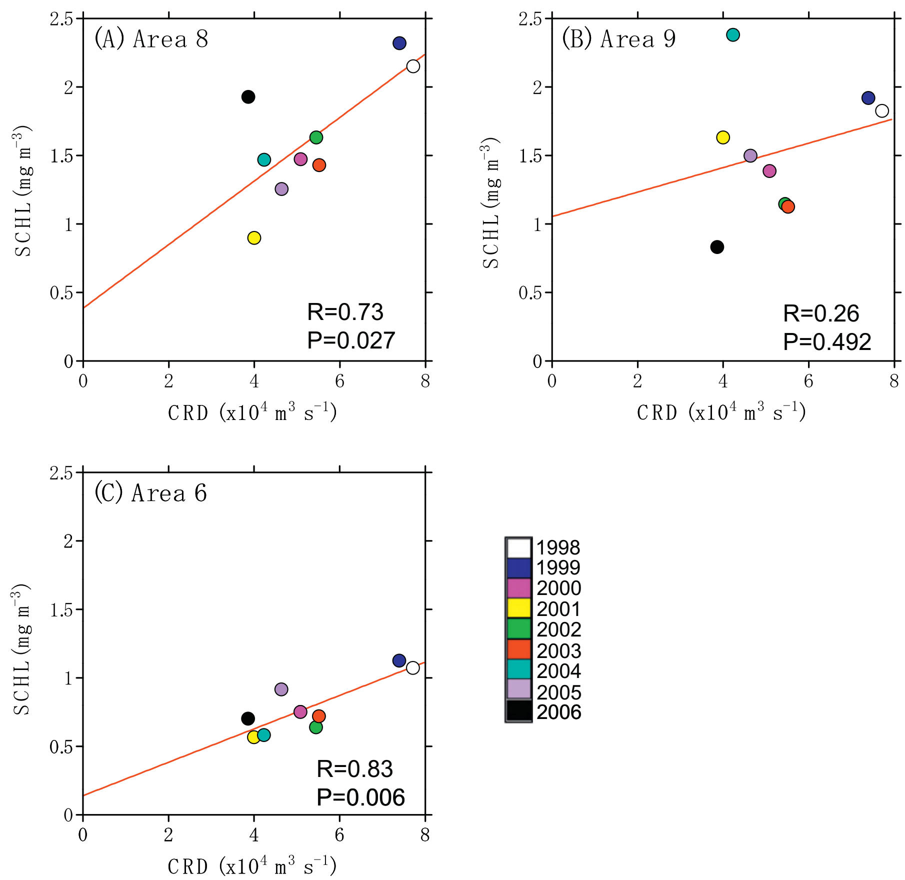

Fig. 8. Scatter plot of the summer maximum SCHL and CRD for Areas 8 (A), 9 (B), and 6 (C). The symbol indicates the month of the maximum value of both SCHL and CRD from June to September in each year. Symbol color shows the year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

furthermore, the areal average of SCHL from offshore of the Changjiang River mouth to around Jeju Island (Areas 8, 9, and 6) and CRD during summer 2003 were in the middle range of values within the 10 years of satellite observation (Fig. 6). In 2006 when the Three Gorges Dam was filled with water during the second phase, the summer SCHL in our study from offshore of the Changjiang River mouth to around Jeju Island (Areas 8, 9, and 6) was lower than in 2003 (Fig. 6). CRD amounts in 2006 were extremely low and reached their lowest for the last 50 years; this was attributable to drought as well as the rise in the water level of the Three Gorges Dam (Dai et al., 2008). Dai et al. (2008) reported that CRD in 2006 was reduced by 54% compared to that in 2005. They estimated that water impounding by the Three Gorges Dam and the extreme drought in 2006 contributed 9% and 45% of the decrease in CRD, respectively. This indicates that filling of the Three Gorges Dam in 2003 and 2006 influenced SCHL and possibly primary production; however, this effect may be small compared with the influence of natural variations in discharge. A more important influence of the dam construction could be the resultant changes in water quality and a decrease in the amount of suspended sediment after full operation of the dam.

Summer SCHL in the Yellow Sea (Areas 1 and 2) increased during the observation period. Lin et al. (2005) reported that DIN increased from year to year in the Yellow Sea from 1976 to 2000 although salinity slightly increased. There was a negative correlation between CRD and SCHL during summer in the middle of the Yellow Sea (Area 2) (Figs. 6 and 7 B). Although Liu et al. (2003) and Lin et al. (2005) suggested that CDW extends to the Yellow Sea from May to October and supplies DIN, it seems that changes in CRD did not directly affect the increase in SCHL in the middle of the Yellow Sea. However, an increase in SCHL is indicative of eutrophication in the middle of the Yellow Sea and might be caused by the increase and accumulation of nutrients from the Changjiang River and other sources including other rivers and atmospheric deposition (Zhang et al., 2007a).

5. Concluding remarks

Analysis of 10-year averages of SCHL and nLw555 of SeaWiFS standard products showed clear seasonal variations in the YECS. During winter, seasonally high SCHL were observed from the Bohai Sea to around the Changjiang Bank because of overestimation of SCHL due to re-suspension of sediment. During spring, a spring bloom was observed from the middle of the Yellow Sea to the middle of the East China Sea. During summer, a shift in maximum seasonal SCHL was observed from the Changjiang River mouth to east of Jeju Island from July to September and this extension corresponded with the movement of CDW. Fundamentally, the presence of CDW during summer and the spring bloom enhance chl-*a* in the YECS.

SCHL and CRD during the summers from 1998 to 2006 were positively correlated with a time lag of 0–2 months from offshore of the Changjiang River mouth to east of Jeju Island, indicating interannual variation. The influence of water impounding by the Three Gorges Dam on SCHL was not as great as that of natural variability. A gradual increase in SCHL in the Yellow Sea during the summer interval might be evidence of eutrophication.

Acknowledgments

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