

Decadal variability in the Yellow and East China Seas as revealed by satellite ocean color data (1979–2003)

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Satellite ocean color data from the Coastal Zone Color Scanner (CZCS) in 1979 to 1984 and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) in 1998 to 2003 are examined to determine whether there have been changes in chlorophyll concentration and suspended sediment as indicated by changes in satellite-derived optical properties during the past two decades in the Yellow and East China Seas (YECS). We compare water-leaving radiance measurements at 443 and 555 nm [the CZCS band is centered at 550 nm, but we consider this comparable to the SeaWiFS 555-nm band] and discuss possible reasons for the changes observed. The shallow coastal areas of the YECS exhibited high water-leaving radiance in the 555-nm band (L_w555) during two time periods, indicating that these waters are sediment-dominated Case-2 waters. Between the CZCS era and the SeaWiFS era, L_w443 increased in these areas by 17%–61%, and L_w555 increased by 67–108%. In the deeper waters, L_w443 decreased by 25%–31%, which would indicate an increase in absorbing materials such as chlorophyll and colored dissolved organic matter (CDOM). Between the CZCS and SeaWiFS eras, the average chlorophyll concentration (based on Case-1 algorithms) increased by 15–60% in these offshore deep waters. Periodical *in situ* measurements from 61 stations in the western coast of Korea from 1978 and 2002 were compared with the trends found in satellite data. The results show that there were increasing trends in temperature and zooplankton biomass, and decreasing trends in salinity and Secchi depth. The satellite data surrounding these stations showed an increase in L_w555 (49 %), a decrease in the L_w443 (–12 %), and an increase in chlorophyll (46 %). From the results, it is inferred that there have been environmental changes in the Yellow Sea during the last two decades from 1979 to 2003.

[**Key words:** Decadal variability, ocean color data, CZCS, SeaWiFS, Yellow Sea, East China Sea, satellite ocean colour]

1. Introduction

Large-scale climatic oscillations, such as El Niño and La Niña, have prompted interest in the effects of climate change on marine ecosystems. The regime shift during 1977–1978 reported in the Northern Pacific Ocean¹, which caused changes in phytoplankton, zooplankton, and fish production^{2–7}, is an example of ecological change brought about by climate change. In Korean waters, Kim & Yoo⁸ reported evidence that fisheries changed in the mid-1970s in association with increasing temperatures, and there have been other reports of climate shifts in Korean waters using zooplankton and fishery data^{9–11}. Significant increases in zooplankton biomass during

the past two decades have been observed in Korean seas^{10,11}. There was an apparent regime shift in Korean waters in 1976 at which time Pacific saury (*Cololabis saira*) decreased and sardine (*Sardinops melanosticta*) biomass increased^{9,11}; anchovy (*Engraulis japonica*), mackerel (*Scomber japonicus*), and sardine (*Sardinops melanosticta*) catches increased along the southern coast of Korea¹⁰.

The US National Aeronautics and Space Administration (NASA) launched the first ocean color satellite sensor, the Coastal Zone Color Scanner (CZCS), in October, 1978. The CZCS collected ocean color data from November 1978 to June 1986. Following an 11-year gap, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) was launched in August, 1997, and continues to provide ocean color data in 2005. The data from these two ocean-color

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sensors can be compared and valuable information can be derived to understand decadal-scale variations in ocean ecosystems. However, a number of constraints [differences in sensor calibrations, atmospheric correction techniques, and the use of different bio-optical algorithms, etc] must be overcome before comparing data from these sensors.

In this paper, we investigated whether there have been decadal trends in the Yellow and East China Seas (YECS) (Fig. 1A). Multi-decadal time series of ocean color remote sensing and *in situ* ecological variables were constructed to provide the observational basis. A conversion algorithm was developed to compare the SeaWiFS chlorophyll concentration with the chlorophyll concentration derived from the CZCS pigment data in YECS. We also compared water-leaving radiances from CZCS and SeaWiFS data in two bands, 443- and 555- (or 550-) nm. Finally, we examined long-term *in situ* measurements provided by the Korea Oceanographic Data Center (KODC) for comparison with trends found in the satellite data.

2. Materials and Methods

2.1. Satellite data

The CZCS level-0 data for the period (1978–1986) and all available SeaWiFS level-1a version-4 data for the Yellow and East China Seas were obtained from the NASA Goddard Space Flight Center (GSFC). Because of large gaps in the CZCS data after 1984, only the CZCS data from 1979 to 1984 were processed. The SeaWiFS data from 1998 to 2003 were processed. The data were processed from level 0 to level 2 and remapped using the SeaWiFS Data Analysis System (SeaDAS) software obtained from NASA GSFC. The standard algorithms in SeaDAS were used for the CZCS and SeaWiFS atmospheric corrections. The standard CZCS pigment algorithm and the SeaWiFS OC4 algorithm were also applied. Then a conversion algorithm (see section 2.2) was applied to the CZCS pigments to obtain a CZCS chlorophyll concentration comparable to the SeaWiFS chlorophyll concentration. Details of this conversion algorithm are described below.

Monthly composites were obtained by averaging all data within each month, and then annual composites of CZCS data from 1979 to 1984, and SeaWiFS data from 1998 to 2003 were derived by averaging the monthly composites. Finally, long-term means were derived by averaging all yearly composites during each period. The study area was

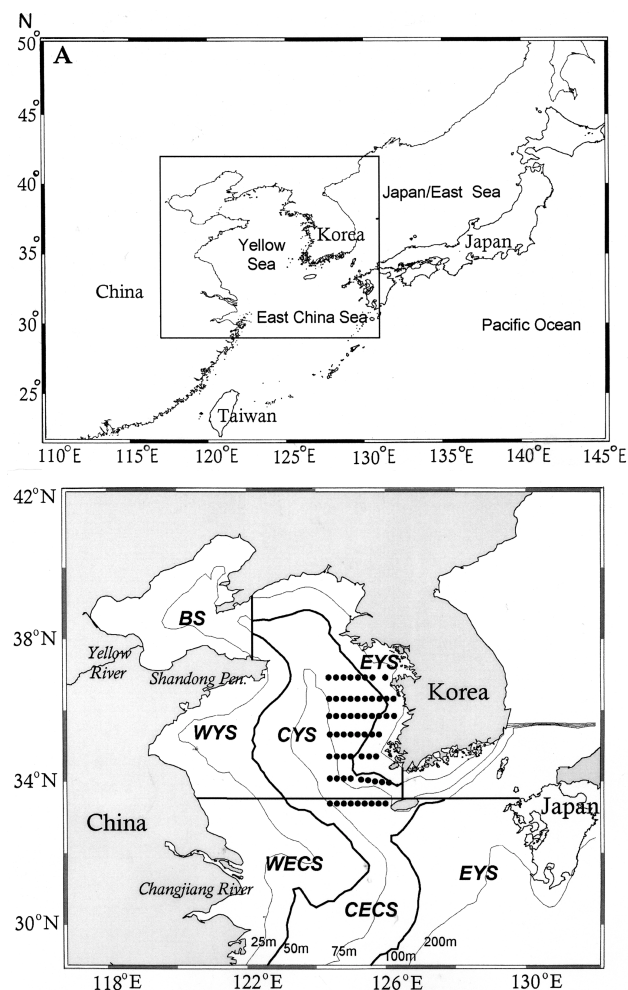


Fig. 1 — (A) Geography of the study area. (B) The study area is categorized into 7 sub-areas (BS: the Bohai Sea, WYS: the western coast of the Yellow Sea, EYS: the eastern coast of the Yellow Sea, WECS: the western East China Sea, CECS: the central East China Sea, and EECS: the eastern East China Sea) and closed circles indicate the serial oceanographic stations of KODC (61 stations).

categorized into seven subregions based on bathymetric contours (Fig. 1B), and the mean and standard deviation of the long-term composite data were calculated within each subregion for the purpose of describing apparent changes that occurred over the two decades. The Bohai Sea (BS) was defined as a subregion distinct from the Yellow Sea. This shallow sea (depths < 50 m) is affected by the Yellow River discharge. The Yellow Sea was categorized into three sub-regions: the western and eastern coastal regions shallower than 50 m, and the central Yellow Sea (CYS) deeper than 50 meters. The CYS stratifies in summer and is considered Case-1 water at that time. The East China Sea was also categorized into 3 sub-regions: the highly turbid, western coastal region

shallower than 50 m, that is affected by the Changjiang (Yangtze) River discharge and tidal mixing; the central East China Sea between 50 and 100 m depth, that is also affected by the buoyant Changjiang River plume, and the eastern subregion deeper than 100 m characterized as clear waters and influenced by the warm and saline Kuroshio current.

2.2. Converting CZCS pigment to chlorophyll concentration

The OC4.V4 chlorophyll algorithm¹² used by the SeaWiFS Project is considered as the standard algorithm for chlorophyll. It gives chlorophyll by the formula:

$$\log_{10}(CHL) = a(0) + a(1) \cdot X + a(2) \cdot X^2 + a(3) \cdot X^3 + a(4) \cdot X^4 \quad \dots(1)$$

where

$X = \log_{10}(\max[R_{rs}(443), R_{rs}(490), R_{rs}(510)] / R_{rs}(555))$ and $a = [0.366, -3.067, 1.930, 0.649, -1.532]$.

The standard pigment algorithm applied to CZCS data¹³ was:

$$\log_{10}(PIG) = a(0) + a(1) \cdot X \quad \dots(2)$$

where PIG is CZCS pigment, $X = \log_{10}(L_w 443 / L_w 550)$ and $a = [1.130, -1.705]$ if the value of $PIG \leq 1.5$; otherwise, $X = \log_{10}(L_w 520 / L_w 550)$ and $a = [3.327, -2.44]$. [Note that this algorithm created a discontinuity at $PIG = 1.5 \text{ mg} \cdot \text{m}^{-3}$].

To account for differences in the CZCS pigment and SeaWiFS chlorophyll algorithms, we used the original SeaBAM data¹⁴. This data set consists of remote sensing reflectance, $R_{rs}(\lambda)$, at wavelengths = 412, 443, 490, 510, 520, 555 and 565 nm, and surface chlorophyll-a concentration (CHL) measurements at 919 stations widely distributed geographically. Our objective was to apply both algorithms to this data set, and then determine a set of equations to convert PIG to CHL . Most of the stations had either the 510-nm band used by the OC4 algorithm, or the 520-nm band used by the CZCS algorithm. The stations that did not have a measured reflectance at 510 nm were not considered, thus reducing the number of stations to $n = 539$. To obtain $R_{rs}(520)$, corresponding to the CZCS band, we used the relationship:

$$R_{rs}(520) = R_{rs}(510) / [a(0) + a(1) \cdot X^1 + a(2) \cdot X^2 + a(3) \cdot X^3 + a(4) \cdot X^4] \quad \dots(3)$$

where $a = [1.0605321, -0.1721619, 0.0295192, 0.0150622, -0.004133924]$ and $X = \log_{10}(CHL)$. This is based on the model of Morel & Maritorena¹⁵. The above-water $R_{rs}(\lambda)$ values were multiplied by the extraterrestrial solar irradiance for each band to obtain the normalized water-leaving radiances, $L_w(\lambda)$. We assumed that the 555-nm band was equivalent to the 550-nm band of CZCS. Using the $L_w(\lambda)$ values for $\lambda = 443, 520$ and 555 , we calculated the CZCS pigment (PIG) according to the standard algorithm¹³ given by equation 2, and using the $R_{rs}(\lambda)$ values for the SeaWiFS bands, we calculated chlorophyll (CHL) by the OC4.V4 algorithm.

Plots of CHL vs. PIG (Fig. 2) shows that a discontinuity occurs when the CZCS algorithm switches from the 443:550 ratio to the 520:555 ratio ($PIG = 1.5 \text{ mg} \cdot \text{m}^{-3}$). At pigment values less than about $0.12 \text{ mg} \cdot \text{m}^{-3}$, there is a deterministic relationship because both algorithms use the 443:550 ratio. The greatest scatter occurs where pigment is between 0.12 and $1.5 \text{ mg} \cdot \text{m}^{-3}$. In this range, PIG is based on the 443:550 radiance ratio whereas CHL is based on the 490:555 ratio. At pigment levels above $1.5 \text{ mg} \cdot \text{m}^{-3}$ (the switching point), the OC4 algorithm uses the 510:555 ratio, whereas PIG uses the 520:550 ratio. The scatter in this range is due to the differences between 510 and 520 nm. The relationship between PIG and CHL is also shown (Fig. 2) as recommended by O'Reilly *et al.*¹⁴, that was subsequently used by Conkright & Gregg¹⁶ for blending CZCS and *in situ* data (see discussion section).

For $PIG < 1.5 \text{ mg} \cdot \text{m}^{-3}$, and $PIG > 5 \text{ mg} \cdot \text{m}^{-3}$, the OC4-derived chlorophyll exceeds the CZCS pigment (despite the conventional view that pigment includes more than just chlorophyll, a view that is reflected in the O'Reilly¹⁴ relationship). However, pigment values in the Yellow Sea region generally fall within the range 1.5 to $5.0 \text{ mg} \cdot \text{m}^{-3}$ where pigment exceeds the OC4 chlorophyll. From these results, we derived formulae for converting level-2 CZCS pigments to obtain a chlorophyll concentration analogous to the OC4-derived SeaWiFS chlorophyll. The lines drawn on Fig. 2 are the formulae:

$$\log_{10} CHL = -0.1813X^4 - 0.1043X^3 + 0.6769X^2 + 1.7495X + 0.3007 \quad PIG < 0.112$$

$$\log_{10} CHL = 0.2311X^2 + 1.1916X + 0.1150 \quad 0.112 < PIG < 1.5$$

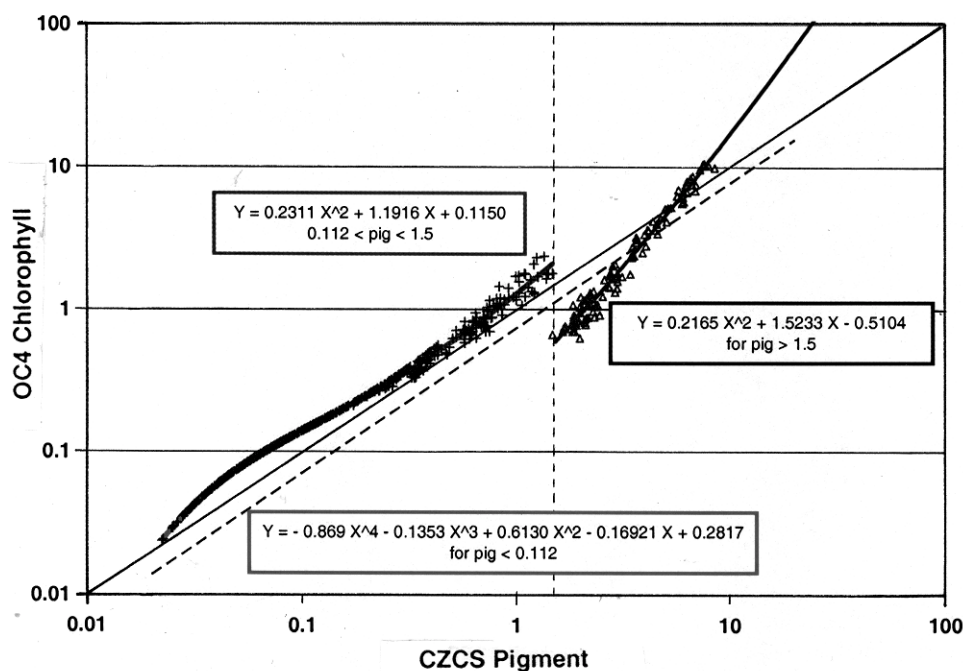


Fig. 2 — Results of applying the OC4 (SeaWiFS) chlorophyll algorithm (vertical axis) and the CZCS pigment algorithm (horizontal axis) to the original SeaBAM data of O'Reilly *et al.*¹⁴ The vertical dashed line marks the value pigment = 1.5 $\text{mg}\cdot\text{m}^{-3}$ where the CZCS algorithm switched from using the 443:550 radiance ratio to the 520:550 ratio. The dashed line is the relationship $\text{CHL} = 0.8 \cdot \text{PIG}$ proposed by O'Reilly *et al.*¹⁴ that was subsequently used by Conkright & Gregg¹⁶.

$$\log_{10} \text{CHL} = 0.2165 X^2 + 1.5233 X - 0.5104$$

$$\text{PIG} > 1.5$$

where $X = \log_{10}(\text{PIG})$, and CHL is the SeaWiFS-compatible (OC4) chlorophyll concentration which we call the “CZCS chlorophyll.”

2.3. The in situ data

For comparison with trends found in the satellite data, we examined temperature, salinity, transparency, and zooplankton data provided by the Korea Oceanographic Data Center (KODC). The serial oceanographic observations in Korean waters are carried out bimonthly (February, April, June, August, October, and December) by the National Fisheries Research and Development Institute (NFRDI). The data for 61 stations in the Yellow Sea from 1978 to 2002 were processed (Fig. 1B).

Zooplankton data were available only from 1978 to 2000 and include the biomass of copepoda, chaetognatha, euphausia, and amphipoda within the water column. Zooplankton samples were collected with NORPAC net with 0.33 mm mesh size and a 45 cm mouth diameter. The net was towed vertically from the bottom to the surface at a speed of 0.5 – 1.0 $\text{m}\cdot\text{s}^{-1}$. Each sample was fixed in 5% formalin and the volume of zooplankton biomass ($\text{mg}\cdot\text{m}^{-3}$) was measured excluding particles larger than 2 cm.

The surface temperature and salinity measurements, Secchi depth, and zooplankton biomass data at the 61 KODC stations were averaged for each year. In addition, the chlorophyll, L_w443 , and L_w555 values were extracted within 3×3 pixel boxes around the 61 KODC stations from the yearly composite CZCS and SeaWiFS data.

3. Results

Individual yearly composites of CZCS data for 1979–1984 and SeaWiFS data for 1998–2002 are shown in Fig. 3. Between the two eras (or, more specifically, between the two satellite data sets), 443 nm radiance in the central Yellow Sea decreased while it increased around the Changjiang River, the southwest coast of Korea, and the Shandong Peninsula. Significant increases in 555 nm radiance are seen in nearly all locations within the study regions of YECS. Likewise, chlorophyll increased nearly everywhere but the apparent increases in the shallow Case-2 waters may be due to changes in other material loadings. The greater interannual variation exhibited by the CZCS data is probably due to its limited coverage.

Long-term composites of CZCS for 1979–1984 and SeaWiFS for 1998–2003 are shown in Fig. 4, and the ratios of SeaWiFS-to-CZCS long-term means are

shown in Fig. 5. For the 443 nm radiance (Fig. 4A), the spatial distribution in the CZCS image is more uniform than that of the SeaWiFS composite image. Compared with the CZCS data, the SeaWiFS L_w443 values have decreased in the central Yellow Sea, but increased around the Changjiang River, along the western coast of Korea, and in the Bohai Sea. The spatial patterns of L_w550 and L_w555 are similar (Fig. 4B), with high values along the coastal regions and

near the Changjiang River. However, L_w555 of the SeaWiFS is much higher around the Changjiang River, off the western coast of Korea, and in the Bohai Sea, and has a wider range between the coastal highs and oceanic lows. The L_w555 and L_w550 values are almost the same, however, in the Sea of Japan/East Sea and eastern portions of the East China Sea.

The spatial pattern of chlorophyll (Fig. 4C) is similar in both data sets, with higher concentrations in

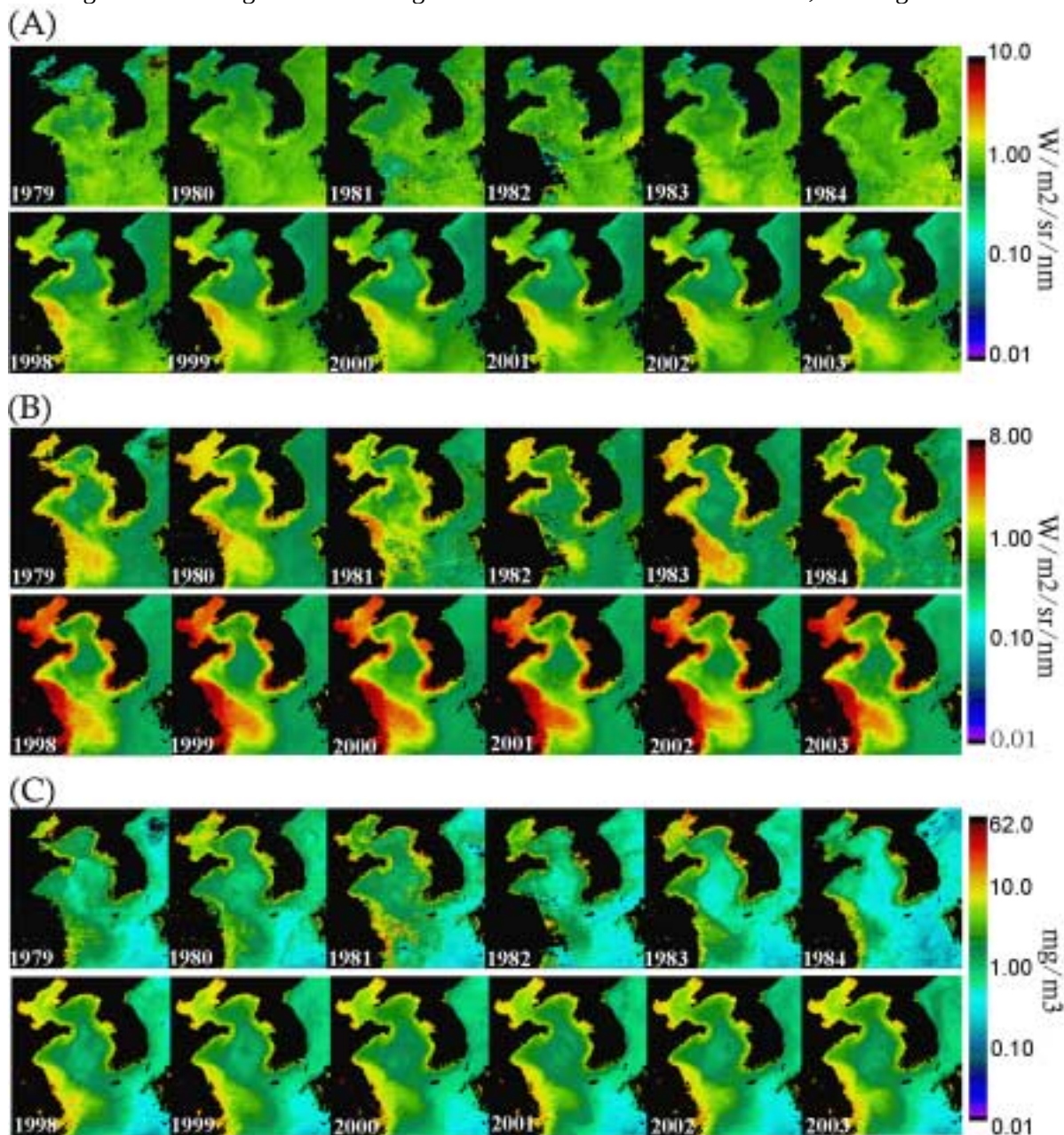


Fig. 3 — Yearly composite CZCS (1979-1984) and SeaWiFS (1998-2003) images of (A) L_w443 , (B) L_w555 and (C) chlorophyll in the Yellow and East China Seas. The scales give water-leaving radiances and chlorophyll.

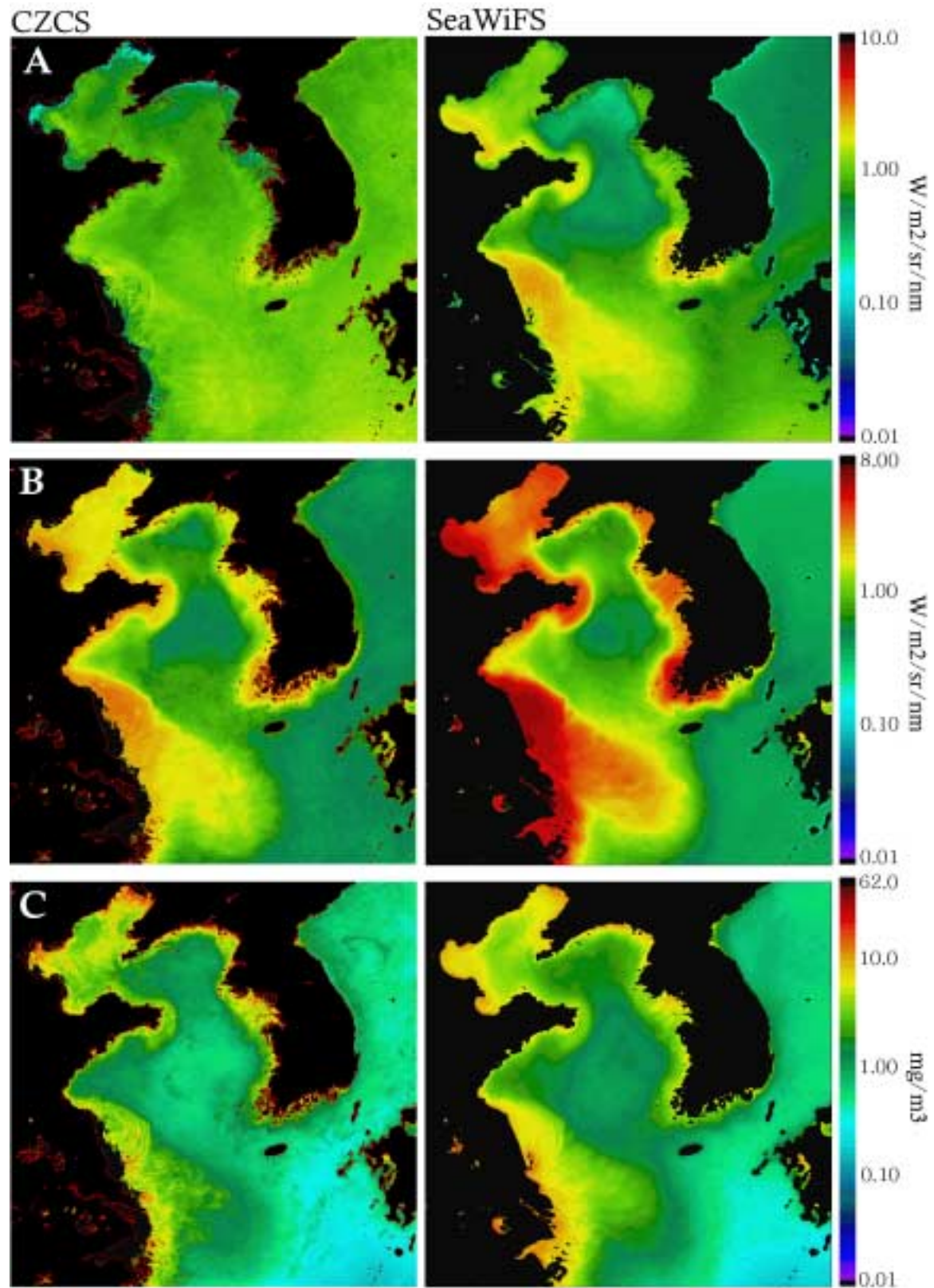


Fig. 4 — Long-term average of CZCS (1979–1984) and SeaWiFS (1998–2003) in (A) L_w443, (B) L_w555, and (C) chlorophyll.

coastal areas and near the Changjiang River, and relatively low values in the central area of the Yellow Sea. The higher chlorophyll concentrations near shore, especially in the western East China Sea and the Bohai Sea, are likely due to resuspended sediments and colored dissolved organic matter. The chlorophyll concentration of SeaWiFS is generally higher than that of CZCS, especially in the area near the Changjiang River, whereas there are slight decreases in the Bohai Sea and the mid-west coastal regions of Korea. Two patches of significantly increased chlorophyll (about 3-fold higher) appear in the Yellow Sea (Fig. 5). The more southerly patch is located around a Korean dump site where dumping has been occurring since 1992. The northerly one, located in North Korean waters, may be the location of another dump site, but is difficult to confirm this.

The means and standard deviations of these variables for the seven sub-regions are listed in Table 1. There were increase in 443 nm radiances in the year-round turbid waters of the Bohai Sea (57%), the west coast of the Yellow Sea (32%), the east coast of the Yellow Sea (17%), and the west-East China Sea (61%). Decrease of 443 nm radiances occurred in the central Yellow Sea (−31%) and the east-East China Sea (−25%), both areas that can be considered as having Case-1 waters at least part of the year. There were dramatic increases in water-leaving radiance at 555 nm for the very turbid shallow regions, the Bohai Sea (92%), west and east margins of the Yellow Sea (68% and 67 %), and the west-East China Sea (108%). There was a smaller increase of 555 nm radiance in the central Yellow Sea (28%), and a decrease in the eastern East China Sea (−5%).

The chlorophyll concentration increased over the entire study area. The greatest increase was in the central Yellow Sea (60%), where the chlorophyll algorithm is more likely to be accurate than in turbid coastal (Case-2) waters. The smallest increase (5%) was found in very turbid areas (the Bohai Sea and east coast of the Yellow Sea). The clearest waters in the region were found in the eastern East China Sea where chlorophyll increased by 15 %.

Unfortunately, there are no *in situ* measurements of optical properties or chlorophyll for the CZCS era that can be used to verify the changes seen in the satellite data. However, we were able to examine long-term monitoring data on temperature, salinity, and Secchi depth for the period 1978 to 2002, and zooplankton biomass for 1978 to 1996 (Fig. 6 A-D). Also shown in this figure are the yearly average chlorophyll, L_w443 ,

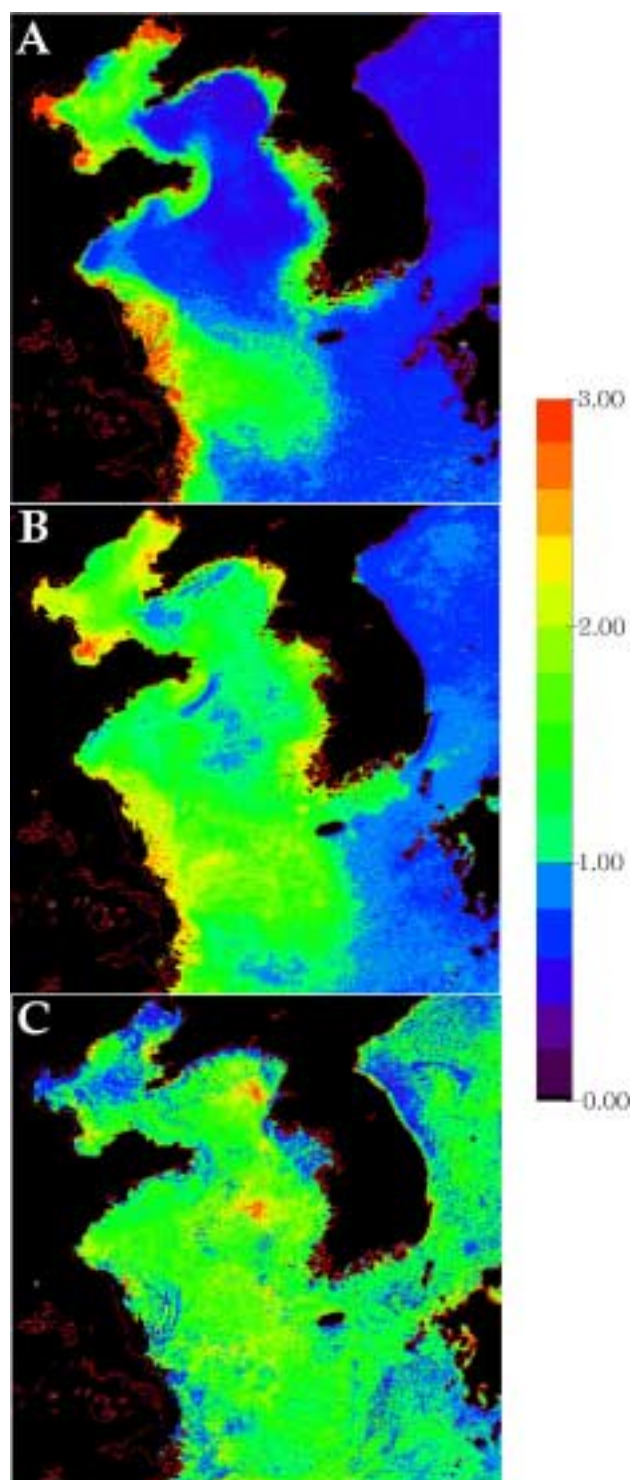


Fig. 5 — Ratios of SeaWiFS-to-CZCS long-term means. (A) L_w443 , (B) L_w555 and (C) chlorophyll. Increases are shown in yellows and reds, decreases in greens and blues, and white indicates no change.

Table 1 — Long-term means and standard deviations of the CZCS (1979–1984) and the SeaWiFS (1998–2003) chlorophyll, L_w443 , and L_w555 for 7 sub-regions: the Bohai Sea (BS), the western coast of the Yellow Sea (WYS), the central Yellow Sea (CYS), the eastern coast of the Yellow Sea (EYS), the west-East China Sea (WECS), the central East China Sea (CECS), and the east-East China Sea (EECS). Ratios and percentiles of SeaWiFS-to-CZCS long-term means were calculated. The units are $\text{mg}\cdot\text{m}^{-3}$ for chlorophyll and $\text{W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}\cdot\text{m}^{-1}$ for water-leaving radiances

Variable	Region	CZCS		SeaWiFS		Ratio	%
		Mean	Stddev	Mean	Stddev		
Chl	BS	5.46	4.10	5.72	2.52	1.05	5
	WYS	2.74	2.11	3.67	2.13	1.34	34
	CYS	0.89	0.31	1.43	0.35	1.60	60
	EYS	3.97	3.54	4.17	2.03	1.05	5
	WECS	3.81	3.06	5.53	3.21	1.45	45
	CECS	1.04	0.68	1.41	0.75	1.36	36
	EECS	0.39	0.20	0.45	0.21	1.15	15
L_w443	BS	0.71	0.23	1.11	0.42	1.57	57
	WYS	1.00	0.23	1.33	0.67	1.32	32
	CYS	0.89	0.15	0.62	0.22	0.69	–31
	EYS	0.79	0.32	0.93	0.53	1.17	17
	WECS	1.02	0.31	1.65	0.34	1.61	61
	CECS	1.11	0.13	1.07	0.22	0.96	–4
	EECS	1.16	0.14	0.87	0.16	0.75	–25
L_w555	BS	1.50	0.39	2.88	1.17	1.92	92
	WYS	1.53	0.64	2.58	0.28	1.68	68
	CYS	0.60	0.15	0.77	0.28	1.28	28
	EYS	1.21	0.41	2.02	1.00	1.67	67
	WECS	1.56	0.34	3.24	1.11	2.08	108
	CECS	0.80	0.26	1.09	0.44	1.36	36

and L_w555 values within 3×3 pixel boxes that were extracted around the 61 stations (Fig. 6E–G). There was an increasing trend in temperature and a decreasing trend in salinity and Secchi depth from 1978 to 2002. Zooplankton biomass showed a clear increasing trend beginning in the late 1980's. Differences between mean values during the CZCS era (1979–1984) and the SeaWiFS era (1998–2002) also reveal changes. The changes between the two satellite eras were: $+0.63^\circ\text{C}$ for temperature, -0.57 psu for salinity, and -0.48 m for Secchi depth, while there were increases in the mean chlorophyll (46%) and L_w555 (49%), and a decrease in L_w443 (–12%).

4. Discussion

The results showed differences between the CZCS and SeaWiFS data in terms of changes in the YECS rather than differences in the sensors or algorithms. However, the apparent changes may be due to differences between the sensors and algorithms. Here we will discuss possible reasons why the normalized water leaving radiances may be different. The changes in chlorophyll concentration are a direct result of differences in water-leaving radiances, since we have eliminated differences due to the bio-optical (chlorophyll vs. pigment) algorithms.

Water-leaving radiances are derived by applying an atmospheric correction to calibrated, top-of-atmosphere (TOA) radiances. Accurate calibration of the sensor is a critical requirement, and inaccurate calibrations are a potential source of differences between CZCS and SeaWiFS. The CZCS calibration was suspected of drifting during its 8-year mission, but there was no means to calibrate the sensor in orbit. Its calibration was adjusted retrospectively by assuming that no real environmental changes had occurred in the global radiance distributions during its lifetime¹⁷. SeaWiFS has collected ocean color data since September 1997, and continues in 2005 to produce global products that are the best examples of climate quality ocean color data currently in existence. Until 2004, SeaWiFS calibration was monitored regularly both for stability (by viewing the moon periodically) and vicariously where atmospherically-corrected satellite radiances are compared with *in situ* water-leaving radiances, and adjustments made to the TOA calibration to force agreement.

We do not believe that differences in calibration can explain the differences between the CZCS and SeaWiFS radiances. Although there are undoubtedly differences, such differences would be manifest as

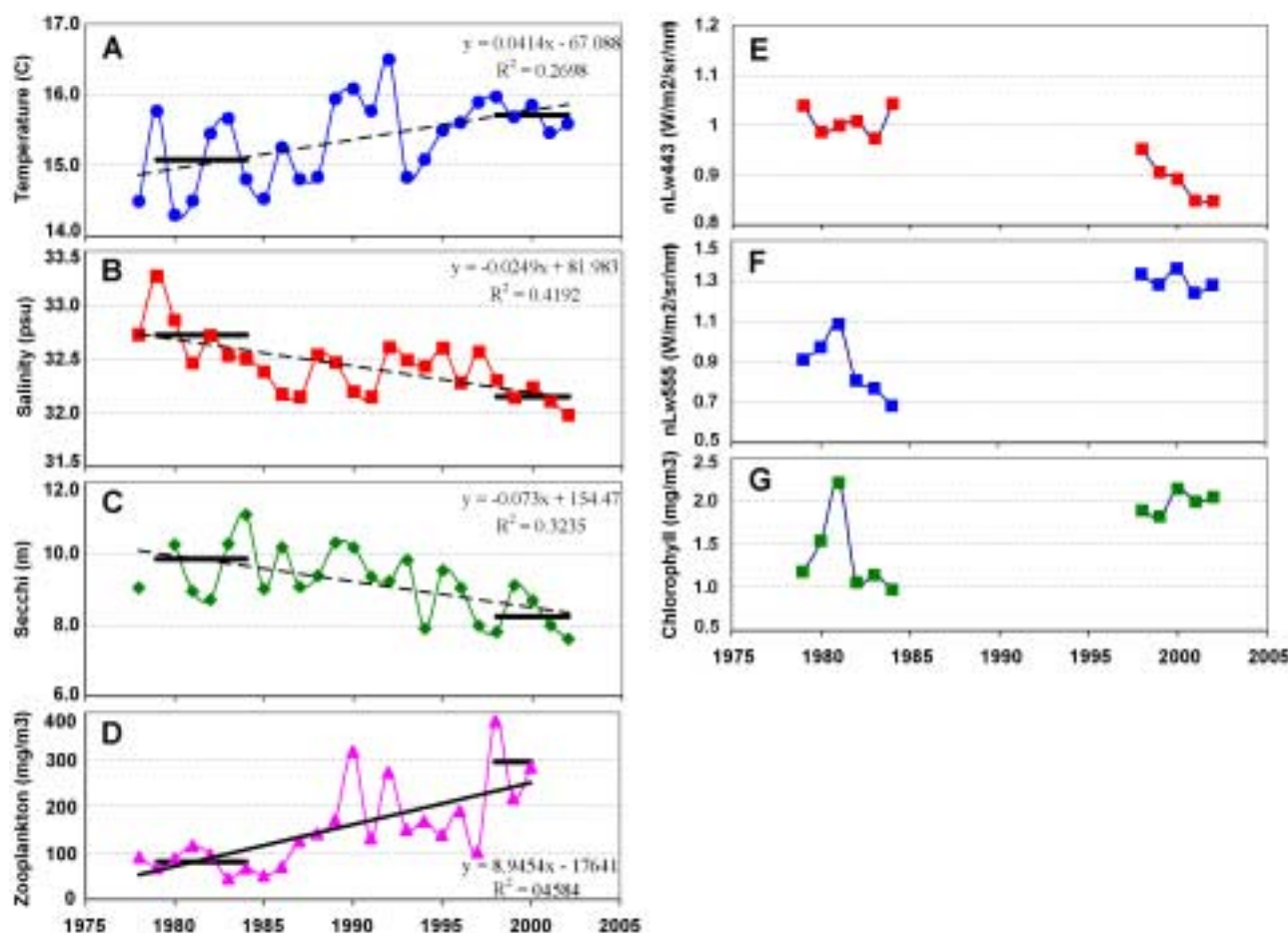


Fig. 6 — The year-to-year variations of (A) temperature, (B) salinity, and (C) Secchi depth from 1978 to 2002, and (D) zooplankton biomass from 1978 to 1996 at the 61 KODC stations in the Yellow Sea. Dashed lines are the trend lines and thick horizontal lines are the means values for the CZCS (1979–1984) and SeaWiFS (1998–2002) eras. The yearly averaged (E) chlorophyll, (F) L_w443 , and (G) L_w555 values of the CZCS (1979–1984) and the SeaWiFS (1998–2002) are also plotted.

systematic biases (i.e., one band being systematically high or low everywhere relative to its counterpart on the other sensor). The most likely sensor-related reason for differences in the water-leaving radiances, other than real ecosystem changes, are differences in the atmospheric corrections.

There are two major differences between the CZCS and SeaWiFS atmospheric correction algorithms. One concerns the aerosol model(s) used and the other concerns the “black pixel assumption” (namely, the assumption that water-leaving radiance is zero in the near-infrared). The CZCS used a single near-infrared band (670 nm), assumed to have zero water-leaving radiance, and a single marine aerosol scattering model which was non-spectral. Continental aerosols tend to scatter more efficiently in the blue region of the spectrum, and thus their contribution to the atmospheric scattering signal would have been underestimated at 443 nm by the CZCS. This would

result in an overestimation of L_w443 by the CZCS, and consequent underestimation of chlorophyll. The black-pixel assumption, on the other hand, fails in turbid coastal waters. It certainly was not valid over the Changjiang River plume or in the Bohai Sea. The result of this assumption (by the CZCS) is that the aerosol optical thickness is overestimated, and thus L_w443 and L_w550 would be underestimated.

The SeaWiFS has two near-infrared bands that are used to estimate the aerosol optical thickness as well as to select an aerosol type. Furthermore, it uses an iterative algorithm developed by Siegel *et al.*¹⁸ which no longer makes the “black pixel” assumption. Neither sensor corrects for absorbing aerosols, however. Absorbing aerosols, such as the yellow dust often found over the YECS region, have the effect of reducing the atmospheric path radiance. If they are not included in the atmospheric correction, this reduction is attributed to absorbing materials in the

water, and thus chlorophyll is overestimated (L_{w443} underestimated).

It is entirely possible that the trends seen in the radiances are due to differences between the atmospheric correction algorithms. The most likely reason is the CZCS algorithm's use of the "black pixel" assumption. This could explain why the turbid coastal regions have much lower water-leaving radiances in the CZCS data compared with the SeaWiFS data. As for differences due to the aerosol models used, this is not as likely to be a reason for the decadal trends observed (Figs. 3 and 4) because the spatial patterns are more oceanic than atmospheric. Continental aerosols, for example, would not be confined to the shallow coastal areas but would extend across the entire region. The prominent Changjiang River plume is clearly a feature in the water rather than the atmosphere. Its apparent increased turbidity between CZCS and SeaWiFS cannot be explained by differences in aerosol models, whereas it can be explained by the black pixel assumption of CZCS. It might be possible to eliminate this problem by reprocessing the CZCS data using the iterative scheme of Siegel *et al.*¹⁸.

Another important point that should be mentioned concerns the chlorophyll distributions. Much of the Yellow and East China Seas are Case-2 waters throughout the year, and therefore the Case-1 algorithms for pigment and chlorophyll are potentially unreliable. Here we were not concerned as much with their accuracy as with the question of whether long-term environmental changes have occurred and might be detectable. If the water-leaving radiances were correct, these results would suggest that absorbing materials (including chlorophyll and CDOM) have increased everywhere in the YECS between the CZCS and SeaWiFS eras. The two regions that can be considered as Case-1 waters, at least part of the year, are the central Yellow Sea in summer and the eastern East China Sea. The central part of the Yellow Sea showed the most extreme increase in chlorophyll (60%) whereas the eastern East China Sea had a smaller change (15%).

The CZCS climatology was compared with a large *in situ* database by Gregg & Conkright¹⁹, and a comprehensive comparison of CZCS and SeaWiFS chlorophyll climatologies has been presented by Conkright & Gregg¹⁶. They used the *in situ* measured chlorophyll as "internal boundary conditions" to blend with the CZCS data, thus producing a blended climatology that was considered to be a better

representation of global chlorophyll distributions. The SeaWiFS climatology (October 1997- June 2001) was within ~10% of the blended climatology derived from CZCS and *in situ* data. In this work, the CZCS pigment was converted to chlorophyll using a formula prescribed by O'Reilly *et al.*¹⁴ (shown as the dashed line in Fig. 2). They found that the CZCS chlorophyll, thus derived, was significantly lower than the *in situ* chlorophyll measurements.

One thing to notice is that their¹⁹ formula for converting *PIG* to *CHL* was substantially different from present formula (see Fig. 2). The ratio of present CZCS chlorophyll to theirs¹⁹ (based on their formula) ranges from 0.76 to 2.5 with only a narrow *PIG* range where the ratio is below 1. In the open ocean, below the switching point of the CZCS algorithm, the ratio is always above 1 (ranging from 1.27 to 2.5). Thus, presumably if Gregg & Conkright¹⁹ had used present formula, their CZCS chlorophyll values would be much higher, and the discrepancies with the *in situ* data would be less.

The difference between CZCS and SeaWiFS chlorophylls in the very turbid waters from our results is much smaller compared with that in Conkright & Gregg's¹⁶ result whereas the range of the chlorophyll difference in the other areas is similar to the result of Conkright & Gregg¹⁶. The difference between CZCS and SeaWiFS chlorophyll was relatively small in the east-East China Sea characterized as open ocean which is affected by the Kuroshio current ($+0.06 \text{ mg m}^{-3}$).

The ratios of radiances at 443 and 555 nm between long-term composite SeaWiFS and CZCS show a very large increase in the SeaWiFS era in the same turbid areas. The Bohai Sea is affected by the Yellow (Hwanghe) River. It has been reported that construction of dams and low rainfall has led to a decrease of about 50% in both water and sediment discharge on the Yellow River in recent years, and the river was dry²⁰ for four months in 1995. The Three Gorges dam, which is the largest one in the world, was being constructed on the Changjiang River since 1992 and recently completed in May, 2003. The dam will be operating in 2009. A recent study has shown that there was more than 20% decrease of sediment discharge in the Changjiang River from 1980s to 1990s while there was increase of water discharge by 10% as a result of human activities such as deforestation and impoundments²¹. Increases in water-leaving radiances at 443 and 555 nm are spatially coherent with higher turbidity occurring in shallow

regions and in the river plumes. The changes in water-leaving radiances could be related to the changes of fresh water and sediment discharges. Changes of discharge in major rivers in Korea are not known, although the amount is smaller compared with that of the Changjiang River²².

In the ratio of SeaWiFS to CZCS chlorophyll, there were two chlorophyll patches in the central Yellow Sea where the chlorophyll had increased much more than in the surrounding area. The more southerly patch is located around a Korean dump site that has been used since 1995. Organic matter dumped in the area could affect the increased chlorophyll concentration. The more northerly patch is located in North Korean waters, and thus it is difficult to know what caused the increase in chlorophyll concentration because there is no information for that area. The ratio of chlorophyll is relatively low in the very high turbid waters, the Bohai Sea, the mid-west coast of Korea, and along the east coast of China (especially, along the Shandong Peninsula and the Changjiang River).

The comparison of year-to-year variation in July and November shows that the chlorophyll values are clearly higher in SeaWiFS images in most of the region, and notably in the central waters of the Yellow Sea which are Case-1 in the summer. There were comparisons between two periods for the satellite ocean-color data and *in situ* data over the 61 KODC stations in the Yellow Sea. In the *in situ* data, there were increasing trends in temperatures and zooplankton biomass and decreasing trends in Secchi depth and salinity. While there were increases in the mean chlorophyll and L_w555 , the L_w443 decreased. The increase of temperature and zooplankton could be associated with increases of chlorophyll, and the decrease of salinity and Secchi depth with increased turbidity due to increase of chlorophyll and/or river runoff. The central regions of the Yellow Sea may be affected by higher levels of atmospheric pollution (e.g., nitrogen species acting as a fertilizer and changes in the deposition of Yellow Dust, which may enhance biomass).

In comparing CZCS with SeaWiFS data, no attempt was made to unify the atmospheric correction algorithms. Thus, it is likely that differences in the atmospheric correction between the ocean color sensors might account for the difference of water-leaving radiance at 443 nm. To resolve this we would need a unified algorithm that can correct for absorbing aerosols. Furthermore, for these Case-2 waters where mixtures of organic and inorganic

materials affect the color of the water, more sophisticated bio-optical algorithms must be developed to account for the unique optical characteristics and variation of environmental parameters. However, from the time series of *in situ* data, it is inferred that there have been environmental changes in the Yellow Sea during the last two decadal from 1979 to 2003.

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